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Estimating impacts of the pollock fishery bycatch on western Alaska Chinook salmon

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Chinook salmon (*Oncorhynchus tshawytscha*) are taken as bycatch in the Bering Sea pollock (*Gadus chalcogrammus*) fishery, with recently revised management measures in place to limit the overall Chinook salmon catch. Historical impact of the bycatch on regional salmon stocks is made difficult because, until recently, sampling for the stock composition of the bycatch was patchy and diverse in approaches. In this study, extensive observer data on the biological attributes (size and age composition) of the bycatch were used to estimate the impact on specific regional stock groups (RSGs), as defined given available genetic stock identification estimates. Our model provides estimates of the impact on Chinook salmon RSGs, given seasonal and spatial variability in the bycatch, and accounts for observed in-river age compositions, uncertainty in age-specific oceanic natural mortality of Chinook salmon, and between-year variability in genetic information. The upper Yukon River stock is transboundary and subject to heightened management interest and international management agreements on escapement goals. Our study updates results from an earlier analysis used to develop the management regulations that went into place in 2011. It shows that the new data result in slight changes in previous estimates, and that the lower overall Chinook salmon bycatch since 2008 has resulted in lower impacts to the main western Alaskan RSGs.

Keywords: adult equivalent, bycatch, Chinook salmon, pollock fishery, western Alaska.

Introduction

Fishery bycatch is a global concern (Alverson *et al.*, 1994; Lewison *et al.*, 2014), and protection of highly valued species taken as bycatch, such as Chinook salmon (*Oncorhynchus tshawytscha*), is a high priority (e.g. Witherell *et al.*, 2002, Gisclair, 2009). The pollock (*Gadus chalcogrammus*) resource in the eastern Bering Sea (EBS) supports a large fishery with annual catches averaging ~1.2 million t per year during 1977–2013 (Ianelli *et al.*, 2013). From 2001 to 2007, Chinook salmon bycatch increased substantially and created a heightened awareness, particularly since some in-river abundance levels were low, and eventually led to revised management measures imposed on the fishery beginning in 2011 (Gisclair, 2009; Stram and Ianelli, in press).

The EBS pollock fishery represents over 40% of the global white-fish production (Fissel *et al.*, 2013). The fishery operates offshore in the Bering Sea, primarily along the shelf edge, and is divided into a winter ("A" season) fishery focused primarily on the harvest of roe from prespawning pollock, which can make up over 4% of the catch in weight (Ianelli *et al.*, 2013), and a summer ("B" season) fishery focused more on the production of filets and surimi. Pollock are considered to be a relatively fast growing and short-lived species and form an important component of the Bering Sea ecosystem (Ianelli *et al.*, 2013).

The EBS pollock fishery is prosecuted exclusively with pelagic trawlnets. Bycatch of species other than pollock remains consistently <1% (Ianelli *et al.*, 2013). However, included in this bycatch are significant numbers of Chinook and chum salmon (*Oncorhynchus keta*; Stram and Ianelli, in press). Chinook salmon spend 1–5 years at sea before returning to their natal streams to spawn; those caught in the pollock fishery range from 3 to 7 years old (NPFMC/NMFS, 2009; Stram and Ianelli, 2009). While migratory patterns of juvenile Chinook salmon have been estimated from a variety of at-sea tagging programmes over the years (e.g. Farley *et al.*, 2005), in-season predictability of temporal and spatial abundance in the Bering Sea remains problematic. As such, designing effective management measures such as time–area closures have been impractical. Before 2011, the bycatch of Chinook salmon was managed using a variety of large-scale time and area closures designed based on historical bycatch patterns. These federally implemented measures were static and unresponsive to changing oceanic conditions and spatial locations of bycatch. Consequently, a more responsive, real time, and industry-run closure system was adopted (Haflinger and Gruver, 2009; Stram and Ianelli, 2009). However, following increasing bycatch levels over several years and the historically high bycatch level in 2007 of ~122 000 Chinook salmon, the North Pacific Fishery Management Council (NPFMC), the regional fishery management body with jurisdiction over the Bering Sea pollock fishery, began to evaluate alternative management measures. The measures under consideration included imposing a range of bycatch limits on the pollock fishery whereby the fishery would close seasonally or annually if limits were reached.

To best inform the fishery about the implications of the measures under consideration and to evaluate the relative impact of past practices and future potential management measures for a fishery that is the largest by volume in the United States (Fissel *et al.*, 2013), extensive analyses of these alternative management strategies for limiting Chinook bycatch in the pollock fishery were conducted in 2009 and formed the basis of a controversial management decision by the NPFMC (NPFMC/NMFS, 2009). Current bycatch management measures for Chinook salmon in the EBS pollock fishery employ a complicated system of caps (or absolute limits on the catch of Chinook in the pollock fishery) combined with industry-designed incentive programmes intended both to reduce bycatch below the regulatory cap levels and to reduce bycatch at all levels of salmon abundance (Stram and Ianelli, in press). The programme, which was Amendment 91 to the Bering Sea Aleutian Islands Fishery Management Plan, was implemented in 2011 (NMFS, 2010).

Of particular management importance to the NPFMC in evaluating management trade-offs is the large proportion of western Alaskan Chinook stocks in the bycatch by the pollock fishery (Myers and Rogers, 1983, 1988; Guthrie and Wilmot, 2004; Myers *et al.*, 2004; Guyon *et al.*, 2010; Guthrie *et al.*, 2012, 2013, 2014). Chinook salmon stocks in western Alaska have been in severe decline for decades (Gisclair, 2009; Hilsinger *et al.*, 2009; Howe and Martin, 2009). Within their riverine habitat, this resource is fully allocated among diverse user groups (subsistence, commercial, and recreational) and is a culturally important species within the State of Alaska. Thus, it is critically important to assess the specific impact of the pollock fishery on the Chinook salmon that would have returned to natal streams in western Alaska.

In this study, we extend the analysis conducted for evaluating bycatch impacts presented in the environmental impact statement that was created to refine management regulations (NPFMC/NMFS, 2009). In that study, available genetic information (collected opportunistically) and observed catch information through 2007 were used in conjunction with an adult equivalents (AEQ) model employed to evaluate the relative retrospective impacts to aggregate river systems of a range of absolute limits employed on the bycatch of Chinook by the pollock fishery (NPFMC/NMFS, 2009). Here, we specifically use the extensive observer data collection programme for the EBS pollock fishery, the genetic sampling and analysis that has been completed annually since 2008 (e.g. Guthrie *et al.*, 2012), and in-river salmon return information to present an evaluation of the current impacts of fishing for Alaska pollock on Chinook salmon. The model accounts for a variety of uncertain assumptions and estimates, including between-year (within stratum) variability in stock composition. The objective is to provide estimates of the additional number of salmon that would have returned to each regional stock group (RSG) had there been no pollock fishery. Combined with Chinook salmon return estimates, these values are used to estimate the impact of the bycatch on these salmon stocks.

Methods

Data preparation

This analysis relies on Chinook bycatch estimates based on the National Marine Fisheries Service (NMFS) observer sampling and catch-accounting methods (Cahalan *et al.*, 2010). From 1991 to 2010, observer procedures in the EBS pollock fishery called for counting every salmon within a haul rather than subsampling. Estimates of total salmon bycatch were then computed based on extrapolating the ratios of observed to total pollock catch. For this period, the level of observer coverage (for the entire pollock fleet) was effectively >50%, and estimates of the total Chinook salmon bycatch in this fishery are considered very precise (e.g. coefficients of variation <5%; Miller *et al.*, 2007). In 2011, Amendment 91 of the Bering Sea and Aleutian Islands (BSAI) Groundfish Fisheries Management Plan (NMFS, 2010) was implemented requiring a 100% observer coverage on board all vessels in the pollock fishery (previously the smaller boats between 18.3 and 38.1 m in length were only required to carry observers on 30% of their trips). Additionally, the salmon bycatch data collection system changed from being sample-based to full census counts of all salmon caught in the pollock fishery.

Observer data were compiled for the period 1991–2013 on Chinook salmon bycatch (in numbers) and pollock catch (in tonnes) at a resolution of week, NMFS area, and fishing sector. Fishing sectors were categorized into three groups: catcher vessels (CVs) delivering to shore-side plants, CVs delivering to motherships (MSs), and at-sea catcher processors (CPs). In addition to these three fishing sectors, a portion of the pollock quota is allocated to the Western Alaska Community Development Quota (CDQ) Programme. (For more information on the CDQ Programme, see http://alaskafisheries.noaa.gov/cdq/.) This programme is designed to provide western Alaskan communities with additional opportunities to invest in BSAI fisheries and to promote economic development and social benefits to residents of western Alaska. The CDQ catch is prosecuted using CPs; however, for purposes of catch accounting for Chinook bycatch and pollock quota, the CDQ catch is listed separately. The biological data on Chinook salmon bycatch were stratified by these sectors and also by three additional spatio-temporal partitions defined as: all areas during the "A" season (from 20 January to the end of April), and east and west of 170°W during the "B" season (10 June–31 October). This spatial division was selected because the geographic extent of the "A" season fishery is limited due to ice cover and the fact that the fishery concentrates on prespawning Pollock, whereas in summer, the fishery is prosecuted over a larger area. The number of length frequency samples for Chinook salmon from each of these nine strata is provided in Table 1, and the estimates of bycatch are given in Table 2.

A key aspect of understanding the impact of bycatch on salmon returns is estimating what fraction would likely have returned to spawn in a given year. This requires estimates of the age composition

Table 1. The number of Chinook salmon measured for lengths in the pollock fishery by season (A and B), area (NW, east of 170°W; SE, west of 170°W), and sector (CV, shore-based catcher vessels; MS, mothership operations; CP, catcher processors).

Season	A			B						
Area	All			NW			SE			
Sector	CV	MS	CP	CV	MS	CP	CV	MS	CP	Total
1991	2227	302	2569		25	87	221	10	47	5488
1992	2305	733	889	2	4	14	1314	21	673	5955
1993	1929	349	370	1	11	172	298	255	677	4062
1994	4756	408	986	3	93	276	781	203	275	7781
1995	1209	264	851		8	31	457	247	305	3372
1996	9447	976	2798		17	161	5658	1721	493	21 271
1997	3498	423	910	12	303	839	12 126	370	129	18 610
1998	3124	451	1329		38	191	8277	2446	1277	17 133
1999	1934	120	1073		1	627	1467	97	503	5822
2000	608	17	1388	4	40	179	564	3	120	2923
2001	4360	268	3583		25	1816	1597	291	1667	13 607
2002	5587	850	3011		23	114	5353	520	494	15 952
2003	9328	1000	5379	258	290	1290	4420	348	467	22 780
2004	7247	594	3514	1352	557	1153	8884	137	606	24 044
2005	9237	694	3998	4081	244	1610	10 336	45	79	30 324
2006	17 875	1574	5716	685	66	480	12 757	3	82	39 238
2007	16 008	1802	9012	881	590	1986	21 725	2	801	52 807
2008	21	272	1306	1	94	164	28	0	22	1908
2009	221	124	653	0	33	106	43	2	0	1182
2010	13	52	916	3	6	27	8	2	0	1027
2011	464	46	228	15	5	131	1386	232	66	2573
2012	480	36	287	9	1	3	338	2	1	1157

Source: NMFS Alaska Fisheries Science Centerobserver data.

Table 2. Chinook salmon bycatch in the pollock fishery by season (A and B), area (NW, east of 170°W; SE, west of 170°W), and sector (CV, shore-based catcher vessels; MS, mothership operations; CP, catcher processors, CDQ, community development quota).

Season	A				B								
Area	All				NW				SE				
Sector	CV	MS	CP	CDQ	CV	MS	CP	CDQ	CV	MS	CP	CDQ	Total
1991	10192	9001	17 645		0	48	318		1667	103	79		39 054
1992	6725	4057	12 631		0	26	187		1604	1739	6702		33 672
1993	3017	3529	8869		29	157	7158		2585	6500	4775		36 619
1994	8346	1790	17 149		0	121	771		1206	452	2055		31 890
1995	2040	971	5971		0	35	77		781	632	2896		13 403
1996	15 228	5481	15 276		0	113	908		9944	6208	2315		55 472
1997	4954	1561	3832		43	2143	4172		22 508	3559	1549		44 320
1998	4334	4284	6500		0	309	511		27 218	6052	2037		51 244
1999	3103	554	2694		13	12	1284		2649	362	1306		11 978
2000	878	19	2525		4	230	286		714	23	282		4961
2001	8555	1664	8264		0	162	5346		3779	1157	4517		33 444
2002	10 336	1976	9481		0	38	211		9560	1717	1175		34 495
2003	15 367	2567	12 982	1693	712	858	2461	504	6286	971	817	368	45 586
2004	11 576	1830	8559	1140	2310	1375	1824	1217	19 921	494	845	609	51 699
2005	13 797	1864	10 328	1299	8870	546	3792	555	25 956	144	105	62	67 319
2006	35 638	4864	16 204	1585	961	148	1251	130	21 687	11	165	26	82 671
2007	36 463	4816	25 841	3113	1637	1825	4558	2023	39 701	20	1748	506	122 252
2008	10 692	1127	4091	605	251	175	339	31	3994	0	38	5	21 347
2009	6241	547	2738	358	115	70	310	89	2092	16	0	0	12 576
2010	3735	493	3066	335	73	20	50	0	1859	64	1	0	9695
2011	4441	459	1806	430	142	69	1244	76	13 809	2357	408	258	25 499
2012	4624	312	2484	344	75	7	52	2	3358	42	40	3	11 343
2013	3640	557	3563	472	13	7	34	6	697	18	32	2	9041

Note that CDQ before 2003 were included in the other sectors and, to this study, are added to the CP fleet for impact estimates. Source: NMFS Alaska Regional Office, Juneau as of 23 August 2013.

of the bycatch. The catch-at-age estimates apply observer-collected length frequency and length-at-age data using the method of Kimura (1989) and modified by Dorn (1992). Age–length keys for each time–area stratum and sex are constructed and applied to randomly sampled catch-at-length frequency data. The stratum-specific age composition estimates are then weighted by the catch within each stratum to arrive at an overall age composition for each year. The length frequency data on Chinook salmon from the NMFS observer database were used to estimate the overall length and age composition of the bycatch for each season (Figure 1). The age data were used to construct annual stratified age–length keys when sample sizes were appropriate and stratified combined-year age–length keys for years where age samples were limited. To the extent possible, sex-specific age–length keys within each stratum were created and where cells were missing, a "global" sex-specific age–length key was used. The global key was computed over all strata within the same season. For years where age data were unavailable, a combined-year age–length key (based on data spanning all years) was applied to observed catch length frequencies. Applying the available length frequencies with stratified catch and age data resulted in age composition estimates in the bycatch that were predominately age 4 (Table 3). Generally, it is inappropriate to use the same age–length key over multiple years because the proportions at age for given lengths can be influenced by variability in relative year-class strengths. Combining age data over all the years averages the year-class effects to some degree, but may mask the actual variability in age compositions in individual years. This practice was evaluated and, given the relatively distinct length frequency modes corresponding to age, the results were found to be relatively

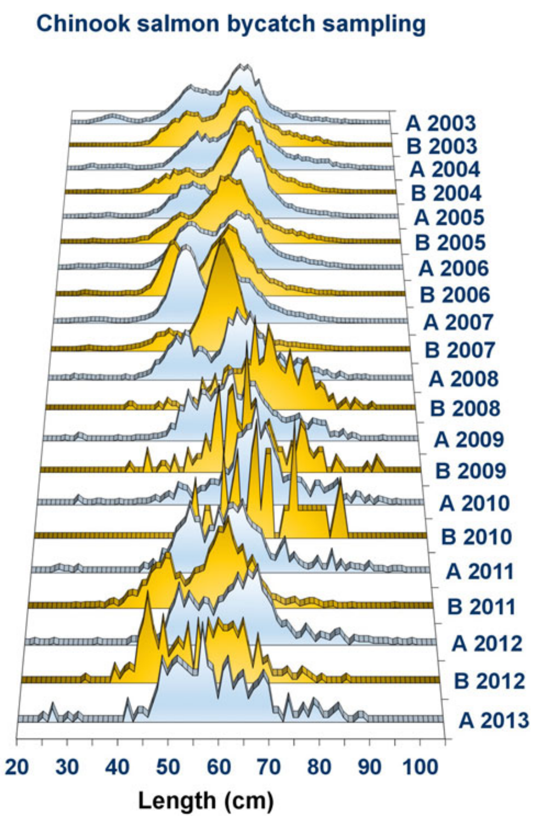

Figure 1. NMFS observer programme Chinook salmon length frequency by season and year, 2003–2013 ("A" season only for 2013).

insensitive (NPFMC/NMFS, 2009). The estimates of uncertainty in the age composition due to sampling have increased substantially due to the lower number of Chinook salmon sampled for lengths since 2008 (Table 4). Note that estimates of age composition were computed using a two-stage bootstrap application in which the first stage was resampling from a population of observed hauls (with replacement), then resampling individual fish within those hauls (also with replacement). In recent years, fewer Chinook salmon are being measured under the new observer protocols since some of their effort has shifted towards collecting genetic tissue for stock identification studies.

Genetic stock identification (GSI) data used for this study include those from the original study (NPFMC/NMFS, 2009), supplemented by ongoing analyses from Guthrie *et al.* (2013). For the purposes of comparing past work with the improved samples and methods, the new data were processed using the same strata (Table 5) as in NPFMC/NMFS (2009). In the earlier study, much effort had to be expended to appropriately weight the available stock ID information according to where and when the bycatch occurred, since sampling was out of proportion to the bycatch. This resulted in a higher variance in the estimates of stock origins than in recent years, when sampling has been precisely proportional (Table 6).

As noted below in the model section, estimates of the maturation rates require data on the in-river age compositions. For our purposes, we computed a mean in-river age composition based on a weighted (by average relative run strength) combination of western Alaska systems (Table 7). Also, to evaluate impacts of bycatch on these systems, data on estimated Chinook salmon run numbers were obtained (Table 8).

Model

Calculation of AEQ by year of return

To convert Chinook salmon bycatch totals into adult equivalents (AEQ; as in Kope, 2006; Ford *et al.*, 2007; and Mantua *et al.*, 2009), the bycatch must be corrected for the estimated proportion of mature and immature fish. For immature salmon, the probabilities of maturing the following or subsequent years are also required. This was estimated (given mean in-river age composition) for calendar ages 3–7 as a function of uncertain ocean survival rates. The reduction in Chinook salmon returns in year t, AEQ_t, can thus be expressed (without stock specificity) as:

$$\mathrm{AEQ}_t = \sum\nolimits_{a=3}^{7} c_{t,a}\gamma_a + \sum\nolimits_{j=3}^{6}\sum\nolimits_{a=j+1}^{7}\left[\gamma_a c_{t-(a-j),j}\prod\nolimits_{i=j}^{a-1}(1-\gamma_i)s_i\right], \quad (1)$$

where $c_{t,a}$ is the bycatch of age a salmon in year t, s_a is the proportion of salmon surviving from age a to $a+1$, and γ_a is the proportion of salmon at sea that would have returned to spawn at age a. In other words, the first term to the right of the equal sign is simply the number of mature Chinook salmon in the bycatch in the current year, whereas the second term accounts for the Chinook salmon caught in previous years that would have been mature in the current year. All age 7 Chinook salmon in the bycatch were assumed to be returning to spawn in the year they were caught (i.e. $\gamma_7 = 1$), and they represent the oldest fish in the model. We assume that 7-year-old Chinook salmon taken in autumn were returning to spawn that year. In fact, these fish would have been more likely to return the following year. This assumption simplified

Table 3. Age-specific Chinook salmon bycatch estimates by season and calendar age based on the mean of 100 bootstrap samples of available length and age data.

Year season	Age 3	Age 4	Age 5	Age 6	Age 7	Total
1991	5624	15 901	13 486	3445	347	38 802
A	5406	14 764	12 841	3270	313	36 593
B	218	1137	646	174	34	2209
1992	5136	9528	14 538	3972	421	33 596
A	1017	4633	13 498	3798	408	23 355
B	4119	4895	1040	174	13	10 241
1993	2815	16 565	12 992	3673	401	36 446
A	1248	3654	7397	2778	290	15 368
B	1567	12 910	5595	895	111	21 078
1994	849	5300	20 533	4744	392	31 817
A	436	3519	18 726	4211	326	27 218
B	413	1781	1807	533	66	4599
1995	498	3895	4827	3796	367	13 382
A	262	1009	3838	3534	327	8969
B	236	2885	989	263	40	4413
1996	5091	18 590	26 202	5062	421	55 366
A	863	7187	23 118	4431	349	35 947
B	4228	11 403	3085	632	71	19 418
1997	5855	23 972	7233	5710	397	43 167
A	456	2013	3595	3899	271	10 234
B	5399	21 958	3638	1811	126	32 933
1998	19 168	16 169	11 751	2514	615	50 216
A	1466	2254	8639	2079	512	14 950
B	17 703	13 915	3112	435	103	35 266
1999	870	5343	4424	1098	21	11 757
A	511	1639	3151	898	18	6217
B	360	3704	1272	200	3	5540
2000	662	1923	1800	518	34	4939
A	365	1167	1406	453	26	3416
B	298	757	395	66	8	1522
2001	6512	12 365	11 948	1994	190	33 009
A	2840	3458	9831	1798	171	18 098
B	3672	8907	2117	196	19	14 910
2002	3843	13 893	10 655	5469	489	34 349
A	1580	5063	9234	5328	478	21 683
B	2263	8830	1421	141	11	12 666
2003	5575	16 297	19 423	3661	286	45 242
A	2707	7204	2678	348	30	12 967
B	2868	9093	16 745	3313	256	32 275
2004	6582	22 662	17 654	4247	390	51 536
A	5502	17 324	5059	616	49	28 550
B	1080	5338	12 595	3631	341	22 986
2005	10 406	30 520	21 661	4295	301	67 184
A	9011	23 608	6302	976	78	39 975
B	1395	6912	15 359	3319	223	27 209
2006	11 801	31 296	32 210	6589	487	82 382
A	8220	13 862	2006	235	25	24 348
B	3581	17 434	30 204	6354	462	58 035
2007	16 129	66 131	33 693	5651	361	121 966
A	10 290	36 460	4608	514	39	51 912
B	5839	29 671	29 085	5137	322	70 054
2008	1144	7025	10 775	2177	108	21 229
A	613	2974	973	151	9	4720
B	531	4051	9802	2026	99	16 510
2009	589	4789	5900	1074	87	12 439
A	296	1783	460	32	3	2573
B	293	3006	5439	1043	85	9866
2010	461	2698	4816	1591	71	9637
A	326	1496	173	17	2	2014
B	135	1202	4643	1574	69	7623
2011	6253	13 203	4944	951	66	25 418
A	5946	11 035	1215	88	3	18 287
B	307	2168	3729	863	63	7131
2012	1722	3959	4650	874	84	11 288
A	1554	1772	192	8	1	3527
B	167	2186	4458	866	83	7761

Continued

Table 3. *Continued*

Age–length keys for 1997–1999 were based on Myers *et al.* (2004) data split by year, while for all other years, a combined-year age–length key was used.

the model and data preparation. Also, relatively few fish of this age were caught late in the season.

Estimation of maturation rates?

Note that the distribution of mature age salmon found in rivers is a function of both the age-specific maturation rate and age-specific survival rates of oceanic salmon (γ_a) used in this model. The oceanic maturity rates were estimated by conditioning on the assumed survival rates and the observed mean in-river age composition. Uncertainty in oceanic age-specific survival rates and the age structure of spawners in each RSG (from both sampling error and between-year variability) was explicitly modelled. The annual age-specific survival rates were modelled as being the same for all RSGs, but with some variability given an assumed prior distribution:

$$\dot{s}_{i,a} = \exp(-M_a + \delta_{i,a}), \quad \delta_{i,a} \sim N(0, 0.1^2). \tag{2}$$

The matrix of parameters $\delta_{i,a}$ represents 115 free parameters (1991–2012 by five ages), which reflect uncertainty in the assumptions about the vector M_a; since there are no data affecting these parameters, the "point estimates" will be zero. Their main purpose is to propagate uncertainty as an assumed prior distribution (with variance term noted above that reflects a 10% coefficient of variation). This approach is intended to reflect part of the model misspecification error in that oceanic survival is uncertain and poorly known.

Partitioning bycatch by RSG

Given estimates of AEQ, the model partitions these into RSGs. This was done by assigning the stratum-specific AEQ estimates to each of the nine identified RSGs (see Table 5; Guthrie *et al.*, 2013 for RSG and GSI determinations). We assumed that, given the number of samples used for GSI within each year (t) and stratum (i), the numbers assigned to RSG k can be assumed to follow a multinomial distribution with parameters

$$p_{t,i,1}, \ldots, p_{t,i,9} \sum_k p_{t,i,k} = 1. \tag{3}$$

For the years where GSI information is missing (all years between 1991 and 2013 absent from Table 5), the estimated proportions by RSGs were based on mean stratum-specific values from the years when GSI data were available. These additional parameters were constrained based on the estimated within-stratum interannual variability. That is, if the proportions assigned to RSGs varied as estimated from the genetics data, then that variability was propagated to the years when genetic data were unavailable. This was a

Table 4. Estimates of coefficients of variation of Chinook salmon bycatch estimates for the A and B seasons and age based on the mean of 100 bootstrap samples of available length and age data.

	Age 3		Age 4		Age 5		Age 6		Age 7	
Year	A	B	A	B	A	B	A	B	A	B
1991	14	23	6	8	6	12	10	27	31	67
1992	20	9	9	9	4	25	9	69	27	87
1993	22	19	9	4	5	9	10	20	37	65
1994	27	17	12	6	3	6	10	14	30	27
1995	25	21	12	5	5	12	6	23	22	48
1996	19	6	6	3	2	7	9	11	21	29
1997	35	12	12	3	6	10	7	12	28	39
1998	16	5	9	6	3	9	10	23	23	36
1999	19	16	10	3	5	8	11	22	91	149
2000	25	9	9	5	6	8	9	25	27	49
2001	10	7	6	3	3	8	7	20	22	52
2002	15	6	6	2	3	8	4	17	16	43
2003	14	8	6	3	3	5	8	15	21	32
2004	15	6	6	2	2	5	5	12	20	30
2005	18	5	6	2	3	5	7	10	23	23
2006	17	4	5	3	3	8	7	15	22	33
2007	22	6	5	2	4	7	8	13	25	28
2008	**75**	**58**	**33**	**14**	**13**	**39**	**39**	**102**	**105**	**145**
2009	**40**	**61**	**12**	**10**	**5**	**36**	**16**	**82**	**45**	**163**
2010	**106**	**77**	**46**	**18**	**13**	**54**	**28**	**96**	**49**	**190**
2011	**29**	**7**	**10**	**4**	**6**	**13**	**12**	**42**	**42**	**234**
2012	**41**	**12**	**10**	**9**	**5**	**32**	**15**	**145**	**42**	**250**

Note bolded values are based on the new length frequency sampling protocol.

Table 5. Stock composition based on genetic samples stratified by year, season, and region (SE, east of 170°W; NW, west of 170°W).

Year	Season	Area	Sample size	PNW (%)	Coast W AK (%)	Cook Inlet (%)	Middle Yukon (%)	N AK Penin (%)	Russia (%)	TBR (%)	Upper Yukon (%)	Other (%)
2005	B	SE	282	45.3	34.2	5.3	0.2	8.8	0.6	3.3	0.0	2.4
2005	B	NW	489	6.5	70.9	2.2	4.7	6.7	2.0	3.5	2.8	0.7
2006	A	All	801	22.9	38.2	0.2	1.1	31.2	1.1	1.1	2.3	1.9
2006	B	SE	304	38.4	37.2	7.5	0.2	7.0	0.6	4.3	0.1	4.7
2006	B	NW	286	6.4	67.3	3.0	8.0	2.1	3.3	0.5	8.0	1.4
2007	A	All	360	9.4	75.2	0.1	0.5	12.0	0.2	0.1	0.1	2.4
2007	B	SE	464	6.1	77.9	3.6	3.3	3.5	0.3	0.9	1.2	3.1
2007	B	NW	402	1.4	71.7	2.6	5.9	5.3	0.4	3.3	0.0	9.3
2008	A	All	788	0.9	59.5	0.0	0.4	33.4	0.0	0.8	0.4	4.4
2008	B	SE	280	11.1	71.0	3.6	2.0	5.7	1.6	1.8	1.8	1.5
2008	B	NW	245	2.0	71.1	2.8	5.3	3.9	0.2	2.2	0.6	11.8
2009	A	All	202	0.5	47.3	2.9	4.9	22.2	0.3	1.1	0.0	21.0
2009	B	SE	78	28.9	54.6	3.1	3.0	3.9	0.0	0.1	2.1	4.4
2009	B	NW	88	0.1	70.8	0.9	11.2	5.2	0.3	1.6	0.9	8.9
2010	A	All	702	3.4	41.4	0.6	12.1	16.2	0.0	2.2	0.3	23.9
2010	B	SE	107	46.2	34.8	4.8	1.0	4.0	2.7	1.0	5.6	0.0
2010	B	NW	17	11.6	45.6	4.8	16.2	0.0	0.0	11.9	0.7	9.2
2011	A	All	695	11.2	54.0	0.6	1.8	21.8	0.0	0.2	3.1	7.4
2011	B	SE	1627	15.1	72.7	4.1	0.9	3.3	1.1	0.7	1.5	0.5
2011	B	NW	151	2.9	75.5	2.8	3.6	2.4	1.7	4.9	1.6	4.6

PNW, Pacific northwest; CWAK, Coast West Alaska; NAK Penin, North Alaska Peninsula; TBR, Taku River.
Source: Templin *et al.* (2011) and Guthrie *et al.* (2013) (as modified by the author to match these categories).

compromise which acknowledges sampling uncertainty for those years and correctly weights the information (due to sample size) between years when GSI information was available. For example, the new observer data collection system for genetic samples has resulted in more precise estimates of GSI in recent years; hence, those years have greater influence on stratum-specific GSI results.

Combining the RSG results derived from the GSI with the Chinook salmon AEQ results requires considering the lag impact of the bycatch. For example, consider that GSI for 100 Chinook salmon occurred in a given year and separately AEQ estimates were made for that same year. Simply multiplying the AEQ value by the proportions estimated from the GSI samples would be incorrect since the 100 Chinook salmon sampled typically represent a number of different brood years. Consequently, adjusting the AEQ for RSG requires estimation over a range of years when GSI results are available. This was accomplished here by applying the

Table 6. NMFS Regional Office estimates of Chinook salmon bycatch in the pollock fishery compared with genetics sampling levels by season and region, 2005–2012 (SE, east of 170°W; NW, west of 170°W) in absolute terms (top eight data rows) and percentages (bottom eight data rows).

	Genetic samples			Chinook salmon bycatch		
Year	A season	B SE	B NW	A season	B SE	B NW
2005	NA	282	489	27209	26425	13793
2006	801	304	286	58035	21922	2484
2007	360	464	402	70054	42353	10089
2008	788	280	245	16510	4017	793
2009	202	78	88	9866	2100	469
2010	702	107	17	7623	1923	143
2011	695	1627	151	7131	16832	1531
2012	NA	NA	NA	7761	3570	136
	Genetic samples			**PSC**		
	A season (%)	**B SE (%)**	**B NW (%)**	**A season (%)**	**B SE (%)**	**B NW (%)**
2005		37	63	40	39	20
2006	58	22	21	70	27	3
2007	29	38	33	57	35	8
2008	60	21	19	77	19	4
2009	55	21	24	79	17	4
2010	85	13	2	79	20	1
2011	28	66	6	28	66	6
2012				68	31	1

PSC, Chinook salmon bycatch.

Table 7. Average age composition estimated by the system for 2003–2012 as provided by ADFG[a].

	Age					
System	3	4	5	6	7	Weighting factor
Norton sound	1%	10%	37%	49%	3%	0.019
Yukon	0%	12%	40%	44%	3%	0.221
Kuskokwim River	0%	25%	39%	34%	2%	0.369
Kuskokwim Bay	1%	35%	35%	28%	1%	0.094
Nushagak	1%	27%	43%	29%	1%	0.297
Weighted mean in river maturity	0%	23%	40%	34%	2%	
Oceanic rates						
Natural mortality	0.300	0.200	0.100	0.100	0.000	
Implied oceanic maturity rate[b]	0.002	0.192	0.500	0.942	1.000	

The "combined" row represents the weighted average over the systems (weights shown in the last column).
[a]http://www.adfg.alaska.gov/CommFishR3/Website/AYKDBMSWebsite/DataSelection.aspx.
[b]Conditioned on the values for mean in-river maturity and oceanic natural mortality rate.

appropriate GSI results (i.e. estimates of proportions within RSGs) for the years as lagged by AEQ. This step is needed to apportion the AEQ results to stock of origin based on genetic samples that consist of mature and immature fish. By splitting the AEQ estimates to relative contributions of bycatch from previous years, and applying GSI data from those years, they can then be realigned and renormalized to get proportions from systems by year. For years in which GSI information was unavailable, mean GSI data (with an error term which accounted for year-effect variability) were used.

Spatial and temporal patterns in the RSG-specific bycatch

Given the posterior distributions of the parameters on ocean survival and GSI proportions (corrected for time-lags), the results could be summarized for presentation purposes. Since Chinook salmon bycatch occurs in both the "A" and "B" seasons of the pollock fishery, data from these seasons were run separately. For each separate run, Monte-Carlo Markov Chain samples from the posterior distribution were obtained based on chain lengths of 1 million (after burn-in) and selecting every 200th parameter draw. Output resulted in 5000 samples from each season (summed over strata) then summed to get annual AEQ totals by the RSG. The model was implemented using the ADMB (Fournier *et al.*, 2012) software.

Annual reduction in returns to RSGs

Separate estimates of run strengths (1994–2012) were used assuming uncertainties in run size:

$$\dot{S}_{t,k} = S_{t,k}e^{\varepsilon_t} \quad \varepsilon_t \sim N(0, \sigma_S^2), \tag{4}$$

where σ_S^2 was a prespecified level of run-size variance (assumed to correspond to a coefficient of variation of 10% for this study). The measure that relates the historical bycatch levels to the subsequent returning salmon run k in year t, the "impact", is thus:

$$u_{t,k} = \frac{AEQ_{t,k}}{AEQ_{t,k} + \dot{S}_{t,k}}, \tag{5}$$

Table 8. Estimated run size in numbers of Chinook salmon by the system for 1976–2012 as provided by ADFG.

Year	Nushagak[a]	Kusko Bay[b]	Kuskokwim River	Norton Sound	Lower and mid-Yukon	CWAK	Upper Yukon
1976	348 677		233 967				
1977	324 983		295 559				
1978	531 783		264 325				
1979	544 859		253 970				
1980	454 644		300 573				
1981	741 073		389 791				
1982	741 092		187 354				148 000
1983	650 754		166 333				158 200
1984	321 238		188 238				123 000
1985	401 845		176 292		224 324		145 700
1986	164 656		129 168		186 298		155 900
1987	231 453		193 465		177 287		156 700
1988	141 908		207 818		146 991		141 000
1989	187 644		241 857		102 297		146 100
1990	156 663		264 802		196 126		161 600
1991	246 718		218 705		156 538		140 600
1992	232 103		284 846		183 889		157 800
1993	283 385		269 305		267 718		141 100
1994	334 604		365 246		253 226	953 077	185 600
1995	271 126		360 513		224 219	855 858	194 800
1996	193 029		302 603	23 080	86 934	605 646	198 500
1997	247 097		303 189	59 196	324 333	933 816	186 900
1998	370 883		213 873	35 916	139 171	759 843	93 090
1999	148 963		189 939	18 972	193 172	551 046	114 600
2000	137 979		136 618	13 087	112 255	399 939	52 660
2001	213 128		223 707	13 586	166 822	617 243	97 910
2002	228 919	29 954	246 296	15 685	159 138	679 992	95 250
2003	224 724	36 908	248 789	16 244	170 637	697 303	160 800
2004	351 930	76 429	388 136	14 581	249 800	1 080 875	135 700
2005	307 245	60 875	366 601	12 528	158 044	905 294	123 900
2006	218 031	45 646	307 662	13 628	178 348	763 315	119 200
2007	125 077	55 511	273 060	15 311	144 449	613 408	87 420
2008	128 445	33 104	237 074	11 505	109 548	519 675	63 640
2009	117 530	32 095	204 747	19 707	111 612	485 692	86 540
2010	93 676	32 312	118 507	8360	96 232	349 086	59 789
2011	144 795	31 463	133 059	6718	126 428	442 464	71 751
2012	196 545	12 043	99 143	6645	73 555	387 930	50 094

The CWAK column represents the sum of five columns to its left. Analyses on impacts were done as aggregated for CWAK and for the Upper Yukon for 1994–2012. Source: K. Howard, pers. comm. and Menard *et al.* (2013). CWAK, Coastal West Alaska.
[a]http://www.adfg.alaska.gov/FedAidPDFs/FMS12-05.pdf.
[b]http://www.adfg.alaska.gov/FedAidPDFs/FMR13-23.pdf.

where $AEQ_{t,k}$ and $\dot{S}_{t,k}$ are the adult-equivalent bycatch and stock size (run return) estimates, respectively. The calculation of $AEQ_{t,k}$ includes the bycatch of salmon returning to spawn in year t and the bycatch from previous years for the same brood year (i.e. at younger, immature ages). Note that the allocation of the AEQ to RSGs is necessarily independent of the age composition of the bycatch. Ideally, estimates of age-specific RSG identification would improve the estimation, but much larger samples would be needed, and apportioning the ages for each genetic sample would be required.

To better inform fishery managers of the impacts [Equation (5)] of their current cap levels, a "what-if" analysis was designed. In this, the actual Chinook salmon bycatch in 2011 and 2012 was artificially increased (proportional to the observed bycatch timing and locales) to a cap level of 47 591 and separately for a cap level of 60 000 Chinook salmon. For simplicity, season and sector-specific limits were ignored, and the full annual bycatch limit was attained by proportionally inflating the observed bycatch totals in each sector and season.

Results

Results from the model show that the peak annual AEQ occurred in 2007 at just over 76 000 Chinook salmon (Table 9), and the impact from bycatch has dropped markedly since 2010 (for the period 1994–2012; Table 9 and Figure 2). The distribution of the uncertainty indicated from the posterior distribution was relatively small (Figure 2). However, when the AEQ totals are decomposed into their constituent parts, the uncertainty increases substantially, particularly in years when the GSI data were unavailable (Figure 3). The largest bycatch is from the coastal western Alaska RSG. Here, the coastal western Alaska RSG includes all major river systems in western Alaska from the Kotzebue region in the north to the Bristol Bay region in the south. This grouping includes Chinook stocks in both the lower and middle Yukon River, but excludes the upper Yukon River (Canadian component) as genetic differentiation is well estimated. Interesting patterns are seen by season for the different RSGs, particularly as compared with when and where the most the bycatch is taken (Table 9). For example, on average

Table 9. Chinook salmon AEQ estimates (annual mean of the posterior distribution) by RSG for the years 1994–2012 (top panel) and the proportion of AEQ for each stock group that occurred during the "A" season (bottom panel).

Year	BC-WA-OR	Coast W AK	Cook Inlet	Middle Yukon	N AK Penin	Other	Russia	SEAK	Upper Yukon	Total	*C.V.* (%)
1994	4157	19 192	570	916	5667	181	376	472	2068	33 644	2.8
1995	3166	14 154	418	649	4310	127	268	343	1543	25 017	4.6
1996	3365	16 111	411	744	5300	130	294	378	1868	28 629	1.4
1997	4942	19 398	718	849	5144	203	384	486	1862	34 029	3.4
1998	5578	18 291	880	725	3809	226	379	479	1407	31 818	3.3
1999	5219	15 841	847	600	2872	212	335	424	1079	27 485	5.0
2000	3416	9654	552	334	1666	132	201	257	610	16 839	6.2
2001	2324	10 582	372	544	2588	122	231	281	1021	18 066	4.3
2002	2878	14 351	386	711	4387	130	281	353	1612	25 115	2.3
2003	3822	18 405	526	901	5470	172	364	454	2012	32 160	2.5
2004	4926	22 340	702	1072	6324	220	447	558	2340	38 979	3.1
2005	6802	25 202	947	1278	6578	297	582	681	2479	44 891	2.8
2006	12 135	28 685	1121	1471	11 681	371	748	953	2535	59 788	2.7
2007	12 528	42 180	1352	1717	11 646	433	874	1086	3024	74 931	2.8
2008	8071	38 950	1216	1360	8946	362	704	853	2565	63 172	4.3
2009	3706	24 984	775	909	5263	230	446	508	2050	38 917	6.0
2010	1705	8228	262	711	2610	81	187	203	1862	15 884	4.8
2011	1358	6312	208	414	1608	64	122	168	1033	11 296	3.0
2012	1589	7697	275	300	1691	81	131	191	675	12 645	3.8
	BC-WA-OR (%)	**Coast W AK (%)**	**Cook Inlet (%)**	**Middle Yukon (%)**	**N AK Penin (%)**	**Other (%)**	**Russia (%)**	**SEAK (%)**	**Upper Yukon (%)**	**Total (%)**	
1994	44	66	15	76	89	24	39	63	83	67	
1995	44	68	16	84	89	24	43	65	85	68	
1996	50	74	20	91	92	29	52	71	89	75	
1997	32	55	10	74	83	16	30	52	76	56	
1998	19	39	5	61	72	9	18	36	63	40	
1999	14	30	4	53	64	6	13	28	54	31	
2000	12	28	3	56	61	5	12	25	52	28	
2001	32	50	9	52	82	16	24	48	70	52	
2002	47	68	16	75	90	26	41	66	84	69	
2003	45	66	15	74	89	25	39	64	83	67	
2004	40	61	13	71	87	21	34	58	80	62	
2005	25	54	10	63	80	19	24	54	77	53	
2006	47	60	13	71	87	33	32	69	76	62	
2007	50	63	15	63	86	50	38	71	71	64	
2008	51	58	14	53	87	55	41	65	64	61	
2009	55	51	15	46	87	58	48	58	68	57	
2010	32	63	25	79	91	35	66	50	91	68	
2011	36	53	16	82	90	27	59	51	94	60	
2012	34	46	11	76	87	19	45	46	91	52	
Average	37	55	13	68	84	26	37	55	76	57	

Last column of the upper panel represents the coefficient of variation (*C.V.*) of the estimated total AEQ. CWAK, Coast West Alaska; BC-WA-OR, British Columbia, Washington and Oregon; N AK Penin, North Alaska Peninsula; SEAK, Southeast Alaska.

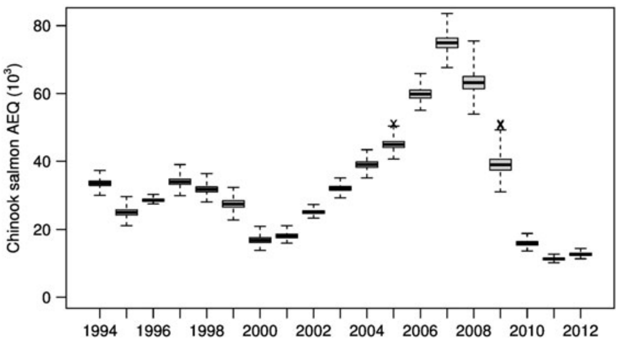

Figure 2. Boxplot showing the posterior distribution of annual total adult-equivalent mortality of Chinook salmon from the EBS pollock fishery, 1994–2012. Units are numbers of salmon and height of boxes represent the uncertainty (inter-quartile ranges) due to oceanic survival and other factors that vary within the model. Horizontal lines within the boxes represent the medians of the posterior distribution.

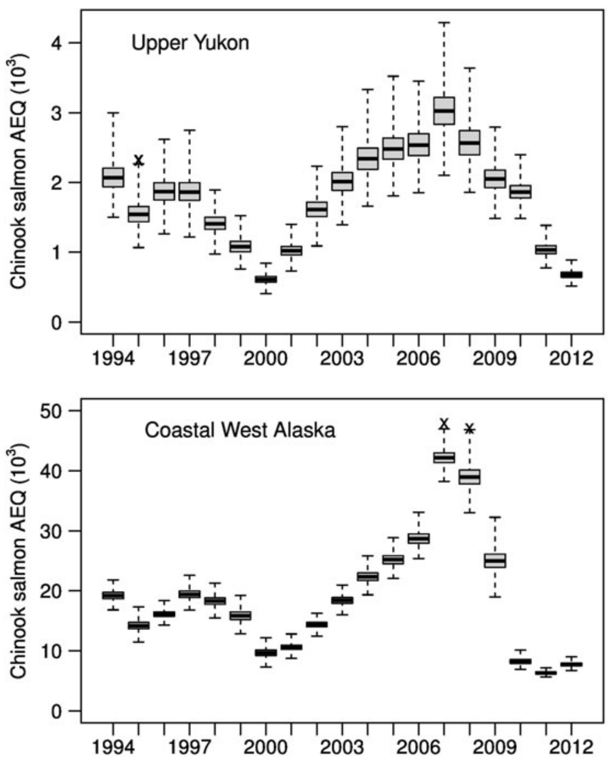

Figure 3. Estimated AEQ mortality of Chinook salmon from the EBS pollock fishery attributed to the Upper Yukon (top) and Coastal Western Alaska (bottom) stocks, 1994–2012. Units are numbers of salmon and height of boxes represent the uncertainty (inter-quartile ranges) due to oceanic survival and other factors that vary within the model. Horizontal lines within the boxes present the medians of the posterior distribution.

76% of the upper Yukon Chinook salmon bycatch is taken during winter fishery, whereas the "A" season bycatch represents only ca. 55% of the overall Chinook salmon AEQ mortality. Conversely, the vast majority of Cook Inlet Chinook salmon bycatch (87%) is taken during summer pollock fisheries, although the total AEQ is fairly small (Table 9).

Introducing run-size information to allow estimation of the impact rates ($u_{t,k}$) shows very little relationship between AEQ

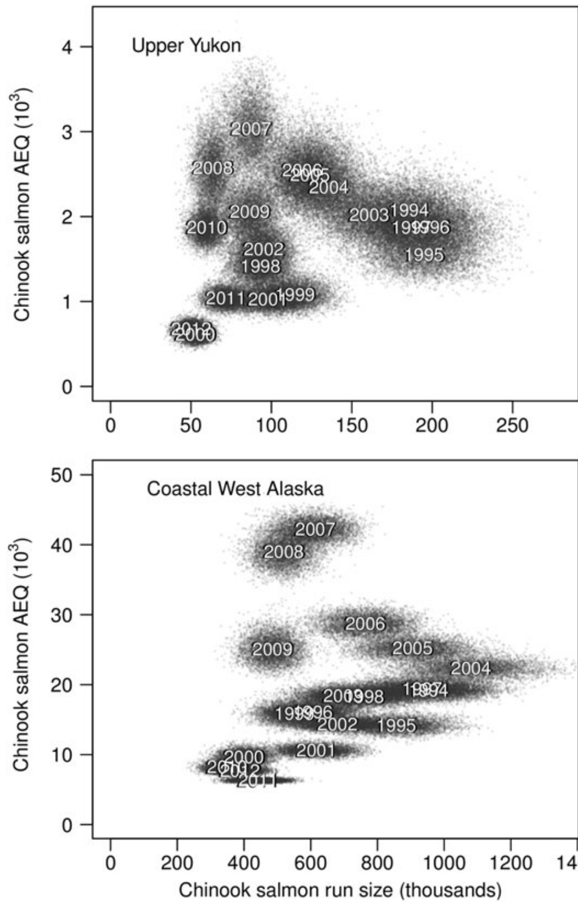

Figure 4. Example comparing the AEQ mortality of Chinook salmon from the EBS pollock fishery attributed to the Upper Yukon (top) and for the Coastal West Alaska (bottom) regions, 1994–2012. Total Chinook salmon run-size estimates (with scatter of points approximating uncertainty) are on the horizontal axis.

mortality due to the pollock fishery and the size of the runs, especially given the uncertainty in the RSG-estimated impacts, and of the run strength (e.g. Figure 4). Here, the focus was on comparing two critical RSG impacts: to coastal western Alaska and to the upper Yukon. The peak estimated impact for both of these regions occurred in 2008 and was estimated at 7.9 and 4.7% of their potential total returns, respectively (Table 10 and Figure 5). As with the AEQ estimates for these RSGs, the uncertainty appears to have decreased considerably under the new genetics sampling protocol.

Hypothetically increasing the 2011 bycatch to its bycatch limit (or cap) of 47 591 resulted in an increase from the 2011 estimate of 1.6% to ∼2.7% on the coastal west Alaska RSG (Table 11). An increasing bycatch to cap levels of 47 591 in 2011 and 60 000 in 2012 showed a greater potential impact in 2012, but still well below the maximum observed (Figures 6 and 7). Note that the greater hypothetical impact in 2012, compared with 2011, is due to AEQ being affected by increased catches in two years (2011 and 2012). While full bycatch limits being reached for all sectors in each season is unrealistic (i.e. some sectors would have reached their limit, while others could remain below), this analysis suggests that had the management caps been reached, the measures of impact rate on some key Alaska stocks at the lower cap levels would likely have been below the historical high level estimated for 2008.

Table 10. Results of the Chinook salmon AEQ analysis combined with the available genetic data for the years 1994–2012 impact as the ratio of AEQ to estimated ADFG run size.

Year	CWAK (%)	Upper Yukon (%)
1994	2.01	1.11
1995	1.65	0.79
1996	2.66	0.94
1997	2.08	1.00
1998	2.41	1.51
1999	2.87	0.94
2000	2.41	1.16
2001	1.71	1.04
2002	2.11	1.69
2003	2.64	1.25
2004	2.07	1.72
2005	2.78	2.00
2006	3.76	2.13
2007	6.88	3.46
2008	7.49	4.03
2009	5.14	2.37
2010	2.36	3.11
2011	1.43	1.44
2012	1.98	1.35

Note that Middle Yukon is added to the Coastal West Alaska group. CWAK, Coastal West Alaska.

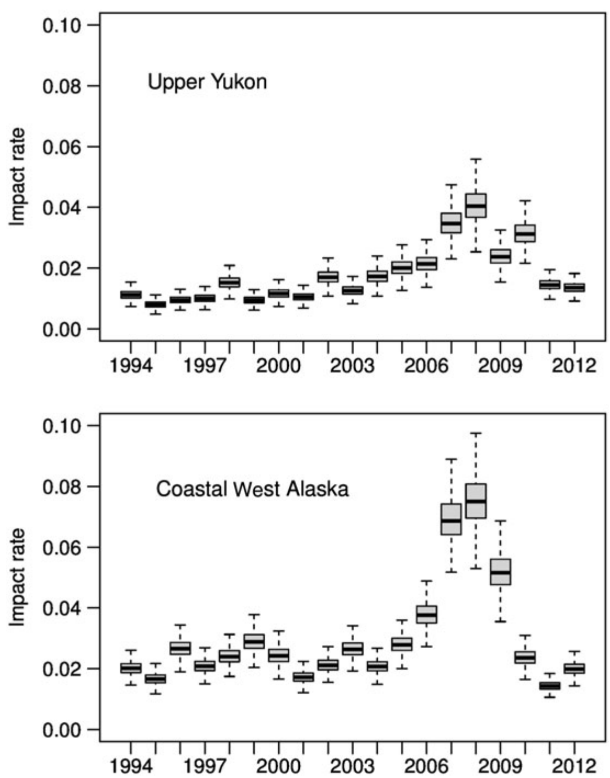

Figure 5. Estimated impact of the EBS pollock fishery on the Upper Yukon stock (top) and Coastal West Alaska (which includes the "Middle Yukon"; bottom), 1994–2012. Vertical axis is the ratio of AEQ over the point estimates of total run sizes.

Discussion

Comparing our estimates of the impact (per cent reduction in salmon returning to their river of origin) shows some differences

Table 11. Results of the Chinook salmon AEQ analysis combined with the available genetic data for 2011 and 2012 with impact estimated as the expected value of the ratio of AEQ to estimated ADFG run size.

Year	Estimated (%)	If 47 591 cap (%)	If 60 000 cap (%)
Coastal West Alaska			
2011	1.5	2.2	2.6
2012	2.0	5.0	6.2
Upper Yukon			
2011	1.5	1.8	2.0
2012	1.4	3.7	4.6

The third and fourth columns are hypothetical impact rates had all sectors of the pollock fleet met their respective upper limits of their bycatch allowance. Note that Middle Yukon is added to the Coastal West Alaska group.

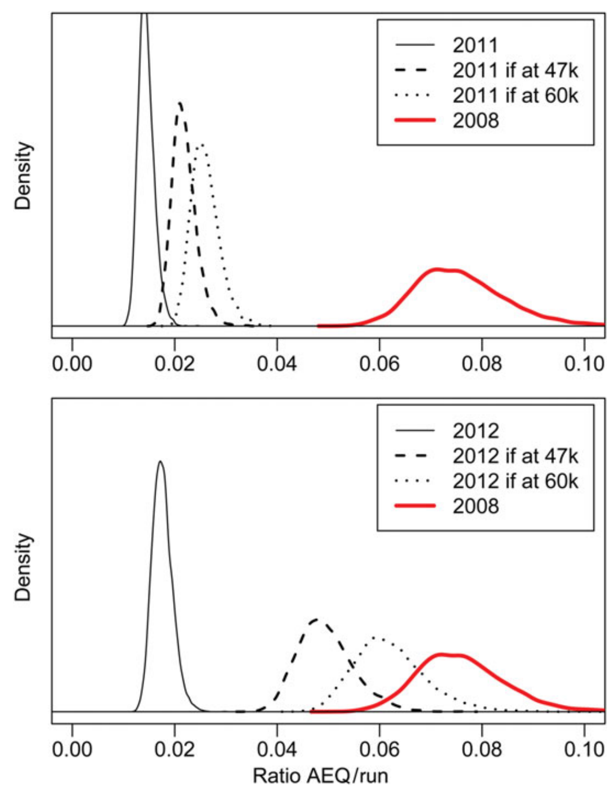

Figure 6. Estimated impact (thin solid line) of the EBS pollock fishery on the Coastal West Alaska (which includes the "Middle Yukon") for 2011 (top) and 2012 (bottom). The height of the shapes is intended to represent the relative probability (density) of impact rates shown on the horizontal scale. Also plotted are densities of impacts estimated for 2008 (the highest year of historical impact) and for 2011 and 2012, if all the current sector-specific bycatch limits had been attained.

relative to earlier methods. Combining minimal run-size estimates for western Alaska with estimates of AEQ, Witherell *et al.* (2002) obtained an average estimated impact due to the trawl fisheries of ~2.7% for the period 1990–2000. This compares with our estimate for 1994–2000 of 2.4%. Previous estimates relied on stock proportions determined from scale-pattern analysis (to assign bycatch to regions) from earlier foreign and joint-venture fisheries (i.e. from 1979 to 1982; Witherell *et al.*, 2002). In addition, contemporary run-size estimates used here are about one-third higher than those applied in the Witherell *et al.* (2002) study, and our AEQ

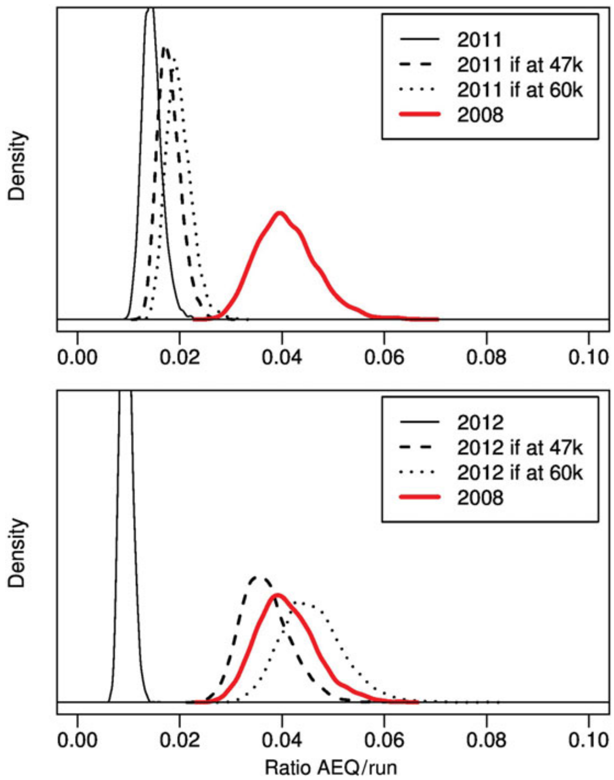

Figure 7. Estimated impact (thin solid line) of the EBS pollock fishery on the Upper Yukon for 2011 (top) and 2012 (bottom). The height of the shapes is intended to represent the relative probability (density) of impact rates shown in the horizontal scale. Also plotted are densities of impacts estimated for 2008 (the highest year of historical impact) and for 2011 and 2012 if all the current sector-specific bycatch limits had been attained.

estimates based on updated GSI information instead of relatively old scale-pattern data allowed a finer breakdown of RSGs and catch strata. The previous study failed to examine impact rates due to concerns over the high uncertainty in run-size strengths for Chinook in western Alaska river systems (NPFMC/NMFS, 2009); recently derived estimates provided by the Alaska Department of Fish and Game (ADFG; K. Howard, pers. comm.) allowed us to make these calculations. This study is also the first to break out the upper Yukon (Canadian-origin portion) from the western Alaskan stocks for estimating both AEQ and impact rates.

Our results show how improved GSI sampling and data have clearly improved estimation of the stock composition of the bycatch. Errors in GSI data (e.g. as considered in Kalinowski, 2004) combined with allowing for stock composition variability between years (for periods when genetics data are missing or less abundant) provide a novel way to estimate impacts and their uncertainty. That is, given observed interannual variability in stock composition from the same spatio-temporal strata, the average stock composition pattern provides reasonably consistent estimates using earlier scale-pattern analysis and more modern GSI methods. Indeed, better estimates of in-river Chinook salmon run strengths would likely improve precision of impact estimates more than more precise GSI. This is largely because total bycatch estimates are considered precise (and, in fact, fully accounted through a census process since 2011; before that, the estimation uncertainty for total bycatch was <3%; Miller, 2005).

In most fisheries sampling situations, data are rarely collected in a manner that can be considered as purely random with respect to the population of interest (in this case, the stock of origin of the bycatch). Composition data, in general, whether stomach contents, lengths, or ages, are commonly afflicted with a situation where the actual number of fish sampled is much higher than the "effective" sample size (e.g. Pennington and Volstad, 1994). For length or age composition data, it is routine to apply an adjustment to the actual sample size in fitting stock assessment models because of the relatively low within-haul variability. While the practice of using these adjustment factors varies in technique, they are widely acknowledged as being an important consideration in stock assessment modelling [see Fournier and Archibald (1982) for early consideration of using the multinomial likelihood for fitting composition data]. The modelling framework presented here allows for alternative weights and evaluations of uncertainties. For example, evaluating the effect of emphasizing only the recent genetics data (due to possible concerns about historical sampling approaches which often had large numbers of samples from single trawl tows) can be conducted as a model sensitivity. Additionally, alternative likelihood functions have been tailored to accept different forms of results from the GSI software (i.e. use of covariance matrix on stock proportions directly within the AEQ model likelihood).

The recent downturn in total bycatch (and concomitant AEQ mortality) of Chinook salmon in the pollock fishery is likely a combination of increased awareness, the development of industry-based, hot-spot closure programmes (e.g. Haflinger and Gruver, 2009), and reduced overall Chinook salmon abundance, but might also be partly due to environmental conditions affecting the overlap in preferred habitat for pollock and salmon. Lower overall pollock quotas (800 000 t in 2009 and 2010) also likely played a role, but recent pollock quotas and catches in 2011 and 2012 have been more than 1.2 million t. Temperature regimes and environmental factors could also have contributed to changes since there is evidence that even after accounting for season and locale, temperature appears to affect bycatch rates (Ianelli *et al.*, 2010).

Chinook salmon migrate through coastal areas as juveniles and returning adults; however, immature Chinook salmon undergo extensive migrations and can be found inshore and offshore throughout the North Pacific and Bering Sea (Farley *et al.*, 2005). In summer, Chinook salmon concentrate around the Aleutian Islands and in the western Gulf of Alaska. Changes in these patterns may also affect vulnerability to the pollock fishery.

The relative impacts rates in recent years are low for aggregate western Alaskan river systems and the upper Yukon and are <8% even in the years of highest bycatch. While there is continued concern regarding all sources of mortality due to low stock sizes of western Alaskan Chinook stocks, there are likely multiple causes of the declines in these stocks that may be unrelated to bycatch by the EBS pollock fishery. Some of these causes include survival in the oceanic life stage, due to competition for prey and the overall carrying capacity in the Pacific Ocean, as well as in-river survival (Schindler *et al.*, 2013; Stachura *et al.*, 2014).

There are international treaty implications of the bycatch of Yukon River bound salmon. Under the Yukon River Agreement, an annexe of the Pacific Salmon Treaty between the United States and Canada, the United States agreed to "maintain efforts to increase the in-river run of Yukon River origin salmon by reducing marine catches and bycatches of Yukon River salmon. They shall further identify, quantify, and undertake efforts to reduce these catches and bycatches" (YRSA, 2002). Our study indicates that, given available genetic breakouts delineating Canadian-origin Yukon Chinook salmon from the bycatch, an evaluation on the intent of the agreement for quantifying impacts is now possible. Our study provides critical information on the relative impact of the bycatch on these runs which is critical to fishery managers, so that appropriate management measures can be designed.

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