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Appendix A

Extended Base Period Metrics for 1990–Present Time Period

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Extended Base Period Metrics for 1990-Present Time Period

NOAA Fisheries evaluated “Base Period” estimates by focusing on the time period used by the ICTRT for recovery planning, which encompasses approximately the 1980 through 1999 brood years (which include spawner returns at age through about 2004 or 2005). Updated estimates that include recent return years are presented in Section 2.1.1.4.2 of this Supplemental Opinion.

NOAA Fisheries also evaluated an alternative historical time period for “base” estimates, which began in 1990, rather than 1980. Prospective estimates based on this alternative time period were included in Tables 1 through 12 of Appendix B of the 2008 BiOp under the headers “Average R/S: 10-yr non-SAR adj.; non-delimited,” “12-yr Lambda HF=0,” “12-yr Lambda HF=1,” and “1990-Current [BRT] Trend.” As described in Appendix B of the 2008 BiOp, productivity estimates were derived from this alternative Base Period of approximately 1990 to the present because this time period is described in the Metrics Memo (NMFS 2006b). It also represents one of the time periods used to calculate trend in the Biological Review Team analysis available at the time (Good et al. 2007). Appendix C of the 2010 Supplement included updated 1990-present extended Base Period lambda and BRT trend estimates based on new information available at the time.

As in the 2010 Supplement, this appendix updates the 1990–present extended Base Period lambda and BRT trend metrics to reflect the most recent observations. Methods used to generate these tables are identical to methods used to produce the tables in Section 2.1.1.4.2 of this Supplemental Opinion. The only difference is the starting year (1990). Some populations with relatively short time series of spawner estimates, which made them unsuitable for the longer Base Period estimates in Section 2.1.1.4.2, are included in these 1990–present tables.

Table A-1. 1990-present Chinook median population growth rate (lambda) under the assumption that hatchery-origin spawners are not reproductively effective (HF=0) and under the assumption that hatchery-origin spawners are as reproductively effective as natural-origin spawners (HF=1). These extended Base Period estimates are based on new information in the NWFSC SPS database that has become available since the 2008 BiOp. The 2008 BiOp's goal for prospective actions for this metric is lambda greater than 1.0.

ESU	MPG	Population	Lambda HF=0				Lambda HF=1			
			Base Period Lambda HF=0	Probability Lambda >1.0	Lower 95% Confidence Limit	Upper 95% Confidence Limit	Extended Base Period Lambda HF=1	Probability Lambda >1.0	Lower 95% Confidence Limit	Upper 95% Confidence Limit
Snake River Spring/ Summer Chinook Salmon	Lower Snake	Tucannon	1.06	0.62	0.63	1.76	0.90	0.28	0.56	1.46
		Asotin - Functionally Extirpated								
	Grande Ronde / Imnaha	Catherine Creek	1.12	0.81	0.78	1.61	0.96	0.38	0.61	1.50
		Upper Grande Ronde	1.02	0.60	0.82	1.27	0.80	0.09	0.54	1.19
		Minam River	1.07	0.86	0.91	1.26	1.02	0.63	0.85	1.24
		Wenaha River	1.09	0.86	0.88	1.36	1.02	0.63	0.85	1.22
		Lostine/Wallowa Rivers	1.11	0.86	0.86	1.45	0.95	0.35	0.68	1.35
		Imnaha River	1.05	0.63	0.71	1.54	0.83	0.14	0.54	1.28
		Big Sheep Creek - Functionally Extirpated								
	Lookingglass - Functionally Extirpated									
	South Fork Salmon	South Fork Salmon Mainstem	1.01	0.56	0.80	1.28	0.90	0.11	0.71	1.12
		Secesh River	1.06	0.67	0.75	1.49	1.04	0.64	0.74	1.47
		East Fork S. Fork Salmon (including Johnson)	1.02	0.54	0.69	1.49	0.94	0.31	0.63	1.38
		Little Salmon River (including Rapid R.)								
	Middle Fork Salmon	Big Creek	1.05	0.62	0.67	1.64	1.05	0.62	0.67	1.64
		Bear Valley/Elk Creek	1.04	0.63	0.72	1.52	1.04	0.63	0.72	1.52
		Marsh Creek	1.05	0.63	0.69	1.60	1.05	0.63	0.69	1.60
		Sulphur Creek	1.01	0.52	0.74	1.37	1.01	0.52	0.74	1.37
		Camas Creek	1.01	0.52	0.58	1.76	1.01	0.52	0.58	1.76
		Loon Creek	1.02	0.53	0.56	1.84	1.02	0.53	0.56	1.84
		Chamberlain Creek ¹	0.94				0.94			
		Lower Middle Fork Salmon (below Ind. Cr.)								
	Upper Middle Fork Salmon (above Ind. Cr.)									
	Upper Salmon	Lemhi River	1.03	0.57	0.66	1.62	1.03	0.57	0.66	1.62
		Valley Creek	1.07	0.72	0.77	1.49	1.07	0.72	0.77	1.49
		Yankee Fork	0.97	0.45	0.51	1.87	0.88	0.30	0.42	1.81
		Upper Salmon River (above Redfish L.)	1.05	0.64	0.71	1.57	0.99	0.47	0.65	1.50
		North Fork Salmon River								
		Lower Salmon River (below Redfish L.)	1.03	0.59	0.74	1.44	1.03	0.59	0.74	1.44
		East Fork Salmon River	1.09	0.71	0.68	1.75	1.07	0.65	0.66	1.73
		Pahsimeroi River	1.22	0.96	0.95	1.57	1.01	0.55	0.82	1.24
	Panther - Extirpated									
	Upper Columbia Spring Chinook Salmon	Eastern Cascades	Wenatchee R.	0.99	0.47	0.65	1.51	0.83	0.11	0.55
Methow R.			0.97	0.44	0.56	1.70	0.76	0.09	0.46	1.25
Entiat R.			1.01	0.54	0.70	1.47	0.92	0.24	0.65	1.29
Okanogan R. (extirpated)										
Snake River Fall Chinook Salmon	Main Stem and Lower Tributaries	Lower Mainstem Fall Chinook 1990-Most Recent BY	1.16	0.95	0.94	1.44	0.94	0.26	0.72	1.23

¹ Valid lambda confidence limit estimates could not be obtained for this population.

Table A-2. 1990-present steelhead median population growth rate (lambda) under the assumption that hatchery-origin spawners are not reproductively effective (HF=0) and under the assumption that hatchery-origin spawners are as reproductively effective as natural-origin spawners (HF=1). These extended Base Period estimates are based on new information in the NWFSC SPS database that has become available since the 2008 BiOp. The 2008 BiOp's goal for prospective actions for this metric is lambda greater than 1.0.

ESU	MPG	Population	Lambda HF=0				Lambda HF=1			
			Base Period Lambda HF=0	Probability Lambda >1.0	Lower 95% Confidence Limit	Upper 95% Confidence Limit	Extended Base Period Lambda HF=1	Probability Lambda >1.0	Lower 95% Confidence Limit	Upper 95% Confidence Limit
Upper Columbia River Steelhead	Eastern Cascades	Wenatchee	1.05	0.67	0.77	1.42	0.82	0.09	0.56	1.18
		Methow	1.05	0.66	0.75	1.48	0.67	0.01	0.52	0.86
		Entiat	1.05	0.69	0.79	1.39	0.78	0.02	0.62	0.98
		Okanogan	1.06	0.68	0.73	1.55	0.58	0.01	0.42	0.80
Snake River Steelhead ¹	Lower Snake	Tucannon								
		Asotin								
	Imnaha River	Imnaha R. (Camp Cr)	1.02	0.61	0.82	1.26	1.02	0.61	0.82	1.26
	Grande Ronde	Upper Mainstem	1.02	0.79	0.95	1.11	0.99	0.33	0.90	1.08
		Lower Mainstem								
		Joseph Cr. Wallowa R.	1.00	0.52	0.84	1.20	1.00	0.52	0.84	1.20
	Clearwater River	Lower Mainstem								
		Lolo Creek								
		Lochsa River								
		Selway River								
		South Fork North Fork - (Extirpated)								
	Salmon River	Upper Middle Fork Tribs								
		Chamberlain Cr.								
South Fork Salmon										
Panther Creek										
Secesh River										
North Fork										
Lower Middle Fork Tribs										
Little Salmon/Rapid										
Lemhi River										
Pahsimeroi River East Fork Salmon Upper Mainstem										
Mid Columbia Steelhead	Yakima	Upper Yakima	1.09	0.86	0.89	1.33	1.08	0.85	0.88	1.33
		Naches	1.09	0.85	0.88	1.36	1.08	0.82	0.87	1.34
		Toppenish	1.09	0.80	0.82	1.45	1.08	0.77	0.82	1.42
		Satus	1.08	0.82	0.86	1.35	1.06	0.78	0.85	1.34
	Eastern Cascades	Deschutes W.	1.05	0.72	0.82	1.35	0.99	0.42	0.79	1.23
		Deschutes East	1.04	0.61	0.68	1.60	0.96	0.38	0.66	1.40
		Klickitat								
		Fifteenmile Cr. Rock Cr.	1.01	0.56	0.75	1.37	1.01	0.56	0.75	1.37
		White Salmon - Extirpated								
	Umatilla/Walla Walla	Umatilla	1.05	0.77	0.87	1.27	0.97	0.30	0.81	1.15
		Walla-Walla	1.03	0.63	0.77	1.37	1.02	0.60	0.76	1.37
		Touchet	1.01	0.62	0.94	1.08	0.97	0.10	0.91	1.03
	John Day	Lower Mainstem	1.01	0.53	0.63	1.63	0.99	0.46	0.61	1.60
		North Fork	1.06	0.77	0.85	1.32	1.04	0.71	0.84	1.30
Upper Mainstem		0.98	0.42	0.75	1.28	0.97	0.36	0.74	1.26	
Middle Fork		0.98	0.42	0.69	1.39	0.96	0.38	0.67	1.38	
South Fork		1.03	0.59	0.73	1.46	1.01	0.54	0.72	1.43	

¹ Only the populations with empirical estimates are shown, as in the 2008 BiOp. In the 2008 BiOp, other populations were analyzed using "average A- and B-run" estimates, as understood at the time.

Table A-3. 1990-present Chinook BRT abundance trend (trend of ln[abundance+1]). These extended Base Period estimates are based on new information in the NWFSC SPS database that has become available since the 2008 BiOp. The 2008 BiOp's goal for prospective actions for this metric is BRT trend greater than 1.0.

ESU	MPG	Population	New Information			
			Extended Base Period BRT Trend	Probability BRT Trend >1.0	Lower 95% Confidence Limit	Upper 95% Confidence Limit
Snake River Spring/ Summer Chinook Salmon	Lower Snake	Tucannon	1.10	0.95	0.98	1.23
		Asotin - Functionally Extirpated				
	Grande Ronde / Imnaha	Catherine Creek	1.11	1.00	1.04	1.19
		Upper Grande Ronde	1.02	0.72	0.95	1.09
		Minam River	1.10	1.00	1.05	1.14
		Wenaha River	1.11	1.00	1.06	1.16
		Lostine/Wallowa Rivers	1.12	1.00	1.07	1.17
		Imnaha River	1.05	0.98	1.00	1.10
		Big Sheep Creek - Functionally Extirpated				
	Lookingglass- Functionally Extirpated					
	South Fork Salmon	South Fork Salmon Mainstem	1.03	0.96	1.00	1.07
		Secesh River	1.06	0.99	1.02	1.11
		East Fork S. Fork Salmon (including Johnson)	1.02	0.77	0.97	1.08
		Little Salmon River (including Rapid R.)				
	Middle Fork Salmon	Big Creek	1.09	0.99	1.01	1.18
		Bear Valley/Elk Creek	1.09	1.00	1.02	1.16
		Marsh Creek	1.10	0.96	0.99	1.23
		Sulphur Creek	1.07	0.91	0.97	1.18
		Camas Creek	1.07	0.95	0.99	1.17
		Loon Creek	1.09	0.94	0.98	1.21
		Chamberlain Creek	1.09	0.99	1.02	1.17
		Lower Middle Fork Salmon (below Ind. Cr.)				
		Upper Middle Fork Salmon (above Ind. Cr.)				
	Upper Salmon	Lemhi River	1.04	0.92	0.98	1.10
		Valley Creek	1.12	1.00	1.04	1.20
		Yankee Fork	1.00	0.52	0.91	1.10
		Upper Salmon River (above Redfish L.)	1.09	1.00	1.04	1.15
		North Fork Salmon River				
		Lower Salmon River (below Redfish L.)	1.06	0.99	1.01	1.11
		East Fork Salmon River	1.15	1.00	1.07	1.23
		Pahsimeroi River	1.22	1.00	1.17	1.27
		Panther - Extirpated				
	Upper Columbia Spring Chinook Salmon	Eastern Cascades	Wenatchee R.	1.03	0.80	0.96
Methow R.			1.02	0.67	0.93	1.12
Entiat R.			1.05	0.95	0.99	1.11
Okanogan R. (extirpated)						
Snake River Fall Chinook Salmon	Main Stem and Lower Tributaries	Lower Mainstem Fall Chinook 1990-Most Recent BY	1.19	1.00	1.15	1.23

Table A-4. 1990-present steelhead BRT abundance trend (trend of ln[abundance+1]). These extended Base Period estimates are based on new information in the NWFSC SPS database that has become available since the 2008 BiOp. The 2008 BiOp's goal for prospective actions for this metric is BRT trend greater than 1.0.

ESU	MPG	Population	New Information			
			Extended Base Period BRT Trend	Probability BRT Trend >1.0	Lower 95% Confidence Limit	Upper 95% Confidence Limit
Upper Columbia River Steelhead	Eastern Cascades	Wenatchee	1.06	0.99	1.01	1.10
		Methow	1.08	1.00	1.03	1.13
		Entiat	1.06	1.00	1.02	1.11
		Okanogan	1.10	1.00	1.04	1.16
Snake River Steelhead ¹	Lower Snake	Tucannon				
		Asotin				
	Imnaha River	Imnaha R. (Camp Cr)	1.05	0.98	1.00	1.09
	Grande Ronde	Upper Mainstem	1.02	0.88	0.99	1.06
		Lower Mainstem				
		Joseph Cr.	1.02	0.86	0.98	1.06
		Wallowa R.				
	Clearwater River	Lower Mainstem				
		Lolo Creek				
		Lochsa River				
		Selway River				
		North Fork - (Extirpated)				
	Salmon River	Upper Middle Fork Tribs				
		Chamberlain Cr.				
		South Fork Salmon				
		Panther Creek				
		Secesh River				
		North Fork				
		Lower Middle Fork Tribs				
Little Salmon/Rapid						
Lemhi River						
Pahsimeroi River						
East Fork Salmon						
Upper Mainstem						
Mid Columbia Steelhead		Yakima	Upper Yakima	1.10	1.00	1.07
	Naches		1.10	1.00	1.07	1.13
	Toppenish		1.12	1.00	1.07	1.16
	Satus		1.10	1.00	1.06	1.13
	Eastern Cascades	Deschutes W.	1.07	1.00	1.03	1.11
		Deschutes East	1.08	1.00	1.02	1.13
		Klickitat				
		Fifteenmile Cr.	1.02	0.83	0.98	1.07
		Rock Cr.				
	Umatilla/Walla Walla	Umatilla	1.06	1.00	1.03	1.09
		Walla-Walla	1.03	0.92	0.99	1.07
		Touchet	1.00	0.48	0.98	1.02
	John Day	Lower Mainstem)	1.01	0.66	0.96	1.07
		North Fork	1.06	1.00	1.02	1.10
		Upper Mainstem	0.99	0.31	0.94	1.04
		Middle Fork	0.98	0.20	0.94	1.03
South Fork		1.04	0.96	0.99	1.08	

¹ Only the populations with empirical estimates are shown, as in the 2008 BiOp. In the 2008 BiOp, other populations were analyzed using "average A- and B-run" estimates, as understood at the time.

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Appendix B

Hinrichsen (2013) Extinction Risk Analysis—Detailed Results

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**Analytical methods for population viability analysis of endangered salmon
ESUs of the interior Columbia River Basin
December 16, 2013**

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Executive summary

Extinction probability estimates were developed for several Chinook and steelhead salmon populations in the interior Columbia River Basin. The extinction probability approach used spawner-recruit (SR) functions which were fit to SR data from brood years 1978 to the present (most recently available observation). The estimated SR production functions were used to estimate extinction probabilities by population simulation. Alternative QETs of 1, 10, 30, and 50 spawners were used with a time horizon of 24 years. In the projections, extinction was assumed to occur when spawner counts fell below the QET over four consecutive years.

Introduction

Population viability analysis is used to gauge the likelihood of extinction of endangered salmon populations in the Columbia River Basin. The 2000 Federal Columbia River Power System (FCRPS) BiOp used the Dennis et al. (1991) model to estimate the probability of absolute extinction (the population falling below 1 individual). The model was estimated using a procedure that accounted for measurement error (Holmes 2001). This method was used as a large-scale, multi-species risk assessment of anadromous salmonids in the Columbia River Basin (McClure et al. 2003).

An important element in the estimation of extinction risks is the production function that is used. The production function is the mathematical rule that describes how spawners in one year are related to adult returns in subsequent years. The models described in Holmes (2001) and McClure et al. (2003), which were used in the 2000 BiOp, were linear. That is, it was assumed that the mean population growth rate was constant regardless of spawner abundance. This assumption is contrary to most fisheries models, such as the Ricker or Beverton-Holt, which assume that the population growth rate declines as spawner numbers increase (Hilborn and Walters 1992). These nonlinear fisheries models include the assumption that populations cannot grow indefinitely, that is, they must level off as spawner numbers increase. Linear production functions do not include this assumption.

Nonlinear models, such as Beverton-Holt and Ricker, which were used in the 2008 BiOp and 2010 Supplemental BiOP, assume that survival increases with declining spawning population until the last spawner disappears (Hilborn and Walters 1992). For these models, as spawner abundance declines, the number of recruits produced per spawner increases. From the perspective of population viability analysis, this assumption of increased survival at low population size may overestimate the resilience of a population and thus lead to underestimates of extinction probability. The hockey stick model addresses this concern by assuming constant recruits produced per spawner when spawner numbers fall below a threshold (Barrowman and Myers 2000). The hockey stick model, however, introduces important estimation difficulties because the likelihood function includes “kinks” where the derivative is not defined and it often exhibits multiple local maxima. Ideally, for the purposes of estimation, the likelihood function would be smooth (without kinks) and have a single maximum value.

This report details an approach to estimating extinction probability and its confidence interval. When estimating extinction probability, the Beverton-Holt and Ricker production functions were used. Parameter estimates for these production functions were obtained by maximizing the likelihood function (Mood et al. 1974). The production function estimates were then used to obtain extinction probabilities by projecting forward spawner abundances 24 years into the future. This procedure was applied to interior Columbia River salmon populations from the listed Snake River Fall Chinook, Snake River Spring/Summer Chinook and Upper Columbia River Spring/Summer Chinook Salmon ESUs and to the Snake River Steelhead, Upper Columbia

River Steelhead, and Mid-Columbia River Steelhead. The time horizon was set at 24 years, and the quasi-extinction threshold (the spawner level below which extinction was assumed to occur) (QET) was set at four alternative values: 1, 10, 30, and 50 spawners.

Data

Spawner recruit data for two spring/summer Chinook ESUs, three Steelhead ESUs, and one fall Chinook ESU were used. Lists of populations analyzed are presented in Tables 1-3.

Spring/summer Chinook ESUs

The data used were Snake River and Upper Columbia River stream-type Chinook spawner-recruit data (Toole 2013a). Spawner data were estimates of annual abundance of salmon arriving at the spawning grounds. Recruitment refers to adult progeny returning to the spawning grounds.

Steelhead ESUs

The data used were Snake River, Mid-Columbia, and Upper Columbia River spawner-recruit data (Toole 2013a).

Snake River Fall Chinook

The data used were Snake River Fall Chinook spawner-recruit estimates (Toole 2013b).

Population viability analysis

The underlying production functions used in the population projections were the Beverton-Holt and Ricker (Hilborn and Walters 1992). The Beverton-Holt model was applied to Chinook salmon populations and the Ricker model was applied to steelhead populations. The Beverton-Holt model was used for the Chinook populations because preliminary work showed that it yielded extinction probability estimates that were similar to the hockey stick model used by the Interior Columbia Basin TRT (ICTRT 2007). The Beverton-Holt model was not applied to the steelhead populations because valid parameter estimates could not be found for many of the steelhead populations. For these populations, the Ricker model was used because it is guaranteed to yield maximum likelihood estimates.

The Beverton-Holt model takes the mathematical form:

$$R_t = S_t \exp(a + f_t) / [1 + \exp(b)S_t], \quad (1)$$

where R_t is recruitment (the adult progeny of fish spawning in year t); S_t represents the number of spawners in brood year t ; a is the intrinsic productivity, which is the maximum log recruits per

spawner; f_t is a stochastic error term, which follows an autoregressive process of order 1; and b is the parameter that describes density dependent growth.

The Ricker model takes the mathematical form

$$R_t = S_t \exp(a - bS + f_t), \quad (2)$$

where R_t is recruitment (the adult progeny of fish spawning in year t); S_t represents the number of spawners in brood year t ; a is the intrinsic productivity, which is the maximum log recruits per spawner; f_t is a stochastic error term, which follows an autoregressive process of order 1; and b is the parameter that describes density dependent growth.

The autoregressive process was used for the error term because lag-1 autocorrelation was evident in the data and extinction probabilities are known to be influenced by autocorrelation (Wichmann et al. 2005). The autoregressive order 1 process is described by:

$$f_{t+1} = af_t + e_{t+1}, \quad (3)$$

where a is the autoregressive parameter, which, according to the Yule-Walker equations, is equivalent to the lag-1 autocorrelation coefficient (Box et al. 1994); and e_{t+1} is an independent and normally distributed random error term with mean zero and variance σ^2 . The e_t process will be referred to as the white noise process. (The f_t errors represent a red noise process because the errors are positively correlated). The initial production function error, f_1 , is set equal to e_1 (i.e., it is normally distributed with mean zero and variance σ^2).

The parameters were estimated by maximizing the likelihood function (Mood et al. 1974). The log likelihood function was formed by taking the natural log of the joint distribution of the white noise errors, e_t :

$$l = -\frac{n}{2} \log(2\sigma^2) - \frac{1}{2\sigma^2} \sum_{t=1}^n e_t^2 \quad (4)$$

$$= -\frac{n}{2} \log(2\sigma^2) - \frac{1}{2\sigma^2} \sum_{t=1}^n [y_t - f(a, b, S_t)]^2 + \frac{1}{2\sigma^2} \sum_{t=1}^{n-1} \{y_{t+1} - f(a, b, S_{t+1}) - a[y_t - f(a, b, S_t)]\}^2$$

where n was the number of spawner-recruit observations; y_t represented $\log(R_t / S_t)$; and $f(a, b, S_t)$ was $a - \log[1 + \exp(b)S_t]$ when the Beverton-Holt production function was used, or was $a - bS_t$ when the Ricker production function was used. Notice that when the autoregressive parameter, a , is equal to zero, the likelihood function is reduced to the usual likelihood function with uncorrelated errors. Altogether, there were four parameters estimated from this likelihood function: a , b , σ , and σ^2 . Because the model was nonlinear in the parameters, interior maximum likelihood estimates were not guaranteed to exist.

In the case of Snake River Fall Chinook, I used the Beverton-Holt production, but estimated a directly from the residuals rather than including it as a parameter to be estimated in the likelihood function. I did this because, I was unable to obtain valid maximum likelihood estimates when a was included in the likelihood as an estimated parameter. When estimating a directly from the residuals, the first-order autocorrelation formula

$$\hat{a} = \frac{\sum_{i=1}^n \hat{f}_i \hat{f}_{i-1}}{\sum_{i=1}^n \hat{f}_i^2} \quad (5)$$

was used (Box et al. 1994), where \hat{f}_i represented the i th residual from the nonlinear least squares fit. As an alternative to this approach for Snake River Fall Chinook, I used the Ricker production

function and estimated the parameter a in the usual way, by including it as an unknown parameter in the likelihood function, which was the approach used in Hinrichsen (2008).

All nonlinear regressions were conducted using the routine *nls* from the R statistical package, which uses a Gauss-Newton algorithm for calculating maximum likelihood estimates (R Core Team 2013).

Extinction probabilities

Once the Beverton-Holt or Ricker parameters were estimated, the production functions were used to estimate probabilities of extinction by projecting spawner numbers into the future (Tables 1-3). In each simulation of a population, $N = 10,000$ a 24-year sequence of spawners was generated. Once the spawner series was initialized, the stochastic production function was used to build a series of future spawners by allocating recruits to the appropriate spawners. A fixed age structure of recruits was assumed in the population projections. Age structure was set to the average age structure from 1978 to present (the year of most recently available data).

The extinction probability was estimated as the fraction of the 10,000 sequences in which spawners fell below the quasi-extinction threshold (QET) for four consecutive years. Extinction probability estimates were obtained using alternative values of QET (1, 10, 30, and 50), and with a time horizon of 24 years. If, during a population projection, the total number of spawners fell below 10, then number of recruits was set to zero (i.e. the reproductive failure threshold was set at 10 spawners). Whenever QET=1, a reproductive failure threshold of 2 spawners was used instead of 10 spawners.

Using the Beverton-Holt production function, the projections took the following mathematical form:

$$R_t^* = S_t^* \exp(\hat{a} + f_t^*) / (1 + \exp[\hat{b}] S_t^*) \quad (6)$$

and

$$S_t^* = \hat{a} \prod_{t=1}^5 \bar{p}_t R_{t-t}^* \quad (7)$$

where R_t^* was the simulated number of recruits generated from spawners in brood year t ; S_t^* was the simulated number of spawners in brood year t ; \hat{a} was the maximum likelihood estimate of the Beverton-Holt density-independent parameter a ; f_t^* represented a random draw from the

autoregressive error model; \hat{b} was the maximum likelihood estimate of the Beverton-Holt density-dependent parameter b ; t represented age of returning adults; and \bar{p}_t represented the average fraction of adults returning at age t . The projections were initialized by setting the first five spawner numbers in the sequence equal to the most recently available 5 spawner observations.

A similar method was used when the Ricker model was employed, in which case, the population projections were accomplished using the relationship

$$R_t^* = S_t^* \exp(\hat{a} - \hat{b}S_t^* + f_t^*), \quad (8)$$

instead of the Beverton-Holt spawner-recruit relationship.

Supplementation

In the extinction probability analysis described above, it was assumed that the relative reproductive effectiveness of hatchery-born spawners was equal to that of the wild-born spawners and that supplementation would not continue into the future.

Extinction probability confidence intervals

Extinction probabilities suffer from high uncertainty, especially over long time horizons (e.g., 100 years). Fieberg and Ellner (2000) demonstrated that reliable extinction probability estimates were possible for short-term time horizons (10 percent-20 percent as long as the time series used for model fitting) only. Using 20 percent as a guide, it follows that 24-year extinction probabilities should be estimated using about 100 years of data. Time series of that duration are not available for Columbia River Basin salmonid populations. This analysis use much shorter time series of data, generally about 30 years. Thus, the imprecision of the extinction probability estimates is due, in part, to a lack of data.

To quantify the uncertainty surrounding the estimates, confidence intervals were constructed. Confidence intervals that are narrow (e.g. 0.50 to 0.51), indicate high reliability of extinction probability estimates. Confidence intervals that are wide (e.g., spanning 0 to 1), indicate low reliability of extinction probability estimates. That is, two different sets of data from the same population process will tend to yield very different extinction probability estimates. Wide confidence intervals are a common problem with the estimation of extinction probabilities, especially for populations that are highly variable and have a paucity of data. Furthermore, confidence intervals are wide because extinction probability usually declines sharply with

increasing intrinsic productivity (Botsford and Brittnacher 1998). Therefore any uncertainty in the intrinsic productivity parameter (which depends strongly on the error variance), will be greatly magnified in the estimation of extinction probability.

To estimate confidence intervals for extinction probabilities, a Monte Carlo technique was used (Press et al. 1992). The Monte Carlo technique proceeds by drawing random samples from the joint sampling distribution of the maximum likelihood estimates, which are known to be approximately normally distributed (Mood et al. 1974). Replications of extinction probability were then obtained by evaluating the extinction probability at these randomly drawn parameter values. Using this method, $N = 1,000$ Monte Carlo replications of an extinction probability estimate were produced, and the 0.025 and 0.975 quantiles of these replications were the confidence limits. This method was applied to steelhead salmon populations (using the Ricker production function) and Chinook salmon populations (using the Beverton-Holt production function).

As an alternative to the Monte Carlo technique, bootstrapping was used to estimate confidence intervals for extinction probabilities (Efron and Tibshirani 1993), but only when the Beverton-Holt production function was applied to Snake River Fall Chinook. In this case, the bootstrapping approach was used instead of the Monte Carlo approach because the parameter a was not included in the likelihood function, making the Monte Carlo approach outlined above invalid. Bootstrapping proceeded by building an empirical distribution of $N = 1,000$ bootstrap replications of an extinction probability estimate, then using the 0.025 and 0.975 quantiles of the distribution as confidence limits. $N = 1,000$ synthetic data sets were constructed using a parametric bootstrap technique (Efron and Tibshirani 1993). Maximum likelihood estimates were obtained for each synthetic data set. Replications of extinction probability were then obtained by evaluating the extinction probability at these maximum likelihood estimates.

References

- Barrowman, N. J., and R. A. Myers. 2000. Still more spawner-recruitment curves: the hockey stick and its generalizations. *Canadian Journal of Fisheries and Aquatic Sciences* 57: 665–676.
- Botsford, L. W., and J. G. Brittnacher. 1998. Viability of Sacramento River winter-run Chinook salmon. *Conservation Biology* 12:65–79.
- Box, G. E. P, G. M. Jenkins, and G. C. Reinsel. 1994. *Time Series Analysis*, 3rd Edition. Prentice-Hall, Inc. Englewood Cliffs, NJ.
- Dennis, B., P. L. Munholland, and J.M. Scott. 1991. Estimation of growth and extinction parameters for endangered species. *Ecological Monographs* 61:115–143.
- Efron, B., and R.J. Tibshirani. 1993. *An introduction to the bootstrap*. Chapman & Hall/CRC, New York.
- Fieberg, J., and S. P. Ellner. 2000. When is it meaningful to estimate an extinction probability. *Ecology* 81:2040–2047.
- Hilborn, R. and C. J. Walters. 1992. *Quantitative fisheries stock assessment: choice dynamics & uncertainty*. Chapman & Hall.
- Hinrichsen, R. A. 2008. Analytical methods for population viability analysis of endangered salmon ESUs of the interior Columbia River basin. Hinrichsen Environmental Services, Seattle, Washington. Attachment 1 to Appendix B of the 2008 Supplemental Comprehensive Analysis, May 5, 2008.
- Holmes, E.E. 2001. Estimating risks in declining populations with poor data. *Proceedings of the National Academy of Science* 98:5072–5077.

- ICTRT (Interior Columbia Basin Technical Recovery Team). 2007. Required Survival Rate Changes to Meet Technical Recovery Team Abundance and Productivity Viability Criteria for Interior Columbia River Basin Salmon and Steelhead Populations. November 30, 66 pp.
- McClure, M., E. Holmes, B. Sanderson, and C. Jordan. 2003. A large-scale, multi-species risk assessment: anadromous salmonids in the Columbia River Basin. *Ecological Applications* 13:964–989.
- Mood, A. M., F. A. Graybill, and D. C. Boes. 1974. *Introduction to the Theory of Statistics*, Third Edition. McGraw-Hill, New York.
- Press, W. H., S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery. 1992. *Numerical Recipes in FORTRAN*. Second Edition. Cambridge University Press. New York, N.Y.
- R Core Team. 2013. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing. Vienna, Austria. <http://www.R-project.org>.
- Toole, C. 2013a. Spreadsheets R_S_Chin_SPS_from Mari_062813_072913ct.xlsx and R_S_Sthd_SPS_from Mari_062813_071813ct.xlsx for spring/summer Chinook and steelhead, respectively.
- Toole, C. 2013b. Spreadsheet R_S_Chin_SPS_from Mari_091713_111813ct.xlsx for Snake River Fall Chinook.
- Wichmann, M. C., K. Johst, M. Schwager, B. Blasius, and F. Jeltsch. 2005. Extinction risk, coloured noise and the scaling of variance. *Theoretical Population Biology* 68:29–40.

Table 1. Probability of extinction for Interior Columbia River Spring/Summer Chinook populations using data from 1978-most currently available year. The data set used was contained in the file R_S_Chin_SPS_from Mari_062813_072913ct.xlsx Extinction probabilities were calculated for a 24-year time horizon. The reproductive failure threshold value was 2 when quasi-extinction threshold (QET)=1, and 10 otherwise. Confidence intervals were calculated by drawing 1,000 random samples from the joint sampling distribution of the maximum likelihood estimates of the Beverton-Holt model parameters, where the error term followed an auto-regressive process of order 1 to account for autocorrelation in the residuals. Extinction probabilities were calculated by generating 10,000 random spawner trajectories and calculating the fraction of these that fell below QET four years running. P=probability of quasi-extinction; L95=lower 95% confidence limit; U95=upper 95% confidence limit;NA = no maximum likelihood estimates of the Beverton-Holt parameters could be found.

	QET=1			QET=10			QET=30			QET=50		
	P	L95	U95	P	L95	U95	P	L95	U95	P	L95	U95
Bear Valley Creek Chinook	0.00	0.00	0.03	0.00	0.00	0.17	0.00	0.00	0.33	0.02	0.00	0.45
Big Creek Chinook	0.00	0.00	0.24	0.01	0.00	0.40	0.10	0.00	0.70	0.29	0.01	0.86
Camas Creek Chinook	0.05	0.00	0.57	0.42	0.01	0.92	0.78	0.12	0.99	0.92	0.43	1.00
Catherine Creek Chinook	0.01	0.00	0.47	0.09	0.00	0.80	0.24	0.00	0.91	0.37	0.05	0.95
Chamberlain Creek Chinook	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Entiat River Spring Chinook	0.00	0.00	0.05	0.00	0.00	0.28	0.01	0.00	0.56	0.05	0.00	0.79
Grande Ronde Upper Mainstem Chinook	0.00	0.00	0.09	0.01	0.00	0.46	0.19	0.01	0.76	0.48	0.07	0.94
Imnaha River Chinook	0.00	0.00	0.45	0.00	0.00	0.96	0.00	0.00	0.98	0.00	0.00	0.94
Lemhi River Chinook	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Loon Creek Chinook	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Lostine River Chinook	0.00	0.00	0.15	0.00	0.00	0.31	0.01	0.00	0.40	0.04	0.00	0.51
Lower Mainstem Salmon River Chinook	0.00	0.00	0.18	0.00	0.00	0.34	0.05	0.00	0.53	0.23	0.00	0.78
Marsh Creek Chinook	0.01	0.00	0.43	0.06	0.00	0.63	0.24	0.00	0.86	0.39	0.01	0.92
Methow River Spring Chinook	0.00	0.00	0.32	0.02	0.00	0.52	0.06	0.00	0.59	0.10	0.00	0.74
Minam River Chinook	0.00	0.00	0.06	0.00	0.00	0.20	0.00	0.00	0.37	0.01	0.00	0.47
Pahsimeroi River Chinook	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Secesh River Chinook	0.00	0.00	0.03	0.00	0.00	0.12	0.00	0.00	0.20	0.00	0.00	0.37
South Fork Salmon East Fork/Johnson Creek Chinook	0.00	0.00	0.01	0.00	0.00	0.07	0.00	0.00	0.22	0.00	0.00	0.37
South Fork Salmon Mainstem Chinook	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.06	0.00	0.00	0.19
Sulphur Creek Chinook	0.00	0.00	0.73	0.04	0.00	0.99	0.37	0.02	1.00	0.67	0.21	1.00
Tucannon Spring Chinook	0.00	0.00	0.20	0.00	0.00	0.34	0.01	0.00	0.46	0.03	0.00	0.56
Upper Mainstem Salmon River Chinook	0.00	0.00	0.03	0.00	0.00	0.09	0.00	0.00	0.29	0.00	0.00	0.44
Upper Salmon East Fork Chinook	0.00	0.00	0.23	0.01	0.00	0.45	0.09	0.00	0.66	0.23	0.01	0.73
Valley Creek Chinook	0.00	0.00	0.17	0.02	0.00	0.56	0.40	0.02	0.92	0.76	0.17	0.99
Wenaha River Chinook	0.00	0.00	0.19	0.01	0.00	0.43	0.05	0.00	0.56	0.10	0.00	0.64
Wenatchee River Spring Chinook	0.00	0.00	0.21	0.00	0.00	0.43	0.02	0.00	0.50	0.04	0.00	0.64
Yankee Fork Salmon River Chinook	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Table 2. Probability of extinction for Interior Columbia River steelhead populations using data from 1978-most currently available year. The data set used was contained in the file R_S_Sthd_SPS_from Mari_062813_071813ct.xlsx. Extinction probabilities were calculated for a 24-year time horizon. The reproductive failure threshold value was 2 when quasi-extinction threshold (QET)=1, and 10 otherwise. Confidence intervals were calculated by drawing 1,000 random samples from the joint sampling distribution of the maximum likelihood estimates of the Ricker model parameters, where the error term followed an auto-regressive process of order 1 to account for autocorrelation in the residuals. Extinction probabilities were calculated by generating 10,000 random spawner trajectories and calculating the fraction of these that fell below QET four years running. P=probability of quasi-extinction; L95=lower 95% confidence limit; U95=upper 95% confidence limit.

	QET=1			QET=10			QET=30			QET=50		
	P	L95	U95	P	L95	U95	P	L95	U95	P	L95	U95
Deschutes River Eastside Steelhead	0.25	0.01	0.56	0.43	0.05	0.79	0.52	0.16	0.88	0.57	0.21	0.90
Deschutes River Westside Steelhead	0.00	0.00	0.12	0.00	0.00	0.28	0.00	0.00	0.29	0.00	0.00	0.37
Entiat River Steelhead	0.03	0.00	0.45	0.41	0.01	0.92	0.74	0.12	1.00	0.89	0.25	1.00
Fifteenmile Creek Steelhead	0.00	0.00	0.07	0.00	0.00	0.12	0.00	0.00	0.18	0.00	0.00	0.26
Grande Ronde Upper Mainstem Steelhead	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Imnaha Camp Creek	0.00	0.00	0.03	0.00	0.00	0.14	0.04	0.00	0.48	0.33	0.01	0.78
John Day Lower Mainstem Steelhead	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.04	0.00	0.00	0.06
John Day Middle Fork River Steelhead	0.00	0.00	0.15	0.00	0.00	0.20	0.00	0.00	0.36	0.00	0.00	0.33
John Day North Fork River Steelhead	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.02
John Day South Fork River Steelhead	0.00	0.00	0.13	0.00	0.00	0.24	0.00	0.00	0.33	0.01	0.00	0.34
John Day Upper Mainstem	0.00	0.00	0.14	0.00	0.00	0.24	0.00	0.00	0.32	0.00	0.00	0.35
Joseph Creek Steelhead	0.00	0.00	0.01	0.00	0.00	0.09	0.00	0.00	0.12	0.00	0.00	0.08
Methow River Steelhead	0.00	0.00	0.23	0.34	0.01	0.95	0.75	0.10	1.00	0.88	0.31	1.00
Naches River Steelhead	0.20	0.01	0.56	0.34	0.04	0.61	0.40	0.11	0.68	0.46	0.17	0.74
Okanogan River Steelhead	0.92	0.39	1.00	1.00	0.70	1.00	1.00	0.77	1.00	1.00	0.78	1.00
Satus Creek Steelhead	0.09	0.00	0.75	0.18	0.00	0.75	0.26	0.00	0.80	0.31	0.00	0.79
Toppenish Creek Steelhead	0.44	0.15	0.73	0.58	0.30	0.87	0.67	0.38	0.94	0.72	0.49	0.97
Touchet River Steelhead	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Umatilla River Steelhead	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.02
Upper Yakima River Steelhead	0.30	0.02	0.66	0.47	0.15	0.76	0.64	0.36	0.93	0.78	0.54	0.99
Walla Walla River Steelhead	0.00	0.00	0.40	0.00	0.00	0.46	0.00	0.00	0.49	0.00	0.00	0.56
Wenatchee River Steelhead	0.00	0.00	0.31	0.03	0.00	0.52	0.12	0.00	0.70	0.20	0.00	0.82

Table 3a. Probability of extinction for the Snake River Fall Chinook Lower Mainstem population using data from 1978-most currently available year. The data set used was contained in the file **R_S_Chin_SPS_from Mari_091713_111813ct.xlsx**. Extinction probabilities were calculated for a 24-year time horizon. The reproductive threshold values used were 2 when quasi-extinction threshold (QET)=1 and 10 otherwise. Confidence intervals were calculated using a parametric bootstrap of the **Beverton-Holt model fit** with 1,000 random samples, where the error term followed an auto-regressive process of order 1 to account for autocorrelation in the residuals. Autocorrelation was estimated directly from the residuals. Extinction probabilities were calculated by generating 10,000 random population trajectories and calculating the fraction of these that fell below QET four years running. P=probability of quasi-extinction; L95=lower 95% confidence limit; U95=upper 95% confidence limit.

	QET=1			QET=10			QET=30			QET=50		
	P	L95	U95	P	L95	U95	P	L95	U95	P	L95	U95
Snake River Lower Mainstem	0.00	0.00	0.00	0.00	0.00	0.06	0.01	0.00	0.15	0.02	0.00	0.24

Table 3b. Probability of extinction for the Snake River Fall Chinook Lower Mainstem population using data from 1978-most currently available year. The data set used was contained in the file **R_S_Chin_SPS_from Mari_091713_111813ct.xlsx**. Extinction probabilities were calculated for a 24-year time horizon. The reproductive threshold values used were 2 when quasi-extinction threshold (QET)=1 and 10 otherwise. Confidence intervals were calculated by drawing 1,000 random samples from the joint sampling distribution of the maximum likelihood estimate of the **Ricker model parameters**, where the error term followed an auto-regressive process of order 1 to account for autocorrelation in the residuals. Extinction probabilities were calculated by generating 10,000 random population trajectories and calculating the fraction of these that fell below QET four years running. P=probability of quasi-extinction; L95=lower 95% confidence limit; U95=upper 95% confidence limit.

	QET=1			QET=10			QET=30			QET=50		
		L9	U9		L9	U9		L9	U9		L9	U9
	P	5	5	P	5	5	P	5	5	P	5	5
Snake River Lower	0.0	0.0	0.3	0.0	0.0	0.4	0.0	0.0	0.5	0.1	0.0	0.6
Mainstem	0	0	6	4	0	5	9	0	6	4	0	3

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Appendix C

Recruits-per-Spawner in base versus current time periods—do they differ?

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Recruits-per-Spawner in base versus current time periods—do they differ?

August 29, 2013

Rich Zabel and Tom Cooney

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Background

The 2008 Supplemental Comprehensive Analysis¹ (SCA) included a quantitative evaluation of the effects of 2008-2018 harvest and hydropower activities² on populations of six species of interior Columbia River salmon and steelhead (Appendix Table 1) listed under the Endangered Species Act. The SCA estimated the following measures of population performance during a “Base Period” for which empirical data were available (approximately 1980-2004, corresponding to the ~1980-2000 completed brood cycles [BY]):

24-year extinction risk

Geometric mean of recruits-per-spawner (R/S)

Median population growth rate (λ) under two assumptions regarding effectiveness of hatchery-origin spawners

Trend of $\ln(\text{abundance}+1)$, referred to as “BRT Trend”

The ~1980-2000 BY Base Period metrics were the starting point for all subsequent calculations and projections in the SCA for the six interior Columbia basin species. There are now 5-7 new years of population data and NOAA Fisheries’ Northwest Regional Office has requested assistance in determining whether the new observations represent a change in the original Base Period estimates or if they are within the expected range of variability.

In general, incorporating the new observations into “extended Base Period” (~1980 to most recent year) estimates³ indicates:

either unchanged or reduced extinction risk for most populations;

¹ Supplemental Comprehensive Analysis of the Federal Columbia River Power System and Mainstem Effects of the Upper Snake and Other Tributary Actions. May 5, 2008. NOAA Fisheries, Northwest Regional Office, Portland, Oregon. Available at: <http://www.nwr.noaa.gov/publications/hydropower/fcrps/final-sca.pdf>

² Activities were: Columbia River harvest under *US v Oregon*, operation of the Federal Columbia River Power System (FCRPS), and operation of Bureau of Reclamation water storage projects in the Upper Snake River.

³ Personal communication, C. Toole, NOAA Fisheries Northwest Regional Office, March 22, 2013.

higher abundance trends for nearly all populations;
variable lambda estimates, depending in part on hatchery assumptions, but including reductions for a number of populations; and
reduced mean R/S estimates for most populations.

Looking at the new observations independently, rather than combined with the original Base Period estimates, the contrast between improved abundance and reduced mean R/S productivity is even more apparent. Twenty-six out of 26 populations of spring and summer Chinook increased in abundance, measured as geometric mean abundance during the previous 10 years, when comparing the recent period to the Base Period, and 14 out of 18 steelhead populations increased in abundance over the same period (Tables 1 and 2). However, mean R/S decreased in 22 out of 26 spring and summer Chinook populations and 14 out of 18 steelhead populations (Tables 1 and 2).

Although the decrease in productivity might suggest that overall population performance has declined, it is also consistent with expectations that recruits-per-spawner will decline as abundance increases due to density-dependent processes (Ricker 1954, Zabel et al. 2006). This is commonly observed in fish populations, and in fact forms the basis of most fisheries management models (e.g., Hilborn and Walters 1992). Here we test the density-dependent hypothesis by first testing whether the spawner and recruit data during the Base Period are consistent with a density-dependent model. Then we examine whether the current data fall within 95% prediction intervals for new observations.

Table 1. Geometric mean abundance and recruits-per-spawner during base (brood years from approximately 1980-2000) and recent (approximately 2001 and later) time periods for interior Columbia basin spring and summer Chinook populations. To calculate the geometric means, we first added 1 to all spawner counts (because some counts were 0), and then subtracted 1 from the calculated mean.

Population	Mean Abundance		Mean Recruits-Per-Spawner	
	Base	Recent	Base	Recent
LS-Tucannon	246	534	0.74	0.60
GR-Wenaha	249	561	0.71	0.72
GR-Lostine	213	661	0.81	0.47
GR-Minam	290	487	0.87	1.03
GR-Upper Mainstem	86	146	0.46	0.30
GR-Catherine Cr	159	276	0.42	0.30
GR-Imnaha	526	1592	0.82	0.17
SF-Mainstem	592	1208	0.89	0.51
SF-Secesh	292	868	1.22	0.46
SF-East Fork	190	325	1.06	0.53
MF-Big Creek	80	182	1.42	0.99
MF-Camas Cr	32	89	0.94	0.54
MF-Loon	39	146	1.32	0.52
MF-Sulfur Cr	38	50	1.1	1.18
MF-Bear Valley/Elk	163	429	1.46	0.72
MF-Marsh Cr	127	203	1.08	1.18
SR-Lemhi	95	116	1.2	0.61
SR-Pahsimeroi	58	376	1.29	0.64
SR-Lower Mainstem	79	177	1.31	0.64
SR-East Fork	106	306	1.32	1.08
SR-Yankee Fork	16	24	1.17	0.54

SR-Valley Cr	42	74	1.36	1.23
SR-Upper Mainstem	164	647	1.71	0.56
UC-Wenatchee	844	915	0.75	0.40
UC-Methow	541	1277	0.92	0.26
UC-Entiat	152	206	0.79	0.51

Table 2. Geometric mean abundance and recruits-per-spawner during base and recent time periods for interior Columbia basin steelhead populations. To calculate the geometric means, we first added 1 to all spawner counts (because some counts were 0), and then subtracted 1 from the calculated mean.

Population	Mean Abundance		Mean Recruits–Per-Spawner	
	Base	Recent	Base	Recent
UC-Wenatchee	1645	2965	0.29	0.33
UC-Entiat	166	656	0.37	0.20
UC-Methow	1297	4942	0.15	0.11
UC-Okanogan	988	2504	0.07	0.06
MC-Fifteenmile Cr	455	828	1.32	0.59
Deschutes-W	483	951	1.03	0.58
JD-Lower Mainstem	1626	2886	1.64	0.40
JD-North Fork	1412	2273	1.37	0.70
JD-Upper Mainstem	939	662	1.24	0.69
JD-Middle Fork	1063	1032	1.37	0.49
JD-South Fork	459	385	1.15	1.06
MC-Umatilla	1632	3211	1.07	0.70
YR-Satus	451	673	1.01	1.73
YR-Toppenish	154	562	1.57	1.06
YR-Naches	392	806	1.14	1.47
YR-Upper Yakma	72	143	1.14	1.57
GR-Upper Mainstem	1538	1333	0.93	1.08
GR-Joseph Cr	1959	2484	1.26	0.80

Data

The spawning time series data for interior Columbia basin Chinook salmon and steelhead populations include estimates for the most recent annual returns obtained from state, tribal and Federal managers. The data series are generated using protocols agreed upon through the Interior Columbia Technical Recovery Team and are updated versions of the data series

available through the Salmonid Population Summary (SPS) data base maintained by the NWFSC (<https://www.webapps.nwfsc.noaa.gov/apex/f?p=261:home:0#>). The SPS includes documentation and is designed to accommodate annual updates. The additional years included in the analysis described below will be available in the SPS later this year.

Spawning abundance, hatchery/wild proportions and age composition follow the protocols used in previous Biological Review Team and Technical Recovery Team reports (e.g., Good et al. 2005). Annual spawning abundance represents the estimated number of hatchery and wild origin fish contributing to spawning in natural production reaches for each population. Spawning abundance does not include 3-year olds (jacks). Brood year recruits are calculated assigning natural origin returns to age at return and then using this information to assign adult recruits to brood year. Because these recruits were estimated after any harvest occurred, we adjusted recruits to account for harvest:

$$R_t = \frac{A_t}{1 - h_t}$$

where R_t are estimated recruits from brood year t , A_t are post-harvest returning adults, and h_t is the harvest rate for adults from brood year t . R_t represent the number of naturally produced fish that would have appeared on the spawning grounds had there not been a harvest. We adjusted recruits to account for harvest because our goal here is to examine whether the inherent productivity of populations, measured as recruits-per-spawner, has changed between the baseline and recent time periods. Harvest removes recruits, and if harvest occurred differentially across time, it could alter the underlying relationships. In Appendix 2, we examined the impacts on results of adjusting for harvest versus not.

Annual estimates of mainstem harvest rates were obtained from the most recent U.S. v Oregon Technical Advisory Team report. Tributary harvest-rate estimates were provided by regional state and tribal fisheries managers.

Analysis

The first step in the analysis was to test whether the spawner and recruit data, by population, are consistent with a density-dependent recruitment model. We used a Ricker model because it is a simple linear model and therefore does not have the potential model-fitting issues that exist with nonlinear models, such as the Beverton-Holt model, when sample sizes are small.

The Ricker model relates recruits (R_t), referenced to brood year t , to spawners (S_t) as

$$R_t = S_t \cdot \exp(a - b \cdot S_t) \quad (1)$$

where a and b are density-independent and density-dependent model parameters, respectively. After rearranging terms and taking the natural log of both sides, the Ricker model can be expressed as

$$\ln(R_t / S_t) = a - b \cdot S_t \quad (2)$$

which is a linear model and easily fit to data using standard linear regression. We can express this in linear regression form as

$$\ln(R_t/S_t) = a + b \cdot S_t + \varepsilon_t \quad (3)$$

where ε_t is the error term which is distributed normally with mean 0 and variance σ^2 . The data support the hypothesis of density-dependence if the b parameter is significantly different from 0 and negative. When this occurs, recruits-per-spawner decreases as spawners increase.

We note that in several populations, there were years where the estimate of spawners was 0. Because this would produce undefined terms in equation 3, we added 1 to every spawner and recruit estimate. This is a standard approach, but we acknowledge that other approaches, such as removing years in which spawner estimates were 0, are also justifiable. In Appendix 3, we assessed the implications of the various approaches.

We fit equation (3) to 44 populations of interior Columbia basin spring and summer Chinook and steelhead populations. To perform these fits, we only used data from the Base Period. For each population, we estimated model parameters, and we also calculated an R^2 and P -value. If the model was deemed significant ($P < 0.1$), we plotted the predicted relationship along with the data points. In addition, we also estimated 95% prediction intervals (Zar 2009) about the predicted relationships. This interval covers the envelope in which 95% of new data points would fall if they follow the modeled relationship and variability. If the model was not deemed significant ($P > 0.1$), we only plotted the data points. We chose this significance level because of the relatively low sample sizes in some of the populations.

For the populations that demonstrated significant relationships, we plotted the current data points and determined whether they fell within the 95% prediction interval, below the interval (indicating the R/S was lower than expected), or above the interval (indicating the R/S was greater than expected). Note that we expect 5% of the points to fall outside the interval by chance alone.

Results

For spring and summer Chinook populations, 20 out of 26 demonstrated significant relationships (Table 3). In all cases where the model was significant, the b (slope) parameter was negative, providing evidence for density dependence. When we plotted the “recent” data points onto the plots with the 95% prediction intervals, the vast majority of points fell within the 95% prediction intervals. In addition, only 1 point fell below the interval and 4 points fell above, providing no support for the hypothesis that recent conditions are less productive than those experienced during the Base Period (Figures 1-2).

For steelhead populations, 18 out of 18 demonstrated significant relationships (Table 4). In all cases, the b parameter was negative, providing strong evidence for density dependence. When we plotted the “recent” data points onto the plots with the 95% prediction intervals, the vast majority of points fell within the 95% prediction interval. In addition, 3 points fell below the

interval and 14 points fell above, providing little support for the hypothesis that recent conditions are less productive than those experienced during the Base Period (Figures 3-4).

Discussion

These analyses provide strong support for the hypothesis that density-dependent recruitment is occurring in these populations. Further, when we plotted “recent” data points onto relationships derived from the “base” period data, the vast majority of these points fell within the 95% prediction intervals, providing strong support for the hypothesis that productivity has not decreased for these populations when comparing base to recent time periods but that the decreased R/S resulted from density-dependent processes as a result of the increased abundance observed recently (Tables 1 and 2, Figures 5-8).

One issue with this analysis was that the basic density-dependence model did not significantly fit the data for some of the populations. This was particularly the case for spring and summer Chinook populations, where 6 out of 26 populations did not exhibit a significant density-dependent relationship. We believe that this was partially due to the fact the base time period encompassed a period where population abundance was generally low and thus did not cover a broad range of abundance levels. In contrast, abundance levels during the recent time period were generally higher. We thus combined the base and recent time periods together and re-fit Ricker model to the combined datasets. When we did this, 24 out of 26 spring and summer Chinook populations had significant fits (Figures 9-12).

References

- Hilborn, R., and C. J. Walters. 1992. Quantitative Fisheries Stock Assessment: Choice Dynamics and Uncertainty. Kluwer Academic Publishers, Norwall, MA.
- Ricker, W.E. (1954) Stock and recruitment. *Journal of the Fisheries Research Board of Canada*, **11**, 559-623.
- Zabel, R.W., Scheuerell, M.D., McClure, M. and Williams, J.G. (2006) The interplay between climate variability and density dependence in the population viability of Chinook salmon. *Conservation Biology*, **20**, 190-200.
- Zar, J. 2009. Biostatistical Anlaysia, 5th edition. Prentice-Hall, Englewood Cliffs, NJ.

Table 3. Results from the regression analysis for interior Columbia basin spring and summer Chinook populations. a and b are model parameters. “above” refers to the number of recent points that fell above the 95% prediction interval, and “below” refers to the number of points that fell below the 95% prediction interval.

Population	a	b	R²	P	above	below
LS-Tucannon	0.68	-0.0028	0.257	0.023	0	0
GR-Wenaha	0.365	-0.0023	0.124	0.128	NA	NA
GR-Lostine	0.893	-0.0036	0.433	0.002	0	0
GR-Minam	1.03	-0.003	0.420	0.002	0	0
GR-Upper Mainstem	0.0697	-0.0045	0.351	0.006	0	0
GR-Catherine Cr	0.109	-0.0036	0.294	0.014	0	0
GR-Imnaha	0.69	-0.0015	0.215	0.040	0	0
SF-Mainstem	0.726	-0.0011	0.395	0.003	0	0
SF-Secesh	0.566	-0.0011	0.033	0.441	NA	NA
SF-East Fork	0.335	-0.0012	0.031	0.459	NA	NA
MF-Big Creek	1.11	-0.0054	0.211	0.042	0	0
MF-Camas Cr	0.892	-0.016	0.237	0.035	0	0
MF-Loon	0.0679	0.0016	0.001	0.893	NA	NA
MF-Sulfur Cr	1.06	-0.0098	0.204	0.045	0	0
MF-Bear Valley/Elk	0.787	-0.0016	0.110	0.152	NA	NA
MF-Marsh Cr	1.03	-0.0045	0.147	0.095	0	0
SR-Lemhi	1.39	-0.0085	0.489	0.001	0	0
SR-Pahsimeroi	2.12	-0.021	0.451	0.006	4	0
SR-Lower Mainstem	1.28	-0.0095	0.412	0.002	0	0
SR-East Fork	1.52	-0.0077	0.331	0.008	0	0
SR-Yankee Fork	1.65	-0.055	0.465	0.001	0	0
SR-Valley Cr	1.49	-0.017	0.438	0.001	0	0
SR-Upper Mainstem	1.51	-0.0039	0.277	0.017	0	0

UC-Wenatchee	0.162	-0.00037	0.060	0.298	NA	NA
UC-Methow	1.13	-0.0014	0.234	0.031	0	1
UC-Entiat	0.658	-0.0045	0.254	0.024	0	0

Table 4. Results from the regression analysis for interior Columbia basin steelhead populations. a and b are model parameters. “above” refers to the number of recent points that fell above the 95% prediction interval, and “below” refers to the number of recent points that fell below the 95% prediction interval.

Population	a	b	R²	P	above	below
UC-Wenatchee	-0.799	-0.00019	0.445	0.001	1	0
UC-Entiat	-0.447	-0.0027	0.270	0.019	0	0
UC-Methow	-0.868	-0.00066	0.537	0.000	4	0
UC-Okanogan	-2.18	-0.00037	0.385	0.004	0	0
MC-Fifteenmile Cr	1.11	-0.0016	0.449	0.006	0	0
Deschutes-W	0.977	-0.0017	0.372	0.004	0	0
JD-Lower Mainstem	1.43	-0.00038	0.514	0.000	0	0
JD-North Fork	1.45	-0.0006	0.785	0.000	0	0
JD-Upper Mainstem	1.01	-0.0006	0.434	0.002	0	1
JD-Middle Fork	1.24	-0.00068	0.547	0.000	0	2
JD-South Fork	0.98	-0.0013	0.404	0.003	0	0
MC-Umatilla	1.19	-0.00064	0.369	0.005	0	0
YR-Satus	1	-0.0018	0.627	0.000	3	0
YR-Toppenish	1.45	-0.0057	0.223	0.076	0	0
YR-Naches	1.28	-0.0026	0.505	0.003	3	0
YR-Upper Yakma	1.16	-0.012	0.536	0.002	3	0
GR-Upper Mainstem	0.968	-0.00056	0.640	0.000	0	0
GR-Joseph Cr	1.33	-0.00042	0.619	0.000	0	0

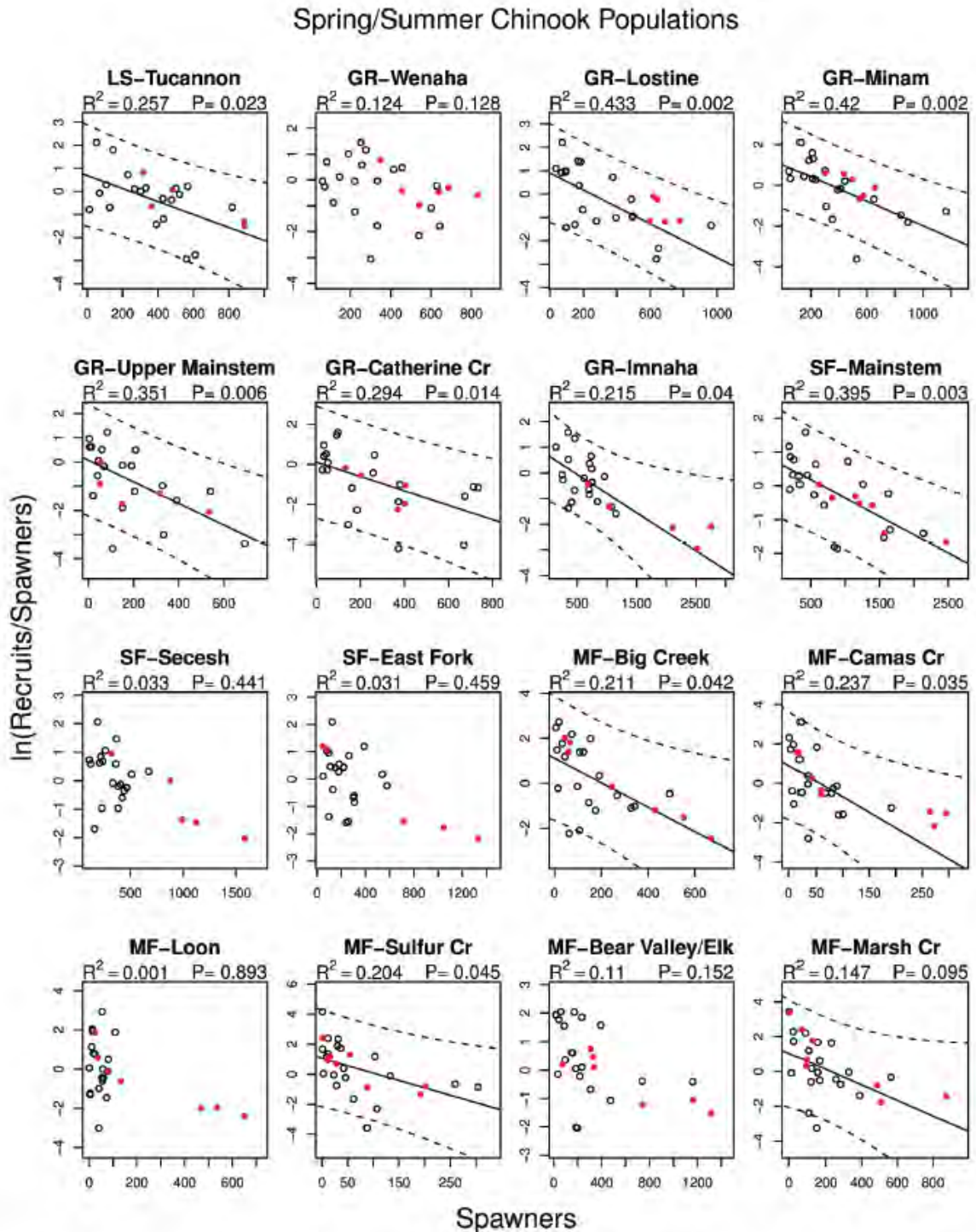
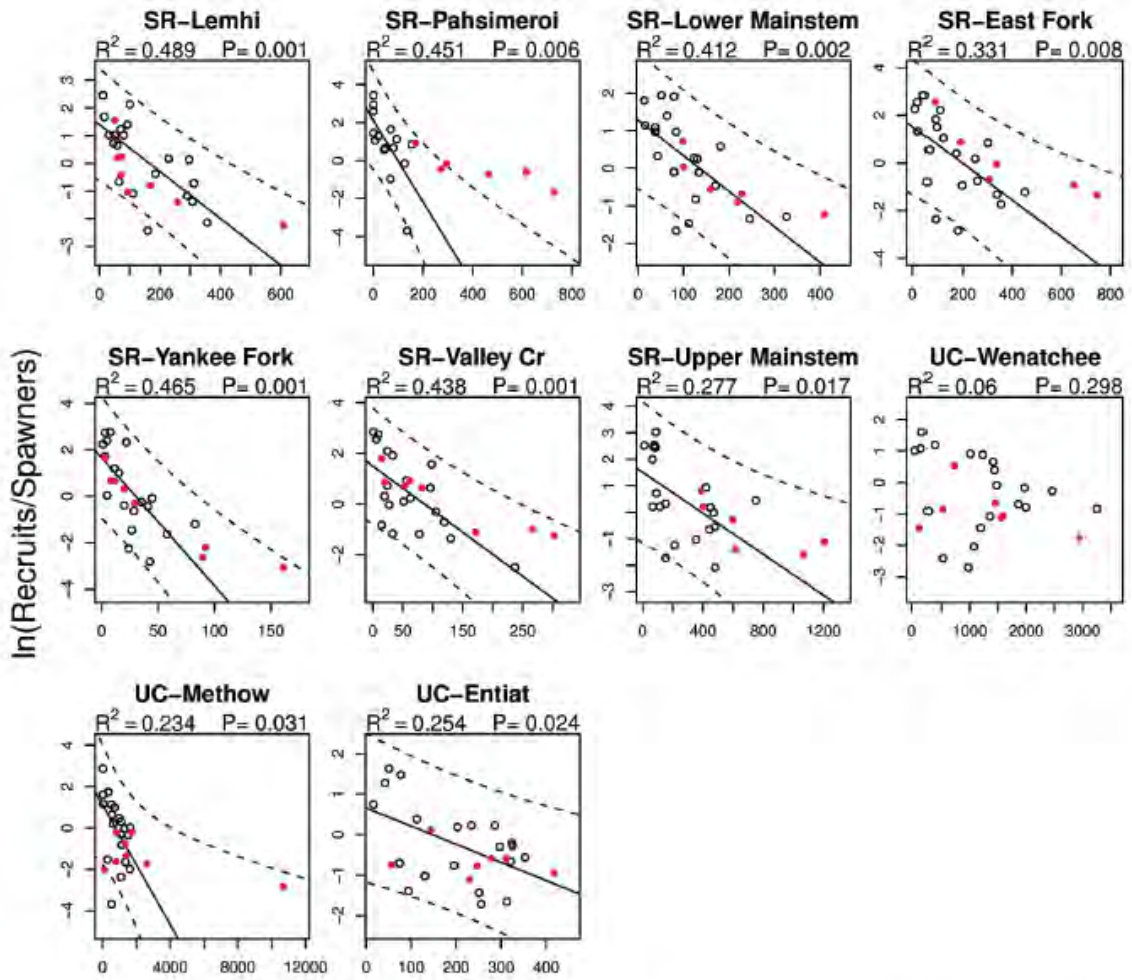


Figure 1. Ln(recruits/spawner) versus spawners for Interior Columbia River spring and summer Chinook populations. Open black points represent base period (1980-2000), and red points represent recent period. Based on linear regression, if $P < 0.1$, the dark line is the best fit, and the dashed lines are the 95% prediction interval for the data.

Spring/Summer Chinook Populations



Spawners

Figure 2. $\ln(\text{recruits/spawner})$ versus spawners for Interior Columbia River spring and summer Chinook populations. Open black points represent base period (1980-2000), and red points represent recent period. Based on linear regression, if $P < 0.1$, the dark line is the best fit, and the dashed lines are the 95% prediction interval for the data.

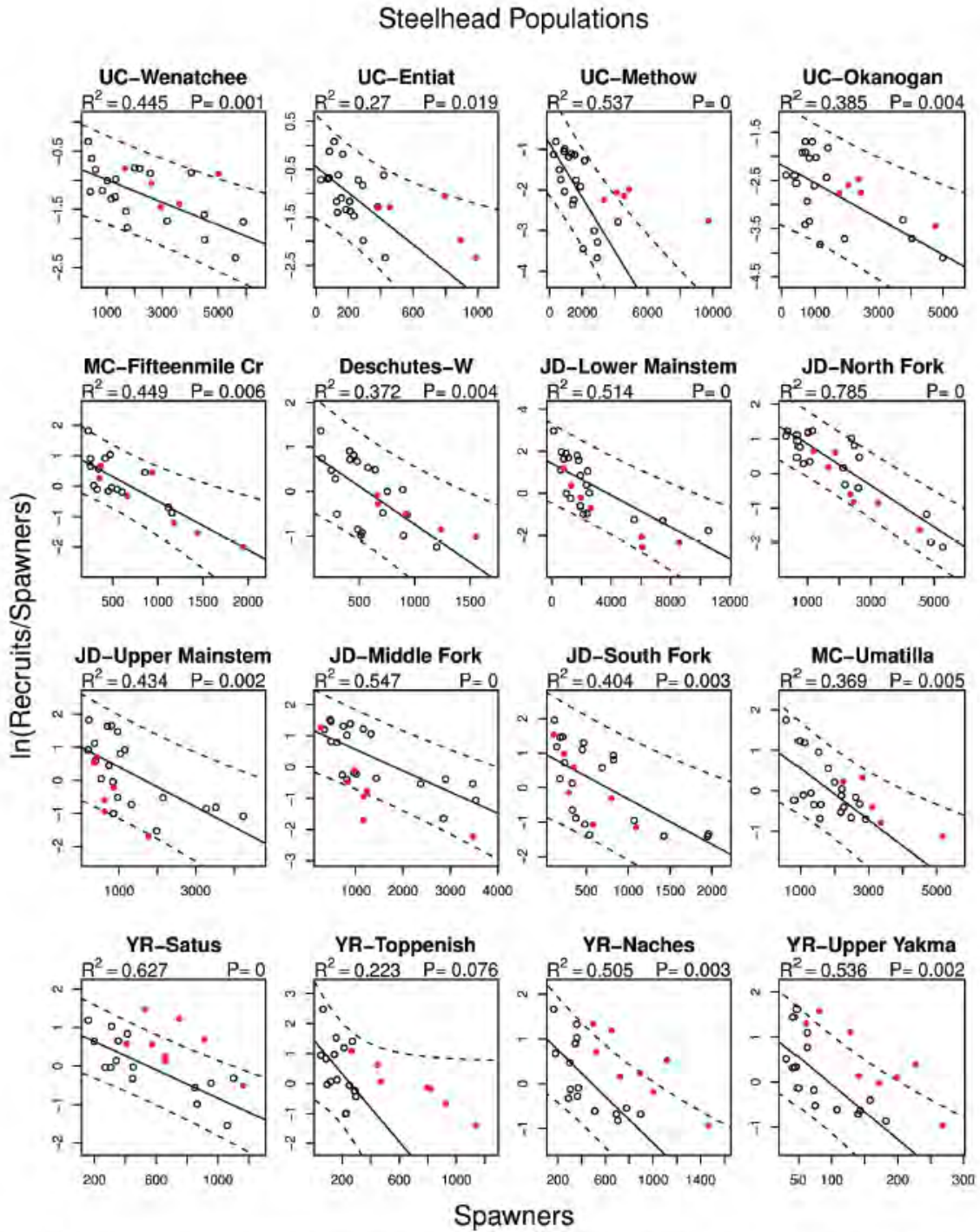


Figure 3. Ln(recruits/spawner) versus spawners for Interior Columbia River steelhead populations. Open black points represent base period (1980-2000), and red points represent recent period. Based on linear regression, if $P < 0.1$, the dark line is the best fit, and the dashed lines are the 95% prediction interval for the data.

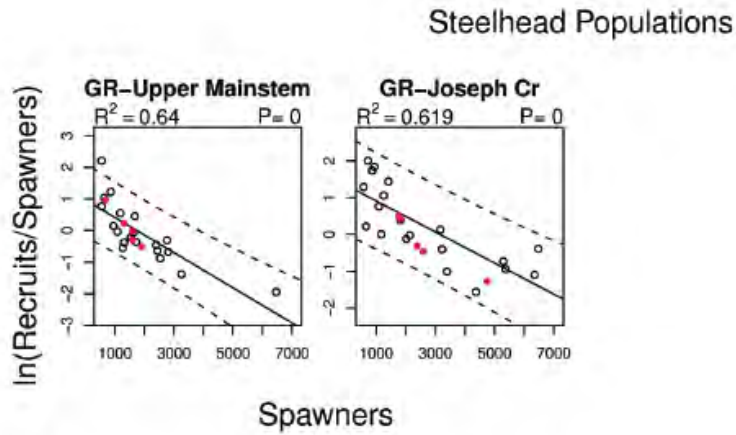


Figure 4. Ln(recruits/spawner) versus spawners for Interior Columbia River steelhead populations. Open black points represent base period (1980-2000), and red points represent recent period. Based on linear regression, if $P < 0.1$, the dark line is the best fit, and the dashed lines are the 95% prediction interval for the data. Note that these 2 populations did not have any harvest data.

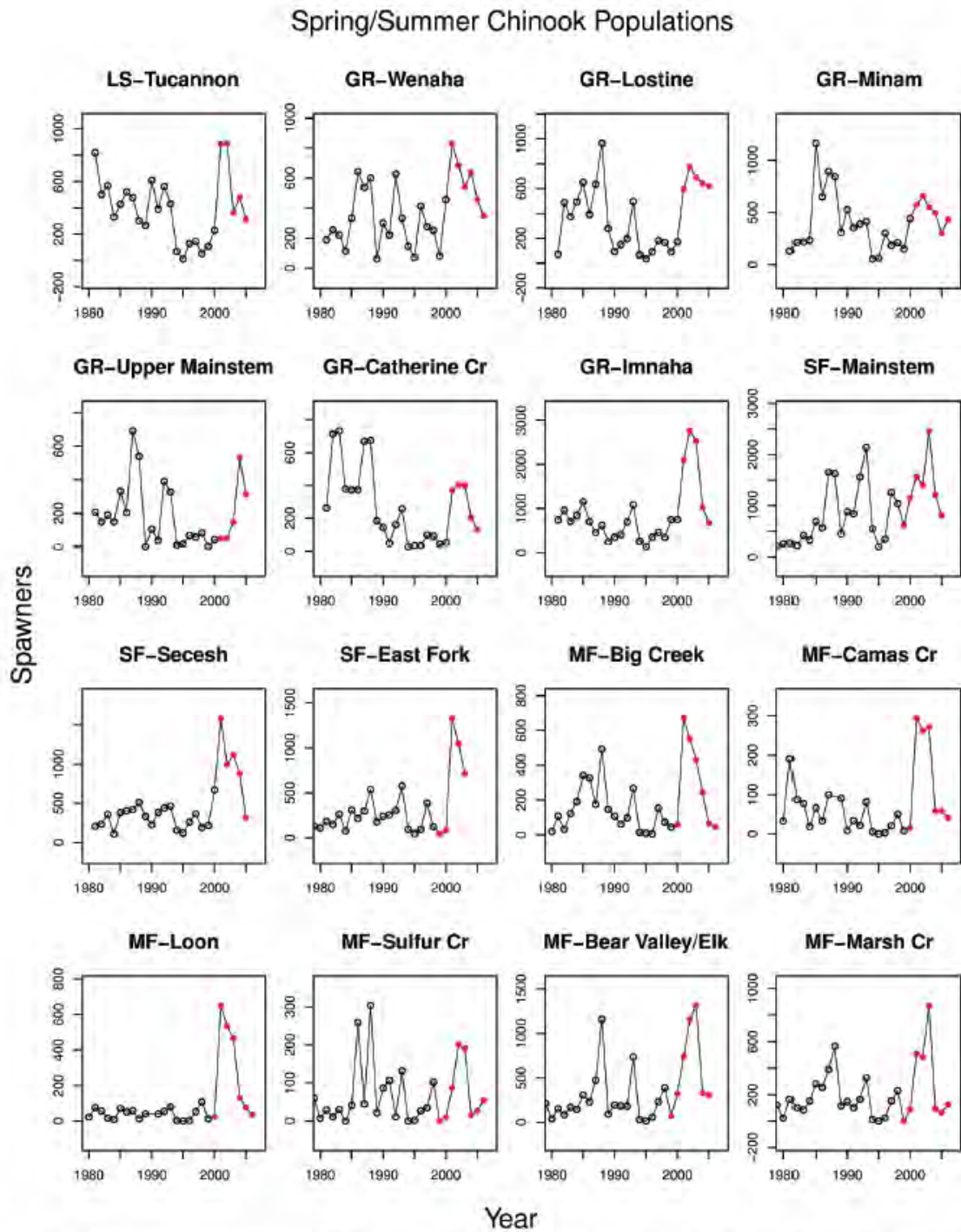


Figure 5. Spawners versus year for Interior Columbia River spring and summer Chinook populations. Open black points represent base period (1980-2000), and red points represent recent period.

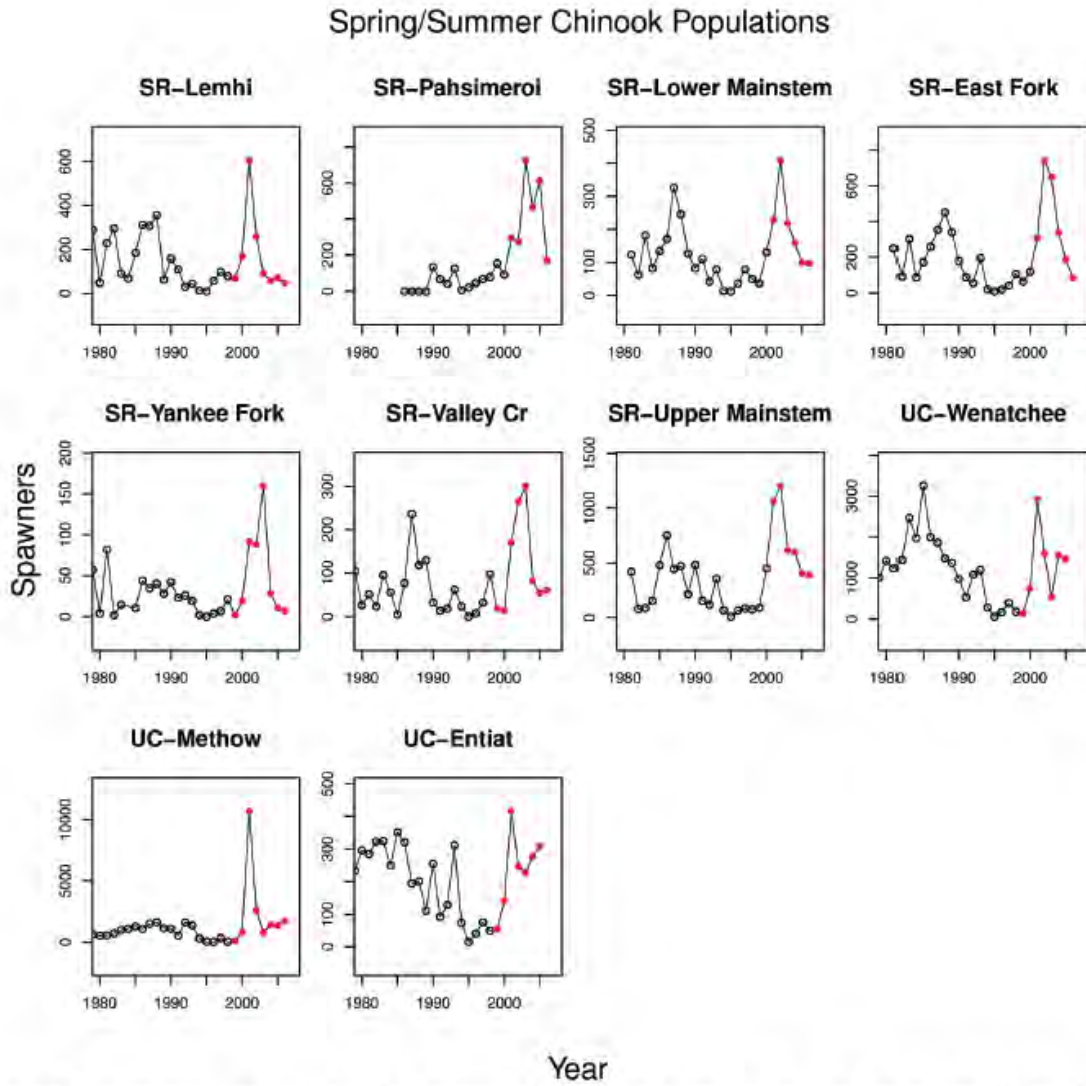


Figure 6. Spawners versus year for Interior Columbia River spring and summer Chinook populations. Open black points represent base period (1980-2000), and red points represent recent period.

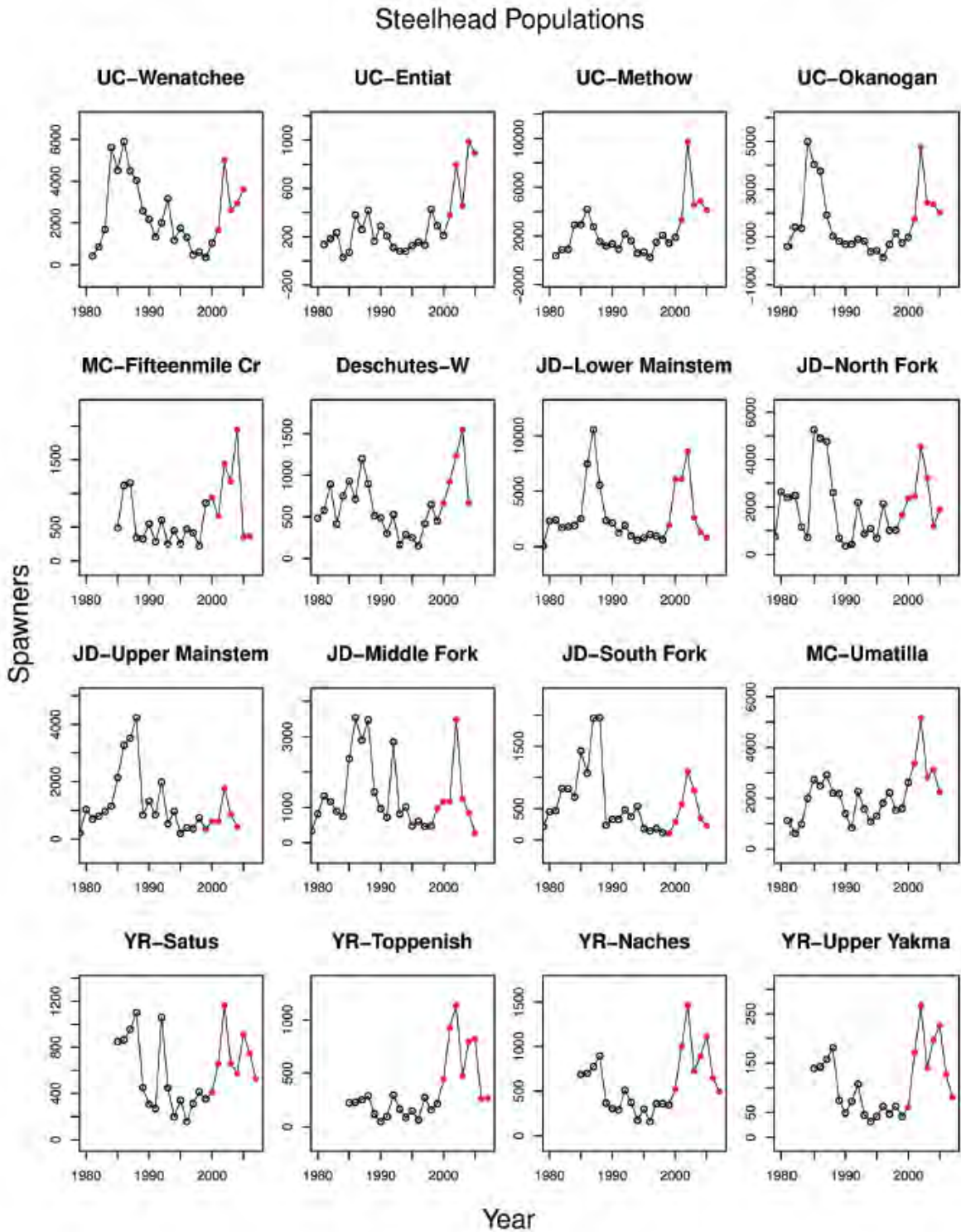


Figure 7. Spawners versus year for Interior Columbia River steelhead populations. Open black points represent base period (1980-2000), and red points represent recent period.

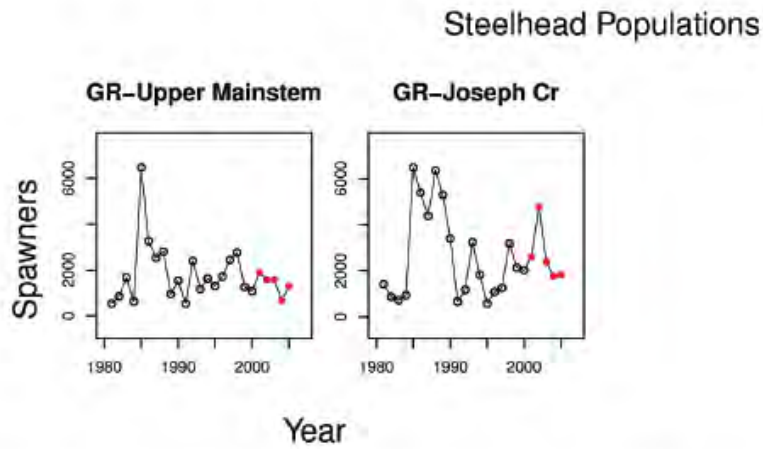


Figure 8. Spawners versus year for Interior Columbia River steelhead populations. Open black points represent base period (1980-2000), and red points represent recent period. Note that these 2 populations did not have any harvest data.

Spring/Summer Chinook Populations

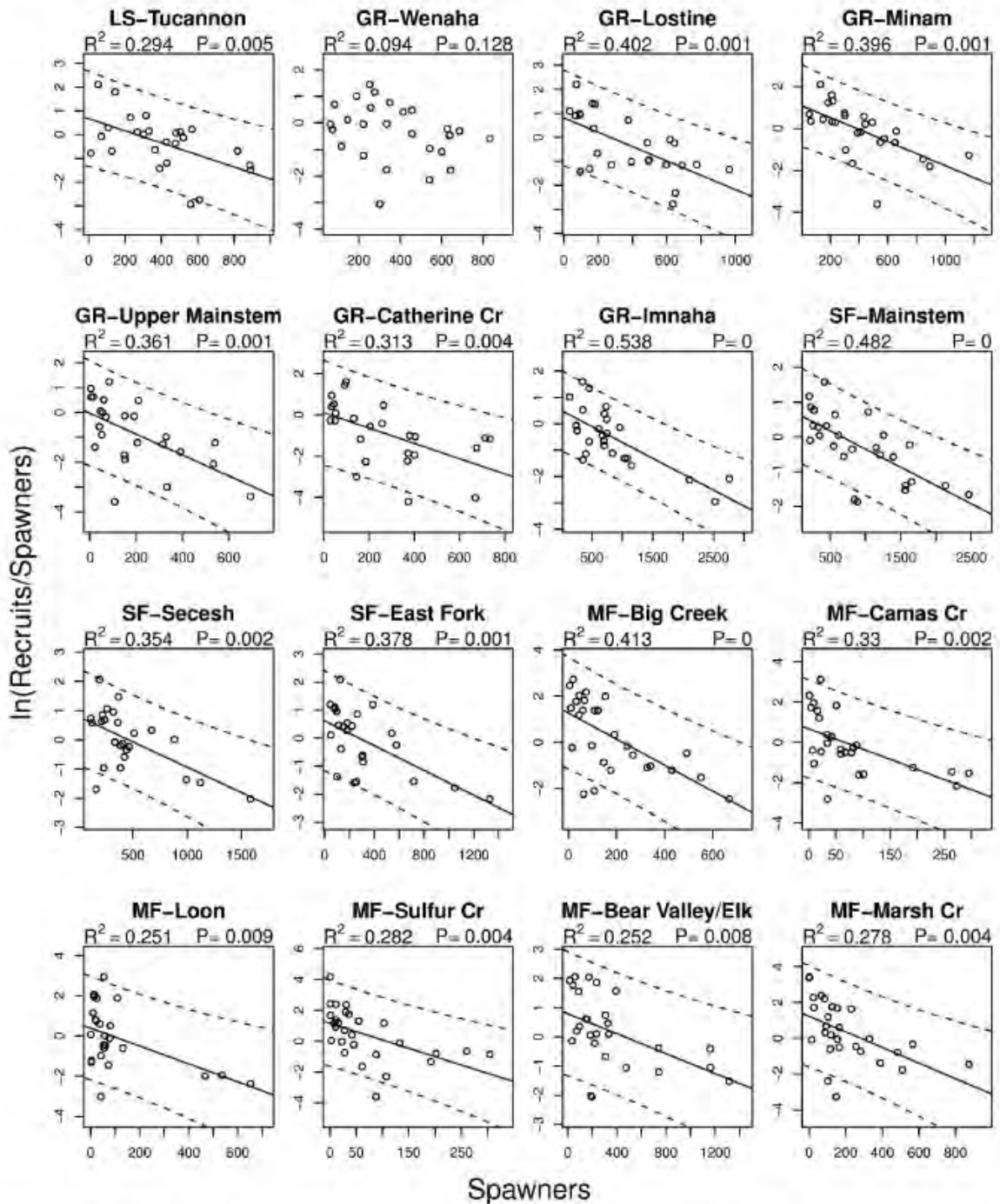


Figure 9. Ln(recruits/spawner) versus spawners for Interior Columbia River spring and summer Chinook populations. Open black points represent base period (1980-2000), and red points represent recent period. **The regression model was fit to all data (base and recent).** Based on linear regression, if $P < 0.1$, the dark line is the best fit, and the dashed lines are the 95% prediction interval for the data.

Spring/Summer Chinook Populations

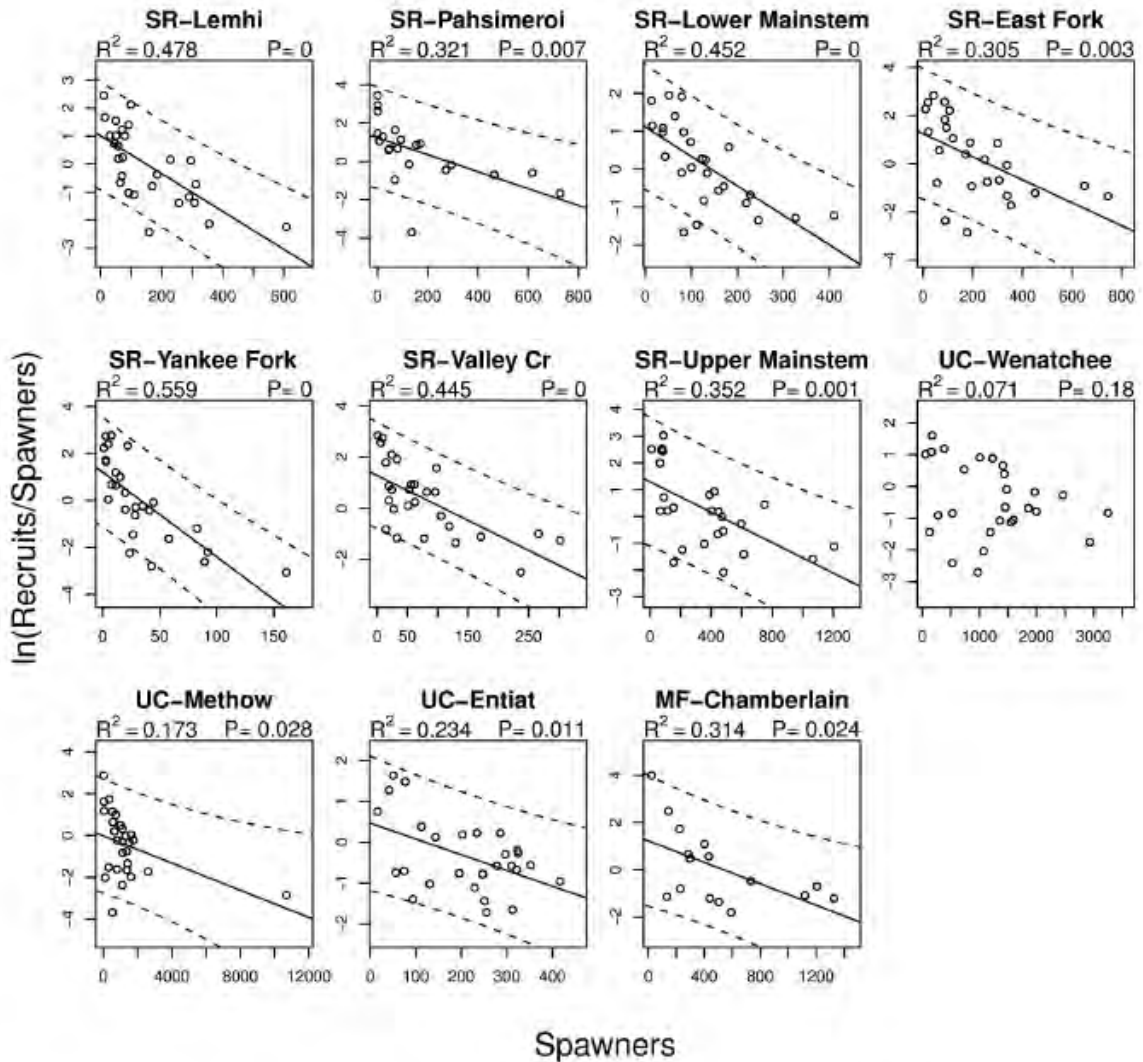


Figure 10. $\ln(\text{recruits/spawner})$ versus spawners for Interior Columbia River spring and summer Chinook populations. Open black points represent base period (1980-2000), and red points represent recent period. **The regression model was fit to all data (base and recent).** Based on linear regression, if $P < 0.1$, the dark line is the best fit, and the dashed lines are the 95% prediction interval for the data. The MF-Chamberlain population did not have any “base period” data, and was not included in the previous analyses.

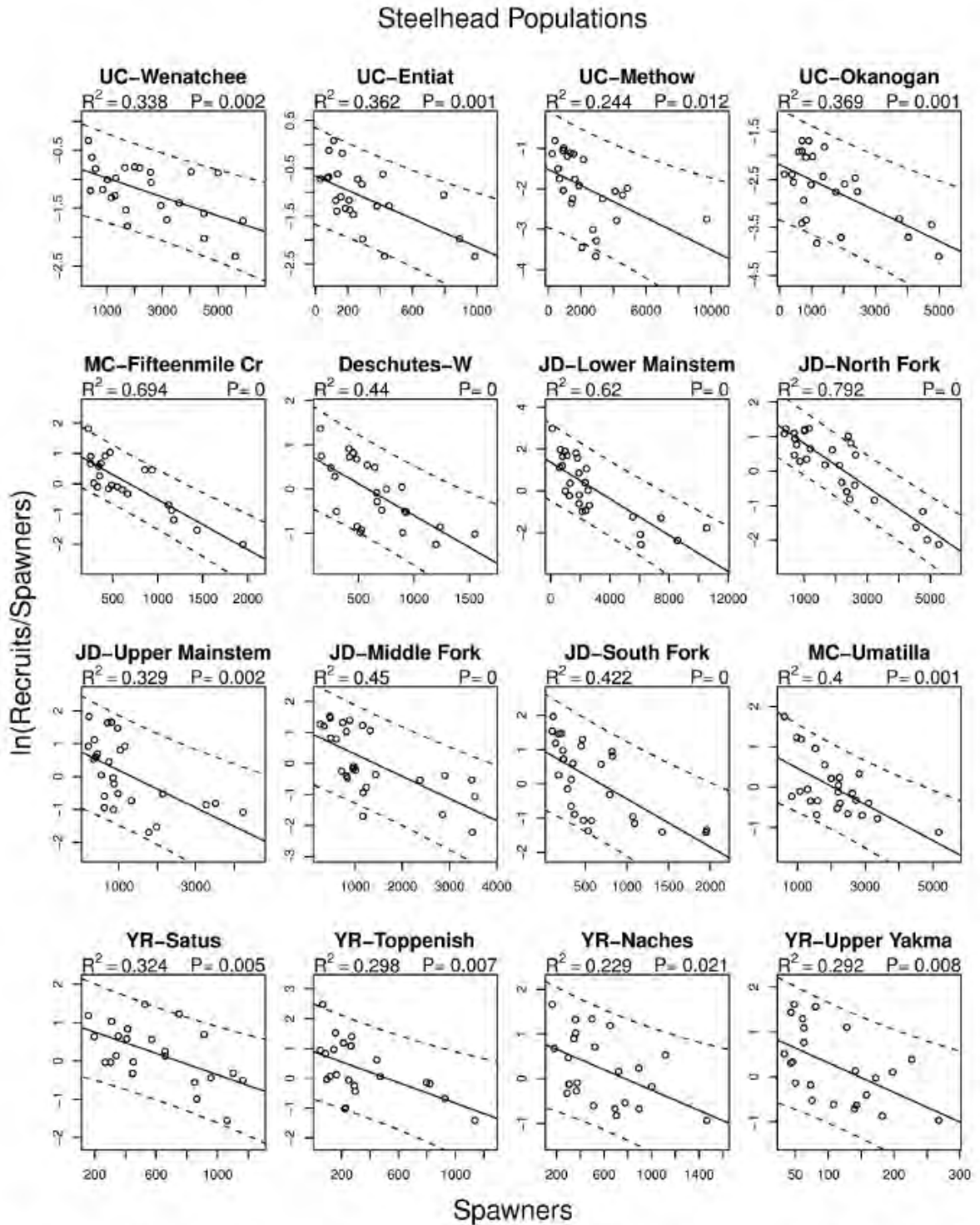


Figure 11. Ln(recruits/spawner) versus spawners for Interior Columbia River steelhead populations. Open black points represent base period (1980-2000), and red points represent recent period. **The regression model was fit to all data (base and recent).** Based on linear regression, if $P < 0.1$, the dark line is the best fit, and the dashed lines are the 95% prediction interval for the data.

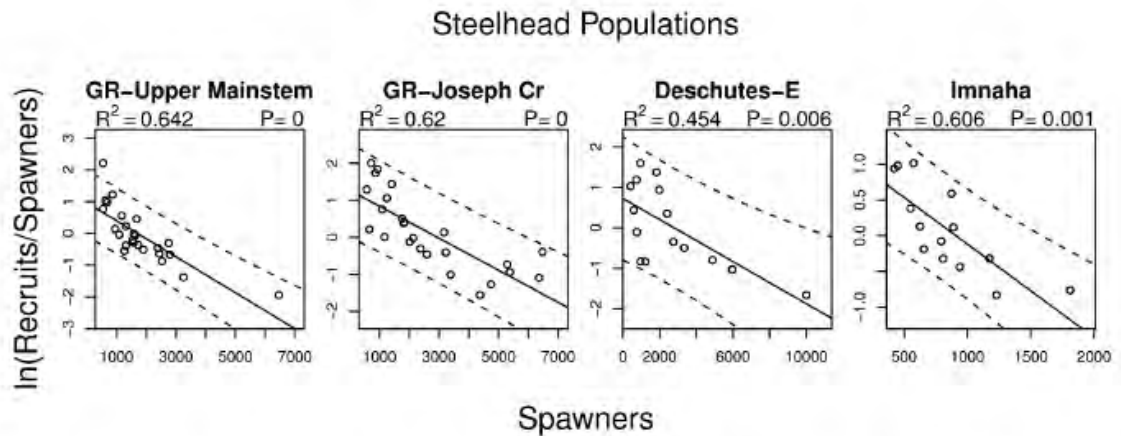


Figure 12. Ln(recruits/spawner) versus spawners for Interior Columbia River steelhead populations. Open black points represent base period (1980-2000), and red points represent recent period. **The regression model was fit to all data (base and recent).** Based on linear regression, if $P < 0.1$, the dark line is the best fit, and the dashed lines are the 95% prediction interval for the data. Note that the GR-Upper Mainstem and GR-Joseph Cr populations did not have harvest data. Also, the Deschutes-E and Imnaha populations did not have any “base period” data, and were not included in the previous analyses.

Appendix Table 1. Populations, major population groups (MPG), evolutionarily significant units (ESU), and distinct population segments (DPS) of salmon and steelhead addressed in this report. Shading indicates populations for which data were lacking or insufficient for the analysis and populations that are functionally extirpated.

ESU	MPG	Population	Codes for Populations Addressed in This Report
Snake River Spring/ Summer Chinook Salmon	Lower Snake	Tucannon River	LS-Tucannon
		Asotin Cr Functionally Extirpated	
	Grande Ronde Imnaha	Catherine Creek	GR-Catherine Cr
		Upper Grande Ronde	GR-Upper Mainstem
		Minam River	GR-Minam
		Wenaha River	GR-Wenaha
		Lostine/Wallowa Rivers	GR-Lostine
		Imnaha Mainstem	GR-Imnaha
		Big Sheep Creek Functionally Extirpated	
		Lookingglass- Functionally Extirpated	
	South Fork Salmon	South Fork Salmon Mainstem	SF-Mainstem
		Secesh River	SF-Secesh
		East Fork S. Fork Salmon (including Johnson Cr)	SF-East Fork
		Little Salmon River (including Rapid R.)	
	Middle Fork Salmon	Big Creek	MF-Big Creek
		Bear Valley/Elk Creek	MF-Bear Valley/Elk
		Marsh Creek	MF-Marsh Cr
		Sulphur Creek	MF-Sulphur Cr
		Camas Creek	MF-Camas Cr
		Loon Creek	MF-Loon
		Chamberlain Creek	MF-Chamberlain
		Lower Middle Fork Salmon (below Ind. Cr.)	
		Upper Middle Fork Salmon (above Ind. Cr.)	
	Upper Salmon	Lemhi River	SR-Lemhi
		Valley Creek	SR-Valley Cr
		Yankee Fork	SR-Yankee Fork
		Upper Salmon River (above Redfish L.)	SR-Upper Mainstem
North Fork Salmon River			
Lower Salmon River (below Redfish L.)		SR-Lower Mainstem	

		East Fork Salmon River	SR-East Fork
		Pahsimeroi River	SR-Pahsimeroi
		Panther Extirpated	

Upper Columbia Spring Chinook Salmon	Eastern Cascades	Wenatchee R.	UC-Wenatchee
		Methow R.	UC-Methow
		Entiat R.	UC-Entiat
		Okanogan R. (extirpated)	
Snake River Fall Chinook Salmon	Main Stem and Lower Tributaries	Lower Mainstem Fall Chinook	

DPS	MPG	Population	Codes for Populations Addressed in This Report
Upper Columbia River Steelhead	Eastern Cascades	Wenatchee River	UC-Wenatchee
		Methow River	UC-Methow
		Entiat River	UC-Entiat
		Okanogan River	UC-Okanogan
Snake River Steelhead	Lower Snake	Tucannon River	
		Asotin Creek	
	Imnaha River	Imnaha River	Imnaha
	Grande Ronde	Upper Mainstem	GR-Upper Mainstem
		Lower Mainstem	
		Joseph Cr.	GR-Joseph Cr
		Wallowa R.	
	Clearwater River	Lower Mainstem	
		Lolo Creek	
		Lochsa River	
Selway River			
South Fork			

		North Fork (Extirpated)	
	Salmon River	Upper Middle Fork Tribs	
		Chamberlain Cr.	
		South Fork Salmon	
		Panther Creek	
		Secesh River	
		North Fork	
		Lower Middle Fork Tribs	
		Little Salmon/Rapid	
		Lemhi River	
		Pahsimeroi River	
		East Fork Salmon	
		Upper Mainstem	
Mid Columbia Steelhead	Yakima	Upper Yakima R.	YR-Upper Yakima
		Naches R.	YR-Naches
		Toppenish Cr	YR-Toppenish
		Satus Cr	YR-Satus
	Eastern Cascades	Deschutes West	Deschutes-W
		Deschutes East	Deschutes-E
		Klickitat R.	
		Fifteenmile Cr.	
		Rock Cr.	
		White Salmon Extirpated	
	Umatilla/ Walla Walla	Umatilla R.	MC-Umatilla
		Walla-Walla R.	
		Touchet R.	
	John Day	Lower Mainstem	JD-Lower Mainstem
		North Fork	JD-North Fork
		Upper Mainstem	JD-Upper Mainstem
Middle Fork		JD-Middle Fork	
South Fork		JD-South Fork	

Appendix 2: Comparisons of alternative approaches

When we compiled the spawner and recruit data for interior Columbia River salmonid populations, we needed to make the following choices: 1) how to treat harvested fish in the estimation of recruits, and 2) how to treat years when few or no spawners returned. In this appendix, we made comparisons of alternative approaches to determine how influential these approaches were to final results.

When we calculated brood year recruits, R_t , we had to choose how to treat fish that were harvested during upstream migration. Harvest removes potential recruits, and if harvest occurred differentially across time, it could alter the underlying relationships that characterize population dynamics. Therefore we chose to add harvested fish to fish that returned to spawning sites in the following manner:

$$R_t = \frac{A_t}{1 - h_t}$$

where R_t are estimated recruits from brood year t , A_t are post-harvest returning adults, and h_t is the harvest rate for adults from brood year t . R_t represent the number of naturally produced fish that would have appeared on the spawning grounds had there not been a harvest. For comparison purposes, we performed an analysis where we did not add harvested to fish to estimate recruits. In this case, we just set $R_t = A_t$.

In some populations for a few years, few or no adults returned to the spawning area. Because the analysis required dividing recruits by spawners, dividing by zero spawners would result in an undefined term. Further, dividing by 5 or fewer spawners could produce biased results (ICTRT analysis). Accordingly, we examined the following three approaches: 1) deleting all years in a population where zero spawners returned; 2) deleting all years in a population where 5 or fewer spawners returned; 3) adding 1 to spawners and recruits for all years.

In this appendix, we made the following 3 comparisons:

- 1) Calculating recruits by adjusting for harvest rate *versus* calculating recruits without adjusting for harvest rate.

2) Deleting years with 0 spawners *versus* deleting years with 5 or fewer spawners.

3) Deleting years with 0 spawners *versus* adding 1 to spawners and recruits and using all data.

For all comparisons, we made pairwise comparisons by population of the following 4 outputs:

1) a parameter in Ricker model; 2) b parameter in Ricker model; 3) P-values from Ricker model fit; 4) Variance of residuals from Ricker model fit.

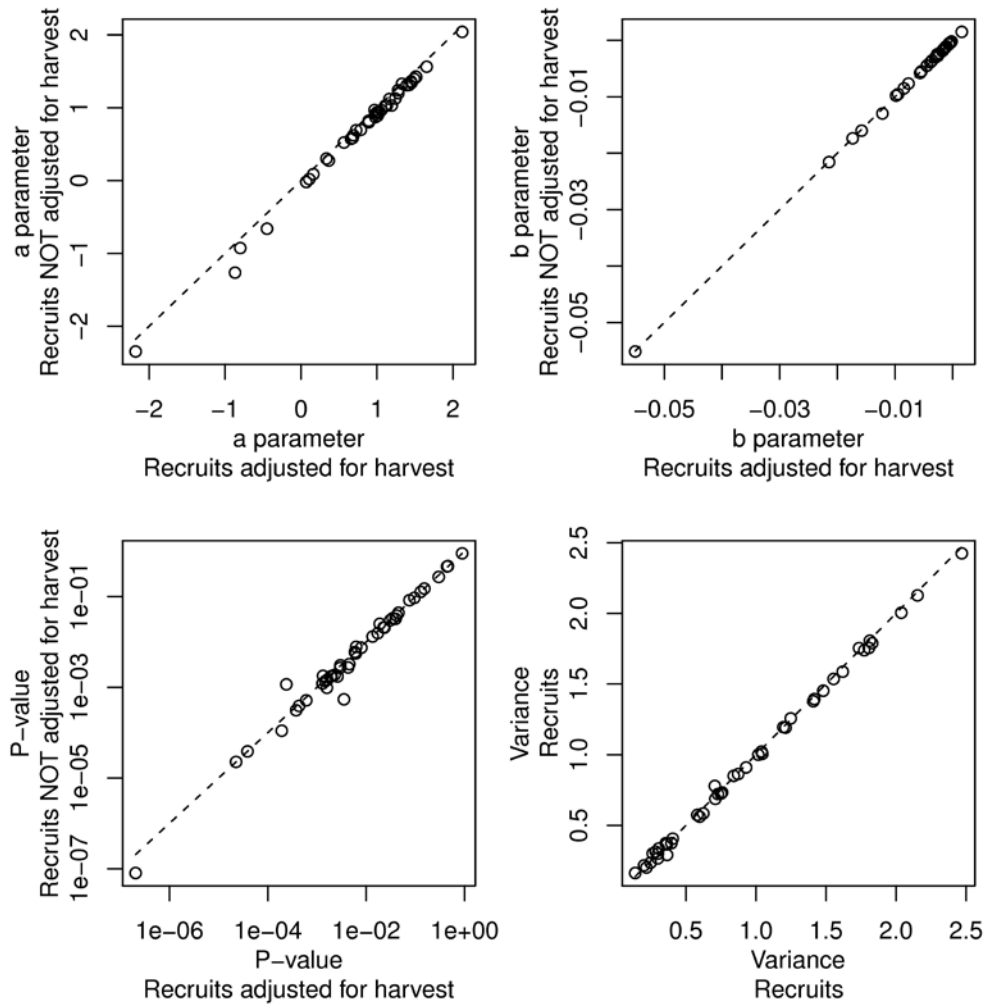


Figure 1. Comparison of calculating recruits by adjusting for harvest rate *versus* calculating recruits without adjusting for harvest rate. In each comparison, each point represents a population. Note that the axes for the comparison of P-values are on a log scale to spread out the points. The dashed line is the one-to-one line.

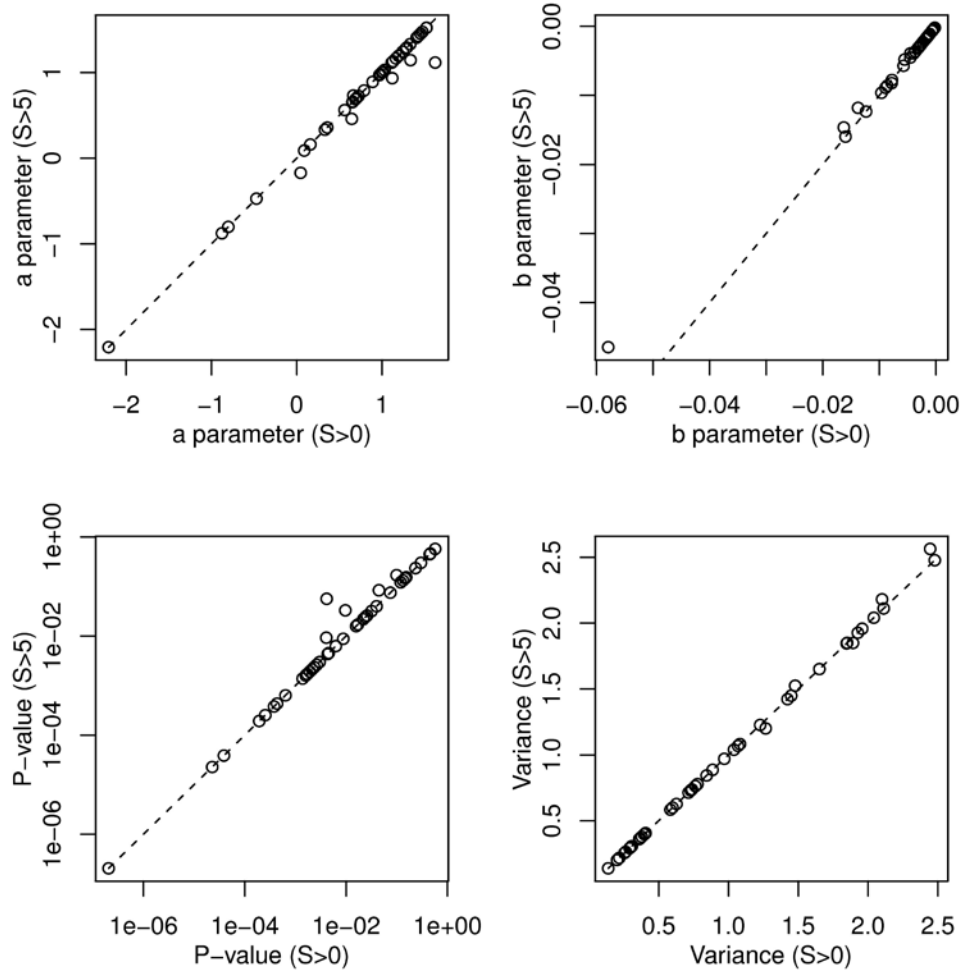


Figure 2. Comparison of deleting years with 0 spawners *versus* deleting years with 5 or fewer spawners. In each comparison, each point represents a population. Note that the axes for the comparison of P-values are on a log scale to spread out the points. The dashed line is the one-to-one line.

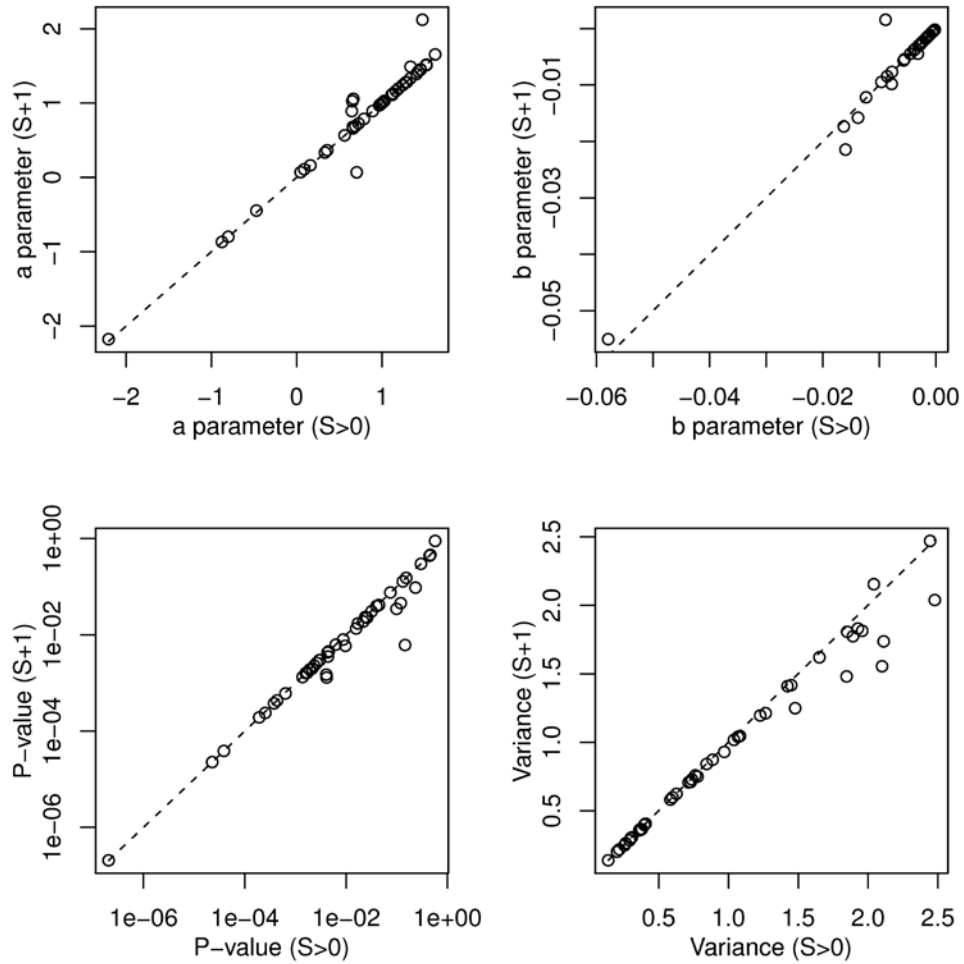


Figure 3. Comparison of deleting years with 0 spawners versus adding 1 to spawners and recruits and using all data. In each comparison, each point represents a population. Note that the axes for the comparison of P-values are on a log scale to spread out the points. The dashed line is the one-to-one line.

Results and Discussion

The comparison between adding harvested fish to recruits versus not adding harvested fish demonstrated little difference in the approaches (Figure 1). The Ricker a parameter (productivity) was slightly greater when harvested fish were added to recruits, but this is expected. Importantly, the Ricker b parameter (density dependence) was nearly identical between the two approaches. Because our analysis in the main document is focused on whether population dynamics have changed across time periods, we chose to add harvested fish to estimate recruits. However, we note that analyses with other goals might choose to ignore harvested fish when estimating recruits.

The comparison between deleting years with 0 spawners versus deleting years with 5 or fewer spawners demonstrated that these two approaches produced very similar results (Figure 2). For one population (Yankee Fork Chinook), deleting years with 0 spawners resulted in a greater b parameter than did the approach of deleting years with 5 or fewer spawners. This was not concerning because this population had the strongest density dependence regardless of approach.

The comparison between deleting years with 0 spawners and adding 1 to spawners and recruits in all years produced slightly more scatter in the Ricker a and b parameters (Figure 3). But there were no apparent biases between approaches because the points fell above and below the 1-to-1 line. However, the variance and P-values were smaller when we added 1 to spawners and recruits. This is expected because removing years from the dataset results in smaller sample sizes. Because of this reduced variance, we adopted the approach of adding 1 to spawners and recruits for all years.

Appendix D

Literature Reviews for Impacts of Climate Change on Columbia River Salmon

- D.1 Impacts of climate change on Columbia River Salmon: Review of the scientific literature published in 2012
- D.2 Literature review for 2010: Biological effects of climate change
- D.3 Literature review for 2011: Biological effects of climate change

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Appendix D.1

Impacts of climate change on Columbia River Salmon: Review of the scientific literature published in 2012

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Impacts of climate change on Columbia River salmon

Review of the scientific literature published in 2012

*Prepared by Lisa Crozier with help from Delaney Dechant
Northwest Fisheries Science Center, NOAA-Fisheries
August, 2013*

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Executive summary

Carbon emissions in 2012 (9.7 PgC) exceeded the previous record set in 2011 producing atmospheric CO₂ concentrations greater than 400 ppm at a majority of Arctic observation stations, although the global mean estimate is just shy of that benchmark at 392.6 ppm. A large number of GCMs have completed processing scenarios for a new IPCC 5th Assessment Report (AR5) to be released in fall 2013. A set of major reviews has also been completed in preparation for the National Climate Assessment, which is now in draft stage (NCADAC 2013). Preliminary reviews of these summaries indicate that they confirm most of the extent and impacts of climate change we have predicted in previous literature reviews. Although some models have revised certain estimates downward, we await the full synthesis to assess changes in projections from the previous IPCC report.

The bulk of the new information released in 2012 focused on sea level rise, sea ice extent, and glacier melting, which collectively was a weakness in the IPCC 4th Assessment Report. A National Academies Report projects global sea level to rise 13.5 cm by 2030 and 82.7 cm by 2100 (mean estimate), which is higher than the previous IPCC report, but comparable with other recent estimates. However, the uncertainty range reported here is much larger than other reports. Projections for Oregon and Washington are: -4 to 23cm by 2030, -3 to 48cm by 2050, and 10 to 143cm by 2100, compared with the 2000 level (Committee on Sea Level Rise in California et al. 2012). An analysis of climate extremes documents a historical and projected increase in extremely hot days, prolonged heat waves, and heavy precipitation events in many regions (IPCC 2012). Severe droughts are very likely to increase (Dai 2012), although the major drought of the 1930s has not been exceeded to date (IPCC 2012), overwhelming the historical trend.

Multiple reviews of historical trends in stream temperature in the Columbia River basin showed significant warming in unregulated streams with sufficiently long time series (mean summer warming of 0.22°C per decade), although certain regulated streams and short records can show reversed trends (Arismendi et al. 2012; Isaak et al. 2012b). One important conclusion is that temperature mitigation through controlled releases from dams can successfully lower stream temperatures (Arismendi et al. 2012; Konrad et al. 2012; Macdonald et al. 2012). New models of streamflow and temperature across the Columbia River basin project that reductions in summer streamflow will increase stream warming to an even greater degree than those that considered increases in air temperature alone, particularly in snow-dominated basins such as the Salmon River basin and the Clearwater basin (Furey et al. 2012; Tang et al. 2012; Wu et al. 2012a). Marine studies showed declining dissolved oxygen and expanded oxygen minimum zones off the Oregon coast (Bjorkstedt et al. 2012; Pierce et al. 2012), and new models project these trends will continue and become more corrosive (Bianucci and Denman 2012; Gruber et al. 2012). Gruber et al. (2012) projected 70% of the euphotic zone in the California Current Ecosystem (CCE) will be undersaturated in aragonite by the 2050s.

Projected impacts of climate change on salmon are similar to those previously described. Multiple papers expanded our understanding of the marine distribution and links with physical drivers and food web processes specifically for Columbia River Chinook salmon (Bi et al. 2012; Pool et al. 2012; Rupp et al. 2012; Ruzicka et al. 2012; Yu et al. 2012), and cautioned that predator pressure might increase in the CCE (Hazen et al. 2012). Freshwater Columbia River basin studies described new information about salmon movement through dams in winter (Kock et al. 2012; Tiffan et al. 2012), the estuary (Harnish et al. 2012), and the ocean (Sharma and Quinn 2012). Multiple efforts to determine drivers of early marine survival produced somewhat contradictory results: some reports detected clear influences of the mainstem CR conditions (Haeseker et al. 2012; Holsman et al. 2012), but others concluded that early marine growth was much more important (Tomaro et al. 2012). Several studies of invasive species in the Columbia River basin showed smallmouth bass distribution is strongly temperature dependent, and that they are widespread in some tributaries, with negative impacts on native prey and salmon behavior (Hughes and Herlihy 2012; Kuehne et al. 2012; Lawrence et al. 2012). On a more optimistic note, evidence of rapid evolutionary responses in migration timing in Alaskan pink salmon (Kovach et al. 2012), and the utility of standing genetic variation for future local adaptation (Miller et al. 2012b) suggested there is adaptive potential in existing populations. Miller et al. (2012) showed that two relatively distantly related populations of *Oncorhynchus mykiss* have evolved rapid development rates using the same conserved genetic variation. This suggests that development rate might be capable of evolving faster in response to future climate warming than would generally be associated with *de novo* mutations. Similarly, successful artificial selection for heat tolerance in rainbow trout indicates that evolutionary processes can proceed quickly under the right conditions (Ojima et al. 2012; Tan et al. 2012).

On the policy side, a perspective on the Columbia River Treaty (Feeley et al. 2012) presented a cautionary note on the success of adaptive management in the Columbia River basin. Climate adaptation strategies are being piloted by the Forest Service with science-based partnerships (Littell et al. 2012), but climate change is still a relatively low priority in conservation actions (Ellenwood et al. 2012).

In conclusion, recent literature provides further support for continuing temperature mitigation actions and maximal population recovery by whatever restoration actions are possible because of continuing threats of rising stream temperature and declining summer flows, and extreme events with potentially negative impacts on cold-water fish.

Abbreviations and Acronyms

A1B, A2, B1	Carbon emission scenarios from AR4
AOGCM	Coupled Atmosphere-Ocean General Circulation Model
AR4	4 th IPCC Assessment Report
AR5	5 th IPCC Assessment Report
ENSO	El Niño-Southern Oscillation
GCM	General Circulation Model
Gt	gigatons
IPCC	Intergovernmental Panel on Climate Change
PDO	Pacific Decadal Oscillation
PgC	Petagram Carbon
VIC	Variable Infiltration Capacity Model
CMIP3	Coupled Model Intercomparison Project Phase 3
CMIP5	Coupled Model Intercomparison Project Phase 5
RCP	Representative Concentration Pathways (Emissions scenarios for AR5)
CCE	California Current Ecosystem
SLR	Sea Level Rise
WRF	Weather Research and Forecasting model
ROMS	Regional Ocean Modeling System
NPGO	North Pacific Gyre Oscillation

Goals and methods of this review

The goal of this review was to identify the literature published in 2012 that is most relevant to predicting impacts of climate change on Columbia River salmon listed under the Endangered Species Act. A large amount of literature related to this topic is not included, because almost anything that affects salmon relates to or is altered in some way by changes in temperature, stream flow, or marine conditions. We have tried to identify the most directly related papers by combining climatic and salmonid terms in search criteria. Thus, many general principles demonstrated in other taxa or with more general contexts in mind have been omitted. This review also does not include potentially relevant gray literature, because the search engine used only includes the major peer-reviewed scientific journals. In total, the methods employed involved review of over 1000 papers. Of these, 224 are included in this summary.

This search was conducted in ISI Web of Science in Jan and July, 2012. Each set of search criteria involved a new search, and results were compared with previous searches to identify missing topics. The specific search criteria all included PY=2012, plus:

- 1) TS=(climat* OR temperature OR streamflow OR flow OR snowpack OR precipitation OR PDO) AND TS=(salmon OR Oncorhynchus OR steelhead);
- 2) TS=(climat* OR Temperature OR Precipitation OR streamflow OR flow) AND TS="Pacific Northwest";
- 3) TS=(marine OR sea level OR hyporheic OR groundwater) AND TS=climat* AND TS=(salmon OR Oncorhynchus OR steelhead);
- 4) TS=(upwelling OR estuary) AND TS=climat* AND TS=Pacific;
- 5) FT=("ocean acidification" OR "California current" OR "Columbia River")
- 6) TS="prespawn mortality"

The review is organized by first considering physical environmental conditions (historical trends and relationships) and then model projections of future climate, snowpack, stream flow, temperature, ocean conditions, etc. A summary follows of the literature on ecosystem and then salmon-specific responses to these environmental drivers, in freshwater and marine environments, respectively.

2 Literature on the physical processes of climate change

Global or national climate analyses

State of the Climate 2012

Global CO₂ emissions from fossil fuel combustion and cement production exceeded the 2011 all-time record (9.5 ± 0.5 PgC in 2011, 9.7 ± 0.5 PgC in 2012), and a majority of Arctic station records of atmospheric CO₂ exceeded 400ppm for the first time. The final global mean estimate of atmospheric CO₂ is 392.6 ppm. Anthropogenic greenhouse gases together now represent a 32% increase in radiative forcing over a 1990 baseline.

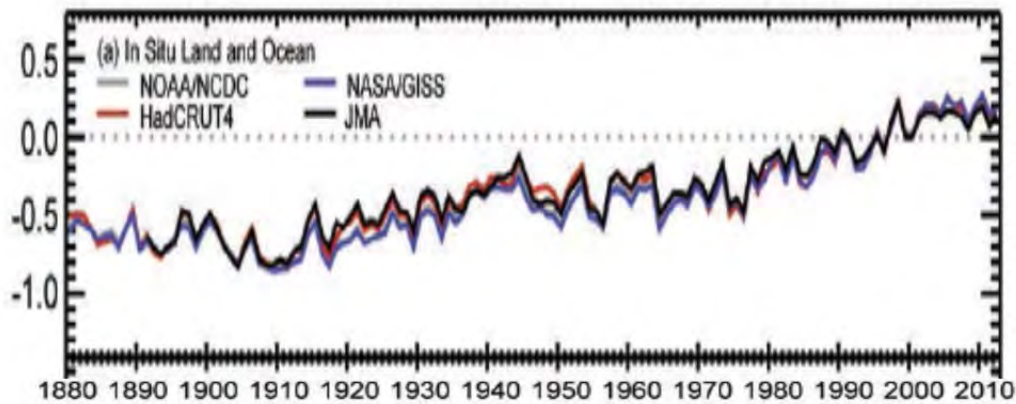


Figure 1. Global average surface temperature annual anomalies combining land and sea surface temperature (°C, 1981–2010 base period, Fig 2.1 in Blunden and Arndt 2013).

The year 2012 was among the 10 warmest years on record, continuing the decade-long phenomenon of above-average temperatures (all of these 10 warmest years occurred since 1998, Figure 1). More specifically, 2012 was 0.14°C to 0.17°C above the 1981–2010 average globally (land was 0.24°C – 0.29°C and the ocean was 0.10°C – 0.14°C above average). The north and northeast Pacific, including the California Current Ecosystem (CCE), however, was cooler than average due primarily to a weak Aleutian Low, related in part to La Niña influences. Cumulatively, Earth is warming at a rate of 0.06°C per decade since 1880 and a more rapid 0.16°C per decade since 1970. However, there has been no trend since 2000, presumably reflecting the cooling effects of a high frequency of La Niña events in the period 1998–2012. Sea ice extent, Greenland ice sheet melting (97% of the ice sheet surface showed signs of melting), and permafrost warming attained new records, reflecting the long warming trends. The hydrological cycle is also more differentiated between dry and wet

locations, with dry locations becoming drier and wet locations becoming wetter. Salinity also intensified (with salty areas getting saltier, and fresh areas getting fresher).

List of upcoming reports in 2013

General Circulation Models (GCMs) are producing new model runs of climate change for the 5th IPCC Assessment Report (AR5) to be released in fall 2013, called the Coupled Model Intercomparison Project Phase 5 (CMIP5). Chapters assessing impacts of climate change will follow in 2014. The CMIP5 developed new emission scenarios called Representative Concentration Pathways (RCP), which replace the 4th IPCC Assessment Report (AR4) scenarios (A2, A1B, B1, etc.). We will wait for the AR5 synthesis to comprehensively assess changes from the AR4 projections. However, the individual reports that turned up in our review did not suggest dramatic changes in the overall projections.

Global climate analyses

A major focus of the climate literature in 2012 was better understanding of sea level and sea ice, which was a weakness in AR4.

The National Academies produced a report focused on sea level rise (SLR) along the Washington, Oregon, and California coasts (Committee on Sea Level Rise in California et al. 2012). The report analyzed both the historical and projected trends of all the components to SLR. In conclusion, they projected a cumulative change in sea level globally of 8 to 23 cm by 2030 relative to 2000, 18 to 48 cm by 2050, and 50–140 cm by 2100. For the geographic region from northern California to Washington, they project a rise of –4 to 23 cm by 2030, –3 to 48 cm by 2050, and 10 to 143 cm by 2100. The large uncertainty for the Pacific Northwest (ranging from sea level *fall* to sea level *rise*) stems from complications in predicting regional geomorphic dynamics. Uplift of Washington and Oregon makes the regional projection lower than the global projection, and might cause local sea level to fall despite globally rising seas. However, the geological tension might also cause a massive subduction zone earthquake that would suddenly lower the land along the Pacific Northwest outer coast, but raise the land in Puget Sound.

The IPCC AR4 report tracked historical global sea level at 1.7 mm per year over the 20th century and recent (1993–2003) rates of 3.1 mm per year (p. 23). The higher recent rates might result from natural variability (especially ENSO), or global warming, or both. More recent reports produced similar estimates (Table 2.1 in the National Academy Report). For a 1 m rise by 2100, the recent rate would have to accelerate 3 to 4 times.

Damage along the coast occurs when large storms coincide with high tides. Some climate models predict that the winter storm track will move north over the 21st century, which would increase storm impact on the Oregon and Washington coasts. However, observational records (35 years) are not long enough to validate the drivers of historical

trends and clarify the role of natural interdecadal and ENSO influences (Committee on Sea Level Rise in California et al. 2012).

In a separate paper, Boon (2012) reports accelerating SLR along the Atlantic coast of the US and Canada. It isn't clear whether this trend will continue, but if it does, they project a rise of 0.2 to 0.9 m above the long-term mean by 2050 in the Northeast region.

Valiela et al. (2012) documented freshening in estuarine, near-shore, and off-shore water in coastal Panama due to increased precipitation. Freshwater added to surface waters by rain increased stream erosion, uprooted stream-edge terrestrial and mangrove trees, increased mortality of benthic fauna, damped upwelling of denser, nutrient-rich water, and enriched nutrients in surface seawater.

Francis and Vavrus (2012) explained links between Arctic and mid-latitude weather, including projections of increased probability of extreme weather events due to the faster rate of warming in the Arctic. Lui et al. (2012) showed how decreases in Arctic sea ice played a role in recent cold and snowy winters in Europe and the mid- and eastern US. The seasonal timing of sea ice showed strong trends in both the Arctic (3 month *longer* ice-free period) and the Antarctic (2 month *shorter* ice-free period). Nonetheless, it is still unclear from the new CMIP5 simulations when the Arctic will be completely ice free due to high variability in natural climate fluctuations (Stroeve et al. 2012). Glaciers and ice caps lost mass at 148 ± 30 Gt/yr from 2003 to 2010, raising sea level by 0.41 ± 0.08 mm/yr (Jacob et al. 2012), which is somewhat less than previously estimated.

Predicting sea level rise was a weakness of previous IPCC projections, which tended to underestimate recently observed rises. Nonetheless, in other respects, critical review showed that IPCC projections were very accurate at the global scale (Rahmstorf et al. 2012). Inconsistencies between ocean heat content estimates from different sources (Loeb et al. 2012) and heat release from warm ocean currents are being resolved (Wu et al. 2012b). Regional climate models still found local climates difficult to reproduce (Soares et al. 2012; Wehner 2013).

Using the new CMIP5 models, Gillett et al. (2012) reported results from the Canadian Earth System Model (CanESM2) with a new form of bias-correction based on regression of modeled and observed historical climates from 1851–2010. They confirm the signature of greenhouse gas forcing over the historical record reported by previous papers, but their estimate of past and projected forcing is lower than other estimates. They projected an overall range for global mean warming by 2100 of 1.2°C to 4.3°C, depending on the emissions scenario. Other papers reanalyzed the extent of historical warming. They found that the northern hemisphere warmed 1.12°C and the southern hemisphere warmed 0.84°C over the past century (Jones et al. 2012). Inputs from glaciers have been recalculated and are projected to raise sea level from 148 mm to 217 mm depending on RCP scenario by 2100 (Marzeion et al. 2012). El Niño analysis and modeling

Climate extremes

The IPCC Special Report (IPCC 2012) summarizes previous information on ENSO and other aspects of decadal variability, but concluded that the impact of global warming on these patterns is still highly variable among models in post-AR4 work. They described the shift toward more central rather than eastern equatorial Pacific El Niño, which we reported previously. They did not specifically focus on the PDO.

Specifically, ENSO studies included:(e.g., Carre et al. 2012; Dewitte et al. 2012; Li and Ren 2012; Li et al. 2012b; Ramesh and Murtugudde 2012; Zhang et al. 2012). Most of these studies are beyond the scope of this review, except for one that produced specific projections for future patterns in the frequency of El Niño events that would affect the California Current. Zhang et al. (2012) used two dynamic forecasting models, the Weather Research and Forecasting model (WRF, driven by GCMs ECHAM5 and CCSM3) and HadRM (driven by HADCM3) to model regional dynamics in the Pacific Northwest and southwest. Teleconnection patterns changed under future climate regimes, causing wet anomalies to dominate in both warm and cold phases of ENSO, unlike the canonical pattern associating wet conditions with cool phases, and dry conditions with warm phases.

Pacific Northwest

Historical analyses

A variety of studies published in 2012 found significant trends in temperature, precipitation and flow both within the Columbia River basin and over broader spatial scales. In brief, studies found stream temperatures getting warmer within the Columbia River basin (Arismendi et al. 2012; Isaak et al. 2012b) and interannual variability in stream flow increasing in the Fraser (Dery et al. 2012). In a few cases, no statistically significant trend emerged, specifically in a small set of regulated rivers (Isaak et al. 2012b) or over short time-series (Arismendi et al. 2012), and in snowfall in California (Christy 2012).

Stream temperature: an important limitation in our description and understanding of historical trends in stream temperature is the paucity of long-term data. Arismendi et al. (2012) conducted a very interesting analysis of the relationship between trends in temperature over time, and both the duration of the record and whether the stream was directly impacted by humans. Arismendi et al. (2012) found significant warming trends when longer records were available – roughly 44% of streams with records prior to 1987 had significant warming trends. However, cooling trends predominated in the shorter time series, despite significant warming of air temperature in many cases. The authors noted a correlation between base flow and riparian shading with these cooling trends. Human-impacted sites showed less variability over time, likely due to flow regulation and reservoir heat storage.

Isaak et al. (2012b) also compared temperature trends in unregulated and regulated streams. They demonstrated statistically significant warming trends from 1980 to 2009 on seven unregulated streams in the Pacific Northwest in summer (0.22°C per decade), fall and winter, producing a net warming trend annually despite a cooling trend in spring. Stream temperature trends were strongly correlated with air temperature, showing the expected signal from regional climate warming. Trends in 11 regulated streams were in the same direction, but were not statistically significant, indicating that modified flows, in some cases explicitly for temperature management, limits stream thermal response to climate drivers.

Runoff: a study of interannual variability and total runoff within the Fraser River basin (Dery et al. 2012) found distinct trends of increasing interannual variability in spring and summer (the period of high flows) over the past 100 years. New datasets of snowfall records in California found no trend since 1878 or within the last 50 years (Christy 2012).

Fire frequency: previous analyses have projected an increase in fire frequency due to rising temperatures and longer fire seasons, but a new study (Holden et al. 2012) showed an added influence of the timing of snowmelt and annual streamflow. Annual area burned and severe-burn area corresponded closely to precipitation variability and total annual streamflow. Another study (Abatzoglou and Brown 2012) compared downscaling methods for future projections of wildfire danger, and found that a new method, the Multivariate

Adapted Constructed Analogs (MACA), outperformed other methods for the high demands of complex fire prediction.

Projected changes

An intensive model of stream flow and temperature in the Pacific Northwest was published in 2012 (Wu et al. 2012a). This group used a physical model of stream temperature based on a dominant river-tracing-based streamflow and temperature model (DRTT). Averaged across the Pacific Northwest, the model projected a 3.5% *decrease* in mean *annual* streamflow for the 2020s, despite a net increase in annual precipitation, but *increases* thereafter (0.6% and 5.5% increases for the 2040s and 2080s, respectively). However, *summer* streamflow decreased from 19.3% (2020s) to 30.3% (2080s). They projected increases in mean annual stream temperature from 0.55°C (2020s) to 1.68°C (2080s), while mean summer stream temperatures warmed from 0.92°C to 2.10°C.

The largest projected increases in stream temperature occurred near the mouth of the Columbia River, which rose 1.88°C (2020s) to 4.37°C (2080s). The simulations indicated that projected climate change will have greater impacts on snow-dominant streams, such as those found in the upper Columbia basin and Salmon and Clearwater basins, with lower summer streamflows acting synergistically with warmer summer stream temperature changes relative to transient- and rain-dominant regimes (Wu et al. 2012a).

Donley et al (2012) analyzed water availability for fish in the Columbia basin by taking output from the Climate Impacts Group downscaled projections (described in previous literature reviews) and incorporating reservoir management rules and human withdrawals for agriculture using the Water Evaluation and Planning System (WEAP). They analyzed four sub-basins (Okanogan, Methow, Wenatchee, and Yakima) under five scenarios (climate change alone, moderate or high increases in agricultural demands, and different potential conservation rules). They found the potential for very serious risks to salmonids unless substantial protections are put in place. They present a set of specific recommendations for each basin.

Kollat et al. (2012) modeled how human population growth and land use change would interact with climate change to dramatically increase the frequency of 100-year return period flood risk – up to 50%–60% in parts of the Pacific Northwest by 2100. This was a US-wide study, not locally downscaled, but the inclusion of the human dimension through impervious surfaces and changes in runoff reinforce previous results that showed the same trends but did not include these effects.

Six studies projected changes in streamflow or stream temperature at specific watersheds within the Columbia River basin. Lutz et al. (2012) focused on the Yakima River basin. They explored tree ring data over 366 years to characterize patterns of natural climate variability. They reconstructed five climate patterns and projected them under future climate change scenarios. The scenarios showed reductions in summer streamflow despite wetter

meteorological conditions. The USGS completed projections using the Precipitation Runoff Modeling System (PRMS) for a number of watersheds across the country, including the Naches basin, which is a tributary to the Yakima (Markstrom et al. 2012). They predicted increased winter runoff and less spring and summer runoff due to shifts in precipitation falling as rain rather than snow.

Efforts to provide thermal refugia in the Snake River have relied on releases from the Dworshak Dam on the Clearwater River in Idaho. Furey et al. (2012) used a simple “conceptual” hydrological model to explore the combinations of temperature and precipitation change that would cause the most substantial shifts in streamflow. They found that increasing precipitation increased runoff if temperature stayed constant, but under warming scenarios annual streamflow declined.

Another sensitivity analysis of stream flow in the sister tributary, the Salmon River basin (Tang et al. 2012) produced similar responses with the more mechanistic Variable Infiltration Capacity (VIC) hydrological model. In response to incremental temperature increases, 1) annual flow decreased (November to February warming increased fall flows, whereas May to July warming decreased summer flows); 2) the timing of 50% of the annual flow shifted 10 to 30 days earlier with 2°C warming, and 15 to 45 days earlier with 3°C warming; and 3) flash flows increased, which tends to increase bank erosion.

The process of projecting the physical consequences of climate change in any given location involves many steps in modeling, and each step has its own uncertainty in model parameters and outcomes. Many studies include multiple GCMs and emission scenarios in their projections to represent these sources of uncertainty. Previous studies have found that sensitivity to uncertainty in different steps in the modeling process depends on such factors as the aspect of the hydrological cycle (wet or dry season) and geographic location of interest. For example, Jung et al. (2012) focused specifically on how a rain-dominated basin differed from a snow-dominated basin, both in the lower Willamette Valley, in sensitivity differences. They found that the snow-dominated basin was more sensitive to hydrological model parameter uncertainty because of difficulties in modeling snowmelt.

Surfleet et al. (2012) compared biases of three hydrological models (VIC, PRMS, and a site-specific GSFLOW model), in the Santiam River basin, a tributary to the Willamette River. They found biases in the large scale, VIC model, especially at small, unregulated sites, which they suspected reflected unmodeled groundwater influences. The models differed in their projected flows, mostly during low-flow periods of summer.

Additional studies developed detailed projections for the Boise and Spokane river basins (Jin and Sridhar 2012), Vancouver Island (Sobie and Weaver 2012) and British Columbia headwaters (but not the Columbia River Basin, Bennett et al. 2012). In general, these studies showed similar trends in responses and the importance of spatial variation in projections as has been reported for the Columbia River basin.

Marine

A report on “The state of the California Current System 2011-2012” focused mostly on 2011, because it was written in mid-2012 (Bjorkstedt et al. 2012). The report described spring 2012 as largely ENSO-neutral, with somewhat incoherent patterns in the PDO and multi-variate ENSO index, and latitudinal variability in the timing, strength, and duration of upwelling. The northern CCE had weaker than average and delayed upwelling. Bjorkstedt et al. (2012) also documented declines in dissolved oxygen, nutrient-enriched water below the mixed layer, and abundant jellyfish.

Climate models predict that **dissolved oxygen** will decrease and the oxygen minimum zone will thicken with global warming. Pierce et al. (2012) documented both of these trends since 1960 along the Newport line off central Oregon. Oxygen is decreasing between 100 and 550 m. The OMZ now occurs at ~800 m, and upwelled water is hypoxic on the Oregon shelf.

Analysis of historical time series found concordance of **upwelling** and the PDO, North Pacific Gyre Oscillation (NPGO) and ENSO at very low frequency especially in the southern half of the CCE (Macias et al. 2012b). Improved coupling of CCE with the atmosphere better reconstructs upwelling and small-scale phenomena (Li et al. 2012a). Iles et al. (2012) concluded that “upwelling events are becoming less frequent, stronger, and longer in duration” off Oregon and California. A new sensitivity analysis that used the Regional Ocean Modeling System (ROMS) model showed an increasing risk of coastal hypoxia and low pH off the Vancouver shelf (Bianucci and Denman 2012).

Literature on **ocean acidification** in 2012 focused on both physical dynamics of ocean acidification and biological sensitivities. A significant review was released by NOAA describing knowledge on this topic to date (Feeley et al. 2012). Papers that focused on physical dynamics to improve our understanding of ocean acidification included several that described historical and future **patterns in pH** in the California Current. This work developed empirical relationships and described recent trends and characteristics of pH and potential drivers (Alin et al. 2012; Wootton and Pfister 2012) and reconstructed ancient time series (Honisch et al. 2012). Wootton and Pfister (2012) found strong trends of declining pH (mean = -0.018 per yr) in the Strait of Juan de Fuca over about 15 years, which proved more consistent with rising atmospheric CO₂ rather than local drivers such as upwelling. Gruber et al. (2012) reported results from a high-resolution oceanographic model of the near-shore CCE simulating the A2 and B1 climate change scenarios from the IPCC AR4. Gruber et al. (2012) projected that by the 2050s, 70% of the euphotic zone (top 60m) of nearshore (10km) habitat will be undersaturated ($\Omega_{\text{arag}} < 1$) the entire summer, and over 50% will be undersaturated year-round, regardless of emissions scenario. No areas were similarly acidic in pre-industrial times (~1750). Sea-floor habitat grew essentially entirely undersaturated by 2025 in the simulation.

Ecosystem responses to climate change

Literature reviews on marine ecosystems and fisheries

Recently, numerous reviews have published evidence for the fingerprints of climate change and projections of future trends in climate, including the IPCC Special Report on Extreme Events (Report 2012), a U.S. National Academy Report on sea level rise (Committee on Sea Level Rise in California et al. 2012), and a Royal Society of Canada report on climate change and marine biodiversity (Hutchings et al. 2012). More fish-centric reviews of impacts of these changes on fisheries are also available, especially for the UK (Cheung et al. 2012; Heath et al. 2012). Most comprehensively, Griffiths et al. (2013), Groffman and Kareiva (2013) and Staudinger et al. (2012) contributed technical input to the 2013 U.S. National Climate Assessment (NCADAC 2013) that reviewed the current state of knowledge on factors affecting oceans and freshwater resources. Doney et al. (2012) reviewed marine ecosystems globally. In the Pacific Northwest, Martins et al. (2012a) reviewed the physiological links between climate and sockeye salmon, with most data coming from the Fraser River. Rand et al. (2012) assessed sockeye extinction risk according to the International Union for the Conservation of Nature Red List criteria, and found that 27% of sockeye populations, mostly in British Columbia and Washington, are at very high risk of extinction, due partly to climate changes.

Ecosystem responses

Several studies focused on the connection between physical drivers and plankton communities. Historical shifts in primary production pointed to important environmental drivers. Chlorophyll-a concentration off central California increased, but north and south (the central North Pacific gyre and off southern Baja California) it decreased from 1996 to 2011 (Kahru et al. 2012). They associated the decrease in the North Pacific with enhanced vertical stratification, as predicted to result from global warming, and increases in upwelling. Other authors also linked the detailed mechanisms of upwelling to primary production (Lachkar and Gruber 2012; Macias et al. 2012a), and larger scale differences in the north and south Bering Sea (Stabeno et al. 2012). Phytoplankton cell size has been shrinking in Pacific equatorial and subtropical oceans, in addition to alternating with the ENSO cycle (Polovina and Woodworth 2012). Microcosm experiments indicated a shift in microzooplankton grazing rates (Chen et al. 2012). Bi et al. (2012) improved our understanding of local variation in effects of PDO on copepod communities in CCE, related in part to upwelling effects (near-shore communities were more responsive to PDO forcing than communities on the shelf slope). Freshwater influence and changing glacial melting rates also influenced community structure (Pirtle et al. 2012).

Two studies of links from physical drivers up the food chain focused specifically on salmon prey items. Ruzicka et al. (2012) developed an especially relevant food web model

for Columbia River salmon for each of the 2003–2007 upwelling seasons for the northern California Current. They found that euphasiids were the most important link between primary productivity and fish productivity. In an alternative food web configuration, jellyfish dominated the biomass without providing much benefit to fish because jellyfish tended to sink to the bottom, causing nutrients to drop out of the pelagic food web. Jellyfish are very sensitive to environmental conditions, and these relationships drew more attention in 2012 (Lebrato et al. 2012; Suchman et al. 2012). Volkov (2012) linked Arctic cold-current patterns to the mass occurrence of the large hyperiid *Themisto libellula*. This species became a major food source for salmon in the Bering Sea from 2007 to 2011. In an alternative modeling approach, Blanchard et al. (2012) projected changes in potential fish production in all the major ecosystems world-wide, including the Pacific Northwest, employing a size-based food web model.

A study of phenological trends at four levels in the food web over 24 years in the North Sea failed to find much coherence among trophic levels (Burthe et al. 2012). Although they concluded a mismatch must be occurring, no adverse effects on breeding success in seabirds was apparent.

A study of top predators in the Pacific projected responses to climate change in 23 species (Hazen et al. 2012). They found that sharks, loggerhead turtles and blue whales were most at risk; California sea lions, elephant seals and tuna face little change or small increases; while sooty shearwaters and albatrosses might see large gains. Hazen et al. (2012) projected greater competition among top predators in the CCE, but also higher risk of anthropogenic impacts such as shipping and fisheries bycatch. The increasing oxygen minimum zones might make prey more vulnerable to air-breathing predators.

Impacts of climate change on salmon

Population declines attributed to climatic factors

Many salmonid populations have declined over the past century, and are currently threatened with extinction. Establishing causal links between declines and climate change presents a challenge because we generally lack the spatially specific and temporally appropriate data to document direct effects of environmental driving factors. Also, other human impacts are confounding factors. Inferential evidence comes from 1) concurrent changes in population and climate metrics, and 2) mechanistic models of habitat area (thermal niche models), population or individual growth models, or cumulative stress models. Several papers have taken each of these approaches.

Isaak et al. (2012a) and Zeigler et al (2012) described recent climate changes within the ranges of a variety of listed species of trout along the Rocky Mountains. They identified trends in air temperature and flow, and the primary climate stressors expected to affect each

species. They discussed how observed changes exacerbate management challenges like increasing wildfires and movement of specific warm-adapted exotic species known to interact with the species of concern. Connors et al. (2012) evaluated a set of hypotheses for the decline of Fraser River sockeye salmon, including sea surface temperature and interactions among drivers in their hypotheses. They concluded that sea surface temperature is a significant contributing factor, either directly or through an interaction with farmed or pink salmon. They suggested that possibly “juvenile sockeye that are exposed to pathogens early in marine life are less able to compete for resources with pink salmon later in marine life. Alternatively, reduced food availability from competition with pink salmon might lead to disease expression in sockeye that are infected but not diseased. The antagonistic interaction between exposure to farmed salmon and oceanographic conditions during early marine life suggests that the effects of warmer sea surface temperature and exposure to farmed salmon production on sockeye productivity may be compensatory whereby some sockeye that die because of poor ocean conditions would have died because of diseases, and vice versa, but not because of both” (p. 310).

Transitioning to the more mechanistic quantitative models, two models involved European brown trout. In the first model, Almodevar et al. (2012) developed a habitat niche model based on presence and absence of brown trout in Iberian Peninsula. They found that suitable habitat has already declined by 12% per decade, which corresponds to 6% decline in population size per year. Under a B2 climate scenario, they expected 50% of the habitat will be lost by the 2040s, and the population will be extinct by 2100. In the second model, Lecomte and Laplanche (2012) developed a temperature-driven growth and production model for use in future population modeling.

Piou and Prevost (2012) developed an even more sophisticated growth and production model for Atlantic salmon that includes genetic structure and microevolution. This versatile model will likely be quite useful in predicting plastic and evolutionary responses to climate change.

Other mechanistic models were more general in their application, but provided a common metric for integrating the net effect of different stressors through aerobic scope and energetic costs (Portner 2012; Sokolova et al. 2012).

Providing a larger temporal context for inferences of population decline due to warming, Turrero et al. (2012) took a paleoecological approach to document fluctuations between high and low salmon abundance and climate. Turrero et al. (2012) identified a longer generation time (more years at sea) in Atlantic salmon and brown trout during the Upper Palaeolithic period. They modeled population growth rates based on mutation rates and concluded that the shifts in life history were associated with a lower population growth rate.

Life-cycle modeling is a useful tool in conservation planning. Zeug et al. (2012) developed a stochastic life-cycle model for winter-run Chinook salmon in the Sacramento

River, California. A sensitivity analysis revealed that a 10% change in temperature had a much larger impact on escapement than comparable changes in other inputs.

Freshwater processes

Juvenile migration

McMillan et al. (2012) found that early maturation or smolting in *O. mykiss* depended on both body size and lipid levels: fatter fish tended to mature earlier, but they were more likely to smolt under warmer temperatures.

Arctic char propensity to go to sea was predicted by lake productivity (and hence growth potential) and the arduousness of the migration, suggesting locally adapted thresholds for anadromy (Finstad and Hein 2012).

Two studies of **in-river movement** behavior found that juveniles migrate past dams over winter. Juvenile fall Chinook move through the hydrosystem on the lower Snake River during winter more than previously thought, which has implications for dam operations, such as removal of fish screens to minimize loss in turbines (Tiffan et al. 2012). Similarly, coho move past Cowlitz Dam over winter (Kock et al. 2012). These behaviors increase as spring approaches. The effect of photoperiod and temperature on rheotactic behavior and swim speed in tanks confirms these mechanisms (Martin et al. 2012). Riley et al. (2012) found that artificial lights, such as those used at dams, can interfere with normal diel and perhaps seasonal behavior.

Migration routes through the Columbia River **estuary** vary, including both the navigation channel and off-channel areas (Harnish et al. 2012). Fish use tidal energy to facilitate migration. However, **ocean migration routes** of ocean-type (subyearling) and stream-type (yearling) Chinook are not differentiated as universally as was previously thought (Sharma and Quinn 2012). The traditional model posits that subyearling Chinook migrate nearer to shore while yearling Chinook go off-shore. They found this to be true for Chinook originating in snow-dominated rearing basins, e.g., the Upper Columbia, Snake River, and Upper Fraser. However, subyearling and yearling migrants from warmer natal environments in lower rivers and coastal areas overlap extensively in their ocean migration routes, contradicting the hypothesis.

Adult migration

Flow and temperature are regulating factors in upstream movement of salmonids. Exposure to high **temperature** is a paramount concern from California to British Columbia, as well as for Atlantic salmon (Moore et al. 2012). Moore et al. (2012) provide a conceptual overview on thermal impacts on the spawning migration. Empirical studies document actual temperatures experienced. Strange (2012) analyzed migration patterns and temperature

exposure in the Klamath River in California. He tracked four run-timing groups: Klamath-Trinity spring, Trinity summer, Klamath fall and Trinity fall. Two runs avoided high temperatures by migrating before or after peak thermal maxima (the spring run and the Trinity fall run). One run avoided excessive cumulative thermal exposure by migrating very quickly (the Trinity summer run). However, the Klamath fall run stayed close to high temperature prior to migrating, which exposed them to moderately high thermal stress. The highest exposures occurred in spring-run fish that migrated very slowly, and hence got caught in summer temperatures for extended periods.

In the Puntledge River on Vancouver Island, BC, a study of biotelemetry plus animal-borne thermal loggers showed that summer-run Chinook are already exposed to temperatures exceeding their thermal limits and it is affecting their spawning migration (Hasler et al. 2012a). Cumulative thermal stress is strongly associated with mortality in early migrating Fraser River sockeye (Hinch et al. 2012), which might also have pre-existing conditions that make them vulnerable.

Flow is also a dominant factor controlling migration due to the energetic cost of migrating against a strong current. The optimal swimming path depends on the details of complex fluvial velocity fields (McElroy et al. 2012). Electromyogram recordings document a large amount of individual variation in the energetic cost of swimming through variation in swimming strategies, migratory behaviors, and habitat use, in addition to river environment drivers like temperature and water velocity (Hasler et al. 2012b). Bendall (2012) summarize multiple models of migration movement, including flow and olfactory signals, among other factors.

Direct effects of temperature

Papers detailing direct effects of temperature on salmonids fell into categories of 1) detailed physiology, 2) factors affecting maximum temperature tolerance, 3) thermal impacts on growth and consequences of various growth rates, 4) swimming performance 5) behavioral consequences of high temperature exposure, such as predator avoidance behaviors and spawn timing, 6) the use of cool water refugia, and 7) fish communities structured by adaptations to winter temperature. Martins (Martins et al. 2012a) reviewed the full range of effects of climate on growth, phenology and survival of sockeye salmon – but 83.4% of the papers reviewed focused on temperature.

Physiological responses to thermal stress include cellular effects, hormonal responses, cardiac function, reproductive capacity, gene expression, and fatty acid production (Anderson et al. 2012a; Anderson et al. 2012b; Arts et al. 2012; Casselman et al. 2012; Jeffries et al. 2012b; Keen and Gamperl 2012; Lahnsteiner and Kletzl 2012; Lahnsteiner and Mansour 2012; LeBlanc et al. 2012; Lewis et al. 2012; Reese and Williams 2012; Tan et al. 2012)

Factors that affected survival after a high temperature challenge included maternal effects (Burt et al. 2012b) and time to spawning, or maturation status -- with more mature fish having much lower survival, especially females (Jeffries et al. 2012a; Martins et al. 2012b). Size effects were somewhat contradictory, with smaller fish generally being more heat tolerant, favoring jacks over older males (Clark et al. 2012), but the effect was negligible or small in several species (Recsetar et al. 2012).

Temperature has a profound impact on growth rates, partially through altered behavior and appetite suppression (Folkedal et al. 2012a; Folkedal et al. 2012b; Hevroy et al. 2012). Atlantic salmon followed different growth trajectories after exposure to different acclimate temperatures, showing a surprising long-term effect of acclimation (Finstad and Jonsson 2012). Similarly, development temperatures produced different reaction norms for growth in cod (Hurst et al. 2012). This interannual variation in reaction norms in cod (Hurst et al. 2012) presents a significant challenge for modeling future responses to climate based on short-term experiments without a full understanding of interacting effects. But the net effects of different temperatures on growth, combined with density effects, produce predictable spatial patterns in body size (Parra et al. 2012). Bioenergetic models and dynamic energy budget models are used to model the impacts of different thermal regimes (Leach et al. 2012; Nisbet et al. 2012), and lead to theories of optimal energy allocation to storage tissue versus growth that varies depending on the length of the growing season and the severity of winter (Mogensen and Post 2012). Long-term consequences of thermally-induced differences in growth rate include reduced allocation to reproduction after compensatory growth following slow growth under cool temperatures (Lee et al. 2012).

Swimming performance in fry suffered after exposure to 16°C (Burt et al. 2012a), but performance was sometimes inversely related to survival (i.e., there was a family effect on both, but a given family might have low survival but high performance). Different metrics of swimming performance showed different patterns in response to increasing temperature (Yan et al. 2012). Importantly, the maximum sustainable swim speed varies with temperature, which has implications for many studies that use this metric under novel thermal conditions.

Behavioral consequences of high temperature exposure were documented in adults and juveniles. Spawners waited to spawn, sometimes reducing net redd production, during warm years, in brook trout in New York over an 11-year study (Warren et al. 2012). Juvenile Chinook salmon produced stronger and more variable anti-predator behaviors in a laboratory experimental exposure to bass (Kuehne et al. 2012). Stenhouse (2012) summarized literature on coho temperature preferences, defining thermal ranges from optimal to detrimental.

Use of thermal refugia as streams warm has been difficult to predict, and several studies shed light on this behavior. Hillyard and Keeley (2012) showed that Bonneville Cutthroat trout used thermal refugia more in unregulated than regulated rivers, perhaps because the refugia were more abundant and closer together. Brook trout also move throughout a stream network in Appalachia differentially in mainstem or tributary habitat in response to high temperatures (Petty et al. 2012), and use of refugia depended also on cover. Coho salmon in the Klamath River congregated around the mouths of cool-water tributaries when mainstem temperatures approach 19°C (Sutton and Soto 2012). If the refugia exceed 23°C, they were no longer used, suggesting this temperature is too hot to provide any benefit.

Finally, Shuter et al. (2012) documents adaptations to winter temperatures that have evolved in different fish species, and emphasizes that this is an important time of year for structuring communities—it isn't all about summer maximum temperatures.

Local adaptation

Predicting evolutionary responses to future climate change relies on various lines of evidence, including: 1) study of existing phenotypic variation among populations exposed to different environmental conditions, 2) genomic studies revealing genetic differences among populations that might be adaptive, 3) measurements of current selection under different environmental conditions within populations, and finally, 4) optimality models that provide the theoretical basis for predicting evolutionary responses to selection under different environmental regimes.

Numerous studies measured **differences in thermal tolerance among populations**. Drinan et al. (2012a) evaluated embryonic survival, development rate, and growth rate at various temperatures in five populations of westslope cutthroat trout from Montana. Although the absolute survival at the highest temperature (14°C) was not correlated with natal stream temperature, the decline in survival from 10°C to 14°C was consistent with stream rank temperature. They found that populations from warmer streams had more similar survival at 10°C and 14°C than populations from cooler streams. In a similar study, Colorado River cutthroat trout showed different thermal maxima, although the different acclimation responses appear to mediate the discrepancy rather than maximum possible heat tolerance under optimal acclimation conditions (Underwood et al. 2012). Larger fish were also less heat tolerant than smaller fish (Underwood et al. 2012). A comparison of hatchery strains of brook trout also showed genetic differences in thermal tolerance (McDermid et al. 2012).

Comparisons of natural populations exposed to different thermal regimes provide indirect evidence of selection on heat tolerance, but much more direct study of rapid evolution in this trait comes from **artificial selection**. A strain of rainbow trout has been

artificially selected for heat tolerance, and several authors have studied the physiological mechanisms of this improved heat tolerance (Ojima et al. 2012; Tan et al. 2012).

Other examples of **local adaptation** to environmental conditions, specifically the **flow regime**, are fin length, body depth, body length, head shape, and eye size (Drinan et al. 2012b; Stelkens et al. 2012). Growth thresholds that determine the probability of smolting at a given age (Sogard et al. 2012), and tolerance of hypoxia (Cote et al. 2012) also appear to be locally adapted.

Distinguishing between phenotypic plasticity and genetic roots of these differences is not easy. Genetic differences among populations can be established with genomic techniques, and secondarily associated with selection (Limborg et al. 2012). Kovach tracked a change over time in a genetic marker in a population of pink salmon that he associated with direct selection on run timing (Kovach et al. 2012). Shorter term oscillations in selection on run timing were also detected in coho (Kodama et al. 2012). Miller et al. (2012b) concluded that most local adaptation in salmon stems from standing genetic variation rather than de novo mutations. This is a very important result because evolution proceeds much faster by this route. A specific quantitative trait loci has been associated with spawn timing in coho (Araneda et al. 2012).

Finally, a theoretical study of selection pressures demonstrated that given plasticity and a stochastic environment, the model predicts a “mismatch” in the timing of breeding and prey availability is optimal when cost of overshooting is more (or less) severe than the cost of the undershooting – in other words, when the fitness curve is asymmetric (Lof et al. 2012).

Invasive species: smallmouth bass and shad

A study of the relative abundance of alien piscivores and native prey species in seven Pacific Northwest (Hughes and Herlihy 2012) rivers found that native prey abundance was inversely related to the abundance of alien fish. They conclude that alien piscivores are present along the entire length of the Okanogan and John Day rivers. They suspect that declines of native prey species can be attributed to these invasions, especially smallmouth bass.

Another study (Lawrence et al. 2012) focused specifically on smallmouth bass invasion of the John Day River. They found extensive overlap in bass and subyearling Chinook habitat in early summer. Both species shifted upstream as temperatures warmed seasonally, but a high-gradient portion of the river might limit bass. Because temperature constituted the primary determinant of bass presence, rising stream temperatures will very likely bring more bass. Restoration activities could focus specifically on maintaining bottlenecks to discourage further upstream movement of bass.

A third study (Kuehne et al. 2012) conducted experiments on bass predation of juvenile Chinook salmon at various temperatures. They found salmon had stronger and more

variable antipredator responses at warmer temperatures, which they thought might limit growth.

American shad have become the most abundant migratory species in the Columbia River. Hasselman et al. (Hasselman et al. 2012) considered the potential ecological effects of shad on coastal ecosystems and salmonids.

Diseases

The *Ceratomyxa shasta* parasite is thought to be inhibiting recovery of Chinook and coho salmon in California. Although it is not currently recognized as driving significant mortality in the Columbia River, morbidity and mortality in salmon is temperature dependent, and is likely to increase as a threat in warmer climates. Hallett et al. (2012) tested spatial and temporal dynamics of disease progression in the Klamath River. They found that coho was more sensitive than Chinook salmon to parasite density and temperature. Ray et al. (2012) tested the effect of temperature on lethality in a laboratory study, and found a positive correlation (higher mortality and faster progression to death at higher temperatures). In the field, parasite density varied from year to year; this also influenced the timing and magnitude of field mortality. The spatial distribution of an intermediate polychaete host for the parasite also affects parasite density, and is itself sensitive to discharge rates (Malakauskas and Wilzbach 2012). Thus these studies indicate that climate change might change disease risk through direct temperature effects on the fish, temperature effects on parasite growth rates, and through flow effects on other hosts.

Contaminants

Studies of the impacts of contaminants covered two focal areas. First, increased mobilization of historically stored pollutants through glacial melting (Elliott et al. 2012) or intensification of flooding. Although Cofalla (2012) focused specifically on modeling managed floods that have the potential to mobilize contaminants stored in sediment, the principle applies similarly to climate change-induced flood intensification. Second, contaminant effects depend strongly on the mixture of contaminants and their interaction with temperature and salinity. Brooks et al. (2012) provide an overview of interacting effects. Others compared the toxicity of different metals with temperature (Terzi and Verep 2012) and their impact on the expression of heat shock proteins (Soyut et al. 2012). Daley et al. (2012) studied the seasonal progression of bioamplification and depletion of persistent organic pollutants in Chinook embryos and larvae. They found that the highest concentrations of POPs occurred in later yolk-sac larvae, before exogenous feeding.

Marine processes

Studies of the effects of climate variability on salmon in their marine stage addressed salmon spatial distribution, growth, survival, and age at maturity. Highlights for Columbia

River fish include greatly improved ocean models (Gruber et al. 2012) and physical-trophic links (Pool et al. 2012; Yu et al. 2012), and mixed results on the importance of freshwater conditions for marine survival of Columbia River Chinook (Haeseker et al. 2012; Holsman et al. 2012; Tomaro et al. 2012).

Spatial distribution

A combination of physical drivers (upwelling, current strength, temperature) and prey distribution shape salmon distribution. Several papers described predictors of juvenile salmon in the California Current to differentiate the role of physical and biological processes that determine salmon distribution. The strength of along-shore currents influences the proportion of smolts that head south versus north from the Columbia River (Yu et al. 2012). Sea surface temperature, chlorophyll-*a* concentration, and copepod indices predict the local density of Chinook yearlings north of the Columbia, but chlorophyll-*a* was the only strong predictor to the south. This latter result was confirmed by Pool (Pool et al. 2012), who further found that coho density was related to decapod larval distribution, salinity and neuston biomass (surface plankton).

Several studies clarified variation in the habitat and migration routes of Atlantic salmon (Mork et al. 2012; Sheehan et al. 2012). These studies also found that wind forcing was the primary driving factor because salmon largely followed current strength, but that the fish also have a tendency to swim toward warmer and saltier water, which likely keeps them in prey-rich areas (Mork et al. 2012).

Growth

Studies of salmon marine growth focused on biological factors, such as maternal effects (Todd et al. 2012), prey densities (Atcheson et al. 2012a; Atcheson et al. 2012b; Dixon et al. 2012; Johnson and Schindler 2012; Sturdevant et al. 2012), and competition with other salmonids (Atcheson et al. 2012b; McKinnell and Reichardt 2012). Many studies also identified significant physical predictors of salmon growth, such as sea surface temperature (Friedland and Todd 2012), the Northern Oscillation Index (Satterthwaite et al. 2012) or climate regime (Huusko and Hyvarinen 2012; McKinnell and Reichardt 2012; Urbach et al. 2012). In general, these papers are consistent with earlier work showing that large-scale physical drivers set up conditions with high or low productivity depending on the location, and if currents are favorable for salmon to reach these prey-rich locations, they grow well. These papers provide much detail on local prey condition and preference, salmon stock-specific responses to physical drivers, and strong density-dependence, principally through competition with pink salmon.

Age at maturation

Long-term trends in spawner age have motivated identification of the factors driving the change. Studies of Atlantic salmon often find a correlation between sea surface

temperature and age at maturity, but the direction of this effect is not consistent. For example, two papers from Norway produced opposite results. A laboratory study showed that salmon mature earlier in response to good growth in their first year and warmer winter temperatures (Jonsson et al. 2012). But another analysis of a long-term trend toward older spawners also attributed this trend to warmer water in fall (Otero et al. 2012). Interestingly, a study with a paleological perspective showed that warmer climates are associated with earlier maturation, and lower population growth rates (Turrero et al. 2012).

Growth conditions also influence the probability of repeat spawning: the probability of Atlantic salmon repeat spawning in the Miramichi River in eastern Canada is correlated with small-fish biomass in nearby ocean waters (Chaput and Benoit 2012). However, when salmon migrated to less prey-rich areas, they were less likely to spawn multiple times.

Survival

The relationship between good growth conditions (high prey quality) and survival is complicated. Most studies have found consistent links from **physical drivers** that provide high levels of nutrients, such as upwelling, tend to transfer the nutrients predictably up the food chain – i.e., high raw nutrients leads to higher primary and secondary production, followed by higher salmon growth and survival (Beaugrand and Reid 2012; Thompson et al. 2012; Tomaro et al. 2012; Trueman et al. 2012). Correlations between physical conditions and salmon survival are generally assumed to be mediated via this mechanism. For example, Rupp found the 4-year average PDO to be a strong predictor of coho survival (Rupp et al. 2012), and more diverse physical predictors (Miller et al. 2012a) and regime shifts seem to drive ocean carrying capacity (Kaeriyama et al. 2012). However, McKinnell and Reichardt (2012) did not see declines in survival when growth rates declined after the 1977 regime shift, possibly because intra- or inter-specific competition reversed the relationship in some years.

Several papers argued that **predator** densities are a major driving force in long-term declines in salmon abundance. For example, Mantyniemi (2012) attributed salmon declines to increasing grey seal populations at longer time scales, although interannual variation at shorter time scales responded to herring abundance. A combination of wind patterns affecting the migration route and causing pelagic piscivores (silver and red hake, *Urophycis chuss*, spiny dogfish) to overlap spatially with the migration suggest Gulf of Maine salmon decline might be driven by predation (Friedland et al. 2012). Holsman et al. (2012) also found predator densities to be a highly weighted predictor of smolt to adult survival of Columbia River Chinook salmon, along with prey density, lipid-rich copepod biomass, upwelling, temperature, and freshwater factors (river flow, transportation through the hydrosystem and hatchery- versus wild-origin).

Anoxic conditions resulting from strong upwelling combined with large respiring fish populations drove a major fish kill in California in 2011 (Stauffer et al. 2012), which

indicates that coincidentally interacting events are likely to drive dramatic events in the future as well.

A long-standing question of interest is the extent to which **freshwater conditions affect marine survival**. As mentioned above, Holsman et al. (2012) found significant effects of smolt migration conditions (especially flow and whether the fish was transported) on smolt to adult survival. Haeseker et al. (2012) also analyzed the Columbia River. They found that spill through dams and water travel time (related to total discharge) were significant predictors of estuarine and marine survival. However, neither body size at the time of ocean entry nor the timing of ocean entry were correlated with adult returns in another Columbia River Chinook analysis (Tomaro et al. 2012). In that study, marine growth rate was the best predictor. However, two studies of Atlantic salmon do attribute long-term declines to smolt quality, which includes both timing and body condition (Russell et al. 2012; Todd et al. 2012). The latter study (Todd et al. 2012) tied poor smolt condition back to maternal effects of poor-condition spawners, positing a multi-generational condition cascade. Fortunately, the recent trend of increased ultraviolet radiation exposure during freshwater life stages (from ozone depletion) does not increase marine mortality (Melnychuk et al. 2012).

Ocean acidification – biological impacts

Numerous groups continue to probe biological sensitivities and evidence of negative impacts of recent trends in ocean acidification. I summarize here only work on pteropods and copepods because of their important role in the food chain. A study of pteropod shell characteristics in the Southern Ocean found that these planktonic mollusks already show signs of shell deterioration (Bednarsek et al. 2012). A laboratory study of Arctic Ocean pteropods determined the pH levels that would erode shells (Comeau et al. 2012a), and Comeau et al. (2012b) projected that under the A2 emissions scenario *Limacina helicina* will be unable to calcify shells over much of the Arctic by the end of the century. Flynn et al. (2012) pointed out that the boundary layer around plankton has much lower pH than surrounding water, and that the ability of seawater to buffer this microenvironment effect will decrease. Lischka and Riebesell (2012) studied field measurements in Svalbard over winter. They concluded that winter undersaturation, in combination with low food supply, might become the population bottleneck for Arctic pteropods.

The proportion of lipid-rich copepods in the plankton is a strong indicator of salmon survival for Oregon coho and Columbia River Chinook (see marine survival section). Some copepods might be only subtly affected by direct effects of pH – for example, *Calanus glacialis* showed no effect on egg production, but possible delayed or reduced success in hatching (Weydmann et al. 2012). However, indirect effects of acidification via the food web presents an additional threat to salmon that has not previously drawn much attention. Rossoll et al. (2012) found a decline in fatty-acid production in copepods in response to changes in their diatom prey.

An important consideration for biological effects of ocean acidification is that many factors interact to drive primary productivity, and under global change, some will enhance productivity while others will counteract these changes. For example, Gao et al. (2012) described the both stimulatory and inhibitory effects of changes in photosynthetically active radiation and ultraviolet exposure, as well as stratification, freshening, and changes in metabolic rates with temperature and nutrient availability. They cautioned against over interpretation of single-factor experiments.

Several authors argued that multiple sources of biological stressors need to be considered together. Pörtner (2012) followed up earlier work with further elaboration of the utility of “oxygen and capacity dependent thermal tolerance” as an index that integrates disparate stressors into a physiological unit: pollutants, hypoxia and thermal stress interact to challenge aerobic scope and energy budgets.

Conservation in practice

Beechie et al. (2012) developed a **decision support framework** to guide restoration planning to incorporate climate change. They provide a list of which restoration actions mitigate for which sorts of climatic factors, and rank various actions for their effectiveness in ameliorating for specific climate threats projected for the Pacific Northwest. Littell et al. (2012) described the **adaptation strategies** identified by science-based partnerships being piloted by the **National Forest Service**. The strategies include increasing resilience, considering limitations, prioritizing treatments from a pragmatic point of view, adaptive management, and a focus on structure and composition as a primary goal. Mainstone et al. (2012) reviewed conservation of river flows in the UK. They recommended maintaining a natural flow regime as the best defense against climate change.

A joint adaptation strategy document (National Fish Wildlife and Plants Climate Adaptation Partnership 2012) was published for a number of U.S. agencies responsible for fish and wildlife (NOAA, USFWS, and a collection of state and tribal representatives). The strategy describes seven major goals. They recommend conserving and connecting habitat, reducing non-climate stressors, enhancing management capacity, increasing awareness and motivate action, supporting adaptive management, increasing knowledge and information, and managing species and habitats. They make specific recommendations for cold-water fish, such as reconnecting channels with floodplains and protecting deep stream beds and riparian shade cover to limit temperature increases.

James et al. (2012) discuss **Ecosystem-based Management in Puget Sound**. They describe the initial framework for selecting and ranking indicators. Review of **prescribed dam releases** in the Sustainable Rivers Project as a conservation strategy showed benefits but the need for longer-term evaluations (Konrad et al. 2012). MacDonald et al. (Macdonald et al. 2012) reviewed the **water temperature management of the Nechako River**, which

involves forecasting meteorological conditions and responding to high air temperatures with controlled water releases to avoid critical maximum water temperature during spawning migrations. They concluded that the program successfully reduced thermal exposure of fish, and prevented prespawn mortality. Cooke et al. (2012) reviewed how science has benefitted management of Fraser River sockeye. They found that recovery from fishery capture has improved, and that thermal tolerances and genomic signatures could be used to predict migration success. Cosens and Williams (2012) reviewed the history of flow management in the Columbia River and the **Columbia River Treaty**.

Economic trade-offs: In a case study of Shasta River management, Null and Lund (2012) optimized out-migrating coho salmon against restoration costs for a diverse set of restoration options, constrained by a total budget. Radeloff (2012) assessed the ability of four policy scenarios to affect land-use change in the U.S. by 2051. All scenarios showed dramatic increases in urban land and loss of agricultural land, but variable increases in forest, depending on the scenario. They suggested that urbanization will increase and should be taken into account when planning.

Priority of climate change in decision-making: Evaluation of decision-making processes in three major sectors in Colorado (forests, biofuels and grazing) revealed that although there is interest in and discussion of climate change issues, threats from climate remain a lower priority than other issues (Ellenwood et al. 2012). From a more general perspective on climate science, Lemos et al. (2012) discussed the gap between information that scientists produce that they think is useful, and the information that decision-makers actually use. They focused on users' perceptions of how well the information fits, interplay with existing types of information, and the quality of the interaction between scientists and users. They recommended varying levels of interaction, customizing the information, and repackaging existing information to meet multiple users' needs.

General conservation principles: For conserving native trout, Hakk and Williams (2012) recommended protecting genetically pure populations across the historical range, restoring life-history diversity, and protecting large, stronghold populations. They advised that larger populations are needed for long-term persistence. Conservation in coastal zones is complicated by a multiple relevant spatial and temporal scales, spatially-diffuse footprints of human actions, and the potential for large consequences from small human decisions (Swaney et al. 2012)

Literature cited

STATE OF THE CLIMATE.

- Abatzoglou, J. T., and T. J. Brown. 2012. A comparison of statistical downscaling methods suited for wildfire applications. *International Journal of Climatology* 32:772-780.
- Alin, S. R., R. A. Feely, A. G. Dickson, J. M. Hernandez-Ayon, L. W. Juraneck, M. D. Ohman, and R. Goericke. 2012. Robust empirical relationships for estimating the carbonate

- system in the southern California Current System and application to CalCOFI hydrographic cruise data (2005-2011). *Journal of Geophysical Research-Oceans* 117.
- Almodovar, A., G. G. Nicola, D. Ayllon, and B. Elvira. 2012. Global warming threatens the persistence of Mediterranean brown trout. *Global Change Biology* 18:1549-1560.
- Anderson, K., H. King, N. Pankhurst, N. Ruff, P. Pankhurst, and A. Elizur. 2012a. Effect of elevated temperature on estrogenic induction of vitellogenesis and zonation in juvenile Atlantic salmon (*Salmo salar*). *Marine and Freshwater Behaviour and Physiology* 45:1-15.
- Anderson, K., P. Swanson, N. Pankhurst, H. King, and A. Elizur. 2012b. Effect of thermal challenge on plasma gonadotropin levels and ovarian steroidogenesis in female maiden and repeat spawning Tasmanian Atlantic salmon (*Salmo salar*). *Aquaculture* 334:205-212.
- Araneda, C., N. F. Diaz, G. Gomez, M. E. Lopez, and P. Iturra. 2012. Comparative mapping reveals quantitative trait loci that affect spawning time in coho salmon (*Oncorhynchus kisutch*). *Genetics and Molecular Biology* 35:515-+.
- Arismendi, I., S. L. Johnson, J. B. Dunham, R. Haggerty, and D. Hockman-Wert. 2012. The paradox of cooling streams in a warming world: Regional climate trends do not parallel variable local trends in stream temperature in the Pacific continental United States. *Geophysical Research Letters* 39:n/a-n/a.
- Arts, M. T., M. E. Palmer, A. B. Skiftesvik, I. E. Jokinen, and H. I. Browman. 2012. UVB Radiation Variably Affects n-3 Fatty Acids but Elevated Temperature Reduces n-3 Fatty Acids in Juvenile Atlantic Salmon (*Salmo salar*). *Lipids* 47:1181-1192.
- Atcheson, M. E., K. W. Myers, D. A. Beauchamp, and N. J. Mantua. 2012a. Bioenergetic Response by Steelhead to Variation in Diet, Thermal Habitat, and Climate in the North Pacific Ocean. *Transactions of the American Fisheries Society* 141:1081-1096.
- Atcheson, M. E., K. W. Myers, N. D. Davis, and N. J. Mantua. 2012b. Potential trophodynamic and environmental drivers of steelhead (*Oncorhynchus mykiss*) productivity in the North Pacific Ocean. *Fisheries Oceanography* 21:321-335.
- Beaugrand, G., and P. C. Reid. 2012. Relationships between North Atlantic salmon, plankton, and hydroclimatic change in the Northeast Atlantic. *Ices Journal of Marine Science* 69:1549-1562.
- Bednarsek, N., G. A. Tarling, D. C. E. Bakker, S. Fielding, E. M. Jones, H. J. Venables, P. Ward et al. 2012. Extensive dissolution of live pteropods in the Southern Ocean. *Nature Geoscience* 5:881-885.
- Beechie, T., H. Imaki, J. Greene, A. Wade, H. Wu, G. Pess, P. Roni et al. 2012. RESTORING SALMON HABITAT FOR A CHANGING CLIMATE. *River Research and Applications*.
- Bendall, B., A. Moore, D. Maxwell, P. Davison, N. Edmonds, D. Archer, D. Solomon et al. 2012. Modelling the migratory behaviour of salmonids in relation to environmental and physiological parameters using telemetry data. *Fisheries Management and Ecology* 19:475-483.
- Bennett, K. E., A. T. Werner, and M. Schnorbus. 2012. Uncertainties in Hydrologic and Climate Change Impact Analyses in Headwater Basins of British Columbia. *Journal of Climate* 25:5711-5730.
- Bi, H. S., W. T. Peterson, J. O. Peterson, and J. L. Fisher. 2012. A comparative analysis of coastal and shelf-slope copepod communities in the northern California Current system:

- Synchronized response to large-scale forcing? *Limnology and Oceanography* 57:1467-1478.
- Bianucci, L., and K. L. Denman. 2012. Carbon and oxygen cycles: Sensitivity to changes in environmental forcing in a coastal upwelling system. *Journal of Geophysical Research-Biogeosciences* 117.
- Bjorkstedt, E. P., R. Goericke, S. McClatchie, E. Weber, W. Watson, N. Lo, W. T. Peterson et al. 2012. STATE OF THE CALIFORNIA CURRENT 2011-2012: ECOSYSTEMS RESPOND TO LOCAL FORCING AS LA NINA WAVERS AND WANES. *California Cooperative Oceanic Fisheries Investigations Reports* 53:41-76.
- Blanchard, J. L., S. Jennings, R. Holmes, J. Harle, G. Merino, J. I. Allen, J. Holt et al. 2012. Potential consequences of climate change for primary production and fish production in large marine ecosystems. *Philosophical Transactions of the Royal Society B-Biological Sciences* 367:2979-2989.
- Boon, J. D. 2012. Evidence of Sea Level Acceleration at U.S. and Canadian Tide Stations, Atlantic Coast, North America. *Journal of Coastal Research* 28:1437-1445.
- Brooks, M. L., E. Fleishman, L. R. Brown, P. W. Lehman, I. Werner, N. Scholz, C. Mitchelmore et al. 2012. Life Histories, Salinity Zones, and Sublethal Contributions of Contaminants to Pelagic Fish Declines Illustrated with a Case Study of San Francisco Estuary, California, USA. *Estuaries and Coasts* 35:603-621.
- Burt, J. M., S. G. Hinch, and D. A. Patterson. 2012a. Developmental temperature stress and parental identity shape offspring burst swimming performance in sockeye salmon (*Oncorhynchus nerka*). *Ecology of Freshwater Fish* 21:176-188.
- . 2012b. Parental identity influences progeny responses to incubation thermal stress in sockeye salmon *Oncorhynchus nerka*. *Journal of Fish Biology* 80:444-462.
- Burthe, S., F. Daunt, A. Butler, D. A. Elston, M. Frederiksen, D. Johns, M. Newell et al. 2012. Phenological trends and trophic mismatch across multiple levels of a North Sea pelagic food web. *Marine Ecology Progress Series* 454:119-+.
- Carre, M., M. Azzoug, I. Bentaleb, B. M. Chase, M. Fontugne, D. Jackson, M. P. Ledru et al. 2012. Mid-Holocene mean climate in the south eastern Pacific and its influence on South America. *Quaternary International* 253:55-66.
- Casselman, M. T., K. Anttila, and A. P. Farrell. 2012. Using maximum heart rate as a rapid screening tool to determine optimum temperature for aerobic scope in Pacific salmon *Oncorhynchus* spp. *Journal of Fish Biology* 80:358-377.
- Chaput, G., and H. P. Benoit. 2012. Evidence for bottom-up trophic effects on return rates to a second spawning for Atlantic salmon (*Salmo salar*) from the Miramichi River, Canada. *Ices Journal of Marine Science* 69:1656-1667.
- Chen, B. Z., M. R. Landry, B. Q. Huang, and H. B. Liu. 2012. Does warming enhance the effect of microzooplankton grazing on marine phytoplankton in the ocean? *Limnology and Oceanography* 57:519-526.
- Cheung, W. W. L., J. Pinnegar, G. Merino, M. C. Jones, and M. Barange. 2012. Review of climate change impacts on marine fisheries in the UK and Ireland. *Aquatic Conservation-Marine and Freshwater Ecosystems* 22:368-388.
- Christy, J. R. 2012. Searching for Information in 133 Years of California Snowfall Observations. *Journal of Hydrometeorology* 13:895-912.
- Clark, T. D., M. R. Donaldson, S. Pieperhoff, S. M. Drenner, A. Lotto, S. J. Cooke, S. G. Hinch et al. 2012. Physiological Benefits of Being Small in a Changing World: Responses of

- Coho Salmon (*Oncorhynchus kisutch*) to an Acute Thermal Challenge and a Simulated Capture Event. *Plos One* 7.
- Cofalla, C., S. Hudjetz, S. Roger, M. Brinkmann, R. Frings, J. Wolz, B. Schmidt et al. 2012. A combined hydraulic and toxicological approach to assess re-suspended sediments during simulated flood events-part II: an interdisciplinary experimental methodology. *Journal of Soils and Sediments* 12:429-442.
- Committee on Sea Level Rise in California, O., Washington, B. o. E. Sciences, Resources, O. S. Board, D. o. Earth, L. Studies et al. 2012, *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future*, The National Academies Press.
- Connors, B. M., D. C. Braun, R. M. Peterman, A. B. Cooper, J. D. Reynolds, L. M. Dill, G. T. Ruggione et al. 2012. Migration links ocean-scale competition and local ocean conditions with exposure to farmed salmon to shape wild salmon dynamics. *Conservation Letters* 5:304-312.
- Cooke, S. J., S. G. Hinch, M. R. Donaldson, T. D. Clark, E. J. Eliason, G. T. Crossin, G. D. Raby et al. 2012. Conservation physiology in practice: how physiological knowledge has improved our ability to sustainably manage Pacific salmon during up-river migration. *Philosophical Transactions of the Royal Society B-Biological Sciences* 367:1757-1769.
- Cote, J., J. M. Roussel, S. Cam, G. Bal, and G. Evanno. 2012. Population differences in response to hypoxic stress in Atlantic salmon. *Journal of Evolutionary Biology* 25:2596-2606.
- Dai, A. 2012. Increasing drought under global warming in observations and models. *Nature Climate Change*.
- Daley, J. M., T. A. Leadley, T. E. Pitcher, and K. G. Drouillard. 2012. Bioamplification and the Selective Depletion of Persistent Organic Pollutants in Chinook Salmon Larvae. *Environmental Science & Technology* 46:2420-2426.
- Dery, S. J., M. A. Hernandez-Henriquez, P. N. Owens, M. W. Parkes, and E. L. Peticrew. 2012. A century of hydrological variability and trends in the Fraser River Basin. *Environmental Research Letters* 7.
- Dewitte, B., J. Vazquez-Cuervo, K. Goubanova, S. Illig, K. Takahashi, G. Cambon, S. Purca et al. 2012. Change in El Nino flavours over 1958-2008: Implications for the long-term trend of the upwelling off Peru. *Deep-Sea Research Part II-Topical Studies in Oceanography* 77-80:143-156.
- Dixon, H. J., M. Power, J. B. Dempson, T. F. Sheehan, and G. Chaput. 2012. Characterizing the trophic position and shift in Atlantic salmon (*Salmo salar*) from freshwater to marine life-cycle phases using stable isotopes. *Ices Journal of Marine Science* 69:1646-1655.
- Doney, S. C., M. Ruckelshaus, J. E. Duffy, J. P. Barry, F. Chan, C. A. English, H. M. Galindo et al. 2012. Climate Change Impacts on Marine Ecosystems, Pages 11-37 in C. A. Carlson, and S. J. Giovannoni, eds. *Annual Review of Marine Science*, Vol 4. *Annual Review of Marine Science*.
- Donley, E. E., R. J. Naiman, and M. D. Marineau. 2012. Strategic planning for instream flow restoration: a case study of potential climate change impacts in the central Columbia River basin. *Global Change Biology* 18:3071-3086.
- Drinan, D. P., A. V. Zale, M. A. H. Webb, B. B. Shepard, and S. T. Kalinowski. 2012a. Evidence of Local Adaptation in Westslope Cutthroat Trout. *Transactions of the American Fisheries Society* 141:872-880.

- Drinan, T. J., P. McGinnity, J. P. Coughlan, T. F. Cross, and S. S. Harrison. 2012b. Morphological variability of Atlantic salmon *Salmo salar* and brown trout *Salmo trutta* in different river environments. *Ecology of Freshwater Fish* 21:420-432.
- Ellenwood, M. S., L. Dilling, and J. B. Milford. 2012. Managing United States Public Lands in Response to Climate Change: A View From the Ground Up. *Environmental Management* 49:954-967.
- Elliott, J. E., J. Levac, M. F. Guigueno, D. P. Shaw, M. Wayland, C. A. Morrissey, D. C. G. Muir et al. 2012. Factors Influencing Legacy Pollutant Accumulation in Alpine Osprey: Biology, Topography, Or Melting Glaciers? *Environmental Science & Technology* 46:9681-9689.
- Feeley, R., T. Klinger, J. Newton, and M. Chadsey. 2012. Scientific summary of ocean acidification in Washington state marine waters, Pages 157, NOAA Office of Atmospheric Research Special Report, <https://fortress.wa.gov/ecy/publications/publications/1201016.pdf>.
- Finstad, A. G., and C. L. Hein. 2012. Migrate or stay: terrestrial primary productivity and climate drive anadromy in Arctic char. *Global Change Biology* 18:2487-2497.
- Finstad, A. G., and B. Jonsson. 2012. Effect of incubation temperature on growth performance in Atlantic salmon. *Marine Ecology-Progress Series* 454:75-82.
- Folkedal, O., L. H. Stien, T. Torgersen, E. Oppedal, R. E. Olsen, J. E. Fosseidengen, V. A. Braithwaite et al. 2012a. Food anticipatory behaviour as an indicator of stress response and recovery in Atlantic salmon post-smolt after exposure to acute temperature fluctuation. *Physiology & Behavior* 105:350-356.
- Folkedal, O., T. Torgersen, R. E. Olsen, A. Ferno, J. Nilsson, F. Oppedal, L. H. Stien et al. 2012b. Duration of effects of acute environmental changes on food anticipatory behaviour, feed intake, oxygen consumption, and cortisol release in Atlantic salmon parr. *Physiology & Behavior* 105:283-291.
- Francis, J. A., and S. J. Vavrus. 2012. Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophysical Research Letters* 39:L06801.
- Friedland, K. D., J. P. Manning, J. S. Link, J. R. Gilbert, A. T. Gilbert, and A. F. O'Connell. 2012. Variation in wind and piscivorous predator fields affecting the survival of Atlantic salmon, *Salmo salar*, in the Gulf of Maine. *Fisheries Management and Ecology* 19:22-35.
- Friedland, K. D., and C. D. Todd. 2012. Changes in Northwest Atlantic Arctic and Subarctic conditions and the growth response of Atlantic salmon. *Polar Biology* 35:593-609.
- Furey, P. R., S. K. Kampf, J. S. Lanini, and A. Q. Dozier. 2012. A Stochastic Conceptual Modeling Approach for Examining the Effects of Climate Change on Streamflows in Mountain Basins. *Journal of Hydrometeorology* 13:837-855.
- Gillett, N. P., V. K. Arora, G. M. Flato, J. F. Scinocca, and K. von Salzen. 2012. Improved constraints on 21st-century warming derived using 160 years of temperature observations. *Geophysical Research Letters* 39.
- Griffiths, R. B. 2013. Oceans and Marine Resources in a Changing Climate. Technical Input to the 2013 National Climate Assessment U.S. Global Change Research Program:available online at <http://www.globalchange.gov/publications/reports>.
- Groffman, P., and P. Kareiva. 2013. Ecosystems, Biodiversity, and Ecosystem Services. Technical Input to the National Climate Assessment.

- Gruber, N., C. Hauri, Z. Lachkar, D. Loher, T. L. Frolicher, and G. K. Plattner. 2012. Rapid progression of ocean acidification in the California Current System. *Science* 337:220-223.
- Haak, A. L., and J. E. Williams. 2012. Spreading the Risk: Native Trout Management in a Warmer and Less-Certain Future. *North American Journal of Fisheries Management* 32:387-401.
- Haeseker, S. L., J. A. McCann, J. Tuomikoski, and B. Chockley. 2012. Assessing Freshwater and Marine Environmental Influences on Life-Stage-Specific Survival Rates of Snake River Spring-Summer Chinook Salmon and Steelhead. *Transactions of the American Fisheries Society* 141:121-138.
- Hallett, S. L., R. A. Ray, C. N. Hurst, R. A. Holt, G. R. Buckles, S. D. Atkinson, and J. L. Bartholomew. 2012. Density of the Waterborne Parasite *Ceratomyxa shasta* and Its Biological Effects on Salmon. *Applied and Environmental Microbiology* 78:3724-3731.
- Harnish, R. A., G. E. Johnson, G. A. McMichael, M. S. Hughes, and B. D. Ebberts. 2012. Effect of Migration Pathway on Travel Time and Survival of Acoustic-Tagged Juvenile Salmonids in the Columbia River Estuary. *Transactions of the American Fisheries Society* 141:507-519.
- Hasler, C. T., S. J. Cooke, S. G. Hinch, E. Guimond, M. R. Donaldson, B. Mossop, and D. A. Patterson. 2012a. Thermal biology and bioenergetics of different upriver migration strategies in a stock of summer-run Chinook salmon. *Journal of Thermal Biology* 37:265-272.
- Hasler, C. T., B. Mossop, D. A. Patterson, S. G. Hinch, and S. J. Cooke. 2012b. Swimming activity of migrating Chinook salmon in a regulated river. *Aquatic Biology* 17:47-56.
- Hasselman, D. J., R. A. Hinrichsen, B. A. Shields, and C. C. Ebbesmeyer. 2012. American Shad of the Pacific Coast: A Harmful Invasive Species or Benign Introduction? *Fisheries* 37:115-122.
- Hazen, E. L., Salvador Jorgensen, Ryan R. Rykaczewski, Steven J. Bograd, David G. Foley, Ian D. Jonsen, Scott A. Shaffer et al. 2012. Predicted habitat shifts of Pacific top predators in a changing climate. *Nature Clim. Change*.
- Heath, M. R., F. C. Neat, J. K. Pinnegar, D. G. Reid, D. W. Sims, and P. J. Wright. 2012. Review of climate change impacts on marine fish and shellfish around the UK and Ireland. *Aquatic Conservation-Marine and Freshwater Ecosystems* 22:337-367.
- Hevroy, E. M., R. Waagbo, B. E. Torstensen, H. Takle, I. Stubhaug, S. M. Jorgensen, T. Torgersen et al. 2012. Ghrelin is involved in voluntary anorexia in Atlantic salmon raised at elevated sea temperatures. *General and Comparative Endocrinology* 175:118-134.
- Hillyard, R. W., and E. R. Keeley. 2012. Temperature-related changes in habitat quality and use by Bonneville cutthroat trout in regulated and unregulated river segments. *Transactions of the American Fisheries Society* 141:1649-1663.
- Hinch, S. G., S. J. Cooke, A. P. Farrell, K. M. Miller, M. Lapointe, and D. A. Patterson. 2012. Dead fish swimming: a review of research on the early migration and high premature mortality in adult Fraser River sockeye salmon *Oncorhynchus nerka*. *Journal of Fish Biology* 81:576-599.
- Holden, Z. A., C. H. Luce, M. A. Crimmins, and P. Morgan. 2012. Wildfire extent and severity correlated with annual streamflow distribution and timing in the Pacific Northwest, USA (1984-2005). *Ecohydrology* 5:677-684.

- Holsman, K. K., M. D. Scheuerell, E. Buhle, and R. Emmett. 2012. Interacting Effects of Translocation, Artificial Propagation, and Environmental Conditions on the Marine Survival of Chinook Salmon from the Columbia River, Washington, USA. *Conservation Biology* 26:912-922.
- Honisch, B., A. Ridgwell, D. N. Schmidt, E. Thomas, S. J. Gibbs, A. Sluijs, R. Zeebe et al. 2012. The Geological Record of Ocean Acidification. *Science* 335:1058-1063.
- Hughes, R. M., and A. T. Herlihy. 2012. Patterns in Catch Per Unit Effort of Native Prey Fish and Alien Piscivorous Fish in 7 Pacific Northwest USA Rivers. *Fisheries* 37:201-211.
- Hurst, T. P., S. B. Munch, and K. A. Lavelle. 2012. Thermal reaction norms for growth vary among cohorts of Pacific cod (*Gadus macrocephalus*). *Marine Biology* 159:2173-2183.
- Hutchings, J. A., I. M. Côté, J. J. Dodson, I. A. Fleming, S. Jennings, N. J. Mantua, R. M. Peterman et al. 2012. Sustaining Canadian marine biodiversity: responding to the challenges posed by climate change, fisheries, and aquaculture. Expert panel report prepared for the Royal Society of Canada, Ottawa: Available at http://rsc.ca/documents/RSCMarineBiodiversity2012_ENFINAL.pdf.
- Huusko, A., and P. Hyvarinen. 2012. Atlantic salmon abundance and size track climate regimes in the Baltic Sea. *Boreal Environment Research* 17:139-149.
- Iles, A. C., T. C. Gouhier, B. A. Menge, J. S. Stewart, A. J. Haupt, and M. C. Lynch. 2012. Climate-driven trends and ecological implications of event-scale upwelling in the California Current System. *Global Change Biology* 18:783-796.
- IPCC. 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, Pages 582 in C. B. Field, V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea et al., eds. Cambridge, UK and New York, NY, USA, Cambridge University Press.
- Isaak, D. J., C. C. Muhlfeld, A. S. Todd, R. Al-Chokhachy, J. Roberts, J. L. Kershner, K. D. Fausch et al. 2012a. The Past as Prelude to the Future for Understanding 21st-Century Climate Effects on Rocky Mountain Trout. *Fisheries* 37:542-556.
- Isaak, D. J., S. Wollrab, D. Horan, and G. Chandler. 2012b. Climate change effects on stream and river temperatures across the northwest US from 1980-2009 and implications for salmonid fishes. *Climatic Change* 113:499-524.
- Jacob, T., J. Wahr, W. T. Pfeffer, and S. Swenson. 2012. Recent contributions of glaciers and ice caps to sea level rise. *Nature* 482:514-518.
- James, C. A., J. Kershner, J. Samhuri, S. O'Neill, and P. S. Levin. 2012. A Methodology for Evaluating and Ranking Water Quantity Indicators in Support of Ecosystem-Based Management. *Environmental Management* 49:703-719.
- Jeffries, K. M., S. G. Hinch, E. G. Martins, T. D. Clark, A. G. Lotto, D. A. Patterson, S. J. Cooke et al. 2012a. Sex and Proximity to Reproductive Maturity Influence the Survival, Final Maturation, and Blood Physiology of Pacific Salmon When Exposed to High Temperature during a Simulated Migration. *Physiological and Biochemical Zoology* 85:62-73.
- Jeffries, K. M., S. G. Hinch, T. Sierocinski, T. D. Clark, E. J. Eliason, M. R. Donaldson, S. R. Li et al. 2012b. Consequences of high temperatures and premature mortality on the transcriptome and blood physiology of wild adult sockeye salmon (*Oncorhynchus nerka*). *Ecology and Evolution* 2:1747-1764.

- Jin, X., and V. Sridhar. 2012. Impacts of Climate Change on Hydrology and Water Resources in the Boise and Spokane River Basins. *Journal of the American Water Resources Association* 48:197-220.
- Johnson, S. P., and D. E. Schindler. 2012. Four decades of foraging history: stock-specific variation in the carbon and nitrogen stable isotope signatures of Alaskan sockeye salmon. *Marine Ecology-Progress Series* 460:155-167.
- Jones, P. D., D. H. Lister, T. J. Osborn, C. Harpham, M. Salmon, and C. P. Morice. 2012. Hemispheric and large-scale land-surface air temperature variations: An extensive revision and an update to 2010. *Journal of Geophysical Research-Atmospheres* 117.
- Jonsson, B., A. G. Finstad, and N. Jonsson. 2012. Winter temperature and food quality affect age at maturity: an experimental test with Atlantic salmon (*Salmo salar*). *Canadian Journal of Fisheries and Aquatic Sciences* 69:1817-1826.
- Jung, I. W., H. Moradkhani, and H. Chang. 2012. Uncertainty assessment of climate change impacts for hydrologically distinct river basins. *Journal of Hydrology* 466:73-87.
- Kaeriyama, M., H. Seo, H. Kudo, and M. Nagata. 2012. Perspectives on wild and hatchery salmon interactions at sea, potential climate effects on Japanese chum salmon, and the need for sustainable salmon fishery management reform in Japan. *Environmental Biology of Fishes* 94:165-177.
- Kahru, M., R. M. Kudela, M. Manzano-Sarabia, and B. G. Mitchell. 2012. Trends in the surface chlorophyll of the California Current: Merging data from multiple ocean color satellites. *Deep-Sea Research Part II-Topical Studies in Oceanography* 77-80:89-98.
- Keen, A. N., and A. K. Gamperl. 2012. Blood oxygenation and cardiorespiratory function in steelhead trout (*Oncorhynchus mykiss*) challenged with an acute temperature increase and zatebradine-induced bradycardia. *Journal of Thermal Biology* 37:201-210.
- Kock, T. J., T. L. Liedtke, D. W. Rondorf, J. D. Serl, M. Kohn, and K. A. Bumbaco. 2012. Elevated streamflows increase dam passage by juvenile coho salmon during winter: Implications of climate change in the Pacific Northwest. *North American Journal of Fisheries Management* 32:1070-1079.
- Kodama, M., J. J. Hard, and K. A. Naish. 2012. Temporal variation in selection on body length and date of return in a wild population of coho salmon, *Oncorhynchus kisutch*. *Bmc Evolutionary Biology* 12.
- Kollat, J. B., J. R. Kasprzyk, W. O. Thomas, A. C. Miller, and D. Divoky. 2012. Estimating the Impacts of Climate Change and Population Growth on Flood Discharges in the United States. *Journal of Water Resources Planning and Management-Asce* 138:442-452.
- Konrad, C. P., A. Warner, and J. V. Higgins. 2012. EVALUATING DAM RE-OPERATION FOR FRESHWATER CONSERVATION IN THE SUSTAINABLE RIVERS PROJECT. *River Research and Applications* 28:777-792.
- Kovach, R. P., A. J. Gharrett, and D. A. Tallmon. 2012. Genetic change for earlier migration timing in a pink salmon population. *Proceedings of the Royal Society B-Biological Sciences* 279:3870-3878.
- Kuehne, L. M., J. D. Olden, and J. J. Duda. 2012. Costs of living for juvenile Chinook salmon (*Oncorhynchus tshawytscha*) in an increasingly warming and invaded world. *Canadian Journal of Fisheries and Aquatic Sciences* 69:1621-1630.
- Lachkar, Z., and N. Gruber. 2012. A comparative study of biological production in eastern boundary upwelling systems using an artificial neural network. *Biogeosciences* 9:293-308.

- Lahnsteiner, F., and M. Kletzl. 2012. The effect of water temperature on gamete maturation and gamete quality in the European grayling (*Thymalus thymallus*) based on experimental data and on data from wild populations. *Fish Physiology and Biochemistry* 38:455-467.
- Lahnsteiner, F., and N. Mansour. 2012. The effect of temperature on sperm motility and enzymatic activity in brown trout *Salmo trutta*, burbot *Lota lota* and grayling *Thymallus thymallus*. *Journal of Fish Biology* 81:197-209.
- Lawrence, D. J., J. D. Olden, and C. E. Torgersen. 2012. Spatiotemporal patterns and habitat associations of smallmouth bass (*Micropterus dolomieu*) invading salmon-rearing habitat. *Freshwater Biology* 57:1929-1946.
- Leach, J. A., R. D. Moore, S. G. Hinch, and T. Gomi. 2012. Estimation of forest harvesting-induced stream temperature changes and bioenergetic consequences for cutthroat trout in a coastal stream in British Columbia, Canada. *Aquatic Sciences* 74:427-441.
- LeBlanc, S., E. Hoglund, K. M. Gilmour, and S. Currie. 2012. Hormonal modulation of the heat shock response: insights from fish with divergent cortisol stress responses. *American Journal of Physiology-Regulatory Integrative and Comparative Physiology* 302:R184-R192.
- Lebrato, M., K. A. Pitt, A. K. Sweetman, D. O. B. Jones, J. E. Cartes, A. Oschlies, R. H. Condon et al. 2012. Jelly-falls historic and recent observations: a review to drive future research directions. *Hydrobiologia* 690:227-245.
- Lecomte, J. B., and C. Laplanche. 2012. A length-based hierarchical model of brown trout (*Salmo trutta fario*) growth and production. *Biometrical Journal* 54:108-126.
- Lee, W. S., P. Monaghan, and N. B. Metcalfe. 2012. The pattern of early growth trajectories affects adult breeding performance. *Ecology* 93:902-912.
- Lemos, M. C., C. J. Kirchhoff, and V. Ramprasad. 2012. Narrowing the climate information usability gap. *Nature Climate Change* 2:789-794.
- Lewis, J. M., G. Klein, P. J. Walsh, and S. Currie. 2012. Rainbow trout (*Oncorhynchus mykiss*) shift the age composition of circulating red blood cells towards a younger cohort when exposed to thermal stress. *Journal of Comparative Physiology B-Biochemical Systemic and Environmental Physiology* 182:663-671.
- Li, G., and B. H. Ren. 2012. Evidence for strengthening of the tropical Pacific Ocean surface wind speed during 1979-2001. *Theoretical and Applied Climatology* 107:59-72.
- Li, H. Q., M. Kanamitsu, and S. Y. Hong. 2012a. California reanalysis downscaling at 10 km using an ocean-atmosphere coupled regional model system. *Journal of Geophysical Research-Atmospheres* 117.
- Li, Y. L., F. Wang, and Y. Sun. 2012b. Low-frequency spiciness variations in the tropical Pacific Ocean observed during 2003-2012. *Geophysical Research Letters* 39.
- Limborg, M. T., S. M. Blankenship, S. F. Young, F. M. Utter, L. W. Seeb, M. H. H. Hansen, and J. E. Seeb. 2012. Signatures of natural selection among lineages and habitats in *Oncorhynchus mykiss*. *Ecology and Evolution* 2:1-18.
- Littell, J. S., D. L. Peterson, C. I. Millar, and K. A. O'Halloran. 2012. U.S. National Forests adapt to climate change through Science-Management partnerships. *Climatic Change* 110:269-296.
- Liu, J. P., J. A. Curry, H. J. Wang, M. R. Song, and R. M. Horton. 2012. Impact of declining Arctic sea ice on winter snowfall (vol 109, pg 4074, 2012). *Proceedings of the National Academy of Sciences of the United States of America* 109:6781-6783.

- Loeb, N. G., J. M. Lyman, G. C. Johnson, R. P. Allan, D. R. Doelling, T. Wong, B. J. Soden et al. 2012. Observed changes in top-of-the-atmosphere radiation and upper-ocean heating consistent within uncertainty. *Nature Geoscience* 5:110-113.
- Lof, M. E., T. E. Reed, J. M. McNamara, and M. E. Visser. 2012. Timing in a fluctuating environment: environmental variability and asymmetric fitness curves can lead to adaptively mismatched avian reproduction. *Proceedings of the Royal Society B-Biological Sciences* 279:3161-3169.
- Lutz, E. R., A. F. Hamlet, and J. S. Littell. 2012. Paleoreconstruction of cool season precipitation and warm season streamflow in the Pacific Northwest with applications to climate change assessments. *Water Resources Research* 48.
- Macdonald, J. S., J. Morrison, and D. A. Patterson. 2012. The Efficacy of Reservoir Flow Regulation for Cooling Migration Temperature for Sockeye Salmon in the Nechako River Watershed of British Columbia. *North American Journal of Fisheries Management* 32:415-427.
- Macias, D., P. J. S. Franks, M. D. Ohman, and M. R. Landry. 2012a. Modeling the effects of coastal wind- and wind-stress curl-driven upwellings on plankton dynamics in the Southern California current system. *Journal of Marine Systems* 94:107-119.
- Macias, D., M. R. Landry, A. Gershunov, A. J. Miller, and P. J. S. Franks. 2012b. Climatic Control of Upwelling Variability along the Western North-American Coast. *Plos One* 7.
- Mainstone, C. P., R. Thomas, C. W. Bean, and T. Waterman. 2012. The role of the UK conservation agencies in protecting river flows. *Fisheries Management and Ecology* 19:557-569.
- Malakauskas, D. M., and M. A. Wilzbach. 2012. Invertebrate assemblages in the lower Klamath River, with reference to *Manayunkia speciosa*. *California Fish and Game* 98:214-235.
- Mantyniemi, S., A. Romakkaniemi, J. Dannewitz, S. Palm, T. Pakarinen, H. Pulkkinen, A. Grdmark et al. 2012. Both predation and feeding opportunities may explain changes in survival of Baltic salmon post-smolts. *Ices Journal of Marine Science* 69:1574-1579.
- Markstrom, S. L., L. E. Hay, C. D. Ward-Garrison, J. C. Risley, W. A. Battaglin, D. M. Bjerklie, K. J. Chase et al. 2012. Integrated watershed-scale response to climate change for selected basins across the United States, Pages 143 U.S. Geological Survey Scientific Investigations Report 2011-5077.
- Martin, P., J. Rancon, G. Segura, J. Laffont, G. Boeuf, and S. Dufour. 2012. Experimental study of the influence of photoperiod and temperature on the swimming behaviour of hatchery-reared Atlantic salmon (*Salmo salar* L.) smolts. *Aquaculture* 362:200-208.
- Martins, E. G., S. G. Hinch, S. J. Cooke, and D. A. Patterson. 2012a. Climate effects on growth, phenology, and survival of sockeye salmon (*Oncorhynchus nerka*): a synthesis of the current state of knowledge and future research directions. *Reviews in Fish Biology and Fisheries* 22:887-914.
- Martins, E. G., S. G. Hinch, D. A. Patterson, M. J. Hague, S. J. Cooke, K. M. Miller, D. Robichaud et al. 2012b. High river temperature reduces survival of sockeye salmon (*Oncorhynchus nerka*) approaching spawning grounds and exacerbates female mortality. *Canadian Journal of Fisheries and Aquatic Sciences* 69:330-342.
- Marzeion, B., A. H. Jarosch, and M. Hofer. 2012. Past and future sea-level change from the surface mass balance of glaciers. *Cryosphere* 6:1295-1322.

- McDermid, J. L., F. A. Fischer, M. Al-Shamli, W. N. Sloan, N. E. Jones, and C. C. Wilson. 2012. Variation in Acute Thermal Tolerance within and among Hatchery Strains of Brook Trout. *Transactions of the American Fisheries Society* 141:1230-1235.
- McElroy, B., A. DeLonay, and R. Jacobson. 2012. Optimum swimming pathways of fish spawning migrations in rivers. *Ecology* 93:29-34.
- McKinnell, S., and M. Reichardt. 2012. Early marine growth of juvenile Fraser River sockeye salmon (*Oncorhynchus nerka*) in relation to juvenile pink (*Oncorhynchus gorbuscha*) and sockeye salmon abundance. *Canadian Journal of Fisheries and Aquatic Sciences* 69:1499-1512.
- McMillan, J. R., J. B. Dunham, G. H. Reeves, J. S. Mills, and C. E. Jordan. 2012. Individual condition and stream temperature influence early maturation of rainbow and steelhead trout, *Oncorhynchus mykiss*. *Environmental Biology of Fishes* 93:343-355.
- Melnichuk, M. C., C. J. Walters, V. Christensen, M. L. Bothwell, and D. W. Welch. 2012. Effects of solar ultraviolet radiation exposure on early ocean survival and fry-to-smolt growth of juvenile salmon. *Marine Ecology-Progress Series* 457:251-264.
- Miller, A. S., T. F. Sheehan, M. D. Renkawitz, A. L. Meister, and T. J. Miller. 2012a. Revisiting the marine migration of US Atlantic salmon using historical Carlin tag data. *Ices Journal of Marine Science* 69:1609-1615.
- Miller, M., J. Brunelli, P. Wheeler, S. Liu, C. Rexroad, Y. Palti, C. Doe et al. 2012b. A conserved haplotype controls parallel adaptation in geographically distant salmonid populations. *Molecular Ecology* 21:237-249.
- Mogensen, S., and J. R. Post. 2012. Energy allocation strategy modifies growth-survival trade-offs in juvenile fish across ecological and environmental gradients. *Oecologia* 168:923-933.
- Moore, A., B. Bendall, J. Barry, C. Waring, N. Crooks, and L. Crooks. 2012. River temperature and adult anadromous Atlantic salmon, *Salmo salar*, and brown trout, *Salmo trutta*. *Fisheries Management and Ecology* 19:518-526.
- Mork, K. A., J. Gilbey, L. P. Hansen, A. J. Jensen, J. A. Jacobsen, M. Holm, J. C. Holst et al. 2012. Modelling the migration of post-smolt Atlantic salmon (*Salmo salar*) in the Northeast Atlantic. *Ices Journal of Marine Science* 69:1616-1624.
- National Fish Wildlife and Plants Climate Adaptation Partnership. 2012. National Fish, Wildlife and Plants Climate Adaptation Strategy, Pages 112 Washington, D.C., Association of Fish and Wildlife Agencies, Council on Environmental Quality, Great Lakes Indian Fish and Wildlife Commission, National Oceanic and Atmospheric Administration, and U.S. Fish and Wildlife Service.
- NCADAC. 2013, National Climate Assessment and Development Advisory Committee. Third National Climate Assessment Draft Report: U.S. Global Change Research Program. <http://www.globalchange.gov/publications/reports>.
- Nisbet, R. M., M. Jusup, T. Klanjscek, and L. Pecquerie. 2012. Integrating dynamic energy budget (DEB) theory with traditional bioenergetic models. *Journal of Experimental Biology* 215:892-902.
- Null, S. E., and J. R. Lund. 2012. FISH HABITAT OPTIMIZATION TO PRIORITIZE RIVER RESTORATION DECISIONS. *River Research and Applications* 28:1378-1393.
- Ojima, N., M. Mekuchi, T. Ineno, K. Tamaki, A. Kera, S. Kinoshita, S. Asakawa et al. 2012. Differential expression of heat-shock proteins in F2 offspring from F1 hybrids produced

- between thermally selected and normal rainbow trout strains. *Fisheries Science* 78:1051-1057.
- Otero, J., A. J. Jensen, J. H. L'Abée-Lund, N. C. Stenseth, G. O. Storvik, and L. A. Vollestad. 2012. Contemporary ocean warming and freshwater conditions are related to later sea age at maturity in Atlantic salmon spawning in Norwegian rivers. *Ecology and Evolution* 2:2192-2203.
- Parra, I., A. Almodovar, D. Ayllon, G. G. Nicola, and B. Elvira. 2012. Unravelling the effects of water temperature and density dependence on the spatial variation of brown trout (*Salmo trutta*) body size. *Canadian Journal of Fisheries and Aquatic Sciences* 69:821-832.
- Petty, J. T., J. L. Hansbarger, B. M. Huntsman, and P. M. Mazik. 2012. Brook Trout Movement in Response to Temperature, Flow, and Thermal Refugia within a Complex Appalachian Riverscape. *Transactions of the American Fisheries Society* 141:1060-1073.
- Pierce, S. D., J. A. Barth, R. K. Shearman, and A. Y. Erofeev. 2012. Declining Oxygen in the Northeast Pacific. *Journal of Physical Oceanography* 42:495-501.
- Piou, C., and E. Prevost. 2012. A demo-genetic individual-based model for Atlantic salmon populations: Model structure, parameterization and sensitivity. *Ecological Modelling* 231:37-52.
- Pirtle, J. L., S. N. Ibarra, and G. L. Eckert. 2012. Nearshore subtidal community structure compared between inner coast and outer coast sites in Southeast Alaska. *Polar Biology* 35:1889-1910.
- Polovina, J. J., and P. A. Woodworth. 2012. Declines in phytoplankton cell size in the subtropical oceans estimated from satellite remotely-sensed temperature and chlorophyll, 1998-2007. *Deep-Sea Research Part II-Topical Studies in Oceanography* 77-80:82-88.
- Pool, S. S., D. C. Reese, and R. D. Brodeur. 2012. Defining marine habitat of juvenile Chinook salmon, *Oncorhynchus tshawytscha*, and coho salmon, *O. kisutch*, in the northern California Current System. *Environmental Biology of Fishes* 93:233-243.
- Portner, H. O. 2012. Integrating climate-related stressor effects on marine organisms: unifying principles linking molecule to ecosystem-level changes. *Marine Ecology Progress Series* 470:273-290.
- Radeloff, V. C., E. Nelson, A. J. Plantinga, D. J. Lewis, D. Helmers, J. J. Lawler, J. C. Withey et al. 2012. Economic-based projections of future land use in the conterminous United States under alternative policy scenarios. *Ecological Applications* 22:1036-1049.
- Rahmstorf, S., G. Foster, and A. Cazenave. 2012. Comparing climate projections to observations up to 2011. *Environmental Research Letters* 7.
- Ramesh, N., and R. Murtugudde. 2012. All flavours of El Niño have similar early subsurface origins. *Nature Climate Change* 2.
- Rand, P. S., M. Goslin, M. R. Gross, J. R. Irvine, X. Augerot, P. A. McHugh, and V. F. Bugaev. 2012. Global Assessment of Extinction Risk to Populations of Sockeye Salmon *Oncorhynchus nerka*. *Plos One* 7.
- Ray, R. A., R. A. Holt, and J. L. Bartholomew. 2012. RELATIONSHIP BETWEEN TEMPERATURE AND CERATOMYXA SHASTA-INDUCED MORTALITY IN KLAMATH RIVER SALMONIDS. *Journal of Parasitology* 98:520-526.
- Recsetar, M. S., M. P. Zeigler, D. L. Ward, S. A. Bonar, and C. A. Caldwell. 2012. Relationship between fish size and upper thermal tolerance. *Transactions of the American Fisheries Society* 141:1433-1438.

- Reese, A. L., and E. E. Williams. 2012. Temperature as a cellular stress of Chinook salmon embryo cells. *Faseb Journal* 26.
- Report, I. S. 2012. Managing the risks of extreme events and disasters to advance climate change adaptation.
- Riley, W. D., B. Bendall, M. J. Ives, N. J. Edmonds, and D. L. Maxwell. 2012. Street lighting disrupts the diel migratory pattern of wild Atlantic salmon, *Salmo salar* L., smolts leaving their natal stream. *Aquaculture* 330:74-81.
- Rupp, D. E., T. C. Wainwright, P. W. Lawson, and W. T. Peterson. 2012. Marine environment-based forecasting of coho salmon (*Oncorhynchus kisutch*) adult recruitment. *Fisheries Oceanography* 21:1-19.
- Russell, I. C., M. W. Aprahamian, J. Barry, I. C. Davidson, P. Fiske, A. T. Ibbotson, R. J. Kennedy et al. 2012. The influence of the freshwater environment and the biological characteristics of Atlantic salmon smolts on their subsequent marine survival. *Ices Journal of Marine Science* 69:1563-1573.
- Ruzicka, J. J., R. D. Brodeur, R. L. Emmett, J. H. Steele, J. E. Zamon, C. A. Morgan, A. C. Thomas et al. 2012. Interannual variability in the Northern California Current food web structure: Changes in energy flow pathways and the role of forage fish, euphausiids, and jellyfish. *Progress in Oceanography* 102:19-41.
- Satterthwaite, W. H., M. S. Mohr, M. R. O'Farrell, and B. K. Wells. 2012. A Bayesian hierarchical model of size-at-age in ocean-harvested stocks - quantifying effects of climate and temporal variability. *Canadian Journal of Fisheries and Aquatic Sciences* 69:942-954.
- Sharma, R., and T. P. Quinn. 2012. Linkages between life history type and migration pathways in freshwater and marine environments for Chinook salmon, *Oncorhynchus tshawytscha*. *Acta Oecologica-International Journal of Ecology* 41:1-13.
- Sheehan, T. F., D. G. Reddin, G. Chaput, and M. D. Renkawitz. 2012. SALSEA North America: a pelagic ecosystem survey targeting Atlantic salmon in the Northwest Atlantic. *Ices Journal of Marine Science* 69:1580-1588.
- Shuter, B. J., A. G. Finstad, I. P. Helland, I. Zweimuller, and F. Holker. 2012. The role of winter phenology in shaping the ecology of freshwater fish and their sensitivities to climate change. *Aquatic Sciences* 74:637-657.
- Soares, P. M. M., R. M. Cardoso, P. M. A. Miranda, P. Viterbo, and M. Belo-Pereira. 2012. Assessment of the ENSEMBLES regional climate models in the representation of precipitation variability and extremes over Portugal. *Journal of Geophysical Research-Atmospheres* 117.
- Sobie, S. R., and A. J. Weaver. 2012. Downscaling of Precipitation over Vancouver Island using a Synoptic Typing Approach. *Atmosphere-Ocean* 50:176-196.
- Sogard, S. M., J. E. Merz, W. H. Satterthwaite, M. P. Beakes, D. R. Swank, E. M. Collins, R. G. Titus et al. 2012. Contrasts in Habitat Characteristics and Life History Patterns of *Oncorhynchus mykiss* in California's Central Coast and Central Valley. *Transactions of the American Fisheries Society* 141:747-760.
- Sokolova, I. M., M. Frederich, R. Bagwe, G. Lannig, and A. A. Sukhotin. 2012. Energy homeostasis as an integrative tool for assessing limits of environmental stress tolerance in aquatic invertebrates. *Marine Environmental Research* 79:1-15.
- Soyut, H., S. Beydemir, S. B. Ceyhun, O. Erdogan, and E. D. Kaya. 2012. Changes in carbonic anhydrase activity and gene expression of Hsp70 in rainbow trout (*Oncorhynchus*

- mykiss) muscle after exposure to some metals. *Turkish Journal of Veterinary & Animal Sciences* 36:499-508.
- Stabeno, P. J., E. V. Farley, N. B. Kachel, S. Moore, C. W. Mordy, J. M. Napp, J. E. Overland et al. 2012. A comparison of the physics of the northern and southern shelves of the eastern Bering Sea and some implications for the ecosystem. *Deep-Sea Research Part II-Topical Studies in Oceanography* 65-70:14-30.
- Staudinger, M. D., N. B. Grimm, A. Staudt, S. L. Carter, F. S. C. III, P. Kareiva, M. Ruckelshaus et al. 2012. Impacts of Climate Change on Biodiversity, Ecosystems, and Ecosystem Services: Technical Input to the 2013 National Climate Assessment, Cooperative Report to the 2013 National Climate Assessment. Available at: <http://assessment.globalchange.gov>.
- Stauffer, B. A., A. G. Gellene, A. Schnetzer, E. L. Seubert, C. Oberg, G. S. Sukhatme, and D. A. Caron. 2012. An oceanographic, meteorological, and biological 'perfect storm' yields a massive fish kill. *Marine Ecology Progress Series* 468:231-243.
- Stelkens, R. B., G. Jaffuel, M. Escher, and C. Wedekind. 2012. Genetic and phenotypic population divergence on a microgeographic scale in brown trout. *Molecular Ecology* 21:2896-2915.
- Stenhouse, S. A., C. E. Bean, W. R. Chesney, and M. S. Pisano. 2012. Water temperature thresholds for coho salmon in a spring-fed river, Siskiyou County, California. *California Fish and Game* 98:19-37.
- Strange, J. S. 2012. Migration strategies of adult Chinook salmon runs in response to diverse environmental conditions in the Klamath River Basin. *Transactions of the American Fisheries Society* 141:1622-1636.
- Stroeve, J. C., V. Kattsov, A. Barrett, M. Serreze, T. Pavlova, M. Holland, and W. N. Meier. 2012. Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations. *Geophysical Research Letters* 39.
- Sturdevant, M. V., J. A. Orsi, and E. A. Fergusson. 2012. Diets and Trophic Linkages of Epipelagic Fish Predators in Coastal Southeast Alaska during a Period of Warm and Cold Climate Years, 1997-2011. *Marine and Coastal Fisheries* 4:526-545.
- Suchman, C. L., R. D. Brodeur, E. A. Daly, and R. L. Emmett. 2012. Large medusae in surface waters of the Northern California Current: variability in relation to environmental conditions. *Hydrobiologia* 690:113-125.
- Surfleet, C. G., D. Tullos, H. Chang, and I. W. Jung. 2012. Selection of hydrologic modeling approaches for climate change assessment: A comparison of model scale and structures. *Journal of Hydrology* 464:233-248.
- Sutton, R., and T. Soto. 2012. Juvenile coho salmon behavioural characteristics in Klamath river summer thermal refugia. *River Research and Applications* 28:338-346.
- Swaney, D. P., C. Humborg, K. Emeis, A. Kannen, W. Silvert, P. Tett, R. Pastres et al. 2012. Five critical questions of scale for the coastal zone. *Estuarine Coastal and Shelf Science* 96:9-21.
- Tan, E. K., C. Wongwarangkana, S. Kinoshita, Y. Suzuki, K. Oshima, M. Hattori, T. Ineno et al. 2012. Global gene expression analysis of gill tissues from normal and thermally selected strains of rainbow trout. *Fisheries Science* 78:1041-1049.
- Tang, C. L., B. T. Crosby, J. M. Wheaton, and T. C. Piechota. 2012. Assessing streamflow sensitivity to temperature increases in the Salmon River Basin, Idaho. *Global and Planetary Change* 88-89:32-44.

- Terzi, E., and B. Verep. 2012. Effects of water hardness and temperature on the acute toxicity of mercuric chloride on rainbow trout (*Oncorhynchus mykiss*). *Toxicology and Industrial Health* 28:499-504.
- Thompson, S. A., W. J. Sydeman, J. A. Santora, B. A. Black, R. M. Suryan, J. Calambokidis, W. T. Peterson et al. 2012. Linking predators to seasonality of upwelling: Using food web indicators and path analysis to infer trophic connections. *Progress in Oceanography* 101:106-120.
- Tiffan, K. F., T. J. Kock, W. P. Connor, F. Mullins, and R. K. Steinhorst. 2012. Downstream Movement of Fall Chinook Salmon Juveniles in the Lower Snake River Reservoirs during Winter and Early Spring. *Transactions of the American Fisheries Society* 141:285-293.
- Todd, C. D., K. D. Friedland, J. C. MacLean, B. D. Whyte, I. C. Russell, M. E. Lonergan, and M. B. Morrissey. 2012. Phenological and phenotypic changes in Atlantic salmon populations in response to a changing climate. *Ices Journal of Marine Science* 69:1686-1698.
- Tomaro, L. M., D. J. Teel, W. T. Peterson, and J. A. Miller. 2012. When is bigger better? Early marine residence of middle and upper Columbia River spring Chinook salmon. *Marine Ecology-Progress Series* 452:237-252.
- Trueman, C. N., K. M. MacKenzie, and M. R. Palmer. 2012. Stable isotopes reveal linkages between ocean climate, plankton community dynamics, and survival of two populations of Atlantic salmon (*Salmo salar*). *Ices Journal of Marine Science* 69:784-794.
- Turrero, P., J. L. Horreo, and E. Garcia-Vazquez. 2012. Same old *Salmo*? Changes in life history and demographic trends of North Iberian salmonids since the Upper Palaeolithic as revealed by archaeological remains and beast analyses. *Molecular Ecology* 21:2318-2329.
- Underwood, Z. E., C. A. Myrick, and K. B. Rogers. 2012. Effect of acclimation temperature on the upper thermal tolerance of Colorado River cutthroat trout *Oncorhynchus clarkii pleuriticus*: thermal limits of a North American salmonid. *Journal of Fish Biology* 80:2420-2433.
- Urbach, D., M. Kang, S. Kang, K. B. Seong, S. Kim, U. Dieckmann, and M. Heino. 2012. Growth and maturation of Korean chum salmon under changing environmental conditions. *Fisheries Research* 134:104-112.
- Valiela, I., L. Camilli, T. Stone, A. Giblin, J. Crusius, S. Fox, C. Barth-Jensen et al. 2012. Increased rainfall remarkably freshens estuarine and coastal waters on the Pacific coast of Panama: Magnitude and likely effects on upwelling and nutrient supply. *Global and Planetary Change* 92-93:130-137.
- Volkov, A. F. 2012. Is the mass emergence of *Themisto libellula* in the northern Bering Sea an invasion or a bloom? *Russian Journal of Marine Biology* 38:465-473.
- Warren, D. R., J. M. Robinson, D. C. Josephson, D. R. Sheldon, and C. E. Kraft. 2012. Elevated summer temperatures delay spawning and reduce redd construction for resident brook trout (*Salvelinus fontinalis*). *Global Change Biology* 18:1804-1811.
- Wehner, M. F. 2013. Very extreme seasonal precipitation in the NARCCAP ensemble: model performance and projections. *Climate Dynamics* 40:59-80.
- Wootton, J. T., and C. A. Pfister. 2012. Carbon system measurements and potential climatic drivers at a site of rapidly declining ocean pH. *Plos One* 7.

- Wu, H., J. S. Kimball, M. M. Elsner, N. Mantua, R. F. Adler, and J. Stanford. 2012a. Projected climate change impacts on the hydrology and temperature of Pacific Northwest rivers. *Water Resources Research* 48.
- Wu, L. X., W. J. Cai, L. P. Zhang, H. Nakamura, A. Timmermann, T. Joyce, M. J. McPhaden et al. 2012b. Enhanced warming over the global subtropical western boundary currents. *Nature Climate Change* 2:161-166.
- Yan, G. J., X. K. He, Z. D. Cao, and S. J. Fu. 2012. The trade-off between steady and unsteady swimming performance in six cyprinids at two temperatures. *Journal of Thermal Biology* 37:424-431.
- Yu, H., H. S. Bi, B. Burke, J. Lamb, and W. Peterson. 2012. Spatial variations in the distribution of yearling spring Chinook salmon off Washington and Oregon using COZIGAM analysis. *Marine Ecology-Progress Series* 465:253-265.
- Zeigler, M. P., A. S. Todd, and C. A. Caldwell. 2012. Evidence of Recent Climate Change within the Historic Range of Rio Grande Cutthroat Trout: Implications for Management and Future Persistence. *Transactions of the American Fisheries Society* 141:1045-1059.
- Zeug, S. C., P. S. Bergman, B. J. Cavallo, and K. S. Jones. 2012. Application of a Life Cycle Simulation Model to Evaluate Impacts of Water Management and Conservation Actions on an Endangered Population of Chinook Salmon. *Environmental Modeling & Assessment* 17:455-467.
- Zhang, Y. X., Y. Qian, V. Duliere, E. P. Salathe, and L. R. Leung. 2012. ENSO anomalies over the Western United States: present and future patterns in regional climate simulations. *Climatic Change* 110:315-346.

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Appendix D.2

Literature review for 2010: Biological effects of climate change

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**Literature review for 2010 citations for BIOP:
Biological effects of climate change**

**Prepared by Lisa Crozier
Northwest Fisheries Science Center, NOAA-Fisheries
August, 2011**

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1 Executive summary

Nationally and globally, the climate of 2010 continued trends of global warming, being one of the two warmest years on record. New analyses of observational data were generally consistent with previously reported historical trends of climate change. Climate, oceanographic, hydrologic, and stream-temperature models continue to be developed, tested, improved, and applied. Most of their assessments and projections indicated worsening physical conditions for salmon in mid-latitude regions, consistent with previous analyses: rising air temperature, moderately rising precipitation, declining snowpack, declining stream flow (partly due to water withdrawals), and rising sea surface temperature (although at reduced rates in upwelling regions). However, a few of the results could have either beneficial or negative implications for salmon. Historical analyses and predictions of net changes in primary productivity are spatially variable, and increases in the intensity of coastal upwelling (see below) could have positive or negative impacts. New studies on the biological effects of most of these processes were consistent with previous analyses, and showed that where salmon are limited by cool temperatures, warming is beneficial, at least over the short term, but in areas that are already relatively warm or where floods or low flows have negative impacts, climate change scenarios consistently project declines in salmon. In the ocean, several new studies pointed to the importance of sea surface temperature for early marine survival (as opposed to the Pacific Decadal Oscillation or smolt condition), but there were large differences among populations included in the study, and the single Columbia River population included did not show a strong ocean effect in this analysis (Sharma et al. 2009). The most geographically relevant papers include stream temperature analyses of the Boise River Basin (Isaak et al. 2010), the Wenatchee River Basin (Cristea and Burges 2010), and the Touchet Basin (Wiseman et al. 2010); and numerous climatological analyses of the Columbia Basin (see sections 4 and 5).

Several new papers documented historical and projected increases in upwelling intensity in the California Current (Bakun et al. 2010; Garcia-Reyes and Largier 2010; Wang et al. 2010). Although stronger upwelling has been positively associated with Columbia River salmon survival in the 20th century, Bakun et al. (2010) presented some possible scenarios (exacerbated by bad fisheries management) in which anoxia, toxic gas eruptions and jellyfish take over. Furthermore, although increased primary productivity predicted by some models would be expected to benefit salmon, most ecosystem models predict declines in salmon productivity south of the Arctic. Arctic conditions were expected to improve for salmon based on increased nitrate concentration (Rykaczewski and Dunne 2010), primary productivity (Kahru et al. 2010; Steinacher et al. 2010), and fisheries catches generally (Cheung et al. 2010; MacNeil et al. 2010).

A few emerging potential threats were documented for Fraser River salmon, with unknown potential for affecting Columbia River salmon. Algal blooms lowered survival of Chilko sockeye smolts (Rensel et al. 2010), and apparently increasing aggregations of sharks might be increasing predation on returning adults (Williams et al. 2010).

One other highly novel study found that gene flow increased during unfavorable river conditions, suggesting that straying might increase in response to rising temperatures (Valiente et al. 2010).

Three studies documented strong trends in salmonid phenology (one smolt-timing and two spawn-timing studies). Two of these studies also involved declining populations, and the authors suggested that part of the problem was a mismatch between rates of temperature change either in fresh- or saltwater (Kennedy and Crozier 2010) or between spring and summer (Wedekind and Kung 2010). In the 2010 BIOP we mentioned a trend toward earlier smolting in Snake River spring Chinook (Achord et al. 2007), so attention to potential phenological mismatches seem warranted. Several other studies attributed population decline more directly to environmental deterioration (Clews et al. 2010; Wiseman et al. 2010).

A large number of recent studies on Fraser River sockeye found negative impacts of high temperatures on adult migration survival and throughout the life cycle, and warned that a majority of populations within the Fraser River Basin are highly vulnerable to extinction due to climate change, based on both quantitative (Hague et al. 2011; Martins et al. 2011) and qualitative analyses (Jacob et al. 2010; McDaniels et al. 2010). McDaniels et al. (2010) considered possible management actions, but found they were limited. One study found individual variation in the use of thermal refugia during migration that depend on individual condition (Donaldson et al. 2010), while another study found that thermal refuge use corresponded to higher survival (Mathes et al. 2010). Disease morbidity and mortality is being exacerbated by warmer temperatures (Braden et al. 2010; Bradford et al. 2010; Marcos-Lopez et al. 2010) and artificial propagation (especially fish farms, Krkosek 2010; Pulkkinen et al. 2010).

Several theoretical papers described new mathematical methods of detecting impending extinction due to environmental deterioration (Drake and Griffen 2010; Ovaskainen and Meerson 2010) and elevated risks from environmental impacts at particular time scales and life stages (Worden et al. 2010).

Several studies demonstrated strong maternal effects on larval survival, compared with stronger genetic effects on juvenile growth and survival. These studies could possibly imply that negative effects of the hydrosystem could persist into the next generation, whereas evolution might modify juvenile growth and survival.

New studies provided additional details on adaptation strategies, such as those previously described in ISAB (2007), for Pacific salmon. For example, Cristea and Burges (2010) found that the cooling potential of riparian vegetation restoration is likely to postpone stressful temperatures for salmonids in Wenatchee River tributaries through the end of the century. However, vegetation restoration did not significantly reduce temperature in the mainstem Wenatchee. Such studies need to be site specific, because, for example, Null et al (2010) found that restoring and protecting cool springs was more beneficial than increasing riparian shading in the Shasta River. Several papers provided more information on adaptation strategies in general and the practical social and technical considerations for implementing them (e.g., Binder et al. 2010; Brekke et al. 2010).

In conclusion, new information from 2010 publications was generally consistent with previous analyses in reporting ongoing trends in climate consistent with climate change projections and negative implications for salmon at mid-latitudes. Modeling techniques continue to improve. A few studies focused on areas that did not receive much attention in our previous report, and thus provide new information. These areas include predicted and observed intensification of upwelling (compared with various similar and contradictory reports published previously), reduced salmon survival due to algal blooms,

climate-induced straying, and climate change-induced mismatches in phenology associated with population declines. Numerous new studies of Fraser River sockeye warn of very severe risk from climate change. Finally, several theoretical papers augment our toolbox for anticipating extinction due to environmental deterioration.

2 Table of acronyms

AO	Arctic Oscillation
BPA	Bonneville Power Administration
CCS	California Current System
ENSO	El Niño-Southern Oscillation
ESU	Evolutionarily Significant Unit
GCM	General Circulation Model
IPCC	Intergovernmental Panel on Climate Change
NPI	North Pacific Index
NPGO	North Pacific Gyre Oscillation
NO	Northern Oscillation
OA	Ocean Acidification
PDO	Pacific Decadal Oscillation
SO	Southern Oscillation or Southern Annual Mode
SST	Sea surface temperature
VIC	Variable Infiltration Capacity model
WACCA	Washington State Climate Change Assessment
WRF	Weather Research and Forecasting

3 Goals and methods of this review

The goal of this review was to identify the literature published in 2010 that is most relevant to predicting impacts of climate change on Columbia River salmon listed under the Endangered Species Act. A large amount of literature related to this topic is not included, because almost anything that affects salmon at all relates to or is altered in some way by changes in temperature, stream flow or marine conditions. We have tried to identify the most directly related papers by combining climatic and salmonid terms in my search criteria. Thus many general principles demonstrated in other taxa or with more general contexts in mind have been omitted. This review also does not include potentially relevant gray literature, because the search engine used only includes the major peer-reviewed scientific journals. Additional references were solicited from NOAA staff and independent scientists who specialize in freshwater habitat, estuary behavior, marine ecosystems, ocean acidification, and climate-fish dynamics in other species. In total, the methods employed involved review of over 800 papers. Of these, 223 are included in this summary.

This search was conducted in ISI Web of Science in June, 2011. Each set of search criteria involved a new search, and results were compared with previous searches to identify missing topics. The specific search criteria all included PY=2010, plus:

- 1) TS=(climat* OR temperature OR streamflow OR flow OR snowpack OR precipitation OR PDO) AND TS=(salmon OR Oncorhynchus OR steelhead);
- 2) TS=(climat* OR Temperature OR Precipitation OR streamflow OR flow) AND TS="Pacific Northwest";
- 3) TS=(marine OR sea level OR hyporheic OR groundwater) AND TS=climat* AND TS=(salmon OR Oncorhynchus OR steelhead);
- 4) TS=(upwelling OR estuary) AND TS=climat* AND TS=Pacific;
- 5) FT=("ocean acidification" OR "California current" OR "Columbia River")
- 6) TS="prespawn mortality"

The review is organized by first considering physical environmental conditions (historical trends and relationships) and then predictions of future climate, snowpack, stream flow, temperature, ocean conditions, etc. A summary follows of the literature on salmonid responses to these environmental conditions, progressing through the life cycle.

4 National Climate Summary of 2010

Nationally and globally, 2010 was at or near record-breaking levels in many respects, based on NOAA's Annual State of the Climate Report (Blunden et al. 2011) Strong El Niño-Southern Oscillation (ENSO), Arctic Oscillation (AO), and Southern Annular Mode (SO) conditions drove very dramatic weather events in many parts of the world, while we emitted greenhouse gases at very high levels (above the average over the past 30 years). Trends consistent with global climate change reported in the 2010 Supplemental Biological Opinion (NMFS 2010) continued: 1) 2010 was one of the two warmest years on record; 2) average global sea surface temperature was the third warmest on record and sea level continued to rise; 3) ocean salinity variations at a global scale showed intensification of the water cycle; and 4) Arctic sea ice shrank to the third smallest area on record, the Greenland ice sheet melted at the highest rate and over the largest area since at least 1958, and alpine glaciers continued to melt.

5 Historical analysis of terrestrial climate, stream flow and stream temperature in the western US and British Columbia

A number of new papers have conducted historical analyses of trends over the past half century or so in air temperature (rising), precipitation (rising), snowpack (declining) and stream flow (declining). Trends in ocean conditions and El Niño events are discussed in the ocean section. These results are generally consistent with trends described in the 2010 Biological Opinion (NMFS 2010). Further, several papers have analyzed how broad-scale climatic conditions such as the Pacific Decadal Oscillation (PDO) and ENSO drive variation in processes with significant biological implications, such as drought, forest fire, landslides, and coastal fog.

Specifically, Fu et al. (2010) showed that in Washington State from 1952 to 2002, annual mean air temperature increased 0.61°C (daily mean), 0.24°C (daily maximum), and 0.93°C (daily minimum), on average (or at a rate of 0.122, 0.048, and 0.185°C, respectively, per 10 years). Despite increasing annual precipitation, stream flow decreased at a rate of -4.88 cms/yr, with the largest effects in May and June on the west side of the Cascade Mountains. Temperature increased throughout the year (except October and December) across the state, with a small area of maximum temperature cooling in the central-eastern portion of the state. Minimum temperatures rose more than maximum temperatures. To explain the declines in streamflow, the authors suggested that human water use and increased evaporation rates due to rising temperature and more surface area exposure (e.g., from reservoirs) play important roles. Ryu et al. (2010) showed a positive relationship between a drought index based on streamflow and El Niño in the Pacific Northwest. Bumbaco and Mote (2010) studied the role of winter and summer precipitation and temperature in causing three droughts in Washington and Oregon (2001, 2003, and 2005), and found a different driver in each case (low winter

precipitation in 2001, low summer precipitation in 2003, and warm winter temperatures during key precipitation events in 2005).

Corresponding to the lower availability of water for biological processes, Meyn et al. (2010) showed that summer drought correlates strongly with the forest area burned in British Columbia. The PDO index the previous winter was related to summer drought in some areas of British Columbia, but is not a very strong driver over most of the province. Johnstone and Dawson (2010) tracked a new index of climate not mentioned in our previous report, which is the frequency of coastal fog along the California coast. They showed that fog levels are correlated with the strength of upwelling and have declined 33% from 1951 to 2008, increasing drought stress for plants.

Intense precipitation events, predicted to increase in winter with climate change, exacerbated by rain on snow events and high wind also increase the risk of landslides (Guthrie et al. 2010).

Average snow depth decreased widely across the western United States, especially at lower-elevation stations (<1000 m, Grundstein and Mote 2010). The vast majority of lower-elevation stations (80%) and a majority of mid-elevation stations (2000-3000m, 62%) showed significantly negative trends. Snow depth was strongly related to the PDO and the North Pacific Index (NPI).

Streamflow reflects both climatic factors and local habitat. For example, recent papers discussed the impact of glacier runoff and projected changes (quantified on Mt Hood by Nolin et al. 2010), and combinations of snow fall and forest integrity, whether due to harvest or fire. Specifically, Jones and Perkins (2010) studied how rain-on-snow events and harvest differentially affected different sized basins, while Eaton et al. (2010) examined changes in peak flows and the timing of the freshet, in addition to channel morphology following fire.

Wetlands are highly dynamic environments. Large scale variability in climate such as oscillations of the PDO can dramatically change local environmental conditions. After the regime shift of 1976, a wetland in southern California experienced a dramatic increase the frequency of extreme storms and floods due to a shift in the storm track across the Pacific. Zedler (2010) classified the types of events and their ecological consequences (mostly for plants) in terms of their relationships, for example, whether the ordering of events matters (e.g., river-mouth closure followed by a drought, that killed many more plants than additive effects would predict. They suggested focusing restoration actions on preparing ecosystems for likely future climates rather than restoring past communities necessarily.

6 Projected changes in terrestrial climate for the 21st century

Some of the most relevant projections of climate change conditions within the Columbia Basin were summarized in the 2010 BIOP based on reports produced for the Washington State Climate Change Assessment (WACCA), but were published in formal climate journals in 2010. In this category, Mote and Salathé (2010) described climate changes in the Pacific Northwest predicted by general circulation models produced for the Intergovernmental Panel on Climate Change (IPCC) fourth assessment report. Salathé et al. (2010) described changes predicted by the regional dynamical climate model Weather Research and Forecasting (WRF) Model. Elsner et al. (2010) summarized the

regional hydrological implications of the global model predictions, and Mantua et al. (2010) described projected increases in peak winter flows, lower late summer flows, and high summer stream temperatures that will threaten salmon. A few other sections of the WACCA report were not mentioned in the BIOP, and are summarized in this report.

Predictions of how rising greenhouse gases will affect climate depend on how functional relationships are modeled. A large body of work describes tests and improvements of the climate models, and are mostly beyond the scope of this review. It is worth noting here that work is ongoing on many aspects with especially large levels of uncertainty at the moment, such as the extent of intra-model variability compared with inter-model variability (over half of the variation between models can be explained by variation within models, Deser et al. 2010), how the global circulation models drive ENSO variability (An et al. 2010) and regional downscaling -- i.e., how to convert the large-scale global model output (~200km² resolution) to the regional scale (~8 km² resolution, Ainslie and Jackson 2010). There are important differences in predictions made by different downscaling approaches. Qian et al. (2010) compare predictions from two dynamical downscaling methods, a subgrid parameterization and a regional climate model. They found that both methods greatly improved the modeled snowpack compared with observations over simpler downscaling methods, but the regional model captured precipitation and snowpack along the coastal mountains much better because of the importance of mountain orientation for wind direction. This model predicted a greater change in snowpack under climate change scenarios than the subgrid approach.

Predictions of changes in snowpack are very sensitive to how temperature changes with elevation. Minder et al. (2010) clarified spatial and temporal variation in the lapse rate in the Cascades, and Minder (2010) studied the effect of different determinants of the snow melting level in physical models. Minder (2010) predicted a loss of 14.8%-18.1% of Cascade snowfall per degree of warming, assuming precipitation increases, and 19.4%-22.6% loss per degree without precipitation increases, with profound impact on accumulated snowpack.

6.1 Stream flow

Many hydrological projections are based on the Variable Infiltration Capacity model (VIC). Wenger et al. (2010) conducted a test of this model in the Pacific Northwest. They found that model predictions were relatively accurate for center of flow timing and mean annual and summer flows, and the frequency of winter floods. However, modeled frequencies of low flows and groundwater-impacted streams did not match observations closely.

Chang and Jung (2010) projected the hydrology of the Willamette River Basin. They considered predictions from 8 general circulation models (GCMs), and downscale to 1/16th degree resolution for their hydrological model. Like previous projections, the models predicted increased winter flow, decreased summer flow, reduced snowpack, and earlier runoff. The different GCMs varied significantly in their predictions, especially later in the century. There was also substantial variation at the subbasin scale, indicating important local controls in hydrology. A new analysis by the Climate Impacts Groups for the Bonneville Power Administration (BPA) showed similar spatial variation, uncertainty, and general trends. This was a comprehensive study in draft form in 2010 (Brekke et al. 2010). It will be summarized more thoroughly in the 2011 report.

Three papers focused on changes in precipitation or hydrologic extremes. Tohver and Hamlet (2010) analyzed shifts in extreme streamflow statistics at 297 sites in the Columbia Basin, based on the Columbia Basin Climate Change Scenarios Project. First they described the same results previously reported: there was a general shift from weakly snow-dominant basins to transient basins, and from transient basins to rain-dominant basins, such that no snow-dominant sources remained in the US portion of the Columbia Basin by 2080, under the A1B scenario, and extremely few even in the highly optimistic B1 scenario. However, they found significant differences between the two downscaling methods employed in flood projections. The “hybrid delta” method predicted flooding increases throughout the Columbia Basin, whereas in Mantua et al. (2010) and the “composite delta” method, increased flooding is more spatially variable. The hybrid delta method is thought to be more accurate in this regard, reflecting the spatial distribution of warming and precipitation increases better than the composite method. Higher winter temperatures and precipitation regimes increase flooding most in transient and rain-dominant basins, but also in snow-dominant basins, despite the reduced accumulation of snowpack. Even greater increases in flooding could be caused by increasing spring storm intensity and more precipitation falling as rain rather than snow. Increased flooding in transitional and rain-dominated basins followed from increased winter precipitation. Low flow risk increased most in rain-dominant and transient basins due to rising summer temperatures and evapotranspiration rates. Snow-dominant basins, so important in the Columbia and Snake tributaries, were relatively resilient to this effect in this analysis possibly because the lowest flows tend to occur in winter, and they did not separate out summer low flows.

Rosenberg et al. (2010) examined precipitation extremes for stormwater infrastructure. They found that uncertainty in projections is too large to make engineering preparations, but that some potential outcomes could be very serious. Towler et al. (2010) similarly examined extreme precipitation events and secondary effects, in this case, turbidity, important for Portland’s water supply. They developed a technique for applying climate change scenarios to detect the impacts of predicted shifts in extreme events.

A study in California (Meyers et al. 2010) found that +2°C and +4°C climate warming and altered precipitation are likely to shift floods from spring to winter, and increase the frequency and intensity of floods. Such a change would negatively affect brook trout more than rainbow trout, which would then experience less competition from brook trout.

Another study (Moradkhani et al. 2010) explored climate change scenarios in the Tualatin River in Oregon using a different hydrological model and found that the 50-year floods and the riparian ecotone decreased in low emissions scenarios, but increased in high emissions scenarios. Thus well-established trees along the riparian corridor were flooded in the high-emission scenarios.

Some streams are currently fed by significant amounts of glacier meltwater. Nolin et al. (2010) studied a stream on Mt Hood that currently derives 41-73% of its late summer flow from glaciers. Under climate change scenarios, glaciers retreated, ultimately reducing summer flow.

7 Historical analyses and projections of ocean conditions

A number of studies published in 2010 provided insight into areas of profound importance for salmon that have been especially uncertain in prior climate change analyses. Two papers indicated that over the 20th century, upwelling in the California Current System (CCS) and the Humboldt Current System have become more intense, which is consistent with a new analysis of GCM projections that predicted it will continue to intensify with global warming. Papers focusing on historical sea surface temperatures (SST) addressed previous criticisms that observed trends are due to instrument bias, re-established the global pattern of decadal oscillations overlaid upon a background of rising SST, and documented the shifting character of El Niño events and their impact on long-term SST trends.

7.1 Upwelling

Upwelling dynamics along the Washington and Oregon coasts are a key element in Columbia River salmon marine survival and growth. The impacts of climate change on upwelling dynamics are among the most uncertain of all the predictions of climate change models. Conflicting predictions stem from 1) changes in the various driving processes that affect upwelling are expected to act in opposite directions, necessitating quantitative comparisons for determining net effects (i.e., rising SST should reduce upwelling, while increasing alongshore winds should increase upwelling) and 2) the spatial resolution of both climate models and empirical datasets have generally been too coarse to accurately capture upwelling dynamics.

Two papers published in 2010 basically supported the intensification prediction by documenting empirical trends over the 20th century, and a 3rd paper analyzed GCM reconstruction and projections of upwelling dynamics over the next century. Garcia-Reyes and Largier (2010) analyzed hourly buoy data off the California coast to describe the historical trend at an appropriate spatial and temporal scale. They found strong evidence for intensification of upwelling from 1982 to 2008, especially in central California (35°N-39°N). Specifically, they documented trends in the upwelling index (based on pressure fields), the strength of upwelling winds (based on alongshore wind speed), SST directly within the upwelling region (hence a negative trend in absolute temperature during the upwelling season), the number of days of upwelling within the season, a lengthening of the upwelling season (more days in March and October, hence earlier spring and later fall transition), and increased variability in upwelling winds (an increase in the 90th percentile and a decrease in 10% percentile), indicating stronger upwelling alternated with more relaxation in winds. They also found correlations of magnitude 0.6 or 0.7 between upwelling winds and the Northern Oscillation and the North Pacific Gyre Oscillation (NPGO), and between SST and the PDO and ENSO.

The second paper (Bakun et al. 2010) reviewed the basic argument that increasing land temperatures will intensify the pressure gradient between ocean and land, and hence intensify the alongshore wind stress, which initiates upwelling. Bakun et al. (2010) then reviewed previous tests of the hypothesis, and described a new test focusing on the relationship between water vapor and upwelling off Peru. This test showed significant correlations most of the time. Because water vapor acts as a greenhouse gas, they concluded this was consistent with a prediction of intensifying upwelling with rising

greenhouse gas concentrations. One very important point they made in this paper, however, is that intensification of upwelling is not necessarily good for fish. They described scenarios in which excessive upwelling advects zooplankton offshore too quickly for effective phytoplankton control. If omnivorous fish such as sardines are overfished or not present for some reason, there could be an ecosystem regime shift toward that currently found off Namibia, in which unconsumed phytoplankton sink and generate hypoxic zones and toxic gas eruptions, which kill fish and leave an ecosystem dominated by jellyfish.

In the third paper, Wang et al. (2010) analyzed the performance of all the major GCMs produced for the 4th IPCC assessment using a number of criteria, including PDO variation across the Pacific and upwelling near the mouth of the Columbia River. Twelve of the 23 GCMs had a reasonable representation of the PDO over the 20th century (i.e., had a spatial correlation coefficient of the first Empirical Orthogonal Function of winter SST of at least 0.7). Half of these models predicted that SST would exceed the variability of the PDO within 50 years under the A1B emissions scenario (the remainder predicted it would happen within 90 years). Averaged over 10 models, SST in the CCS was expected to increase 0.26°C per decade in the 21st century. Although the GCMs were not designed to characterize dynamics at the spatial scale of coastal upwelling, these models did remarkably well at capturing the seasonality of upwelling, even if they overestimated seasonal variation somewhat. Representation of the California Current was better than the Humboldt Current. In the CCS, 17 models predicted increases in July upwelling while only two models predicted decreases.

7.2 *Ocean temperatures*

Three studies analyzed historical trends in ocean temperatures. Carson and Harrison (2010) examined the impact of instrument bias in previously reported interdecadal trends at the ocean surface, 50m, 100m, and 300m temperatures. They found coherent signals of interdecadal variability at multiple depths, even with bias correction and comparisons of different datasets. This contrasts with recent work on the global average temperature, which showed reduced decadal variability after bias correction. Schwing et al. (2010) describe global atmospheric and oceanic teleconnections (e.g., the PDO, AO, NO, SO, and major current systems) and the major factors driving large marine ecosystems. Atmospheric teleconnections synchronize much of the decadal variability in the California and Humboldt Current Systems, as well as the Gulf of Alaska. Schwing et al. (2010) showed a persistent warming trend of 1-2°C over 100 years in SST in all large marine ecosystems, although the rate of warming was weaker in the upwelling (or downwelling) dominated coastal region. The general patterns (overall trend and decadal fluctuations) were similar to global mean surface temperature, despite some regional differences. The western Pacific showed roughly similar trends, but lags behind the eastern Pacific by about 10 years, and was driven by quite different physical processes. Thus they predicted similarities among the eastern Pacific large marine ecosystems in responses to climate change, but less so between eastern and western Pacific large marine ecosystems. Another paper (Moore et al. 2010), made a very interesting point, which is that ENSO warm water events usually only affect winter temperature in Pacific Northwest waters, while the PDO warm phase often persists through summer and fall. This has important implications for the salmonid life stage that

is affected by these events, which then has implications for impacts on population dynamics (Worden et al. 2010), as described below in the Population Dynamics Modelling Section.

Finally, Lee and McPhaden (2010) paper parsed out sea surface temperature increases in the central Pacific during El Niño events, and found that the increasing frequency and intensity of these events in this region drove most of the overall trend in sea surface temperature (SST). SST during El Niño events warmed by 0.24°C/decade, whereas SST warming in neutral and La Niña years was positive, but much smaller (0.05-0.07°C/decade) and not statistically significant over the 1982-2008 time frame. The reason for this shift in the position of the maximum warm anomaly is not known, but increasing intensity and frequency of El Niño events has been predicted to follow from rising greenhouse gases (Yeh et al. 2009), as cited in the 2010 Biological Opinion.

7.3 *Ocean acidification*

Two papers found that measured declines in pH near urban areas are faster than expected from CO₂ uptake alone and partially reflect nutrient loading (in the Hood Canal of Puget Sound, Washington, Feely et al. 2010; along the Dutch coast, Provoost et al. 2010). Wong et al. (2010) studied trends in pCO₂ in seawater along line P out from Vancouver Island, and found that it has risen in the oceanic zone at a rate of 1.36 μatm per year, tracking the atmospheric growth rate. The coastal zone pCO₂ rose at a similar rate in winter, but spring levels showed no trend.

8 Impact of stream temperature and flow on juvenile salmon

8.1 *Effects of temperature on embryo development*

There has been much concern that warmer winter temperatures will increase embryo mortality, cause earlier fry emergence, smaller fry size, and a mismatch between larval needs and food supply. In an experiment on coho survival, Lohmus et al. (2010b) found the optimal temperature for hatching and alevin survival was a relatively high 12°C; they found substantial survival (40%) still at 16°C, but very low survival at 18°C (2.5%). In a review article, Teletchea and Fontaine (2010) found a strong positive relationship between egg size and larval energy reserves, and a strong negative relationship between temperature and time to first mixed feeding (i.e., requiring external food supply) among Pacific salmon. Thus although Pacific salmon have relatively large eggs and hence more flexibility in temporally matching food availability than other fish, higher temperatures are likely to produce smaller, less flexible fry. Janhunen et al. (2010) found that alevins hatched at the higher temperature were developmentally less advanced.

If either egg or larval survival is reduced under future climatic conditions, it is theoretically possible that they might evolve in response to selection. Several studies showed that populations from different climates have locally adapted development rates and thermal tolerances. Narum et al. (2010) found evidence of selection for differing climates by comparing genetic markers in redband trout: temperature was strongly correlated with allele frequencies. And Kavanagh et al. (2010) found evidence of local

adaptation to cool temperatures and reduced critical maximum temperatures in European grayling within 22 generations. However, Evans et al. (2010) and Janhunen et al. (2010) found similar results in Chinook salmon and Arctic charr, respectively, that genetic variation was relatively weak for embryo survival, but was slightly greater for larval length. Maternal effects were strong in both studies especially at the earlier developmental stages, indicating that adult migration and prespawn condition could have long-lasting effects through the next generation.

The effect of temperature during development might have more complicated effects beyond body size and emergence time. In sticklebacks, developmental temperatures and consequent compensatory growth affected skeletal and muscle morphology, with potential effects on locomotor performance (Lee et al. 2010). In zebra fish, brief exposures to cool developmental temperatures affected dorsal, anal, caudal, and pelvic fin positions, as well as gill cover and the position of the lower jaw (Georga and Koumoundouros 2010). It is not clear whether these shape changes have functional implications, but they were preserved through adulthood. Zabel et al. (2010) showed that different Chinook salmon ESU (fall vs spring/summer life history types) had different otolith/fish length relationships, demonstrating differences in morphology that are not simply explained by different growth rates. The populations do rear in very different environments, but the role of environmental temperature requires further study.

Other effects of high temperature during development include sex reversal. Magerhans and Horstgen-Schwark (2010) reported an experiment that showed that sensitivity to temperature in sex determination in rainbow trout is substantial and heritable. The initial population had a sex ratio of 51.9% female when eggs were reared at 18°C, and 49.3% female when reared at 12°C. After one generation of selection, they produced a sex ratio of either 57.6% or 44.5% female at 18°C, indicating a heritability of 0.63 for this trait. Stelkens and Wedekind (2010) reviewed the various mechanisms of sex determination and sex reversal in teleost fish.

8.2 Effects of temperature and flow on juvenile growth and survival

Many papers have continued to demonstrate strong effects of temperature and flow on juvenile salmon growth and survival. Most papers are consistent in showing improved growth when relatively cool habitat warms up: spring in Massachusetts, (Xu et al. 2010a), fall in Idaho (Jenkins and Keeley 2010); and a long-term trend of larger smolts in the Baltic (Vainikka et al. 2010). However, negative effects of warming were typical during summer (Xu et al. 2010b) and winter (Xu et al. 2010a), when consumption cannot compensate for increased metabolic demands. In northern Europe, the net effects are expected to still be positive except under the warmest climate change scenario examined (+4°C). This prediction was consistent with observations of increased size at age over 23 years in Baltic Sea Atlantic salmon, although hatchery practices and size-selective fishing also affect these populations. In more southerly locations, the negative effects were predicted to outweigh positive effects even in moderate warming scenarios (Xu et al. 2010a). Changes in growth rates might affect the timing of vulnerability to predators such as bass, which are very size selective (Christensen and Moore 2010).

Similarly, several papers showed that higher flow has positive effects when it is relatively low to start with (e.g., in spring in the heavily water-withdrawn Lemhi Creek, in fall in the more natural Marsh Creek, and higher spring flows in the Columbia for both populations of Chinook salmon (Arthaud et al. 2010), and throughout the brook trout growing season in Massachusetts, (Xu et al. 2010a), and in bringing in more insect drift to cutthroat trout in Jenkins and Keeley (2010), and increasing Atlantic salmon habitat volume (Teichert et al. 2010). However, the highest flows (floods) had negative effects (Hayes et al. 2010; Xu et al. 2010a). Hayes et al. (2010) found that relaxed density-dependent mortality over the following season compensated for the immediate negative effects on brown trout, thus there was no net effect in this case.

The rest of this section provides more detail on the papers mentioned in the previous two paragraphs. Xu et al. (2010a) tracked individual brook trout growth over an 8 year study. They found strongly interacting effects of temperature, flow, season, and density. Highest growth rates occurred in spring, and were positively correlated with temperature and flow. In the warmest season, summer, temperature was negatively correlated with growth. Flow was generally positively correlated with growth, except in winter. Furthermore, density had greater negative effects at high temperatures. Because current climate predictions indicated the greatest increases in temperature and flow are in the winter, and that flow decreases in the summer, the net prediction based on their data was a decrease in mean fish spawner size and fecundity under a moderate (1.5°C) warming scenario.

Davidson et al. (2010) studied the same study system as Xu et al. (2010a), but analyzed Atlantic salmon growth instead of brook trout growth, and included the impacts of the density of both Atlantic salmon and brook trout. Using a linear mixed model, they found that environmental effects (both temperature and discharge) were much more important than density in driving variation in growth. Warmer temperatures within a season generally had a very small negative effect, while high discharge had a strong positive effect. Interestingly, they found that more variability in temperature (the second principle component in temperature) had a negative impact at low discharge, but a positive impact at high discharge.

Habitat quality depends in part on food availability and the cost of acquiring it, which in turn depend on flow and temperature. Jenkins and Keeley (2010) found that cutthroat trout foraging location matched that predicted by the amount of energy gained (net energy intake NEI), with habitat type (pool versus riffle) and temperature explaining most of the variation among sites. Using an energetic model, they concluded that warmer temperatures will have negative effects on smaller fish, but will lengthen the growing season for larger fish.

Hayes et al. (2010) used changes in the relationship between weight and density in a New Zealand brown trout population over time to assess the impact of unusually low flows and one flood on population dynamics. They argued that although the flood caused substantial emigration or mortality, survival after the flood was higher than in other years (i.e., reduced density-dependent mortality), such that the population recovered quickly. The low-flow events had no effect on survival or biomass.

Arthaud et al. (2010) examined how well variation in flow during freshwater stages affected egg-smolt and egg-adult rates in a pristine stream (Marsh Creek, Idaho) and a stream subject to very high rates of water withdrawal (Lemhi Creek, Idaho). In

Lemhi Creek, water withdrawals are so severe that spring flows during the parr year strongly limited production and drove variation in both egg-smolt and egg-adult survival. In Marsh Creek, egg-smolt survival was correlated with parr-year August flow, but the cumulative impact on egg-adult survival was much weaker. In both populations, smolt-adult return rates were best predicted by Columbia River spring flow and ENSO.

Rising temperatures increase not only the metabolic rate of salmonids, but that of their predators, and potentially the risk from warm-adapted invasives such as bass. Christensen and Moore (2010) documented levels of bass predation on stocked rainbow trout in Twin Lakes, Washington. They found that trout sizes in fall (100-160mm) made them vulnerable to predation by large largemouth bass, but larger trout (>210mm) escaped predation. This suggests that changing growth rates due to temperature might affect not just total predation, but also the temporal period salmon are vulnerable to bass predation.

Westley et al. (2010) considered the affects of dispersal of anadromous fish through lake systems and discover a consequent lag in the community response to environmental forcing, in addition to habitat change and fishing mortality. By examining fish composition over 46 years, they found an immediate response and a 1-year time lagged response to the PDO in an upper lake where sockeye rear their first year, but just a 1-year time-lagged response in a lower lake. They emphasized these processes are important for anticipating the impact of environmental variability on community composition.

Lohmus et al. (2010a) studied variation in juvenile growth among wild-type and growth-enhanced coho salmon at 3 temperatures. They saw little evidence of compensatory growth, perhaps because fish were fed to satiation, so rank order in size was relatively consistent throughout the experiment. The fish grew more at 16°C than at 12°C, which is consistent with previous studies that found 15°C to be the optimal temperature for growth.

8.2.1 Local adaptation/genetic control in growth rates

Growth rate in general and the growth response to temperature in particular is a heritable trait, and several papers showed differences between populations consistent with a history of different selection pressures. Latitudinal gradients are especially useful for demonstrating evolutionary effects of different thermal regimes. In general, colder temperatures slow growth rate within populations, producing a latitudinal gradient of smaller size at age in cooler locations (Chavarie et al. 2010; Morita and Nagasawa 2010). However, over evolutionary time populations in cooler environments have compensated for this effect by evolving faster growth rates and better tolerance of adverse conditions at northern latitudes. Chavarie et al. (2010) demonstrated these higher growth rates in northern populations across 66 populations of lacustrine Arctic charr in eastern North America, although their anadromous forms did not showed the same strong effect. Finstad et al. (2010) showed that compared to southern Norwegian populations, northern populations of Atlantic salmon have adapted higher feeding activity and reduced metabolic expenditures to sustain them over a longer winter.

Although these patterns prove that fish evolve to different thermal regimes over long time periods, potential evolutionary responses to rapid climate change are a very

different matter. Understanding the roles of phenotypic plasticity, genetic variability, and maternal effects controlling larval survival and fry growth is key to predicting plastic and evolutionary responses to climate change. In a carefully controlled breeding design plus translocation experiment, Evans et al. (2010) quantify the strengths of these various effects in Chinook salmon from Quinsam and Big Qualicum rivers. They found that all processes were important for explaining their results, but that maternal effects were the most important process for larval survival, while additive genetic effects dominated fry survival and fry growth. These results suggest that maternal condition is very important for cross-generational effects, and that there is substantial genetic variation available for an evolutionary response to environmental change.

Van Doorslaer et al. (2010) explored rapid evolution in *Daphnia*, which are a major prey item of lake-dwelling salmonids, to increased temperature through artificial selection. They compared these newly evolved populations to *Daphnia* from a historically warmer climate. After only six months of exposure to unusually warm conditions, size at maturity had evolved. In this semi-natural experiment, the intrinsic population growth rate did not evolve. However, in a previous study (Van Doorslaer et al. 2009a) they showed the reverse effect, where population growth rate evolved but not size at maturity, demonstrating that either response is feasible, depending on ecological conditions. Furthermore, another previous study (Van Doorslaer et al. 2009b) showed that *in situ* evolution might reduce the competitive advantage and hence likelihood of invasion of more southerly, warm-adapted genotypes. Thus rapid evolution is possible, at least in *Daphnia* and perhaps other planktonic prey of salmonids, but it remains to be seen how this will pan out in natural communities and longer-lived species like salmon.

8.2.2 The timing of growth

In addition to total growth in a season being important, the rate of growth early in the season can have complex repercussions for smolting decisions, negative consequences of compensatory growth, and the ability to capitalize on ephemeral resources with large potential benefits. By manipulating the timing of food supply for California steelhead, Beakes et al. (2010) confirmed previous work indicating that the decision whether to smolt in a given year is based on growth rates the previous year, and that early size advantages are maintained over the year. Lee et al. (2010) showed that in three-spined sticklebacks, compensatory growth after cool temperature-induced slow growth negatively impacted swimming endurance, especially when it occurred near to the breeding season. Armstrong et al. (2010) found that juvenile coho salmon in the Wood River system in Alaska can only benefit from eating sockeye eggs if they are large enough to swallow them. Because growth rates are very temperature-dependent, coho juveniles in warmer streams were able to exceed the 70mm size limit necessary for eating the highly nutritious eggs. This enormous nutrient gain led to a highly non-linear response of growth rate to temperature.

8.2.3 Assessment of survival and growth risks from climate change in European salmonids

Elliott and Elliott (2010) reviewed the temperature limits for European salmonids in regard to survival, feeding and growth. They did not find evidence of local

adaptation (within species) in temperature tolerance, although there were marked differences in the upper thermal limits among species. They described the relationship between the North Atlantic Oscillation and emergence dates and adult return ages and rates. Using a growth model under climate change conditions, they predicted improved growth and earlier smolting in brown trout (age 1 instead of 2) except under the most extreme conditions ($>4^{\circ}\text{C}$), but suggested eggs of Arctic charr in some streams in southern Britain and Ireland might be at risk from high temperatures and low oxygen content. They noted several examples in which fish preferred cooler temperatures despite low oxygen levels over warmer temperatures with more oxygen, and emphasized the importance of maintaining deep pool refugia.

8.3 Behavioral and survival responses to winter conditions

Several papers described *in situ* behavioral responses to environmental conditions, especially concealment behavior and nocturnality. Winter (cold) temperatures tend to induce concealment behavior in both Grande Ronde River Chinook salmon (Van Dyke et al. 2010) and Oregon steelhead (Reeves et al. 2010), but Reeves et al. (2010) found that the response was stronger in a montane population than a coastal population. Reeves et al. (2010) also found an increase in nocturnality was more pronounced in winter in the montane population. Orpwood et al. (2010) found that riparian cover increased concealment and nocturnality in both summer and winter, regardless of food supply.

Linnansaari and Cunjak (2010) found that juvenile Atlantic salmon mortality or emigration over winter in New Brunswick, Canada was highest in early winter, before ice formation, and mortality was low during ice cover. They noted that this suggests that warmer winters that have shorter ice cover will not necessarily improve survival. Furthermore, they found that high discharge events and early maturation lowered apparent survival, although the latter might have been related to spawning-related dispersal.

One additional study (Pettersson et al. 2010) compared the suitability of different diets for aquaculture, but found that swimming ability at low temperature can be greatly impaired by an inadequate composition of fatty acids. This could have implications for wild fish if prey availability changes.

8.4 Juvenile residency, migration timing and straying responses to growth and environmental conditions

Life history diversity is a profoundly important issue in relation to environmental variability, both in facilitating a rapid response to directional environmental change and in maintaining bet-hedging strategies in case of unpredictable environmental conditions. One key trait in salmonids that is very sensitive to environmental conditions is the decision of whether to migrate to sea or not, and if they do migrate, when do they do it, and do they return to the natal rearing grounds to spawn or do they stray to a new location. Papers published in 2010 addressed all of these issues.

Johnson et al. (2010) showed that resident and migratory life-history forms of cutthroat trout were not genetically differentiated in two lower Columbia River tributaries (Abernathy Creek and the Chinook River). This study showed that resident and migratory families were not reproductively isolated, but not whether there is genetic basis to the

behavior (a genetic basis has been found with brook and rainbow trout). Thus it is still not completely resolved whether the long-term trend in these populations toward residency is an evolutionary or plastic response.

Steelhead/rainbow trout also have significant variation among populations in the probability of migrating to sea. Satterthwaite et al. (2010) built on previous models to argue that reduced smolt survival is the most important vital rate that could drive anadromous populations toward residency. The next most important rate was freshwater survival and growth.

Reed et al. (2010a) also found a strong relationship between smolt size and timing and growth opportunities. They found that sockeye salmon outplants from the same hatchery smolted earlier and at a larger size when they reared in a more productive lake, despite negative density dependence. They also had higher marine survival.

Morita and Nagasawa (2010) focused on the rate of maturation of age 0+ males and females in relation to temperature and latitude within Japan. Masu salmon matured as parr at higher rates in warmer streams, and May stream temperature was the best predictor of maturation rates across 12 populations. Furthermore, masu matured at smaller sizes in warmer streams.

8.5 Freshwater ecosystem processes

A variety of studies explored the effects of changes in temperature and flow on freshwater plankton communities. For example, raising the temperature reduced mean body size and prevalence of smaller phytoplankton, and total phytoplankton biomass (but not zooplankton, Yvon-Durocher et al. 2010), affected trophic dynamics (predator impact) and carrying capacities in bacteria-protist mesocosms (Beveridge et al. 2010) and increased overall productivity (Stich and Brinker 2010). Variation in the seasonality of flow (increased winter and decrease summer flow) increased phytoplankton abundance (Jones et al. 2010).

Moore and Schindler (2010) showed that insects in Alaskan streams with large salmon populations have adapted to salmon phenology by developing faster than insects in non-salmon streams so that they emerge prior to spawning, and the enormous habitat disturbance salmon create by digging redds.

McDermott et al. (2010) studied the development of hyporheic communities in recently de-glaciated streams in Alaska. These communities were negatively affected by redd-digging.

9 Environmental impacts on salmon marine stages and marine ecosystems

9.1 Smolt timing and early ocean survival

When salmon migrate from fresh to saltwater, they must balance the opportunities and constraints in both habitats. As discussed above, growth rates strongly influence whether and when to smolt from a freshwater perspective, and better growth might lead to earlier smolting or larger smolts (or both, e.g., Reed et al. 2010a). Similarly, some interference with the natural growth or behavioral pattern by stocking at an inappropriate

time can lead to delayed smolting (Skilbrei et al. 2010). Kennedy and Crozier (2010) showed a trend from 1978 to 2008 toward earlier smolting in wild Atlantic salmon in the River Bush, Northern Ireland. The emigration has shifted 10-14 days (depending on whether one tracks the start of the emigration or the peak emigration date), which correlates with the 5th day of river temperatures over 10°C. Nonetheless, marine survival has declined dramatically (from 30-35% early in the time series to 5-10% more recently), which the authors attributed to increasing disparity between river and ocean temperatures. Thus despite apparent tracking of some thermal cue for smolting, river temperatures still increased too fast to avoid a potentially dangerous differential (2.5°C) between river and ocean temperatures. It is not clear whether other aspects of marine conditions could be driving the population decline.

Smolt timing is well-known to be population-specific, presumably reflecting adaptation to the particular balance of trade-offs between freshwater and marine growth and survival at a given location. Spence and Hall (2010) analyzed the large scale geographic patterns in smolt timing across 53 coho populations from Alaska to central California, and found very strong geographic clustering of smolt timing, duration and variability with oceanographic zones. They suggested links to the predictability of ocean conditions. Because climate change might directly alter the timing of maximal ocean productivity and predictability, meaning specifically interannual variation in the optimal arrival time for smolts, these observations have important implications. Spence and Hall (2010) found that high latitude (mostly Alaskan) populations smolt relatively late, over a short temporal window, and with very little variability from year to year. They argued this is adaptive given the high predictability of the photoperiod-driven increases in productivity characteristic of the Arctic ocean. Southern populations (mostly Oregonian and Californian) that migrate into an ocean dominated by upwelling dynamics tend to enter earlier, but over a much larger temporal window. They argued that this is a bet-hedging strategy given the high interannual variability and unpredictability (from freshwater locations) of the spring transition. They also identified a third cluster in a transitional area mostly from British Columbia and Washington that were intermediate in smolt characteristics, and mostly migrated into buffered areas of Puget Sound and the Strait of Georgia. Although they also discussed alternative explanations and additional important factors, such as natal site elevation, migration distance, and watershed and stream size, these other factors are less likely to change with climate change.

What determines optimal ocean arrival timing is not well understood. Nonetheless, juvenile salmon survival is correlated with forage fish abundance, possibly because they provide alternative prey for predators. Zooplankton or food supply has also been identified as important. Kaltenberg et al. (2010) described the phenology and patterns of variability of forage fish and mesozooplankton populations near the Columbia River plume in 2008 and 2009. Kaltenberg et al. (2010) found a very sudden appearance in mid-May both years of large schools of forage fish which corresponded with similar sea surface temperature, salinity, and river flow (from the Columbia) each year. Zooplankton peaks occurred throughout the spring and summer as fronts passed over the sampling stations, and thus did not show strong seasonality compared with the forage fish. Litz et al. (2010) found that forage fish switched from eating mainly dinoflagellates early in 2005, during the very delayed upwelling season, to a mostly diatom-based food

source after the more normal upwelling season of 2006. They based this conclusion on lipid and fatty acid composition of the forage fish.

Chittenden et al. (2010) analyzed the survival of coho from Seymour and Quinsam Rivers, British Columbia 2007-2009, as a function of release date and marine plankton productivity. They found that coho stayed in the estuary during low marine productivity. Fish that arrived during zooplankton blooms passed quickly through the estuary and had the highest marine detection rates and smolt-adult survival (1.5-3x higher). The optimal time in both years was intermediate among the release groups.

MacFarlane (2010) measured growth in the San Francisco Bay estuary and coastal ocean over 11 cohorts. They found that the first month following ocean entry was critical for subyearling Chinook. They found very little growth accrued in the estuary, but far better growth upon arrival in the ocean. Higher salinity and lower freshwater outflow produced better growth in the estuary, while cooler temperatures, lower sea level, and greater upwelling improved growth in the ocean. They concluded that climate change conditions would yield reduced growth.

Juvenile salmon presumably do not always encounter adequate food resources. To develop a reference point for interpreting the amount of deprivation that marine fish experience, Fergusson et al. (2010) conducted a laboratory starvation experiment and compared various indices of condition with that usually observed in wild-caught Southeast Alaskan chum salmon in 2003. They found that whole body energy content, percent moisture content, and condition residuals were better indicators of starvation than weight or length, and that after 10-15 days of starvation, laboratory fish fell outside the range normally observed in wild fish.

Two studies found that sea surface temperatures during the first year in the ocean best explained adult returns. Focusing on 24 stocks of northwest Pacific Chinook salmon, Sharma and Liermann (2010) found that the PDO and ENSO indices explained much less variation in recruitment than local sea surface temperatures, which were strongly affected by the strength of upwelling and hence reflected more information about ocean productivity than basin-wide average temperatures. They simulated the effect of a 1°C change in SST, and found a 13% decline in productivity on average across populations. However, the only one population from the Columbia River was included in this analysis, Deschutes River fall Chinook, and this population showed a minimal effect of ocean predictors (SST, PDO and ENSO). Saito et al. (2010) studied the factors that best predicted smolt-adult return rates of chum salmon in Nemuro Strait in Hokkaido, Japan, 1999-2002. They found that somatic condition and growth rates during the coastal residency period (first 2-3 months in the ocean) did not predicted adult returns. Instead, sea surface temperatures during the first year (especially winter) in the ocean and the size of smolts at release best explained variation in smolt-adult returns.

Petrosky and Schaller (2010) found that warm ocean conditions in March, reduced upwelling in April, and slower river velocity (or additional trips through powerhouses at dams) during the spring migration period were the best predictors of poor ocean survival for both Chinook and steelhead. They recommended increasing spill to help compensate for lower flows and poorer ocean conditions due to climate change.

9.1.1 Algal bloom lowers survival

Although most studies of early marine survival focused on food availability and predation, algal blooms can cause high mortality in Fraser River sockeye salmon. Rensel et al. (2010) found that earlier and larger spring and early summer Fraser River flows were linked to major blooms of harmful raphidophyte flagellate *Heterosigma akashiwo* in the Strait of Georgia. Chilko sockeye salmon survival declined from 10.9% in non-bloom years to 2.7% in bloom years.

9.2 Marine habitat usage

Several studies have focused on ocean habitat usage, especially thermal preference. NOAA scientists have documented a strong aversion to temperatures over 19°C in the Columbia estuary. This is a strong limitation on habitat usage in the late summer, when juvenile salmon were once abundant (Dan Bottom, personal comm., technical reports). Peterson et al. (2010) synthesized 15 years of survey data to describe the distribution of yearling coho and Chinook salmon distribution and abundance in June and September (after leaving the estuary). The species differed in depth preference and distance offshore. Higher catches correlated positively with chlorophyll and copepod biomass in both species, and with temperature in Chinook salmon. Duffy et al. (2010) described Chinook salmon diet and habitat usage in Puget Sound. “At nearshore sites, insects (all months) and gammarid amphipods (July) were dominant prey sources, whereas in offshore diets decapods (primarily crab larvae; July) and fish (September) were most important.” They emphasized that the terrestrial sources of many of the prey items demonstrates an important link between waterfront landuse and salmon survival.

Based on trawl data, Morita et al. (2010a) found that larger and older adult sockeye, chum, and pink salmon inhabited cooler areas than smaller and younger salmon. Using this information, Morita et al. (2010b) developed a bioenergetic model explaining this pattern as a function of the optimal temperature for growth decreasing with body size, which was validated with a laboratory experiment. They concluded that the negative effects of climate warming on growth will be more severe for larger fish. Radchenko et al. (2010) described the results from surveys in the eastern Pacific, documenting the location of salmon and many other ecosystem components in 2009.

Using a combined bioenergetic-ecosystem model, Kishi et al. (2010) explained trends of declining body size in chum from 1970 to 2000 in terms of reduced densities of zooplankton and rising sea surface temperatures. They then characterized suitable potential ocean habitat for Hokkaido chum as 8-12°C in the summer and 4-6°C in the winter, based on survival studies and relationships between CPUE and SST. Using global circulation models to simulate global warming conditions, they predicted future distribution shifts: loss of habitat in the eastern North Pacific (Gulf of Alaska), and a northward shift in the Arctic Ocean. Furthermore, they predicted a lower carrying capacity in several areas. Finally, they predicted the current migration route to the Sea of Okhotsk will become unsuitable by 2050. Somewhat along similar lines, Genner et al. (2010) analyzed trends in size and abundance in the English Channel from 1911 to 2007, and found that smaller-sized fish fluctuated in abundance with temperature, showing quick responses to environmental change. Larger-sized fish, however, showed persistent

declines in the larger size classes and overall abundance, perhaps due to size-selective overharvesting.

9.3 Biological Implications of ocean acidification

Literature on how ocean acidification (OA) will affect marine species and communities is exploding, making a complete review beyond of the scope of this report. A recent meta-analysis of the impacts of OA on marine species indicated that there is significant variation in how sensitive marine species are to OA, and, if sensitive, what aspect of organismal biology changes in the face of low pH (Kroeker et al. 2010). However, in general, when all taxa are pooled, OA had negative impacts on survival, calcification, growth and reproduction (Kroeker et al. 2010). Here, we focused on laboratory experiments that explored the sensitivity of fish and salmon prey to OA.

Given the paucity of research, it is impossible to conclude whether the direct and indirect impacts of OA on salmon prey, as a whole, will be positive, negative, or neutral. Development timing of amphipods increased in response to low pH conditions, which may negatively impact population dynamics of this important food source (Egilsdottir et al. 2009; Hauton et al. 2009). Pteropod calcification rate declined with ocean pH, although pteropods can calcify below an aragonite saturation state of 1 (Comeau et al. 2010a; Comeau et al. 2009a; Comeau et al. 2009b; Comeau et al. 2010b). Pteropods in the laboratory survived without shells (Comeau et al. 2010a), though their ability to do this in the field is unknown. How OA affects pteropod population dynamics is also unknown, but energetic challenges (e.g., respiration rates) increase (Comeau et al. 2010b). A study on Antarctic krill indicated that OA is unlikely to affect the progression of early development until CO₂ levels exceed 1000ppm (effect observed at 2000ppm; Kawaguchi et al. 2011). Surface oceans may reach this level by 2100, though deep, cold water may exceed it sooner. The impact of OA on copepods varied with species and life stage, but includes evidence for increased nauplius mortality and decreased egg hatching rate (Kurihara and Ishimatsu 2008; Kurihara et al. 2004a; Kurihara et al. 2004b; Mayor et al. 2007; Pascal et al. 2010). In addition, high CO₂ levels countered some toxic effects of cadmium and copper ions on benthic copepods (Pascal et al. 2010). However, mercury and silver accumulation in *Loligo* squid paralarvae increased with CO₂ levels, which has implications for transfer of metals through food webs (Lacoue-Labarthe et al. 2011).

The role of gelatinous zooplankton in North Pacific ecosystems is steadily increasing. Analysis of time series data from the North Sea showed a negative correlation between gelatinous zooplankton and pH (Attrill and Edwards 2008; Richardson et al. 2009; Richardson and Gibbons 2008), although asexual reproduction and polyp survival in *Aurelia labiata* were not affected by OA in the laboratory (Winans and Purcell 2010).

The direct impacts of OA on salmonids are uncertain, especially because the species group spends its early life stages in fresh, not marine, waters. In the last BiOp, we reported no effect of pH 7.0 on *Salmo salar* mortality, growth, condition, metabolism, or plasma pH, hematocrit, sodium, or chloride (Fivelstad et al. 1998) and impairment of olfactory abilities in tropical clownfish (Dixson et al. 2010; Munday et al. 2009b). Recent research provides more insight on how fishes may respond (or not) to OA: 1) increased otolith size in some but not all species (Checkley Jr. et al. 2009; Franke and Clemmesen

2011; Munday et al. 2011a; Munday et al. 2011b), 2) erosion of auditory based behavior and induction of behavior linked with higher mortality due to predation in a tropical clownfish (Munday et al. 2010; Simpson et al. 2011), 3) decrease in aerobic scope in two tropical coral reef fishes (Munday et al. 2009a), 4) upregulation of some proteins in stickleback and cod and RNA expression in Atlantic herring (Franke and Clemmesen 2011), 5) no impact on early development (survival, growth, skeletal development) in a tropical damselfish and Atlantic herring (Franke and Clemmesen 2011; Munday et al. 2011a).

Two recent modeling papers explored the ecological impacts of OA and other aspects of climate change. Ainsworth et al. (2011) predicted that ocean acidification may cause salmon landings to decrease in Southeast Alaska and Prince Williams Sound food webs and increase in Northern British Columbia and Northern California Current food webs. However, when the authors applied five impacts of global change to these food webs simultaneously (primary productivity, species range shifts, zooplankton community size structure, ocean acidification, and ocean deoxygenation), projected salmon landings decreased in all locales (Ainsworth et al. 2011). Incorporating ocean acidification and ocean deoxygenation into bioclimatic envelop models for harvested fishes in the Northeast Atlantic caused 20-30% declines in projected future harvest, likely due to reduced growth performance and faster range shifts (Cheung et al. 2011). This study is informative to Pacific salmon management as it indicates how changes in physiological performance of finfishes due to ocean acidification may impact harvested populations.

9.4 Ocean ecosystem effects

9.4.1 Evidence of changes in Arctic marine ecosystems

Of the global reviews of documented changes in biota that appear to be responses to climate change, very few have focused on marine ecosystems. Thus the review of the “footprint” of climate change in Arctic marine biota by Wassmann et al. (2010) fills a very important hole. Wassmann reviewed 13 studies of benthos, 9 studies of fish (5 on cod, 2 on pollock, 1 each for turbot and pipefish), 7 studies of birds (5 species), 9 studies of polar bears, 2 seals and 1 whale. Responses ranged from behavioral to growth to range shifts and community reorganization (Greenland cod and shrimp). Most observations are consistent with predictions from climate change simulations: increased primary productivity, declines in endemic, ice-associated species, and invasions or increases in more temperate zone species. One study documenting a change in primary producers was Kahru et al. (2010), who showed that the annual phytoplankton bloom maximum has advanced by up to 50 days in certain areas of the Arctic, with significant trends in 11% of the Arctic Ocean, primarily reflecting the reduction in sea ice. Bloom timing has also advance in the North Pacific.

9.4.2 Ecosystem models

Several very complex models explored the ocean ecosystem dynamics of climate forcing and climate change. Popova et al. (2010) focused on the Arctic Ocean under current conditions, and found that two key processes drove variability in primary

production: the extent of winter mixing and short-wave radiation at the ocean surface, which controls phytoplankton blooms.

Two studies analyzed climate change simulations. Rykaczewski and Dunne (2010) used NOAA's Geophysical Fluid Dynamics Laboratory earth system model to study changes in nutrient supply and productivity of the California Current Ecosystem. They focused on nitrate because it is the main nutrient limiting primary production in the CCE. The model predicted a 2°C rise in ocean temperatures across the basin from 1860 to 2100 under the SRES A2 scenario. They found weaker wind-stress curl, which reduced the strength of upwelling (and downwelling, in the subtropical gyre), but other changes produced a modest increase in upwelling. They note, however, that global models might not have sufficient resolution to fully represent upwelling dynamics. Despite increased stratification, they predicted an 80% increase in nitrate concentration by 2100 in the upper 200m of the CCE, but decreases elsewhere in the Pacific. The increased nitrate concentration in the CCE comes mainly from longer transit times of deep water that are subsequently upwelled. This water is also more depleted in oxygen (18%) and more acidic (0.5 pH units). This produced a net increase in productivity of 10% in the CCE presumably benefitting surface feeding fish, but more frequent hypoxic events threatening benthic and mid-water fauna.

Steinacher et al. (2010) compared four coupled global carbon cycle-climate models that incorporated marine biogeochemical-ecosystem models. All four models predicted a decreasing trend in global net primary production and particulate organic carbon export. The models all predicted increasing temperature and stratification in all regions and increasing light in the Arctic where sea ice retreats. The high-latitude ocean retained sufficient nutrients to increase primary production and particulate organic carbon export (with increases in the Bering Sea). Nonetheless, they still projected declines in biomass throughout the north Pacific. They discussed differences among the models compared in quantitative predictions. Despite broad agreement on a regional scale, none of the models appear to do exceptionally well at modeling the coastal Pacific Northwest and Alaska (hence the upwelling-specific analyses described previously). Brown et al. (2010a) also predicted increases in primary productivity around Australia, benefitting fisheries and threatened turtles and sharks. They cautioned that the ecological benefit is sensitive to species interactions, which could reverse the benefit for some species.

Several studies in the San Francisco Bay estuary described complex physical and biological processes. MacNally et al. (2010) analyzed the factors affecting the decline of four pelagic fish in the San Francisco estuary. A combination of physical and food web driven factors suggested a diverse array of factors are responsible, but changes in freshwater flow and water clarity had strong effects. The results suggested a relatively good understanding of the ecosystem, but few management options. Cloern et al. (2010) described strong effects of the PDO and the NPGO on demersal fish, crabs and shrimp in San Francisco Bay. They emphasized the interconnectedness of the estuary in linking oceanography and watershed hydrology.

9.4.3 Seabirds, rockfish, and sharks

Several studies explored potential impacts of climate on seabird populations. Wolf et al. (2010) predicted 11-45% declines in Cassin's auklet in response to climate change. Ainley and Hyrenbach (2010) explored bottom-up and top-down drivers of a

large number of seabird species in the California Current. Black et al. (2010) analyzed ocean drivers of seabird and rockfish dynamics, emphasizing the importance of February ocean conditions.

Williams et al. (2010) documented very large aggregations of 20,000 sharks in the western Queen Charlotte Sound, British Columbia in a 2004-2006 study. Although it is not absolutely certain that this is a new phenomenon, it has not been documented until recently, and they suggested that the aggregations might be a response to rising sea temperatures. The sharks might present a “feeding gauntlet” deadly for Fraser River salmon, that typically prefer the northern migration route through Queen Charlotte Sound during warm years.

In addition to sharks, other marine fish are likely to shift their distribution in response to rising ocean temperatures. In Australia, coral reef fishes usually limited by winter temperature are predicted to survive as far south as Sydney by 2080 (Figueira and Booth 2010).

9.5 Effects on fisheries

Cheung et al. (2010) combined models that predicted increases in primary productivity with bioclimatic envelop models of species distribution to predicted the impact of climate change on fisheries catch for 1066 species of fish and invertebrates (assuming the geographic location of the fishery doesn't change). They predicted a 30–70% increase in high-latitude catches, including Alaska, a decline of about 10% in the contiguous US, and a drop of up to 40% in the tropics. MacNeil et al. (2010) similarly concluded that Arctic fisheries will benefit from invasions of southern species and increased primary productivity, while there will be species turnover in the temperate zone and significant losses in the tropics.

9.6 Review of hypotheses/frameworks for ocean climate forcing fish populations

Two papers present overviews of the prevailing physical and ecological hypotheses or conceptual frameworks currently in the literature on climate-ocean interactions. Ottersen et al. (2010) focused on three major oceanographic phenomena that drive variability in fish recruitment: temperature, mixing, and advection. They discussed the debate on bottom-up versus top-down population regulation, and trophic cascades, and the key role of forage fish as having both effects. They described immediate and delayed effects of climate, and factors that differentiate local climate drivers from large-scale climate processes such as the NAO and the PDO. They discussed direct, indirect, integrated (i.e., processes that occur over longer time scales than a particular extreme climate event) and translation (i.e., organism movement) effects of climate drivers. Any of these responses might be linear or nonlinear, at the individual or community level. They then detailed specific geographic regions and their particular climate-ecological dynamics. In the Northeast Pacific they emphasized ENSO and the PDO and biological responses. They finally discussed teleconnections and regional differences between the Atlantic and the Pacific.

Bakun (2010) reviews a number of different concepts of population regulation, such as the match-mismatch hypothesis, issues with schooling fish, and the predation

risk-nutrient level trade-off (which he calls “loopholes”). Bakun emphasized three major physical processes that provided favorable conditions for fish: nutrient enrichment through upwelling or mixing, concentration through convergence or front formation, for example, and retention processes, such as eddies. Overall this paper emphasized that oceans are complex adaptive systems, and cautioned against assuming simpler concepts from the terrestrial literature adequately capture their complexity.

10 Impact of temperature and flow on adult migrants

10.1 Migration bioenergetic cost

Upstream migrating salmon face several additional stresses due to climate change. Most importantly, rising temperatures increases the metabolic cost of swimming and holding prior to spawning. Cumulative energetic costs or acute thermal stress also increase prespawn mortality. Several papers studied the bioenergetics of migration, which are relevant for calculating these costs. Clark et al. (2010) developed a biologging tag technique for measuring energy expenditure and heart rate in actively migrating sockeye. Cook and Coughlin (2010) found that rainbow trout alter their kinematics around obstructions in the water in a way that improves their efficiency. Forgan and Forster (2010) explored the physiology of oxygen consumption in different tissues. Nadeau et al. (2010) analyzed the relative costs of swimming in the lab against low and high flows that span much of the range typical for Fraser River sockeye. They found that higher flows elevated stress, but not mortality. However, overall females had higher mortality than males. Roscoe et al. (2010) studied the behavior of natural migrants through a lake with cooler bottom water. They found that more mature females with lower energy content preferred the cooler water, while other females and males showed less preference. They posited that use of the thermal refuge slowed maturation and helped maintain energy reserves.

10.2 Migration survival and timing

Migrating upstream is an energetic and thermal bottleneck for many salmon populations. New papers clarified the role of temperature in stimulating upstream migration in a very warm river (the Klamath), and the relationship between timing, temperature, flow, and survival in the cooler Fraser River. Projections in the Fraser River of the consequences of warming over the next century are especially dire.

In the Klamath River, Strange et al. (2010) found that Chinook volitionally migrated through much warmer water than previously thought. Chinook initiated migration at 21.8-24°C. These high river temperatures produced a mean average body temperature of 21.9°C, and mean average maximum body temperature of 23.1°C over the first week of the migration. These temperatures usually cause migration blockages in the Columbia River, but apparently reflect adaptation to the much warmer conditions in the Klamath. Declining temperatures triggered migration, even when the river was still very hot. It is not known whether these fish experienced high prespawn mortality or reduced fecundity or fertility. In the Fraser River, several new papers showed a positive correlation between river temperature and mortality. MacDonald et al. (2010) developed a forecasting model for fisheries managers to facilitate real time predictions of migration

survival for various groups of populations. They found that temperature, flow, the timing of entry relative to the average for that population, and fish abundance were good predictors of migration survival. Interestingly, the best predictors did not necessarily match the *a priori* prediction based on the absolute environmental conditions. For example, temperature was an important predictor for Early Stuart sockeye, even though these fish encounter relatively lower temperatures than other fish. The authors point out that these fish still encounter high temperatures upstream, and that they might have lower thermal tolerances than other populations.

Several papers simulating future conditions in the Fraser River predicted significant declines in sockeye salmon. Hague et al. (2011) found that a 1.0 °C increase in average summer water temperature tripled the number of days per year exceeding critical salmonid thermal thresholds (i.e. 19.0 °C). Martins et al. (2011) found evidence of thermal stress-induced mortality during the migration in three of the four stock-aggregates examined. Under warming scenarios, migration survival in these stocks was projected to decline 9-16%.

Particular attention has focused on the unusual behavior among some Fraser River sockeye populations of migrating much earlier than the historical norm. The early migrants experience much higher temperatures than normally-timed fish, and have significantly lower survival. Mathes et al. (2010) found that early migrants that utilized cool lake habitat as a thermal refuge during their migration had much higher survival than fish that took the river corridor directly to spawning grounds. The early-entry river migrants accumulated extraordinarily high cumulative temperatures and none survived. The early-entry lake migrants had similar cumulative thermal exposure to normally-timed fish that stayed in the river, and similar survival. Donaldson et al. (2010) compared physiological responses to stress (gillnet capture), migration rate and survival in Adams-Shuswap and Chilko populations. The unusually early migrants of the former migrate at the same time as the normal-timed migrants of the latter population. They found delayed effects (near spawning grounds) on survival that differed between the populations. Although the two groups had similar physiological condition when they entered the river, survival among the early-entry Adams-Shuswap group correlated with migration rate (slower migrants had lower survival) and physiological condition (metabolic and osmoregulatory impairment), but not among the Chilko fish.

In the Columbia River, Jepson et al. (2010) studied the migration timing of fall Chinook. They found clear differentiation between the Upper Columbia River and Hanford Reach populations, but Deschutes, Yakima, and Snake River populations migrated throughout the season. They also found harvest was concentrated in late August and early September, and preferentially selected larger fish.

10.2.1 Traditional tribal knowledge and effects of climate change on migration survival and timing

Jacob et al. (2010) described the effects of changes in the salmon runs on native people, and the very serious long-term implications of climate change for both people and fish. Through interviews, they identified changes in salmon abundance (diminished), timing (later in summer and fall), and condition (much less healthy, both in fat content

and disease prevalence) from people's recollections of traditional conditions. They discussed potential adaptations, but predicted relatively poor prospects for both people and fish.

11 Impact of high temperatures on prespawn mortality and spawning behavior

11.1 Diseases

The prevalence and virulence of many diseases in fish are much more severe under warmer conditions, and several papers reported disease spread over recent years. Marcos-Lopez et al. (2010) reviewed the increasing risk from a number of diseases (e.g. enteric red mouth, furunculosis, proliferative kidney disease and white spot) due to climate change. The risk from some exotic pathogens that prefer cool water declines (e.g., viral haemorrhagic septicaemia (VHSV), infectious haematopoietic necrosis virus (IHNV) and spring viraemia of carp virus (SVCV), while the risk from warm-loving exotic pathogens (epizootic haematopoietic necrosis and epizootic ulcerative syndrome) increases. They recommended revising management actions to control disease to take into account changing risk levels due to climate change.

Braden et al. (2010) reported spread of proliferative kidney disease (PKD) in natural populations of pink salmon in Quinsam river, Vancouver Island. Bradford et al. (2010) reported widespread prevalence (70% of samples) of the myxozoan parasite *Parvicapsula minibicornis* throughout the Fraser River watershed, and a very advanced stage of infection in most fish on spawning grounds. Ray et al. (2010) quantified levels of *Ceratomyxa shasta* that kill juvenile Chinook salmon in the Klamath River, improving our understanding of this disease. Tonteri et al. (2010) found selection on immune related genes more common than selection on non-immune-related genes in Atlantic salmon, and that allele frequencies were related to temperature and latitude, suggesting an important role of climate in driving this selection pressure.

Although not directly related to climate change, Koel et al. (2010) reported that Great Blue herons are viable vectors of whirling disease, which affects salmonids in 25 states. Krkosek (2010) warned that sea lice are an increasing threat from farmed salmon in the Pacific, and that the abiotic and biotic factors affecting this disease are not well studied. Pulkkinen et al. (2010) found that fish farms actually select for more virulent strains of *Flavobacterium columnare*, a disease exacerbated by warmer temperatures.

11.2 Prespawn behavior and mortality

Keefer et al. (2010) documented a strong correlation between prespawn mortality in Willamette River Chinook and water temperature and fish condition. Mortality ranged from 0-90%, depending on year and release group. Fish in poor or fair condition had twice the mortality risk of fish in good condition. These fish were transported above a

dam, and thus do not represent a natural migration. Nonetheless, they do reflect a dramatic increase in risk due to high temperatures.

Young et al. (2010) found that over summer, brown trout adults in New Zealand tended to hold in deep pools, and only moved during higher flow events and cooler temperatures (below 19°C). A severe flood killed 60-70% of the tagged population.

11.2.1 A correlation between gene flow and the NAO

Valiente et al. (2010) addressed the population genetic consequences of increased male parr maturation in response to climate change. In addition to describing effects on maturation, they discovered a strong pattern in straying. Specifically, they found a strong correlation between the North Atlantic Oscillation Index and immigration from a neighboring stream. I believe that this is the first study system to document this phenomenon, and hence is especially interesting. They found that straying increased linearly when conditions in the natal stream deteriorated (became too warm). This paper is also especially notable in referring specifically to adverse conditions induced by global warming at the southern edge of a species range.

11.3 Spawning behavior

The timing of reproduction is often crucial in determining successful population growth. How climate change will affect spawn timing raises concern because of high risks of prespawn mortality with lengthening freshwater residence, extreme sensitivity of eggs to high temperature (compared to other life stages), and the potential for a mismatch between emergence suitable environmental conditions for fry. Two studies documented long-term shifts in spawn timing in freshwater fish. Wedekind and Kung (2010) showed that European grayling have advanced their spawn timing by more than 3 weeks since 1948, which they attributed to rising temperature. However, a difference between spring and summer warming rates exposed fry to inappropriate temperatures, possibly contributing to population decline. Schneider et al. (2010) showed that walleye are now spawning up to 2 weeks earlier throughout Minnesota (26 populations), with a 0.5-1 day advance for every 1 day advance in ice break up.

Several studies explored the stimulus for spawning. Wilkinson et al. (2010) experimentally manipulated temperature and photoperiod for rainbow trout, and found that under natural photoperiods, elevated winter-spring temperatures only slightly increased maturation rates. Under advanced photoperiod, temperature had a much larger relative effect, but the overall maturation rate was much lower. O'Malley et al. (2010) studied the genetic basis of variation in spawn timing. They compared geographical variation in a gene (*OtsClock1b*) associated with photoperiod among 53 populations of chum, coho and pink salmon. Combined with a previous study of Chinook salmon, they found that daylength at spawn timing explained much of the variation in allele frequencies of *OtsClock1b* in chum and Chinook, but not coho and pink salmon.

In addition to affecting juvenile survival and migration success, temperature and flow affect access to and quality of spawning sites. Taylor et al. (2010) documented the distribution of redds over 12 years in a Nova Scotia stream in relation to the timing and intensity of fall rains and beaver dams. They found that stream usage by salmon was

linearly related to precipitation, except when blocked by beaver dams. Moir and Pasternack (2010) described a strong positive relationship between substrate coarseness and faster flow in Chinook salmon spawning site selection, demonstrating interactions between habitat characteristics that are not always included in habitat suitability analysis.

12 Direct heat stress

Several papers studied direct heat stress, population variation in heat tolerance, and its genetic basis. Bellgraph et al. (2010) found that juvenile Chinook salmon survived temperatures up to 23.2°C. The fish increased swimming behavior and heart rate under higher temperatures. Brook char reduced swimming performance at temperatures over 15°C, especially in combination with ammonia (Tudorache et al. 2010). Feldhaus et al. (2010) found that redband trout amplify production of heat shock proteins (hsp70) between 19 and 22°C, indicating thermal stress. Healy et al. (2010) studied the genetic basis of variation in the heat shock response in killifish, and found a fairly complicated pattern. They concluded that variation among subspecies must be due to more than simple upregulation of a particular regulator, but involves evolution in a variety of genes. In a comprehensive review, Pankhurst and King (2010) explained the physiological processes mediating the negative effects of high temperature on reproduction.

Sublethal temperature effects interact with other stressors. Boyd et al. (2010) found higher mortality after catch-and-release under elevated temperatures in the evening in rainbow trout. A very large fish kill (25,000 carp) occurred in the St. Lawrence River in 2001, which Ouellet et al. (2010) attributed to a combination of high air temperature and low flow, which depleted oxygen in the lake. They also discussed indirect effects of long-term stress, such as immunosuppression.

Pörtner (2010) reviewed the concept of oxygen supply to the tissues being the fundamental process that determines thermal windows, and as a means for understanding the synergistic effects of multiple stressors. Ocean hypercapnia and acidification interact with warming temperature to further reduce oxygen availability. On the other hand, exposure to high CO₂ also depresses metabolic rates, which might help tolerate reduced availability of oxygen. This fundamental process is general, and hence not species-specific. Seebacher et al. (2010) made an analogous argument that the fundamental limiting factor is cellular damage from the production of reactive oxygen byproducts of metabolism.

13 Higher-level processes

13.1 Population-dynamics modeling

Key to understanding the factors regulating salmon populations (which is essential for predicting effects of climate change) is an appreciation of how different scales of variability interact with the internal periods of variation inherent in populations with overlapping generations. Worden et al. (2010) studied the frequencies of population variability as a function of 1) environmentally-induced variation in survival in the first

ocean year only, 2) environmentally-induced variation in survival in all ocean years, and 3) environmentally-induced variation in the age at reproduction. They considered these effects within the larger context of increased variability due to fishing mortality, and different censusing techniques. They found different patterns of fluctuations in all the different scenarios explored. Salmon are more sensitive to some time scales of environmental variability than others, and with fishing they are doubly sensitive to low frequency environmental variability. Long-term changes in climate could thus interact with additional fishing-induced variability to induce fluctuations that pose much greater risks of population collapse than that induced by reduced abundance alone.

Two papers focused on the mathematical properties of population decline to extinction when environmental factors are driving the decline, and provide tools for identifying this trajectory. Drake and Griffen (2010) identified an early warning signal that anticipates a tipping point, beyond which extinction is almost inevitable. The early warning signal is a “critical slowing down”. They demonstrated the statistical properties of this signal using an experimental *Daphnia* population. A reliable baseline prior to environmental degradation is crucial for successful application of this technique. Ovaskainen and Meerson (2010) reviewed recent advances in theoretical physics that characterized the properties of stochasticity useful for determining mean extinction times under various conditions.

Animals often compensate for environmental variability through phenotypic plasticity, i.e., modifying their behavior or physiology in response to environmental conditions. Reed et al. (2010b) focused on the adaptiveness of phenotypic plasticity. Specifically, they demonstrated that plasticity is only adaptive when there is a reliable cue that anticipates environmental conditions. When the cue becomes less reliable (which might result from different aspects of climate changing at different rates, for example), plasticity shifts from being adaptive to increasing population extinction risk. They emphasized that population models will need to explicitly incorporate plasticity to include this potential effect.

13.2 Population-level effects

13.2.1 Population declines attributed to climatic factors

Clews et al. (2010) studied how environmental variation correlated with population fluctuations of Atlantic salmon and brown trout in Wales from 1985 to 2004. Local catchment processes were not useful in explaining population decline, but broader scale climatic variables correlated strongly with population densities. They found that weather conditions in the previous summer explained most of the variation. Specifically, a principle component analysis showed that reductions in density were highest following hotter, sunnier, and drier conditions. Over the course of the study, summer stream temperatures were estimated to have increased by 0.5°C in headwaters and 0.6°C in larger tributaries, and in winter by 0.7°C and 1°C, respectively. This amount of warming could explain on the order of a 40% decline in density (or ~3-3.5 fewer salmon per 100m²), based on the principle component score (which also includes discharge). Winter warmed more than summer due in part to trends in the NAO, but was not strongly correlated with salmon abundance. The similarity in response between the anadromous salmon and

freshwater resident brown trout indicates that freshwater indices are either driving the declines in both species, or are correlated with ocean phenomena in salmon.

After a comprehensive physical and biological assessment, Wiseman et al. (2010) found that warm water temperature and sedimentation were the primary drivers of habitat decline in the Touchet River in Washington, contributing to contraction of spring Chinook, summer steelhead, and bull trout.

Robinson et al. (2010) reported that stressful summer temperatures (determined by cumulative degree days over 20°C measured at the bottom of an Adirondack lake) reduced stomach fullness, reproductive activity, and survival of brook trout over one year old, and especially fish over two years old. Like Crozier et al. (2010), they found a positive correlation between temperature and growth at low fish density, and a negative correlation at high fish density.

13.2.2 Expert judgment of overall risks to Fraser River sockeye

A synthetic, expert-opinion analysis of the threat of climate change over the entire life cycle of Fraser River sockeye salmon (McDaniels et al. 2010) found that the cumulative threats are very high. A substantial proportion of responses indicated the fish were highly vulnerable (the highest threat level) at all life stages except the overwintering fry stage. They identified the most vulnerable life stages to be the egg and returning adult stage for populations throughout the Fraser River drainage, especially under a +4°C warming scenario. They also considered the prospect of reducing the threat through management quite limited.

13.2.3 Paleological perspective

Finney et al. (2010) conducted a major review of the paleological literature on fluctuations in fish abundance (including salmon) over thousands of years. The most relevant topics focused on positive correlations between SST and salmon abundance in Alaska both recently and over most of the past 300 years and again over 2500 years based on sedimentary collection of marine-derived nitrogen carried into freshwater by anadromous salmon. Anomalies in the SST-salmon correlation occurred in several sections of the long-term record, which the authors attributed to changes in ocean-atmosphere circulation during these periods, producing alternate patterns of North Pacific climate variability relative to the PDO and variation in the Aleutian Low. The longer time series showed a bimodal pattern of fluctuations between low and high abundance, with high abundance during the 1250-1890 AD cooler period of the Little Ice Age. This suggests different longer term patterns than suggested from recent data. They also discussed patterns driving anchovy, sardines, and other major ecosystem players throughout the world, and synchronous shifts in all ecosystems. However, specific relationships varied across the time series between in-phase and out-of-phase correlations, indicating alternative modes of climatic forcing of ecosystem dynamics.

13.3 Trends in phenology worldwide

Worth noting here is that phenological responses to climate change have been observed across all taxa, worldwide. A new review out in 2010 (Thackeray et al. 2010) assessed 25,532 rates of phenological change for 726 UK terrestrial, freshwater, and marine taxa. Most taxa showed earlier spring phenomena at rates higher than previously reported. They separated out taxa at different trophic levels, and found that secondary consumers were responding the slowest, and hence were at most risk of a mismatch in timing between predator and prey. Because this trend was so widespread and not restricted to individual species, it highlights a growing risk of the disruption of ecosystem function and services.

14 Habitat

14.1 Stream flow habitat models

Quite a few papers used models of stream flow (or temperature, covered in the next section) to quantify habitat availability for salmonids. Hilker and Lewis (2010) developed a theoretical model of how water velocity affects potential prey populations subject to advection and diffusion downstream, and the minimum flow requirements for drift-feeders like juvenile salmon. Cover et al. (2010) examined the impact of debris flows and debris floods on headwater stream communities. They found that debris flows raised stream temperature, reduced large wood and benthic communities and most vertebrates, with the exception of rainbow trout, which were abundant in recent debris-flooded areas. Escobar-Arias and Pasternack (2010) developed a functional flows model based on shear stress dynamics to characterize fall Chinook spawning habitat; the model could be parameterized for other species. High flow events provided access to new habitat, which can have both positive and negative impacts on salmon. Access to a floodplain that contains pollutants could be detrimental for juvenile salmon. Henery et al. (2010) showed that growth was higher in free swimming Chinook that utilized the Yolo Bypass floodplain than fish that stayed in the Sacramento River, but that the fish in the floodplain accumulated 3.2% more methylmercury per day than fish in the river.

A large group of scientists worked on a new framework for assessing environmental flow needs for many streams and rivers simultaneously to foster development and implementation of environmental flow standards at the regional scale (Poff et al. 2010), and this can be a basis for initiating an adaptive management program.

14.2 Thermally-suitable habitat models and trends

Enhancing riparian vegetation is a major conservation tool recommended for reducing maximum stream temperatures. Two studies showed strong empirical effects of vegetation on stream temperature. In response to high temperature-induced disease-related fish kills, Roth et al. (2010) developed a physical model of stream temperature in Switzerland. They found that existing vegetation (mostly in-stream reeds) lowered the expected temperature by 0.7°C, but a further decrease of 1.2°C could be achieved by a mature riparian forest. Brown et al. (2010b) found that coniferous forest plantations

lowered summer temperatures in a comparison of 3 forested and 3 moorland sites in northern England.

Statistical models of stream temperature have been used to quantify habitat area that meets particular criteria for species of interest, and to track trends in habitat area over time. Larnier et al. (2010) developed and compared models to identify conditions in the Garonne River in France that are thermally stressful for salmonid migration and survival. Isaak et al. (2010) developed a spatial autocorrelation model to predicted stream temperature throughout the 2500 km² upper Boise River Basin in Idaho based on temperatures measured at particular sites. The model performed well against observed temperatures. Historical analysis showed a trend of mean basin stream temperature from 1993 to 2006 rising at a rate of 0.27°C/decade, and maximum temperatures rose by 0.34°C/decade. They detected a strong thermal signature of wildfires in the basin: stream temperatures in affected reaches rose 2-3 times more than the basin average due largely to increases in radiation. Rising temperatures shifted rainbow trout habitat to slightly higher elevations but caused 11-20% loss of bull trout habitat.

High temperature already threatens some populations in warmer climates. Null et al. (2010) explored restoration alternatives to mitigate stressful temperatures in California's Shasta River. They found that a focused on restoring and protecting cool springs provided the most benefit for salmon (much greater benefit than increasing riparian shading, for example). This conclusion might apply to regions anticipating increasing temperature stress.

14.3 Habitat projections

Wiley et al. (2010) developed a series of models to explore the effects of land cover and climate change on fish habitat in the Great Lakes. They found very significant climate change impacts, and that these impacts were very sensitive to land management. Increasing forest cover and limiting urban development had very large impacts on projected flows, temperatures, and consequently modeled fish habitat. Nonetheless, even the best-case land use scenarios involved destabilization of 57%-76% of the channel system by the end of this century due to increasing rainfall and discharge rates. Summer temperatures rose sharply, with severe consequences for cold-water fish. They projected a loss of ~74% of adult Chinook habitat (but little impact on juvenile Chinook habitat), and the reverse for steelhead: a loss of ~50% of juvenile steelhead habitat, but only ~15% loss of adult habitat. They projected large benefits of climate change for smallmouth bass and walleye.

Several papers explored the potential for riparian vegetation to mitigate future warming. Cristea and Burges (2010) explored climate change impacts in the Wenatchee watershed, a tributary to the Columbia River. They found greater potential for mitigation in smaller tributaries (-1.5°C in Icicle Creek and -2.8°C in Nason Creek) compared with the mainstem Wenatchee River (-0.3°C), due to stream width. The cooling benefit of vegetation restoration will be surpassed by climate change by the 2020s in the mainstem, but postpone stressful temperatures for salmonids in the tributaries until the end of the century, which is a significant benefit.

A study in Scotland (Hrachowitz et al. 2010) produced a comparable result. In this case, however, the highest mean weekly temperatures currently occur in small exposed streams, and these streams are projected to reach extremely stressful

temperatures for salmonids in a + 4°C climate change scenario, which raised the catchment-wide mean stream temperature by 1.4°C. They suggested that vegetation restoration would ameliorate these stresses.

Hill et al. (2010) showed that certain pristine and environmentally heterogeneous areas in northern coastal British Columbia with salmon have high potential resilience, but relatively low productivity, and hence might not be sufficient to maintain a “salmon stronghold”.

14.4 Temperature-driven air pollution

Although mountain areas often support relatively pristine habitat, they are vulnerable to transport of pollutants generated long distances away. In particular, they are especially vulnerable to chemicals that are globally distributed by atmospheric deposition in a temperature-dependent way. Persistent organic pollutants, polycyclic aromatic hydrocarbons, and organochlorine compounds are concentrated in alpine streams because of the strong temperature gradients over short distances. Jarque et al. (2010) studied the response to organochlorine compounds in brown trout from the Pyrenees to Norway. They found biologically significant concentrations of pollutants in fish muscle correlated negatively with lake temperature, but biological activity might increase their negative consequences for fish with climate change

15 Policy/human social factors

Several papers addressed policy and management issues in adapting to climate change. All emphasized the need for more applied science and dialogue between researchers, managers, and the public. Some discussed specific climatic and biological information gaps and agreement, and the need for priority setting (Wilby et al. 2010), while others focused more on human social processes (Perry et al. 2010; Slaughter et al. 2010).

More specifically, Wilby et al. (2010) claim there is a lot of confusion about how best to proceed due to uncertainty in regional climate projections, biological responses, and environmental objectives. They emphasized that certain taxonomic groups are underrepresented in baseline data and impact studies, such as macrophytes, and that whole ecosystem responses need to be understood. Environmental objectives differ across managers, the public, conservation groups, etc., who further have different time frames of concern. They argued that even standard advice, such as increasing riparian shading to lower water temperatures and reducing abstraction from river flows, needs site-specific analysis and comparison with alternative actions before implementation. They argued that information gaps include site-specific information, underrepresented taxa, ecosystem goods and services, and risks and definitions of invasive species, given recommendations for increased connectedness. Overall they recommended more applied interdisciplinary research, adaptive management and cost-benefit analysis, in addition to reevaluation of goals and priorities.

Binder et al. (2010) summarized implications for adaptation based on the Washington State Climate Change Assessment. They summarized key ingredients in

successful adaptation planning, such as political leadership, money, stakeholder engagement, actionable science, triggering extreme climatic events that motivate action and a long-term perspective. To adapt to changing water resources, they recommended expanding and diversifying water supplies, reducing demand, implementing operational changes, increasing summer drought and winter flood preparedness. To protect salmon, they recommended reducing summer stream temperatures, increasing minimum stream flows, and reducing peak winter flows by various means. They warned that these actions will involve more tradeoffs between water for fish and people.

Perry et al. (2010) emphasized that marine ecosystems and human behaviors are interconnected and showed similar features such as variability at many time scales. They suggested that fisheries focused on opportunistic species (e.g., anchovy) provide a model of flexibility that should be adopted by fisheries focussed on traditionally more stable species (e.g., cod) to adapt to increasing variability due to climate change. They cautioned that spontaneous human responses to increasing ocean variability might further de-stabilize marine ecosystem (e.g., switching to un-fished species). They recommended proactive, flexible management and communication among a broad group of stakeholders to prepare for the diversity of stresses coming to marine ecosystems.

Slaughter et al. (2010) argued that the free market (and reduced subsidies) is a better way to address over-allocation of Pacific Northwest water resources than court or regulator mandates in some respects, although both will be necessary.

The Washington State Integrated Climate Change Response Strategy: Species, Habitats and Ecosystems (Brekke et al. 2010) outlines an integrated approach to climate adaptation strategies that applies to a very wide range of ecosystems and threats. They focused on three conceptual approaches – resistance, resilience and response to facilitate natural system responses, and then building scientific and institutional readiness to support adaptation.

In their book, *Climate Savvy*, Hansen and Hoffman (2010) considered how a wide range of resource conservation issues—such as managing invasive species, harvest management, or ecological restoration—will need to change in response to climate change. Climate responses of ecosystems or organisms can be one of three types: resistance (stays the same), resilience (recovers after a disturbance), and response (e.g., movement or change). Key adaptation strategies for managing ecosystems in a changing climate included (1) protect adequate and appropriate space, (2) reduce non-climate stressors, (3) manage for uncertainty, (4) reduce local and regional climate effects, and (5) reduce the rate and extent of global climate change.

16 Literature cited

- Ainley, D. G., and K. D. Hyrenbach. 2010. Top-down and bottom-up factors affecting seabird population trends in the California current system (1985-2006). *Progress in Oceanography* 84:242-254.
- Ainslie, B., and P. L. Jackson. 2010. Downscaling and Bias Correcting a Cold Season Precipitation Climatology over Coastal Southern British Columbia Using the Regional Atmospheric Modeling System (RAMS). *Journal of Applied Meteorology and Climatology* 49:937-953.
- Ainsworth, C. H., J. F. Samhuri, D. S. Busch, W. W. L. Chueng, J. Dunne, and T. A. Okey. 2011. Potential impacts of climate change on Northeast Pacific marine fisheries and food webs. *ICES Journal of Marine Science* 68:1217-1229.
- An, S. I., Y. G. Ham, J. S. Kug, A. Timmermann, J. Choi, and I. S. Kang. 2010. The Inverse Effect of Annual-Mean State and Annual-Cycle Changes on ENSO. *Journal of Climate* 23:1095-1110.
- Armstrong, J. B., D. E. Schindler, K. L. Omori, C. P. Ruff, and T. P. Quinn. 2010. Thermal heterogeneity mediates the effects of pulsed subsidies across a landscape. *Ecology* 91:1445-1454.
- Arthaud, D. L., C. M. Greene, K. Guilbault, and J. V. Morrow. 2010. Contrasting life-cycle impacts of stream flow on two Chinook salmon populations. *Hydrobiologia* 655:171-188.
- Attrill, M. J., and M. Edwards. 2008. Reply to Haddock, S. H. D. Reconsidering evidence for potential climate-related increases in jellyfish. *Limnology and Oceanography* 53:2763-2766.
- Bakun, A. 2010. Linking climate to population variability in marine ecosystems characterized by non-simple dynamics: Conceptual templates and schematic constructs. *Journal of Marine Systems* 79:361-373.
- Bakun, A., D. B. Field, A. Redondo-Rodriguez, and S. J. Weeks. 2010. Greenhouse gas, upwelling-favorable winds, and the future of coastal ocean upwelling ecosystems. *Global Change Biology* 16:1213-1228.
- Beakes, M. P., W. H. Satterthwaite, E. M. Collins, D. R. Swank, J. E. Merz, R. G. Titus, S. M. Sogard et al. 2010. Smolt Transformation in Two California Steelhead Populations: Effects of Temporal Variability in Growth. *Transactions of the American Fisheries Society* 139:1263-1275.
- Bellgraph, B. J., G. A. McMichael, R. P. Mueller, and J. L. Monroe. 2010. Behavioural response of juvenile Chinook salmon *Oncorhynchus tshawytscha* during a sudden temperature increase and implications for survival. *Journal of Thermal Biology* 35:6-10.
- Beveridge, O. S., O. L. Petchey, and S. Humphries. 2010. Direct and indirect effects of temperature on the population dynamics and ecosystem functioning of aquatic microbial ecosystems. *Journal of Animal Ecology*:no-no.
- Binder, L. C. W., J. K. Barcelos, D. B. Booth, M. Darzen, M. M. Elsner, R. Fenske, T. F. Graham et al. 2010. Preparing for climate change in Washington State. *Climatic Change* 102:351-376.

- Black, B. A., I. D. Schroeder, W. J. Sydeman, S. J. Bograd, and P. W. Lawson. 2010. Wintertime ocean conditions synchronize rockfish growth and seabird reproduction in the central California Current ecosystem. *Canadian Journal of Fisheries and Aquatic Sciences* 67:1149-1158.
- Blunden, J., D. S. Arndt, M. O. Baringer, and Eds. 2011. State of the Climate in 2010. *Bulletin of the American Meteorological Society* 92:S1-S266.
- Boyd, J. W., C. S. Guy, T. B. Horton, and S. A. Leathe. 2010. Effects of Catch-and-Release Angling on Salmonids at Elevated Water Temperatures. *North American Journal of Fisheries Management* 30:898-907.
- Braden, L. M., G. Prospero-Porta, E. Kim, and S. R. M. Jones. 2010. *Tetracapsuloides bryosalmonae* in spawning pink salmon, *Oncorhynchus gorbuscha* (Walbaum), in the Quinsam River, British Columbia, Canada. *Journal of Fish Diseases* 33:617-621.
- Bradford, M. J., J. Lovy, and D. A. Patterson. 2010. Infection of gill and kidney of Fraser River sockeye salmon, *Oncorhynchus nerka* (Walbaum), by *Parvicapsula minibicornis* and its effect on host physiology. *Journal of Fish Diseases* 33:769-779.
- Brekke, L., B. Kuepper, and S. Vaddey. 2010. Draft Report: Climate and Hydrology Datasets for use in the RMJOC Agencies' Longer-Term Planning Studies: Part I - Future Climate and Hydrology Datasets.
- Brown, C. J., E. A. Fulton, A. J. Hobday, R. J. Matear, H. P. Possingham, C. Bulman, V. Christensen et al. 2010a. Effects of climate-driven primary production change on marine food webs: implications for fisheries and conservation. *Global Change Biology* 16:1194-1212.
- Brown, L. E., L. Cooper, J. Holden, and S. J. Ramchunder. 2010b. A comparison of stream water temperature regimes from open and afforested moorland, Yorkshire Dales, northern England. *Hydrological Processes* 24:3206-3218.
- Bumbaco, K. A., and P. W. Mote. 2010. Three Recent Flavors of Drought in the Pacific Northwest. *Journal of Applied Meteorology and Climatology* 49:2058-2068.
- Carson, M., and D. E. Harrison. 2010. Regional interdecadal variability in bias-corrected ocean temperature data. *Journal of Climate* 23:2847-2855.
- Chang, H. J., and I. W. Jung. 2010. Spatial and temporal changes in runoff caused by climate change in a complex large river basin in Oregon. *Journal of Hydrology* 388:186-207.
- Chavarie, L., J. B. Dempson, C. J. Schwarz, J. D. Reist, G. Power, and M. Power. 2010. Latitudinal variation in growth among Arctic charr in eastern North America: evidence for countergradient variation? *Hydrobiologia* 650:161-177.
- Checkley Jr., D. M., A. G. Dickson, M. Takahashi, J. A. Radich, N. Eisenkolb, and R. Asch. 2009. Elevated CO₂ enhances otolith growth in young fish. *Science* 324:1683.
- Cheung, W. W. L., J. Dunne, J. L. Sarmiento, and D. Pauly. 2011. Integrating ecophysiology and plankton dynamics into projected maximum fisheries catch potential under climate change in the Northeast Atlantic. *ICES Journal of Marine Science: Journal du Conseil* 68:1008-1018.
- Cheung, W. W. L., V. W. Y. Lam, J. L. Sarmiento, K. Kearney, R. E. G. Watson, D. Zeller, and D. Pauly. 2010. Large-scale redistribution of maximum fisheries catch

- potential in the global ocean under climate change. *Global Change Biology* 16:24-35.
- Chittenden, C. M., J. L. A. Jensen, D. Ewart, S. Anderson, S. Balfry, E. Downey, A. Eaves et al. 2010. Recent salmon declines: A result of lost feeding opportunities due to bad timing? *Plos One* 5.
- Christensen, D. R., and B. C. Moore. 2010. Largemouth bass consumption demand on hatchery rainbow trout in two Washington lakes. *Lake and Reservoir Management* 26:200-211.
- Clark, T. D., E. Sandblom, S. G. Hinch, D. A. Patterson, P. B. Frappell, and A. P. Farrell. 2010. Simultaneous biologging of heart rate and acceleration, and their relationships with energy expenditure in free-swimming sockeye salmon (*Oncorhynchus nerka*). *Journal of Comparative Physiology B-Biochemical Systemic and Environmental Physiology* 180:673-684.
- Clews, E., I. Durance, I. P. Vaughan, and S. J. Ormerod. 2010. Juvenile salmonid populations in a temperate river system track synoptic trends in climate. *Global Change Biology* 16:3271-3283.
- Cloern, J. E., K. A. Hieb, T. Jacobson, B. Sanso, E. Di Lorenzo, M. T. Stacey, J. L. Largier et al. 2010. Biological communities in San Francisco Bay track large-scale climate forcing over the North Pacific. *Geophysical Research Letters* 37.
- Comeau, S., G. Gorsky, S. Alliouane, and J. P. Gattuso. 2010a. Larvae of the pteropod *Cavolina inflexa* exposed to aragonite undersaturation are viable but shell-less. *Marine Biology Letters* 157:2341-2345.
- Comeau, S., G. Gorsky, R. Jeffree, J.-L. Teyssié, and J. P. Gattuso. 2009a. Impact of ocean acidification on a key Arctic pelagic mollusc (*Limacina helicina*). *Biogeosciences* 6:1877-1882.
- . 2009b. Key Arctic pelagic mollusc (*Limacina helicina*) threatened by ocean acidification. *Biogeosciences Discuss* 6:2523-2537.
- Comeau, S., R. Jeffree, J.-L. Teyssié, and J.-P. Gattuso. 2010b. Response of the arctic pteropod *Limacina helicina* to projected future environmental conditions. *PLoS ONE* 5:e11362.
- Cook, C. L., and D. J. Coughlin. 2010. Rainbow trout *Oncorhynchus mykiss* consume less energy when swimming near obstructions. *Journal of Fish Biology* 77:1716-1723.
- Cover, M. R., J. A. de la Fuente, and V. H. Resh. 2010. Catastrophic disturbances in headwater streams: the long-term ecological effects of debris flows and debris floods in the Klamath Mountains, northern California. *Canadian Journal of Fisheries and Aquatic Sciences* 67:1596-1610.
- Cristea, N. C., and S. J. Burges. 2010. An assessment of the current and future thermal regimes of three streams located in the Wenatchee River basin, Washington State: some implications for regional river basin systems. *Climatic Change* 102:493-520.
- Crozier, L., R. W. Zabel, S. Achord, and E. E. Hockersmith. 2010. Interacting effects of density and temperature on body size in multiple populations of Chinook salmon. *Journal of Animal Ecology* 79:342-349.

- Davidson, R. S., B. H. Letcher, and K. H. Nislow. 2010. Drivers of growth variation in juvenile Atlantic salmon (*Salmo salar*): an elasticity analysis approach. *Journal of Animal Ecology* 79:1113-1121.
- Deser, C., A. Phillips, V. Bourdette, and H. Teng. 2010. Uncertainty in climate change projections: the role of internal variability. *Climate Dynamics* online 31 December 2010.
- Dixson, D. L., P. L. Munday, and G. P. Jones. 2010. Ocean acidification disrupts the innate ability of fish to detect predator olfactory cues. *Ecology Letters* 13:68-75.
- Donaldson, M. R., S. G. Hinch, D. A. Patterson, A. P. Farrell, J. M. Shrimpton, K. M. Miller-Saunders, D. Robichaud et al. 2010. Physiological Condition Differentially Affects the Behavior and Survival of Two Populations of Sockeye Salmon during Their Freshwater Spawning Migration. *Physiological and Biochemical Zoology* 83:446-458.
- Drake, J. M., and B. D. Griffen. 2010. Early warning signals of extinction in deteriorating environments. *Nature* advance online publication.
- Duffy, E. J., D. A. Beauchamp, R. M. Sweeting, R. J. Beamish, and J. S. Brennan. 2010. Ontogenetic Diet Shifts of Juvenile Chinook Salmon in Nearshore and Offshore Habitats of Puget Sound. *Transactions of the American Fisheries Society* 139:803-823.
- Eaton, B. C., R. D. Moore, and T. R. Giles. 2010. Forest fire, bank strength and channel instability: the 'unusual' response of Fishtrap Creek, British Columbia. *Earth Surface Processes and Landforms* 35:1167-1183.
- Egilsdottir, H., J. I. Spicer, and S. D. Rundle. 2009. The effect of CO₂ acidified sea water and reduced salinity of aspects of the embryonic development of the amphipods *Echinogammarus marinus* (Leach). *Marine Pollution Bulletin* 58:1187-1191.
- Elliott, J. M., and J. A. Elliott. 2010. Temperature requirements of Atlantic salmon *Salmo salar*, brown trout *Salmo trutta* and Arctic charr *Salvelinus alpinus*: predicting the effects of climate change. *Journal of Fish Biology* 77:1793-1817.
- Elsner, M. M., L. Cuo, N. Voisin, J. S. Deems, A. F. Hamlet, J. A. Vano, K. E. B. Mickelson et al. 2010. Implications of 21st century climate change for the hydrology of Washington State. *Climatic Change* 102:225-260.
- Escobar-Arias, M. I., and G. B. Pasternack. 2010. A hydrogeomorphic dynamics approach to assess in-stream ecological functionality using the function flows model Part 1--Model characteristics. *River Research and Applications* 26:1103-1128.
- Evans, M. L., B. D. Neff, and D. D. Heath. 2010. Quantitative genetic and translocation experiments reveal genotype-by-environment effects on juvenile life-history traits in two populations of Chinook salmon (*Oncorhynchus tshawytscha*). *Journal of Evolutionary Biology* 23:687-698.
- Feely, R. A., S. R. Alin, J. Newton, C. L. Sabine, M. Warner, A. Devol, C. Krembs et al. 2010. The combined effects of ocean acidification, mixing, and respiration on pH and carbonate saturation in an urbanized estuary. *Estuarine Coastal and Shelf Science* 88:442-449.
- Feldhaus, J. W., S. A. Heppell, H. Li, and M. G. Mesa. 2010. A physiological approach to quantifying thermal habitat quality for Redband Rainbow Trout (*Oncorhynchus*

- mykiss gairdneri) in the south Fork John Day River, Oregon. *Environmental Biology of Fishes* 87:277-290.
- Fergusson, E. A., M. V. Sturdevant, and J. A. Orsi. 2010. Effects of starvation on energy density of juvenile chum salmon (*Oncorhynchus keta*) captured in marine waters of Southeastern Alaska. *Fishery Bulletin* 108:218-225.
- Figueira, W. F., and D. J. Booth. 2010. Increasing ocean temperatures allow tropical fishes to survive overwinter in temperate waters. *Global Change Biology* 16:506-516.
- Finney, B. P., J. Alheit, K. C. Emeis, D. B. Field, D. Gutierrez, and U. Struck. 2010. Paleocological studies on variability in marine fish populations: A long-term perspective on the impacts of climatic change on marine ecosystems. *Journal of Marine Systems* 79:316-326.
- Finstad, A. G., O. K. Berg, T. Forseth, O. Ugedal, and T. F. Naesje. 2010. Adaptive winter survival strategies: defended energy levels in juvenile Atlantic salmon along a latitudinal gradient. *Proceedings of the Royal Society B-Biological Sciences* 277:1113-1120.
- Fivelstad, S., H. Haavik, G. Løvik, and A. B. Olsen. 1998. Sublethal effects and safe levels of carbon dioxide in seawater for Atlantic salmon postsmolts (*Salmo salar* L.): ion regulation and growth. *Aquaculture* 160:305-316.
- Forgan, L. G., and M. E. Forster. 2010. Oxygen-dependence of metabolic rate in the muscles of craniates. *Journal of Comparative Physiology B-Biochemical Systemic and Environmental Physiology* 180:715-729.
- Franke, A., and C. Clemmesen. 2011. Effect of ocean acidification on early life stages of Atlantic herring (*Clupea harengus* L.). *Biogeosciences Discuss* 8:7097-7126.
- Fu, G. B., M. E. Barber, and S. L. Chen. 2010. Hydro-climatic variability and trends in Washington State for the last 50 years. *Hydrological Processes* 24:866-878.
- Garcia-Reyes, M., and J. Largier. 2010. Observations of increased wind-driven coastal upwelling off central California. *Journal of Geophysical Research-Oceans* 115.
- Genner, M. J., D. W. Sims, A. J. Southward, G. C. Budd, P. Masterson, M. McHugh, P. Rendle et al. 2010. Body size-dependent responses of a marine fish assemblage to climate change and fishing over a century-long scale. *Global Change Biology* 16:517-527.
- Georga, I., and G. Koumoundouros. 2010. Thermally Induced Plasticity of Body Shape in Adult Zebrafish *Danio rerio* (Hamilton, 1822). *Journal of Morphology* 271:1319-1327.
- Grundstein, A., and T. L. Mote. 2010. Trends in average snow depth across the western United States. *Physical Geography* 31:172-185.
- Guthrie, R. H., S. J. Mitchell, N. Lanquaye-Opoku, and S. G. Evans. 2010. Extreme weather and landslide initiation in coastal British Columbia. *Quarterly Journal of Engineering Geology and Hydrogeology* 43:417-428.
- Hague, M. J., M. R. Ferrari, J. R. Miller, D. A. Patterson, G. L. Russell, A. P. Farrell, and S. G. Hinch. 2011. Modelling the future hydroclimatology of the lower Fraser River and its impacts on the spawning migration survival of sockeye salmon. *Global Change Biology* 17:87-98.
- Hansen, L. J., and J. R. Hoffman. 2010. *Climate Savvy: Adapting Conservation and Resource Management to a Changing World*. Washington DC, Island Press.

- Hauton, C., T. Tyrrell, and J. Williams. 2009. The subtle effects of sea water acidification on the amphipod *Gammarus locusta*. *Biogeosciences* 6:1479-1489.
- Hayes, J. W., D. A. Olsen, and J. Hay. 2010. The influence of natural variation in discharge on juvenile brown trout population dynamics in a nursery tributary of the Motueka River, New Zealand. *New Zealand Journal of Marine and Freshwater Research* 44:247-269.
- Healy, T. M., W. E. Tymchuk, E. J. Osborne, and P. M. Schulte. 2010. Heat shock response of killifish (*Fundulus heteroclitus*): candidate gene and heterologous microarray approaches. *Physiological Genomics* 41:171-184.
- Henery, R. E., T. R. Sommer, and C. R. Goldman. 2010. Growth and Methylmercury Accumulation in Juvenile Chinook Salmon in the Sacramento River and Its Floodplain, the Yolo Bypass. *Transactions of the American Fisheries Society* 139:550-563.
- Hilker, F. M., and M. A. Lewis. 2010. Predator-prey systems in streams and rivers. *Theoretical Ecology* 3:175-193.
- Hill, A. C., T. S. Bansak, B. K. Ellis, and J. A. Stanford. 2010. Merits and Limits of Ecosystem Protection for Conserving Wild Salmon in a Northern Coastal British Columbia River. *Ecology and Society* 15.
- Hrachowitz, M., C. Soulsby, C. Imholt, I. A. Malcolm, and D. Tetzlaff. 2010. Thermal regimes in a large upland salmon river: a simple model to identify the influence of landscape controls and climate change on maximum temperatures. *Hydrological Processes* 24:3374-3391.
- Isaak, D. J., C. H. Luce, B. E. Rieman, D. E. Nagel, E. E. Peterson, D. L. Horan, S. Parkes et al. 2010. Effects of climate change and wildfire on stream temperatures and salmonid thermal habitat in a mountain river network. *Ecological Applications* 20:1350-1371.
- Jacob, C., T. McDaniels, and S. Hinch. 2010. Indigenous culture and adaptation to climate change: sockeye salmon and the St'at'imc people. *Mitigation and Adaptation Strategies for Global Change* 15:859-876.
- Janhunen, M., J. Piironen, and N. Peuhkuri. 2010. Parental effects on embryonic viability and growth in Arctic charr *Salvelinus alpinus* at two incubation temperatures. *Journal of Fish Biology* 76:2558-2570.
- Jarque, S., E. Gallego, M. Bartrons, J. Catalan, J. O. Grimalt, and B. Pina. 2010. Altitudinal and thermal gradients of hepatic Cyp1A gene expression in natural populations of *Salmo trutta* from high mountain lakes and their correlation with organohalogen loads. *Environmental Pollution* 158:1392-1398.
- Jenkins, A. R., and E. R. Keeley. 2010. Bioenergetic assessment of habitat quality for stream-dwelling cutthroat trout (*Oncorhynchus clarkii bouvieri*) with implications for climate change and nutrient supplementation. *Canadian Journal of Fisheries and Aquatic Sciences* 67:371-385.
- Jepson, M. A., M. L. Keefer, G. P. Naughton, C. A. Peery, and B. J. Burke. 2010. Population Composition, Migration Timing, and Harvest of Columbia River Chinook Salmon in Late Summer and Fall. *North American Journal of Fisheries Management* 30:72-88.
- Johnson, J. R., J. Baumsteiger, J. Zydlewski, J. M. Hudson, and W. Ardren. 2010. Evidence of Panmixia between Sympatric Life History Forms of Coastal

- Cutthroat Trout in Two Lower Columbia River Tributaries. *North American Journal of Fisheries Management* 30:691-701.
- Johnstone, J. A., and T. E. Dawson. 2010. Climatic context and ecological implications of summer fog decline in the coast redwood region. *Proceedings of the National Academy of Sciences of the United States of America* 107:4533-4538.
- Jones, I. D., T. Page, J. Alex Elliott, S. J. Thackeray, and A. Louise Heathwaite. 2010. Increases in lake phytoplankton biomass caused by future climate-driven changes to seasonal river flow. *Global Change Biology*:no-no.
- Jones, J. A., and R. M. Perkins. 2010. Extreme flood sensitivity to snow and forest harvest, western Cascades, Oregon, United States. *Water Resources Research* 46.
- Kahru, M., V. Brotas, M. Manzano-Sarabia, and B. G. Mitchell. 2010. Are phytoplankton blooms occurring earlier in the Arctic? *Global Change Biology*:no-no.
- Kaltenberg, A. M., R. L. Emmett, and K. J. Benoit-Bird. 2010. Timing of forage fish seasonal appearance in the Columbia River plume and link to ocean conditions. *Marine Ecology-Progress Series* 419:171-184.
- Kavanagh, K. D., T. O. Haugen, F. Gregersen, J. Jernvall, and L. A. Vollestad. 2010. Contemporary temperature-driven divergence in a Nordic freshwater fish under conditions commonly thought to hinder adaptation. *Bmc Evolutionary Biology* 10.
- Kawaguchi, S., H. Kurihara, R. King, L. Hale, T. Berli, J. P. Robinson, A. Ishida et al. 2011. Will krill fare well under Southern Ocean acidification? *Biology Letters* 7:288-291.
- Keefer, M. L., G. A. Taylor, D. F. Garletts, G. A. Gauthier, T. M. Pierce, and C. C. Caudill. 2010. Prespaw mortality in adult spring Chinook salmon outplanted above barrier dams. *Ecology of Freshwater Fish* 19:361-372.
- Kennedy, R. J., and W. W. Crozier. 2010. Evidence of changing migratory patterns of wild Atlantic salmon *Salmo salar* smolts in the River Bush, Northern Ireland, and possible associations with climate change. *Journal of Fish Biology* 76:1786-1805.
- Kishi, M. J., M. Kaeriyama, H. Ueno, and Y. Kamezawa. 2010. The effect of climate change on the growth of Japanese chum salmon (*Oncorhynchus keta*) using a bioenergetics model coupled with a three-dimensional lower trophic ecosystem model (NEMURO). *Deep-Sea Research Part II-Topical Studies in Oceanography* 57:1257-1265.
- Koel, T. M., B. L. Kerans, S. C. Barras, K. C. Hanson, and J. S. Wood. 2010. Avian Piscivores as Vectors for *Myxobolus cerebralis* in the Greater Yellowstone Ecosystem. *Transactions of the American Fisheries Society* 139:976-988.
- Krkosek, M. 2010. Sea lice and salmon in Pacific Canada: ecology and policy. *Frontiers in Ecology and the Environment* 8:201-209.
- Kroeker, K. J., R. L. Kordas, R. N. Crim, and G. G. Singh. 2010. Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. *Ecology Letters* 13:1419-1434.
- Kurihara, H., and A. Ishimatsu. 2008. Effects of high CO₂ seawater on the copepod (*Acartia tsuensis*) through all life stage and subsequent generations. *Marine Pollution Bulletin* 56:1086-1090.

- Kurihara, H., S. Shimode, and Y. Shirayama. 2004a. Effects of raised CO₂ concentration on the egg production rate and early development of two marine copepods (*Acartia steueri* and *Acartia erythraea*). *Marine Pollution Bulletin* 49:721-727.
- . 2004b. Sub-lethal effects of elevated concentrations of CO₂ on planktonic copepods and sea urchins. *Journal of Oceanography* 60:743-750.
- Lacoue-Labarthe, T., E. Réveillac, F. Oberhänsli, J. L. Teyssié, R. Jeffree, and J. P. Gattuso. 2011. Effects of ocean acidification on trace element accumulation in the early-life stages of squid *Loligo vulgaris*. *Aquatic Toxicology* 105:166-176.
- Larnier, K., H. Roux, D. Dartus, and O. Croze. 2010. Water temperature modeling in the Garonne River (France). *Knowledge and Management of Aquatic Ecosystems*.
- Lee, T., and M. J. McPhaden. 2010. Increasing intensity of El Niño in the central-equatorial Pacific. *Geophysical Research Letters* 37.
- Lee, W. S., P. Monaghan, and N. B. Metcalfe. 2010. The trade-off between growth rate and locomotor performance varies with perceived time until breeding. *Journal of Experimental Biology* 213:3289-3298.
- Linnansaari, T., and R. A. Cunjak. 2010. Patterns in apparent survival of Atlantic salmon (*Salmo salar*) parr in relation to variable ice conditions throughout winter. *Canadian Journal of Fisheries and Aquatic Sciences* 67:1744-1754.
- Litz, M. N. C., R. D. Brodeur, R. L. Emmett, S. S. Heppell, R. S. Rasmussen, L. O'Higgins, and M. S. Morris. 2010. Effects of variable oceanographic conditions on forage fish lipid content and fatty acid composition in the northern California Current. *Marine Ecology-Progress Series* 405:71-85.
- Lohmus, M., M. Bjorklund, L. F. Sundstrom, and R. H. Devlin. 2010a. Effects of temperature and growth hormone on individual growth trajectories of wild-type and transgenic coho salmon *Oncorhynchus kisutch*. *Journal of Fish Biology* 76:641-654.
- Lohmus, M., L. F. Sundstrom, M. Bjorklund, and R. H. Devlin. 2010b. Genotype-Temperature Interaction in the Regulation of Development, Growth, and Morphometrics in Wild-Type, and Growth-Hormone Transgenic Coho Salmon. *Plos One* 5.
- Mac Nally, R., J. R. Thomson, W. J. Kimmerer, F. Feyrer, K. B. Newman, A. Sih, W. A. Bennett et al. 2010. Analysis of pelagic species decline in the upper San Francisco Estuary using multivariate autoregressive modeling (MAR). *Ecological Applications* 20:1417-1430.
- Macdonald, J. S., D. A. Patterson, M. J. Hague, and I. C. Guthrie. 2010. Modeling the Influence of Environmental Factors on Spawning Migration Mortality for Sockeye Salmon Fisheries Management in the Fraser River, British Columbia. *Transactions of the American Fisheries Society* 139:768-782.
- MacFarlane, R. B. 2010. Energy dynamics and growth of Chinook salmon (*Oncorhynchus tshawytscha*) from the Central Valley of California during the estuarine phase and first ocean year. *Canadian Journal of Fisheries and Aquatic Sciences* 67:1549-1565.
- MacNeil, M. A., N. A. J. Graham, J. E. Cinner, N. K. Dulvy, P. A. Loring, S. Jennings, N. V. C. Polunin et al. 2010. Transitional states in marine fisheries: adapting to predicted global change. *Philosophical Transactions of the Royal Society B-Biological Sciences* 365:3753-3763.

- Magerhans, A., and G. Horstgen-Schwark. 2010. Selection experiments to alter the sex ratio in rainbow trout (*Oncorhynchus mykiss*) by means of temperature treatment. *Aquaculture* 306:63-67.
- Mantua, N., I. Tohver, and A. Hamlet. 2010. Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State. *Climatic Change* 102:187-223.
- Marcos-Lopez, M., P. Gale, B. C. Oidtmann, and E. J. Peeler. 2010. Assessing the Impact of Climate Change on Disease Emergence in Freshwater Fish in the United Kingdom. *Transboundary and Emerging Diseases* 57:293-304.
- Martins, E. G., S. G. Hinch, D. A. Patterson, M. J. Hague, S. J. Cooke, K. M. Miller, M. F. Lapointe et al. 2011. Effects of river temperature and climate warming on stock-specific survival of adult migrating Fraser River sockeye salmon (*Oncorhynchus nerka*). *Global Change Biology* 17:99-114.
- Mathes, M. T., S. G. Hinch, S. J. Cooke, G. T. Crossin, D. A. Patterson, A. G. Lotto, and A. P. Farrell. 2010. Effect of water temperature, timing, physiological condition, and lake thermal refugia on migrating adult Weaver Creek sockeye salmon (*Oncorhynchus nerka*). *Canadian Journal of Fisheries and Aquatic Sciences* 67:70-84.
- Mayor, D. J., C. Matthews, K. Cook, A. F. Zuur, and S. Hay. 2007. CO₂-induced acidification affects hatching success in *Calanus finmarchicus*. *Marine Ecology Progress Series* 350:91-97.
- McDaniels, T., S. Wilmot, M. Healey, and S. Hinch. 2010. Vulnerability of Fraser River sockeye salmon to climate change: A life cycle perspective using expert judgments. *Journal of Environmental Management* 91:2771-2780.
- McDermott, M. J., A. L. Robertson, P. J. Shaw, and A. M. Milner. 2010. The hyporheic assemblage of a recently formed stream following deglaciation in Glacier Bay, Alaska, USA. *Canadian Journal of Fisheries and Aquatic Sciences* 67:304-313.
- Meyers, E. M., B. Dobrowski, and C. L. Tague. 2010. Climate Change Impacts on Flood Frequency, Intensity, and Timing May Affect Trout Species in Sagehen Creek, California. *Transactions of the American Fisheries Society* 139:1657-1664.
- Meyn, A., S. W. Taylor, M. D. Flannigan, K. Thonicke, and W. Cramer. 2010. Relationship between fire, climate oscillations, and drought in British Columbia, Canada, 1920–2000. *Global Change Biology* 16:977-989.
- Minder, J. R. 2010. The Sensitivity of Mountain Snowpack Accumulation to Climate Warming. *Journal of Climate* 23:2634-2650.
- Minder, J. R., P. W. Mote, and J. D. Lundquist. 2010. Surface temperature lapse rates over complex terrain: Lessons from the Cascade Mountains. *Journal of Geophysical Research-Atmospheres* 115.
- Moir, H. J., and G. B. Pasternack. 2010. Substrate requirements of spawning Chinook salmon (*Oncorhynchus tshawytscha*) are dependents on local channel hydraulics. *River Research and Applications* 26:456-468.
- Moore, J. W., and D. E. Schindler. 2010. Spawning salmon and the phenology of emergence in stream insects. *Proceedings of the Royal Society B-Biological Sciences* 277:1695-1703.
- Moore, S. K., N. J. Mantua, B. M. Hickey, and V. L. Trainer. 2010. The relative influences of El Nino-Southern Oscillation and Pacific Decadal Oscillation on

- paralytic shellfish toxin accumulation in Pacific northwest shellfish. *Limnology and Oceanography* 55:2262-2274.
- Moradkhani, H., R. G. Baird, and S. A. Wherry. 2010. Assessment of climate change impact on floodplain and hydrologic ecotones. *Journal of Hydrology* 395:264-278.
- Morita, K., M. Fukuwaka, and N. Tanimata. 2010a. Age-related thermal habitat use by Pacific salmon *Oncorhynchus* spp. *Journal of Fish Biology* 77:1024-1029.
- Morita, K., M. Fukuwaka, N. Tanimata, and O. Yamamura. 2010b. Size-dependent thermal preferences in a pelagic fish. *Oikos* 119:1265-1272.
- Morita, K., and T. Nagasawa. 2010. Latitudinal variation in the growth and maturation of masu salmon (*Oncorhynchus masou*) parr. *Canadian Journal of Fisheries and Aquatic Sciences* 67:955-965.
- Mote, P. W., and E. P. Salathe. 2010. Future climate in the Pacific Northwest. *Climatic Change* 102:29-50.
- Munday, P. L., N. E. Crawley, and G. E. Nilsson. 2009a. Interacting effects of elevated temperature and ocean acidification on the aerobic performance of coral reef fishes. *Marine Ecology Progress Series* 388:235-242.
- Munday, P. L., D. L. Dixon, J. M. Donelson, G. P. Jones, M. S. Pratchett, G. V. Devitsina, and K. B. Døving. 2009b. Ocean acidification impairs olfactory discrimination and homing ability of a marine fish. *Proceedings of the National Academy of Sciences* 106:1848-1852.
- Munday, P. L., D. L. Dixon, M. I. McCormick, M. Meekan, M. C. O. Ferrari, and D. P. Chivers. 2010. Replenishment of fish populations is threatened by ocean acidification. *Proceedings of the National Academy of Sciences*:-
- Munday, P. L., M. Gagliano, J. M. Donelson, D. L. Dixon, and S. R. Thorrold. 2011a. Ocean acidification does not affect the early life history development of a tropical marine fish. *Marine Ecology Progress Series* 423:211-221.
- Munday, P. L., V. Hernaman, D. L. Dixon, and S. R. Thorrold. 2011b. Effect of ocean acidification on otolith development in larvae of a tropical marine fish. *Biogeosciences Discuss* 8:2329-2356.
- Nadeau, P. S., S. G. Hinch, K. A. Hruska, L. B. Pon, and D. A. Patterson. 2010. The effects of experimental energy depletion on the physiological condition and survival of adult sockeye salmon (*Oncorhynchus nerka*) during spawning migration. *Environmental Biology of Fishes* 88:241-251.
- Narum, S. R., N. R. Campbell, C. C. Kozfkay, and K. A. Meyer. 2010. Adaptation of redband trout in desert and montane environments. *Molecular Ecology* 19:4622-4637.
- NMFS. 2010. Endangered Species Act Section 7(a)(2) Consultation Supplemental Biological Opinion, Pages 246, Supplemental Consultation on Remand for Operation of the Federal Columbia River Power System, 11 Bureau of Reclamation Projects in the Columbia Basin and ESA Section 10(a)(I)(A) Permit for Juvenile Fish Transportation Program, NOAA Fisheries Northwest Region.
- Nolin, A. W., J. Phillippe, A. Jefferson, and S. L. Lewis. 2010. Present-day and future contributions of glacier runoff to summertime flows in a Pacific Northwest watershed: Implications for water resources. *Water Resources Research* 46.

- Null, S. E., M. L. Deas, and J. R. Lund. 2010. FLOW AND WATER TEMPERATURE SIMULATION FOR HABITAT RESTORATION IN THE SHASTA RIVER, CALIFORNIA. *River Research and Applications* 26:663-681.
- O'Malley, K. G., M. J. Ford, and J. J. Hard. 2010. Clock polymorphism in Pacific salmon: evidence for variable selection along a latitudinal gradient. *Proceedings of the Royal Society B-Biological Sciences* 277:3703-3714.
- Orpwood, J. E., J. D. Armstrong, and S. W. Griffiths. 2010. Interactions between riparian shading and food supply: a seasonal comparison of effects on time budgets, space use and growth in Atlantic salmon *Salmo salar*. *Journal of Fish Biology* 77:1835-1849.
- Ottersen, G., S. Kim, G. Huse, J. J. Polovina, and N. C. Stenseth. 2010. Major pathways by which climate may force marine fish populations. *Journal of Marine Systems* 79:343-360.
- Ouellet, V., M. Mingelbier, A. Saint-Hilaire, and J. Morin. 2010. Frequency Analysis as a Tool for Assessing Adverse Conditions During a Massive Fish Kill in the St. Lawrence River, Canada. *Water Quality Research Journal of Canada* 45:47-57.
- Ovaskainen, O., and B. Meerson. 2010. Stochastic models of population extinction. *Trends in Ecology & Evolution* 25:643-652.
- Pankhurst, N. W., and H. R. King. 2010. Temperature and salmonid reproduction: implications for aquaculture. *Journal of Fish Biology* 76:69-85.
- Pascal, P.-Y., J. W. Fleeger, F. Galvez, and K. R. Carman. 2010. The toxicological interaction between ocean acidity and metals in coastal meiobenthic copepods. *Marine Pollution Bulletin* 60:2201-2208.
- Perry, R. I., R. E. Ommer, M. Barange, and F. Werner. 2010. The challenge of adapting marine social-ecological systems to the additional stress of climate change. *Current Opinion in Environmental Sustainability* 2:356-363.
- Peterson, W. T., C. A. Morgan, J. P. Fisher, and E. Casillas. 2010. Ocean distribution and habitat associations of yearling coho (*Oncorhynchus kisutch*) and Chinook (*O-tshawytscha*) salmon in the northern California Current. *Fisheries Oceanography* 19:508-525.
- Petrosky, C. E., and H. A. Schaller. 2010. Influence of river conditions during seaward migration and ocean conditions on survival rates of Snake River Chinook salmon and steelhead. *Ecology of Freshwater Fish* 19:520-536.
- Pettersson, A., J. Pickova, and E. Brannas. 2010. Swimming performance at different temperatures and fatty acid composition of Arctic charr (*Salvelinus alpinus*) fed palm and rapeseed oils. *Aquaculture* 300:176-181.
- Poff, N., B. Richter, A. Arthington, S. Bunn, R. Naiman, E. Kendy, M. Acrement et al. 2010. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. *Freshwater Biology* 55:147-170.
- Popova, E. E., A. Yool, A. C. Coward, Y. K. Aksenov, S. G. Alderson, B. A. de Cuevas, and T. R. Anderson. 2010. Control of primary production in the Arctic by nutrients and light: insights from a high resolution ocean general circulation model. *Biogeosciences* 7:3569-3591.

- Portner, H. O. 2010. Oxygen- and capacity-limitation of thermal tolerance: a matrix for integrating climate-related stressor effects in marine ecosystems. *Journal of Experimental Biology* 213:881-893.
- Provoost, P., S. van Heuven, K. Soetaert, R. Laane, and J. J. Middelburg. 2010. Seasonal and long-term changes in pH in the Dutch coastal zone. *Biogeosciences* 7:3869-3878.
- Pulkkinen, K., L. R. Suomalainen, A. F. Read, D. Ebert, P. Rintamaki, and E. T. Valtonen. 2010. Intensive fish farming and the evolution of pathogen virulence: the case of columnaris disease in Finland. *Proceedings of the Royal Society B-Biological Sciences* 277:593-600.
- Qian, Y., S. J. Ghan, and L. R. Leung. 2010. Downscaling hydroclimatic changes over the Western US based on CAM subgrid scheme and WRF regional climate simulations. *International Journal of Climatology* 30:675-693.
- Radchenko, V. I., S. V. Loboda, A. L. Figurkin, K. M. Gorbatenko, and E. E. Ovsyannikov. 2010. Environmental conditions and compositions of plankton and nekton in the epipelagic zone of the northwestern Pacific Ocean in summer 2009, the year of the largest spawning migration of pink and Chum Salmon. *Russian Journal of Marine Biology* 36:473-488.
- Ray, R. A., P. A. Rossignol, and J. L. Bartholomew. 2010. Mortality threshold for juvenile Chinook salmon *Oncorhynchus tshawytscha* in an epidemiological model of *Ceratomyxa shasta*. *Diseases of Aquatic Organisms* 93:63-70.
- Reed, T. E., G. Martinek, and T. P. Quinn. 2010a. Lake-specific variation in growth, migration timing and survival of juvenile sockeye salmon *Oncorhynchus nerka*: separating environmental from genetic influences. *Journal of Fish Biology* 77:692-705.
- Reed, T. E., R. S. Waples, D. E. Schindler, J. J. Hard, and M. T. Kinnison. 2010b. Phenotypic plasticity and population viability: the importance of environmental predictability. *Proceedings of the Royal Society B-Biological Sciences* 277:3391-3400.
- Reeves, G. H., J. B. Grunbaum, and D. W. Lang. 2010. Seasonal variation in diel behaviour and habitat use by age 1+Steelhead (*Oncorhynchus mykiss*) in Coast and Cascade Range streams in Oregon, USA. *Environmental Biology of Fishes* 87:101-111.
- Rensel, J. E. J., N. Haigh, and T. J. Tynan. 2010. Fraser river sockeye salmon marine survival decline and harmful blooms of *Heterosigma akashiwo*. *Harmful Algae* 10:98-115.
- Richardson, A. J., A. Bakun, G. C. Hays, and M. J. Gibbons. 2009. The jellyfish joyride: causes, consequences and management responses to a more gelatinous future. *Trends in Ecology and Evolutionary Biology* 24:312-322.
- Richardson, A. J., and M. J. Gibbons. 2008. Are jellyfish increasing in response to ocean acidification? *Limnology and Oceanography* 53:2040-2045.
- Robinson, J. M., D. C. Josephson, B. C. Weidel, and C. E. Kraft. 2010. Influence of Variable Interannual Summer Water Temperatures on Brook Trout Growth, Consumption, Reproduction, and Mortality in an Unstratified Adirondack Lake. *Transactions of the American Fisheries Society* 139:685-699.

- Roscoe, D. W., S. G. Hinch, S. J. Cooke, and D. A. Patterson. 2010. Behaviour and thermal experience of adult sockeye salmon migrating through stratified lakes near spawning grounds: the roles of reproductive and energetic states. *Ecology of Freshwater Fish* 19:51-62.
- Rosenberg, E. A., P. W. Keys, D. B. Booth, D. Hartley, J. Burkey, A. C. Steinemann, and D. P. Lettenmaier. 2010. Precipitation extremes and the impacts of climate change on stormwater infrastructure in Washington State. *Climatic Change* 102:319-349.
- Roth, T. R., M. C. Westhoff, H. Huwald, J. A. Huff, J. F. Rubin, G. Barrenetxea, M. Vetterli et al. 2010. Stream Temperature Response to Three Riparian Vegetation Scenarios by Use of a Distributed Temperature Validated Model. *Environmental Science & Technology* 44:2072-2078.
- Rykaczewski, R. R., and J. P. Dunne. 2010. Enhanced nutrient supply to the California Current Ecosystem with global warming and increased stratification in an earth system model. *Geophysical Research Letters* 37.
- Ryu, J. H., M. D. Svoboda, J. D. Lenters, T. Tadesse, and C. L. Knutson. 2010. Potential extents for ENSO-driven hydrologic drought forecasts in the United States. *Climatic Change* 101:575-597.
- Saito, T., I. Shimizu, J. Seki, T. Kaga, E. Hasegawa, H. Saito, and K. Nagasawa. 2010. Can research on the early marine life stage of juvenile chum salmon *Oncorhynchus keta* forecast returns of adult salmon? A case study from eastern Hokkaido, Japan. *Fisheries Science* 76:909-920.
- Salathe, E. P., L. R. Leung, Y. Qian, and Y. X. Zhang. 2010. Regional climate model projections for the State of Washington. *Climatic Change* 102:51-75.
- Satterthwaite, W. H., M. P. Beakes, E. M. Collins, D. R. Swank, J. E. Merz, R. G. Titus, S. M. Sogard et al. 2010. State-dependent life history models in a changing (and regulated) environment: steelhead in the California Central Valley. *Evolutionary Applications* 3:221-243.
- Schneider, K. N., R. M. Newman, V. Card, S. Weisberg, and D. L. Pereira. 2010. Timing of Walleye Spawning as an Indicator of Climate Change. *Transactions of the American Fisheries Society* 139:1198 - 1210.
- Schwing, F. B., R. Mendelsohn, S. J. Bograd, J. E. Overland, M. Y. Wang, and S. Ito. 2010. Climate change, teleconnection patterns, and regional processes forcing marine populations in the Pacific. *Journal of Marine Systems* 79:245-257.
- Seebacher, F., M. D. Brand, P. L. Else, H. Guderley, A. J. Hulbert, and C. D. Moyes. 2010. Plasticity of Oxidative Metabolism in Variable Climates: Molecular Mechanisms. *Physiological and Biochemical Zoology* 83:721-732.
- Sharma, R., and M. Liermann. 2010. Using hierarchical models to estimate effects of ocean anomalies on north-west Pacific Chinook salmon *Oncorhynchus tshawytscha* recruitment. *Journal of Fish Biology* 77:1948-1963.
- Simpson, S. D., P. L. Munday, M. L. Wittenrich, R. Manassa, D. L. Dixon, M. Gagliano, and H. Y. Yan. 2011. Ocean acidification erodes crucial auditory behaviour in a marine fish. *Biology Letters*.
- Skilbrei, O. T., V. Wennevik, G. Dahle, B. Barlaup, and T. Wiers. 2010. Delayed smolt migration of stocked Atlantic salmon parr. *Fisheries Management and Ecology* 17:493-500.

- Slaughter, R. A., A. F. Hamlet, D. Huppert, J. Hamilton, and P. W. Mote. 2010. Mandates vs markets: addressing over-allocation of Pacific Northwest River Basins. *Water Policy* 12:305-317.
- Spence, B. C., and J. D. Hall. 2010. Spatiotemporal patterns in migration timing of coho salmon (*Oncorhynchus kisutch*) smolts in North America. *Canadian Journal of Fisheries and Aquatic Sciences* 67:1316-1334.
- Steinacher, M., F. Joos, T. L. Frolicher, L. Bopp, P. Cadule, V. Cocco, S. C. Doney et al. 2010. Projected 21st century decrease in marine productivity: a multi-model analysis. *Biogeosciences* 7:979-1005.
- Stelkens, R. B., and C. Wedekind. 2010. Environmental sex reversal, Trojan sex genes, and sex ratio adjustment: conditions and population consequences. *Molecular Ecology* 19:627-646.
- Stich, H. B., and A. Brinker. 2010. Oligotrophication outweighs effects of global warming in a large, deep, stratified lake ecosystem. *Global Change Biology* 16:877-888.
- Strange, J. S. 2010. Upper Thermal Limits to Migration in Adult Chinook Salmon: Evidence from the Klamath River Basin. *Transactions of the American Fisheries Society* 139:1091-1108.
- Taylor, B. R., C. Macinnis, and T. A. Floyd. 2010. INFLUENCE OF RAINFALL AND BEAVER DAMS ON UPSTREAM MOVEMENT OF SPAWNING ATLANTIC SALMON IN A RESTORED BROOK IN NOVA SCOTIA, CANADA. *River Research and Applications* 26:183-193.
- Teichert, M. A. K., E. Kvingedal, T. Forseth, O. Ugedal, and A. G. Finstad. 2010. Effects of discharge and local density on the growth of juvenile Atlantic salmon *Salmo salar*. *Journal of Fish Biology* 76:1751-1769.
- Teletchea, F., and P. Fontaine. 2010. Comparison of early life-stage strategies in temperate freshwater fish species: trade-offs are directed towards first feeding of larvae in spring and early summer. *Journal of Fish Biology* 77:257-278.
- Thackeray, S. J., T. H. Sparks, M. Frederiksen, S. Burthe, P. J. Bacon, J. R. Bell, M. S. Botham et al. 2010. Trophic level asynchrony in rates of phenological change for marine, freshwater and terrestrial environments. *Global Change Biology* 16:3304-3313.
- Tohver, I., and A. F. Hamlet. 2010. Impacts of 21st century climate change on hydrologic extremes in the Pacific Northwest region of North America. Chapter 7 in Final Report for the Columbia Basin Climate Change Scenarios Project, Climate Impacts Group, Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, Seattle. <http://www.hydro.washington.edu/2860/>.
- Tonteri, A., A. Vasemagi, J. Lumme, and C. R. Primmer. 2010. Beyond MHC: signals of elevated selection pressure on Atlantic salmon (*Salmo salar*) immune-relevant loci. *Molecular Ecology* 19:1273-1282.
- Towler, E., B. Rajagopalan, E. Gilleland, R. S. Summers, D. Yates, and R. W. Katz. 2010. Modeling hydrologic and water quality extremes in a changing climate: A statistical approach based on extreme value theory. *Water Resources Research* 46.
- Tudorache, C., R. A. O'Keefe, and T. J. Benfey. 2010. The effect of temperature and ammonia exposure on swimming performance of brook charr (*Salvelinus*

- fontinalis). *Comparative Biochemistry and Physiology a-Molecular & Integrative Physiology* 156:523-528.
- Vainikka, A., I. Kallio-Nyberg, M. Heino, and M. L. Koljonen. 2010. Divergent trends in life-history traits between Atlantic salmon *Salmo salar* of wild and hatchery origin in the Baltic Sea. *Journal of Fish Biology* 76:622-640.
- Valiente, A. G., E. Beall, and E. Garcia-Vazquez. 2010. Population genetics of south European Atlantic salmon under global change. *Global Change Biology* 16:36-47.
- Van Doorslaer, W., R. Stoks, C. Duvivier, A. Bednarska, and L. De Meester. 2009a. Population dynamics determine genetic adaptation to temperature in *Daphnia*. *Evolution* 63:1867-1878.
- Van Doorslaer, W., R. Stoks, I. Swillen, H. Feuchtmayr, D. Atkinson, B. Moss, and L. De Meester. 2010. Experimental thermal microevolution in community-embedded *Daphnia* populations. *Climate Research* 43:81-89.
- Van Doorslaer, W., J. Vanoverbeke, C. Duvivier, S. Rousseaux, M. Jansen, B. Jansen, H. Feuchtmayr et al. 2009b. Local adaptation to higher temperatures reduces immigration success of genotypes from a warmer region in the water flea *Daphnia*. *Global Change Biology* 15:3046-3055.
- Van Dyke, E. S., D. L. Scarnecchia, B. C. Jonasson, and R. W. Carmichael. 2010. Ecology of Winter Concealment Behavior of Juvenile Spring Chinook Salmon in the Grande Ronde River Basin, Oregon. *Northwest Science* 84:9-19.
- Wang, M. Y., J. E. Overland, and N. A. Bond. 2010. Climate projections for selected large marine ecosystems. *Journal of Marine Systems* 79:258-266.
- Wassmann, P., C. M. Duarte, S. Agustí, and M. K. Sejr. 2010. Footprints of climate change in the Arctic Marine Ecosystem. *Global Change Biology*:no-no.
- Wedekind, C., and C. Kung. 2010. Shift of Spawning Season and Effects of Climate Warming on Developmental Stages of a Grayling (*Salmonidae*). *Conservation Biology* 24:1418-1423.
- Wenger, S. J., C. H. Luce, A. F. Hamlet, D. J. Isaak, and H. M. Neville. 2010. Macroscale hydrologic modeling of ecologically relevant flow metrics. *Water Resources Research* 46.
- Westley, P. A. H., D. E. Schindler, T. P. Quinn, G. T. Ruggerone, and R. Hilborn. 2010. Natural habitat change, commercial fishing, climate, and dispersal interact to restructure an Alaskan fish metacommunity. *Oecologia* 163:471-484.
- Wilby, R. L., H. Orr, G. Watts, R. W. Battarbee, P. M. Berry, R. Chadd, S. J. Dugdale et al. 2010. Evidence needed to manage freshwater ecosystems in a changing climate: Turning adaptation principles into practice. *Science of the Total Environment* 408:4150-4164.
- Wiley, M. J., D. W. Hyndman, B. C. Pijanowski, A. D. Kendall, C. Riseng, E. S. Rutherford, S. T. Cheng et al. 2010. A multi-modeling approach to evaluating climate and land use change impacts in a Great Lakes River Basin. *Hydrobiologia* 657:243-262.
- Wilkinson, R. J., R. Longland, H. Woolcott, and M. J. R. Porter. 2010. Effect of elevated winter-spring water temperature on sexual maturation in photoperiod manipulated stocks of rainbow trout (*Oncorhynchus mykiss*). *Aquaculture* 309:236-244.
- Williams, R., T. A. Okey, S. S. Wallace, and V. F. Gallucci. 2010. Shark aggregation in coastal waters of British Columbia. *Marine Ecology-Progress Series* 414:249-256.

- Winans, A. K., and J. E. Purcell. 2010. Effects of pH on asexual reproduction and statolith formation of the scyphozoan, *Aurelia labiata*. *Hydrobiologia* 645:39-52.
- Wiseman, C. D., M. LeMoine, and S. Cormier. 2010. Assessment of Probable Causes of Reduced Aquatic Life in the Touchet River, Washington, USA. *Human and Ecological Risk Assessment* 16:87-115.
- Wolf, S. G., M. A. Snyder, W. J. Sydeman, D. F. Doak, and D. A. Croll. 2010. Predicting population consequences of ocean climate change for an ecosystem sentinel, the seabird Cassin's auklet. *Global Change Biology* 16:1923-1935.
- Wong, C. S., J. R. Christian, S. K. E. Wong, J. Page, L. S. Xie, and S. Johannessen. 2010. Carbon dioxide in surface seawater of the eastern North Pacific Ocean (Line P), 1973-2005. *Deep-Sea Research Part I-Oceanographic Research Papers* 57:687-695.
- Worden, L., L. W. Botsford, A. Hastings, and M. D. Holland. 2010. Frequency responses of age-structured populations Pacific salmon as an example. *Theoretical Population Biology* 78:239-249.
- Xu, C. L., B. H. Letcher, and K. H. Nislow. 2010a. Context-specific influence of water temperature on brook trout growth rates in the field. *Freshwater Biology* 55:2253-2264.
- . 2010b. Size-dependent survival of brook trout *Salvelinus fontinalis* in summer: effects of water temperature and stream flow. *Journal of Fish Biology* 76:2342-2369.
- Yeh, S. W., J. S. Kug, B. Dewitte, M. H. Kwon, B. P. Kirtman, and F. F. Jin. 2009. El Nino in a changing climate. *Nature* 461:511-U570.
- Young, R. G., J. Wilkinson, J. Hay, and J. W. Hayes. 2010. Movement and Mortality of Adult Brown Trout in the Motupiko River, New Zealand: Effects of Water Temperature, Flow, and Flooding. *Transactions of the American Fisheries Society* 139:137-146.
- Yvon-Durocher, G., J. M. Montoya, M. Trimmer, and G. Woodward. 2010. Warming alters the size spectrum and shifts the distribution of biomass in freshwater ecosystems. *Global Change Biology*:no-no.
- Zabel, R. W., K. I. Haught, and P. M. Chittaro. 2010. Variability in fish size/otolith radius relationships among populations of Chinook salmon. *Environmental Biology of Fishes* 89:267-278.
- Zedler, J. B. 2010. How frequent storms affect wetland vegetation: a preview of climate-change impacts. *Frontiers in Ecology and the Environment* 8:540-547.

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Appendix D.3

Literature review for 2011: Biological effects of climate change

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**Literature review for 2011 citations for BIOP:
Biological effects of climate change**

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July, 2012**

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1 Executive summary

In 2011, the accumulation of more “fingerprints” of global warming continues (Blunden and Arndt 2012). CO₂ concentrations in the atmosphere broke new records, driving radiative forcing to 30% above 1990 levels. Rapid warming in high latitudes produced record losses of snow and ice from ice sheets and sea ice. Average summer temperatures throughout the U.S. were the second warmest on record, and despite the typically cool La Niña, 2011 was one of the 15 warmest years on record in the US, contributing to a very active wildfire season. The rise in 30-year average daily temperatures, reflected in the U.S. “Normals” for 1981-2010, was several degrees above that for the 1971-2000 period, reflecting the longer trends (Arguez et al. 2012). The frequency of extreme precipitation events (1-day and 5-day events) has increased over much of the Northern Hemisphere, despite natural forcing toward a decrease, thus presenting another “fingerprint” of the effects of anthropogenic forcing (Min et al. 2011).

In the PNW, hydrological impacts of warming have been strongest in rain-snow transient watersheds, where discharge has increased in the winter and decreased in the summer, producing earlier peak flows and lower low flows since 1962 (Jefferson 2011). New projections of hydrological responses in the PNW are consistent with the observed historical trends in hydrology (Cuo et al. 2011) and fire frequency and severity (Rogers et al. 2011), and emphasize the additional sensitivity in our region to higher projected rates of summer warming compared with winter warming for total annual discharge (Das et al. 2011). A statistically significant rise in summer sea level over the past century reflects larger patterns of sea level rise, while controlling for the effects of El Niño in winter (Komar et al. 2011). Similarly, summer upwelling intensity at 39°-42°N has increased (Black et al. 2011), and upwelling has advanced earlier in the year, with a shorter upwelling period off British Columbia (Foreman et al. 2011). Hypoxia in the Columbia River estuary has been linked to upwelling events (Roegner et al. 2011b), and frequently reaches stressful levels for fish (2mg/L, Roegner et al. 2011a). Although some models project that hypoxic water from upwelling will decrease with climate change (Glessmer et al. 2011), sensitivity to hypoxia is much greater in warmer water, so it continues to present a serious risk (Vaquer-Sunyer and Duarte 2011). Numerous papers explore the hydrodynamics of the Columbia River, including sediment transport which might affect salmon survival (Jay et al. 2011; Jay and Naik 2011; Naik and Jay 2011b; Naik and Jay 2011a). Ecological fingerprints of climate change include a strong signal of long-term trends and regime shifts in marine ecosystems, described in a recent review of 300 time series in waters around the UK (Spencer et al. 2011).

A major concern is the extent to which natural responses to climate change must include range shifts or range contractions, because the current habitat will become unsuitable. The rate of range shifts and phenological shifts necessary to track climate change might be significantly larger in the ocean than on land, despite the slower absolute rate of warming in the ocean, due to shallower spatial and temporal gradients in temperature (Burrows et al. 2011). Abdul-Aziz et al (2011) illustrate this point dramatically for PNW salmon by showing that climate scenarios imply an enormous contraction (30-50% by the 2080s) of the summer thermal range suitable for chum, pink, coho, sockeye and steelhead in the marine environment, with an especially large contraction (86-88%) of Chinook salmon summer range (A1B and A2 scenarios). Previous analyses focusing on sockeye salmon (Welch et al.

1998) came to similar conclusions, but updated climate change projections and the multi-species perspective make this a particularly relevant paper.

Most of the other impacts of climate change on salmon reported in 2011 are consistent with the direction of previous studies. Copeland and Meyer (2011) found a positive effect of flow on juvenile Chinook density in the Salmon River Basin. Although demonstrated in Atlantic salmon (Marschall et al. 2011), observations that very long delays at dams can lead to exposure to extremely high river temperatures during smolting also could apply to the Columbia River. Bi et al (Bi et al. 2011a; Bi et al. 2011b) found strong correlations between marine distribution and growth and cold-water flow from the north, which presumably will decline with rising SST.

Numerous papers on adult migration demonstrate that migration timing is both genetically and plastically determined, and that changes in timing have already occurred (e.g., an evolutionary response in Columbia River sockeye, Crozier et al. 2011) and will continue with climate change. Projections of warming in the Fraser River produced much lower estimates of migration survival than occur now (Hague et al. 2011; Martins et al. 2011), although they aren't expected to drive the populations extinct on their own (i.e., acting on this life stage alone, Reed et al. 2011). Much of the current mortality might be due to diseases as yet unidentified (Miller et al. 2011a).

Several papers emphasize that focusing exclusively on effects of individual life stages gravely unrepresents the cumulative impacts of climate change on salmon (Healey 2011; Pankhurst and Munday 2011). Analyses of the factors correlated with salmon extinctions in California (Zeug et al. 2011) and Japan (Fukushima et al. 2011) point to changes in flow regimes and rising air temperatures.

The risk of diseases throughout the life cycle is probably one of the least well quantified areas of concern (e.g., little is known about virus responses to climate change, Danovaro et al. 2011). The best way to protect salmon from disease risk is to maintain large population sizes with high genetic diversity (de Eyto et al. 2011). Species interactions are also poorly predicted, although recent work shows that competition among trout species can significantly alter predicted effects of climate change (Wenger et al. 2011).

On the positive side, some papers found less negative impacts of rising temperatures than expected (e.g., high tolerance of Snake River fall Chinook for 23°C, Geist et al. 2011), and substantial genetic variation (and thus theoretically, the potential for evolution) in growth parameters, smolt behavior, migration timing, cardiac performance and heat tolerance. However, the existence of genetic variation and local adaptation in physiological traits does not support much optimism that evolution is likely to rescue Chinook salmon from risk of lowered survival due to climate change (unlike migration timing, as mentioned above). Typically, evolution relies on large population sizes and plenty of time. This is especially true if fisheries selection, e.g., on age at return, opposes adaptive responses to climate change or enhances population variability in response to environmental forcing (Botsford et al. 2011; Rouyer et al. 2011).

Adaptation plans for responding to climate change in the Pacific Northwest are being developed (e.g., review in National Wildlife Federation 2011). However, several papers emphasize that institutional barriers are a serious impediment to proactive climate change adaptation in water management (Farley et al. 2011b; Hamlet 2011; Safford and Norman 2011).

In conclusion, new information from 2011 publications was generally consistent with previous analyses in reporting ongoing trends in climate consistent with climate change projections and negative implications for salmon. A few studies focused on areas that did not receive much attention in our previous report, and thus provide new information. These areas include the expected loss of significant portions of the marine distribution, albeit it mainly in the second half of this century, the current risk of hypoxia in the Columbia River estuary, as well as documented and projected rates of evolutionary changes in migration timing. Disease impacts on migration survival documented in Fraser River sockeye warn of the potential for a very rapid decline in survival, unlike the linear projections generally forecasted, with little managerial recourse. Several papers demonstrated how cumulative effects of climate change over the entire life cycle are likely to be much higher than previously predicted from effects on individual life stages. Finally, new adaptation plans for the PNW are being developed but institutional barriers to climate change adaptation for some agencies and water use sectors create challenges for effective response.

Table of acronyms

A1B, A2, B1	Carbon emission scenarios from IPCC Fourth Assessment Report
AOGCM	Coupled Atmosphere-Ocean General Circulation Model
ENSO	El Niño-Southern Oscillation
GCM	General Circulation Model
IPCC	Intergovernmental Panel on Climate Change
PDO	Pacific Decadal Oscillation
PNW	Pacific Northwest
SST	Sea surface temperature

2 Goals and methods of this review

The goal of this review was to identify the literature published in 2011 that is most relevant to predicting impacts of climate change on Columbia River salmon listed under the Endangered Species Act. A large amount of literature related to this topic is not included, because almost anything that affects salmon at all relates to or is altered in some way by changes in temperature, stream flow or marine conditions. We have tried to identify the most directly related papers by combining climatic and salmonid terms in search criteria. Thus many general principles demonstrated in other taxa or with more general contexts in mind have been omitted. This review also does not include potentially relevant gray literature, because the search engine used only includes the major peer-reviewed scientific journals. In total, the methods employed involved review of over 500 papers. Of these, 135 are included in this summary.

This search was conducted in ISI Web of Science in July, 2012. Each set of search criteria involved a new search, and results were compared with previous searches to identify missing topics. The specific search criteria all included PY=2011, plus:

- 1) TS=(climat* OR temperature OR streamflow OR flow OR snowpack OR precipitation OR PDO) AND TS=(salmon OR Oncorhynchus OR steelhead);
- 2) TS=(climat* OR Temperature OR Precipitation OR streamflow OR flow) AND TS="Pacific Northwest";
- 3) TS=(marine OR sea level OR hyporheic OR groundwater) AND TS=climat* AND TS=(salmon OR Oncorhynchus OR steelhead);
- 4) TS=(upwelling OR estuary) AND TS=climat* AND TS=Pacific;
- 5) FT=("ocean acidification" OR "California current" OR "Columbia River")
- 6) TS="prespawn mortality"

The review is organized by first considering physical environmental conditions (historical trends and relationships) and then predictions of future climate, snowpack, stream flow, temperature, ocean conditions, etc. A summary follows of the literature on salmonid responses to these environmental conditions, progressing through the life cycle.

3 Climate

3.1 *Global, national, regional climate*

3.1.1 *1981-2010 U.S. “Normals”*

NOAA released a new set of “Normal” temperatures, i.e., 30-year average temperatures for the U.S for the 1981-2010 period (Arguez et al. 2012). The new normals include some methodological and station changes, and thus are not recommended for describing long-term trends in climate. Nonetheless, there is a striking increase in most of the indices. January minimum temperature has risen 2-4°F throughout the north-central US, with nearly the entire central US seeing at least 1°F increases compared with 1971-2000 normals. July maximum temperatures have increased at least 0.5°F in the entire West.

3.1.2 *State of the Climate 2011*

Despite the cooling effect of La Niña, 2011 was still one of the 15 warmest years on record and above the 1981-2010 average (Blunden and Arndt 2012). Global sea surface temperature (SST) was 0.1°C cooler than El Niño-driven 2010, but the global upper ocean heat content was still higher than for all prior years. Atmospheric CO₂ concentrations increased by 2.1ppm in 2011, exceeding 390ppm for the first time since instrumental records began. Together with increases in other greenhouse gases, radiative forcing is now 30% higher than in 1990. Ocean uptake of CO₂ was 12% below the long-term average. The Arctic continued to warm at twice the rate of lower latitudes, continuing extreme surface warming and net snow and ice loss on the Greenland ice sheet and the greatest loss in the Canadian Arctic since Gravity Recovery and Climate Experiment satellite measurements began. Arctic sea ice extent in September 2011 was the second-lowest on record, and 4-5yr old ice set a new record minimum of 19% of normal. Similar records were set in Antarctica.

The nationally-averaged summer temperature was the second warmest on record, but the Pacific Northwest (PNW) was cooler than average. The tornado season was one of the most destructive and deadly recorded, and historic flooding soaked much of the central US, surpassing the great floods of the 1920s and 1930s. The US also had a very active wildfire year (Blunden and Arndt 2012).

Observations of weather over the past 60 years (shifts in the position of warm and cold fronts across US) are consistent with projections of climate change associated with elevated greenhouse gas concentrations. The overall shift toward cold fronts and away from warm fronts across the northern US arises from a combination of an enhanced ridge over western North America and a northward shift of storm tracks throughout the mid-latitudes (Hondula and Davis 2011).

3.1.3 *Extreme events*

General circulation models (GCM) predict that anthropogenic forcing will increase the frequency of extreme events, such as heavy precipitation events, that cause massive flooding in the PNW. Min et al (2011) identified positive trends in extreme precipitation

events in GCM projections. These trends were most consistent in the anthropogenic-forcing experiment only (without natural forcing), because natural forcing over the 20th century would have led to decreases in extreme precipitation events in many areas, thus producing a weaker observed signal of the anthropogenic fingerprint (i.e., without correction for natural forcing). Statistical comparisons of model representations and observed data show that coarse-resolution models are not capable of capturing the frequency of extreme events, but regional climate models nested within them greatly improve the dynamics (Duliere et al. 2011). Note that in 2012 the Intergovernmental Panel on Climate Change (IPCC) released a thorough analysis of changes in the frequency of extreme events, which will be included in the 2012 literature review.

3.1.4 El Niño analysis and modelling

The 2009-2010 El Niño differed from classical El Niño because it exhibited a “Modoki phenomenon”, or a “warm-pool” El Niño, with most warming in the central Pacific but a rapid transition to La Niña in 2011. Kim et al (2011) postulate the “fast phase transition” is due to a very warm Indian ocean and record-high SST in the central Pacific (see also Barnard et al. 2011).

Much work has been dedicated to improving the oceanographic data going into climate models, e.g., from autonomous gliders (Todd et al. 2011), and the spatial resolution of coupled atmosphere-ocean general circulation models (AOGCM) (Dawson et al. 2011), so that the next round of the IPCC’s Fifth Assessment Report models should have better representation of El Niño-Southern Oscillation (ENSO).

The importance of El Niño modeling has been emphasized in many papers, particularly for the PNW. Paleological data indicates that the recent century has been unusually wet in the perspective of much longer time-series. Long-term droughts have occurred throughout the last 6000 years, especially during the last 1000 years. Shifts in the severity of both wet and dry multidecadal events appear to be driven by changes in the ENSO pattern, and its effect on the Pacific Decadal Oscillation (PDO) (Nelson et al. 2011).

3.2 Terrestrial

3.2.1 Historical trends in streamflow in PNW

Like previous studies, new analyses of historical trends in streamflow in the PNW emphasize the sensitivity of transitional watersheds (i.e., where precipitation falls as both snow and rain) and transitional elevations within watersheds to recent (and projected) warming. Specifically, in an analysis of 29 watersheds in the PNW (Jefferson 2011), transitional areas demonstrate the most significant historical trends (i.e., greater winter and lower summer discharge). Snow-dominated watersheds showed changes in the timing of runoff (22-27 days earlier) and lower low flows (5-9% lower) currently than in 1962. Peak flows increased in the more heavily snow-dominated watersheds exposed to more frequent rain-on-snow events at higher elevations, but there was no trend in most of the transient or rain-dominated watersheds.

A series of papers on the impact of climate, dams, water withdrawal, and other human impacts on the Columbia and Willamette Rivers demonstrate that 1) human factors dominate the change in outflow of the Columbia River over the 20th century (Jay and Naik 2011; Naik

and Jay 2011a), 2) climate factors, especially ENSO and the PDO, but also more fine-scale details about the timing of winter storms and spring warming rates also drive significant changes in the annual flow, as well as the detailed flow profile and winter and spring freshets (Naik and Jay 2011a), 3) sediment loads have been strongly reduced due mostly to flow management and withdrawals, but climate-driven flow reductions also lower sediment transport, which has negative impacts on juvenile salmon survival (Jay and Naik 2011; Naik and Jay 2011a).

Many papers explore how habitat generally and flow in particular are related to juvenile salmonid density or growth. We focus here only on those in the Columbia River Basin.

In the lower Columbia, low flows in summer and fall through a tidal channel in the lower Columbia River (from Portland, OR to Vancouver, WA) have gotten lower and tidal range has increased due to both tidal changes and river flow and harbor modifications (Jay et al. 2011).

In Idaho, water diversion patterns vary with water availability in the Snake River Plain over the past 35 years from 1971 to 2005 (Hoekema and Sridhar 2011). Overall trends of declining mid- and late-season diversion is due to lack of water supply due to lower summer flows. Diversions have increased in April in response to unusually wet springs.

In a study of temporal variability in stream habitat characteristics over nine years in 47 headwater streams, Al-Chokhachy et al (2011) used landscape, climate, and disturbance attributes as explanatory factors. Although the factors were significant, most of the variability was difficult to explain.

A high proportion of groundwater input to a basin significantly affects the flow regime. Streams in the Klamath Basin with major groundwater inflow have a smoother and delayed response to snowmelt. However, July to September baseflows decrease under climate change scenarios much faster than mostly surface-input streams (Mayer and Naman 2011).

3.2.2 Projected changes in stream flow and ice-cover

An analysis of how land-cover and climate change in the Puget Sound basin will drive hydrological change (Cuo et al. 2011) showed that land use, leading to younger vegetation and urbanization will likely have more impact at lower elevations than climate change alone. In the rain-snow transition zone, increased winter precipitation and less snow led to earlier winter and spring runoff, with increases in these seasons due to projected increases in precipitation. Reductions in late spring and summer runoff followed, but the net change was a slight increase in annual runoff. Land-cover change had greater impact on the total runoff, especially at lower elevations, due to an increase in impervious surfaces and loss of mature vegetation in forested areas.

Das et al (2011) explore the sensitivity of streamflow across the Columbia Basin (and three other basins) to the seasonality of warming. They find that annual streamflow is much more sensitive to warming in the summer than in the winter. This is because winter warming causes an initial increase in streamflow that partly compensates for the later low flows in the summer. Summer warming dries out soil immediately through greater evapotranspiration rates with no compensation during the next rainy season. Because the A2 scenario predicts

greater summer warming (5°C) than winter warming (3°C), this has a greater impact than uniform warming or a bias in the other direction would have. Application of a 2°C cool season warming and 4°C warm season warming produced a decline in annual streamflow of 9.8% in the Columbia Basin (Das et al. 2011). Work continues (Bohn, Sonessa et al. 2010) on the Variable Infiltration Model hydrology model, downscaling bias correction, and understanding how best to use multi-model ensembles compared with best-fitting individual models.

Scenarios of climate change in the Willamette Basin predicted increases in flows in winter (September through February), and decreases in summer (March through August, Jung and Chang 2011). The spring freshet is expected to advance seasonally, the 7-day low flows decrease, and peak flows increase due to winter flooding, especially at higher elevations.

Similar to watersheds and elevations in the rain-snow transition zone, lakes where winter ice cover is short with winter minimum temperatures closer to 0°C are most sensitive to warming. Weyhenmeyer et al (2011) predict that “3.7% of the world's lakes larger than 0.1 km² are at high risk of becoming open-water systems in the near future.”

In an analysis of uncertainty around flooding in urban areas, Jung et al (2011) explicitly focus on the uncertainty at all levels of modeling, from GCM model and emissions scenarios to land use change to hydrological model parameters and natural variability in climate. The development versus conservation land use scenarios in watersheds around Portland, OR made little difference to the overall projections, especially in the more developed watershed. In that watershed, hydrological parameters drove much more uncertainty than in the more pristine watershed. Uncertainty from GCM model structure (i.e., different GCMs) was larger than hydrological model uncertainty, and natural variability was larger still, especially at long flood frequencies. Overall, flood frequencies are expected to increase by the 2050s.

3.2.3 Fire

Simulations of PNW fire frequency in future climates predict large increases in the area burned (76%-310%) and burn severities (29%-41%) by the end of the twenty-first century (Rogers et al. 2011). The changing fire regime lowers carbon storage west of the Cascades in the absence of fire suppression, but raises it in the dry eastern PNW. Fire frequency is expected to increase in most areas of the PNW. Fire has a profound effect on stream temperature and nutrient input. An analysis of historical stream changes and trout response in burned and unburned areas of Montana showed stream temperatures increased 2-6°C right after the fire, but recovery by fish was generally swift (Sestrich et al. 2011).

3.3 Marine

3.3.1 ENSO

State of the California Current System 2010-2011: The 2009-2010 El Niño was relatively weak and short-lived, and it was quickly followed by La Niña. La Niña produced some record-breaking cool conditions throughout the California Current system, with anomalously strong upwelling in summer 2010. Impacts of both El Niño and La Niña were weaker and the transition between them was less abrupt off southern California compared

with off Washington and Oregon. Productivity in the pelagic ecosystem enhanced with La Niña off central and southern California, but El Niño-condition copepod assemblages persisted later in the northern California Current system (Bjorkstedt et al. 2011).

Heinemann et al (2011) developed a simplified ENSO and ecosystem (nutrient-phytoplankton-zooplankton) model that demonstrates how the ecosystem itself could moderate ENSO variability by the effect of phytoplankton on the absorption of shortwave radiation in the water column. This biological feedback to the climate system leads to (1) warming of the tropical Pacific, (2) reduction of the ENSO amplitude, and (3) prolonging the ENSO period. In a somewhat similar analysis, Lin et al (2011) showed that the spatial distribution of chlorophyll-a actually influences the mean state of the ocean in the tropical Pacific. Because chlorophyll-a blocks solar radiation to some extent, a shallow thermocline and stronger currents lead to decreased annual mean SST in the eastern equatorial Pacific. They conclude that the seasonal cycle of chlorophyll-a can dramatically change the ENSO period in the coupled model.

3.3.2 Sea Level Rise, wind speed and wave height

Sea level varies seasonally and with significant ocean phenomena, such as El Niño events. Determining whether there has been a significant rise in sea level must first, therefore, account for this effect. Komar et al (2011) separated out the seasonal trends in sea level in the PNW. Strong El Niño events dominate the winter record, but the more stable summer sea levels show statistically significant trends toward higher sea level.

Using satellite data, Young et al (2011) documented increasing oceanic wind speeds and wave height over 23 years globally, with a higher rate of increase in extreme events.

3.3.3 Upwelling

Most analyses published in 2011 found that upwelling has become more intense over the past century. The California Current System demonstrates two seasonal upwelling “modes” (Black et al. 2011). Summer upwelling shows longer frequency variation, reflecting multi-decadal processes. Significant linear trends over 64 years show the intensity of summer upwelling has increased at 39°N to 42°N. Winter upwelling reflects North Pacific Index and ENSO cycles. Chinook salmon growth-increment chronology correlated significantly with the summer upwelling mode (Black et al. 2011). Similarly, upwelling off British Columbia (Foreman et al. 2011) starts later and ends earlier, based on trends over the past 50 years. Nonetheless, cumulative upwelling and downwelling has significantly increased, because of the increase in intensity. The intensity of coastal upwelling off California, however, has not increased over the past 60 years (Pardo et al. 2011), based on SST and the upwelling index from the National Centers for Environmental Prediction/ National Center for Atmospheric Research reanalysis project database.

The effects of upwelling off the coast extend into the Columbia River estuary. Roegner et al (2011b) investigated whether the source of chlorophyll in the estuary was freshwater or marine. High flows in spring brought freshwater chlorophyll into the estuary, although production was relatively low. In the summer, upwelling winds transported

chlorophyll from the ocean. Tidal cycles determined stratification, which was higher during neap tides than spring tides.

3.3.4 Oxygen minimum zones and O₂ sensitivity

Oxygen minimum zones (OMZs), have been expanding over the 20th century. Studies of a 2.4-4.5°C warming event in the Miocene indicates that similar low oxygen conditions occurred at that time as have recently been observed (Belanger 2011). An analysis of anchovy and sardine oscillations indicates that oxygen levels, rather than temperature or food availability could be the primary factor driving anchovy/sardine oscillations in the Peruvian upwelling region (Bertrand et al. 2011).

The Columbia River estuary experiences low oxygen conditions (2mg/L) when strong upwelling combines with neap tides (Roegner et al. 2011a). Mortality caused by low oxygen is significantly increased by warmer water. In a meta-analysis, Vaquer-Sunyer and Duarte (2011) found that increasing temperature reduced marine benthic macrofauna survival times and increased minimum oxygen thresholds for survival by 74%, and 16%, respectively, on average. They project that 4°C ocean warming will lower survival times by 35.6% and raise minimum oxygen concentrations by 25.5%, potentially causing many more die-offs in the future.

A separate model of upwelling in an AOGCM predicts a reduction in the impact of OMZs from upwelling. Glessmer et al (Glessmer, Park et al. 2011) found that 25% less low oxygen water reached the surface in their double CO₂ scenario, compared with the current climate.

3.3.5 Ocean acidification

Ocean pH is often thought of as being fairly static, but Hofmann et al (2011) demonstrate very high spatial and temporal variability in diverse marine habitats. Others (Joint et al. 2011) similarly argue that natural variability is very high, pointing out that pH can change much more in freshwater lakes. Models of future pH and biological responses and feedbacks are still challenging (Tagliabue et al. 2011).

Much work has continued on the sensitivity of different organisms and life stages to ocean acidification. Gruber (2011) published an overview of the combined threats of ocean acidification, rising temperatures, and lowered oxygen levels. Many species have been studied in 2011, including herring (Franke and Clemmesen 2011), coral reef fishes (Munday et al. 2011a), clownfish (Munday et al. 2011b), an intact invertebrate community (Hale et al. 2011), crustaceans (Whiteley 2011) plus many studies on pteropods (Lischka et al. 2011) and phytoplankton (Low-DECarie et al. 2011). The results are mixed, but many stages and species are not especially sensitive. Pteropods are a concern for salmon because they are a prey item and have an aragonitic shell. They are sensitive to temperature increases in addition to rising acidity (Lischka et al. 2011).

3.3.6 Ecosystem effects

Large-scale climate factors and ocean chemistry drive the distribution and productivity of the entire marine biota. Factors such as the PDO, ENSO, and Northern Oscillation Index are strong predictors of larval fish concentration and diversity in the northern California Current (Auth et al. 2011). Upwelling indices are a significant predictor of herring and surf smelt catches in the Skagit River estuary (Reum et al. 2011). The Aleutian Low Pressure Index is correlated with seabird productivity and timing (Bond et al. 2011). Long-term trends in community composition this past century have been documented in a majority of time series of marine ecosystems. In a study of 300 biological time series from seven marine regions off western Europe, Spencer et al (Spencer et al. 2011) found most regions showed both long-term trends and regime shifts. Pollock, for example, changed its role in the food web during warm periods (Coyle et al. 2011). Regime shifts (i.e., a step in some measure of biological response over a short temporal interval or in response to a small physical change) are also widespread, although they might be overestimated by failure to account for temporal trends (Spencer et al. 2011).

Predicting how ecosystems will change with the climate typically relies on environmental correlates of organism distribution. Lenoir et al (2011) developed a model that explains observed shifts in the distribution of eight exploited fish in the North Atlantic, and projects that these species should continue to move northward, but some might be hindered by barriers and rate limitations. Finally, mesocosm experiments show how warming accelerates the phytoplankton bloom timing by about 1 day/°C, and decreases biomass (Sommer and Lewandowska 2011).

Using NOAA's Geophysical Fluid Dynamics Laboratory Earth System Model, Polovina et al (2011) project shifts in large marine ecosystems. They use modeled phytoplankton density to distinguish 3 biomes in the North Pacific. Under the A2 emissions scenario, the model predicts that temperate and equatorial upwelling biomes will occupy 34 and 28% less area by 2100. The subtropical biome, on the other hand, expands. Extending this change in area to primary productivity and fisheries catches, they expect a 38% decrease in the temperate biome, and a 26% increase in the subtropical biome catch.

An additional concern throughout the ecosystem is the increasing prevalence of persistent organic pollutants, especially polycyclic aromatic hydrocarbons from fossil fuel burning (De Laender et al. 2011). This direct source of pollution is a major concern for salmon, especially coho, in urban areas, but might become a more widespread marine phenomenon.

Jones (2011) discusses the potential for increasing marine productivity by enriching the oceans artificially with macronutrients (the Haber-Bosch process). He argues that phosphorus appears to limit the carbon storage capacity of nitrogen and hence additional new primary production.

3.3.7 Viruses

A typically overlooked consequence of global change is a potential increase in the impacts from viruses. Danovario et al (2011) review the very large impacts viruses have on phytoplankton, especially, but also throughout the ecosystem. They point out many positive

correlations between temperature (and other expected changes in ocean chemistry) and viral abundance, but the relationships are complicated and more work is needed.

3.4 Comparing rates of climate change in marine and terrestrial environments

Burrows et al (2011) compared the rates of historical climate change in marine and terrestrial environments. Focusing on the rates of temperature change that organisms might be expected to track through either range shifts or phenological change, they calculated the velocity of temperature change in terms of the latitudinal distance an isotherm has shifted (km/year), and the seasonal shift in spring and fall temperatures (days per year). These two quantities are ratios of the long-term temperature trend and either the spatial or temporal gradients across the landscape. Using these metrics, they found that although the absolute rate is a little slower in the ocean, because the spatial and seasonal gradients in temperature are shallower, the overall velocity and seasonal rates of change are faster for marine than terrestrial ecosystems, implying faster range shifts will be needed to track climate change. The ocean also differs from land because many ocean areas are cooling, especially in areas where upwelling has intensified, generating a bimodal distribution of rates of temperature change.

4 Salmon life-stage effects

4.1 Freshwater stages

4.1.1 Juvenile behavior and survival

Copeland and Meyer (2011) studied the correlations in juvenile salmonid density since 1985 in the Salmon and Clearwater River Basins. Densities in all six species were positively correlated, and flow and Chinook salmon redds were correlated with densities overall. For Chinook salmon, models with spawner density combined with either annual mean discharge or drought (Palmer Drought Severity Index) had similar Akaike information criterion (AIC) weights, and explained 52% of the variation.

Hypoxia limits the suitability of many nesting sites, and is often affected by changes in flow via deposition rate of fine sediments or flushing and groundwater infiltration. Malcolm et al (2011) found that interstitial velocity is not a good predictor of hyporheic dissolved oxygen. Miller et al (2011b) explore how rainbow trout compensate for low oxygen by altering their cardiac ontogenic program.

Heat tolerance varies by life stage in salmon. Breau et al (2011) show that differences in thermal-refuge-seeking behavior between age 0+ and age 1+ and 2+ Atlantic salmon stems from higher tolerance in respiration and cardiac performance in younger fish.

Given the dramatic changes in winter temperature expected throughout the PNW, it is a concern that winter ecology is not well understood. Stream environments create complicated ice dynamics that are very sensitive to fine scale variation in temperature and flow (Brown et al. 2011). Fish responses to thermally elevated areas overwinter (e.g., near nuclear power plants) sometimes have negative consequences for reproduction, but likely responses to long-term, gradual changes throughout the stream are not clear. Undercut banks are critical winter habitat for brook trout in small mountain stream, affected only slightly by winter flow reductions (Krimmer et al. 2011).

4.1.2 Juvenile growth

Salmon growth rates depend on temperature both directly because of temperature-governed chemical reaction rates, and indirectly because of elevated energetic demands of higher metabolic rates. Increased consumption can sometimes compensate for higher metabolic rates, leading to an interaction between ration and temperature effects. Geist et al (2011) tested the growth rate of Snake River fall Chinook below Hells Canyon Dam, and found high tolerance to short periods of high temperature (23°C) even at relatively low rations (down to 4% of body weight). However, at 1% ration, fish grew better at constant cool temperatures, suggesting that this low consumption rate was insufficient to cover metabolic costs of high temperatures. Natural consumption rates at this location are unknown. Steelhead in Los Angeles County grow year-round and produce large smolts, despite spending a week each year at mean temperatures over 22°C (Bell et al. 2011). It is important to note that although growth is sensitive to temperature, other factors, such as negative effects of fish density, can be more limiting (Bal et al. 2011).

Bioenergetic models are a primary means of analyzing changes in stream quality on growth. A crucial element of these models is the interaction between metabolic rate and energy supply through food consumption. Individual variation in bioenergetic parameters is generally ignored, but Armstrong et al (2011) show through a modelling exercise that this variation can significantly affect the impact of flow and food variability on growth.

Energetic rates were measured in rainbow trout exposed to various flows in a natural environment. The crucial difference between their environment and a typical laboratory set up was the existence of refuges from high flows, which allowed swim speed to decline at peak flows (Cocherell et al. 2011). Taguchi and Liao (2011) also explored how microhabitat utilization can be very energetically efficient.

By coupling a bioenergetic model with a simplified stream temperature model, Beer and Anderson (2011) demonstrate potential changes in Chinook and steelhead growth rates as a sensitivity analysis of change in mean air temperature and change in snowpack. They describe 4 characteristic stream types in the PNW -- warm winter and cool summer (North Santium); cold stream with high snowpack (Clearwater); warm summer with high snowpack (Salmon River) and warm summer with low snowpack (Snake River). They found that in the streams with cooler summers, warming and loss of snow increased growth rates, but in the warmer-summer streams, growth decreased.

4.1.3 Smolt behavior and survival

Bjornsson et al (2011) review physiological characteristics of smolting and environmental drivers. Acidification, as well as endocrine disruptors and other contaminants could lower survival through interfering with this carefully controlled process. Perkins and Jager (2011) created a development model for Snake River fall Chinook salmon that proposes a mechanism by which delayed growth leads to a yearling smolt behavior. This type of behavioral switch could make a big difference in population responses to climate change, but is hard to predict ahead of time. Other studies (Hayes et al. 2011) of California steelhead document different hormone levels between fish that smolt at different times over the season, and some fish that return upstream before smolting the following year. This rich variety of behavior will be crucial to effective responses to climate change.

Many anthropogenic habitat modifications have the potential to exacerbate effects of climate change on stream temperature. Smolt survival is often reduced at high temperatures, and due to direct and indirect effects of dam passage. Marschall et al (2011) explicitly modeled the interaction between delays at dams and exposure to high temperatures during smolt migration. Assuming that a threshold temperature causes fish to initiate migration in spring, they explore the range of initiation temperatures likely to ensure a successful migration with and without delays caused by dams. They find that even short delays at dams greatly reduce this window of opportunity. Particularly dangerous were irregular warm river sections that occurred downstream, and caused high delayed mortality (i.e., after successful passage through a dam) in late migrants. Their model is based on temperatures, flows, and migration distances measured in the Connecticut River for Atlantic salmon, but bears high relevance to Columbia River salmonids. Finally, conditions during smolting can affect maturation age. Exposure to elevated temp (16°C) and continuous light can trigger early maturation in male Atlantic salmon (Fjellidal et al. 2011).

4.1.4 Adult migration

The return to freshwater to spawn is a delicately timed behavior. Each population has adapted the timing of return to minimize mortality in freshwater prior to spawning, and to maximize fecundity which depends on marine growth and energetic expenditure during the migration, among other things. Migration mortality is closely tied to environmental conditions, especially temperature, experienced during the migration. Many papers published in 2011 explore the genetic and behavioral controls on timing and resulting mortality.

Adult migration timing in sockeye has been progressing earlier in the year in the Columbia River over the 20th century. Crozier et al (2011) explore how changes in river temperature and flow, as well as ocean conditions might be driving this advance. They found evidence that this trait evolved genetically due to mortality of late migrants exposed to higher Columbia River temperatures during the historical migration period. The fish also show a strong annual response to river flow, such that they migrate earlier in low-flow years. These two processes combined suggest both plastic and evolutionary responses are involved in an adaptive shift likely to continue in response to climate change. Genetic studies have identified candidate genetic markers in Columbia River adult Chinook salmon associated with run-timing (Hess and Narum 2011). Liedvogel et al (2011) review the genetics of migration more broadly.

Early migration in Adams and Weaver Creek sockeye in the Fraser River has a very different explanation and result, however. Early migrants in the Fraser experience very high temperatures and have high mortality, so the sudden change in behavior that began in 1995 has been hard to explain. Thomson and Hourston (2011) correlated early entry timing with weaker wind stress for Adams River stocks, and with lower surface salinity for Weaver Creek stocks. They postulate that both factors lead physiologically to earlier entry because the former entails easier swimming against weaker currents and the latter entails earlier osmoregulatory adaptation to freshwater, noting that early migrants were exposed to relatively fresh water earlier in the year.

Several genetic studies of Fraser River sockeye have found that gene expression varies systematically over the course of the migration (Evans et al. 2011), and that certain gene expression patterns were strongly correlated with mortality during the migration (Miller et al. 2011a). The genes that were upregulated are associated with the immune defense system, and the authors propose that viral infection might be to blame for the low survival. Other papers developed statistical correlates of migration survival for in-season fisheries management, in which temperature and flow were strong predictors of survival for some stocks, especially those exposed to harsher conditions (Cummings et al. 2011). Warmer water lowers catch-and-release survival (Gale et al. 2011), and might be important in interpreting tagging studies. A comparison of migration survival of fish tagged at sea versus those tagged in freshwater (which is much warmer) found that those tagged at sea had much higher survival (Martins et al. 2011).

The timing of the adult migration among Yukon River Chinook salmon is correlated with SST, air temperature and sea ice cover. As these factors change with climate change, migration is expected to occur earlier (Mundy and Evenson 2011).

Projected adult migrant survival

Several papers used observed survival of migrating Fraser River sockeye to project survival under future climate scenarios. Martins et al (2011) modeled 9-16% declines by the end of the century. Hague et al (2011) quantified the number of day per year that migrating fish will experience less optimal temperatures. They found that the number of days over 19°C tripled, reducing their aerobic scope to zero in some cases. They found that exposure varied within each run, such that there is potential for shifts in run-timing to drive adaptive responses to rising temperature. An individual-based simulation model of the evolutionary response to rising river temperatures with climate change showed that Fraser River sockeye with a reasonable heritability (0.5) would theoretically shift their migration 10 days earlier in response to 2°C warming. Nonetheless, this study did not generally predict extinction of these populations even if they did not respond to selection (Reed et al. 2011). But evolution in run timing has clearly occurred in Chinook salmon introduced to New Zealand, where populations from a common ancestry have diverged 18 days in their spawning-migration (Quinn et al. 2011).

Local adaptation and acclimation in heat tolerance

Evolution in response to rising temperatures could occur in adult migration timing, as discussed above, or in heat tolerance. Eliason et al (2011) studied variation in cardiac tissue. Local adaptation in thermal optima for aerobic, cardiac tissue and performance among populations migrating at different times through the Fraser River. They argue that the heart has adapted to population-specific migration temperatures, in addition to the length of migration. This is consistent with interspecific differences. Pink salmon have higher heat tolerance during migratory stages than sockeye (Clark et al. 2011). Similar differences can also reflect acclimation. Studies of cardiac tissue in rainbow trout identified very distinct morphology and tissue composition in distinct cold-acclimated and warm-acclimated fish (Klaiman et al. 2011).

4.2 *Marine stage*

4.2.1 *Marine survival*

Because ocean survival is the strongest correlate of population growth rate for most populations, understanding the factors that drive marine survival has been a high priority for decades.

The primary factors thought to govern survival are growing conditions, which are generally correlated with overall ocean productivity. In a new paper confirming and refining previously recognized patterns for PNW salmon, Bi et al (2011b) explore the relationship between coho early marine survival, copepod species composition, water transport in the California Current, and larger climatic indices (the PDO). Cold copepod biomass correlates with coho survival. Seasonally, they found that lipid-rich copepods associated with cool water are less abundant in the winter, when the current is coming predominantly from the south (“positive alongshore current”) and more abundant in summer, when current is coming from the north (“negative alongshore current”). At the annual and decadal scale, when the PDO is positive, more water comes from the south in winter; when PDO is negative, more water comes from north during summer. In a separate paper, Bi et al. (2011a) confirmed the spatial relationships between yearling Chinook and coho distributions and copepod assemblages. Both species are strongly positively correlated with the cold copepod assemblage and chlorophyll a concentration. Yearling coho had similar relationships, but also positively correlated with temperature. Nonetheless, the adult migration does not necessarily track annual variation in zooplankton location. Bristol Bay sockeye do not seem to vary their migration route among years in response to variation in marine productivity and temperature (Seeb et al. 2011).

Salmon growth and survival often correlates with SST (e.g., Norwegian Atlantic salmon growth at sea is positively correlated with SST in the Barents and Norwegian Seas (Jensen et al. 2011), and Japanese chum salmon growth is positively correlated with summer/fall SST in coastal areas while fish stay near shore, and off-shore temperatures later in the year (Saito et al. 2011). Much of the mortality is size-selective, with smaller fish having higher mortality rates. Size-selective mortality could stem from either an energetic constraint (insufficient resources to survive harsh conditions) or size-selective predation. In Alaskan sockeye, Farley et al (2011a) found that the energetic status of juvenile sockeye was adequate to survive winter, and suggest predation-avoidance behavior as a better explanation for size-selective mortality and ongoing energy loss. They suggest that higher temperatures in climate projections might lead to declines in age-0 pollock, a high quality prey for salmon, and lead to lower winter survival.

Marine survival is tightly linked to ocean conditions at the time of smolting. The Rivers Inlet sockeye population in British Columbia has been depressed since the 1990s. High flows in this river decrease marine productivity because the river is nutrient-poor. Thus the negative correlation between high river flow and marine survival appears to result from the impact of low nutrient, brackish water depressing marine plankton growth (Ainsworth et al. 2011b). This system-specific impact on marine productivity explains the difference

between a positive correlation for high-nutrient rivers, like the Columbia, and low-nutrient rivers like Rivers Inlet.

More broadly, salmon survival is often correlated with broader indicators of ecosystem productivity. Lower trophic level productivity generally supports better growth and survival all the way up the food chain. Borstad et al (2011) found that regional chlorophyll abundance in April, timing of spring wind transition and phytoplankton bloom are important for survival of Canadian Triangle Island sockeye salmon, sandlance and rhinoceros auklets.

4.2.2 Projected future marine habitat availability

In an important paper, Abdul-Aziz et al (2011) constructed maps of potential salmon marine distributions under climate change scenarios. They developed thermal niche models for summer and winter separately for five Pacific salmon species and steelhead based on high-seas catch records over the last 50 years. These are not mechanistically-determined range limits, e.g. through physiological constraints, and thus might not correlate with future distributions exactly the way they do now. It is likely that changes in the distribution of food availability will play a very large role in future distributions, which might depend on many factors. However, they do indicate how projected changes in SST translate into one characterization of potential salmon habitat. Historical analysis showed that salmon thermal habitat, using observed temperature ranges, changed very little over the 20th century. However, under the A1B and A2 emissions scenarios, the multi-model ensemble average SST imply a reduction in summer habitat for coho 5-32%, where the range goes from the 2020s to the 2080s, Chinook habitat declines 24-88%, and Steelhead habitat area declines 8-43%. Winter habitat area shows much less effect in these species, ranging from 0 to 10% for the 3 species and three future time periods. Sockeye had much greater sensitivity in their winter range, reducing from 6-41%. The B1 scenario had a similar result for 2020s and 2040s, but was less severe by 2080 (-66% for Chinook summer habitat, -21 to -24% for coho and steelhead summer, and 0 to -7% for all three species in winter). One reason for the high percentage reduction in Chinook summer habitat was that their historical absolute area was estimated to be much smaller in summer than the other species (7 million km² compared with 10-11 million km²). But the projection is for a complete loss of Gulf of Alaska habitat by the 2040s, and complete loss of Okhotsk Sea and Subarctic subdomains, and most of the Bering Sea habitat. There is a small extension into the Arctic Ocean that is not currently occupied, but net reductions vastly outweighed this potential expansion.

4.2.3 Ocean acidification

Two recent modeling papers explored the ecological impacts of ocean acidification and other aspects of climate change. Ainsworth et al. (2011a) predicted that ocean acidification may cause salmon landings to decrease in Southeast Alaska and Prince Williams Sound food webs and increase in Northern British Columbia and Northern California Current food webs. However, when the authors applied five impacts of global change to these food webs simultaneously (primary productivity, species range shifts,

zooplankton community size structure, ocean acidification, and ocean deoxygenation), projected salmon landings decreased in all locales (Ainsworth et al. 2011a). Incorporating ocean acidification and ocean deoxygenation into bioclimatic envelope models for harvested fishes in the Northeast Atlantic caused 20-30% declines in projected future harvest, likely due to reduced growth performance and faster range shifts (Cheung et al. 2011).

5 Higher-level processes

5.1 Population-level effects

Warming temperatures in Alaska have opened up potential habitat for colonization. Pink salmon and Dolly Varden were among the first fish to colonize one such stream in Glacier Bay (Milner et al. 2011). The stream community has developed over the past 30 years. Having robust populations at the edge of the current range to provide colonists facilitates range expansion.

5.2 Diseases

The negative impact of multiple stressors, such as UV-B exposure and high temperatures, on immune function, together with predicted increases in pathogen load in warmer waters resulting from global climate change, suggest an increased risk of diseases in fishes (Jokinen et al. 2011). De Eyto et al (2011) show that selection on immunological adaptation at the major histocompatibility genes in Atlantic salmon varied with life stage and were strongly correlated with juvenile survival. They emphasize the importance of maintaining genetic diversity to evolve in response to novel disease pressures expected to result from climate change.

Many diseases are more prevalent or virulent at warmer temperatures. Salmonid parasites often require intermediate hosts, and parasite risk to fish can be lower in areas unsuitable for the other host. *Tubifex tubifex*, the host of whirling disease, cannot tolerate very hot streams affected by geothermal processes in Yellowstone National Park, thus reducing infection of rainbow trout in these reaches (Alexander et al. 2011). However, some expected negative effects of rising temperatures have not been detected. In an Alaskan stream summer water temperature has increased 1.9°C over the past 46 years. However, the presumed increase in consumption rates in sockeye has not led to an increase in tapeworm load (Bentley and Burgner 2011). Algal blooms are affected by environmental conditions, and can kill large numbers of fish. When an algal bloom moved through a fish farm in New Zealand, a large fish kill occurred (MacKenzie et al. 2011). The extent to which wild fish could have avoided the bloom is unknown.

5.3 Population declines and variability attributed to climatic factors

A fairly rare but important element of evaluating the importance of environmental effects is a comparison between environmental and anthropogenic or a variety of alternative hypotheses. Most studies look at only a single type of explanation – i.e., they just compare environmental effects. But Otero et al (2011) conducted a comprehensive analysis of the catch of Atlantic

grilse over the whole length of the Norwegian coast as a function of environmental effects during the smolt stage and the return migration, marine, and anthropogenic (fish farms, fishery, dams) potential driving factors. They find water temperature and flow interact with dams to shape catches, and aquaculture and fisheries have negative effects.

Many spring and fall run Chinook salmon populations have been extirpated from the Central Valley of California. Migration barriers completely explain Central Valley California fall Chinook extirpation, but for spring Chinook, habitat loss and altered flow regimes, especially enhanced summer flows, predicted extirpation (Zeug et al. 2011). An analysis of population extinction of Sakhalin taimen (*Parahucho perryi*) in Japan showed that in comparing populations that ranged from extinct to endangered to extant, lower air temperatures and minimal agricultural development set extant populations apart. Lagoons also provided refugia (Fukushima et al. 2011).

When fisheries alter the age structure of a population, it can lose some of its resiliency to environmental variation. Long-term shifts toward a shorter generation time, and reduced age overlap within the population adds variability to population growth rates. Environmental conditions driving that variability thus become more important. Cod show increasing sensitivity to environmental fluctuations, which could ultimately make climate impacts more severe (Rouyer et al. 2011). Age structure can also be important if generation time coincides with the periodicity of a key environmental driving factor. Age-structured models with periodic environmental forcing and fishing pressure generate the cohort resonance effect, which can drive much more variability in population abundance than predicted by an ecosystem or stage-structured model if the frequency of the forcing factor is close to the mean age of reproduction (Botsford et al. 2011).

5.4 Projected cumulative effects throughout the life cycle

A holistic perspective demonstrates that climate change will pose significant stress not just on one or two stages, but potentially on every life stage. Healy (2011) outlines adverse impacts throughout the life cycle, as well as pointing out how responses in one stage can carry over and affect survival or growth in a subsequent stage, and even subsequent generations. Cumulatively, he argues they pose enormous risk for Fraser River sockeye. Healy also lists management and policy responses that would reduce these stresses by life stage.

Elevated temperatures often inhibit reproduction. Pankhurst and Munday (2011) review the entire suite of known endocrine effects in salmonids, as well as the diverse sensitivities in juvenile stages as well. They emphasize that the ramifications of chemical, thermal and hydrological change will be complex and pervasive throughout the life cycle and geographic range of these fish.

5.5 Species interactions

Wenger et al (2011) used thermal criteria, flow frequency, and interaction strengths with other salmonids to predict habitat availability for all trout in the interior west under climate change scenarios. Under A1B scenarios, average habitat decline across all species is 47%. Brook trout loses the most habitat (77%) and rainbow trout the least (35%). Species

interactions shaped the outcome negatively for some species and positively for others. It does demonstrate that considering species interactions could significantly alter predicted responses to climate change.

Temperature gradients cause variation in salmon behavior that can either enhance ecosystem productivity, or reduce it. The large spread in Alaskan sockeye salmon spawn timing due to thermal differences among streams supports most of the growth in rainbow trout, who eat salmon eggs over a relatively long temporal window in the fall (Ruff et al. 2011). On the other hand, a study of paleoecological and recent lake productivity in Tuya Lake, British Columbia revealed an interaction between salmon consumption and warming, such that salmon enhanced climate-induced nitrogen deficiencies (Selbie et al. 2011). They emphasize that ecosystem structure is very sensitive to temperature.

6 Human adaptation

Extensive work explores adaptation responses to climate change. This literature is mostly beyond the scope of this review, but we just highlight a few examples here. Several papers concentrate on human responses to climate change. A comprehensive review of marine and aquatic vulnerabilities, adaptation strategies, and existing adaptation plans in the PNW was drafted in 2011 (National Wildlife Federation 2011). This report identified common elements of adaptation plans in the PNW and elsewhere, including: remove other threats and reduce non-climate stressors that interact negatively with climate change or its effects; establish or increase habitat buffer zones and corridors; increase monitoring and facilitate management under uncertainty, including scenario-based planning and adaptive management. The report includes additional approaches from available literature in the broad areas of information gathering and capacity building; monitoring and planning; infrastructure and development; governance, policy, and law; and, conservation, restoration, protection and natural resource management. This information is intended to guide development of climate change adaptation strategies through the North Pacific Landscape Conservation Cooperative. At the national level, adaptation strategies have been proposed for ecosystems including coastal and aquatic systems affecting salmonids (USFWS et al. 2011). The draft inland aquatic ecosystems strategy focuses on protecting and restoring existing habitat; maintaining ecosystem functions that will continue to provide benefits in a changing climate; reducing impacts of non-climate stressors; and including climate considerations in resource management planning, monitoring, and outreach programs. A final national adaptation strategy is expected in 2012. Safford and Norman (2011) describe the institutional forces that shape the way recovery planning groups in Puget Sound develop plans to manage water to improve salmon survival. They found that asymmetrical roles (e.g., tribal veto power), coupled with lack of explicit support for tribal sovereignty (which might reduce the likelihood of tribal vetoes) contribute to institutional problems. Similarly, allowing technical planners to also contribute to citizen committees reduces the ability of the planning groups to achieve diverse social and technical objectives. The lack of broader participation has generally led to calls for increasing water supply for salmon, but there has been a lack of concrete recommendations for accomplishing this. Farley et al (2011b) describe capacity for institutional responses to climate change among four water sectors in Oregon's McKenzie River basin and found that some sectors have more flexibility (e.g., fish habitat recovery and flood control) than others (e.g., municipal water and fishing guides) for

responding to climate change. Hamlet (2011) also examines institutional capacity for water management adaptation, and finds that, although existing institutions have resources to deal with moderate changes, substantial obstacles to climate change adaptation exist for large and complex systems such as the Columbia River basin. Lack of a centralized authority for water management decisions, layers of existing laws and regulations, and lack of specificity in some management plans contribute to this concern. He suggests that the most progress in large systems may be expected at smaller geographical scales such as subbasins. He does note that in the last several years, significant progress has been made in surmounting some of these obstacles, and the PNW region's water resources agencies at all levels of governance are making progress in addressing the fundamental challenges inherent in adapting to climate change. Thorpe and Stanley (2011) emphasize that restoration goals must focus on building resilient functioning ecosystems with the capacity to respond to climate change, rather than historical models. Two papers project stress on regional and urban water supplies (House-Peters and Chang 2011; Traynham et al. 2011). House-Peters and Chang (2011) identify potential solutions through dense development in urban areas and tree planting. Koehn et al (2011) review the major impacts of climate change on fishes, and step through potential adaptation measures. *Scanning the Conservation Horizon: A Guide to Climate Change Vulnerability Assessment* is a document produced by the NWF that provides an overview of species and ecosystem sensitivity, exposure, and vulnerability to climate change. They propose a systematic approach to evaluating risks and selecting conservation measures that most efficiently address those risks (Glick et al. 2011).

6.1 Human impact on stream temperature

A review paper (Hester and Doyle 2011) on human impacts on stream temperature describes the most common actions with thermal impacts and calculates the mean temperature change reported. The actions summarized are: loss of riparian shading, loss of upland forest, reductions of groundwater exchange, increased width-to-depth ratio, input of effluent discharges, diversion of tributary input, releases from below the thermocline of reservoirs, and global warming. Cold water reservoir releases in summer were the primary means of cooling streams, although diverting warm tributaries can also lower stream temperatures. Hester and Doyle (2011) also collected thermal performance curves for stream and river species. They summarized the amount of temperature change from the thermal optimum to 50% performance (growth, development, reproductive activity, or survival) both above and below the optimum. They found that most performance curves are asymmetrical, and that most species are more sensitive to temperatures above the optimum (typical breadth from optimum to 50% for fish is about 4°C above the optimum, and 6°C below the optimum). Most human impacts shift temperature less than 5°C, but reservoir releases, riparian shading and changes in groundwater exchange can change stream temperature up to 12-14°C.

In a review of the impact of logging on stream temperature in the Oregon Coast Range, Groom et al (2011b) found that maximum, mean, minimum, and diel fluctuations in summer stream temperature increased with a reduction in shade, longer treatment reaches, and low gradient. Shade was best predicted by riparian basal area and tree height. In a

separate paper, Groom et al (2011a) found that typical logging practices on private land generally caused streams to exceed water quality thresholds, but that recent management rules successfully lowered this probability greatly.

Some rivers have management options for lowering stream temperature over a short period of time, which can be crucial for preventing lethal temperatures for fish. For example, Lewiston Dam can release cold water into the Klamath; water can also be protected from withdrawals. These methods can be effective if they are timed precisely. A simulation study found short-term (7-10 day) water temperature forecasts prove useful for increasing fish production in the Klamath and John Day Rivers (Huang et al. 2011).

7 Literature cited

- Abdul-Aziz, O. I., N. J. Mantua, and K. W. Myers. 2011. Potential climate change impacts on thermal habitats of Pacific salmon (*Oncorhynchus* spp.) in the North Pacific Ocean and adjacent seas. *Canadian Journal of Fisheries and Aquatic Sciences* 68:1660-1680.
- Ainsworth, C. H., J. F. Samhouri, D. S. Busch, W. W. L. Chueng, J. Dunne, and T. A. Okey. 2011a. Potential impacts of climate change on Northeast Pacific marine fisheries and food webs. *ICES Journal of Marine Science* 68:1217-1229.
- Ainsworth, L. M., R. Routledge, and J. Cao. 2011b. Functional Data Analysis in Ecosystem Research: The Decline of Oweekeno Lake Sockeye Salmon and Wannock River Flow. *Journal of Agricultural Biological and Environmental Statistics* 16:282-300.
- Al-Chokhachy, R., B. B. Roper, E. K. Archer, and S. Miller. 2011. Quantifying the Extent of and Factors Associated with the Temporal Variability of Physical Stream Habitat in Headwater Streams in the Interior Columbia River Basin. *Transactions of the American Fisheries Society* 140:399-414.
- Alexander, J. D., B. L. Kerans, T. M. Koel, and C. Rasmussen. 2011. Context-specific parasitism in *Tubifex tubifex* in geothermally influenced stream reaches in Yellowstone National Park. *Journal of the North American Benthological Society* 30:853-867.
- Arguez, A., I. Durre, S. Applequist, R. S. Vose, M. F. Squires, X. Yin, R. R. Heim et al. 2012. NOAA's 1981–2010 U.S. Climate Normals: An Overview. *Bulletin of the American Meteorological Society*.
- Armstrong, J. D., K. J. Millidine, and N. B. Metcalfe. 2011. Ecological consequences of variation in standard metabolism and dominance among salmon parr. *Ecology of Freshwater Fish* 20:371-376.
- Auth, T. D., R. D. Brodeur, H. L. Soulen, L. Ciannelli, and W. T. Peterson. 2011. The response of fish larvae to decadal changes in environmental forcing factors off the Oregon coast. *Fisheries Oceanography* 20:314-328.
- Bal, G., E. Rivot, E. Prevost, C. Piou, and J. L. Bagliniere. 2011. Effect of water temperature and density of juvenile salmonids on growth of young-of-the-year Atlantic salmon *Salmo salar*. *Journal of Fish Biology* 78:1002-1022.
- Barnard, P. L., J. Allan, J. E. Hansen, G. M. Kaminsky, P. Ruggiero, and A. Doria. 2011. The impact of the 2009-10 El Niño Modoki on US West Coast beaches. *Geophysical Research Letters* 38.
- Beer, W. N., and J. J. Anderson. 2011. SENSITIVITY OF JUVENILE SALMONID GROWTH TO FUTURE CLIMATE TRENDS. *River Research and Applications* 27:663-669.
- Belanger, C. L. 2011. Coastal dysoxia accompanies Early Miocene warming based on benthic foraminiferal and sedimentary records from Oregon. *Marine Micropaleontology* 80:101-113.

- Bell, E., S. M. Albers, J. M. Krug, and R. Dagit. 2011. Juvenile growth in a population of southern California steelhead (*Oncorhynchus mykiss*). *California Fish and Game* 97:25-35.
- Bentley, K. T., and R. L. Burgner. 2011. An assessment of parasite infestation rates of juvenile sockeye salmon after 50 years of climate warming in southwest Alaska. *Environmental Biology of Fishes* 92:267-273.
- Bertrand, A., A. Chaigneau, S. Peraltilla, J. Ledesma, M. Graco, F. Monetti, and F. P. Chavez. 2011. Oxygen: A Fundamental Property Regulating Pelagic Ecosystem Structure in the Coastal Southeastern Tropical Pacific. *Plos One* 6.
- Bi, H. S., W. T. Peterson, J. Lamb, and E. Casillas. 2011a. Copepods and salmon: characterizing the spatial distribution of juvenile salmon along the Washington and Oregon coast, USA. *Fisheries Oceanography* 20:125-138.
- Bi, H. S., W. T. Peterson, and P. T. Strub. 2011b. Transport and coastal zooplankton communities in the northern California Current system. *Geophysical Research Letters* 38.
- Bjorkstedt, E. P., R. Goericke, S. McClatchie, E. Weber, W. Watson, N. Lo, B. Peterson et al. 2011. State of the California Current 2010-2011: Regionally variable responses to a strong (but fleeting?) La Nina. *California Cooperative Oceanic Fisheries Investigations Reports* 52:36-68.
- Bjornsson, B. T., S. O. Stefansson, and S. D. McCormick. 2011. Environmental endocrinology of salmon smoltification. *General and Comparative Endocrinology* 170:290-298.
- Black, B. A., I. D. Schroeder, W. J. Sydeman, S. J. Bograd, B. K. Wells, and F. B. Schwing. 2011. Winter and summer upwelling modes and their biological importance in the California Current Ecosystem. *Global Change Biology* 17:2536-2545.
- Blunden, J., and D. S. Arndt. 2012. State of the Climate in 2011. *Bulletin of the American Meteorological Society* 93:S1-S282.
- Bond, A. L., I. L. Jones, W. J. Sydeman, H. L. Major, S. Minobe, J. C. Williams, and G. V. Byrd. 2011. Reproductive success of planktivorous seabirds in the North Pacific is related to ocean climate on decadal scales. *Marine Ecology-Progress Series* 424:205-U218.
- Borstad, G., W. Crawford, J. M. Hipfner, R. Thomson, and K. Hyatt. 2011. Environmental control of the breeding success of rhinoceros auklets at Triangle Island, British Columbia. *Marine Ecology-Progress Series* 424:285-302.
- Botsford, L. W., M. D. Holland, J. F. Samhuri, J. W. White, and A. Hastings. 2011. Importance of age structure in models of the response of upper trophic levels to fishing and climate change. *Ices Journal of Marine Science* 68:1270-1283.
- Breau, C., R. A. Cunjak, and S. J. Peake. 2011. Behaviour during elevated water temperatures: can physiology explain movement of juvenile Atlantic salmon to cool water? *Journal of Animal Ecology* 80:844-853.
- Brown, R. S., W. A. Hubert, and S. F. Daly. 2011. A Primer on Winter, Ice, and Fish: What Fisheries Biologists Should Know about Winter Ice Processes and Stream-Dwelling Fish. *Fisheries* 36:8-26.

- Burrows, M. T., D. S. Schoeman, L. B. Buckley, P. Moore, E. S. Poloczanska, K. M. Brander, C. Brown et al. 2011. The Pace of Shifting Climate in Marine and Terrestrial Ecosystems. *Science* 334:652-655.
- Cheung, W. W. L., J. Dunne, J. L. Sarmiento, and D. Pauly. 2011. Integrating ecophysiology and plankton dynamics into projected maximum fisheries catch potential under climate change in the Northeast Atlantic. *ICES Journal of Marine Science: Journal du Conseil* 68:1008-1018.
- Clark, T. D., K. M. Jeffries, S. G. Hinch, and A. P. Farrell. 2011. Exceptional aerobic scope and cardiovascular performance of pink salmon (*Oncorhynchus gorbuscha*) may underlie resilience in a warming climate. *Journal of Experimental Biology* 214:3074-3081.
- Cocherell, S. A., D. E. Cocherell, G. J. Jones, J. B. Miranda, L. C. Thompson, J. J. Cech, and A. P. Klimley. 2011. Rainbow trout *Oncorhynchus mykiss* energetic responses to pulsed flows in the American River, California, assessed by electromyogram telemetry. *Environmental Biology of Fishes* 90:29-41.
- Copeland, T., and K. A. Meyer. 2011. Interspecies Synchrony in Salmonid Densities Associated with Large-Scale Bioclimatic Conditions in Central Idaho. *Transactions of the American Fisheries Society* 140:928-942.
- Coyle, K. O., L. B. Eisner, F. J. Mueter, A. I. Pinchuk, M. A. Janout, K. D. Cieciel, E. V. Farley et al. 2011. Climate change in the southeastern Bering Sea: impacts on pollock stocks and implications for the oscillating control hypothesis. *Fisheries Oceanography* 20:139-156.
- Crozier, L. G., M. D. Scheuerell, and R. W. Zabel. 2011. Using Time Series Analysis to Characterize Evolutionary and Plastic Responses to Environmental Change: A Case Study of a Shift toward Earlier Migration Date in Sockeye Salmon. *American Naturalist* 178:755-773.
- Cummings, J. W., M. J. Hague, D. A. Patterson, and R. M. Peterman. 2011. The Impact of Different Performance Measures on Model Selection for Fraser River Sockeye Salmon. *North American Journal of Fisheries Management* 31:323-334.
- Cuo, L., T. K. Beyene, N. Voisin, F. G. Su, D. P. Lettenmaier, M. Alberti, and J. E. Richey. 2011. Effects of mid-twenty-first century climate and land cover change on the hydrology of the Puget Sound basin, Washington. *Hydrological Processes* 25:1729-1753.
- Danovaro, R., C. Corinaldesi, A. Dell'Anno, J. A. Fuhrman, J. J. Middelburg, R. T. Noble, and C. A. Suttle. 2011. Marine viruses and global climate change. *Fems Microbiology Reviews* 35:993-1034.
- Das, T., D. W. Pierce, D. R. Cayan, J. A. Vano, and D. P. Lettenmaier. 2011. The importance of warm season warming to western US streamflow changes. *Geophysical Research Letters* 38.
- Dawson, A., A. J. Matthews, and D. P. Stevens. 2011. Rossby wave dynamics of the North Pacific extra-tropical response to El Nino: importance of the basic state in coupled GCMs. *Climate Dynamics* 37:391-405.
- de Eyto, E., P. McGinnity, J. Huisman, J. Coughlan, S. Consuegra, K. Farrell, C. O'Toole et al. 2011. Varying disease-mediated selection at different life-history stages of Atlantic salmon in fresh water. *Evolutionary Applications* 4:749-762.

- De Laender, F., J. Hammer, A. J. Hendriks, K. Soetaert, and C. R. Janssen. 2011. Combining Monitoring Data and Modeling Identifies PAHs as Emerging Contaminants in the Arctic. *Environmental Science & Technology* 45:9024-9029.
- Duliere, V., Y. X. Zhang, and E. P. Salathe. 2011. Extreme Precipitation and Temperature over the U.S. Pacific Northwest: A Comparison between Observations, Reanalysis Data, and Regional Models. *Journal of Climate* 24:1950-1964.
- Eliason, E. J., T. D. Clark, M. J. Hague, L. M. Hanson, Z. S. Gallagher, K. M. Jeffries, M. K. Gale et al. 2011. Differences in Thermal Tolerance Among Sockeye Salmon Populations. *Science* 332:109-112.
- Evans, T. G., E. Hammill, K. Kaukinen, A. D. Schulze, D. A. Patterson, K. K. English, J. M. R. Curtis et al. 2011. Transcriptomics of environmental acclimatization and survival in wild adult Pacific sockeye salmon (*Oncorhynchus nerka*) during spawning migration. *Molecular Ecology* 20:4472-4489.
- Farley, E. V., A. Starovoytov, S. Naydenko, R. Heintz, M. Trudel, C. Guthrie, L. Eisner et al. 2011a. Implications of a warming eastern Bering Sea for Bristol Bay sockeye salmon. *Ices Journal of Marine Science* 68:1138-1146.
- Farley, K. A., C. Tague, and G. E. Grant. 2011b. Vulnerability of water supply from the Oregon Cascades to changing climate: Linking science to users and policy. *Global Environmental Change-Human and Policy Dimensions* 21:110-122.
- Fjellidal, P. G., T. Hansen, and T. S. Huang. 2011. Continuous light and elevated temperature can trigger maturation both during and immediately after smoltification in male Atlantic salmon (*Salmo salar*). *Aquaculture* 321:93-100.
- Foreman, M. G. G., B. Pal, and W. J. Merryfield. 2011. Trends in upwelling and downwelling winds along the British Columbia shelf. *Journal of Geophysical Research-Oceans* 116.
- Franke, A., and C. Clemmesen. 2011. Effect of ocean acidification on early life stages of Atlantic herring (*Clupea harengus* L.). *Biogeosciences* 8:3697-3707.
- Fukushima, M., H. Shimazaki, P. S. Rand, and M. Kaeriyama. 2011. Reconstructing Sakhalin Taimen *Parahucho perryi* Historical Distribution and Identifying Causes for Local Extinctions. *Transactions of the American Fisheries Society* 140:1-13.
- Gale, M. K., S. G. Hinch, E. J. Eliason, S. J. Cooke, and D. A. Patterson. 2011. Physiological impairment of adult sockeye salmon in fresh water after simulated capture-and-release across a range of temperatures. *Fisheries Research* 112:85-95.
- Geist, D. R., Z. Q. Deng, R. P. Mueller, V. Cullinan, S. Brink, and J. A. Chandler. 2011. The Effect of Fluctuating Temperatures and Ration Levels on the Growth of Juvenile Snake River Fall Chinook Salmon. *Transactions of the American Fisheries Society* 140:190-200.
- Glessmer, M. S., W. Park, and A. Oschlies. 2011. Simulated reduction in upwelling of tropical oxygen minimum waters in a warmer climate. *Environmental Research Letters* 6.
- Glick, P., B. A. Stein, and N. A. Edelson. 2011. *Scanning the Conservation Horizon: A Guide to Climate Change Vulnerability Assessment*. Washington, D.C., National Wildlife Federation.

- Groom, J. D., L. Dent, and L. J. Madsen. 2011a. Stream temperature change detection for state and private forests in the Oregon Coast Range. *Water Resources Research* 47.
- Groom, J. D., L. Dent, L. J. Madsen, and J. Fleuret. 2011b. Response of western Oregon (USA) stream temperatures to contemporary forest management. *Forest Ecology and Management* 262:1618-1629.
- Gruber, N. 2011. Warming up, turning sour, losing breath: ocean biogeochemistry under global change. *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences* 369:1980-1996.
- Hague, M. J., M. R. Ferrari, J. R. Miller, D. A. Patterson, G. L. Russell, A. P. Farrell, and S. G. Hinch. 2011. Modelling the future hydroclimatology of the lower Fraser River and its impacts on the spawning migration survival of sockeye salmon. *Global Change Biology* 17:87-98.
- Hale, R., P. Calosi, L. McNeill, N. Mieszkowska, and S. Widdicombe. 2011. Predicted levels of future ocean acidification and temperature rise could alter community structure and biodiversity in marine benthic communities. *Oikos* 120:661-674.
- Hamlet, A. F. 2011. Assessing water resources adaptive capacity to climate change impacts in the Pacific Northwest Region of North America. *Hydrology and Earth System Sciences* 15:1427-1443.
- Hayes, S. A., M. H. Bond, C. V. Hanson, A. W. Jones, A. J. Ammann, J. A. Harding, A. L. Collins et al. 2011. Down, up, down and "smolting" twice? Seasonal movement patterns by juvenile steelhead (*Oncorhynchus mykiss*) in a coastal watershed with a bar closing estuary. *Canadian Journal of Fisheries and Aquatic Sciences* 68:1341-1350.
- Healey, M. 2011. The cumulative impacts of climate change on Fraser River sockeye salmon (*Oncorhynchus nerka*) and implications for management. *Canadian Journal of Fisheries and Aquatic Sciences* 68:718-737.
- Heinemann, M., A. Timmermann, and U. Feudel. 2011. Interactions between marine biota and ENSO: a conceptual model analysis. *Nonlinear Processes in Geophysics* 18:29-40.
- Hess, J. E., and S. R. Narum. 2011. Single-Nucleotide Polymorphism (SNP) Loci Correlated with Run Timing in Adult Chinook Salmon from the Columbia River Basin. *Transactions of the American Fisheries Society* 140:855-864.
- Hester, E. T., and M. W. Doyle. 2011. Human Impacts to River Temperature and Their Effects on Biological Processes: A Quantitative Synthesis. *Journal of the American Water Resources Association* 47:571-587.
- Hoekema, D. J., and V. Sridhar. 2011. Relating climatic attributes and water resources allocation: A study using surface water supply and soil moisture indices in the Snake River basin, Idaho. *Water Resources Research* 47.
- Hofmann, G. E., J. E. Smith, K. S. Johnson, U. Send, L. A. Levin, F. Micheli, A. Paytan et al. 2011. High-Frequency Dynamics of Ocean pH: A Multi-Ecosystem Comparison. *Plos One* 6.
- Hondula, D. M., and R. E. Davis. 2011. Climatology of winter transition days for the contiguous USA, 1951-2007. *Theoretical and Applied Climatology* 103:27-37.

- House-Peters, L. A., and H. Chang. 2011. Modeling the impact of land use and climate change on neighborhood-scale evaporation and nighttime cooling: A surface energy balance approach. *Landscape and Urban Planning* 103:139-155.
- Huang, B., C. Langpap, and R. M. Adams. 2011. Using instream water temperature forecasts for fisheries management: an application in the Pacific Northwest. *Journal of the American Water Resources Association* 47:861-876.
- Jay, D. A., K. Leffler, and S. Degens. 2011. Long-Term Evolution of Columbia River Tides. *Journal of Waterway Port Coastal and Ocean Engineering-Asce* 137:182-191.
- Jay, D. A., and P. K. Naik. 2011. Distinguishing human and climate influences on hydrological disturbance processes in the Columbia River, USA. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques* 56:1186-1209.
- Jefferson, A. J. 2011. Seasonal versus transient snow and the elevation dependence of climate sensitivity in maritime mountainous regions. *Geophysical Research Letters* 38.
- Jensen, A. J., P. Fiske, L. P. Hansen, B. O. Johnsen, K. A. Mork, and T. F. Naesje. 2011. Synchrony in marine growth among Atlantic salmon (*Salmo salar*) populations. *Canadian Journal of Fisheries and Aquatic Sciences* 68:444-457.
- Joint, I., S. C. Doney, and D. M. Karl. 2011. Will ocean acidification affect marine microbes? *Isme Journal* 5:1-7.
- Jokinen, I. E., H. M. Salo, E. Markkula, K. Rikalainen, M. T. Arts, and H. I. Browman. 2011. Additive effects of enhanced ambient ultraviolet B radiation and increased temperature on immune function, growth and physiological condition of juvenile (parr) Atlantic Salmon, *Salmo salar*. *Fish & Shellfish Immunology* 30:102-108.
- Jones, I. S. F. 2011. Contrasting micro- and macro-nutrient nourishment of the ocean. *Marine Ecology-Progress Series* 425:281-296.
- Jung, I. W., and H. J. Chang. 2011. Assessment of future runoff trends under multiple climate change scenarios in the Willamette River Basin, Oregon, USA. *Hydrological Processes* 25:258-277.
- Kim, W., S. W. Yeh, J. H. Kim, J. S. Kug, and M. Kwon. 2011. The unique 2009-2010 El Nino event: A fast phase transition of warm pool El Nino to La Nina. *Geophysical Research Letters* 38.
- Klaiman, J. M., A. J. Fenna, H. A. Shiels, J. Macri, and T. E. Gillis. 2011. Cardiac Remodeling in Fish: Strategies to Maintain Heart Function during Temperature Change. *Plos One* 6.
- Koehn, J. D., A. J. Hobday, M. S. Pratchett, and B. M. Gillanders. 2011. Climate change and Australian marine and freshwater environments, fishes and fisheries: synthesis and options for adaptation. *Marine and Freshwater Research* 62:1148-1164.
- Komar, P. D., J. C. Allan, and P. Ruggiero. 2011. Sea Level Variations along the U.S. Pacific Northwest Coast: Tectonic and Climate Controls. *Journal of Coastal Research* 27:808-823.
- Krimmer, A. N., A. J. Paul, A. Hontela, and J. B. Rasmussen. 2011. Behavioural and physiological responses of brook trout *Salvelinus fontinalis* to midwinter flow

- reduction in a small ice-free mountain stream. *Journal of Fish Biology* 79:707-725.
- Lenoir, S., G. Beaugrand, and É. Lecuyer. 2011. Modelled spatial distribution of marine fish and projected modifications in the North Atlantic Ocean. *Global Change Biology* 17:115-129.
- Liedvogel, M., S. Akesson, and S. Bensch. 2011. The genetics of migration on the move. *Trends in Ecology & Evolution* 26:561-569.
- Lin, P. F., H. L. Liu, Y. Q. Yu, and X. H. Zhang. 2011. Response of Sea Surface Temperature to Chlorophyll-a Concentration in the Tropical Pacific: Annual Mean, Seasonal Cycle, and Interannual Variability. *Advances in Atmospheric Sciences* 28:492-510.
- Lischka, S., J. Budenbender, T. Boxhammer, and U. Riebesell. 2011. Impact of ocean acidification and elevated temperatures on early juveniles of the polar shelled pteropod *Limacina helicina*: mortality, shell degradation, and shell growth. *Biogeosciences* 8:919-932.
- Low-DÉCarie, E., G. F. Fussmann, and G. Bell. 2011. The effect of elevated CO₂ on growth and competition in experimental phytoplankton communities. *Global Change Biology* 17:2525-2535.
- MacKenzie, L. A., K. F. Smith, L. L. Rhodes, A. Brown, V. Langi, M. Edgar, G. Lovell et al. 2011. Mortalities of sea-cage salmon (*Oncorhynchus tshawytscha*) due to a bloom of *Pseudochattonella verruculosa* (Dictyochophyceae) in Queen Charlotte Sound, New Zealand. *Harmful Algae* 11:45-53.
- Malcolm, I. A., A. F. Youngson, C. Soulsby, C. Imholt, and R. J. Fryer. 2011. Is Interstitial Velocity a Good Predictor of Salmonid Embryo Survival? *Transactions of the American Fisheries Society* 140:898-904.
- Marschall, E. A., M. E. Mather, D. L. Parrish, G. W. Allison, and J. R. McMenemy. 2011. Migration delays caused by anthropogenic barriers: modeling dams, temperature, and success of migrating salmon smolts. *Ecological Applications* 21:3014-3031.
- Martins, E. G., S. G. Hinch, D. A. Patterson, M. J. Hague, S. J. Cooke, K. M. Miller, M. F. Lapointe et al. 2011. Effects of river temperature and climate warming on stock-specific survival of adult migrating Fraser River sockeye salmon (*Oncorhynchus nerka*). *Global Change Biology* 17:99-114.
- Mayer, T. D., and S. W. Naman. 2011. Streamflow response to climate as influenced by geology and elevation. *Journal of the American Water Resources Association* 47:724-738.
- Miller, K. M., S. R. Li, K. H. Kaukinen, N. Ginther, E. Hammill, J. M. R. Curtis, D. A. Patterson et al. 2011a. Genomic Signatures Predict Migration and Spawning Failure in Wild Canadian Salmon. *Science* 331:214-217.
- Miller, S. C., T. E. Gillis, and P. A. Wright. 2011b. The ontogeny of regulatory control of the rainbow trout (*Oncorhynchus mykiss*) heart and how this is influenced by chronic hypoxia exposure. *Journal of Experimental Biology* 214:2065-2072.
- Milner, A. M., A. L. Robertson, L. E. Brown, S. H. Sonderland, M. McDermott, and A. J. Veal. 2011. Evolution of a stream ecosystem in recently deglaciated terrain. *Ecology* 92:1924-1935.

- Min, S. K., X. B. Zhang, F. W. Zwiers, and G. C. Hegerl. 2011. Human contribution to more-intense precipitation extremes. *Nature* 470:378-381.
- Munday, P. L., M. Gagliano, J. M. Donelson, D. L. Dixson, and S. R. Thorrold. 2011a. Ocean acidification does not affect the early life history development of a tropical marine fish. *Marine Ecology-Progress Series* 423:211-221.
- Munday, P. L., V. Hernaman, D. L. Dixson, and S. R. Thorrold. 2011b. Effect of ocean acidification on otolith development in larvae of a tropical marine fish. *Biogeosciences* 8:1631-1641.
- Mundy, P. R., and D. F. Evenson. 2011. Environmental controls of phenology of high-latitude Chinook salmon populations of the Yukon River, North America, with application to fishery management. *Ices Journal of Marine Science* 68:1155-1164.
- Naik, P. K., and D. A. Jay. 2011a. Distinguishing human and climate influences on the Columbia River: Changes in mean flow and sediment transport. *Journal of Hydrology* 404:259-277.
- . 2011b. Human and climate impacts on Columbia River hydrology and salmonids. *River Research and Applications* 27:1270-1276.
- National Wildlife Federation. 2011. Climate Change Effects and Adaptation Approaches in Marine and Coastal Ecosystems of the North Pacific Landscape Conservation Cooperative Region: A Compilation of Scientific Literature. Phase 1 Draft Final Report. http://www.nwf.org/~media/PDFs/Global-Warming/Reports/NPLCC%20Reports/NPLCC_Marine_Climate-Effects_Draft-Final_FullReport.ashx
- Nelson, D. B., M. B. Abbott, B. Steinman, P. J. Polissar, N. D. Stansell, J. D. Ortiz, M. F. Rosenmeier et al. 2011. Drought variability in the Pacific Northwest from a 6,000-yr lake sediment record. *Proceedings of the National Academy of Sciences of the United States of America* 108:3870-3875.
- Otero, J., A. J. Jensen, J. H. L'Abee-Lund, N. C. Stenseth, G. O. Storvik, and L. A. Vollestad. 2011. Quantifying the Ocean, Freshwater and Human Effects on Year-to-Year Variability of One-Sea-Winter Atlantic Salmon Angled in Multiple Norwegian Rivers. *Plos One* 6.
- Pankhurst, N. W., and P. L. Munday. 2011. Effects of climate change on fish reproduction and early life history stages. *Marine and Freshwater Research* 62:1015-1026.
- Pardo, P. C., X. A. Padin, M. Gilcoto, L. Farina-Busto, and F. F. Perez. 2011. Evolution of upwelling systems coupled to the long-term variability in sea surface temperature and Ekman transport. *Climate Research* 48:231-246.
- Perkins, T. A., and H. I. Jager. 2011. Falling Behind: Delayed Growth Explains Life-History Variation in Snake River Fall Chinook Salmon. *Transactions of the American Fisheries Society* 140:959-972.
- Polovina, J. J., J. P. Dunne, P. A. Woodworth, and E. A. Howell. 2011. Projected expansion of the subtropical biome and contraction of the temperate and equatorial upwelling biomes in the North Pacific under global warming. *Ices Journal of Marine Science* 68:986-995.

- Quinn, T. P., M. J. Unwin, and M. T. Kinnison. 2011. Contemporary divergence in migratory timing of naturalized populations of chinook salmon, *Oncorhynchus tshawytscha*, in New Zealand. *Evolutionary Ecology Research* 13:45-54.
- Reed, T. E., D. E. Schindler, M. J. Hague, D. A. Patterson, E. Meir, R. S. Waples, and S. G. Hinch. 2011. Time to Evolve? Potential Evolutionary Responses of Fraser River Sockeye Salmon to Climate Change and Effects on Persistence. *Plos One* 6.
- Reum, J. C. P., T. E. Essington, C. M. Greene, C. A. Rice, and K. L. Fresh. 2011. Multiscale influence of climate on estuarine populations of forage fish: the role of coastal upwelling, freshwater flow and temperature. *Marine Ecology-Progress Series* 425:203-215.
- Roegner, G. C., J. A. Needoba, and A. M. Baptista. 2011a. Coastal Upwelling Supplies Oxygen-Depleted Water to the Columbia River Estuary. *PLoS ONE* 6 e18672.
- Roegner, G. C., C. Seaton, and A. M. Baptista. 2011b. Climatic and Tidal Forcing of Hydrography and Chlorophyll Concentrations in the Columbia River Estuary. *Estuaries and Coasts* 34:281-296.
- Rogers, B. M., R. P. Neilson, R. Drapek, J. M. Lenihan, J. R. Wells, D. Bachelet, and B. E. Law. 2011. Impacts of climate change on fire regimes and carbon stocks of the U.S. Pacific Northwest. *Journal of Geophysical Research-Biogeosciences* 116.
- Rouyer, T., G. Ottersen, J. M. Durant, M. Hidalgo, D. A. G. Ø. Hjermann, J. Persson, L. C. Stige et al. 2011. Shifting dynamic forces in fish stock fluctuations triggered by age truncation? *Global Change Biology*:no-no.
- Ruff, C. P., D. E. Schindler, J. B. Armstrong, K. T. Bentley, G. T. Brooks, G. W. Holtgrieve, M. T. McGlauflin et al. 2011. Temperature-associated population diversity in salmon confers benefits to mobile consumers. *Ecology* 92:2073-2084.
- Safford, T. G., and K. C. Norman. 2011. Water water everywhere, but not enough for salmon? Organizing integrated water and fisheries management in Puget Sound. *Journal of Environmental Management* 92:838-847.
- Saito, T., T. Kaga, E. Hasegawa, and K. Nagasawa. 2011. Effects of juvenile size at release and early marine growth on adult return rates for Hokkaido chum salmon (*Oncorhynchus keta*) in relation to sea surface temperature. *Fisheries Oceanography* 20:278-293.
- Seeb, L. W., J. E. Seeb, C. Habicht, E. V. Farley, and F. M. Utter. 2011. Single-Nucleotide Polymorphic Genotypes Reveal Patterns of Early Juvenile Migration of Sockeye Salmon in the Eastern Bering Sea. *Transactions of the American Fisheries Society* 140:734-748.
- Selbie, D. T., J. N. Sweetman, P. Etherton, K. D. Hyatt, D. P. Rankin, B. P. Finney, and J. P. Smol. 2011. Climate change modulates structural and functional lake ecosystem responses to introduced anadromous salmon. *Canadian Journal of Fisheries and Aquatic Sciences* 68:675-692.
- Sestrich, C. M., T. E. McMahon, and M. K. Young. 2011. Influence of Fire on Native and Nonnative Salmonid Populations and Habitat in a Western Montana Basin. *Transactions of the American Fisheries Society* 140:136-146.
- Sommer, U., and A. Lewandowska. 2011. Climate change and the phytoplankton spring bloom: warming and overwintering zooplankton have similar effects on phytoplankton. *Global Change Biology* 17:154-162.

- Spencer, M., S. N. R. Birchenough, N. Mieszkowska, L. A. Robinson, S. D. Simpson, M. T. Burrows, E. Capasso et al. 2011. Temporal change in UK marine communities: trends or regime shifts? *Marine Ecology-an Evolutionary Perspective* 32:10-24.
- Tagliabue, A., L. Bopp, and M. Gehlen. 2011. The response of marine carbon and nutrient cycles to ocean acidification: Large uncertainties related to phytoplankton physiological assumptions. *Global Biogeochemical Cycles* 25.
- Taguchi, M., and J. C. Liao. 2011. Rainbow trout consume less oxygen in turbulence: the energetics of swimming behaviors at different speeds. *Journal of Experimental Biology* 214:1428-1436.
- Thomson, R. E., and R. A. S. Hourston. 2011. A matter of timing: the role of ocean conditions in the initiation of spawning migration by late-run Fraser River sockeye salmon (*Oncorhynchus nerka*). *Fisheries Oceanography* 20:47-65.
- Thorpe, A. S., and A. G. Stanley. 2011. Determining appropriate goals for restoration of imperilled communities and species. *Journal of Applied Ecology* 48:275-279.
- Todd, R. E., D. L. Rudnick, R. E. Davis, and M. D. Ohman. 2011. Underwater gliders reveal rapid arrival of El Nino effects off California's coast. *Geophysical Research Letters* 38.
- Traynham, L., R. Palmer, and A. Polebitski. 2011. Impacts of Future Climate Conditions and Forecasted Population Growth on Water Supply Systems in the Puget Sound Region. *Journal of Water Resources Planning and Management-Asce* 137:318-326.
- USFWS, NOAA-Fisheries Service, and Association of Fish and Wildlife Agencies. 2011. National Fish, Wildlife and Plants Climate Adaptation Strategy, Agency Review Draft, November 2011. <http://www.wildlifeadaptationstrategy.gov:153>
- Vaquier-Sunyer, R., and C. M. Duarte. 2011. Temperature effects on oxygen thresholds for hypoxia in marine benthic organisms. *Global Change Biology* 17:1788-1797.
- Welch, D. W., Y. Ishida, and K. Nagasawa. 1998. Thermal limits and ocean migrations of sockeye salmon (*Oncorhynchus nerka*): long-term consequences of global warming. *Canadian Journal of Fisheries and Aquatic Sciences* 55:937-948.
- Wenger, S. J., D. J. Isaak, C. H. Luce, H. M. Neville, K. D. Fausch, J. B. Dunham, D. C. Dauwalter et al. 2011. Flow regime, temperature, and biotic interactions drive differential declines of trout species under climate change. *Proceedings of the National Academy of Sciences of the United States of America* 108:14175-14180.
- Weyhenmeyer, G. A., D. M. Livingstone, M. Meili, O. Jensen, B. Benson, and J. J. Magnuson. 2011. Large geographical differences in the sensitivity of ice-covered lakes and rivers in the Northern Hemisphere to temperature changes. *Global Change Biology* 17:268-275.
- Whiteley, N. M. 2011. Physiological and ecological responses of crustaceans to ocean acidification. *Marine Ecology-Progress Series* 430:257-271.
- Young, I. R., S. Zieger, and A. V. Babanin. 2011. Global Trends in Wind Speed and Wave Height. *Science* 332:451-455.
- Zeug, S. C., L. K. Albertson, H. Lenihan, J. Hardy, and B. Cardinale. 2011. Predictors of Chinook salmon extirpation in California's Central Valley. *Fisheries Management and Ecology* 18:61-71.

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Appendix E

Double-crested Cormorant Estuary Smolt Consumption BiOp Analysis

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UNITED STATES DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
 NATIONAL MARINE FISHERIES SERVICE
 West Coast Region
 1201 NE Lloyd Boulevard, Suite 1100
 Portland, OR 97232

December 9, 2013

MEMORANDUM FOR: Bruce Suzumoto and Ritchie Graves
FROM: Gary Fredricks
SUBJECT: Double-crested Cormorant Estuary Smolt Consumption BiOp Analysis

The primary goal for addressing double-crested cormorant (DCCO) smolt consumption in the 2013 BiOp is to determine the smolt survival “gap” that has resulted from the dramatic increase in cormorant population and smolt consumption between the base and current years that was not captured in the 2008 BiOp analysis.

Once the 2008 BiOp was completed it became apparent that the analysis did not completely address the full impact of rapidly increasing cormorant populations in the estuary on the current salmon ESU productivity estimates. The BiOp had to assess the likely effect of hydro/mitigation actions (i.e., continuing and future actions) on population/ESU productivity. The BiOp considers three periods of time.

- Base (roughly Brood Year 1981 to 2000 or Migration Year 1983 to 2002)
- Current (roughly Brood Year 2001 – 2006 or Migration Year 2003 to 2009)
- Prospective (2018 – after the implementation of all BiOp actions)

Base-to-Current and Current-to-Prospective multipliers were estimated for many factors (including Hydro) in order to estimate effects on listed stock productivity. “Current” estimates include all measured sources of mortality in the estuary and ocean attributable to birds, harvest, etc. Since the 2008 BiOp did not consider the dramatic estuary cormorant population increase in its analysis, the estimate of the current period productivity was somewhat less than it should have been. Because of this, a partitioning of this impact would be a negative multiplier. While this shortfall (or gap) can be addressed with any actions that improve productivity, it is logical that cormorant management objectives assist in this goal. This analysis calculates the size of the productivity gap for steelhead and yearling Chinook.

Sockeye are a special case in this analysis since this species was not included in the original 2008 BiOp Base to Current analysis, primarily due to a lack of information. In order to at least get an idea of the relative effect of cormorant predation on these fish, this analysis includes an estimate of consumption rate of sockeye compared to steelhead and yearling Chinook.

Analytical Approach

The gap analysis consists of a Microsoft Excel workbook that was completed primarily to calculate the negative multiplier for steelhead and yearling Chinook salmon. The analysis also

uses a per capita (per bird) consumption level to calculate the number of cormorants that would likely need to be removed to zero the multiplier (fill the gap).

The analysis first presents the gap analysis for each species (steelhead and Chinook worksheet pages). The analysis uses annual cormorant species specific smolt consumption levels and the annual estimated estuary smolt population levels to calculate annual species specific smolt consumption rates. The resultant annual survival rates are then used to calculate average base and current period survival rates depending on what years are in the two periods. The average current period survival estimate divided by the average base period survival estimate provides the base-to-current survival estimate. The difference between this and 100% is considered as the base to current survival gap.

The key data sets for this analysis are the estimates of smolt consumption, estimates of cormorant population and estimates of smolt population.

Estuary double-crested cormorant smolt consumption estimates were based on bioenergetics modeling conducted by the avian researchers at Oregon State University and Real Time Research. Species-specific smolt consumption levels (numbers of smolt consumed) for the years 1998 to 2009 were provided by Collis (2010) and are presented in the data worksheet in the gap analysis. Consumption levels for 2010 through 2012 were found in the individual annual research reports for those years (Roby et al. 2011, 2012 and 2013). Consumption levels for years before 1998 were not available. Consumption and survival rates for these years were calculated based on the average current period consumption rates (approximately 2003-2009) adjusted for the cormorant population for the year or years in question and the area where those birds lived at that time. Birds nesting on Rice Island had a higher smolt consumption rate than birds nesting on East Sand Island. Collis et al. (2002) reported that cormorants nesting on Rice Island consumed approximately three times more salmon per bird than birds nesting on East Sand Island. No adjustment was made for the years 1980 through 1987 since birds were dispersed in the lower estuary (primarily Trestle Bay) during this time frame (Carter et al. 1995). The literature did provide Rice/East Sand population breakouts for the years 1988, 1991, 1992 and 1997 (Carter et al. 1995, Roby et al. 1998).

Estuary double-crested cormorant population estimates were determined for the years 1980 to 2012, which encompasses all the base to current years. The early year population estimates were presented in the literature only for the years 1980, 1987, 1988, 1991-92 and 1997. The data were extended approximately equally between these years for years where no estimates exist. For example, the estimates for 1980 to 1994 were based on information provided by Carter et al 1995. The 1980 to 1987 rough estimate of <150 pairs was based on Carter's report of 262 birds nesting on structures in Trestle Bay and "other small colonies that may have been present" in 1980. The 1988 and 1989 estimate of 1,847 pairs was based on Carter's estimate of 3,694 individual birds in 1988. The 1990 to 1994 estimate of 3,364 pairs was based on an aggregate estimate from 1990 to 1992 of 6,728 birds surveyed in various locations in the Columbia River estuary (Carter et al. 1995, Appendix 1). The 1995 to 1997 estimate of 6,104 pairs was based on Roby et al. 1998 (page 16). For the years 1998 through 2009, cormorant population estimates were provided in the western North America cormorant status assessment (Adkins et al. 2010).

For 2010 to 2012, the estimates were provided in the annual research reports (Roby et al. 2011, 2012, 2013).

All smolt population data (1998-2012) are from annual smolt population estimate memos issued by the NOAA Northwest Fisheries Science Center (Schiewe 1998 - 2002, Ferguson 2003-2010, Day 2011, Zabel 2012). Appendix 3 lists the specific data used for this analysis for each year. The species-specific population data were derived from the estimated smolt population arriving at Tongue Point in the estuary. These numbers are provided in the memos for full transport and spill with transport scenarios, thus the conditions that occurred for the year in question had to be determined before the best estimate was chosen.

A per capita consumption analysis was added to the gap analysis to determine how many cormorants might have to be removed from the estuary to achieve the steelhead survival levels that would eliminate the estimated negative productivity multiplier or gap. This analysis used the 1998 through 2012 cormorant consumption and population estimates to determine an average per capita consumption level for the East Sand Island cormorant colony. This fifteen year data set encompasses a fairly wide variation in cormorant salmonid consumption levels and river conditions and therefore likely serves as a decent predictor of per capita cormorant consumption rates in the near future, as long as the birds remain on or in the vicinity of East Sand Island. Also in support of this is the fact that East Sand Island cormorant population has remained fairly stable at about 10,500 to 13,500 pairs for the past ten years.

Analysis Results and Discussion

The results of the gap analysis indicate a 3.6% survival gap for steelhead exists between the average base period survival (migration years 1983-2002) and the average current period survival (2003-2009). For yearling Chinook, a 1.1% gap exists between the base period survival (1982-2001) and current period survival (2002-2009). Table 1 presents the average survivals calculated by the analysis and the resultant gap for each species. The specific data used for each year are presented in Appendix 1.

Steelhead	
Ave Base Survival(MY1983-2002)	0.971
Ave Current Survival(MY2003-2009)	0.935
Current/Base	0.964
Base to Current Gap	0.036
Yearling Chinook	
Ave Base Survival(MY1982-2001)	0.988
Ave Current Survival(MY2002-2009)	0.978
Current/Base	0.989
Base to Current Gap	0.011

The results of the per capita analysis indicated a fifteen year average annual total consumption rate of 6.7% and 2.7% for steelhead and yearling Chinook, respectively, for a fifteen year average annual cormorant population of 10,378 pairs. These respective values for the current period were 6.5% and 2.5% for an average current period (for steelhead) cormorant population of 12,024 pairs. The base period consumption rate values were 2.9% and 1.2% for steelhead and Chinook, respectively. Since steelhead consumption rates are higher, a larger number of birds would need to be removed to achieve elimination of the negative multiplier or gap. Because of this, the steelhead portion of the analysis will likely drive the management actions. The per capita consumption rates for steelhead translate to a needed reduction of the cormorant colony size to a range of between 5,380 and 5,939 pairs in order to achieve the base (2.9%) consumption rate value. The range in the colony size reflects the average 95% confidence interval for the East Sand Island cormorant population estimates.

The results of the comparison of the fifteen year period average consumption rates for smolts of each salmonid species are presented in table 2. Sockeye were consumed at somewhat lower rates than either steelhead or yearling Chinook.

Yearling Chinook	2.7%
Steelhead	6.7%
Sockeye	1.3%

A couple of issues have arisen regarding the application of these results. The issue of hatchery vs. wild susceptibility was investigated by Collis et al. (2001) and Ryan et al. (2003 and 2008). These investigators found through PIT tag analysis that, at least for steelhead, there was no consistent indication of a cormorant preference for prey based on rearing type. Another issue is the idea of compensatory predation mortality which would argue that at least some portion of the fish consumed by predators would have died from other factors subsequent to the predation event. There is evidence that fish condition, size and rearing history may affect the vulnerability of fish to double-crested cormorant predation (Hostetter et al. 2012) and it is likely that predation losses to avian predators is compensated somewhat due to these vulnerabilities. This argument is not, however, particularly important to the treatment of cormorant predation in the supplemental BiOp. The analysis presented here considers only that double-crested cormorant population in the lower Columbia River Estuary has increased dramatically between the base and current periods. It is therefore, our assumption that the vulnerabilities are likely equal on both sides of the base and current periods in the analysis. The ultimate difference between these two periods is still the difference in the effect the increase in cormorant population has had on the populations of listed salmon. As an example for steelhead, if we assume that compensation is 50% and this was applied to the analysis equally during both periods, the resulting difference would be half of the calculated 3.6%, or 1.8%. However, the number of cormorants that would need to be reduced to get back to the base period consumption rate would still be between 5,380 and 5,939 pairs.

Literature Cited:

Adkins, J. Y., D. D. Roby and 27 coauthors. 2010. A status assessment of the double-crested cormorant (*Phalacrocorax auritus*) in western North America: 1998-2009. Final Report to U. S. Army Corps of Engineers, Portland District. 59 pp. plus appendices.

Carter, H. R., A. L. Sowls, M. S. Rodway, U. W. Wilson, R. W. Lowe, G. J. McChesney, F. Gress, and D. W. Anderson. 1995. Population size, trends, and conservation problems of the double-crested cormorant on the Pacific Coast of North America. In: Nettleship DN, Duffy DC, editors. The double-crested cormorant: biology, conservation and management. Colonial Waterbirds 18 (Special Publication 1). p 189–207.

Collis, K. D., D. D. Roby, D. P. Craig, B. A. Ryan, and R. D. Ledgerwood. 2001. Colonial waterbird predation on juvenile salmonids tagged with passive integrated transponders in the Columbia River Estuary: vulnerability of different salmonid species, stocks, and rearing types. *Trans. Am. Fish. Soc.*, 130:385-396.

Collis, 2002 Colony size and diet composition of piscivorous waterbirds on the lower Columbia River: implications for losses of juvenile salmonids to avian predation. *Trans Am. Fish. Soc.* 131:537-550.

Collis, K. 2010. Email (Subject: RE: Cormorant Consumption Data) to Gary.Fredricks@noaa.gov dated 3/30/10.

Dey, D. B. 2012. Estimation of percentages for listed Pacific salmon and steelhead smolts arriving at various locations in the Columbia River Basin in 2011. National Marine Fisheries Service, Northwest Fisheries Science Center, March 6, 2012, memo to James H. Lecky.

Ferguson, J. W. 2010. Estimation of percentages for listed Pacific salmon and steelhead smolts arriving at various locations in the Columbia River Basin in 2010. National Marine Fisheries Service, Northwest Fisheries Science Center, November 9, 2010, memo to James H. Lecky.

Ferguson, J. W. 2009. Estimation of percentages for listed Pacific salmon and steelhead smolts arriving at various locations in the Columbia River Basin in 2009. National Marine Fisheries Service, Northwest Fisheries Science Center, October 15, 2009, memo to James H. Lecky.

Ferguson, J. W. 2008. Final estimation of percentages for listed Pacific salmon and steelhead smolts arriving at various locations in the Columbia River Basin in 2008. National Marine Fisheries Service, Northwest Fisheries Science Center, December 4, 2008, memo to James H. Lecky.

Ferguson, J. W. 2007. Revised estimation of percentages for listed Pacific salmon and steelhead smolts arriving at various locations in the Columbia River Basin in 2007. National Marine Fisheries Service, Northwest Fisheries Science Center, September 11, 2007, memo to James H. Lecky.

Ferguson, J. W. 2006. Estimation of percentages for listed Pacific salmon and steelhead smolts arriving at various locations in the Columbia River Basin in 2006. National Marine Fisheries Service, Northwest Fisheries Science Center, April 10, 2006, memo to James H. Lecky.

Ferguson, J. W. 2005. Revised estimation of percentages for listed Pacific salmon and steelhead smolts arriving at various locations in the Columbia River Basin in 2005 based on June 2005 changes in listing status. National Marine Fisheries Service, Northwest Fisheries Science Center August 24, 2005, memo to James H. Lecky.

Ferguson, J. W. 2004. Estimation of percentages for listed Pacific salmon and steelhead smolts arriving at various locations in the Columbia River Basin in 2004. National Marine Fisheries Service, Northwest Fisheries Science Center, March 29, 2004, memo to Laurie Allen.

Ferguson, J. W. 2003. Estimation of percentages for listed Pacific salmon and steelhead smolts arriving at various locations in the Columbia River Basin in 2003. National Marine Fisheries Service, Northwest Fisheries Science Center, March 20, 2003, memo to Laurie Allen.

Hostetter, N. J., A. F. Evans, D. D. Roby and K. Collis. 2012. Susceptibility of juvenile steelhead to avian predation: the influence of individual fish characteristics and river conditions. *Trans. Am. Fish. Soc.* 141:1586-1599.

Marsh, D. 2013. March 12, 2013 email to Gary Fredricks. 1998 steelhead population estimates.

Roby, D. D., and 19 co-authors. 2012. Research, monitoring and evaluation of avian predation on salmonid smolts in the lower and mid-Columbia River. Final 2011 Annual Report to the Bonneville Power Administration and the U.S. Army Corp of Engineers. 88 pp plus figures and tables.

Roby, D. D. and 20 co-authors. 2011. Research, monitoring and evaluation of avian predation on salmonid smolts in the lower and mid-Columbia River. Final 2010 Final Report to the Bonneville Power Administration and the U.S. Army Corp of Engineers. 81 pp plus figures and tables.

Roby, D. D., K. Collis and 22 co-authors. 2013. Research, monitoring and evaluation of avian predation on salmonid smolts in the lower and mid-Columbia River. DRAFT 2012 Annual Report to the Bonneville Power Administration and the U.S. Army Corp of Engineers. 103 pp plus figures and tables.

Roby, D. D., D. P. Craig, K. Collis, and S. L. Adamany. 1998. Avian predation on juvenile salmonids in the lower Columbia River. 1997 Annual Report to the Bonneville Power Administration and the U. S. Army Corps of Engineers. 32 pp plus figures and tables.

Ryan, B. A., S. G. Smith, J. M. Butzerin, and J. W. Ferguson. 2003. Relative vulnerability to avian predation of juvenile salmonids tagged with passive integrated transponders in the Columbia River Estuary, 1998-2000. *Trans. Am. Fish. Soc.* 132:275-288.

Ryan, B. A., M. C. Carper, B. P. Sandford and G. M. Matthews. 2008. Detection of passive integrated transponder (PIT) tags on piscivorous bird colonies in the Columbia River Basin, 2006. Report of research for Walla Walla District Corps of Engineers. 18 pp.

Schiewe, M. H. 2002. Estimation of percentages for listed Pacific salmon and steelhead smolts arriving at various locations in the Columbia River Basin in 2002. National Marine Fisheries Service, Northwest Fisheries Science Center, March 28, 2002, memo to Donna J. Darm.

Schiewe, M. H. 2001. Estimation of percentages for listed Pacific salmon and steelhead smolts arriving at various locations in the Columbia River Basin in 2001. National Marine Fisheries Service, Northwest Fisheries Science Center, May 2, 2001, memo to Donald R. Knowles.

Schiewe, M. H. 2000. Estimation of percentages for listed Pacific salmon and steelhead smolts arriving at various locations in the Columbia River Basin in 2000. National Marine Fisheries Service, Northwest Fisheries Science Center, March 16, 2000, memo to Donald R. Knowles.

Schiewe, M. H. 1999. Estimation of percentages for listed spring/summer and fall Chinook, sockeye salmon and steelhead smolts arriving at various locations in the Columbia River Basin in 1999. National Marine Fisheries Service, Northwest Fisheries Science Center, March 3, 1999, memo to Kevin Collins.

Schiewe, M. H. 1998. Estimation of percentages for listed spring/summer and fall Chinook, sockeye salmon smolts arriving at various locations in the Columbia River Basin in 1998. National Marine Fisheries Service, Northwest Fisheries Science Center, February 11, 1998, memo to Nancy Chu.

Zabel, R. W. 2013. Estimation of percentages for listed spring/summer and fall Chinook, sockeye salmon smolts arriving at various locations in the Columbia River Basin in 2012. National Marine Fisheries Service, Northwest Fisheries Science Center, January 23, 2013, memo to James H. Lecky.

Appendix 1. Gap analysis tables.**Table 1. Estuary Cormorant Consumption - Steelhead**

Year	Cormorant Population (pairs)	Sthd Consumption (Millions)	Sthd Population (Millions)	Consumption Rate	Survival Rate
1980	150			0.001	0.999
1981	150			0.001	0.999
1982	150			0.001	0.999
1983	150			0.001	0.999
1984	150			0.001	0.999
1985	150			0.001	0.999
1986	150			0.001	0.999
1987	150			0.001	0.999
1988	1847			0.017	0.983
1989	1847			0.017	0.983
1990	3364			0.031	0.969
1991	3364			0.031	0.969
1992	3364			0.031	0.969
1993	3364			0.031	0.969
1994	3364			0.031	0.969
1995	6104			0.045	0.955
1996	6104			0.045	0.955
1997	6104			0.045	0.955
1998	6285	0.817	13.0	0.063	0.937
1999	6561	1.092	13.9	0.079	0.921
2000	7162	0.966	14.0	0.069	0.931
2001	8120	0.516	14.9	0.035	0.965
2002	10230	0.119	13.9	0.009	0.991
2003	10646	0.701	14.5	0.048	0.952
2004	12480	0.605	13.7	0.044	0.956
2005	12287	0.166	13.7	0.012	0.988
2006	13738	1.855	14.3	0.130	0.870
2007	13771	1.311	13.9	0.094	0.906
2008	10950	0.931	14.1	0.066	0.934
2009	12087	0.796	13.8	0.058	0.942
2010	13596	1.500	14.1	0.106	0.894
2011	13045	1.200	15.7	0.076	0.924
2012	12300	1.700	14.3	0.119	0.881

Table 2. Estuary Cormorant Consumption - Yearling Chinook

Year	Cormorant Population (pairs)	YrCH Consumption (Millions)	YrCH Population (Millions)	Consumption Rate	Survival Rate
1980	150			0.000	1.000
1981	150			0.000	1.000
1982	150			0.000	1.000
1983	150			0.000	1.000
1084	150			0.000	1.000
1985	150			0.000	1.000
1986	150			0.000	1.000
1987	150			0.000	1.000
1988	1847			0.006	0.994
1989	1847			0.006	0.994
1990	3364			0.011	0.989
1991	3364			0.011	0.989
1992	3364			0.011	0.989
1993	3364			0.011	0.989
1994	3364			0.011	0.989
1995	6104			0.016	0.984
1996	6104			0.016	0.984
1997	6104			0.016	0.984
1998	6285	0.687	18.4	0.037	0.963
1999	6561	0.937	26.9	0.035	0.965
2000	7162	0.874	30.6	0.029	0.971
2001	8120	0.430	23.7	0.018	0.982
2002	10230	0.089	34.3	0.003	0.997
2003	10646	0.704	36.9	0.019	0.981
2004	12480	0.515	33.8	0.015	0.985
2005	12287	0.080	38.5	0.002	0.998
2006	13738	1.723	38.8	0.044	0.956
2007	13771	1.091	28.7	0.038	0.962
2008	10950	0.934	29.5	0.032	0.968
2009	12087	0.668	26.9	0.025	0.975
2010	13596	1.300	37.5	0.035	0.965
2011	13045	0.900	32.8	0.027	0.973
2012	12300	1.500	33.5	0.045	0.955

Table 3. Per capita analysis for steelhead.

Per Capita consumption analysis to estimate a cormorant colony size (pairs) that would close the Base to Current gap in juvenile steelhead survival*.

Columbia River Estuary

Year	% Consumption		DCCO Population (pairs)			Per Capita Consumption	
		<95%CI	Best	>95%CI	<95%CI	Best	>95%CI
1998	6.3%	5908	6285	6662	0.0000106	0.0000100	0.0000094
1999	7.9%	6167	6561	6955	0.0000128	0.0000120	0.0000113
2000	6.9%	6732	7162	7592	0.0000103	0.0000096	0.0000091
2001	3.5%	7633	8120	8607	0.0000045	0.0000043	0.0000040
2002	0.9%	9616	10230	10844	0.0000009	0.0000008	0.0000008
2003	4.8%	10007	10646	11285	0.0000048	0.0000045	0.0000043
2004	4.4%	11731	12480	13229	0.0000038	0.0000035	0.0000033
2005	1.2%	11550	12287	13024	0.0000011	0.0000010	0.0000009
2006	13.0%	12914	13738	14562	0.0000101	0.0000095	0.0000089
2007	9.4%	12945	13770	14597	0.0000073	0.0000068	0.0000065
2008	6.6%	10585	10950	11315	0.0000063	0.0000061	0.0000059
2009	5.8%	11929	12087	12245	0.0000048	0.0000048	0.0000047
2010	10.6%	13130	13596	14062	0.0000081	0.0000078	0.0000076
2011	7.6%	12781	13045	13309	0.0000060	0.0000059	0.0000057
2012	11.9%	12035	12300	12567	0.0000099	0.0000097	0.0000095
Average	6.7%	10378	10884	11390	0.0000007	0.0000006	0.0000006
Ave "Current" (03-09)	6.5%	11666	12280	12894	0.0000005	0.0000005	0.0000005
An average colony size (pairs) of:					5380	5661	5939
Would achieve the Base Period consumption rate of:						2.9%	

Table 4. Per capita analysis for yearling Chinook.

Per Capita consumption analysis to estimate a cormorant colony size (pairs) that would close the Base to Current gap in juvenile Yr Chinook survival*.

Columbia River Estuary

Year	%	DCCO Population (Pairs)				Per Capita Consumption	
		Consumption <95%CI	Best	>95%CI	<95%CI	Best	>95%CI
1998	3.7%	5908	6285	6662	0.0000063	0.0000059	0.0000056
1999	3.5%	6167	6561	6955	0.0000057	0.0000053	0.0000050
2000	2.9%	6732	7162	7592	0.0000042	0.0000040	0.0000038
2001	1.8%	7633	8120	8607	0.0000024	0.0000022	0.0000021
2002	0.3%	9616	10230	10844	0.0000003	0.0000003	0.0000002
2003	1.9%	10007	10646	11285	0.0000019	0.0000018	0.0000017
2004	1.5%	11731	12480	13229	0.0000013	0.0000012	0.0000012
2005	0.2%	11550	12287	13024	0.0000002	0.0000002	0.0000002
2006	4.4%	12914	13738	14562	0.0000034	0.0000032	0.0000030
2007	3.8%	12945	13770	14597	0.0000029	0.0000028	0.0000026
2008	3.2%	10585	10950	11315	0.0000030	0.0000029	0.0000028
2009	2.5%	11929	12087	12245	0.0000021	0.0000021	0.0000020
2010	3.5%	13130	13596	14062	0.0000026	0.0000025	0.0000025
2011	2.7%	12781	13045	13309	0.0000021	0.0000021	0.0000021
2012	4.5%	12035	12300	12567	0.0000037	0.0000036	0.0000036
Average	2.7%	10378	10884	11390	0.000002	0.000002	0.000002
Ave "Current" (02-09)	2.5%	11410	12024	12638	0.000002	0.000002	0.000002
An average colony size (pairs) of:					6221	6536	6848
Would achieve the Base Period consumption rate of:						1.2%	

Appendix 2. Data sources for the Columbia River estuary double-crested cormorant consumption rate analysis for the 2013 BiOp.

1980-1997 All data from Fredricks 2008 and 2010 BiOp memos.

1997 Cormorant population estimates and Rice Island vs. East Sand Island proportions from Roby et al 1998 (1997 Annual Report).

1998 Cormorant population estimates from Collis et al. 2000 (1998 Annual Report). Steelhead consumption rates from Collis 3/30/2010 email attachment: V3 98-09 Estuary DCCO Consumption.xls. Steelhead estuary population estimate from Doug Marsh 3/12/13 email – 98sthdest with LCR fish.xls.

1999 Cormorant population estimates from Adkins et al. 2010. Steelhead consumption rates from Collis 3/30/2010 email attachment: V3 98-09 Estuary DCCO Consumption.xls. Steelhead estuary population estimate from Schiewe 3/3/99 Population estimate memo.

2000 Cormorant population estimates from Adkins et al. 2010. Steelhead consumption rates from Collis 3/30/2010 email attachment: V3 98-09 Estuary DCCO Consumption.xls. Steelhead estuary population estimate from Schiewe 3/16/00 Population estimate memo.

2001 Cormorant population estimates from Adkins et al. 2010. Steelhead consumption rates from Collis 3/30/2010 email attachment: V3 98-09 Estuary DCCO Consumption.xls. Steelhead estuary population estimate from Schiewe 5/2/01 Population estimate memo.

2002 Cormorant population estimates from Adkins et al. 2010. Steelhead consumption rates from Collis 3/30/2010 email attachment: V3 98-09 Estuary DCCO Consumption.xls. Steelhead estuary population estimate from Schiewe 3/28/02 Population estimate memo.

2003 Cormorant population estimates from Adkins et al. 2010. Steelhead consumption rates from Collis 3/30/2010 email attachment: V3 98-09 Estuary DCCO Consumption.xls. Steelhead estuary population estimate from Ferguson 3/20/03 Population estimate memo.

2004 Cormorant population estimates from Adkins et al. 2010. Steelhead consumption rates from Collis 3/30/2010 email attachment: V3 98-09 Estuary DCCO Consumption.xls. Steelhead estuary population estimate from Ferguson 3/29/04 Population estimate memo.

2005 Cormorant population estimates from Adkins et al. 2010. Steelhead consumption rates from Collis 3/30/2010 email attachment: V3 98-09 Estuary DCCO Consumption.xls. Steelhead estuary population estimate from Ferguson 8/24/05 Population estimate memo.

2006 Cormorant population estimates from Adkins et al. 2010. Steelhead consumption rates from Collis 3/30/2010 email attachment: V3 98-09 Estuary DCCO Consumption.xls. Steelhead estuary population estimate from Ferguson 4/10/06 Population estimate memo.

2007 Cormorant population estimates from Adkins et al. 2010. Steelhead consumption rates from Collis 3/30/2010 email attachment: V3 98-09 Estuary DCCO Consumption.xls. Steelhead estuary population estimate from Ferguson 9/11/07 Population estimate memo.

2008 Cormorant population estimates from Adkins et al. 2010. Steelhead consumption rates from Collis 3/30/2010 email attachment: V3 98-09 Estuary DCCO Consumption.xls. Steelhead and Chinook estuary population estimate from Ferguson 12/4/08 Population estimate memo.

2009 Cormorant population estimates from Adkins et al. 2010. Steelhead consumption rates from Collis 3/30/2010 email attachment: V3 98-09 Estuary DCCO Consumption.xls. Steelhead and Chinook estuary population estimate from Ferguson 10/15/09 Population estimate memo.

2010 Cormorant population estimates from Roby et al 2011 (2010 Annual Report). Steelhead consumption rates from Roby et al. 2011. Steelhead and Chinook estuary population estimate from Ferguson 11/9/10 Population estimate memo.

2011 Cormorant population estimates from Roby et al 2012 (2011 Annual Report). Steelhead and Chinook consumption rates also from Roby et al 2012. Steelhead and Chinook estuary population estimate from Dey 3/6/12 Population estimate memo.

2012 Cormorant population estimates from Roby et al. 2013 (Draft 2012 Annual Report). Steelhead consumption rates from Annual Report. Steelhead and Chinook estuary population estimate from Zabel 1/23/13 Population estimate memo.

Appendix 3. Smolt population data summary memo.

July 29, 2013

F/NWR-5

FILE MEMORANDUM**FROM:** Gary Fredricks**SUBJECT:** Smolt Population Estimates for Estuary Cormorant Consumption Analysis

The data for steelhead and yearling Chinook estuary (Tongue Point) population estimates for the double crested cormorant analysis came from the following NOAA Science Center memos and correspondence for each year from 1998 to 2012. These data were used to estimate consumption rates for these species of fish by cormorants feeding in the lower estuary. Since the consumption rates are total number of fish eaten by species, the population estimate has to be based on the total number of fish available (not just listed fish available).

1998 – Steelhead: 3/12/13 email from Doug Marsh No page number, Table 12. Added wild (813,901) and hatchery (12,173,677) estimates at Tongue Point for a total steelhead estimate of **12,987,578**. Yearling Chinook: Schiewe 1998, February 11, 1998. Table 5, full transport with spill scenario - **18,397,190**. Sockeye: Schiewe 1998, Table 5 with spill - **1,291,687**.

1999 – Schiewe 1999, March 3, 1999. Steelhead: Table 12, transport with spill. Added wild (983,624) and hatchery (12,865,635) estimates at Tongue Point for a total steelhead estimate of **13,849,259**. Yearling Chinook: Table 6, transport with spill. Added wild (2,059,807) and hatchery (24,816,940) estimates at Tongue Point for a total yearling Chinook estimate of **26,876,747**. Sockeye: Table 5, transport with spill – **1,283,905**.

2000 - Schiewe 2000, March 16, 2000. Steelhead: Table 6, transport with spill. Added wild (1,792,916) and hatchery (12,184,824) estimates at Tongue Point for a total steelhead estimate of **13,977,740**. Yearling Chinook: Table 6, transport with spill. Added wild (8,733,906) and hatchery (21,831,929) estimates at Tongue Point for a total yearling Chinook estimate of **30,565,835**. Sub Chinook: Table 5, transport with spill – **47,345,104**. Sockeye: Table 5, transport with spill – **3, 257, 494**.

2001 - Schiewe 2001, May 2, 2001. Steelhead: Table 9, Full transportation at Tongue Point - **14,923,748**. Yearling Chinook: Table 7, Full transportation at Tongue Point – **23,704,323**. Sub Chinook: Same table – **38,571,680**. Sockeye: Table 7, full transport – **2,122,764**.

2002 - Schiewe 2002, March 28, 2002. Steelhead: Table 10, transport with spill. Added wild (2,165,789) and hatchery (11,700,319) estimates at Tongue Point for a total steelhead estimate of **13,866,108**. Yearling Chinook: Table 8, transport with spill. Added wild (10,771,077) and hatchery (23,531,162) estimates at Tongue Point for a total yearling Chinook estimate of **34,302,239**. Sub Chinook: Table 7, transportation with spill – **47,139,165**. Sockeye: Table 7, transport with spill – **2,081,468**.

2003 - Ferguson 2003, March 20, 2003 memo. Steelhead: Table 10, Transportation with spill - Added wild (2,702,533) and hatchery (11,781,527) estimates at Tongue Point for a total steelhead estimate of **14,484,060**. Yearling Chinook: Table 8, transport with spill. Added wild (12,651,681) and hatchery (24,200,009) estimates at Tongue Point for a total yearling Chinook estimate of **36,851,690**. Sub Chinook: Table 7, full transportation – **59,463,290**. Sockeye: Table 7, with spill – **1,781,584**.

2004 - Ferguson 2004, March 29, 2004 memo. Steelhead: Table 10, Full transportation - Added wild (2,602,246) and hatchery (11,060,851) estimates at Tongue Point for a total steelhead estimate of **13,663,097**. Yearling Chinook: Table 8, full transportation - Added wild (12,142,606) and hatchery (21,683,696) estimates at Tongue Point for a total yearling Chinook estimate of **33,826,302**. Sub Chinook: Table 7, full transportation – **60,475,322**. Sockeye: Table 7, full transport - **1,850,321**.

2005 - Ferguson 2005, August 24, 2005 memo. Steelhead: page 45, Table 9, Full Transportation - **13,692,289**. Yearling Chinook: page 36, Table 7a, Full Transportation – **38,509,029**. Sub Chinook: page 38, Table 7b (transport with spill) – **81,247,508**. Sockeye: Table 7c, full transport – **1,781,663**.

2006 - Ferguson 2006, April 10, 2006 memo. Steelhead: page 51, Table 9, Transportation with spill - **14,278,819**. Yearling Chinook: page 44, Table 7b, Transportation with spill – **38,832,655**. Sub Chinook: same page and table – **89,791,172**. Sockeye: Table 7c, with spill – **1,368,440**.

2007 - Ferguson 2007, September 11, 2007 memo. Steelhead: page 52, Table 9, Transportation with spill - **13,922,277**. Yearling Chinook: page 45, Table 7b, Transportation with spill – **28,719,701**. Sub Chinook: same page and table – **90,003,337**. Sockeye: Table 7c, with spill – **1,663,764**.

2008 - Ferguson 2008, December 4, 2008 memo. Steelhead: page 52, Table 9, Transportation with spill - **14,046,231**. Yearling Chinook: page 45, Table 7b, Transportation with spill – **29,538,756**. Sub Chinook: same page and table – **81,940,043**. Sockeye: Table 7c, with spill – **1,650,027**.

2009 – Ferguson 2009, October 15, 2009 memo. Steelhead: page 53, Table 9, Transportation with spill - **13,800,640**. Yearling Chinook: page 46, Table 7b, Transportation with spill – **26,902,885**. Sub Chinook: same page and table – **87,612,607**. Sockeye: Table 7c, with spill – **1,489,029**.

2010 – Ferguson 2010, November 9, 2010 memo. Steelhead: page 56, Table 9, Transportation with spill - **14,091,647**. Yearling Chinook: page 49, Table 7b, Transportation with spill – **35,517,282**. Sub Chinook: same page and table – **80,208,807**. Sockeye: Table 7c, with spill – **1,492,268**.

2011 – Dey 2012, March 6, 2012 memo. Steelhead: page 56, Table 9, Transportation with spill - **15,706,982**. Yearling Chinook: page 49, Table 7b, Transportation with spill – **32,807,329**. Sub Chinook: same page and table – **88,555,553**. Sockeye: Table 7c, with spill – **1,489,406**.

2012 – Zabel et al, January 23, 2013 memo. Steelhead: page 56, Table 9, Transportation with spill -**14,282,359**. Yearling Chinook: page 49, Table 7b, Transportation with spill – **33,476,396**. Sub Chinook: same page and table – **82,710,393**. Sockeye: Table 7c, with spill – **1,657,481**.

Estuary Cormorant Consumption - Steelhead

Year	Cormorant Population (pairs)	Sthd Consumption (Millions)	Sthd Population (Millions)	Consumption Rate	Per Capita Consumption Rate	Survival Rate	Ave Period Survivals (for Graphics)		
1980	150			0.001	0.000005	0.999	0.971	Ave 1987 and earlier Cormorant Population	150
1981	150			0.001	0.000005	0.999	0.971	1988 cormorant Population	1847
1982	150			0.001	0.000005	0.999	0.971	Ave 1991-1992 Cormorant Population	3364
1983	150			0.001	0.000005	0.999	0.971	Ave 1997 Cormorant Population	6104
1984	150			0.001	0.000005	0.999	0.971	Ave Current Cormorant Population (03-09)	12280
1985	150			0.001	0.000005	0.999	0.971	Ave Current Consumption Rate (03-09)	0.065
1986	150			0.001	0.000005	0.999	0.971		
1987	150			0.001	0.000005	0.999	0.971	Rice Island (RI) consumption rate multiplier	3.14
1988	1847			0.017	0.000009	0.983	0.971	<1987 Rice Island Population Proportion	0
1989	1847			0.017	0.000009	0.983	0.971	1988 Rice Island Population Proportion	0.36
1990	3364			0.031	0.000009	0.969	0.971	1991-92 Rice Island Population Propotion	0.36
1991	3364			0.031	0.000009	0.969	0.971	1997 Rice Island Population Proportion	0.193
1992	3364			0.031	0.000009	0.969	0.971		
1993	3364			0.031	0.000009	0.969	0.971		
1994	3364			0.031	0.000009	0.969	0.971		
1995	6104			0.045	0.000007	0.955	0.971	<1987 Consumption rate	0.001
1996	6104			0.045	0.000007	0.955	0.971	1988 Consumption rate	0.017
1997	6104			0.045	0.000007	0.955	0.971	1991-92 Consumption rate	0.031
1998	6285	0.817	13.0	0.063	0.000010	0.937	0.971	1997 Consumption rate	0.045
1999	6561	1.092	13.9	0.079	0.000012	0.921	0.971		
2000	7162	0.966	14.0	0.069	0.000010	0.931	0.971		
2001	8120	0.516	14.9	0.035	0.000004	0.965	0.971		
2002	10230	0.119	13.9	0.009	0.000001	0.991	0.971		
2003	10646	0.701	14.5	0.048	0.000005	0.952		0.935 Ave Base Consumption Rate (1983-2002)	0.029
2004	12480	0.605	13.7	0.044	0.000004	0.956		0.935 Ave Base Survival(1983-2002)	0.971
2005	12287	0.166	13.7	0.012	0.000001	0.988		0.935 Ave Current Survival(2003-2009)	0.935
2006	13738	1.855	14.3	0.130	0.000009	0.870		0.935 Current/Base	0.964
2007	13770	1.311	13.9	0.094	0.000007	0.906		0.935 Base to Current Gap	0.036
2008	10950	0.931	14.1	0.066	0.000006	0.934		0.935	
2009	12087	0.796	13.8	0.058	0.000005	0.942		0.935	
2010	13596	1.500	14.1	0.106	0.000008	0.894			
2011	13045	1.200	15.7	0.076	0.000006	0.924			
2012	12300	1.700	14.3	0.119	0.000010	0.881			
								1998 -2012 Ave Consumption rate	0.067247
								Base Period Per Capita Consumption Rate	0.000008
								Current Period Per Capita Consumption Rate	0.000005
								Ave Base Population (prs)	3897
								Ave Current Population (prs)	12280
								Ave Base Consumption	0.029367
								Ave Current Consumption	0.063506
								Current/Base Consumption	2.162519016

Notes:

Base year cormorant populations were reported in the literature as averages for certain years or as estimates for specific years. The known base year cormorant population estimates were expanded in years equal distant to the next known estimates. Estimates of base consumption rates for the various cormorant population levels assumes a constant juv steelhead population across pre-1998. All smolt population data from NOAA NWFSC population estimate memos (1998-2012). Smolt consumption for 1998 - 2009 from Collis 3/30/10 emailed spreadsheet (copied to DATA tab, this workbook). Smolt consumption for 2010 and later from Bird Research Annual Reports.

Estuary Cormorant Consumption - Yearling Chinook

Year	Cormorant Population (pairs)	YrCH Consumption (Millions)	YrCH Population (Millions)	Consumption Rate	Per Capita Consumption Rate	Survival Rate	Ave Period Survivals (for Graphics)		
1980	150			0.000	0.000002	1.000	0.988	Ave 1987 and earlier Cormorant Population	150
1981	150			0.000	0.000002	1.000	0.988	1988 cormorant Population	1847
1982	150			0.000	0.000002	1.000	0.988	Ave 1991-1992 Cormorant Population	3364
1983	150			0.000	0.000002	1.000	0.988	Ave 1997 Cormorant Population	6104
1084	150			0.000	0.000002	1.000	0.988	Ave Current Cormorant Population (02-09)	12024
1985	150			0.000	0.000002	1.000	0.988	Ave Current Consumption Rate (02-09)	0.022
1986	150			0.000	0.000002	1.000	0.988		
1987	150			0.000	0.000002	1.000	0.988	Rice Island (RI) consumption rate multiplier	3.1
1988	1847			0.006	0.000003	0.994	0.988	<1987 Rice Island Population Proportion	0
1989	1847			0.006	0.000003	0.994	0.988	1988 Rice Island Population Proportion	0.36
1990	3364			0.011	0.000003	0.989	0.988	1991-92 Rice Island Population Propotion	0.36
1991	3364			0.011	0.000003	0.989	0.988	1997 Rice Island Population Proportion	0.193
1992	3364			0.011	0.000003	0.989	0.988		
1993	3364			0.011	0.000003	0.989	0.988		
1994	3364			0.011	0.000003	0.989	0.988		
1995	6104			0.016	0.000003	0.984	0.988	<1987 Consumption rate	0.000
1996	6104			0.016	0.000003	0.984	0.988	1988 Consumption rate	0.006
1997	6104			0.016	0.000003	0.984	0.988	1991-92 Consumption rate	0.011
1998	6285	0.687	18.4	0.037	0.000006	0.963	0.988	1997 Consumption rate	0.016
1999	6561	0.937	26.9	0.035	0.000005	0.965	0.988		
2000	7162	0.874	30.6	0.029	0.000004	0.971	0.988		
2001	8120	0.430	23.7	0.018	0.000002	0.982	0.988		
2002	10230	0.089	34.3	0.003	0.000000	0.997	0.988		
2003	10646	0.704	36.9	0.019	0.000002	0.981		0.978 Ave Base Consumption Rate (1982-2001)	0.012
2004	12480	0.515	33.8	0.015	0.000001	0.985		0.978 Ave Base Survival(1982-2001)	0.988
2005	12287	0.080	38.5	0.002	0.000000	0.998		0.978 Ave Current Survival(2002-2009)	0.978
2006	13738	1.723	38.8	0.044	0.000003	0.956		0.978 Current/Base	0.989
2007	13770	1.091	28.7	0.038	0.000003	0.962		0.978 Base to Current Gap	0.011
2008	10950	0.934	29.5	0.032	0.000003	0.968		0.978	
2009	12087	0.668	26.9	0.025	0.000002	0.975		0.978	
2010	13596	1.300	37.5	0.035	0.000003	0.965			
2011	13045	0.900	32.8	0.027	0.000002	0.973			
2012	12300	1.500	33.5	0.045	0.000004	0.955			
								1998 -2012 Ave Consumption rate	0.027
								Base Period Per Capita Consumption	0.000003
								Current Period Per Capita Consumption	0.000002
								Ave Base Population (prs)	3393
								Ave Current Population (prs)	12024
								Ave Base Consumption	0.010020499
								Ave Current Consumption	0.021586
								Current/Base Consumption	2.15422747

<Adjust these two cell data ranges to account <for different current periods.

Population Location Breakout
 RI Pop ESI Pop
 665 1182
 1211 2153
 1178 4926

<Adjust these two cell data ranges to account <for different base and current periods.

Notes:

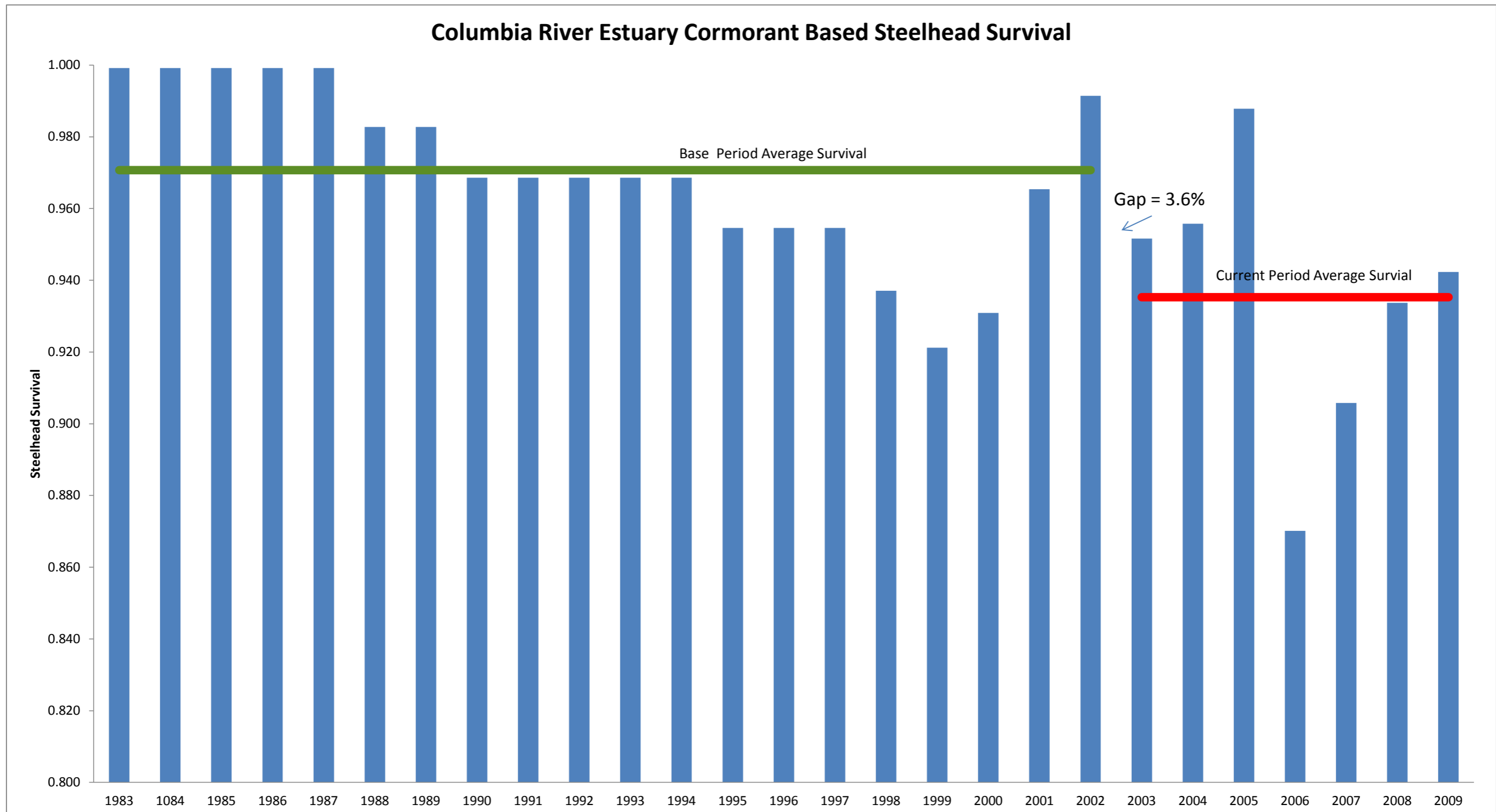
Base year cormorant populations were reported in the literature as averages for certain years or as estimates for specific years. The known base year cormorant population estimates were expanded in years equal distant to the next known estimates. Specific cormornat population and smolt consumption data are available for 1998 and later (data from annaul reports and Collis 3/30/10 email d: Estimates of base consumption rates for the various cormorant population levels assumes a constant juv steelhead population across pre-1998 t All smolt population data from NOAA NWFSC population estimate memos (1998-2012). Smolt consumption for 2010 and later from Bird Research Annual Reports.

Estuary Cormorant Consumption - Sockeye

Year	Cormorant Population (pairs)	Sockeye Consumption (Millions)	Sockeye Population (Millions)	Consumption Rate	Survival Rate		
1998	6285	0.0214		1.3	0.017	0.983	
1999	6561	0.0304		1.3	0.024	0.976	
2000	7162	0.0314		3.3	0.010	0.990	
2001	8120	0.0140		2.1	0.007	0.993	
2002	10230	0.0002		2.1	0.000	1.000	
2003	10646	0.0255		1.8	0.014	0.986	0.987
2004	12480	0.0159		1.9	0.009	0.991	0.987
2005	12287	0.0020		1.8	0.001	0.999	0.987
2006	13738	0.0477		1.4	0.035	0.965	0.987
2007	13770	0.0249		1.7	0.015	0.985	0.987
2008	10950	0.0274		1.7	0.017	0.983	0.987
2009	12087	0.0203		1.5	0.014	0.986	0.987
2010	13596	0.0200		1.5	0.013	0.987	
2011	13045	0.0300		1.5	0.020	0.980	
2012	12300	0.0100		1.7	0.006	0.994	
						1998 -2012 Ave Consumption rate	0.013

Notes:

Specific cormorant population and smolt consumption data are available for 1998 and later (data from annual reports and Collis 3/30/10 email data).
 All smolt population data from NOAA NWFSC population estimate memos (1998-2012).
 Smolt consumption for 2010 and later from Bird Research Annual Reports.



Data from Ken Collis' spreadsheet: Copy of v3 98-09 estuary dcco consumption.xls (sheet: Consumption Data with 95% CI).

scenario	date of estimate	model revision	total salmonids			chinook, sub-yearling			chinook, yearling			coho			sockeye			steelhead		
			min	best	max	min	best	max	min	best	max	min	best	max	min	best	max	min	best	max
1998 Total	39304	3	7.972538	14.99552	22.01851	6.04632	12.11229	18.17826	0.345553	0.686643	1.027732	0.694745	1.35783	2.020914	0.006254	0.021446	0.036638	0.437698	0.817314	1.19693
1999 Total			5.914695	12.36584	18.81698	3.95545	8.556197	13.15694	0.305362	0.937002	1.568641	0.620176	1.750721	2.881266	-0.0002	0.030401	0.061003	0.425491	1.091518	1.757545
2000 Total			3.768665	7.862304	11.95594	2.130427	4.585188	7.039949	0.324045	0.87426	1.424474	0.586009	1.405932	2.225856	0.000866	0.031405	0.061944	0.418328	0.965519	1.51271
2001 ES	39304	3	3.241129	6.778788	10.31645	2.326869	5.003389	7.67991	0.16876	0.429913	0.691066	0.326893	0.815697	1.304501	0.000834	0.01398	0.027126	0.211946	0.515809	0.819672
2002 ES	39304	3	2.004261	4.637369	7.270477	1.727224	4.094756	6.462288	0.014227	0.089318	0.164408	0.060313	0.333841	0.607369	6.35E-06	0.000164	0.000322	0.01938	0.11929	0.2192
2003 ES	39304	3	1.532003	3.409985	5.287966	0.443927	0.974876	1.505824	0.23442	0.703683	1.172947	0.374034	1.005018	1.636002	-0.00028	0.025485	0.051248	0.254959	0.700922	1.146885
2004 ES	39304	3	3.496283	7.34712	11.19796	2.372198	5.214959	8.057721	0.188358	0.514915	0.841471	0.380753	0.996701	1.612649	0.001327	0.01591	0.030494	0.230124	0.604634	0.979144
2005 ES	39304	3	1.082384	2.408425	3.734466	0.81047	1.893767	2.977064	0.029429	0.079764	0.1301	0.109716	0.266637	0.423558	9.16E-05	0.001999	0.003906	0.070572	0.166258	0.261944
2006 ES	39304	3	4.060271	9.137534	14.2148	0.86507	1.945474	3.025877	0.672846	1.722527	2.772209	1.431976	3.566875	5.701773	-0.00413	0.047702	0.099538	0.776325	1.854957	2.933588
2007 ES	39414	3	4.302968	9.156402	14.00984	1.845794	4.073863	6.301932	0.431452	1.090545	1.749639	1.040227	2.65604	4.271853	0.002184	0.024908	0.047633	0.549902	1.311046	2.072189
2008 ES	40140	4	7.105007	9.289814	11.47462	3.713252	5.62834	7.543428	0.684605	0.933507	1.182409	1.33029	1.769495	2.2087	0.00976	0.027402	0.045044	0.72447	0.93107	1.13767
2009 ES	40140	4	7.740189	11.13764	14.5351	5.079365	8.256174	11.43298	0.489313	0.667771	0.846229	1.048515	1.397404	1.746294	0.005849	0.020302	0.034755	0.616623	0.795992	0.97536

Steelhead

Per Capita consumption analysis to estimate a cormorant colony size (pairs) that would close the Base to Current gap in juvenile steelhead survival*.

Columbia River Estuary

Year	% Consumption			DCCO Population (pairs)			Per Capita Consumption		
		<95%CI	Best	>95%CI	<95%CI	Best	>95%CI	Best	>95%CI
1998	6.3%	5908	6285	6662	0.0000106	0.0000100	0.0000094		
1999	7.9%	6167	6561	6955	0.0000128	0.0000120	0.0000113		
2000	6.9%	6732	7162	7592	0.0000103	0.0000096	0.0000091		
2001	3.5%	7633	8120	8607	0.0000045	0.0000043	0.0000040		
2002	0.9%	9616	10230	10844	0.0000009	0.0000008	0.0000008		
2003	4.8%	10007	10646	11285	0.0000048	0.0000045	0.0000043		
2004	4.4%	11731	12480	13229	0.0000038	0.0000035	0.0000033		
2005	1.2%	11550	12287	13024	0.0000011	0.0000010	0.0000009		
2006	13.0%	12914	13738	14562	0.0000101	0.0000095	0.0000089		
2007	9.4%	12945	13770	14597	0.0000073	0.0000068	0.0000065		
2008	6.6%	10585	10950	11315	0.0000063	0.0000061	0.0000059		
2009	5.8%	11929	12087	12245	0.0000048	0.0000048	0.0000047		
2010	10.6%	13130	13596	14062	0.0000081	0.0000078	0.0000076		
2011	7.6%	12781	13045	13309	0.0000060	0.0000059	0.0000057		
2012	11.9%	12035	12300	12567	0.0000099	0.0000097	0.0000095		
Average	6.7%	10378	10884	11390	0.000007	0.000006	0.000006		
Ave "Current" (03-09)	6.5%	11666	12280	12894	0.000005	0.000005	0.000005		

An average colony size (pairs) of: 5380 5661 5939

Would achieve the Base Period consumption rate of: 2.9% <This cell is linked to the Steelhead sheet base consumption rate estimate.

*All data from Bird Research Northwest and NOAA Northwest Fisheries Science Center

Assumptions:

OSU/RTR entergetics model is reasonably accurate for species specific consumption levels.

NOAA smolt populaiton estimates to Tongue Point are resonably accurate.

Past 15 years per capita consumption rates reasonably capture future variability.

Cormorant population remains in vacinity of East Sand Island.

Yearling Chinook

Per Capita consumption analysis to estimate a cormorant colony size (pairs) that would close the Base to Current gap in juvenile Yr Chinook survival*.

Columbia River Estuary

Year	% Consumption	DCCO Population (Pairs)			Per Capita Consumption		
		<95%CI	Best	>95%CI	<95%CI	Best	>95%CI
1998	3.7%	5908	6285	6662	0.000063	0.000059	0.000056
1999	3.5%	6167	6561	6955	0.000057	0.000053	0.000050
2000	2.9%	6732	7162	7592	0.000042	0.000040	0.000038
2001	1.8%	7633	8120	8607	0.000024	0.000022	0.000021
2002	0.3%	9616	10230	10844	0.000003	0.000003	0.000002
2003	1.9%	10007	10646	11285	0.000019	0.000018	0.000017
2004	1.5%	11731	12480	13229	0.000013	0.000012	0.000012
2005	0.2%	11550	12287	13024	0.000002	0.000002	0.000002
2006	4.4%	12914	13738	14562	0.000034	0.000032	0.000030
2007	3.8%	12945	13770	14597	0.000029	0.000028	0.000026
2008	3.2%	10585	10950	11315	0.000030	0.000029	0.000028
2009	2.5%	11929	12087	12245	0.000021	0.000021	0.000020
2010	3.5%	13130	13596	14062	0.000026	0.000025	0.000025
2011	2.7%	12781	13045	13309	0.000021	0.000021	0.000021
2012	4.5%	12035	12300	12567	0.000037	0.000036	0.000036
Average	2.7%	10378	10884	11390	0.000002	0.000002	0.000002
Ave "Current" (02-09)	2.5%	11410	12024	12638	0.000002	0.000002	0.000002

An average colony size (pairs) of:

6221

6536

6848

Would achieve the Base Period consumption rate of:

1.2%

<This cell is linked to the Yr Chinook sheet base consumption rate es

*All data from Bird Research Northwest and NOAA Northwest Fisheries Science Center

Assumptions:

OSU/RTR entergetics model is reasonably accurate for species specific consumption levels.

NOAA smolt populaiton estimates to Tongue Point are resonably accurate.

Past 15 years per capita consumption rates reasonably capture future variability.

Cormorant population remains in vacinity of East Sand Island.

Data from Don Lyons, August 6, 2013, email.

Double-crested Cormorant Breeding Pairs

	East Sand Island			Rice Island			Combined		
	Breeding Pairs	95% Confidence Limits		Best Estima	95% Confidence Limits		Best Estima	95% Confidence Limits	
		LCL	UCL		LCL	UCL		LCL	UCL
1997	5,023	4722	5324	1,141	943	1339	6,164	5802	6526
1998	6,285	5908	6662	795	744	846	7,080	6691	7469
1999	6,561	6167	6955				6,561	6167	6955
2000	7,162	6732	7592				7,162	6732	7592
2001	8,120	7633	8607				8,120	7633	8607
2002	10,230	9616	10844				10,230	9616	10844
2003	10,646	10007	11285				10,646	10007	11285
2004	12,480	11731	13229				12,480	11731	13229
2005	12,287	11550	13024				12,287	11550	13024
2006	13,738	12914	14562				13,738	12914	14562
2007	13,771	12945	14597				13,771	12945	14597
2008	10,950	10585	11315				10,950	10585	11315
2009	12,087	11929	12245				12,087	11929	12245
2010	13,596	13130	14062				13,596	13130	14062
2011	13,045	12781	13309				13,045	12781	13309
2012	12,301	12035	12567				12,301	12035	12567

Appendix F

2013 Update to Hatchery Effects in the Environmental Baseline

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2013 Update to Hatchery Effects in the Environmental Baseline

In the 2008 BiOp, most benefits and risks from past and present hatchery practices were imbedded in the environmental baseline. However, because estimates of productivity and extinction risk in the 2008 BiOp were based on the performance of populations during a 20-year “Base Period” that ended in most cases with the 1999 brood year (with adults returning through 2003–2006, depending on the population), the Environmental Baseline had to be adjusted to account for the effects of hatchery reform actions, for which empirical data had not yet been gathered or did not yet exist. For example, the empirical data from the Base Period did not fully reflect the effects of hatchery reform actions taken in the latter portion of the Base Period or after the Base Period (e.g., elimination of an out-of-basin broodstock in the Upper Grande Ronde). The Stier and Hinrichsen (2008) methodology was used to make Base-to-Current (i.e. base-to-2008) adjustments in survival from completed hatchery reform actions. Survival adjustments were based on changes in the productivity of the entire naturally spawning population, which includes hatchery-origin fish when they spawn naturally. Therefore, hatchery management actions that improved the productivity of hatchery-origin fish spawning naturally affected the Base-to-Current adjustment. This methodology was described in Appendix I of the 2008 Supplemental Comprehensive Analysis.¹

In the 2008 BiOp, Base-to-Current (i.e. Base-to-2008) adjustments for hatchery reform actions were only applied to five populations in the Snake River spring/summer Chinook ESU and four populations in the UCR steelhead DPS (Table E-1). NOAA Fisheries must determine whether there is new information that reveals a change in the Environmental Baseline that would affect conclusions made in the 2008 BiOp. Therefore, NOAA Fisheries updated the data used in the Stier and Hinrichsen (2008) methodology to see if it affected the 2008 BiOp’s base-to-2008 integrated productivity increase. The Northwest Fishery Science Center’s SPS database² was used to identify new data on the fraction of natural-origin spawners (f) for these populations. “Future f ” values were assumed to be an average of recent f values. NOAA Fisheries used a variety of sources to estimate the relative reproductive success of hatchery-origin spawners (“ e ” values and “future e ” values). The rationale for changes in e values is summarized in Table F-1 by population. Revised calculations for the integrated productivity increases over the Base Period are included in Table F-2 through Table F-11.

¹ The 2008 BiOp used these base-to-current adjustments to estimate the prospective effects of *then-completed* hatchery reform actions, but there was no quantification of the expected effects of the *prospective* hatchery reform actions identified in the RPA.

² <http://www.webapps.nwfsc.noaa.gov/apex/f?p=238:home:0>

Because the Steir and Hinrichsen (2008) methodology does not account for genetic and ecological effects on natural productivity from naturally spawning hatchery-origin fish quantitatively (i.e., the model does not account for potential reductions in the productivity of natural-origin fish from interbreeding with hatchery-origin fish), NOAA Fisheries considered these prospective effects qualitatively in the 2008 BiOp's effects analysis.

Table F-1. Summary of the 2008 BiOp's hatchery reform multipliers with a 2013 update.

Population	2008 BiOp's Base-to-Current Integrated Productivity Increase as a Ratio	2008 BiOp's Assumptions for Base-to-Current Adjustment	2013 Supplemental BiOp's Base-to-Current Integrated Productivity Increase as a Ratio	2013 Update
Upper Grande Ronde Spring/Summer Chinook Salmon	1.21	<p>The 2008 BiOp assumed that the future fraction of natural-origin fish on the spawning ground would be 0.67.</p> <p>The 2008 BiOp assumed that hatchery-origin spawners would be 0.45 as reproductively effective as natural-origin spawners.</p>	1.29	<p>The recent 5-year average of the fraction of natural-origin fish on the spawning grounds was 0.26 (based on 2007 through 2011), which is lower than what was expected in the 2008 BiOp.</p> <p>New data shows that the reproductive effectiveness of hatchery-origin spawners in Catherine Creek is 0.83 relative to natural-origin spawners in the Catherine Creek. The Upper Grande Ronde hatchery program is similar to the Catherine Creek hatchery program because it releases spring/summer Chinook salmon derived from local stock. Therefore, the relative reproductive success of hatchery-origin spring/summer Chinook salmon in the Upper Grande Ronde is probably similar to the relative reproductive success of hatchery-origin spawners in Catherine Creek, which is higher than what was expected in the 2008 BiOp (Williamson et al. 2010)</p> <p>Based on new data, the Base-to-Current integrated productivity increase has increased relative to the 2008 BiOp (Table 2).</p>

Population	2008 BiOp's Base-to-Current Integrated Productivity Increase as a Ratio	2008 BiOp's Assumptions for Base-to-Current Adjustment	2013 Supplemental BiOp's Base-to-Current Integrated Productivity Increase as a Ratio	2013 Update
Lostine River Spring/Summer Chinook Salmon	1.03	<p>The 2008 BiOp assumed that the future fraction of natural-origin fish on the spawning ground would be 0.67.</p> <p>The 2008 BiOp assumed that hatchery-origin spawners would be 0.45 as reproductively effective as natural-origin spawners.</p>	1.11	<p>The recent 5-year average of the fraction of natural-origin fish on the spawning grounds was 0.33 (based on 2007 through 2011), which is lower than what was expected in the 2008 BiOp.</p> <p>New data shows that the reproductive effectiveness of hatchery-origin spawners in Catherine Creek is 0.83 relative to natural-origin spawners in the Catherine Creek (Williamson et al. 2010). The Lostine River hatchery program is similar to the Catherine Creek hatchery program because it releases spring/summer Chinook salmon derived from local stock. Therefore, the relative reproductive success of hatchery-origin spring/summer Chinook salmon in the Lostine River is probably similar to the relative reproductive success of hatchery-origin spawners in Catherine Creek, which is higher than what was expected in the 2008 BiOp.</p> <p>Based on new data, the Base-to-Current integrated productivity increase has increased relative to the 2008 BiOp (Table 3).</p>

Population	2008 BiOp's Base-to-Current Integrated Productivity Increase as a Ratio	2008 BiOp's Assumptions for Base-to-Current Adjustment	2013 Supplemental BiOp's Base-to-Current Integrated Productivity Increase as a Ratio	2013 Update
Catherine Creek Spring/Summer Chinook Salmon	1.20	<p>The 2008 BiOp assumed that the future fraction of natural-origin fish on the spawning ground would be 0.67.</p> <p>The 2008 BiOp assumed that hatchery-origin spawners would be 0.45 as reproductively effective as natural-origin spawners.</p>	1.31	<p>The recent 5-year average of the fraction of natural-origin fish on the spawning grounds was 0.39 (based on 2007 through 2011), which is lower than what was expected in the 2008 BiOp.</p> <p>However, new data shows that the reproductive effectiveness of hatchery-origin spawners in Catherine Creek is 0.83 relative to natural-origin spawners in the Catherine Creek (Williamson et al. 2010), which is higher than what was expected in the 2008 BiOp.</p> <p>Based on new data, the Base-to-Current integrated productivity increase has increased relative to the 2008 BiOp (Table 4).</p>
Minam River Spring/Summer Chinook Salmon	1.22	<p>The 2008 BiOp assumed that the future fraction of natural-origin fish on the spawning ground would be 0.96.</p> <p>The 2008 BiOp assumed that hatchery-origin spawners would be 0.20 as reproductively effective as natural-origin spawners.</p>	1.16	<p>The recent 5-year average of the fraction of natural-origin fish on the spawning grounds was 0.85 (based on 2008 through 2012), which is lower than what was expected in the 2008 BiOp.</p> <p>New data shows that the reproductive effectiveness of hatchery-origin spawners in Catherine Creek is 0.83 relative to natural-origin spawners in the Catherine Creek (Williamson et al. 2010). Because the hatchery-origin spawners straying into Wenaha River would likely be from the Catherine Creek, Upper Grande Ronde, and Lostine River hatchery programs, the 2008 BiOp likely underestimated the reproductive effectiveness of hatchery-origin spawners in the</p>

Population	2008 BiOp's Base-to-Current Integrated Productivity Increase as a Ratio	2008 BiOp's Assumptions for Base-to-Current Adjustment	2013 Supplemental BiOp's Base-to-Current Integrated Productivity Increase as a Ratio	2013 Update
				<p>Minam River. Although the spring/summer Chinook salmon from Catherine Creek, Upper Grande Ronde, and Lostine River would not be expected to have a reproductive effectiveness of 0.83 when spawning the Minam River, these fish would be more reproductively effective than the highly domesticated Rapid River hatchery-origin fish that previously strayed into the Minam River. The Rapid River stock is no longer released into the Grande Ronde River basin.</p> <p>Based on new data, the Base-to-Current integrated productivity increase has decreased relative to the 2008 BiOp (Table 5).</p>
Wenaha River Spring/Summer Chinook Salmon	1.39	<p>The 2008 BiOp assumed that the future fraction of natural-origin fish on the spawning ground would be 0.95.</p> <p>The 2008 BiOp assumed that hatchery-origin spawners would be 0.20 as reproductively effective as natural-origin spawners.</p>	1.36	<p>The recent 5-year average of the fraction of natural-origin fish on the spawning grounds was 0.87 (based on 2008 through 2012), which is lower than what was expected in the 2008 BiOp.</p> <p>New data shows that the reproductive effectiveness of hatchery-origin spawners in Catherine Creek is 0.83 relative to natural-origin spawners in the Catherine Creek (Williamson et al. 2010). Because the hatchery-origin spawners straying into Wenaha River would likely be from the Catherine Creek, Upper Grande Ronde, and Lostine River hatchery programs, the 2008 BiOp likely underestimated the reproductive effectiveness of hatchery-origin spawners in the Wenaha River. Although the spring/summer Chinook salmon</p>

Population	2008 BiOp's Base-to-Current Integrated Productivity Increase as a Ratio	2008 BiOp's Assumptions for Base-to-Current Adjustment	2013 Supplemental BiOp's Base-to-Current Integrated Productivity Increase as a Ratio	2013 Update
				<p>from Catherine Creek, Upper Grande Ronde, and Lostine River would not be expected to have a reproductive effectiveness of 0.83 when spawning the Minam River, these fish would be more reproductively effective than the highly domesticated Rapid River hatchery-origin fish that previously strayed into the Minam River. The Rapid River stock is no longer released into the Grande Ronde River basin.</p> <p>Based on new data, the Base-to-Current integrated productivity increase has decreased relative to the 2008 BiOp (Table 6).</p>
Wenatchee River Steelhead	1.60	<p>The 2008 BiOp assumed that the future fraction of natural-origin fish on the spawning ground would be 0.38.</p> <p>The 2008 BiOp assumed that hatchery-origin spawners would be 0.45 as reproductively effective as natural-origin spawners.</p>	1.78	<p>The recent 5-year average of the fraction of natural-origin fish on the spawning grounds was 0.47 (based on 2007 through 2011), which is higher than what was expected in the 2008 BiOp.</p> <p>The expected reproductive effectiveness of the hatchery-origin spawners has increased to 0.53 based a new relative reproductive study on the Wenatchee that shows that hatchery-origin steelhead in the Wenatchee River basin are 0.53 as reproductively effective as natural-origin spawners in the Wenatchee River Basin (Berntson et al. 2012)).</p> <p>Based on new data, the Base-to-Current integrated productivity increase has increased relative to the 2008 BiOp (Table 7).</p>

Population	2008 BiOp's Base-to-Current Integrated Productivity Increase as a Ratio	2008 BiOp's Assumptions for Base-to-Current Adjustment	2013 Supplemental BiOp's Base-to-Current Integrated Productivity Increase as a Ratio	2013 Update
Entiat River Steelhead	0.82 (low) 1.30 (high)	<p>The 2008 BiOp assumed that the future fraction of natural-origin fish on the spawning ground would be between 0.22 (low estimate) and 0.50 (high estimate).</p> <p>The 2008 BiOp assumed that hatchery-origin spawners would be 0.20 as reproductively effective as natural-origin spawners.</p>	0.93	<p>The recent 5-year average of the fraction of natural-origin fish on the spawning grounds was 0.29 (based on 2007 through 2011), which is higher than what was expected in the low estimate in the 2008 BiOp.</p> <p>The reproductive effectiveness of the hatchery-origin spawners is still expected to be 0.20 after considering new data because the hatchery-origin fish are from non-local, domesticated broodstock</p> <p>Based on new data, the current Base-to-Current integrated productivity increase falls within the range anticipated in the 2008 BiOp (Table 8).</p>
Methow River Steelhead	1.17 (low) 1.55 (high)	<p>The 2008 BiOp assumed that the future fraction of natural-origin fish on the spawning ground would be between 0.30 (low estimate) and 0.45 (high estimate).</p> <p>The 2008 BiOp assumed that hatchery-origin spawners would be 0.10 as reproductively effective as natural-origin spawners.</p>	1.84	<p>The recent 5-year average of the fraction of natural-origin fish on the spawning grounds was 0.18 (based on 2007 through 2011), which is higher than what was expected in both the low and high estimates in the 2008 BiOp.</p> <p>New data shows that the reproductive effectiveness of hatchery-origin spawners in the Wenatchee River is 0.53 relative to natural-origin spawners in the Wenatchee River (Berntson et al. 2012). The Methow River hatchery program is similar to the Wenatchee River hatchery program because it releases steelhead derived from local stock. Therefore, the relative reproductive success of hatchery-origin steelhead in the Methow River is probably</p>

Population	2008 BiOp's Base-to-Current Integrated Productivity Increase as a Ratio	2008 BiOp's Assumptions for Base-to-Current Adjustment	2013 Supplemental BiOp's Base-to-Current Integrated Productivity Increase as a Ratio	2013 Update
				<p>similar to the relative reproductive success of hatchery-origin spawners in Wenatchee River, which is higher than what was expected in the 2008 BiOp.</p> <p>Therefore, based on new data, the Base-to-Current integrated productivity increase has increased relative to the 2008 BiOp (Table 9).</p>
Okanogan River Steelhead	1.34 (low) 1.88 (high)	<p>The 2008 BiOp assumed that the future fraction of natural-origin fish on the spawning ground would be 0.07</p> <p>The 2008 BiOp assumed that hatchery-origin spawners would be between 0.30 (low estimate) and 0.45 (high estimate) as reproductively effective as natural-origin spawners.</p>	1.42 (low) 1.87 (high)	<p>The recent 5-year average of the percentage of natural-origin fish on the spawning grounds was 0.10 (based on 2007 through 2011), which is higher than what was expected in in the 2008 BiOp.</p> <p>NOAA Fisheries does not have any new information that would suggest that <i>e</i> values from the 2008 BiOp's calculations need to be revised.</p> <p>Based on new data, the current low Base-to-Current integrated productivity increase has increased over the low estimate in the 2008 BiOp (Table 10). However, the current high Base-to-Current productivity increase has decreased from the high estimate in the 2008 BiOp (Table 11).</p>

Table F-2. Estimates of Base-to-Current survival multiplier for the Upper Grande Ronde population of Snake River spring/summer Chinook salmon.

Year		%Wild (f) from 1/30/13 SPS Data	e from 3/5/12 NMFS draft estimates	ln(Proportion of Natural Spawner Equivalents) = ln(f+(1-f)*e)	Proportion of Natural Spawner Equivalents	future e	future f	future ln(f+(1-f)*e)	Integrated productivity increase (from base period) as a ratio
1981	2008 BiOp Base	1.00	0.2	0	1.00	0.83	0.26	-0.134446097	1.29
1982	2008 BiOp Base	1.00	0.2	0	1.00				
1983	2008 BiOp Base	1.00	0.2	0	1.00				
1984	2008 BiOp Base	1.00	0.2	0	1.00	Future e from 3/5/12 NMFS draft estimates			
1985	2008 BiOp Base	1.00	0.2	0	1.00	Future f based on the average f for most recent 5 years of data.			
1986	2008 BiOp Base	0.86	0.2	-0.118783536	0.89				
1987	2008 BiOp Base	0.18	0.2	-1.067113622	0.34				
1988	2008 BiOp Base	0.08	0.2	-1.331806176	0.26				
1989	2008 BiOp Base	0.00	0.2	-1.609437912	0.20				
1990	2008 BiOp Base	0.50	0.2	-0.510825624	0.60	NOTE: This would replace the 1.21 multiplier in the 2008 BiOp			
1991	2008 BiOp Base	0.60	0.2	-0.385662481	0.68	It would not be added to it			
1992	2008 BiOp Base	0.21	0.2	-0.999672341	0.37	The effective change would be: 1.06			
1993	2008 BiOp Base	0.23	0.2	-0.957112726	0.38				
1994	2008 BiOp Base	0.33	0.2	-0.767870727	0.46				
1995	2008 BiOp Base	1.00	0.2	0	1.00			0.84	
1996	2008 BiOp Base	1.00	0.2	0	1.00			0.15	
1997	2008 BiOp Base	1.00	0.2	0	1.00			0.16	
1998	2008 BiOp Base	1.00	0.2	0	1.00			0.05	
1999	2008 BiOp Base	1.00	0.2	0	1.00			0.1	
2000	2008 BiOp Base	1.00	0.2	0	1.00				
2001	New	1.00	0.2	0	1.00			1.3	
2002	New	0.95	0.2	-0.040821995	0.96				
2003	New	0.81	0.83	-0.032833157	0.97			0.26	
2004	New	0.05	0.83	-0.176140698	0.84				
2005	New	0.04	0.83	-0.178170186	0.84				
2006	New	0.48	0.83	-0.092553982	0.91				
2007	New	0.84	0.83	-0.027576768	0.97				
2008	New	0.15	0.83	-0.156069186	0.86				
2009	New	0.16	0.83	-0.154084015	0.86				
2010	New	0.05	0.83	-0.176140698	0.84				
2011	New	0.10	0.83	-0.166054584	0.85				
Base Period Average		0.70	0.20	-0.39	0.76				
Post-Base Average		0.42	0.72	-0.11	0.90				
Last 10-yr Average		0.36	0.77	-0.12	0.89				

Table F-3. Estimates of Base-to-Current survival multiplier for the Lostine River population of Snake River spring/summer Chinook salmon.

Year		%Wild (f) from 1/30/13 SPS Data	e from 3/5/12 NMFS draft estimates	ln(Proportion of Natural Spawner Equivalents) = $\ln(f+(1-f)*e)$	Proportion of Natural Spawner Equivalents	future e	future f	future $\ln(f+(1-f)*e)$	Integrated productivity increase (from base period) as a ratio
1981	2008 BiOp Base	1.00	0.2	0	1.00	0.83	0.33	-0.120925468	1.11
1982	2008 BiOp Base	1.00	0.2	0	1.00				
1983	2008 BiOp Base	1.00	0.2	0	1.00				
1984	2008 BiOp Base	1.00	0.2	0	1.00	Future e from 3/5/12 NMFS draft estimates			
1985	2008 BiOp Base	1.00	0.2	0	1.00	Future f based on the average f for most recent 5 years of data.			
1986	2008 BiOp Base	0.77	0.2	-0.203340924	0.82				
1987	2008 BiOp Base	0.68	0.2	-0.295714244	0.74				
1988	2008 BiOp Base	0.55	0.2	-0.446287103	0.64				
1989	2008 BiOp Base	0.24	0.2	-0.936493439	0.39				
1990	2008 BiOp Base	0.60	0.2	-0.385662481	0.68	NOTE: This would replace the 1.03 multiplier in the 2008 BiOp			
1991	2008 BiOp Base	0.65	0.2	-0.328504067	0.72	It would not be added to it			
1992	2008 BiOp Base	0.25	0.2	-0.916290732	0.40	The effective change would be: 1.08			
1993	2008 BiOp Base	0.49	0.2	-0.524248644	0.59				
1994	2008 BiOp Base	0.75	0.2	-0.223143551	0.80			0.33	
1995	2008 BiOp Base	1.00	0.2	0	1.00			0.28	
1996	2008 BiOp Base	1.00	0.2	0	1.00			0.43	
1997	2008 BiOp Base	0.95	0.2	-0.040821995	0.96			0.27	
1998	2008 BiOp Base	1.00	0.2	0	1.00			0.33	
1999	2008 BiOp Base	0.92	0.2	-0.066139803	0.94				
2000	2008 BiOp Base	0.83	0.2	-0.14618251	0.86			1.64	
2001	New	0.77	0.2	-0.203340924	0.82				
2002	New	0.47	0.2	-0.551647618	0.58			0.328	
2003	New	0.51	0.83	-0.086975014	0.92				
2004	New	0.23	0.83	-0.140297086	0.87				
2005	New	0.25	0.83	-0.136392625	0.87				
2006	New	0.36	0.83	-0.11518641	0.89				
2007	New	0.33	0.83	-0.120925468	0.89				
2008	New	0.28	0.83	-0.13056437	0.88				
2009	New	0.43	0.83	-0.10192199	0.90				
2010	New	0.27	0.83	-0.13250335	0.88				
2011	New	0.33	0.83	-0.120925468	0.89				
Base Period Average		0.78	0.20	-0.23	0.83				
Post-Base Average		0.38	0.72	-0.17	0.85				
Last 10-yr Average		0.35	0.77	-0.16	0.86				

Table F-4. Estimates of Base-to-Current survival multiplier for the Catherine Creek population of Snake River spring/summer Chinook salmon.

Year		%Wild (f) from 1/30/13 SPS Data	e from 3/5/12 NMFS draft estimates	ln(Proportion of Natural Spawner Equivalents) = ln(f+(1-f)*e)	Proportion of Natural Spawner Equivalents	future e	future f	future ln(f+(1-f)*e)	Integrated productivity increase (from base period) as a ratio
1981	2008 BiOp Base	1.00	0.2	0	1.00	0.83	0.39	-0.109480101	1.31
1982	2008 BiOp Base	1.00	0.2	0	1.00				
1983	2008 BiOp Base	1.00	0.2	0	1.00				
1984	2008 BiOp Base	1.00	0.2	0	1.00	Future e from 3/5/12 NMFS draft estimates			
1985	2008 BiOp Base	1.00	0.2	0	1.00	Future f based on the average f for most recent 5 years of data.			
1986	2008 BiOp Base	0.80	0.2	-0.174353387	0.84				
1987	2008 BiOp Base	0.22	0.2	-0.978166136	0.38				
1988	2008 BiOp Base	0.24	0.2	-0.936493439	0.39				
1989	2008 BiOp Base	0.38	0.2	-0.685179011	0.50				
1990	2008 BiOp Base	0.00	0.2	-1.609437912	0.20	NOTE: This would replace the 1.20 multiplier in the 2008 BiOp			
1991	2008 BiOp Base	0.13	0.2	-1.190727578	0.30	It would not be added to it			
1992	2008 BiOp Base	0.25	0.2	-0.916290732	0.40	The effective change would be: 1.10			
1993	2008 BiOp Base	0.40	0.2	-0.653926467	0.52				
1994	2008 BiOp Base	0.50	0.2	-0.510825624	0.60				
1995	2008 BiOp Base	1.00	0.2	0	1.00				
1996	2008 BiOp Base	1.00	0.2	0	1.00				0.29
1997	2008 BiOp Base	1.00	0.2	0	1.00				0.35
1998	2008 BiOp Base	1.00	0.2	0	1.00				0.46
1999	2008 BiOp Base	1.00	0.2	0	1.00				0.48
2000	2008 BiOp Base	1.00	0.2	0	1.00				0.35
2001	New	0.77	0.2	-0.203340924	0.82				
2002	New	0.50	0.2	-0.510825624	0.60				1.93
2003	New	0.41	0.83	-0.105693905	0.90				
2004	New	0.17	0.83	-0.152102778	0.86				
2005	New	0.26	0.83	-0.134446097	0.87				0.386
2006	New	0.37	0.83	-0.113280686	0.89				
2007	New	0.29	0.83	-0.128629143	0.88				
2008	New	0.35	0.83	-0.117095772	0.89				
2009	New	0.46	0.83	-0.09629066	0.91				
2010	New	0.48	0.83	-0.092553982	0.91				
2011	New	0.35	0.83	-0.117095772	0.89				
Base Period Average		0.70	0.20	-0.38	0.76				
Post-Base Average		0.40	0.72	-0.16	0.86				
Last 10-yr Average		0.36	0.77	-0.16	0.86				

Table F-5. Estimates of Base-to-Current survival multiplier for the Minam River population of Snake River spring/summer Chinook salmon.

Year		%Wild (f) from 1/30/13 SPS Data	e from 3/5/12 NMFS draft estimates	ln(Proportion of Natural Spawner Equivalents) = ln(f/(1-f)*e)	Proportion of Natural Spawner Equivalents	future e	future f	future ln(f/(1-f)*e)	Integrated productivity increase (from base period) as a ratio
1981	2008 BiOp Base	1.00	0.2	0	1.00	0.5	0.85	-0.077961541	1.16
1982	2008 BiOp Base	1.00	0.2	0	1.00				
1983	2008 BiOp Base	1.00	0.2	0	1.00				
1984	2008 BiOp Base	1.00	0.2	0	1.00	Future e from 3/5/12 NMFS draft estimates			
1985	2008 BiOp Base	1.00	0.2	0	1.00	Future f based on the average f for most recent 5 years of data.			
1986	2008 BiOp Base	0.50	0.2	-0.510825624	0.60				
1987	2008 BiOp Base	0.50	0.2	-0.510825624	0.60				
1988	2008 BiOp Base	0.63	0.2	-0.350976923	0.70				
1989	2008 BiOp Base	1.00	0.2	0	1.00				
1990	2008 BiOp Base	0.44	0.2	-0.594207233	0.55	NOTE: This would replace the 1.22 multiplier in the 2008 BiOp			
1991	2008 BiOp Base	0.62	0.2	-0.362405619	0.70	It would not be added to it			
1992	2008 BiOp Base	0.10	0.2	-1.272965676	0.28	The effective change would be: 0.95			
1993	2008 BiOp Base	0.56	0.2	-0.433864583	0.65				
1994	2008 BiOp Base	0.56	0.2	-0.433864583	0.65				
1995	2008 BiOp Base	1.00	0.2	0	1.00				
1996	2008 BiOp Base	0.95	0.2	-0.040821995	0.96				
1997	2008 BiOp Base	0.96	0.2	-0.032523192	0.97			0.88	
1998	2008 BiOp Base	1.00	0.2	0	1.00			1	
1999	2008 BiOp Base	0.95	0.2	-0.040821995	0.96			0.65	
2000	2008 BiOp Base	0.97	0.2	-0.024292693	0.98			0.83	
2001	New	0.94	0.2	-0.049190244	0.95			0.91	
2002	New	0.99	0.2	-0.008032172	0.99				
2003	New	0.99	0.5	-0.005012542	1.00			4.27	
2004	New	0.99	0.5	-0.005012542	1.00			0.854	
2005	New	1.00	0.5	0	1.00				
2006	New	1.00	0.5	0	1.00				
2007	New	1.00	0.5	0	1.00				
2008	New	0.88	0.5	-0.061875404	0.94				
2009	New	1.00	0.5	0	1.00				
2010	New	0.65	0.5	-0.192371893	0.83				
2011	New	0.83	0.5	-0.088831214	0.92				
2012	New	0.91	0.5	-0.046043939	0.96				
Base Period Average		0.79	0.20	-0.23	0.83				
Post-Base Average		0.93	0.45	-0.04	0.96				
Last 10-yr Average		0.93	0.50	-0.04	0.96				

Table F-6. Estimates of Base-to-Current survival multiplier for the Wenaha River population of Snake River spring/summer Chinook salmon.

Year		%Wild (f) from 1/30/13 SPS Data	e from 3/5/12 NMFS draft estimates	ln(Proportion of Natural Spawner Equivalents) = $\ln(f+(1-f)*e)$	Proportion of Natural Spawner Equivalents	future e	future f	future $\ln(f+(1-f)*e)$	Integrated productivity increase (from base period) as a ratio
1981	2008 BiOp Base	1.00	0.2	0	1.00	0.5	0.87	-0.06720875	1.36
1982	2008 BiOp Base	1.00	0.2	0	1.00				
1983	2008 BiOp Base	1.00	0.2	0	1.00				
1984	2008 BiOp Base	1.00	0.2	0	1.00	Future e from 3/5/12 NMFS draft estimates			
1985	2008 BiOp Base	1.00	0.2	0	1.00	Future f based on the average f for most recent 5 years of data.			
1986	2008 BiOp Base	1.00	0.2	0	1.00				
1987	2008 BiOp Base	0.09	0.2	-1.301953213	0.27				
1988	2008 BiOp Base	0.28	0.2	-0.858021824	0.42				
1989	2008 BiOp Base	0.75	0.2	-0.223143551	0.80				
1990	2008 BiOp Base	0.22	0.2	-0.978166136	0.38	NOTE: This would replace the 1.39 multiplier in the 2008 BiOp			
1991	2008 BiOp Base	0.33	0.2	-0.767870727	0.46	It would not be added to it			
1992	2008 BiOp Base	0.09	0.2	-1.301953213	0.27	The effective change would be: 0.98			
1993	2008 BiOp Base	0.54	0.2	-0.458865885	0.63				
1994	2008 BiOp Base	0.20	0.2	-1.021651248	0.36				
1995	2008 BiOp Base	0.67	0.2	-0.30652516	0.74				
1996	2008 BiOp Base	0.98	0.2	-0.016129382	0.98			0.94	
1997	2008 BiOp Base	0.97	0.2	-0.024292693	0.98			1	
1998	2008 BiOp Base	0.98	0.2	-0.016129382	0.98			0.86	
1999	2008 BiOp Base	0.85	0.2	-0.127833372	0.88			0.7	
2000	2008 BiOp Base	0.97	0.2	-0.024292693	0.98			0.86	
2001	New	0.85	0.2	-0.127833372	0.88				
2002	New	1.00	0.2	0	1.00			4.36	
2003	New	1.00	0.5	0	1.00				
2004	New	0.98	0.5	-0.010050336	0.99			0.87	
2005	New	0.97	0.5	-0.015113638	0.99				
2006	New	1.00	0.5	0	1.00				
2007	New	0.96	0.5	-0.020202707	0.98				
2008	New	0.94	0.5	-0.030459207	0.97				
2009	New	1.00	0.5	0	1.00				
2010	New	0.86	0.5	-0.072570693	0.93				
2011	New	0.70	0.5	-0.162518929	0.85				
2012	New	0.86	0.5	-0.072570693	0.93				
	Base Period Average	0.70	0.20	-0.37	0.76				
	Post-Base Average	0.93	0.45	-0.04	0.96				
	Last 10-yr Average	0.93	0.50	-0.04	0.96				

Table F-7. Estimates of Base-to-Current survival multiplier for the Wenatchee River population of Upper Columbia River steelhead.

Year		%Wild (f) from 1/30/13 SPS Data	e from 3/5/12 NMFS draft estimates	In(Proportion of Natural Spawner Equivalents) = $\ln(f+(1-f)*e)$	Proportion of Natural Spawner Equivalents	future e	future f	future $\ln(f+(1-f)*e)$	Integrated productivity increase (from base period) as a ratio
1981	2008 BiOp Base	0.20	0.2	-1.021651248	0.36	0.53	0.47	-0.286482792	1.78
1982	2008 BiOp Base	0.22	0.2	-0.978166136	0.38				
1983	2008 BiOp Base	0.17	0.2	-1.090644119	0.34				
1984	2008 BiOp Base	0.08	0.2	-1.331806176	0.26	Future e from 3/5/12 NMFS draft estimates			
1985	2008 BiOp Base	0.11	0.2	-1.244794799	0.29	Future f based on the average f for most recent 5 years of data.			
1986	2008 BiOp Base	0.15	0.2	-1.139434283	0.32				
1987	2008 BiOp Base	0.17	0.2	-1.090644119	0.34				
1988	2008 BiOp Base	0.35	0.2	-0.733969175	0.48				
1989	2008 BiOp Base	0.35	0.2	-0.733969175	0.48				
1990	2008 BiOp Base	0.39	0.2	-0.669430654	0.51	NOTE: This would replace the 1.60 multiplier in the 2008 BiOp			
1991	2008 BiOp Base	0.33	0.2	-0.767870727	0.46	It would not be added to it			
1992	2008 BiOp Base	0.40	0.2	-0.653926467	0.52	The effective change would be: 1.11			
1993	2008 BiOp Base	0.16	0.2	-1.114741671	0.33				
1994	2008 BiOp Base	0.24	0.2	-0.936493439	0.39				
1995	2008 BiOp Base	0.15	0.2	-1.139434283	0.32				
1996	2008 BiOp Base	0.26	0.2	-0.896488105	0.41				
1997	2008 BiOp Base	0.51	0.2	-0.497580397	0.61			0.44	
1998	2008 BiOp Base	0.42	0.53	-0.318278746	0.73			0.39	
1999	2008 BiOp Base	0.69	0.53	-0.157472859	0.85			0.41	
2000	2008 BiOp Base	0.35	0.53	-0.733969175	0.48			0.36	
2001	New	0.43	0.53	-0.311838162	0.73			0.73	
2002	New	0.39	0.53	-0.33785319	0.71				
2003	New	0.33	0.53	-0.378190466	0.69			2.33	
2004	New	0.22	0.53	-0.456653145	0.63				
2005	New	0.23	0.53	-0.449260268	0.64				
2006	New	0.41	0.53	-0.324761081	0.72			0.466	
2007	New	0.44	0.53	-0.305438794	0.74				
2008	New	0.39	0.53	-0.33785319	0.71				
2009	New	0.41	0.53	-0.324761081	0.72				
2010	New	0.36	0.53	-0.357818455	0.70				
2011	New	0.73	0.53	-0.135705182	0.87				
	Base Period Average	0.29	0.25	-0.86	0.44				
	Post-Base Average	0.39	0.53	-0.34	0.72				
	Last 10-yr Average	0.39	0.53	-0.34	0.71				

Table F-8. Estimates of Base-to-Current survival multiplier for the Entiat River population of Upper Columbia River steelhead.

%Wild (f) from 1/30/13 SPS Data	e from 3/5/12 NMFS draft estimates	ln(Proportion of Natural Spawner Equivalents) = ln(f+(1-f)*e)	Proportion of Natural Spawner Equivalents	future e	future f	future ln(f+(1-f)*e)	Integrated productivity increase (from base period) as a ratio
0.25	0.2	-0.916290732	0.40	0.2	0.29	-0.839329691	0.93
0.17	0.2	-1.090644119	0.34				
0.18	0.2	-1.067113622	0.34				
0.38	0.2	-0.685179011	0.50	Future e from 3/5/12 NMFS draft estimates			
0.40	0.2	-0.653926467	0.52	Future f based on the average f for most recent 5 years of data.			
0.23	0.2	-0.957112726	0.38				
0.40	0.2	-0.653926467	0.52				
0.44	0.2	-0.594207233	0.55				
0.69	0.2	-0.285018955	0.75				
0.38	0.2	-0.685179011	0.50				
0.27	0.2	-0.877070019	0.42				
0.94	0.2	-0.049190244	0.95				
0.76	0.2	-0.21319322	0.81				
0.45	0.2	-0.579818495	0.56	Based on new data, the current base-to-current integrated productivity increase falls within the range anticipated in the 2008 BiOp			
0.28	0.2	-0.858021824	0.42				
0.31	0.2	-0.802962047	0.45				
0.23	0.2	-0.957112726	0.38				
0.09	0.2	-1.301953213	0.27				
0.13	0.2	-1.190727578	0.30				0.22
0.24	0.2	-0.936493439	0.39				0.44
0.26	0.2	-0.896488105	0.41				0.15
0.33	0.2	-0.767870727	0.46				0.29
0.26	0.2	-0.896488105	0.41				0.36
0.09	0.2	-1.301953213	0.27				1.46
0.13	0.2	-1.190727578	0.30				
0.28	0.2	-0.858021824	0.42				0.292
0.22	0.2	-0.978166136	0.38				
0.44	0.2	-0.594207233	0.55				
0.15	0.2	-1.139434283	0.32				
0.29	0.2	-0.839329691	0.43				
0.36	0.2	-0.717439873	0.49				
0.36	0.20	-0.77	0.49				
0.26	0.20	-0.93	0.40				
0.26	0.20	-0.93	0.40				

Table F-9. Estimates of Base-to-Current survival multiplier for the Methow River population of Upper Columbia River steelhead.

Year		%Wild (f) from 1/30/13 SPS Data	e from 3/5/12 NMFS draft estimates	In(Proportion of Natural Spawner Equivalents) = $\ln(f+(1-f)*e)$	Proportion of Natural Spawner Equivalents	future e	future f	future $\ln(f+(1-f)*e)$	Integrated productivity increase (from base period) as a ratio
1981	2008 BiOp Base	0.12	0.2	-1.217395825	0.30	0.53	0.19	-0.479165471	1.84
1982	2008 BiOp Base	0.12	0.2	-1.217395825	0.30				
1983	2008 BiOp Base	0.08	0.2	-1.331806176	0.26				
1984	2008 BiOp Base	0.02	0.2	-1.532476871	0.22	Future e from 3/5/12 NMFS draft estimates			
1985	2008 BiOp Base	0.03	0.2	-1.496109227	0.22	Future f based on the average f for most recent 5 years of data.			
1986	2008 BiOp Base	0.05	0.2	-1.427116356	0.24				
1987	2008 BiOp Base	0.04	0.2	-1.461017907	0.23				
1988	2008 BiOp Base	0.26	0.2	-0.896488105	0.41				
1989	2008 BiOp Base	0.25	0.2	-0.916290732	0.40				
1990	2008 BiOp Base	0.28	0.2	-0.858021824	0.42	NOTE: This would replace the 1.17 - 1.55 range of multipliers in the 2008 BiOp. It would not be added to them			
1991	2008 BiOp Base	0.32	0.2	-0.785262469	0.46	The effective change would be:			1.57
1992	2008 BiOp Base	0.24	0.2	-0.936493439	0.39	to			1.19
1993	2008 BiOp Base	0.15	0.2	-1.139434283	0.32				
1994	2008 BiOp Base	0.20	0.2	-1.021651248	0.36				
1995	2008 BiOp Base	0.16	0.2	-1.114741671	0.33				
1996	2008 BiOp Base	0.30	0.2	-0.820980552	0.44				
1997	2008 BiOp Base	0.10	0.2	-1.272965676	0.28				
1998	2008 BiOp Base	0.03	0.53	-0.608622225	0.54				
1999	2008 BiOp Base	0.09	0.53	-0.55809195	0.57				
2000	2008 BiOp Base	0.14	0.53	-1.164752091	0.31				0.11
2001	New	0.10	0.53	-0.549913012	0.58				0.21
2002	New	0.06	0.53	-0.583037958	0.56				0.16
2003	New	0.11	0.53	-0.541800428	0.58				0.14
2004	New	0.13	0.53	-0.525770071	0.59				0.31
2005	New	0.12	0.53	-0.533753128	0.59				
2006	New	0.14	0.53	-0.517850239	0.60				0.93
2007	New	0.11	0.53	-0.541800428	0.58				
2008	New	0.21	0.53	-0.464101084	0.63				0.186
2009	New	0.16	0.53	-0.502196297	0.61				
2010	New	0.14	0.53	-0.517850239	0.60				
2011	New	0.31	0.53	-0.392006088	0.68				
Base Period Average		0.15	0.25	-1.09	0.35				
Post-Base Average		0.14	0.53	-0.52	0.60				
Last 10-yr Average		0.15	0.53	-0.51	0.60				

Table F-10. Low Estimates of Base-to-Current survival multiplier for the Okanogan River population of Upper Columbia River steelhead.

Year		%Wild (f) from 1/30/13 SPS Data	e from 3/5/12 NMFS draft estimates	ln(Proportion of Natural Spawner Equivalents) = ln(f+(1-f)*e)	Proportion of Natural Spawner Equivalents	future e	future f	future ln(f+(1-f)*e)	Integrated productivity increase (from base period) as a ratio
1981	2008 BiOp Base	0.07	0.2	-1.362577835	0.26	0.3	0.10	-0.994252273	1.42
1982	2008 BiOp Base	0.07	0.2	-1.362577835	0.26				
1983	2008 BiOp Base	0.04	0.2	-1.461017907	0.23				
1984	2008 BiOp Base	0.01	0.2	-1.570217199	0.21	Future e from 3/5/12 NMFS draft estimates			
1985	2008 BiOp Base	0.02	0.2	-1.532476871	0.22	Future f based on the average f for most recent 5 years of data.			
1986	2008 BiOp Base	0.03	0.2	-1.496109227	0.22				
1987	2008 BiOp Base	0.02	0.2	-1.532476871	0.22				
1988	2008 BiOp Base	0.11	0.2	-1.244794799	0.29				
1989	2008 BiOp Base	0.11	0.2	-1.244794799	0.29				
1990	2008 BiOp Base	0.16	0.2	-1.114741671	0.33	NOTE: This would replace the 1.34 low multiplier in the 2008 BiOp. It would not be added to them			
1991	2008 BiOp Base	0.13	0.2	-1.190727578	0.30	The effective change would be:			
1992	2008 BiOp Base	0.16	0.2	-1.114741671	0.33				1.06
1993	2008 BiOp Base	0.03	0.2	-1.496109227	0.22				
1994	2008 BiOp Base	0.08	0.2	-1.331806176	0.26				
1995	2008 BiOp Base	0.07	0.2	-1.362577835	0.26				
1996	2008 BiOp Base	0.08	0.2	-1.331806176	0.26				
1997	2008 BiOp Base	0.03	0.2	-1.496109227	0.22				
1998	2008 BiOp Base	0.02	0.3	-1.158362293	0.31				
1999	2008 BiOp Base	0.05	0.3	-1.093624747	0.34				
2000	2008 BiOp Base	0.07	0.3	-1.362577835	0.26				
2001	New	0.06	0.3	-1.072944542	0.34				
2002	New	0.03	0.3	-1.136314156	0.32				
2003	New	0.06	0.3	-1.072944542	0.34				
2004	New	0.08	0.3	-1.032824548	0.36				
2005	New	0.07	0.3	-1.052683357	0.35				
2006	New	0.08	0.3	-1.032824548	0.36				
2007	New	0.06	0.3	-1.072944542	0.34				
2008	New	0.12	0.3	-0.957112726	0.38				
2009	New	0.09	0.3	-1.013352445	0.36				
2010	New	0.09	0.3	-1.013352445	0.36				
2011	New	0.16	0.3	-0.88673193	0.41				
	Base Period Average	0.07	0.22	-1.34	0.26				
	Post-Base Average	0.08	0.30	-1.03	0.36				
	Last 10-yr Average	0.08	0.30	-1.03	0.36				

Table F-11. High Estimates of Base-to-Current survival multiplier for the Okanogan River population of Upper Columbia River steelhead.

Year		%Wild (f) from 1/30/13 SPS Data	e from 3/5/12 NMFS draft estimates	ln(Proportion of Natural Spawner Equivalents) = ln(f+(1-f)*e)	Proportion of Natural Spawner Equivalents	future e	future f	future ln(f+(1-f)*e)	Integrated productivity increase (from base period) as a ratio
1981	2008 BiOp Base	0.07	0.2	-1.362577835	0.26	0.45	0.10	-0.678849876	1.87
1982	2008 BiOp Base	0.07	0.2	-1.362577835	0.26				
1983	2008 BiOp Base	0.04	0.2	-1.461017907	0.23				
1984	2008 BiOp Base	0.01	0.2	-1.570217199	0.21	Future e from 3/5/12 NMFS draft estimates			
1985	2008 BiOp Base	0.02	0.2	-1.532476871	0.22				
1986	2008 BiOp Base	0.03	0.2	-1.496109227	0.22	Future f based on the average f for most recent 5 years of data.			
1987	2008 BiOp Base	0.02	0.2	-1.532476871	0.22				
1988	2008 BiOp Base	0.11	0.2	-1.244794799	0.29				
1989	2008 BiOp Base	0.11	0.2	-1.244794799	0.29				
1990	2008 BiOp Base	0.16	0.2	-1.114741671	0.33	NOTE: This would replace the 1.88 low multiplier in the 2008 BiOp. It would not be added to them			
1991	2008 BiOp Base	0.13	0.2	-1.190727578	0.30	The effective change would be:			
1992	2008 BiOp Base	0.16	0.2	-1.114741671	0.33				1.00
1993	2008 BiOp Base	0.03	0.2	-1.496109227	0.22				
1994	2008 BiOp Base	0.08	0.2	-1.331806176	0.26				
1995	2008 BiOp Base	0.07	0.2	-1.362577835	0.26				
1996	2008 BiOp Base	0.08	0.2	-1.331806176	0.26				
1997	2008 BiOp Base	0.03	0.2	-1.496109227	0.22				
1998	2008 BiOp Base	0.02	0.45	-0.774357236	0.46			0.06	
1999	2008 BiOp Base	0.05	0.45	-0.739191119	0.48			0.12	
2000	2008 BiOp Base	0.07	0.45	-1.362577835	0.26			0.09	
2001	New	0.06	0.45	-0.727738625	0.48			0.09	
2002	New	0.03	0.45	-0.762497259	0.47			0.16	
2003	New	0.06	0.45	-0.727738625	0.48				
2004	New	0.08	0.45	-0.705219762	0.49			0.52	
2005	New	0.07	0.45	-0.716415807	0.49				
2006	New	0.08	0.45	-0.705219762	0.49			0.104	
2007	New	0.06	0.45	-0.727738625	0.48				
2008	New	0.12	0.45	-0.661648514	0.52				
2009	New	0.09	0.45	-0.694147681	0.50				
2010	New	0.09	0.45	-0.694147681	0.50				
2011	New	0.16	0.45	-0.619896719	0.54				
	Base Period Average	0.07	0.24	-1.31	0.28				
	Post-Base Average	0.08	0.45	-0.70	0.50				
	Last 10-yr Average	0.08	0.45	-0.70	0.50				

Appendix G

Estimating Survival Benefits of Estuary Habitat Improvement Projects

- G.1 History and Development of a Method to Assign Survival Benefit Units
- G.2 ERTG Scoring Criteria
- G.3 Design Template and ERTG SBU Scores for a LCRE Habitat Restoration Project: North Unit, Sauvie Island Wildlife Area
 - G.3.1 Sauvie Island North Unit Access and Habitat Diversity Project
 - G.3.2 Sauvie Island North Unit ERTG – Project SBU Report

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History and Development of a Method to Assign Survival Benefit Units



Prepared by the Expert Regional Technical Group of the Columbia Estuary Ecosystem Restoration Program

Prepared for the Bonneville Power Administration, U.S. Army Corps of Engineers, and NOAA Fisheries

December 2011

Preface

The Expert Regional Technical Group (ERTG) was formed by the Action Agencies (Bonneville Power Administration [BPA] and U.S. Army Corps of Engineers [USACE]) in 2009 in response to the National Marine Fisheries Service's (NMFS's) 2008 Biological Opinion (BiOp) on the operation of the Federal Columbia River Power System. The ERTG reviews ecosystem restoration actions in the floodplain of the lower Columbia River and estuary proposed by the Action Agencies under the Columbia Estuary Ecosystem Restoration Program (CEERP). The ERTG's main role is to assign survival benefit units (SBUs)¹ for ocean- and stream-type juvenile salmon from the restoration actions. The ERTG's work is directed by a steering committee composed of representatives from BPA, NMFS, and USACE.

The purpose of *History and Development of a Method to Assign Survival Benefit Units* (ERTG 2010-03, Rev 1) is to document the procedure the ERTG uses to assign SBUs. In the 2008 BiOp, NMFS charged the ERTG with applying the general methodology used in the 2007 Biological Assessment to assign SBUs to proposed restoration projects. The ERTG modified this method to make it transparent, repeatable, and quantitative. This procedure is now known as the "ERTG Calculator." Besides the ERTG, the Calculator is applied by restoration practitioners and managers to make unofficial calculations of possible SBUs to inform the CEERP project selection process.

This document was prepared by the ERTG: Ed Casillas (followed by Dan Bottom), Greg Hood, Kim Jones, Kirk Krueger, and Ron Thom. It was reviewed by the ERTG Steering Committee, led by Blaine Ebberts, Cathy Tortorici (followed by Lynne Krasnow), and Tracey Yerxa (followed by Ben Zelinsky). The original document was revised for clarity in December 2011.

Suggested citation: ERTG (Expert Regional Technical Group). 2011. *History and Development of a Method to Assign Survival Benefit Units*. ERTG 2010-03, Rev 1, prepared for the Bonneville Power Administration, U.S. Army Corps of Engineers, and NOAA Fisheries. Portland, Oregon. Available from <http://cbfish.org/ERTG>.

¹ A survival benefit unit (SBU) is an index intended to represent the effect of LCRE habitat restoration on juvenile salmon survival. The SBU method uses an ecosystem-based approach to assess improvements to habitats supporting juvenile salmon and other species. SBUs are assigned on a restoration project-specific basis.

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Introduction

The initial subsections below describe the purpose and background for the establishment of the Expert Regional Technical Group (ERTG), its membership and approach. The ensuing sections describe the ERTG's chronology of events, the existing method that was modified to develop a quantitative, transparent, repeatable way to assign survival benefit units (SBUs) for estuary habitat projects, and associated ERTG accomplishments.

Purpose

The purpose of the ERTG is to assign SBUs for ocean- and stream-type juvenile salmon from estuary habitat actions implemented by the Action Agencies (AA) as called for in the 2008 Biological Opinion of Federal Columbia River Power System Operations (BiOp).

Background

In the BiOp's Reasonable and Prudent Alternative action #37, the National Marine Fisheries Service (NMFS) stated, "...To support [restoration] project selection the Action Agencies will convene an expert regional technical group. This group will use the habitat metrics to determine the estimated change in survival which would result from full implementation...The expert regional technical group will use the approach originally applied in the Federal Columbia River Power System Biological Assessment (Attachment B.2.2; Estimated Benefits of Federal Agency Habitat Projects in the Lower Columbia River Estuary) and all subsequent information on the relationship between actions, habitat and salmon productivity models developed through the FCRPS RM&E to estimate the change in overall estuary habitat and resultant change in population survival..."

ERTG Composition

The ERTG was formed in June 2009 by invitation of the AA. Current ERTG members are Mr. Dan Bottom (Ocean and Estuary Ecologist; NMFS), Dr. Greg Hood (Estuarine Ecologist; Skagit River System Cooperative), Mr. Kim Jones (Fisheries Biologist; ODFW), Dr. Kirk Krueger (Fisheries Biologist; WDFW), and Dr. Ron Thom (Restoration Ecologist; PNPL). ERTG activities are overseen by a steering committee currently composed of Anderson (NMFS), Ebberts (Corps Portland District), Foster (BPA), Krasnow (NMFS), Rose (Corps Northwest Division), and Zelinsky (BPA). Support to the ERTG and the Steering Committee is provided by Johnson (PNPL) and Trask (PC Trask and Assoc.).

Transparency, Accessibility, and Documentation

ERTG meetings are open to all interested parties, with the exception of when the ERTG is in executive session. Meeting announcements are sent at least one week in advance. Meetings are usually held at the Northwest Power and Planning Council conference room. Highlights of key points at meetings are documented in the regular meeting notes, which are made available to all interested parties.

ERTG Chronology of Events

- July 2009 – Held its first meeting.
- July 2009 to July 2010 – Convened formal, open meetings with interested parties (10 total) in July, August, October 2009; February (2), March, April, May, June, and July 2010. These meetings often included site visits, presentations, and interchange between the ERTG and project sponsors.
- August 2009 to October 2010 – Worked to establish a quantitative approach to assigning SBUs, called the Calculator (see details below).
- February to October 2010 – Developed a standard template for sponsors to use to describe projects.
- June to October 2010 – Worked to improve the scoring criteria initiated in the existing method.
- October 2010 – Revised the Calculator and presented it to the Steering Committee.
- December 2010 – Regional release of the Calculator.
- August 2011 – Revised weighting factors based on fisheries literature review (see Document # ERTG 2011-01).
- December 2011 – Regional release of SBU reports for 20 projects (see Document # ERTG 2011-04).

Existing Method (2008 BiOp)

The ERTG was charged with applying the method used in the 2007 BA and adopted in the 2008 BiOp (called the existing or the BiOp method). The existing method (Figure 1) uses NOAA's 2006 Estuary Module and assigned potential survival improvements for juvenile salmon using and transiting through the estuary for each of the 22 actions outlined in the Module (based on a possible 20% total cumulative increases over time in the numbers of both ocean- and stream-type Chinook salmon exiting the estuary relative to annual totals established in the "Ferguson" memo).

In the 2007 Biological Assessment (BA), using the potential survival improvements outlined in the Module, the AAs identified habitat restoration projects, scored each project for certainty of success and potential survival benefits, linked the projects to actions/subactions from the Module, and then qualitatively assigned SBUs (reported as a proportion of the 20% outlined above) to each project. The sum of project contributions (over the time period the 2008 BiOp is in effect) was used as the estimated survival benefit for the estuary habitat actions – 10% for ocean-type and 6% for stream-type Chinook salmon. The key step was "assigning" of SBUs.

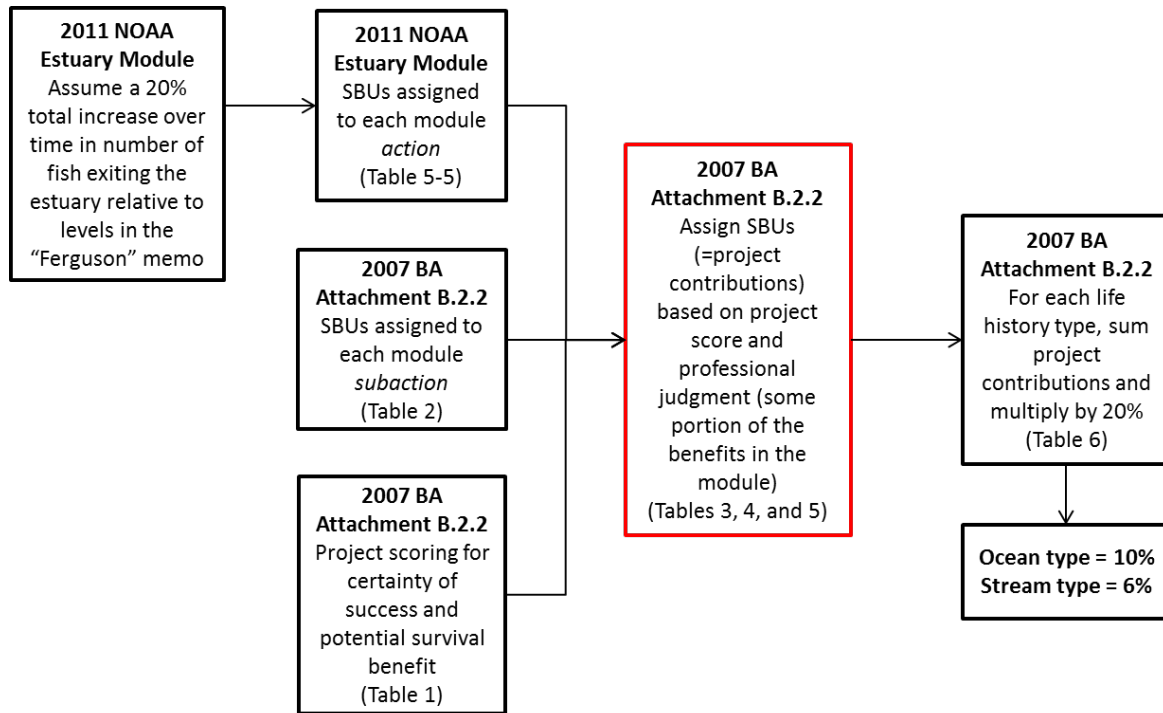


Figure 1. Flow Chart for the Existing Method to Estimate Survival Benefits from Habitat Actions in the Estuary. The red box is qualitative, professional judgment in the existing method. The ERTG quantified this step (see below). (Figure 1 was edited for clarity on 21 January 2013.)

Calculator to Assign SBUs

The ERTG’s Calculator to assign SBUs by subaction is based on values in the 2010 Estuary Module (revised from the 2006 version) for total possible SBUs, total subaction goal (acres/miles), and total juvenile salmon produced. While it is not possible to predict the actual incremental survival benefit to salmon populations from a restoration project, the ERTG could address the rearing potential of a site. In doing so, though, they identified inconsistencies in the relationships between the potential number of juvenile salmon produced and the total possible SBUs as outlined as goals in the Module/BA. For example, off-channel restoration (CRE 9.4) seemed to be under-valued in total SBUs because the estimated fish densities were overly low, whereas riparian restoration (CRE 1.4) was over-valued in the ERTG’s opinion because the expected fish densities were too high.

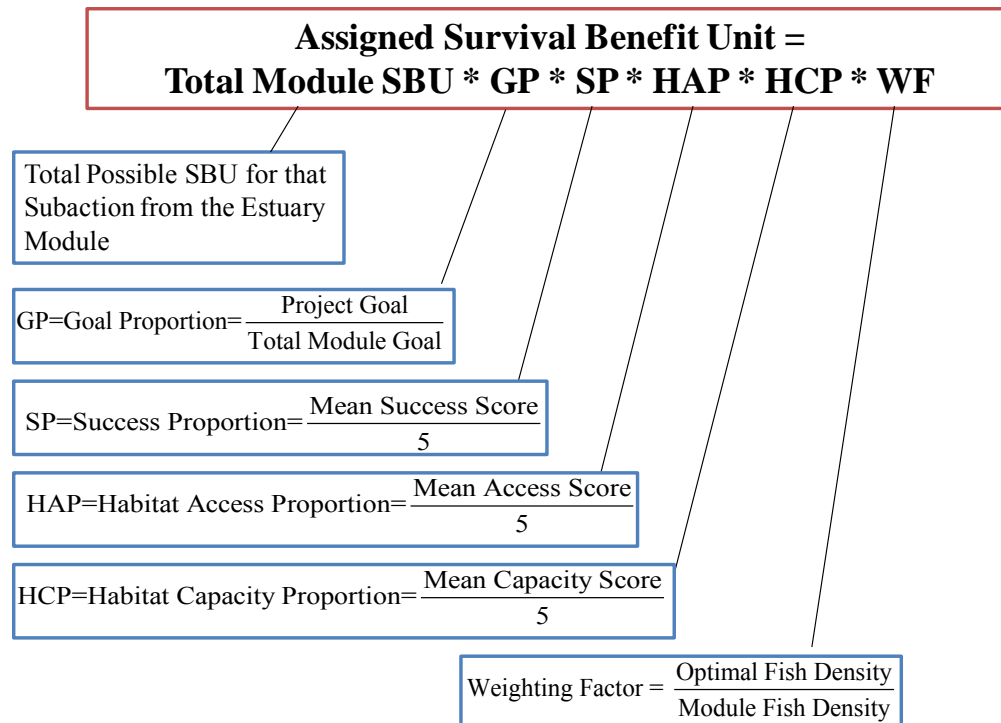
To alleviate this issue, the ERTG used the Module/BA goals on acreages and survival benefits in terms of total possible fish numbers to compute a “Module Fish Density” value ($\#/m^2$). Then, the ERTG used existing literature to ascribe an “Optimal Fish Density” value for each subaction. A weighting factor was derived by dividing the Optimal Density by the Module Density (see following example for ocean-type in Table 1). The weighting factor was incorporated into the Calculator as another multiplier.

Table 1. Derivation of weighting factors by Subaction.

Module CRE	Description	Module Goal (acres or miles)	Module Fish Production (#/acre or mile)	Computed Module Fish Density (#/m ²)	ERTG Optimal Fish Density (#/m ²)	Weight*
CRE-1.4	Restore and maintain ecological benefits in riparian areas	28	2,500	0.625	0.1	0.16
CRE-9.4	Restore degraded off-channel habitats	6,000	25	0.006	0.1	16.7
CRE-10.1	Breach or lower the elevation of dikes and levees	5,000	65	0.016	0.1	6.25
CRE-10.2	Remove tide gates to improve the hydrology between wetlands and the channel	2,000	35	0.009	0.05	5.56
CRE-10.3	Upgrade tide gates	1,000	50	0.0125	0.025	2.0
CRE-15.3	Remove invasives	10,000	2.5	0.0006	0.0006	1.0

*Note: the relative value of the weights does not imply restoration priority. The weights simply reflect the relationships between the ERTG's view of optimal fish density and what was in the Module.

Thus, the ERTG Calculator may be expressed as follows:



Summary of the ERTG Process to Assign SBUs

For a given project, the steps in the process for the ERTG to assign SBUs are as follows:

Step 1 – Initiation

The Steering Committee prioritizes and selects the project, then requests the sponsor prepare a project template and supporting material.

Step 2 – Project Review

- 2A. Delivery of the project template and supporting materials to the ERTG for them to study.
- 2B. Presentation at an ERTG meeting involving interchange between the ERTG and the project sponsor. Additional information requested (optional).
- 2C. Site visit (optional).
- 2D. Second presentation at an ERTG meeting (optional).

Step 3 – Scoring

- 3A. Organization of the project into the appropriate subactions and associated Module goals and total possible SBUs.
- 3B. Review and potential recalculation of acres/miles for project subactions, culmination with values for project subaction goals.
- 3C. Scoring for certainty of success using the scoring criteria. ERTG's comments are documented.
- 3D. Same for habitat access.
- 3E. Same for habitat capacity.

Step 4 – Calculator

The ERTG facilitator compiles the data from Step 3 in an Excel spreadsheet and runs the Calculator.

Step 5 – Review of Results

The ERTG and Steering Committee review and discuss the results.

Step 6 – Dissemination

The results for assigned SBUs and scoring comments are disseminated as appropriate.

Step 7 – Dialogue and Feedback

An opportunity is provided for dialogue and feedback between the ERTG, Steering Committee, project sponsors, and interested parties.

ERTG Accomplishments

Since July 2009, the ERTG has accomplished the following:

- Project Template – Developed a template for project descriptions to facilitate efficient and standard project review.
- Scoring Criteria – Revised and enhanced the scoring criteria initiated in the existing method.
- Preliminary Feedback – Provided preliminary feedback on six projects. (The AA and sponsors need input from the ERTG ahead of committing resources to develop full projects alternative and designs. It was decided the ERTG would review project templates and presentations, then provide comments and feedback on a proposed project.)
- Calculator – Modified the existing method to produce a quantitative, transparent, repeatable way to assign SBUs.
- Assigned SBUs – Scored and assigned survival benefit units for 14 projects involving 36 subactions.
- Reviewed fisheries literature and revised some weighting factors.
- Released SBU reports for 20 projects (December 2011).

Conclusion

The ERTG has grown to become a cohesive, functional scientific panel. Each member brings unique perspective and expertise that collectively form an effective and credible group for review and assessment of estuary habitat actions to fulfill the AA's obligation defined in RPA 37. The ERTG has developed a quantitative, transparent, repeatable way to assign SBUs for estuary habitat projects.

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ERTG Scoring Criteria



Prepared by the Expert Regional Technical Group of the Columbia Estuary Ecosystem Restoration Program

Prepared for the Bonneville Power Administration, U.S. Army Corps of Engineers, and NOAA Fisheries

December 2010

Preface

The Expert Regional Technical Group (ERTG) was formed by the Action Agencies (Bonneville Power Administration [BPA] and U.S. Army Corps of Engineers [USACE]) in 2009 in response to the National Marine Fisheries Service's (NMFS's) 2008 Biological Opinion on the operation of the Federal Columbia River Power System. The ERTG reviews ecosystem restoration actions in the floodplain of the lower Columbia River and estuary proposed by the Action Agencies under the Columbia Estuary Ecosystem Restoration Program. The ERTG's main role is to assign survival benefit units (SBUs)¹ for ocean- and stream-type juvenile salmon from the restoration actions. The ERTG's work is directed by a steering committee composed of representatives from BPA, NMFS, and USACE.

The purpose of the *ERTG Scoring Criteria* (ERTG 2010-02) is to provide standard criteria for the ERTG to apply when it scores projects as part of the process to assign SBUs to proposed restoration projects. The ERTG developed criteria for scoring three factors: certainty of success, potential benefit for habitat access/opportunity, and potential benefit for habitat capacity/quality. The scoring criteria contribute to the consistency of the ERTG review process.

This document was prepared by the following ERTG members: Ed Casillas, Greg Hood, Kim Jones, Kirk Krueger, and Ron Thom. It was reviewed by the ERTG Steering Committee, led by Blaine Ebberts, Cathy Tortorici, and Tracey Yerxa.

Suggested citation: ERTG (Expert Regional Technical Group). 2010. *ERTG Scoring Criteria*. ERTG 2010-02, prepared for the Bonneville Power Administration, U.S. Army Corps of Engineers, and NOAA Fisheries. Portland, Oregon. Available from <http://cbfish.org/ERTG>.

¹ A survival benefit unit (SBU) is an index intended to represent the effect of lower Columbia River and estuary habitat restoration on juvenile salmon survival. The SBU method uses an ecosystem-based approach to assess improvements of habitats supporting juvenile salmon and other species. SBUs are assigned on a restoration project-specific basis.

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Introduction

The purpose and scope of the Expert Regional Technical Group (ERTG) scoring criteria are described below, followed by the individual criteria.

Purpose

The process the ERTG uses to assign survival benefits for habitat restoration projects in the lower Columbia River and estuary (LCRE) involves scoring for three factors:

- certainty of success
- potential benefit for habitat access/opportunity²
- potential benefit for habitat capacity/quality.³

This document provides criteria for scores (1 to 5) for each factor that will help standardize the review process.

Scope

The ERTG scoring criteria apply primarily to restoration and enhancement projects. Acquisition projects are also considered provided there is a vision for restoration in future phases of the project. In addition, conservation projects that have an obvious significant contribution to functioning of the broader ecosystem may also be scored. Ocean- and stream-type fish will not be scored separately because the Estuary Module already differentiates between the two life history strategies.

Certainty of Success

- 5 – Restoring a natural process or landforms; proven restoration method; highly likely to be self-maintaining; little to no risk of detrimental effects; highly manageable *project complexity*⁴; minimal to no uncertainties regarding benefit to fish, minimal to no exotic/invasive species expected.

² *Habitat access/opportunity* is a habitat assessment metric that "appraises the capability of juvenile salmon to access and benefit from the habitat's capacity," for example, tidal elevation and geomorphic features (cf. Simenstad and Cordell 2000).

³ *Habitat capacity/quality* is a habitat assessment metric involving "habitat attributes that promote juvenile salmon production through conditions that promote foraging, growth, and growth efficiency, and/or decreased mortality," for example, invertebrate prey productivity, salinity, temperature, and structural characteristics (cf. Simenstad and Cordell 2000).

⁴ As used here, *project complexity* refers to the number of elements (i.e., steps or actions) required to achieve the anticipated restoration project habitat conditions and the degree of interdependence of elements to achieve the anticipated habitat functionality. More steps and greater interdependence leads to increased complexity, increasing the risk of not achieving the restoration goal. In addition, the amount of engineered control structures and maintenance necessary for project success adds to project complexity.

- 4 – Largely restoring a natural process or landforms; proven restoration method; likely to be self-maintaining; minimal risk of detrimental effects; manageable project complexity; minimal uncertainties regarding benefit to fish; minimal exotic/invasive species expected.
- 3 – Partially restoring a natural process or landforms; proven restoration method; potentially self-maintaining; minimal risk of detrimental effects; manageable project complexity; moderate uncertainties regarding benefit to fish; exotic/invasive species expected.
- 2 – Partially restoring a natural process or landforms; poorly proven restoration method; unlikely to be self-maintaining; risk of detrimental effects; moderate project complexity; moderate uncertainties regarding benefit to fish; exotic/invasive species expected.
- 1 – Unlikely to restore natural processes and landforms; unproven or risky restoration method; will likely require intervention to maintain; some risk of detrimental effects; excessive project complexity; excessive uncertainties regarding benefit to fish; exotic/invasive species expected.

Potential Benefit for Habitat Access/Opportunity

- 5 – High *connectivity*⁵ of site for most species, populations and life history types coming down river at most water level stages; located in a mainstem area or a priority (TBD) reach; unencumbered access to site.
- 4 – Intermediate connectivity of site for most species, populations and life history types coming down river at most water level stages; located in a mainstem area or a priority (TBD) reach; unencumbered access to site.
- 3 – Intermediate connectivity; only accessible to a few life history types or species coming down river at most water level stages; located in a mainstem area, lower end of tributary or a priority (TBD) reach; moderate site access.
- 2 – Intermediate to low connectivity; only accessible to specific life history types or one species coming down river at most water level stages; located in a mainstem area, lower end of tributary or a priority (TBD) reach; moderate site access.
- 1 – Low to no connectivity for any species, populations or life history types coming down river at most water level stages; located in areas far from main stem or lower ends of tributaries; poor site access.

⁵ As used here, *connectivity* refers to the degree to which water and aquatic organisms can move between the project site and the surrounding landscape. Typical barriers to movement include dikes and levees (complete barrier), tidegates and culverts (complete to partial barriers depending on configuration), jetties, groins, etc. Site proximity to population sources or to migratory corridors also affects connectivity. Assuming no barriers to organismal movement or water flow, sites near tributary junctions to the mainstem Columbia River have high connectivity; likewise sites surrounded by river distributaries are highly connected. Connectivity may also be seasonal. Sites where connectivity occurs only during occasional high flow conditions are less connected than those that are connected during low flows.

Potential Benefit for Habitat Capacity/Quality (C/Q)

- 5 – Maximum natural habitat *complexity*⁶; well-developed natural disturbance regime and ecosystem functions; extensive channel and edge network and large wood; much prey resource production and export; no invasive species or nuisance predators; water quality/temperature quality excellent; site relatively large (>100 acres).
- 4 – Very good natural habitat *complexity*; natural disturbance regime and ecosystem functions; very good channel and edge network and large wood; much prey resource production and export; minimal invasive species or nuisance predators; water quality/temperature quality very good; site moderate to large in size (30 to 100 acres).
- 3 – Moderate habitat complexity; moderately-developed natural disturbance regime and ecosystem functions; some channel and edge network and large wood; moderate prey resource production and export; moderate potential invasive species or predators; water quality/temperature quality moderate; site intermediate in size (~30 to 100 acres).
- 2 – Moderate to low habitat complexity; moderately-developed natural disturbance regime and ecosystem functions; some channel and edge network and large wood; moderate to low prey resource production and export; moderate potential invasive species or predators; water quality/temperature quality moderate to low; site intermediate to small in size (≥30 acres).
- 1 – Low habitat complexity; poorly developed natural disturbance regime and ecosystem functions; poor channel and edge network and large wood; moderate to poor prey resource production and export; moderate to high potential invasive species or predators; water quality/temperature poor; site small in size (<30 acres).

⁶ As used here, *habitat complexity* refers to the diversity of habitat types and structures within a given area.

ERTG Template for LCRE Habitat Restoration Project Summary



Prepared by the Expert Regional Technical Group of the Columbia Estuary Ecosystem Restoration Program

Prepared for the Bonneville Power Administration, U.S. Army Corps of Engineers, and NOAA Fisheries

May 2012

Preface

The Expert Regional Technical Group (ERTG) was formed by the Action Agencies (Bonneville Power Administration [BPA] and U.S. Army Corps of Engineers [USACE]) in 2009 in response to the National Marine Fisheries Service's (NMFS's) 2008 Biological Opinion on the operation of the Federal Columbia River Power System. The ERTG reviews ecosystem restoration actions in the floodplain of the lower Columbia River and estuary (LCRE) proposed by the Action Agencies under the Columbia Estuary Ecosystem Restoration Program. The ERTG's main role is to assign survival benefit units (SBUs)¹ for ocean- and stream-type juvenile salmon from the restoration actions. The ERTG's work is directed by a steering committee composed of representatives from BPA, NMFS, and USACE.

The purpose of the *ERTG Template for LCRE Habitat Restoration Project Summary* (ERTG 2010-01, Rev. 1) is to provide restoration project sponsors with a standard form to fill out as part of the ERTG's project review process. The template is designed to provide specific material summarizing a proposed project. Summary material includes basin project information, a description of the proposed project, linkage to the Estuary Module,² a pre-assessment of conditions, and the anticipated performance in terms of the certainty of success, potential access benefits, and potential habitat quality benefits. The template also serves as the basis for a monitoring plan before construction and a site evaluation card afterwards. The template helps foster the consistency and transparency of the ERTG review process.

This document was prepared by the ERTG: Ed Casillas, Greg Hood, Kim Jones, Kirk Krueger, and Ron Thom. It was reviewed by the ERTG Steering Committee (led by Blaine Ebberts, Cathy Tortorici, and Tracey Yerxa) and various restoration practitioners. Based on user feedback, the original document was revised in May 2012.

Suggested citation: ERTG (Expert Regional Technical Group). 2012. *ERTG Template for LCRE Habitat Restoration Project Summary*. ERTG 2010-01, Rev. 1, prepared for the Bonneville Power Administration, U.S. Army Corps of Engineers, and NOAA Fisheries. Portland, Oregon. Available from <http://cbfish.org/ERTG>.

¹ A survival benefit unit (SBU) is an index intended to represent the effect of lower Columbia River and estuary habitat restoration on juvenile salmon survival. The SBU method uses an ecosystem-based approach to assess improvements of habitats supporting juvenile salmon and other species. SBUs are assigned on a restoration project-specific basis.

² NMFS (National Marine Fisheries Service). 2011. Columbia River Estuary ESA Recovery Plan Module for Salmon and Steelhead. NMFS Northwest Region, Seattle, Washington. Available at <http://www.nwr.noaa.gov/Salmon-Recovery-Planning/ESA-Recovery-Plans/Estuary-Module.cfm>.

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Project Description.....	1

Project Description

The information requested below provides input to the scoring of projects. Refer to the Expert Regional Technical Group (ERTG) Scoring Criteria (Attachment 1) and definitions below when developing the project information. Reference to the Columbia River Estuary Conceptual Model (see link below) can also be made to help standardize terminology and to provide descriptions for stressors, habitats, processes and functions.

Header:	
Date	<i>Date the summary was prepared</i>
Prepared by	<i>Name, phone number, and email address</i>
Sponsoring agency	<i>Contact name, phone number, and email address</i>
Funding agency	<i>Contact name, phone number, and email address</i>
Site	<i>Name, location, river, river mile, latitude/longitude</i>
Project status or stage	<i>Status or stage of the proposed project</i>
Proposed Project:	
Problem statement	<i>Summarize the site-specific problem(s) the proposed restoration(s) is intended to address. What are the causes of the problems?</i>
Vision/goal	<i>Describe the expected outcome, i.e., what the site would look like if restoration is successful.</i>
Objectives	<i>State the project's objectives in terms of functions for salmon. For example, how will access, capacity etc. be increased or enhanced?</i>
Project actions, phases, sizes by year	<i>List the proposed restoration³ actions and phases by year. For each restoration action, state the number of barriers to be removed, the width of the breach or reconnection, and/or the number of acres/miles to be restored by year. In a multi-year effort, be sure to identify the action(s)/phase(s) that are being proposed at this time.</i>
Linkage to Estuary Module:	
Estuary module action, subaction(s), and project goal; Maps of the site, landscape, and site location in the LCRE	<i>Identify the appropriate subaction (Attachment 2) and state the size (number of acres or miles) the project subaction will provide. Document how the value was obtained. Show these subactions on a map of the site. Also include a map of the project site in its landscape and a map of the project's location in the lower Columbia River and estuary.</i>
Pre-Assessment:	
Photo point	<i>Whenever possible, provide summary data (values). Provide a digital photograph(s) of the site; note the point and orientation of the photograph, time of year, and tide/water level stage.</i>
Aerial image	<i>Provide an aerial image from a satellite or plane. Annotate the image to convey information about the project. Prepare map(s) with landform types delineated.</i>
Condition of physical metrics	<i>Describe the major stressors and physical controlling factors⁴. Basically summarize the existing condition of the site. What is the average tidal range, salinity? What is the ordinary-high-water tide elevation? Extreme-high-water elevation? Two-year flood elevation?</i>
Condition of habitat metrics	<i>Describe the key results of a vegetation survey.</i>

³ As used here, the term “restoration” refers to conservation, protection, enhancement, restoration, or creation.

⁴ Controlling factors are the basic physical and chemical conditions that construct and influence the structure of the ecosystem.

Condition of functional metrics	<i>Assess using existing data whether juvenile salmonids are present in the area and within the site. Describe the species composition and population sizes in the immediate or nearby watershed; use any available historical and current fish species and abundance data. Provide context for the potential of the site for fish availability.</i>
Performance Anticipated:	
Physical change	<i>Describe how the action(s) will affect physical controlling factors.</i>
Habitat change	<i>Describe the expected condition of habitat after restoration.</i>
Process/Function change	<i>Describe the expected changes in ecosystem processes and functions, e.g., Juvenile salmon feeding, rearing, refuge, water quality improvement, off site food web support.</i>
Certainty of Success:	
Landowner support	<i>Describe the willingness and support of the landowner.</i>
Constraints or show-stoppers	<i>Describe potential issues that could inhibit or prevent execution and fulfillment of the project goals and objectives.</i>
Restoration technique	<i>Describe the level of acceptance and maturity of the restoration technique; e.g., tried and true or experimental.</i>
Natural processes and self-maintenance	<i>Explain the extent to which natural processes would be restored and how well the restoration action(s) are anticipated to be maintained through natural processes.</i>
Potential, Anticipated Access Benefit:	
Distance of the project to the main stem Columbia River	<i>State distance in river miles from the main stem Columbia River</i>
Connectedness to mainstem	<i>Describe how well the project site is currently connected and will be connected to the main stem after the restoration. Include any historical data on habitat access and quality.</i>
Species impacted	<i>Describe which species, stocks, or populations are likely to benefit, based on the best available data.</i>
Potential, Anticipated Capacity Benefit:	
Habitat complexity	<i>Describe habitat complexity, channels, large woody debris.</i>
Water quality	<i>Describe water quality.</i>
Invasive species	<i>Describe impacts from invasive plant and animal species.</i>
Adjacent lands	<i>Describe the condition of adjacent lands.</i>
Comments	<i>Include comments or other pertinent information.</i>

North Unit Access and Habitat Diversity Project

The Sauvie Island North Unit project will reconnect over 292 acres of freshwater wetlands, channels, and backswamps to Cunningham Slough, which is located near the confluence of Multnomah Channel and the Columbia River. Removal of three water control structures and other barriers along with channel enhancements will improve hydrology to existing slough networks and restore juvenile salmonid access. Lowering the marsh plain through soil excavations will help control invasive plant species and benefit native species, and expand the range of habitat affected by flooding frequency and duration throughout the wetlands.

Header:

Date	April 9, 2013
Prepared by	Tom Josephson (503) 943-2651 tjosephson@columbiaestuary.org Allan Whiting (503) 517-0705 Allan@pctrask.com
Sponsoring agency	Columbia River Estuary Study Taskforce (CREST) Matt Van Ess, CREST Habitat Restoration Program Manager (503) 325-0435, ext. 21 mvaness@columbiaestuary.org
Funding agency	Bonneville Power Administration (BPA) Jason Karnezis (503) 230-3098 jpkarnezis@bpa.gov
Site	Sauvie Island Wildlife Area – North Unit River miles 87-90 4N, 1W, Sections 15, 21, 22, & 27
Project status or stage	50% Design phase 1, and permitting. Actions completed to date include a geomorphic assessment, calibration and running of a 2-d hydraulic model, topographic surveys, vegetation surveys, and consultation of a technical advisory team. Feasibility has been completed for Phase 1 and planning for Phases 2 and 3 has commenced.

Proposed Project: Summary

The Sauvie Island Wildlife Area (SIWA) North Unit is owned and managed for aquatic species and wildlife by Oregon Department of Fish & Wildlife. The North Unit includes approximately 1600 acres of sloughs, wetlands, and bottomland forests that support a diversity of fish and wildlife species. North Unit wetlands are subject to diurnal tidal inundations and seasonal riverine flows from the mainstem Columbia and Multnomah Channel, a major tributary of the Willamette river system. The North Unit's tidal wetlands are connected to Multnomah Channel via Cunningham Slough, a 3.5 mile channel terminating into 145 acre Cunningham Lake.

The North Unit is part of a large complex of floodplain wetlands downstream of the Willamette River confluence. Adjacent lands in this section of river include the Vancouver Lowlands, Shillapoo Wildlife Area, the John R. Palensky Area, Scappoose Bottomlands, Ridgefield National Wildlife Reserve, and several large private wetland holdings (See Attachment 1 for Locator Map).

This restoration project will remove the water control structures and return full hydrologic access to the site. In strategic locations marsh plain surfaces will be scraped down to lower elevations, allowing a larger portion of the wetlands to be inundated at deeper depths for longer periods of time, benefiting native plant species. Removal of structures will re-establish upriver and local volitional juvenile salmonid access to over 292 acres of historical habitats. Fish stranding danger will be minimized and food web connectivity will be enhanced.

Water control structures were installed throughout the SIWA to extend the period of flooding in wetlands and impede growth of the invasive *Phalaris arundinacea* reed canarygrass. Water control structures have been a standard practice for many state and federal refuges to assist managers in achieving wildlife and habitat objectives. In the North Unit area of the SIWA, the structures were “experimental in nature” and intended to be monitored closely for their effectiveness in achieving their objectives. Structures were installed in channels connecting Ruby, Millionaire, and Widgeon/Deep Lakes to Cunningham Slough and ultimately to the Columbia and Willamette systems. Figure 1 shows a schematic of the three water control structures. A 10” fish passage pipe is part of the water control structures, however this undersized pipe is frequently perched and it is questionable whether juvenile fish are attracted to this passageway (see fish egress pipe photos on page 14). Other than the fish egress pipe, juvenile salmonids must pass through the interior plumbing of the water control structures to travel upstream and downstream. Riser boards are manually removed to optimize wetland surface water levels while maintaining ingress/egress for juveniles. The structures have increased water temperatures and lowered dissolved oxygen. They have also reduced channel velocities, effecting sediment transport throughout the sloughs and wetlands.

It is hypothesized that juvenile salmonid stranding may occur in the North Unit’s wetlands when the Columbia River floods the North Unit (e.g. during freshet conditions). Flows directly from the Columbia River periodically overtop the southern and eastern shorelines in natural breach locations (this recently occurred in late May and June of 2011). At the same time, flows entering the North Unit from Cunningham Slough also allow overtopping within the natural and built sills, levees, and structures of the North Unit. Juveniles have excellent accessibility within the wetland basins until flow elevations decrease and juvenile salmon must find their way out through water control structures or other barriers.

Invasive plants are a significant issue for the site. Reed canarygrass out-competes many native species due to its early season germination and ability to grow throughout a range of elevations.

Vegetation surveys have shown that the reed canarygrass does better in the slightly higher wetland elevations (>8.5 NAVD88). In the lower elevation areas where it is wetter for longer periods of time and at deeper depths, there is a greater abundance of native plants.

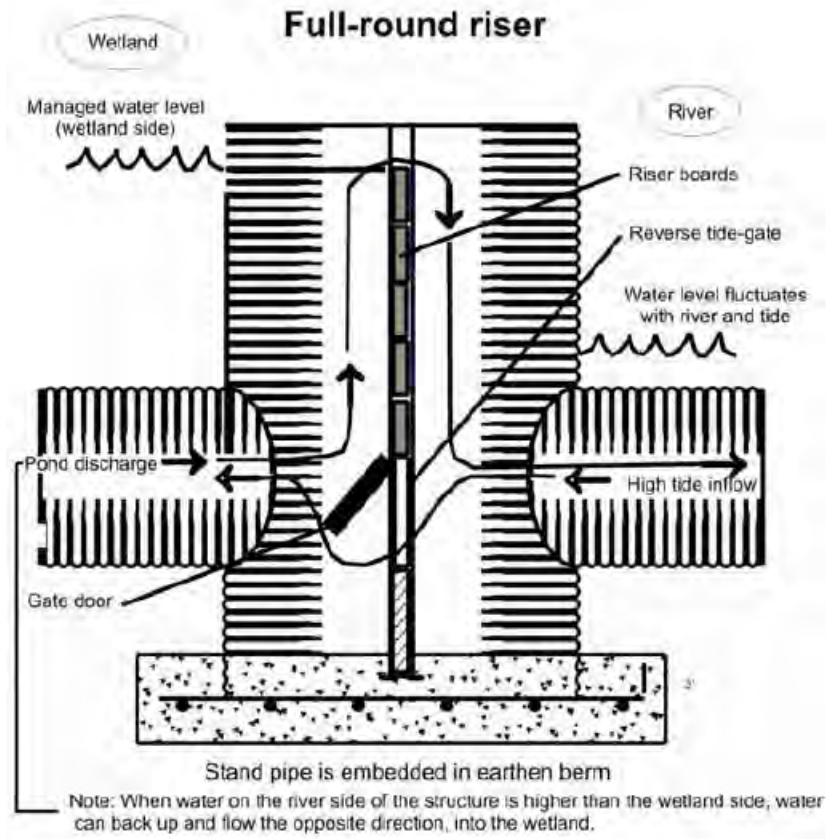


Figure 1: Water Control Structure schematic

Problem statement Juvenile fish access has been limited at the Sauvie Island North Unit due to the installation of water control structures and construction of other barriers. These structures have restricted hydrology and tidal exchange to the site and pose a fish stranding danger. Invasive plants such as reed canarygrass have dominated the wetland vegetation community, outcompeting native vegetation. Reed canarygrass infestation is considered detrimental to salmon habitat by clogging small floodplain channels, trapping sediments, and altering channel edge prey relationships.

- Vision/goal** The vision for the North Unit Wetland Restoration and Enhancement project is to implement a series of actions that result in an accessible mosaic of sloughs, wetlands, and backswamps that invite and support juvenile salmonids use. Specific project goals for the North Unit include:
- providing effective and safe ingress/egress to juvenile salmonid habitats through historical channels and sloughs
 - providing egress to juvenile salmonids entering North Unit wetlands via crevasse splays during freshet over-topping events
 - increasing tidal prism and natural channel maintenance by re-establishing the full tidal range within wetlands
 - increasing habitat capacity for salmonids, waterbirds, and waterfowl by re-establishing native vegetation communities
 - establishing a long term stewardship site focusing on treatment of reed canarygrass and promoting native plant colonization
 - incorporating design features to demonstrate restoration resiliency (e.g., climate change)

Objectives Planning discussions with the SIWA staff have led to the development of project specific goals and objectives (see Table1). These have been vetted to ensure alignment with existing management goals of the SIWA and Oregon Conservation Strategy.

Table 1. Objectives

OBJECTIVE	DESCRIPTION
Goal 1:	Re-establish the natural hydrology and vegetation of the North Unit in order to increase estuarine habitat availability and capacity for salmonids, waterfowl, and shore birds
Obj 1a – Habitat Opportunity	Improve access to North Unit interior backwater ponds, wetlands and channels
Obj 1b – Habitat Quality	Improve habitat capacity for juvenile salmonids, waterfowl, and shore birds by reducing invasive plant species, increasing open water habitat, increasing wetland plant diversity, and expanding mudflat habitat
Obj 1c – Ecological Function	Increase prey resource production and availability for juvenile salmonids
Goal 2:	Establish the North Unit as a long-term demonstration and monitoring site that will highlight effective methods for restoring and enhancing habitats common to juvenile salmonids, waterfowl, shore birds, and ecosystem health
Obj 2a – Landscape Planning Framework	Use Landscape Planning Framework to test the validity of “Fish Habitat Catena” and associated metrics that are important to juvenile salmonid needs
Obj 2b – Adaptive Management	Use monitoring results to inform adaptive management for future restoration and stewardship efforts
Obj 2c – Sustained Stewardship	Identify and secure long-term stewardship resources for sustaining success of habitat restoration actions within the North Unit

Design Criteria

Measureable design criteria were established for the North Unit project to help ensure that project objectives are achieved. Some objectives are met by meeting absolute measurements (i.e. elevation levels within a set range) and others are met by achieving a percent of change (i.e. increasing native plant cover by a certain percent or more). Design criteria are intended not only for the design phase of the project, but can be translated into performance criteria to ensure ecological success of the project through an emerging adaptive management program for the project. Table 2 highlights the design criteria developed in the planning phases of the project.

Table 2. Design Criteria

Objective 1a – Habitat Opportunity	
Design Criteria 1:	Establish full volitional access to interior wetlands of existing backwater areas by 100% channel width ingress/egress (free and open connection)
Design Criteria 2:	Expand access to interior channel edge network by 25%
Design Criteria 3:	Expand surface water area connection and duration to interior wetlands and channels by 20 acres (seasonality)
Design Criteria 4:	No adverse impacts on in channel habitat conditions: velocity < 2 ft/s and depths > 0.5 feet (90% of the time)
Objective 1b – Habitat Quality	
Design Criteria 5:	At strategic locations, lower/maintain ground elevation to 7.5-8.0 feet NAVD88 to induce native plant propagation
Design Criteria 6:	Maintain 2 feet of water level elevation over wetland surface during February-March to restrict germination capacity of invasive species
Design Criteria 7:	Increase area of native plant community by 25% Objective 1c – Ecological Function
Design Criteria 8:	Maintain floodplain activation zone (shrub-scrub, woody vegetation layer) at >9.0 feet NAVD88 to increase estuarine food web capacity during juvenile rearing period (November-June)

Current Design Project Actions:

- Year 1 (2012):** Complete feasibility analysis (geomorphic assessment, hydraulic modeling, vegetation surveys, topographic survey). Recommend phasing for project.
- Year 2 (2013-14):** **Phase I – Ruby:** remove water control structure, soil scrapedown, channel work, implement vegetation enhancement plan. Begin modeling and design of Phase II.
- Year 3 (2014-15):** **Phase II – Millionaire & Deep/Widgeon:** remove water control structures, soil scrapedown, channel work, implement vegetation enhancement plan. Begin modeling and design of Phase III.
- Year 4 (2015-16):** **Phase III – McCormick Lake & Other Structures:** remove structures around McCormick Lake and South Slough. Perform channel work and vegetation enhancements.

Figure 2 highlights various North Unit barriers and their removal by phases. Note that additional barriers may be removed as part of Phase III.

Project actions, phases, sizes by year	Phase I Implementation 2013 – 14	123 acres
	Phase II Implementation 2014 – 15	138 acres
	Phase III Implementation 2015 – 16.....	<u>>31 acres</u>
		292 acres

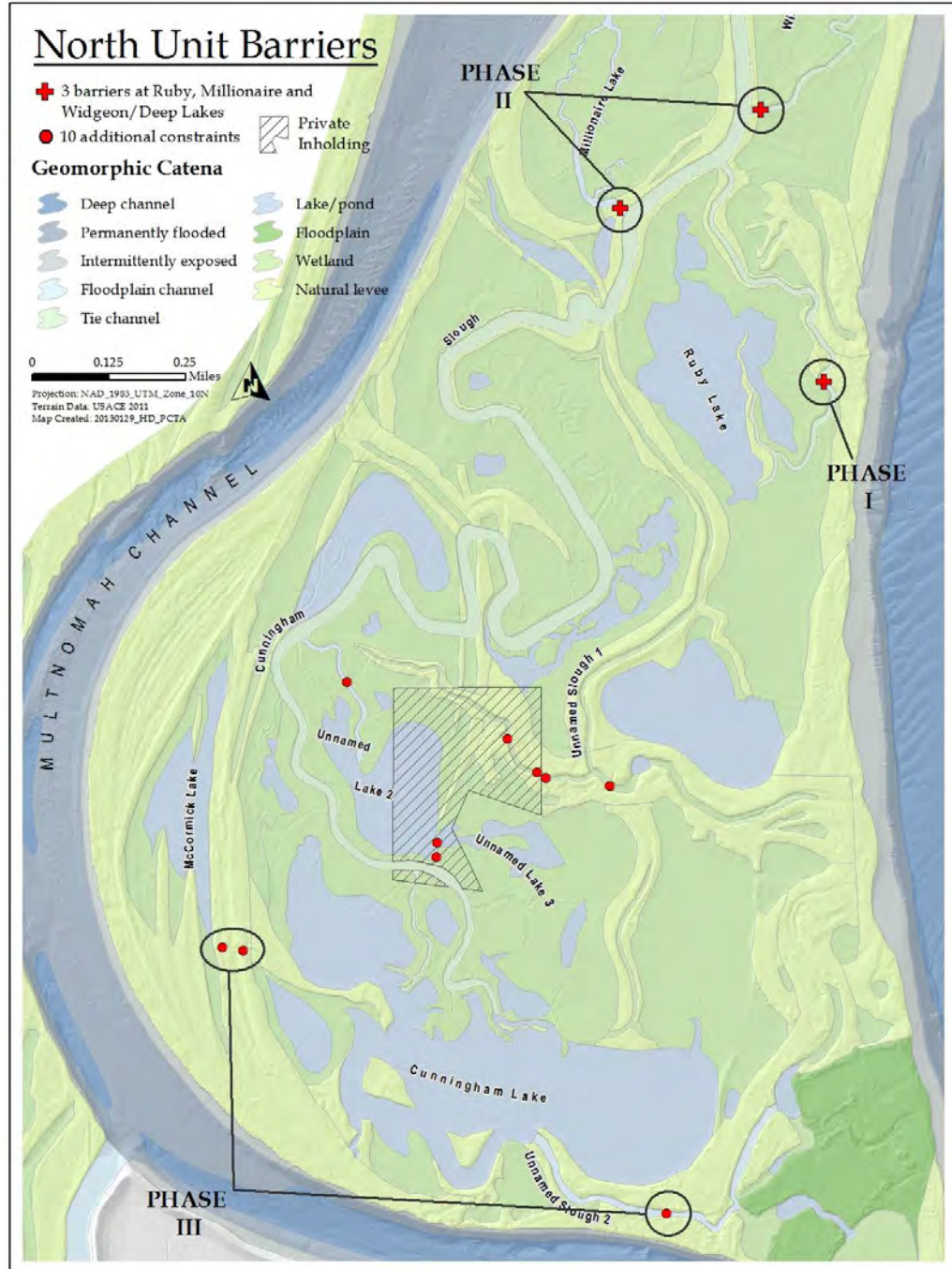


Figure 2. North Unit Barriers. The larger symbols represent Phases I and II. The smaller dots are potential Phase III restoration actions.

Linkage to Estuary Module:

Estuary module action. subaction(s) and project goal; Maps of the site, landscape, and site location in the LCRE

The subactions identified below resulted from an extensive collection of baseline conditions and feasibility analysis conducted by the project team and its subcontractors. This process and its results are documented in the *Existing Conditions, Alternatives Feasibility Analysis, and Preferred Alternative Report North Unit, Sauvie Island Wildlife Area* (PC Trask et al. 2013) and the *Geomorphic Assessment* (ESA-PWA 2012). Modeling results and other analyzes were presented in this report to estimate areas of benefit from resulting from a subactions proposed for Phase I and Phase II implementation.

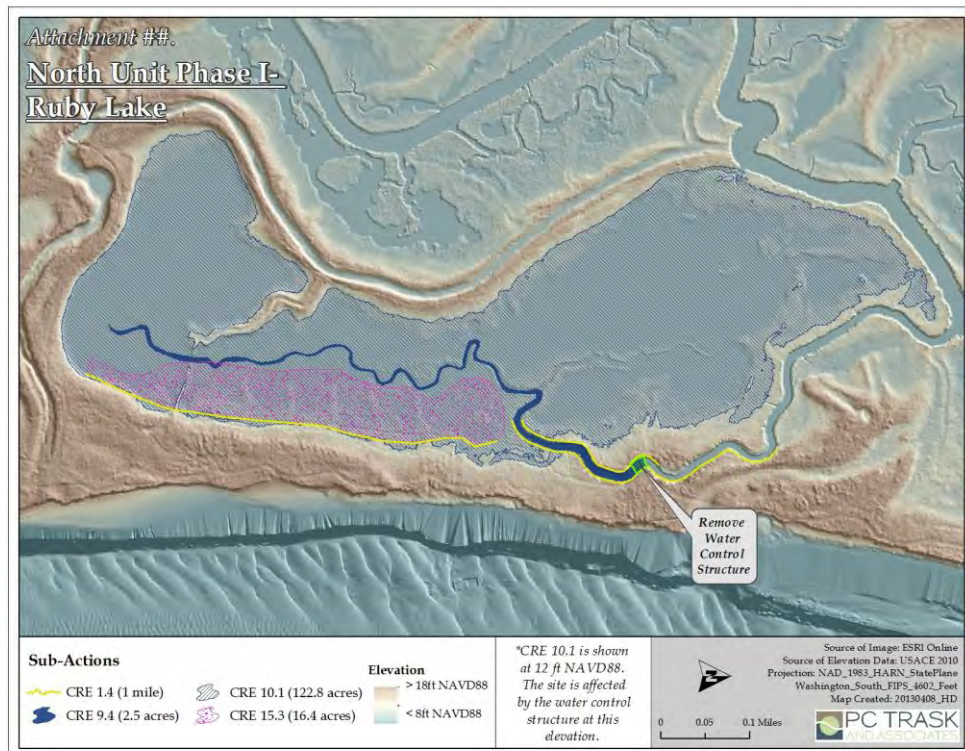
Phase 1 Implementation: Ruby Lake – Project Goal Map

CRE 1.4 Riparian Restoration 0.5 miles
 (NOTE: Plantings are largely focused on upper herbaceous edge of wetland to expand shrub/scrub edge and help shade out invasives). There will also be riparian plantings inside and outside of the water control structure along the channel edge.

CRE 9.4 Channel Restoration.....2.5 acres
 The restoration site was measured by tracing floodplain channels and estimating excavated channel areas in ArcMap.

CRE 10.1 Levee Removal (restore full hydrology) 122.8 acres
 Using LiDAR, the site was inundated under a flow scenario that characterizes the area when it is totally isolated (i.e. no other sloughs connecting; no sheet flow). The flow elevation used was 12 feet NAVD88 and was measured in ArcMap. See attachment 2 for inundation at the 2-year flood.

CRE 15.3 Invasives Removal 16.4 acres
 The invasives removal area was measured in ArcMap.



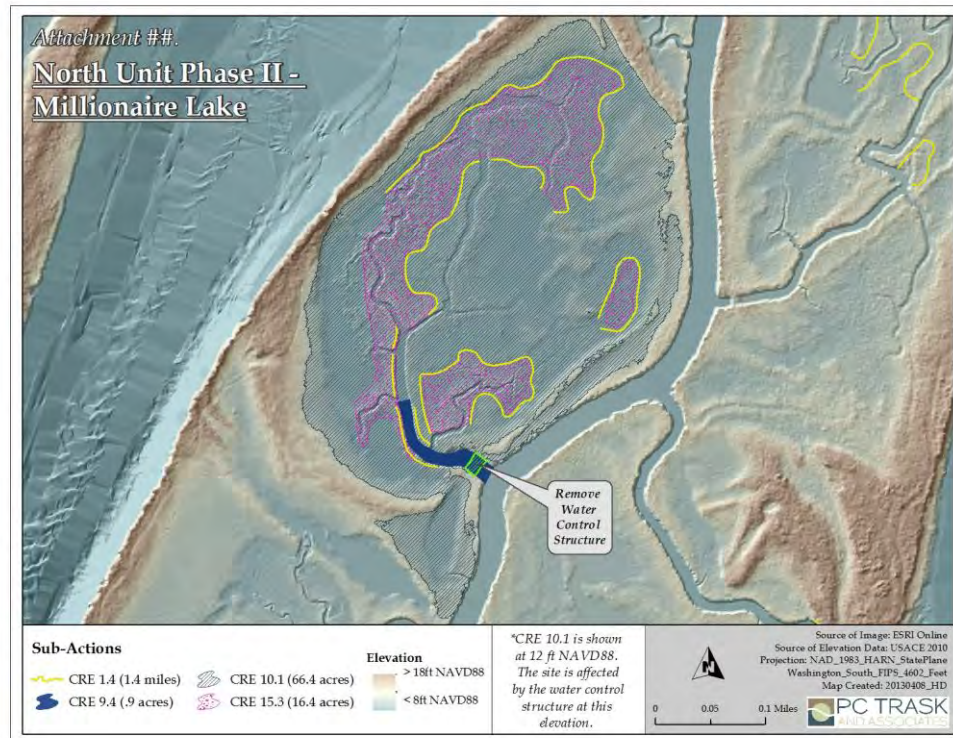
Phase 2 Implementation: Millionaire Lake – Project Goal Map

CRE 1.4 Riparian Restoration 1.2 miles
 Plantings are largely focused on upper herbaceous edge of wetland to expand shrub/scrub edge and help shade out invasives. There will also be riparian plantings inside of the water control structure along the channel edge.

CRE 9.4 Channel Restoration.....0.9 acres
 The restoration site was measured by tracing floodplain channels and estimating excavated channel areas in ArcMap.

CRE 10.1 Levee Removal (restore full hydrology) 66.4 acres
 Using LiDAR, the site was inundated under a flow scenario that characterizes the area when it is totally isolated (i.e. no other sloughs connecting; no sheet flow). The flow elevation used was 12 feet NAVD88 and was measured in ArcMap. See attachment 2 for inundation at the 2-year flood.

CRE 15.3 Invasives Removal 16.4 acres
 The invasives removal area was measured in ArcMap.



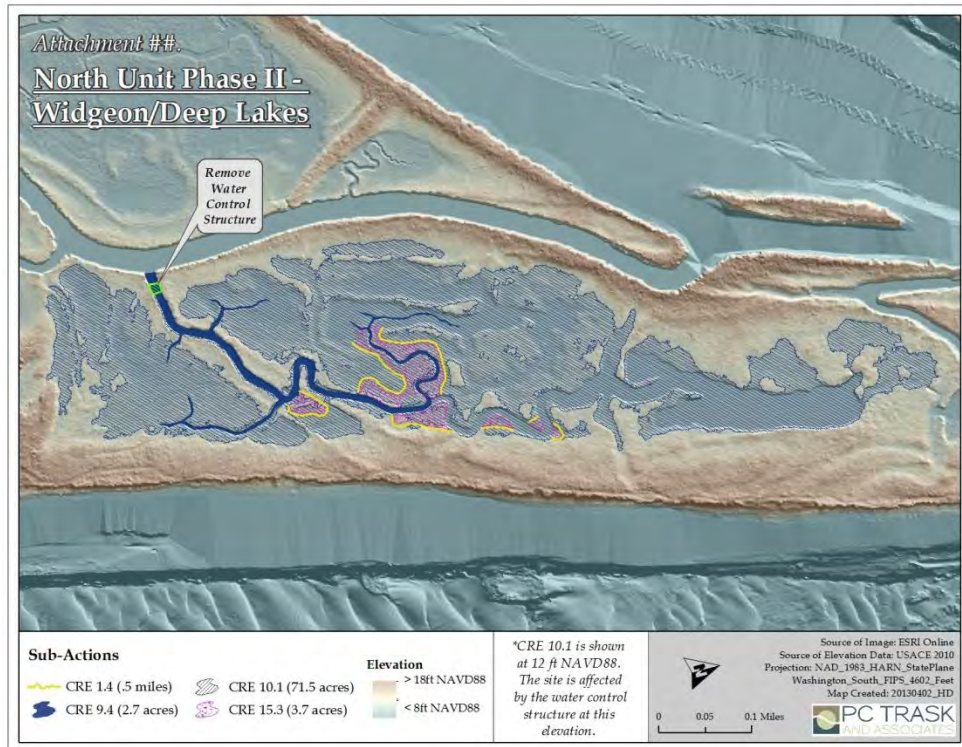
Phase 2 Implementation: Widgeon/Deep Lakes – Project Goal Map

CRE 1.4 Riparian Restoration 0.5 miles
Plantings are largely focused on upper herbaceous edge of wetland to expand shrub/scrub edge and help shade out invasives.

CRE 9.4 Channel Restoration.....2.7 acres
The restoration site was measured by tracing floodplain channels and estimating excavated channel areas in ArcMap.

CRE 10.1 Levee Removal (restore full hydrology) 71.5 acres
Using LiDAR, the site was inundated under a flow scenario that characterizes the area when it is totally isolated (i.e. no other sloughs connecting; no sheet flow). The flow elevation used was 12 feet NAVD88 and was measured in ArcMap. See attachment 2 for inundation at the 2-year flood.

CRE 15.3 Invasives Removal 3.7 acres
The invasives removal area was measured in ArcMap.

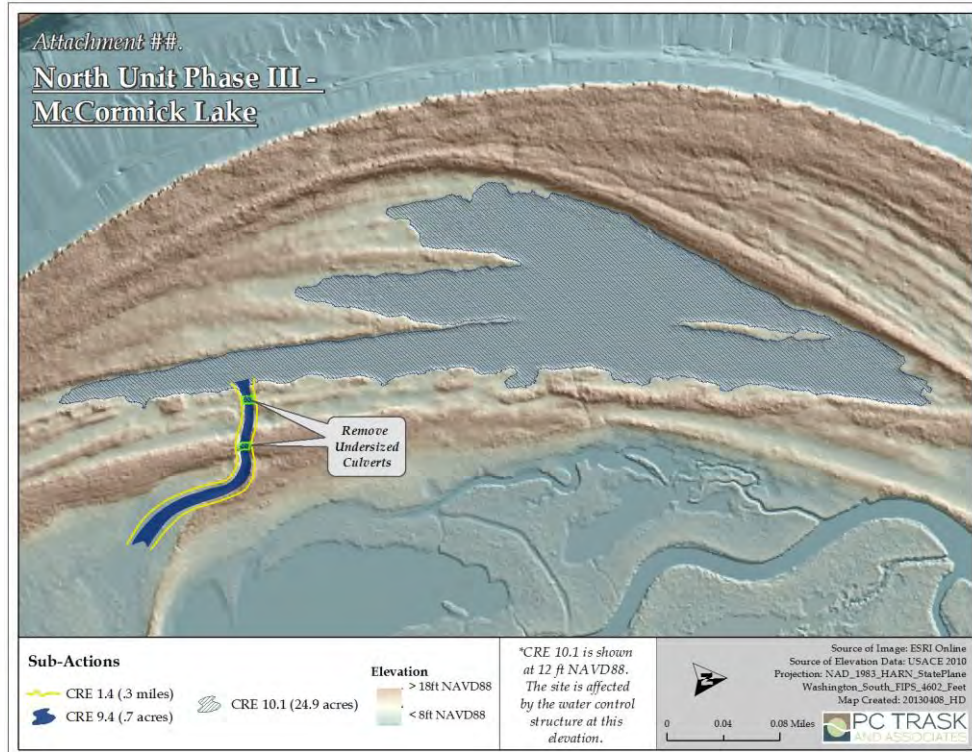


Phase 3 Implementation: McCormick Lake – Project Goal Map

CRE 1.4 Riparian Restoration 0.3 miles
 Plantings are largely focused on upper herbaceous edge of wetland to expand shrub/scrub edge and help shade out invasives.

CRE 9.4 Channel Restoration......7 acres
 The restoration site was measured by tracing floodplain channels and estimating excavated channel areas in ArcMap.

CRE 10.1 Levee Removal (restore full hydrology) 24.9 acres
 Using LiDAR, the site was inundated under a flow scenario that characterizes the area when it is totally isolated (i.e. no other sloughs connecting; no sheet flow). The flow elevation used was 12 feet NAVD88 and was measured in ArcMap. See attachment 2 for inundation at the 2-year flood.



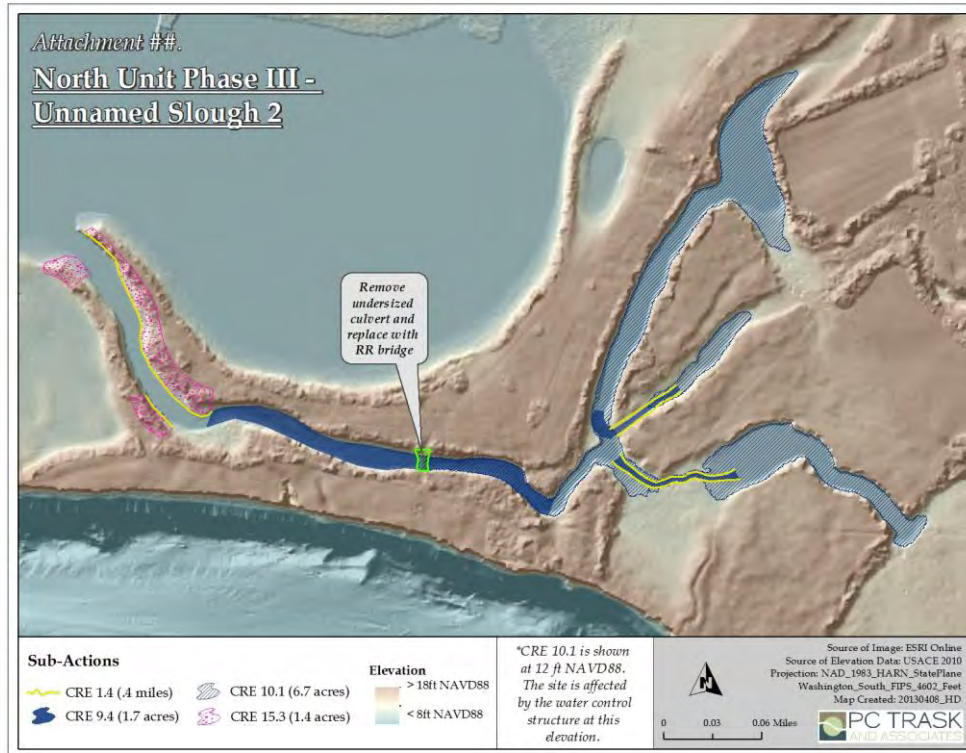
Phase 3 Implementation: Unnamed Slough 2 – Project Goal Map

CRE 1.4 Riparian Restoration 0.4 miles
 Plantings are largely focused on upper herbaceous edge of wetland to expand shrub/scrub edge and help shade out invasives.

CRE 9.4 Channel Restoration.....1.7 acres
 The restoration site was measured by tracing floodplain channels and estimating excavated channel areas in ArcMap.

CRE 10.1 Levee Removal (restore full hydrology) 6.7 acres
 Using LiDAR, the site was inundated under a flow scenario that characterizes the area when it is totally isolated (i.e. no other sloughs connecting; no sheet flow). The flow elevation used was 12 feet NAVD88 and was measured in ArcMap. See attachment 2 for inundation at the 2-year flood.

CRE 15.3 Invasives Removal 1.4 acres
 The invasives removal area was measured in ArcMap.



**Pre-
Assessment:**
Photo Point



Inside of Water Control Structure at Ruby Lake, 12.10.2010, (looking North) at 12:38pm (elevation =~10 feet NAVD88). (Data from NOAA Tides and Currents St. Helens gage).



Outlet fish egress pipe at Ruby Water Control Structure looking south. Photo was taken at 10:20am on 3.28.2013 during an outgoing tide. Water stage was approximately 8.75 NAVD88 and the low tide for the day was 3 hours after this photo was taken.



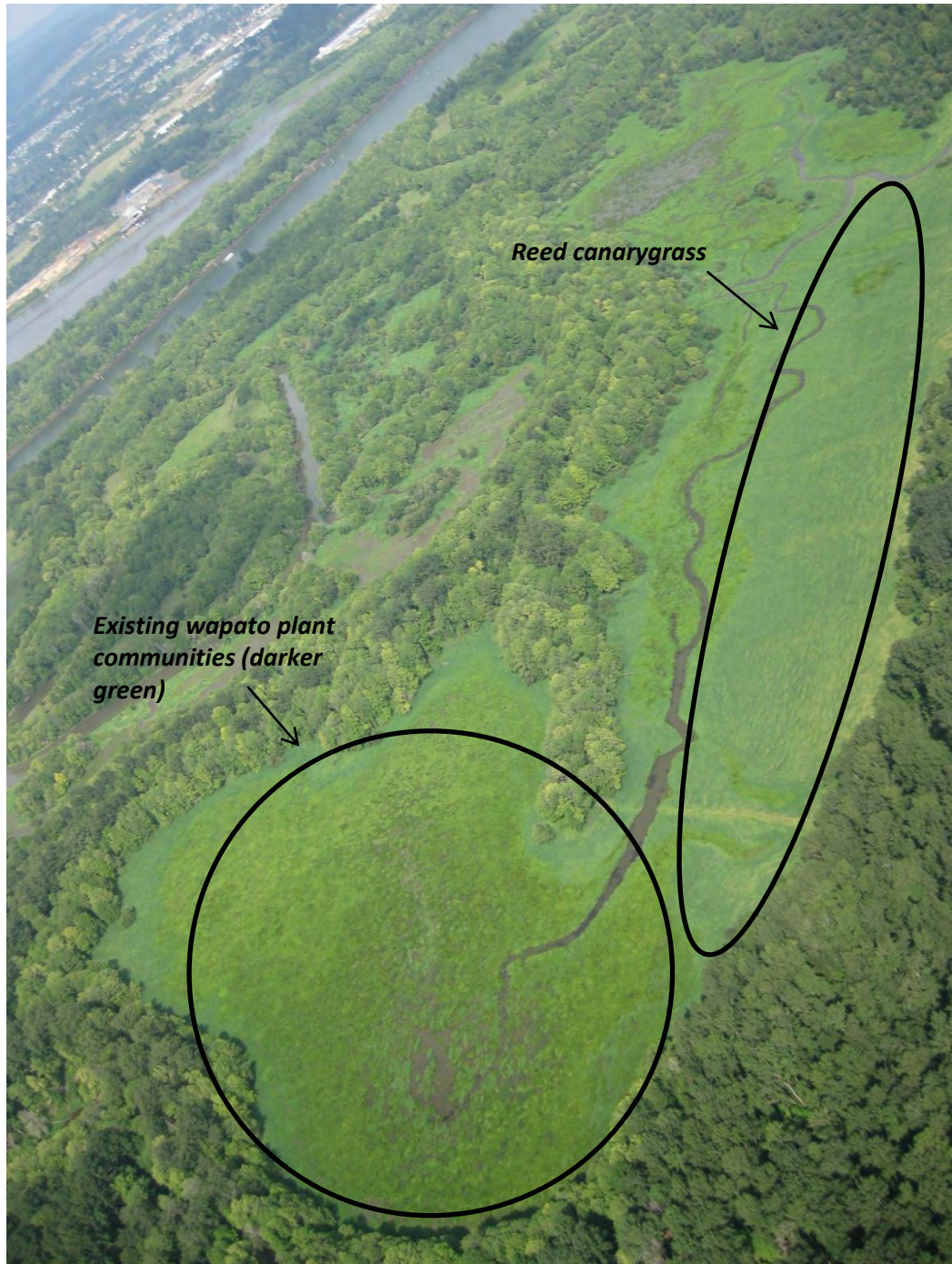
North Unit inundation 5.18.2011- Near Cunningham Slough (looking north). The tide was rising at 18.06 feet NAVD88. The spring freshet contributed to about 9 feet over the predicted tide level at this time. (Data from NOAA Tides and Currents St. Helens gage).



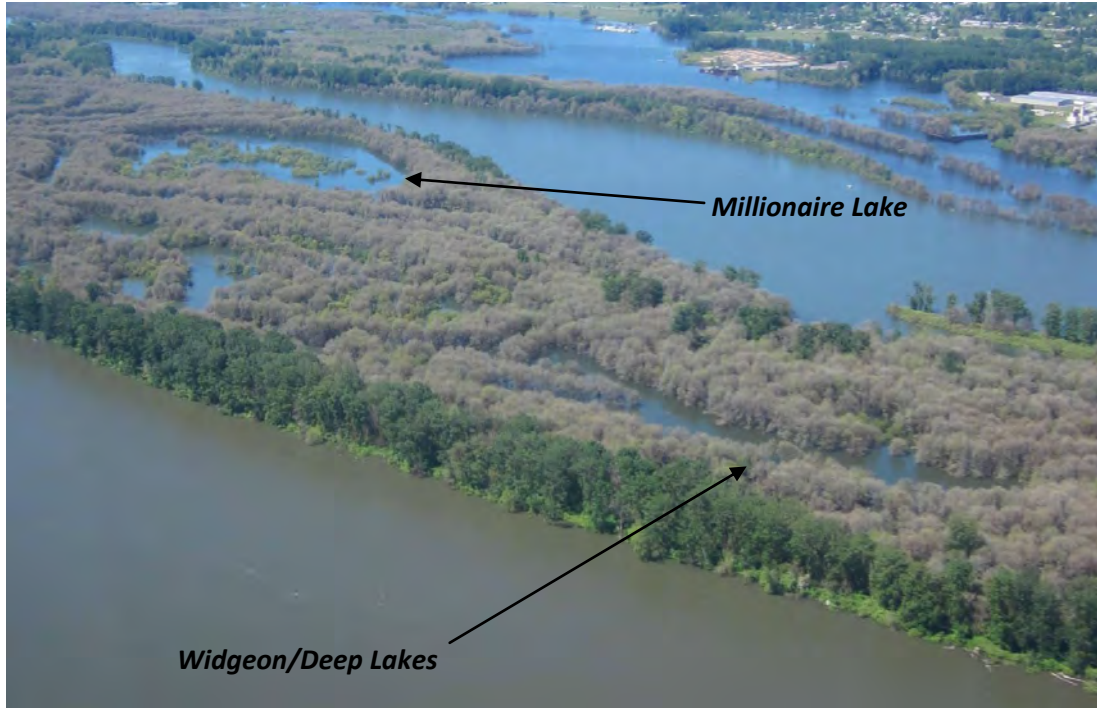
Typical channel in the North Unit with reed canarygrass. 4.27.2011 – Close to low tide, inundation was at 11.15 feet NAVD88 which was almost 6 feet over the predicted tide level. (Data from NOAA Tides and Currents St. Helens gage).



Low flow in the North Unit looking south on Ruby Slough at the water control structure. 08.26.2011 @ 11:30am – Close to low tide at predicted 5.73 feet NAVD88 (Data from NOAA Tides and Currents St. Helens gage).



Ruby Lake in September 2009, looking Northwest.



Millionaire and Widgeon-Deep lakes at freshet (looking southwest). 06.06.11 @ 11:00am flow was 19.24 feet NAVD88. (Data from NOAA Tides and Currents St. Helens gage).

Condition of physical metrics

Findings of a geomorphic assessment characterize reach scale physical processes and distribution of landforms that shape the contemporary habitat structure of North Unit. Some of these landforms are relics of the pre-dam hydrologic regime but remain important in framing the range of restoration actions consistent with the current geomorphic trajectory of the area. Figure 3 highlights landscape features in the vicinity of the North Unit. Landscape and site-scale physical processes that shape the North Unit wetlands include:

- **Spring freshets** remain a dominant influence on landforms, although timing and amplitude have substantially changed from climate, hydrosystem operations, and water withdrawals
- **Crevasse splays** are relic features within North Unit wetland complex interior from past overtopping events of the historical hydrologic regime of the Columbia River. Several large splays are oriented from the Columbia mainstem expanding west to Northwest toward Cunningham slough. Smaller splays have formed from more recent overtopping events during contemporary hydrologic regime. These higher elevation depositional features in combination with natural levees dictate shape and size of discrete depressional swamps (i.e. Ruby, Millionaire, Cunningham) generally throughout North Unit
- **Natural levees** forming a perimeter berm around exterior areas of North Unit drives most habitat forming processes in North Unit. These are formed largely from complex hydraulics between Multnomah Channel and Columbia River mainstem. Features are particularly prominent near the mouth of Cunningham slough
- **Backswamp areas** are low elevation emergent wetlands formed in part due to a low velocity, sheltering effect from splays and levees described above. Backswamp areas are mostly below MHHW resulting in extended inundation periods and function as sediment sinks for suspended load events from Multnomah and/or backwater from Columbia mainstem
- **Tidal channel** formation processes are a result of tidal prism volumes throughout the whole complex. Maximum tidal fluctuations are at four feet and appear to be sufficient to form and maintain channels and mobilize fine sediments

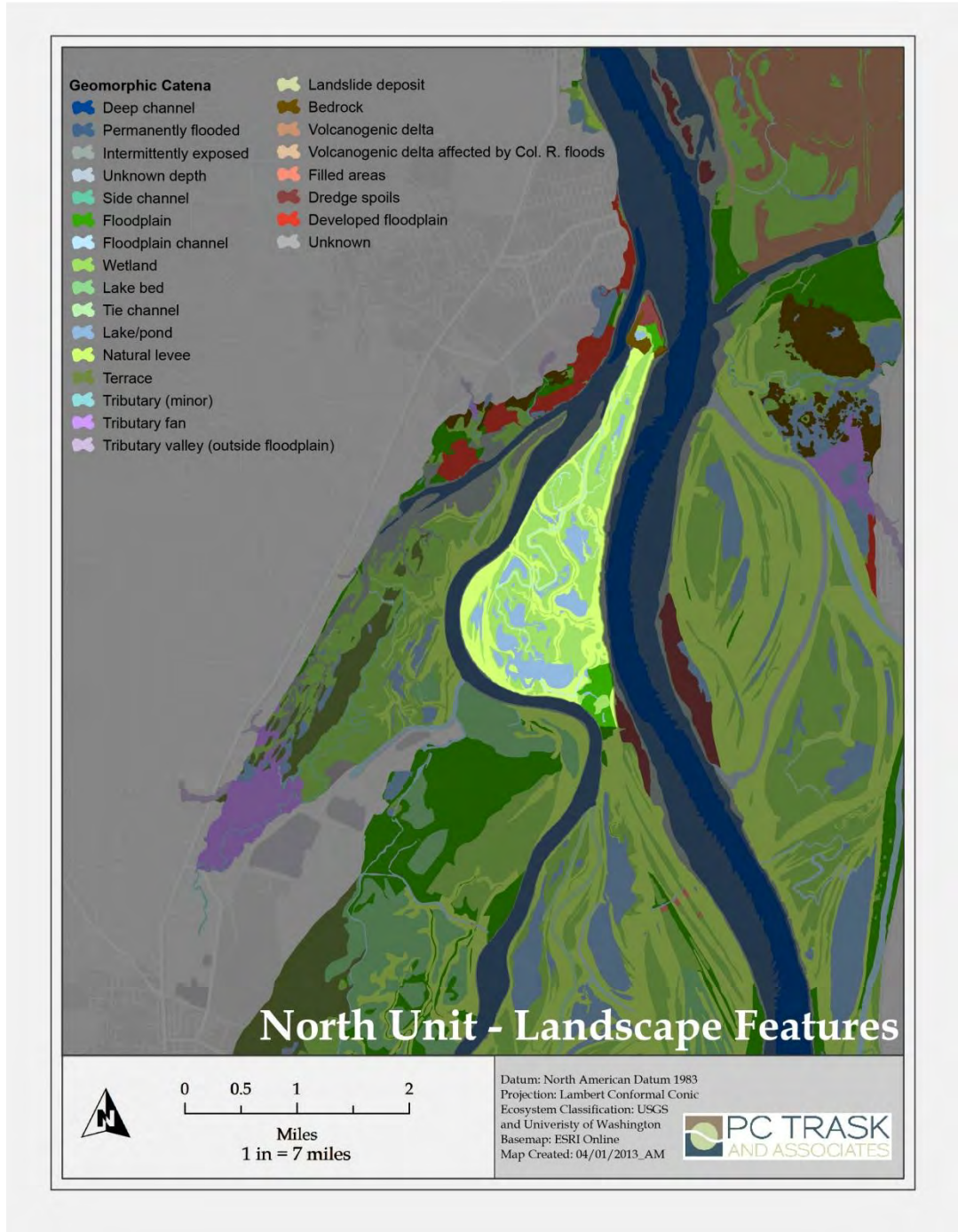


Figure 3: North Unit Landscape Features

Less frequent and lower amplitude inundations increased the extent of drier conditions on the North Unit contributing to high levels of invasive plant infestation and an elevated temperature regime. Overtopping events are less frequent and limit the potential for expanding and /or altering current crevasse splay and natural levee network.

Experimental water control structures installed to emulate historical hydrology have not only been ineffective in retarding invasive plant colonization, they have also limited access by juvenile salmonids to functioning channel/wetland fringe habitat within backwater areas of North Unit.

What is the average tidal range? 3.3 feet
 Salinity? 0
 What is the ordinary-high-water tide elevation? 9.95 feet NAVD88
 Higher-high-water elevation? 10.48 feet NAVD88
 2 year flood elevation? 17.36 feet NAVD88¹

Condition of habitat metrics

A recently completed vegetation survey inventoried the current native and non-native vegetation structure of North Unit area. Elevations were taken at vegetation plots and linked to known survey datums (NAVD88) to characterize vegetation-elevation relationships (Figure 4). These relationships were then used to develop project design criteria and identify restoration opportunities. The vegetation structure of North Unit is consistent with geomorphic features described above. The survey confirmed the following communities along the floodplain gradient of North Unit:

- **Natural levees and splays** are characterized by mature ash forest/cottonwood, stinging nettles (*urtica dioica*) and tufted hairgrass (*deschampsia cespitosa*)
- **Wetted perimeters of channels and slightly higher elevations from the herbaceous strata** are dominated by wetland shrub-scrub species (e.g., native willows (*salix lucida*, *salix lasiandra*), douglas spiraea (*spirea douglasii*), and snowberry (*Symphoricarpos albus*)
- **Mid-marsh to higher marsh areas** (>8.5 feet NAVD88) with few exceptions, are dominated by reed canary grass (*phalaris arundinacea*)
- **Low marsh**, depending on character of inundation patterns, are characterized by expressions of wapato (*sagitaria latifolia*), common spike rush (*eleocharis obtuse*), soft stem bulrush (*Scirpus tabernaemontanii*) and water purslane (*ludwigia palustris*).

¹ See Attachment 2 for two-year flood graphic.

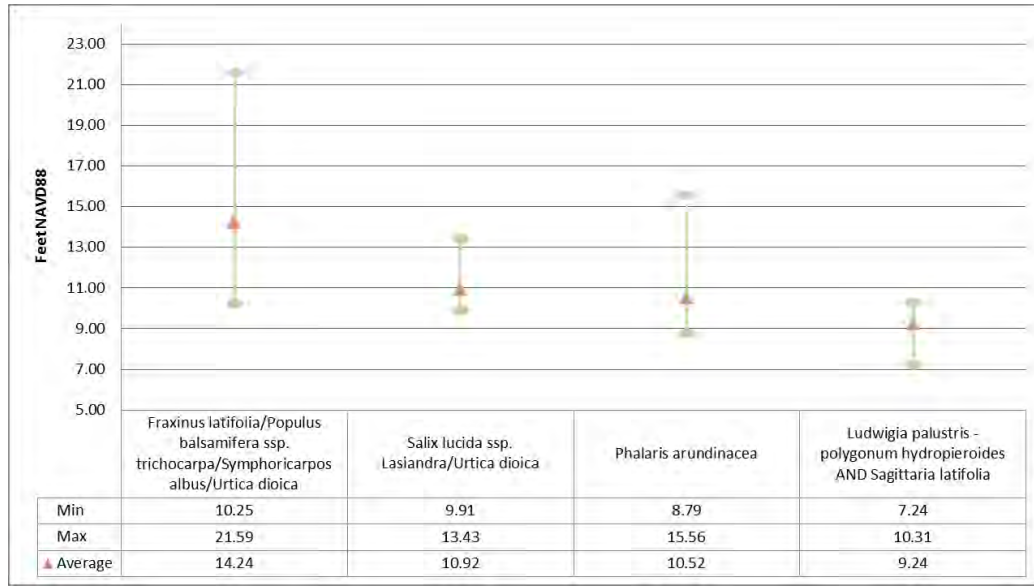


Figure 4. Minimum, maximum, and average elevation of vegetation sample plots within Ruby Lake study area (2012).

Condition of functional metrics

NOAA Fisheries research staff is investigating juvenile life history contributions from the North Unit, the adjacent Columbia River shoreline, and the Willamette River system. During this initial sampling effort, both seining and trap net methods were used along with installation of a PIT tag station near the mouth of Cunningham Slough. Initial findings (additional results are in-progress) show a diversity of age classes of non-clipped juvenile salmon including a disproportional amount of unmarked subyearling and yearling Chinook age classes. During the July 2011 sampling event, 92 subyearling Chinook were caught in Cunningham Slough of Upper Columbia Summer/Fall origin; only eight percent of these fish were marked.

Preliminary genetics sampling analysis has also been conducted for this area of the Lower Multnomah/Cunningham slough area. Dominant expressions of life histories shift based on timing of entry to Reach F system. For example, in April the largest contributions were Willamette River Spring (~40%), Spring Creek Fall (~30%), and West Cascade Fall (~20%) stocks. However in July the population structure shifted towards Upper Columbia Summer/Fall stocks (~75%) and West Cascade Fall (~20%).



82 mm juvenile Chinook captured 4/26/11 at Ruby Slough by NOAA Fisheries

Performance

Anticipated:

Physical change

Anticipated physical changes resulting from removal of Phase I and II water control structures, channel enhancements, and targeted lowering of marsh plain elevations include:

- Reduce channel aggradation processes described in the project’s geomorphic assessment and improving tidal prism dynamics to naturally increase channel depths
- Enhance dynamism of hydrologic conditions by increasing frequency, extent, and duration of inundation levels in North Unit wetlands
- Shift vegetation community toward native wetland species through earlier and longer inundation periods
- Increase channel sinuosity and edge length
- Extend period of access for juvenile salmonids to increase rearing opportunities for a diversity of life histories
- Decrease stands of Reed canary grass
- Increase resiliency against climate change and other flow-related effects

Habitat change

Anticipated habitat changes resulting from implementation will manifest from re-establishing processes that will promote development of a more diverse and complex estuarine habitat structure on the North Unit. The following habitat changes are expected:

- **Reduced germination and propagation capacity of Reed canarygrass.** Removal of water control structure and scrape down of existing marsh plain will increase extent and duration of inundation at Ruby Lake area. This will lead to reducing germination and propagation capacity of reed canary grass and facilitate the colonization of more moisture tolerant, native wetland species (i.e. wapato, soft-stem bulrush)
- **Expanded native shrub-scrub community.** Strategic placement of removal volumes from scrape-down activities in combination with native plantings will expand native shrub-scrub plant community along higher elevation herbaceous marsh edge to reduce risk of additional reed canarygrass
- **Increased foraging channel edge and depth.** Expansion of tidal prism (volume) will increase areas of refugia and foraging channel edge and depth. It will also increase overall channel density and complexity overtime as channel network adjusts to higher tidal prism volumes from restoration measures
- **Decreased channel temperatures.** Baseline temperature data collected will also help affirm if thermal improvements have been made within the water column to increase areas of cold water refugia and reduce predation risk from warmer water species

Process/Function change

Expanded inundation frequency and duration to slough channel and interior wetland complex will increase estuarine habitat function for needs of juvenile salmon both directly and indirectly. This comes in the form of expanded backwater access to productive wetlands through increased interaction with prey resources along channel edges (see design criteria above: edge density). Increased channel connectivity and wetland diversity will increase pathways for macro-detrital inputs at a broader reach scale to enhance estuarine food web productivity and diversity for needs of juvenile salmon. This is achieved through diurnal flooding from tidal as well as seasonal, higher volume events from spring freshets.

Using the Columbia River Estuary Ecosystem Classification as a guide, about 10,000 acres of estuary habitat (i.e. salmon habitat) in Reach F have been lost to diking the floodplain and altering hydrology for anthropogenic use. This is more than half of the habitat capacity that the area consisted of historically. Restoration of the North Unit's wetlands will increase approximately 11% of Reach F's existing fish habitat.

The marsh plains, channels and sloughs associated with the North Unit historically provided rearing opportunities under a variety of flows and system conditions. Improving hydrology and increasing tidal prism through scrape-down of strategic areas of the marsh plain will result in a more complex tidal channel network. Over time, this will result in a greater density of access points which are thought to be important habitat rearing areas for juvenile salmonids.

Certainty of Success:

Landowner support

SIWA staff and the ODFW Regional Biologist support this project. They are in support of project concepts proposed and view them as very complimentary their recently completed management plan and broader Conservation Strategy for the State of Oregon. Additional outreach to the West Multnomah Soil and Water Conservation District and the Sauvie Island Habitat Partnership has occurred. In addition, relationships have been established with Ducks Unlimited, the Pacific Coast Joint

	Venture, and the US Fish & Wildlife Service.
Constraints or show-stoppers	Phase I design and permitting is currently underway. Regulatory support from state agencies will be needed in order to proceed.
Restoration technique	The removal of structures and earthen berms are a common technique used throughout the lower Columbia River and elsewhere. Channel excavations have also been widely utilized. Completed hydrologic modeling, hypsometry, vegetation survey, along with recommendations from technical team (John Christy, Laura Brophy - Estuary Technical Group) have led to a design target grade of <8.5 feet NAVD 88 as an optimal elevation for native plant species. Monitoring data analysis will be incorporated iteratively in future phases of the project to help provide insight to wetland development trajectory from restoration treatments.
Natural processes and self-maintenance	Central to the project success is maximizing diurnal and seasonal hydrology to shape channel and habitat structure over the long term and minimize need for regular maintenance. Results from ongoing monitoring efforts will provide an important platform for ODFW staff and project team to track site trajectory and ensure project objectives are met. Monitoring results will be used as needed to inform long-term stewardship and maintenance activities of the site.
Potential, Anticipated Access Benefit:	
Distance of the project to the main stem Columbia River	The project site is located on the northern tip of Sauvie Island, near the Multnomah Channel confluence with the mainstem of the Columbia River. During typical flows, juvenile salmonids access the project site via Cunningham Slough at its confluence with Multnomah Channel. This confluence is about 1.25 miles from Warrior Point which marks the confluence of Multnomah Channel and the Columbia River.
Connectedness to mainstem	This project improves physical access of North Unit wetlands to Multnomah Channel and the mainstem Columbia River. All project phases include increasing connectivity to Cunningham Slough, a major tie channel to the Multnomah Channel confluence area with the mainstem. Fish use data depicted above suggests that interior wetlands perform important refuge area from high volume spring freshet events, especially when the Columbia River overtops natural levees into North Unit wetlands.
Species impacted	<p>Fish use monitoring by NOAA fisheries research continues at Cunningham Slough/Lower Multnomah Channel. Preliminary reports from this effort provide information particularly important to backswamp areas at North Unit. Detection efficiencies of PIT tags is somewhat influenced by outflow volumes at Bonneville Dam. Preliminary sampling analysis has also been conducted for this area is consistent with research findings elsewhere in Reach F. Lower Multnomah/Cunningham slough area.</p> <p>The contrast in juvenile salmonid population structure from lower flow conditions in April, (Willamette River Spring (~40%), Spring Creek Fall (~30%), and West Cascade Fall (~20%)), to freshet conditions in July (Upper Columbia Summer/Fall stocks (~75%) and West Cascade Fall (~20%)), may hold important implications for the role of backwater restoration activities at North Unit. Fish data collected at Ruby after the construction of the water control structure provide baseline datasets to track potential biological response from evolving estuarine structure from restoration. It also may help bridge existing research gaps and bolster emerging life cycle modeling research from existing RME program for the Estuary.</p>

Potential, Anticipated Capacity Benefit:

Habitat complexity

North Unit channel complexity remains largely intact despite a muted tidal signal resulting from the water control structures and an altered hydrograph. Wetland habitat structure remains heavily impacted by monotypical stands of invasive species. An improved tidal signal from water control structure removal combined with scrape downs will contribute to a new inundation regime that is intended to increase estuarine plant diversity. Channel enhancement measures will contribute to tidal prism expressions that will expand channel density and complexity over time.

In addition, it is anticipated that the level of wetland patch interspersion between and among a diversity of wetland habitat types will also be increased because of a more dynamic inundation regime.

Water quality

Recently-collected data from the North Unit reflect the temperature trend of the Lower Columbia River (Figure 5). Temperature data was collected to confirm the above trends and to better understand localized temperature patterns within the North Unit. In spring 2012, additional temperature probes were placed inside and outside of each lake within the North Unit to assess the potential effects to temperature from operation of the water control structures. Figure 6 illustrates the preliminary temperature data collected at Ruby Slough from May 2011 to October 2012. In general, the water temperatures in the North Unit mirror the same seasonal trend. Additional data continues to be collected to analyze the effects of the WCSs on North Unit water temperatures.

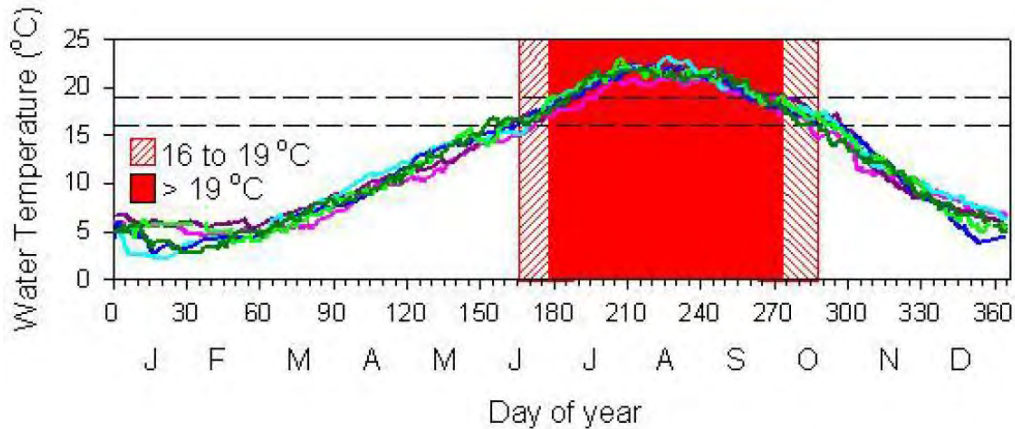


Figure 5. Temperature by day of year at Bonneville Dam 2002-2007. Data courtesy of Columbia River Data Access in Real Time (CRDART 1995) as presented in Bottom et al. 2008.

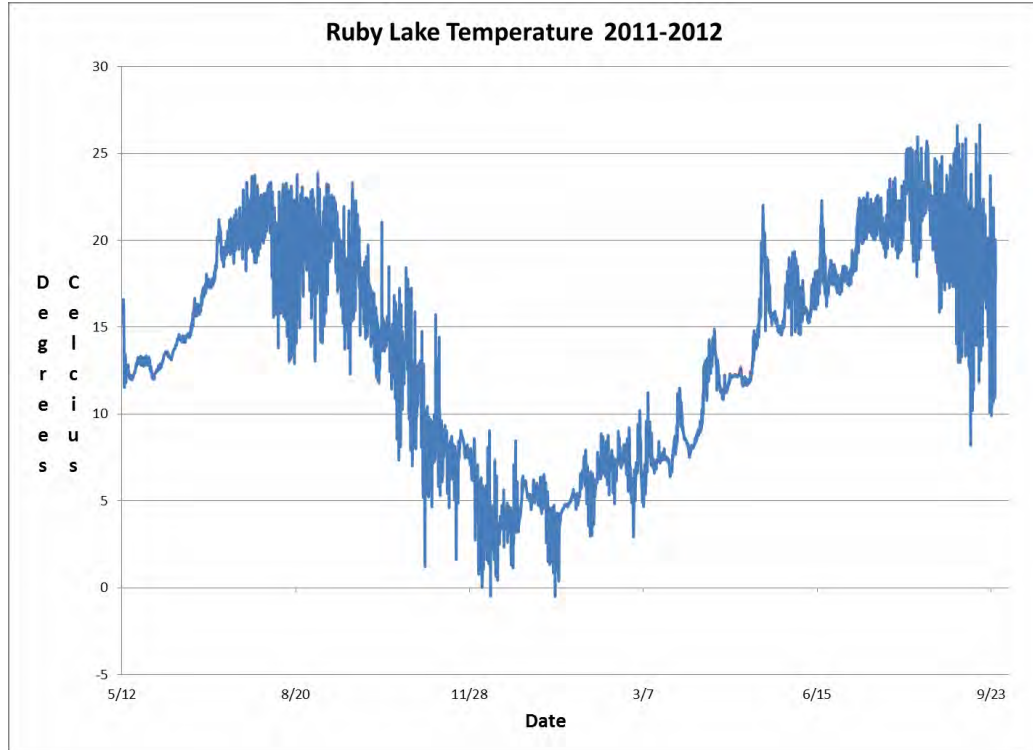


Figure 6. Temperature by date at Ruby Lake, Sauvie Island Wildlife Area North Unit 2011-2012.

Invasive species

Reed canarygrass is the dominant invasive plant species in the low marshes of North Unit wetlands. Figure 7 graphically depicts the results of an extensive vegetation survey in Ruby Lake. Reed canarygrass has most successfully colonized mid marsh (>8.5 NAVD88) to higher marsh areas. Grading the marsh surface elevation in strategic locations to 7.5 - 8.0 feet NAVD88 will improve inundation conditions favorable to desirable native wetland species such as wapato, softstem bulrush, and spike-rush. Planting native shrub-scrub species on higher edge herbaceous and shrub-scrub strata will increase competition and reduce colonization potential of reed canary grass while expanding important plant community ecotone.

SIWA staff will build upon these efforts to manage reed canarygrass by employing wet soil management techniques (e.g., mowing, disking, selected herbicides, etc.). Funding for invasive species management is part of this project.

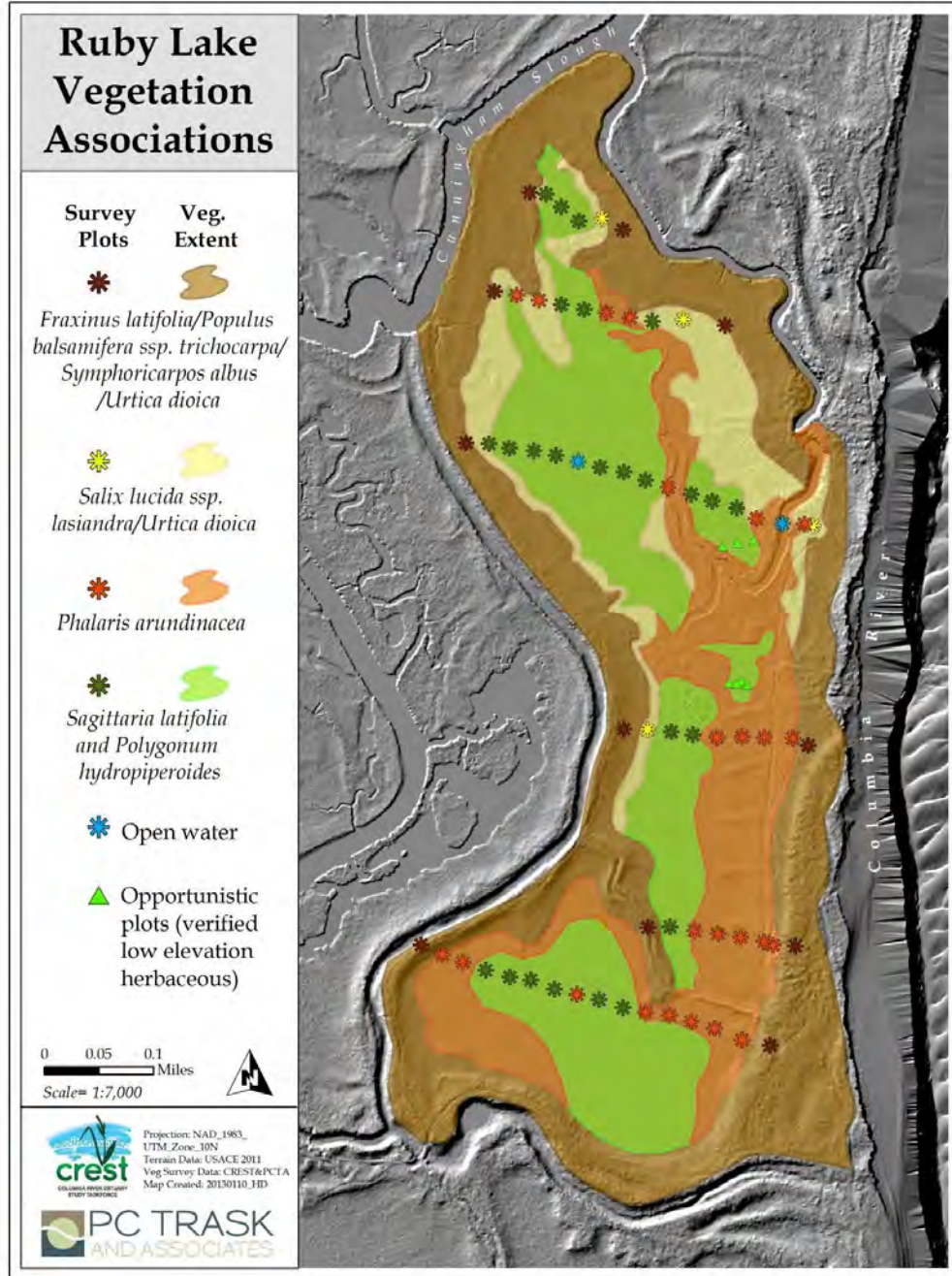


Figure 7. Vegetation associations based on the results of field surveys conducted in August 2012.

Adjacent lands

SIWA is located in Columbia and Multnomah Counties, south of the confluence of the Columbia River and Willamette River, approximately 12 miles from downtown Portland. The North Unit (~1600 acres) is contained within the larger SIWA complex (~11,564 acres). Adjacent properties are managed for select waterbird and waterfowl species (ducks, seven species of geese and swans), salmonids, and amphibians. Other nearby public ownerships includes the John R Palensky Reserve, Wapato Access, Lake River/Vancouver Lake area and Ridgefield National Wildlife Refuge. Areas along Multnomah Channel and south portion of Sauvie Island are diked and drained for agricultural use. While many potential restoration sites are shown on Figure 8 below, few restoration actions have been implemented to-date. This reach has significant untapped potential for salmon restoration efforts.

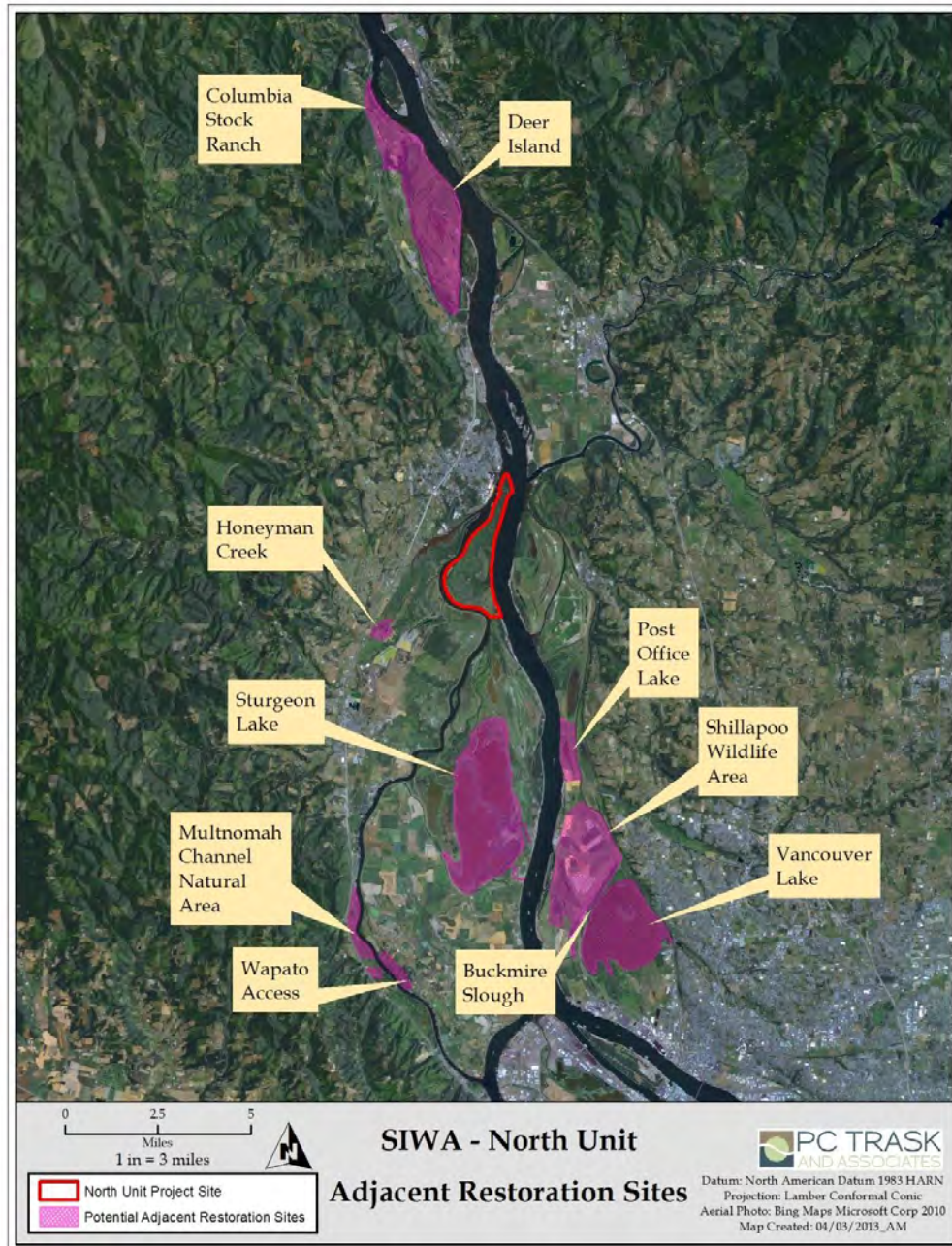
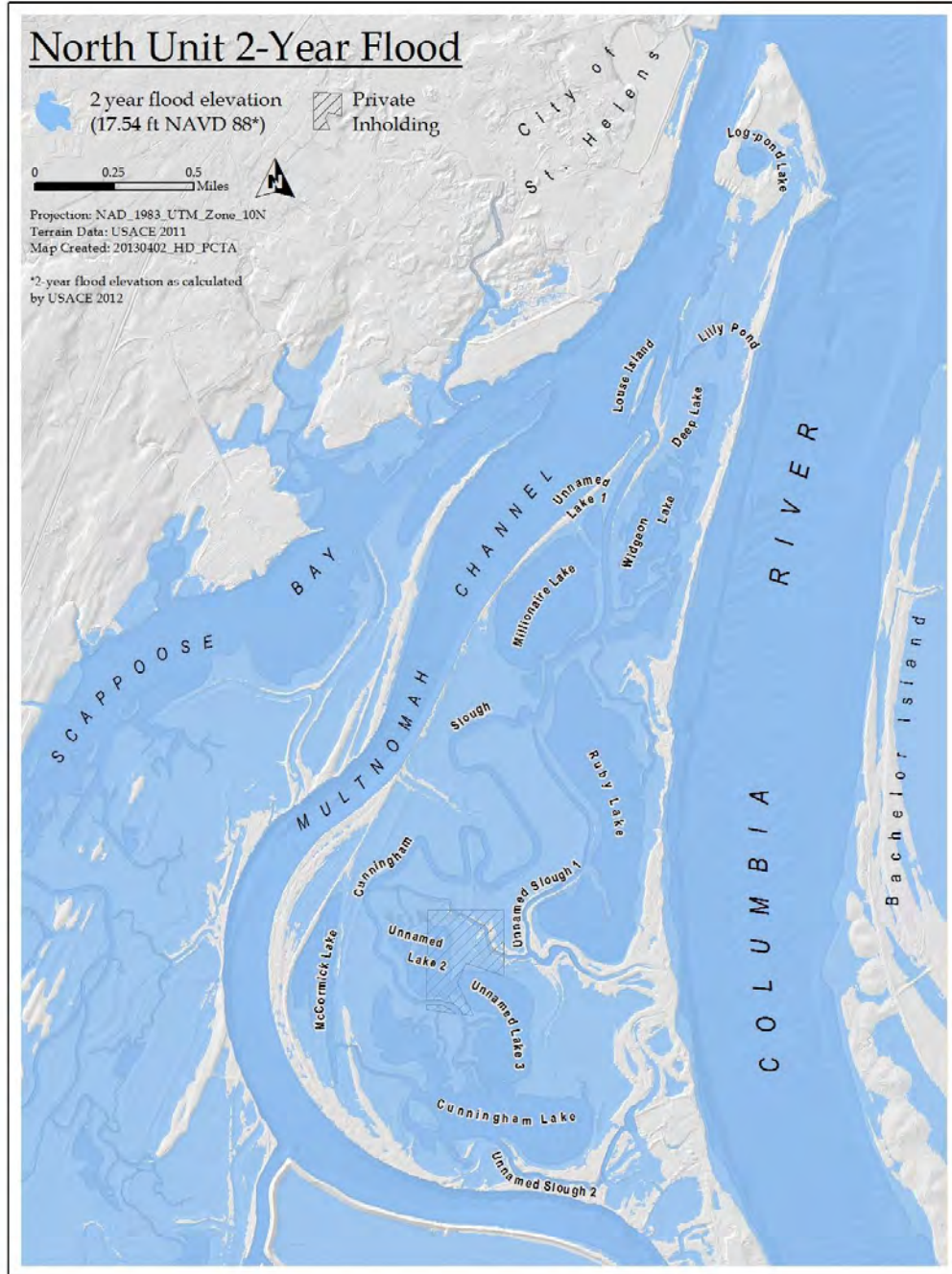


Figure 8: Potential Adjacent Restoration Sites in relation to SIWA – North Unit

Comments The North Unit Backswamp Access and Revitalization project is focused on symbiotic restoration benefitting multiple species. Project partners, including SIWA and Ducks Unlimited, view this project as an opportunity to explore restoration methods that benefit a diversity of species rather than one species over another. One facet of project success can be measured by increased opportunities to implement effective multispecies management in the Columbia River estuary while meeting specific juvenile salmonid objectives in the North Unit wetlands.



Attachment 1: North Unit Locator Map



Attachment 2: North Unit Two Year Flood Scenario

ERTG -- Project SBU Report

Report Date: 7/9/2013 FINAL
 Prepared By: GEJ
 Name: North Unit (Phase 1) Ruby Lake
 Id. No.: 2013-05

Total Project SBUs

North Unit (Phase 1) Ruby Lake Ocean-type: 0.924
 Stream-type: 0.287

Scores	Subaction	Project Goal	Certainty of Success	Access Benefit	Capacity Benefit
North Unit (Phase 1) Ruby Lake	1.4	0.5	3.88	2.70	3.02
	9.4	0.6	4.40	2.95	3.20
	10.1	122.8	4.72	2.85	4.28
	15.3	16.4	3.41	2.85	3.40

Comments

General Comments

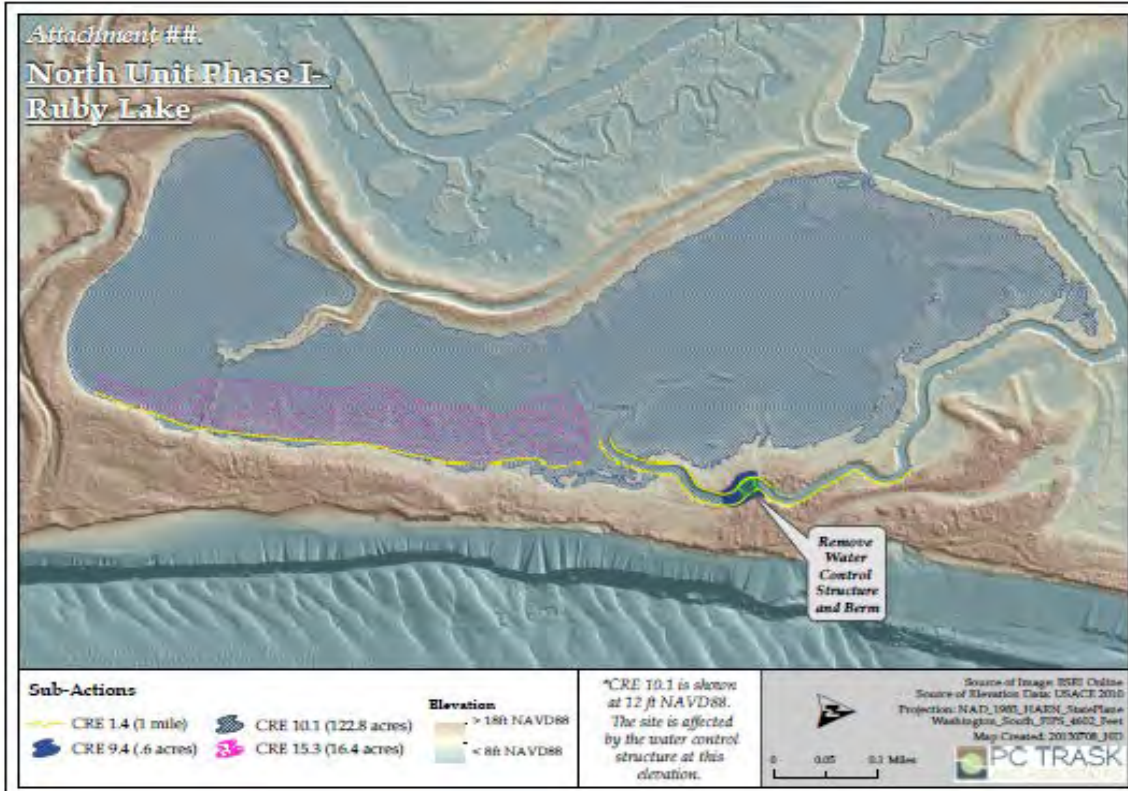
- Only access is thru Cunningham Slough, not the main stem Col directly. General uncertainty as to how many how often fish move up Cunningham Slough and access the site.
- Subaction 9.4 seems inappropriate. Unclear from the template what's intended here. ERTG decided not to score this subaction pending additional information. Channel areas close to the location where the water control structure and levee is being removed.
- Overall, good looking habitat in a strategic location in the LCRE with lots of genetic diversity. Water circulation is complex and variable. It's uncertain under what flow conditions fish can access the areas.
- Except for Phase 3, the actions/strategies for Ph 1 and 2 are comparable. Ruby and Millionaire are similar, but there'll be site-specific nuances.
- Would have been a much better project if Phases 1 and 2 were combined because of the cumulative effects of the restoration with multiple sites being restored. The ERTG assumed each phase is independent and stand-alone. Anytime sponsors can restore multiple areas within a landscape, the better.
- More emergent marsh than open water. Depths are likely shallower than other lakes on Sauvie Island. Seems to be more naturally tidally influenced than a place like Sturgeon Lake.
- Access -- At lower flows, relatively few fish are likely get up into the area. Also, there's some uncertainty about how much fish can access the Ruby Lake area on the backside of Sauvie Island; not the best access but not the worst. Access will likely be episodic.
- FPL determination -- This is a wetland site because there's not much open water, shallow depths, channel structure accesses much of the area as a tidal channel would, and is seasonally flooded.

Subaction Comments

- Subaction 1.4 – Edge plantings seem like a good idea.
- Subaction 9.4 -- Include the acreage where they are excavating channel and removing the structure, but not the entire remnant channel.
- Subaction 10.1 – If fish are at the site during a high water event, they'll have ready routes to leave from. Egress should be improved w/ the barrier removal. Good potential for improved habitat capacity, although some concern about WQ and invasives, especially RCG.

- Subaction 10.1 -- Yes, this is correct; full, natural hydrologic reconnection. Levees on river side were natural, so the 2-yr flood would likely inundate the site; seems to be unrestricted natural hydrology.
- Subaction 15.3 – Using scrape down and planting shrubs to control RCG is good.

MAP



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This is the last page of the 2014 FCRPS Supplemental Biological Opinion