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ARTICLE

The Synchronous Failure of Juvenile Pacific Salmon and Herring Production in the Strait of Georgia in 2007 and the Poor Return of Sockeye Salmon to the Fraser River in 2009

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Abstract
Trawl studies from 1998 to 2009 indicated that juvenile Pacific salmon *Oncorhynchus* spp. and Pacific herring *Clupea pallasii* represented 98% of the fish in the surface waters of the Strait of Georgia during the day in the spring and early summer. Standardized catches of all juvenile Pacific salmon in the trawl surveys were lowest in 2007. Catches of young-of-the-year Pacific herring were also extremely low in 2007. Three years later, the 2007 year-class had the lowest recruitment to the fishery in recorded history. In 2007, juvenile coho salmon *O. kisutch* and Chinook salmon *O. tshawytscha* were small and had the lowest condition of the fish in all surveys as well as a high percentage of empty stomachs. The early marine survival of coho salmon in 2007 and the total survival in 2008 were exceptionally poor. Trawl catches of juvenile chum salmon *O. keta* in 2007 were the lowest of all surveys. Adult chum salmon from these juveniles that returned in 2010 had extremely poor survival. Juvenile sockeye salmon *O. nerka* that entered the Strait of Georgia in the spring of 2007 and returned to the Fraser River as adults in 2009 also had such exceptionally poor marine survival that a judicial inquiry was conducted to determine the causes. The synchronous poor growth, survival, or both of all of the major species in the surface waters of the Strait of Georgia in the spring of 2007 indicated that there was a common cause which we propose as poor food production. The causes of the high mortality likely represented a unique extreme in the variability of the factors that normally affect the survival of juvenile Pacific salmon and Pacific herring in the early marine period in the Strait of Georgia.

The Strait of Georgia is the most important rearing area for juvenile Pacific salmon *Oncorhynchus* spp. on Canada's West Coast. Historically, approximately one-third of all five species of Pacific salmon caught in British Columbia entered the Strait of Georgia as juveniles. The major source of Pacific salmon juveniles is the Fraser River, but there are approximately 48 smaller rivers flowing into the Strait of Georgia that collectively contribute millions of juvenile Pacific salmon to the Strait of Georgia. There also are large abundances of Pacific herring *Clupea pallasii* that spawn in the intertidal areas around the Strait of Georgia (Hourston and Haegele 1980). Mature Pacific herring migrate into the Strait of Georgia late in the year and spawn about March of the following year (Hourston and Haegele 1980). Recent spawning abundances in the last 10 years averaged about 40,000 tons (Schweigert et al. 2009), or about 425 million adults. The larval Pacific herring begin to feed about mid-April and remain in the Strait of Georgia for about 1 year before they migrate offshore (Hay et al. 2009).

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In 1998 we began a systematic study of the early marine survival of juvenile Pacific salmon in the Strait of Georgia (Beamish et al. 2000; Sweeting et al. 2003). Our study also provided information on the early survival of young-of-the-year Pacific herring. Because Pacific salmon and herring produce large numbers of eggs, it is to be expected that the mortality of the very young fish in the ocean will be high (Colinvaux 1978). However, in 2007 the amount of early marine mortality was extreme. The juvenile sockeye salmon *O. nerka* that entered the Strait of Georgia from the Fraser River in 2007 would return as adults in 2009. There was an unexpected and historically low return in 2009 that became an issue for the Canadian government and resulted in a Can$27 million commission of inquiry (see www.cohencommission.ca) to determine the reasons for the poor sockeye salmon production. In this paper we provide evidence of a synchronous failure in the production of juvenile Pacific salmon and herring in the Strait of Georgia in 2007. It is likely that the conditions causing the poor production in the Strait of Georgia were a major cause of the poor returns of the adult sockeye salmon to the Fraser River in 2009.

The life histories of the five species of Pacific salmon in our study area are summarized in a number of publications, including Hart (1973) and Groot and Margolis (1991). Most of the juveniles of these species enter the Strait of Georgia between mid-April and mid-May, or about 6–7 weeks prior to our July survey. Virtually all sockeye salmon and pink salmon *O. gorbuscha* originate from the Fraser River. Pink salmon spawn in the Fraser River in years ending in an odd number. The fry emerge from the gravel in the late winter of the following year and enter the Strait of Georgia about April in years ending in an even number. Thus, there would not be spawning pink salmon in 2006 and virtually no juvenile pink salmon from the Fraser River in the Strait of Georgia in 2007. For this reason our analysis excluded this particular species.

METHODS

From 1998 to 2009, we used a modified midwater trawl to sample juvenile Pacific salmon in the Strait of Georgia. The design of the trawl and the method of fishing are described in Beamish et al. (2000) and Sweeting et al. (2003). The trawl was fished at a speed that was sufficient to capture all sizes of Pacific salmon in most areas of the coast and in most types of weather. The net opening was approximately 15 m, and we recorded fishing depths in 15-m intervals from the surface to 15 m, 15 m to 30 m, 30 m to 45 m, 45 m to 60 m, and deeper than 60 m. Beginning in 1998, we standardized the sampling track lines (Figure 1) and methods for the July and September surveys. In this paper, we focus on the results of the July survey for Pacific salmon and the September survey for Pacific herring. The exact dates of the surveys varied slightly (Table 1), according to the allocation of vessel time, but the "July" surveys were during the daytime between late June and mid-July. In general, a survey lasted 9–10 d with an average of about 88, 30-min sets. Fishing days may not be continuous because of crew issues or mechanical breakdowns. Sets were fished at different depths, with most sets fishing the top 30 m. We used the catches of Pacific herring in the September surveys, as the size and behavior of Pacific herring made them more catchable by the trawl in September than in July. Juvenile Pacific herring in their first ocean year move from the nearshore area where they hatch in the spring to more open waters in the summer and fall. Catches in the trawls for Pacific herring were recorded for depths from the surface to 45 m. Length was used to separate the young-of-the-year from older Pacific herring. The number in each catch was either counted or estimated by counting a volume of the catch and expanding the count to the total volume. The abundance of young-of-the-year Pacific herring (age 0) was estimated for September 1998 to 2009 using the method described in Beamish et al. (2000) and Sweeting et al. (2003). The swept-volume estimate included all sets in the standard survey that were fished between 0 and 45 m. We compared the relative interannual changes in abundance with the published results from a purse seine survey to estimate the relative abundance of juvenile Pacific herring in the Strait of Georgia (Schweigert et al. 2009). The purse seine survey occurred over 2 weeks with sets along 10 transects distributed throughout the Strait of Georgia.

Previous surveys established that juvenile pink, sockeye, and chum salmon *O. keta* were virtually all captured in the surface 30 m in the spring. Therefore, the habitat depth for these species was the top 30 m. The habitat depth for coho salmon *O. kisutch* was the top 45 m and that for Chinook salmon *O. tshawytscha* the top 60 m. Catches are for the number of fish in a 30-min set unless they are standardized to 1 h (identified as catch per unit effort [CPUE]). Average survey CPUE is the number of fish captured at the specified depths divided by the total number of hours fished. The number of sets at each depth was proportional to the expected catches for coho salmon. There was no survey in July 2003.

All fish were identified to species and counted, and most were measured for fork length. Weights were taken when possible, but not all fish could be weighed accurately because of sea conditions and the available sampling time. Condition was estimated as weight (g) divided by the cube of length (mm), all times 100,000. The 95% confidence intervals are included for average length and condition.

Stomach contents were identified at sea from the fresh specimens. The portion of the gut that was examined included the stomach and the anterior part of the gut leading to the stomach. The term "stomach contents" is used to facilitate our reporting, but it is not just the stomach that was examined. Beginning in 1999, an empty stomach was defined as one having less than 0.1 g of material.

We estimated the number of sockeye salmon entering the Strait of Georgia from the Fraser River by two methods and then took the average value. The first method used the marine survival of Chilko Lake sockeye salmon (updated from data in Grant et al. 2010, 2011) and applied this to all sockeye salmon

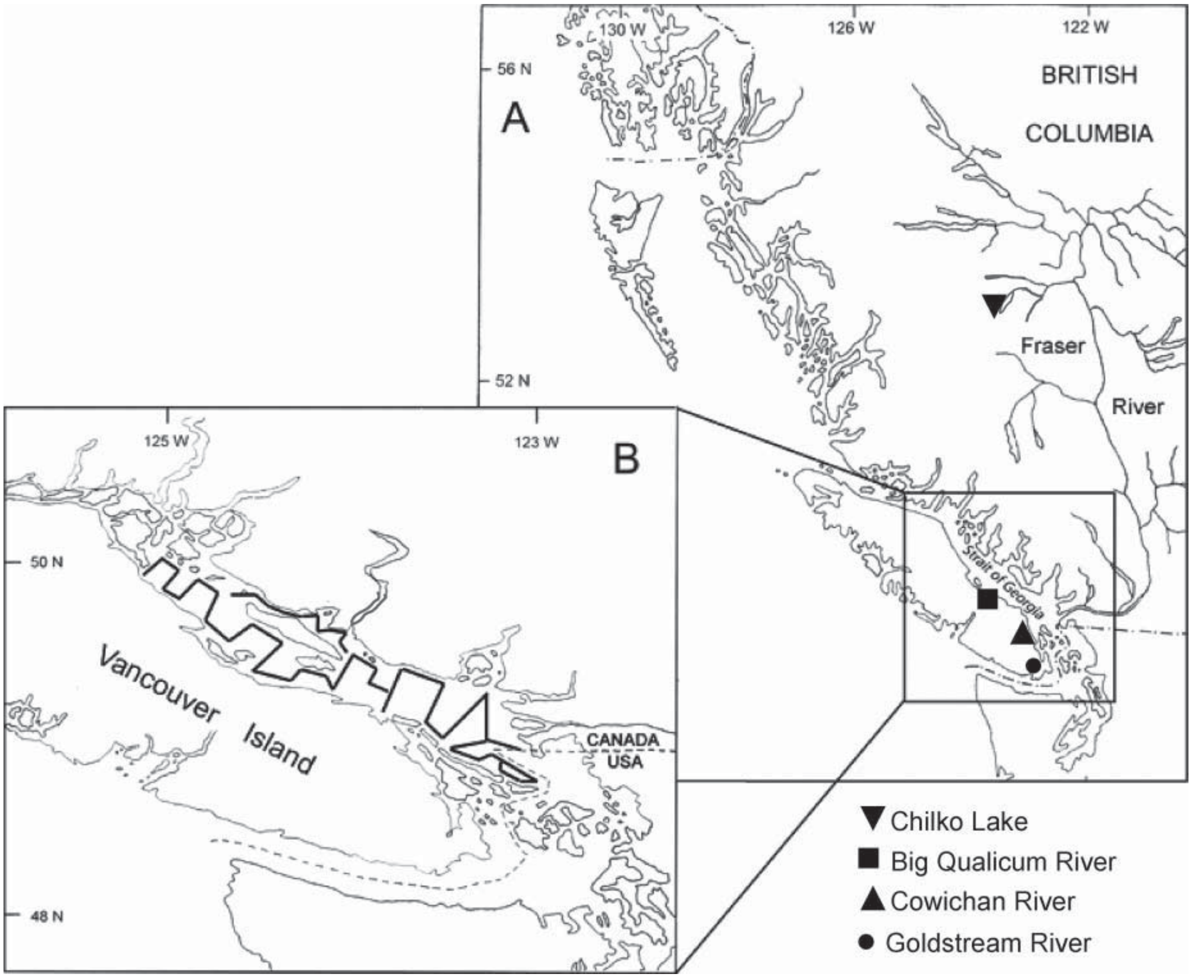

FIGURE 1. **(A)** Pacific coast of Canada and Vancouver Island showing the Strait of Georgia, the Fraser River, and other locations mentioned in the article and **(B) t**he trawl survey tracks (solid dark lines) in the Strait of Georgia.

populations. We used the total return of adults 2 years later and the marine survival for sockeye salmon from Chilko Lake to estimate the total number of juvenile sockeye salmon that entered the ocean in 2007. Our second method assumed that the proportion of Chilko Lake sockeye salmon entering the ocean was the same as the proportion of adult Chilko Lake sockeye salmon in the return 2 years later. We used the proportion of adult Chilko Lake sockeye salmon returning in 2009 and the known number of Chilko Lake sockeye salmon that were enumerated leaving Chilko Lake in 2007 (Grant et al. 2010, 2011) to estimate the total number of juvenile sockeye salmon in those 2 years.

RESULTS

The 11 years of surveys from late June to mid-July 1998–2009 (no survey in 2003) averaged 88 sets each year along the standard track line, with a range of 74 to 105 (Table 1). Most sets (48%) were in the surface 0–15 m, but there were 22% at 15–30 m, 15% at 30–45 m, 8% at 45–60 m, and 7% below 60 m in depth (Table 1). The total catch of Pacific herring and salmon in the upper 30 m in all July surveys was 2,126,300 and 151,200, respectively, representing an average of 98.1% of the total number of all fishes captured in the surveys. The average numbers of Pacific herring accounted for 91.6% of the total catch, and the average numbers of Pacific salmon were 6.5% of the catch. The total catch of all other fish species was 44,000. Major species that made up the remaining 1.9% of the catch were Pacific sand lance *Ammodytes hexapterus*, northern anchovy *Engraulis mordax*, spiny dogfish *Squalus acanthias*, and walleye pollock *Theragra chalcogramma*. The smallest total catch (CPUE) for all juvenile Pacific salmon in the July surveys in all years occurred in 2007 (Table 1).

Most pink (87%) and chum (88%) salmon were captured in the surface 15 m. Catches of coho salmon at the surface 0–15 m and 15–30 m were 79% and 16% of all catches, respectively. Juvenile Chinook salmon were captured at deeper depths, with 56% in the surface 15 m, 29% at 15–30 m, 9% at 30–45 m, and 5% at 45–60 m. Standardized catches of juvenile chum

TABLE 1. Number of sets for each depth stratum and total catch and CPUE (catch per hour) for each habitat depth and species.

Variable	1998 Jun 30–Jul 11	1999 Jun 30–Jul 8	2000 Jul 10–20	2001 Jul 7–15	2002 Jul 2–11	2004 Jul 4–13	2005 Jul 14–21	2006 Jul 9–20	2007 Jul 8–15	2008 Jun 27–Jul 6	2009 Jun 26–Jul 7
Total number of sets	91	98	85	89	93	105	82	79	74	90	83
0–15 m	24	40	37	44	52	55	49	39	36	47	40
15–30 m	21	25	19	18	19	21	18	17	16	20	20
30–45 m	15	13	17	14	15	15	9	9	12	14	12
45–60 m	15	9	7	10	5	10	0	7	6	6	7
≥60 m	16	11	5	3	2	4	6	7	4	3	4
Catch											
Sockeye salmon	481	729	252	1,014	224	2,345	317	163	65	1,662	1,572
Coho salmon	1,215	1,593	4,601	4,270	1,867	2,702	418	3,325	1,290	733	2,270
Chinook salmon	1,785	1,679	2,809	2,511	1,964	3,894	692	3,115	2,030	1,770	2,035
Chum salmon	4,811	4,066	12,251	6,673	1,093	10,262	11,473	3,902	547	2,694	18,379
Pink salmon	2,036	8	3,553	44	2,722	4,685	26	3,082	0	2,425	71
Total	10,328	8,075	23,466	14,512	7,870	23,888	12,926	13,587	3,932	9,284	24,327
CPUE											
Sockeye salmon	21.7	22.4	9.0	32.7	6.3	62.0	9.4	5.9	2.6	49.9	53.0
Coho salmon	41.1	40.9	126.1	112.4	43.1	59.6	10.9	102.9	41.6	18.2	63.6
Chinook salmon	50.8	38.6	70.2	58.4	42.9	77.4	18.1	87.0	60.0	40.6	49.7
Chum salmon	217.0	125.1	437.5	215.3	30.5	271.4	340.5	140.3	21.8	80.8	605.7
Pink salmon	91.9	0.3	126.7	1.4	76.0	123.9	0.8	110.8	0	72.8	2.4
Total CPUE of 5 species	422.5	227.3	769.5	420.2	198.8	594.3	379.7	446.9	126.0	262.3	774.4

salmon were generally the largest of all species, followed by pink salmon in even-numbered years. In 2007, the CPUE of chum salmon was the lowest in the 11 years of surveys (Table 1; Figure 2). Catches of sockeye salmon in the surface 15 m and at 15–30 m were 78% and 19%, respectively. The CPUE of juvenile sockeye salmon was generally the smallest for all Pacific salmon species (excluding pink salmon in even-numbered years), except for 2004, 2008, and 2009. Catches of juvenile sockeye salmon generally were larger in the northern two-thirds of the Strait of Georgia and smaller in the southern strait, which is dominated at the surface by the Fraser River plume in July. In 2007, juvenile sockeye salmon catches were about evenly spaced throughout the north two-thirds of the Strait of Georgia.

Length, Weight, Condition, CPUE, and Percentage of Empty Stomachs

Lengths were recorded for 19,465 coho salmon, 20,232 Chinook salmon, 20,024 chum salmon, 9,049 pink salmon, and 5,739 sockeye salmon (Table 2). Juvenile pink salmon were virtually absent in the catches in 2007, as previously reported. The average length of juvenile coho salmon was significantly smaller in 2007 than in all other years (analysis of variance [ANOVA]: $P < 0.001$; Figure 3). The smaller lengths and weights produced the lowest estimate of condition in 2007 (Figure 4). Coho salmon also had the largest percentage of empty stomachs in 2007 (Figure 5). The CPUE in 2007 was about average (Figure 2). The average length of juvenile Chinook salmon was significantly smaller in 2007 than in all other years of surveys (ANOVA: $P < 0.001$; Figure 3). This resulted in the lowest estimate of condition in the survey years (Figure 4). The largest percentage of empty stomachs for Chinook salmon also occurred in 2007 (Figure 5). The CPUE for Chinook salmon was about average (Figure 2). Chum salmon were the least abundant in 2007, as shown by the very low CPUE (Figure 2). Chum salmon were relatively large in 2007 and had above average condition compared with other years (Figure 4). The percentage of empty stomachs was about average (Figure 5). Juvenile sockeye salmon were not abundant in the survey in 2007; however, the few fish ($N = 65$) that were caught in the trawls were small (Figure 3; Table 2). These fish also had the lowest estimate of condition among all years (Figure 4). The smallest average lengths were in 2006 (Figure 3). Juvenile sockeye salmon in 2007 also had a relatively high percentage of empty stomachs (Figure 5).

Diet of Juvenile Chinook and Coho Salmon in the July 2007 Trawl Surveys

A total of 8,699 juvenile Chinook salmon and 7,661 juvenile coho salmon were examined for stomach contents in the July surveys from 1998 to 2009. Major diet items included fish, euphausiids, decapods, and amphipods. Fish were the dominant item for both species, averaging 69.5% for Chinook salmon and 42.3% for coho salmon (Figure 6; Table 3). Pacific herring was the dominant species of fish in the diet (Table 3). In 2007,

TABLE 2. Average lengths (mm) and weights (g) and SDs for juvenile Pacific salmon caught in the standard survey in the Strait of Georgia for each species from 1998 to 2009. In 2006, only 5 sockeye salmon were weighed, resulting in the exclusion of all weight data.

Species	Variable	1998 Jun 30–Jul 9	1999 Jun 30–Jul 8	2000 Jul 10–20	2001 Jul 5–15	2002 Jul 2–11	2003	2004 Jul 4–13	2005 Jul 14–21	2006 Jul 9–20	2007 Jul 8–24	2008 Jun 27–Jul 6	2009 Jun 26–Jul 7
Coho	Length	172.8	167.8	200.3	184.5	168.5		178.9	190.9	192.6	153.6	178	166.4
salmon	SD	23.27	22.28	22.8	21.08	22.82		28.13	24.28	23.92	23.19	22.1	24.58
	N	1,189	1,606	2,987	2,928	1,871		2,251	414	2,023	1,233	723	2,240
	Weight	70.4	61.7	104.2	77.7	62.0		77.3	90.5	97	46.2	72.2	62.1
	SD	33.58	23.30	37.85	29.89	28.67	N	38.57	33.08	41.01	29.67	27.2	30.63
	N	820	1,294	2,129	964	1,120	O	958	411	897	640	426	912
Chinook	Length	119.6	139.3	142.7	145.3	135.6		119.6	134.5	127.2	106.5	128.4	132.8
salmon	SD	36.77	28.88	37.16	29.78	24.1		32.16	26.4	36.37	19.85	30.9	27.16
	N	1,319	1,646	1,821	2,200	1,964	S	3,070	640	2,258	1,806	1,674	1,834
	Weight	35.5	43.6	47.8	51.8	38.3	U	33.8	37	40.81	18.5	32.5	34.9
	SD	28.92	30.22	35.74	28.12	21.19	R	27.9	19.93	31.88	11.41	23.0	20.47
	N	656	882	729	284	925	V	724	459	645	701	966	757
Chum	Length	122.5	116.1	128.2	130.5	114.7	E	123.1	153.4	143.6	140.6	101.8	114
salmon	SD	15.12	19.32	18.48	17.62	14.57	Y	15.76	13.77	26.67	19.45	19.9	13.33
	N	1,108	1,188	2,149	2,104	1,054		2,759	2,673	1,641	560	1,204	3,584
	Weight	20.4	17.8	25.7	27.4	17.4		21.7	43.8	37.7	34.1	17.8	16.3
	SD	8.55	11.69	11.46	11.17	6.41		9.46	11.95	17.21	15.82	14.27	7.06
	N	400	285	314	193	278		389	479	414	264	178	310
Sockeye	Length	85.8	119.7	117.6	132.5	123.1		107.3	146.7	75.2	107.9	106	116.5
salmon	SD	17.53	17.57	20.63	12.81	14.74		16.3	15.78	11.61	16.69	10.68	9.91
	N	365	624	243	824	224		518	314	160	65	1,239	1,163
	Weight	8	17.9	16.5	24.3	19.6		13.9	35.9		12.7	11.9	16.6
	SD	4.91	7.27	6.80	6.80	8.03		8.64	10.28		5.34	4.44	5.1
	N	167	161	112	131	124		100	254		51	361	310
Pink	Length	118.9	106.2	119.1		111.3		115.9	145.7	126.9		95.3	111.3
salmon	SD	13.87	8.76	12.95		15.43		15.56	24.06	21.37		15.84	12.41
	N	1293	5	1,617		2,161		1,430	26	1,279		1,167	71
	Weight	18		18.4		17.1		17.9	36.8	23.4		10.28	13.8
	SD	5.33		5.22		7.64		7.7	16.28	10.65		4.76	3.78
	N	336		213		316		240	24	339		114	20

there was a dramatic reduction in the amount of fish in the diets of Chinook and coho salmon (Figure 6; Table 3). No juvenile Pacific herring were found in the diet of 716 Chinook salmon that were examined in 2007 (Table 3). Juvenile Pacific herring were found in the stomachs of the 563 juvenile coho salmon examined in 2007, but there was a 79% decrease in the average percentage (Table 3).

TABLE 3. Diet of juvenile Chinook and coho salmon captured in the July trawl studies (1998–2009) and in 2007, showing the percentage by volume of fish and Pacific herring.

	1998–2009		2007	
	% Volume in the diet		% Volume in the diet	
Speices	All fish	Pacific herring	All fish	Pacific herring
Chinook salmon	69.5	34.1	9.5	0.0
Coho salmon	42.3	27.5	11.2	5.8

Pacific Herring

The abundance of juvenile Pacific herring in the September trawl surveys was low in 2003 and 2005 and the lowest in 2007 (Figure 7). Catches from the purse seine survey conducted by the Pacific Herring Assessment Group (Schweigert et al. 2009) had the lowest catches in 2005 and 2007, with 2007 being the absolute lowest at 0.01 kg/set (Figure 7). The purse seine catch in 2007 was the lowest in the 18 years of surveys.

Abundance of Juvenile Sockeye Salmon Entering the Strait of Georgia in 2007

The total return of sockeye salmon to the Fraser River in 2009 was 1.4 million. The estimated marine survival of Chilko Lake sockeye salmon for this return was 0.3%. Assuming that the marine survival for all populations was similar, the number of juveniles that entered the Strait of Georgia in 2007 would be 417 million. In 2007 there were an estimated 77 million juveniles leaving Chilko Lake. The proportion of adult Chilko Lake sockeye salmon that returned 2 years later in 2009 was 15.7%. Assuming similar marine survival for all populations, this would result in an estimate of 492 million juveniles entering

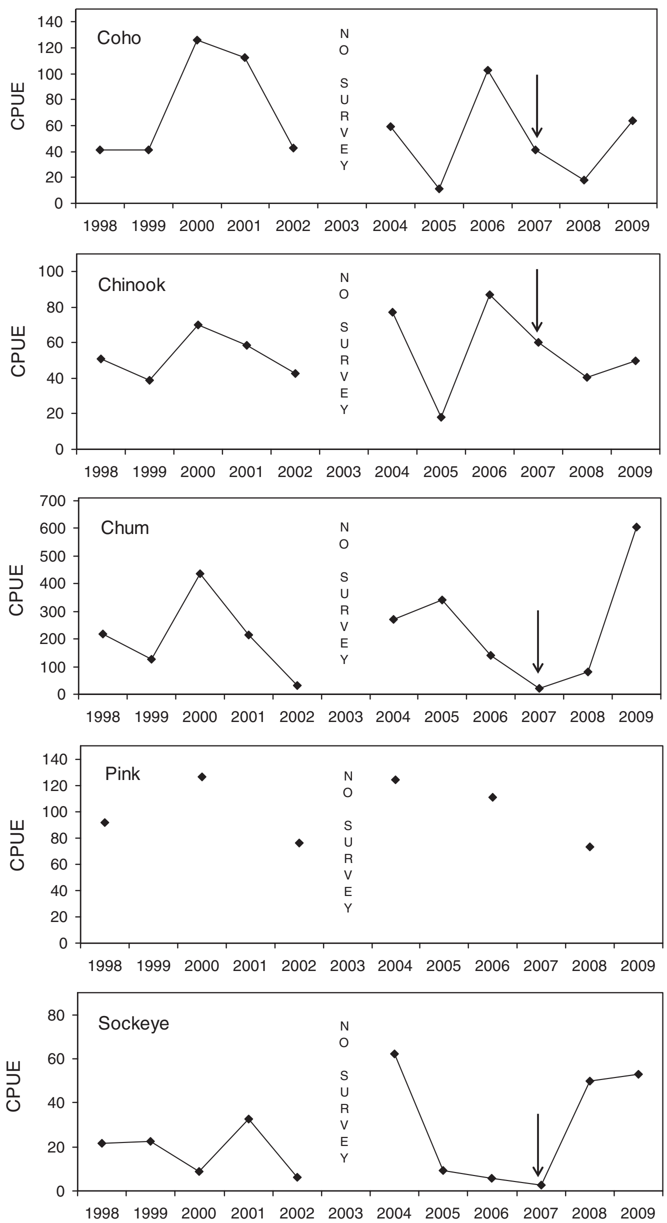

FIGURE 2. Catch standardized to 1 h (CPUE) of juvenile Pacific salmon in the July trawl surveys within the habitat depths in the Strait of Georgia from 1998 to 2009. Arrows show the CPUE for 2007.

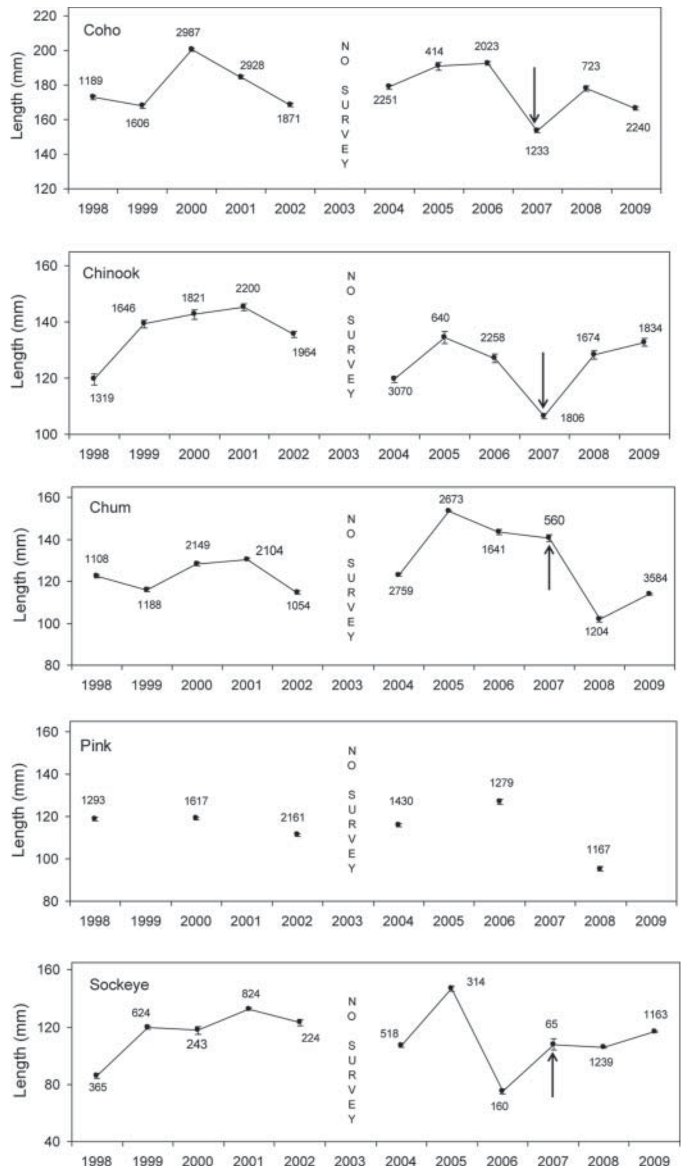

FIGURE 3. Average length of juvenile Pacific salmon in the July trawl surveys in the Strait of Georgia from 1998 to 2009. Error bars represent the 95% confidence intervals. The number of fish measured is shown for each year. Arrows show the average lengths in 2007.

the Strait of Georgia in 2007. The average of these two methods was 454 million juvenile sockeye salmon produced in the Fraser River in 2007.

DISCUSSION

Numerically, Pacific herring and coho, Chinook, chum, and sockeye salmon represented almost all of the fishes in the survey in the surface waters of the Strait of Georgia in the daytime in early summer. The total catches of these species in the July surveys were lowest in 2007. Juveniles of the most numerous species in July 2007 (Pacific herring and chum salmon) were all in extremely low abundance, indicating that the early marine survival of juveniles probably had been very poor.

The very low catches of juvenile Pacific herring in the trawl and purse seine surveys in 2007 was another indication of poor conditions for survival. The trends in the catches in the purse seine and trawl surveys were not similar in all years, possibly because in some years the juvenile Pacific herring remained closer to shore and were more accessible by the purse seine than the trawl net. The newly recruited year-class of Pacific herring into the commercial fishery in the Strait of Georgia normally represents about 40% to 60% of all fish (Schweigert et al. 2009). Recruitment of the 2007 year-class into the 2010 fishery was the

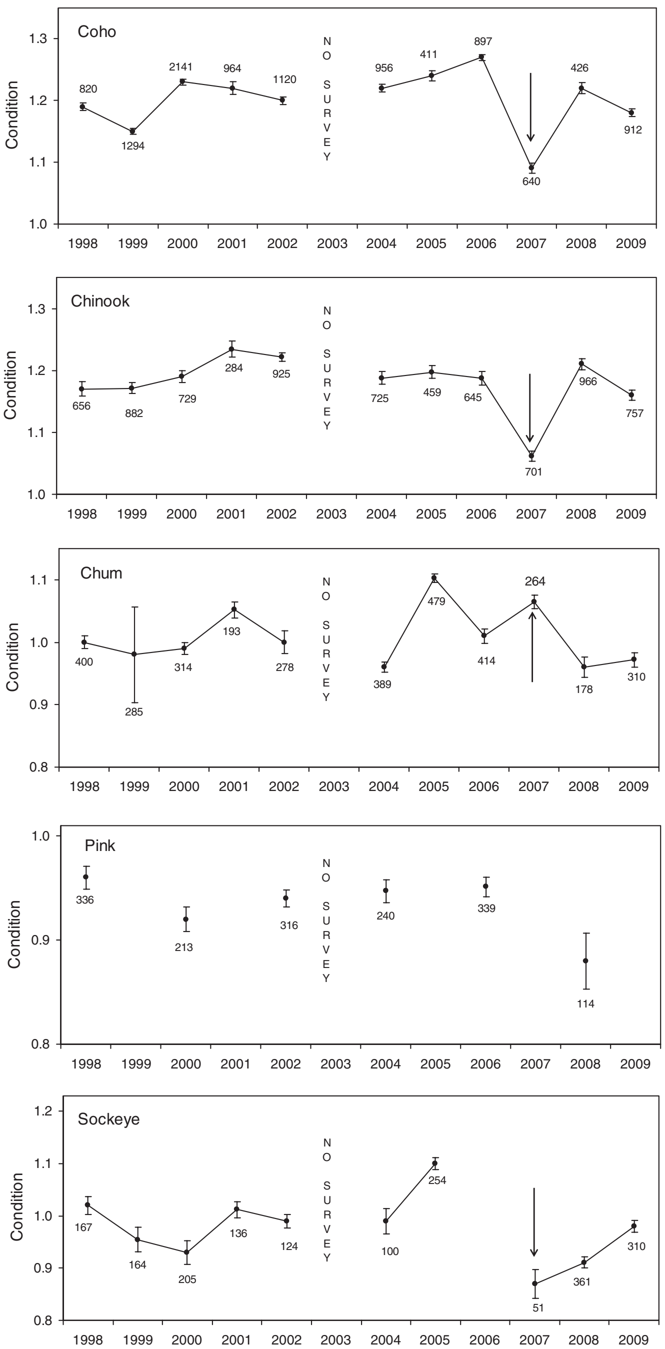

FIGURE 4. Condition of juvenile Pacific salmon sampled in the July trawl surveys in the Strait of Georgia from 1998 to 2009. Error bars represent the 95% confidence intervals. The number of fish that were weighed and measured for length in each year is shown. Arrows show the condition in 2007.

lowest on record at 2% (updated from Schweigert et al. 2009), confirming that the 2007 year-class of Pacific herring was the least abundant in recorded history and almost a complete failure. Recruitment from the 2005 year-class was also poor, but not as low as that from the 2007 year-class. Juvenile Pacific herring were a common diet item for juvenile Chinook and coho salmon in the Strait of Georgia. In 2007, Pacific herring were absent from the diet samples of Chinook salmon and greatly reduced in the diet samples of coho salmon. We interpret this to indicate that young-of-the-year Pacific herring were mostly dead by July 2007. A most likely explanation for such a basin-scale event would be a collapse of the plankton in the Strait of Georgia that are normally consumed by larval and juvenile Pacific herring.

It is known that juvenile coho salmon generally remain in the Strait of Georgia through to the late fall (Beamish et al. 2008, 2010; Chittenden et al. 2009); thus, the poor growth and poor condition in 2007 represented a response by the population to conditions within the Strait of Georgia. The poor food production that we propose occurred for Pacific herring continued for coho salmon in the survey area into the early summer, as indicated by the high percentage of empty stomachs. Early marine survival from ocean entry until September was estimated for coho salmon by Beamish et al. (2008, 2010). The early marine survival in odd-numbered years (when no pink salmon were in the Strait of Georgia) was the lowest in the data series in 2007 (Figure 8A). Total marine survival (from ocean entry in 2007 until adult return in 2008) of the coho salmon that went to sea in 2007 and returned as adults in 2008 was the lowest in a data set beginning in 1980 (Figure 8B, updated from Beamish et al. 2008). The lower total marine survival of returning adults in 2008 indicated that the surviving fish that were in poor condition in July 2007 continued to die through the summer and the winter, possibly as a consequence of their poor condition, as proposed by the critical size–critical period hypothesis (Beamish and Mahnken 2001). However, marine survival had been low since 2003, and although the poor survival in 2007 was extreme, it was a continuation of the trend of poor marine survival. Beamish et al. (2008, 2010) identified a strong relationship between the CPUE of juvenile coho salmon in the September surveys and total returns in the following year, confirming that in recent years most of the juvenile coho salmon mortality occurs in the Strait of Georgia.

Juvenile Chinook salmon in July 2007 were also the smallest in length and weight in the 11 years of surveys and, like coho salmon, had the lowest condition factor of all years. Like coho salmon, Chinook salmon had a high percentage of empty stomachs. The CPUE of Chinook salmon in July 2007 was about average but, like coho salmon, Chinook salmon had poor survival in recent years (Beamish et al. 2012). The average CPUE observed in July 2007 may indicate that the previous factors causing the trend in poor survival continued to affect Chinook salmon production, but in 2007 the surviving fish had the additional stress of being in poorer condition. Most Chinook salmon that entered the Strait of Georgia in 2007 will return in late 2010 or 2011. Until ages are determined, we will not have an estimate of the marine survival.

The CPUE of chum salmon in July 2007 was the lowest of all survey years. The sizes and condition of the surviving fish were above average and the percentage of empty stomachs was

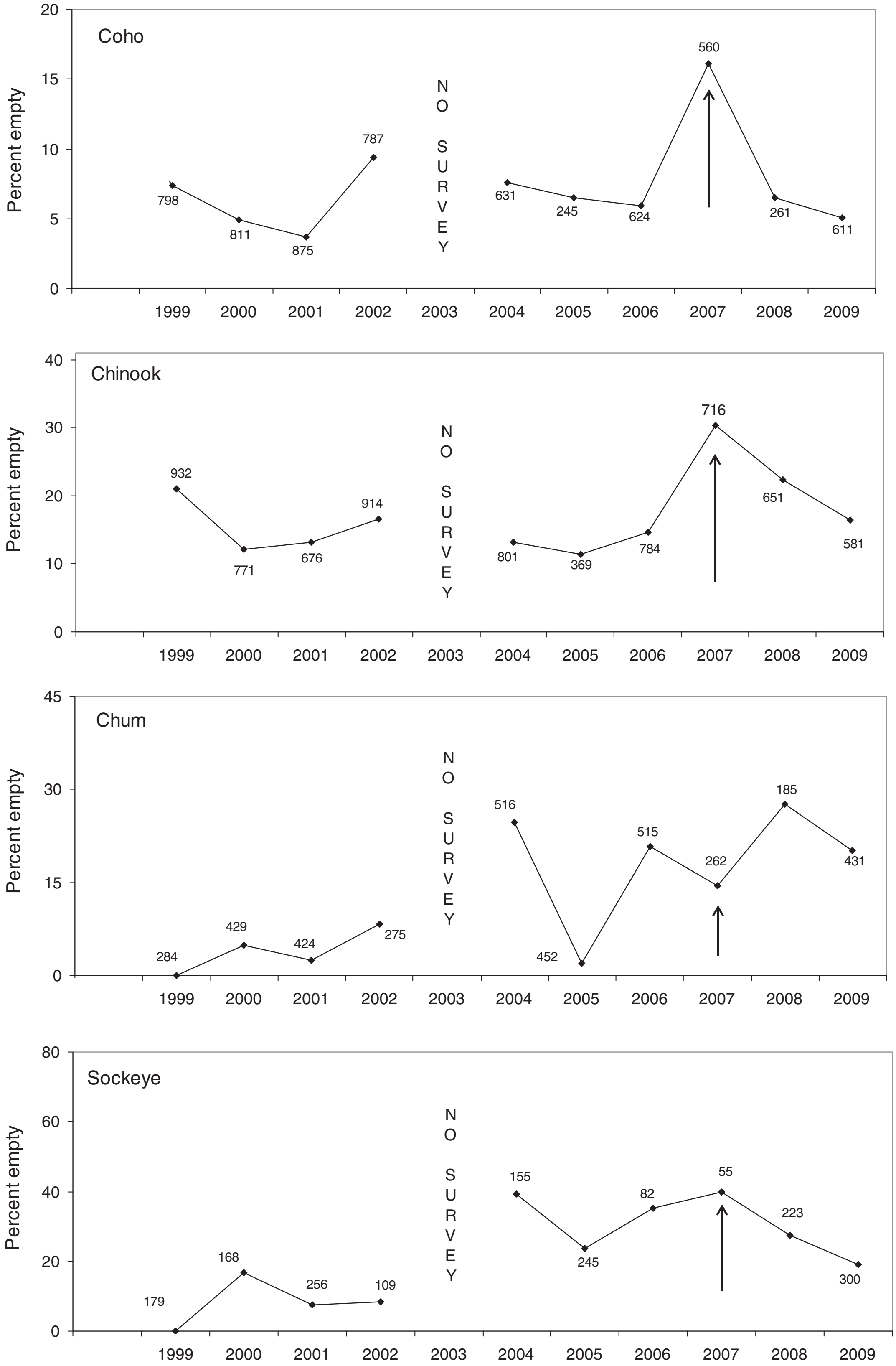

FIGURE 5. Percentages of empty stomachs for juvenile Pacific salmon sampled in the July trawl surveys in the Strait of Georgia from 1999 to 2009. The number of fish sampled is shown for each year. Arrows show the percentages in 2007.

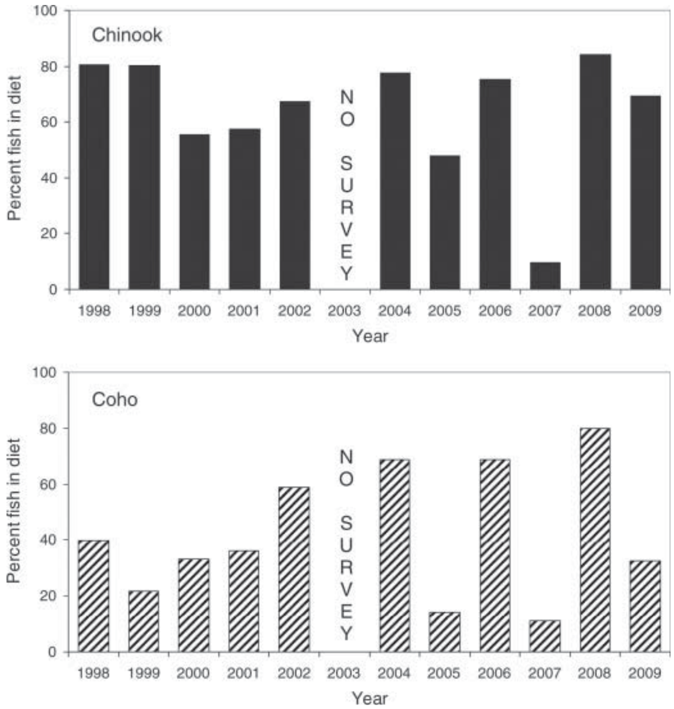

FIGURE 6. Percentages of fish in the diet (by volume) for juvenile Chinook and coho salmon captured in July trawl surveys in the Strait of Georgia in 1998–2009.

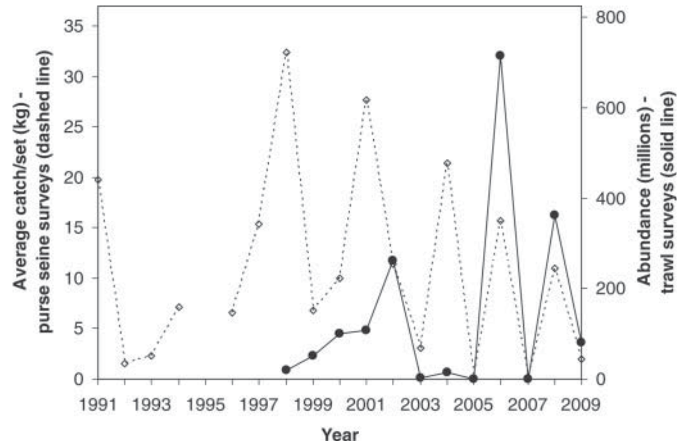

FIGURE 7. Abundance of young-of-the-year Pacific herring in the Strait of Georgia in September. The dashed line shows the average abundance in the purse seine survey (kg/set) and the solid line the average abundance in the trawl survey (millions of fish). The dashed line is updated from Schweigert et al. (2009).

similar to that in other years in the study. Chum salmon probably were larger in 2007 because most of the smaller fish died before the July survey. Juvenile chum salmon were usually the most abundant in the surveys, and the low abundance in 2007 would result from exceptionally large mortalities or exceptionally low production of juveniles in freshwater. Most juvenile chum salmon entering the Strait of Georgia were produced by adults that spawned in 2006. Estimates of escapements from major populations of chum salmon in the Cowichan River, Big Qualicum River, and Goldstream River in 2006 (Figure 9) confirm that the escapements in 2006 were about average for recent years. Thus, it is unlikely that the production of juveniles in freshwater was exceptionally low. Most juvenile chum salmon that entered the Strait of Georgia in 2007 would return as 4-year-olds in 2010. Estimates of the abundance of adult chum salmon from three major chum salmon producing rivers around the Strait of Georgia in 2010 indicate that the returns were extremely low in 2010 (Figure 9). The low CPUE in 2007 therefore appeared to be a consequence of reduced survival in the early marine period and probably was the reason for the poor adult return in 2010.

Catches of juvenile sockeye salmon in the Strait of Georgia would be influenced by the number of spawning females and the production in freshwater. Sockeye salmon abundances generally follow a 4-year cycle (Foerster 1968; Ricker 1997), with a dominant year corresponding to a large return to the Adams River. Juveniles from this brood year would enter the Strait of Georgia in 2000, 2004, and 2008. However, there was exceptional freshwater production of juvenile sockeye salmon in Chilko Lake in 2006 that resulted in an estimate of large abundances of juvenile sockeye salmon entering the Strait of Georgia in 2007. Thus, the low catch of juvenile sockeye salmon in our survey in 2007 was not a consequence of reduced production of

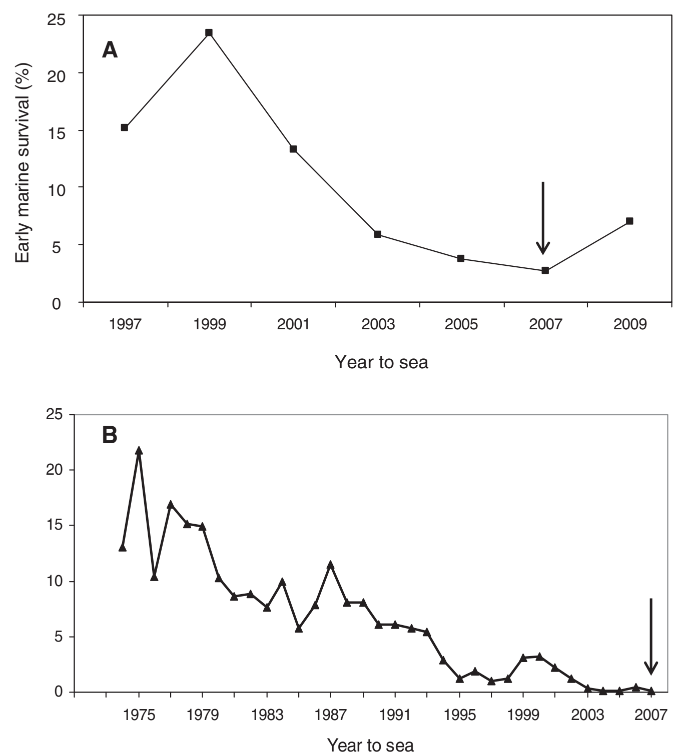

FIGURE 8. **(A)** Early marine survival (mid-May to mid-September) for odd-numbered years and **(B)** total marine survival (from ocean entry until adult return) of coho salmon that entered the Strait of Georgia from 1974 to 2007. Arrows show the marine survival for 2007. The data were updated from Beamish et al. (2008).

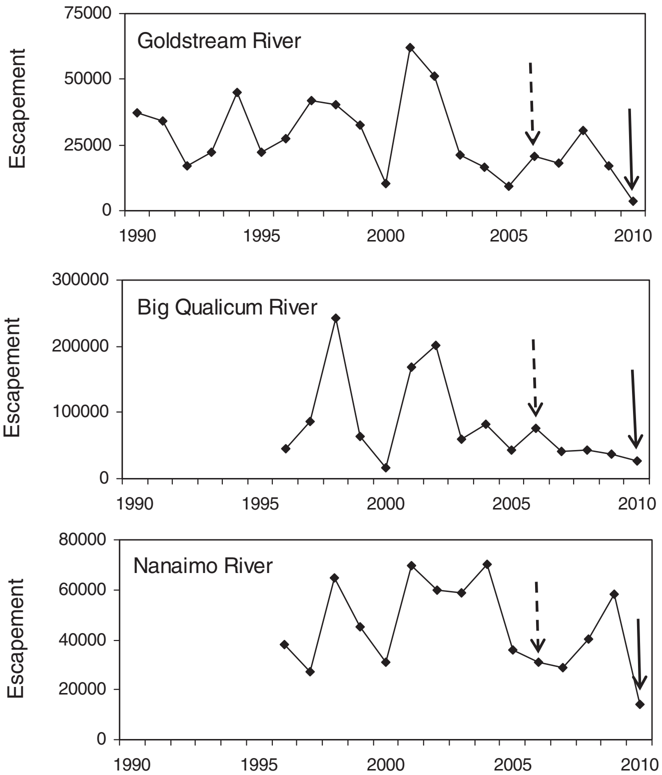

FIGURE 9. Number of adult chum salmon returning (escapement) to three rivers in southeastern Vancouver Island from 1990 to 2010. In all three rivers, the escapement in 2010 (solid arrows) is very low. The dashed arrows denote escapement in 2006. The data are from the Department of Fisheries and Oceans Canada (http://sci.info.pac.dfo.ca/sein_prod/nuSEDS%20v1.0/nuSEDS%20V1.htm).

smolts in freshwater. Our survey from early to mid July would be late relative to the movement of juvenile sockeye salmon out of the Strait of Georgia (Preikshot et al. 2012, this volume). Consequently, the small size of the catch is related to the timing of migration out of the Strait of Georgia, but we propose that it is also related to anomalous large mortalities of the juvenile sockeye salmon in the Strait of Georgia. The small size of the fish and their poorer condition appear to represent the state of the population, as there were samples of juvenile Fraser River sockeye salmon collected in 2007, north of the strait of Georgia in Queen Charlotte Sound and Hecate Strait that were also small relative to samples from the same areas in 2008 and 2009 (Thomson et al. 2012, this volume).

Explanation for the Poor Return of Sockeye Salmon in 2009

Rensel et al. (2010) state that toxic blooms of the alga *Heterosigma akashiwo* were likely the cause of the poor marine survival of the juvenile sockeye salmon in the Strait of Georgia in 2007 due to acute or chronic toxicity to the fish, food web and prey impoverishment, or some combination of these factors. It was only in the southern region along the western area of the Strait of Georgia where they reported large concentrations of toxic algae during the last week of May and early June 2007 when juvenile sockeye salmon would be most abundant throughout the strait. The central and northern areas of the Strait of Georgia were not sampled for the toxic algae (J. Rensel, personal communication). Thus, the role of harmful algae in the mortality of juvenile Pacific herring and salmon remains to be fully determined, but if it was associated with the elevated mortality and poor growth, we suggest that it was an impact in addition to a dramatic reduction in prey.

The Rensel et al. (2010) paper identified a very convincing relationship between the index of juvenile Pacific herring survival and the marine survival of sockeye salmon from Chilko Lake from 1997 to 2007. They showed that for ocean entry years 1998 to 2007, the smolt-to-adult survival of adult sockeye salmon returning to Chilko Lake was closely related to the survival of juvenile Pacific herring 2 years earlier, when the juvenile sockeye salmon entered the Strait of Georgia. The authors interpreted the close relationship to indicate that in recent years the brood year strength of Chilko Lake sockeye salmon was strongly affected by the same conditions in the Strait of Georgia that affected juvenile Pacific herring survival. Because juvenile Pacific herring remain in the Strait of Georgia for about a year, this relationship shows that a major source of mortality of all juvenile sockeye salmon occurs within the Strait of Georgia, and mortality was exceptionally large in 2007.

We propose that the synchrony in response of all fishes in the surface 30 m in the Strait of Georgia in 2007 was a response to conditions in the strait during the early marine period. We suggest that although freshwater production is important, it was the early marine period that strongly influenced the production of sockeye salmon that entered the Strait of Georgia in 2007, as shown in the Rensel et al. (2010) study. The estimate of 454 million sockeye salmon smolts produced in the Fraser River drainage in 2007 is an approximate estimate of total smolt (juvenile) production in freshwater. The actual number entering the ocean would be smaller because of mortalities in the river, but there would still be hundreds of millions of juveniles entering the Strait of Georgia and large mortalities would be expected to occur. MacFarlane (2010) determined that the greatest rates of somatic tissue growth and energy accumulation in juvenile Chinook salmon occurred in about the first 30 d in the ocean. The MacFarlane (2010) study and other studies (Hjort 1914; Houde 1987; Pearcy 1992) show that the early marine period is critical for the growth and survival for Chinook salmon and possibly for all juvenile Pacific salmon. An average residence time of about 35–42 d, as identified in Preikshot et al. (2012), would place an average number of juvenile sockeye salmon in the ocean environment in the Strait of Georgia that we show was stressful for Pacific herring and all of the other Pacific salmon. It is most improbable that the large abundances of juvenile sockeye salmon that were produced in the Fraser River drainage in 2007 somehow managed an average survival in the Strait of Georgia in 2007 while Pacific herring and other Pacific salmon were experiencing poor growth and survival.

What Happened in the Strait of Georgia Early in 2007?

We consider that extremely poor prey production occurred in 2007 because of the anomalous ocean and climate conditions in the Strait of Georgia in the winter and spring of 2007. There were large amounts of rain and greatly reduced periods of bright sunlight early in 2007 (Thomson et al. 2012). Anomalous strong winds from the southwest retained much of the freshwater that flowed into the strait because of the large rainfall in the drainage area for the Strait of Georgia. A calculation of the mixing layer depth by Thomson et al. (2012) showed that in 2007 the mixing layer depth was the shallowest since the early 1970s. A shallow mixing layer is evidence of the instability of this layer, which would prevent an escalation of plankton production, as explained by Gargett (1997). The physical conditions associated with the poor prey production in the Strait of Georgia extended into areas north of the strait in Queen Charlotte Sound and the Gulf of Alaska (Thomson et al. 2012). The historic low return of sockeye salmon to the Fraser River in 2009, therefore, would be a consequence of the mortalities that occurred in the Strait of Georgia and subsequent mortalities through to their first ocean winter that resulted from their generally poor condition in the early marine period.

In the Strait of Georgia, there would be variability in the match between food supply and food demand among years, with 2007 being the extreme example of a mismatch. Pacific herring would be the first major species to be affected in 2007, as their eggs hatch throughout the Strait of Georgia before most juvenile Pacific salmon enter the strait. Because Pacific herring spawn throughout the Strait of Georgia, beginning in the north and ending in the south (Hourston and Haegele 1980; Hay et al. 2009), it is reasonable to assume that the source or sources of mortality were widespread and persistent over the hatching period. Juvenile chum salmon would be the next major species to require adequate food immediately after they entered the Strait of Georgia. Juvenile chum salmon are produced in a number of streams around the Strait of Georgia, and their low abundance in the July survey is evidence that the source or sources of mortality occurred throughout the strait and were continuous with the impacts on the juvenile Pacific herring. Juvenile sockeye salmon would be the next major species group to enter the surface waters of the Strait of Georgia. Our catches in July were small, but there was an indication that the juvenile sockeye salmon in the Strait of Georgia and in Queen Charlotte Sound in 2007 were not in good condition, suggesting that the surviving fish had experienced difficult feeding conditions. Juvenile coho and Chinook salmon would be the last major group of Pacific salmon to enter the Strait of Georgia. There was evidence of poor survival of coho salmon and poor growth and condition of the fish surviving to July 2007. Even by early July, there was still evidence of food limitation in the relatively large percentage of empty stomachs. Thus, we consider that there was a failure in survival because there was a synchronous failure in prey production.

We suggest that it is remarkable and even unique that virtually all juveniles of the major species that reared in the surface waters of the Strait of Georgia in the spring of 2007 had extremely poor survival or were in very poor condition or both. The event represented an extreme in the variability of the natural mortality in the early marine period of all these species. It would seem to be appropriate to conduct the research that would identify the sources of this early marine mortality.

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