The ecology of juvenile sockeye salmon in the Strait of Georgia and an explanation for the poor return of sockeye salmon to the Fraser River in 2009

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Preface

This report summarizes information collected in our juvenile Pacific salmon studies in the Strait of Georgia that relates to sockeye salmon originating in the Fraser River. Our intent is to provide information to people interested in the reasons for the recent production trends in sockeye salmon from the Fraser River, including the very poor return in 2009 and the exceptionally large return in 2010. Relevant information from other studies is also included. Material is presented in a way to inform a reader without the rigor commonly used in scientific publications. This was done so that general audiences can read the report and so that we can include a wide range of topics. It is our intent to write a number of scientific papers based on the information in this report. Several have been included in the 2010 meeting of the North Pacific Anadromous Fish Commission and several are being prepared for peer review.

The report is focused on explaining the very poor return of sockeye salmon to the Fraser River in 2009 and begins with a synthesis that summarizes the key information. The synthesis concludes with a list of reasons why the poor return of sockeye salmon in 2009 was mostly a result of conditions within the Strait of Georgia. Each section also has a brief summary followed by results and discussion including some speculations. A table of contents identifies the sections in the report and a subject index identifies the pages where specific subjects are included in the text. This is the final draft.

R. Beamish

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(Draft 20)

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The ecology of juvenile sockeye salmon in the Strait of Georgia and an explanation for the poor return of sockeye salmon to the Fraser River in 2009

Synthesis

The low returns of sockeye salmon in 2009 were likely the result of poor growth and poor marine survival of juveniles in the Strait of Georgia in 2007. Juvenile sockeye salmon sampled in 2007 from the Strait of Georgia were small and in poor condition. In Hecate Strait and Queen Charlotte Sound they were the smallest of all sockeye salmon sampled in the surveys. These small fish were the survivors, indicating that the fish that died probably were even smaller. The poor marine survival of juvenile sockeye salmon probably resulted from the reduced availability of food in the first few months after they entered the Strait of Georgia. All other juvenile Pacific salmon entering the Strait of Georgia in the spring of 2007 also had either poor survival or poor growth or both. Reduced production of food is also the most likely explanation for the poor growth of juvenile coho and chinook salmon and the poor early marine survival of juvenile chum salmon. Reduced food production would affect other species and there is evidence that larval Pacific herring experienced very poor survival in the spring of 2007. The unfavourable conditions for growth and survival probably also occurred in areas north of the Strait of Georgia which would affect the survival of juvenile sockeye salmon after they left the Strait of Georgia. The poor condition of the juvenile sockeye salmon would also result in high mortalities in the first ocean winter, particularly if conditions in the winter were harsh.

There is a relationship between the trawl catches of juvenile sockeye salmon in July and total returns, two years later. The early July trawl surveys occur at a time that juvenile sockeye salmon are not all in the Strait of Georgia, but a proportion remains that appears to be generally predictive of the future return. An estimate of average catch or catch per unit effort (CPUE) of these remaining fish can be used as an index of survival within the Strait of Georgia. It is the relationship between this index and total return that can be used to predict the total return. In 2008, we used this relationship to forecast that the return to the Fraser River in 2009 would be very poor. The accuracy of the prediction remains to be determined, but a qualitative prediction of returns of very poor, poor, average, good and very good appears to be valid. The reliability of this relationship will be confirmed if the total return of sockeye to Fraser River is very good in 2011 and poor in 2012.

The environmental forcing that resulted in the poor food production in 2007 and poor sockeye salmon returns in 2009, was probably caused by a combination of large, early flows from the Fraser River, strong winds blowing up the strait, followed by a period of relatively weak winds. High freshwater discharge combined with winds that confine the brackish surface waters within the strait appear to have affected the stability of the surface mixing layer. Analysis shows that the spring of 2007 was highlighted by an estimate of mixing layer depth that was the shallowest in 30 years, most likely resulting in a poorly developed plankton producing layer. This would likely result in reduced production of the preferred food for juvenile Pacific salmon.

Juvenile sockeye salmon that rear in lakes before entering the Strait of Georgia leave fresh water from early April to late May. The average first feeding day of most (lake-type) sockeye salmon in the Strait of Georgia was May 25, for one sample collected in early July 2008 or about three weeks after the average smolts are migrating out of the Fraser River. In 2009, some Chilko Lake juvenile sockeye salmon remained and grew in the Strait of Georgia through to early July. The differences in average sizes between leaving Chilko Lake and in the July surveys indicates that some juvenile sockeye salmon may remain in the Strait of Georgia for up to two months and grow at rates consistent with the published literature. To grow at these average rates and achieve the reported sizes, the juvenile sockeye salmon would not leave the Strait of Georgia quickly. Abundance estimates of juveniles in the Strait of Georgia in early July and catches in Queen Charlotte Sound and Hecate Strait about the same time indicate that in early July, juvenile sockeye salmon from the Fraser River are distributed from the Strait of Georgia to Hecate Strait. In 2007, between 467 and 491 million sockeye salmon smolts may have entered the Strait of Georgia from the Fraser River. It is a general principle in ecology that plants and animals that produce large numbers of seeds and offspring will have a large early mortality. It is also a fundamental hypothesis in fishery science that the availability of prey when larval fish begin feeding is related to the variability in production in freshwater and marine fish populations (Hjort 1914; Lasker 1975; Cushing 1990; Houde 2008). Thus, it would be expected that there will be a large mortality of juvenile sockeye salmon in the Strait of Georgia even in very good ocean conditions. The generally poor growth and survival indicates that a very large mortality of the juvenile sockeye salmon occurred in the Strait of Georgia in 2007. The small size of juvenile sockeye in 2007 would also indicate that mortalities would be large in the first ocean winter according to the critical size, critical period hypothesis (Beamish and Mahnken 2001).

Juvenile Harrison River sockeye salmon were 24 times more abundant in the trawl survey in September 2007 than all other juvenile sockeye salmon were in July. Harrison River sockeye salmon are sea type Pacific salmon that do not rear in a lake for one year prior to entering the Strait of Georgia. Instead, they remain in the river after hatching and enter the Strait of Georgia in the same year that they hatch. Very few juvenile Harrison sockeye salmon were caught in the July surveys except in Howe Sound. However, virtually all of the juvenile sockeye salmon caught in the survey in September 2007 were Harrison River sockeye. In general, Harrison River sockeye salmon enter the Strait of Georgia approximately 8-10 weeks later than the average juvenile sockeye salmon. A sample of Harrison River sockeye salmon collected in the Strait of Georgia in September 2008 had an average first feeding day about six weeks after the other sockeye salmon entered the ocean, confirming that they enter the ocean later than the other sockeye salmon. Juvenile Harrison River sockeye salmon abundances in September 2007 were relatively large compared to other years. The condition of these juvenile sockeye salmon in September 2007 was much better than the condition observed for the juvenile sockeye salmon in the Strait of Georgia in July, indicating that feeding conditions improved by early summer either because there was more plankton or less competition, or both. Harrison River sockeye salmon remained in the Strait of Georgia for approximately four months from July to November and probably left the Strait of Georgia through Juan de

Fuca Strait. There is a weak relationship between the trawl catches of juvenile Harrison River sockeye in September and the total returns for each brood year. The very large catches of juvenile Harrison River sockeye salmon in September 2007 and 2008 could indicate a large return to the Harrison River in 2010 and 2011.

South Thompson summer chinook salmon have a late ocean entry life history that is similar to the Harrison River sockeye salmon. There are 14 populations in the aggregate of South Thompson chinook salmon and these populations are currently experiencing very good survival, as indicated by the exceptionally large escapements relative to most other chinook populations in the Fraser River drainage. Our studies showed that South Thompson chinook salmon enter the Strait of Georgia approximately 8 weeks after most other chinook salmon. Juveniles from these stocks increase in abundance through the summer and by September they represent 70% to 80% of all juvenile chinook salmon in the Strait of Georgia. The very good survival of these chinook salmon is evidence that it is the late ocean entry life history that is the reason for the improved production.

There has been a declining trend in the total production of sockeye salmon in the Fraser River since the early 1990s. There has also been a declining trend in the early marine survival of coho salmon at the same time, indicating that the most likely cause of the declining trend is related to climate. There is a relationship between the total mortality of coho salmon and the catch of juvenile coho salmon in the September trawl surveys. This identifies that conditions in the Strait of Georgia in recent years are directly related to the total return of coho salmon and that these conditions have not been favourable for coho salmon survival. Coho salmon also changed their migration pattern in the early 1990s resulting in a collapse of the commercial and sports fishery. The synchrony in the response of coho and sockeye salmon in the Strait of Georgia is evidence of a linkage to climate. In previous studies we showed that there are distinct trends in the production of Fraser River sockeye salmon that are related to climate regimes. We noted a regime change in 1989 that we reported was associated with declining productivity of sockeye salmon in the 1990s.

Juvenile sockeye salmon around the subarctic Pacific have the most restricted diet of all Pacific salmon, making it difficult for them to use alternate sources of food. Juvenile sockeye salmon in the Strait of Georgia fed heavily on decapods when they first enter the Strait of Georgia and on amphipods later. Our studies show that it is the quantity of prey that was available rather than the quality of prey available that is related to the growth and survival in the early marine period. Thus, poor growth and the resulting poor survival most likely is a result of reduced prey availability.

Our studies did not identify the sources of the very large early marine mortality of juvenile sockeye salmon in 2007. Predation is an obvious source of mortality, but evidence of predation in general was difficult to find. There is evidence that juvenile sockeye salmon in the Strait of Georgia compete for prey with pink and chum salmon, resulting in reduced growth of the juvenile sockeye salmon. The decline in the abundance of Fraser River sockeye salmon since 1994 is associated with increased abundances of juvenile pink and chum salmon suggesting that the competition may contribute to the reduced sockeye salmon production.

The events that affected all juvenile Pacific salmon entering the Strait of Georgia in the spring of 2007 appear to be highly unusual and possibly unique. The reduced production of sockeye salmon since the early 1990s, however, appears to be part of a general trend that has also reduced the productivity of coho and chinook salmon and increased the productivity of pink and chum salmon. Thus, it is important to recognize that the long-term changes are ecosystem changes affecting all Pacific salmon and not specific to sockeye salmon. It is important to know why sockeye salmon survived so poorly in 2007, but it is also important to understand the reasons for the increased survival of pink and chum salmon. The best way to answer these questions is to take a look. The technology is available if people and ships are also available. Juvenile Pacific salmon abundance surveys, in particular, provide one index of adult production and should continue. An index of plankton production is relatively easy to produce and would be most useful in assessing adult salmon production. The causes of the mortalities in the early marine period need to be identified. Hundreds of millions of juvenile sockeye and other Pacific salmon enter the Strait of Georgia each year and in a short time the abundances are down to millions. Predation is an obvious source of mortality but fish that are stressed because of poor growth may be more susceptible to common diseases than healthy fish. Research needs to continue to identify how common diseases may be related to the increased mortality of coho, chinook and sockeye salmon.

Reasons why the poor return of sockeye salmon to the Fraser River in 2009 was mostly a result of conditions in the Strait of Georgia in 2007

- There was low abundance of juvenile sockeye salmon in the Strait of Georgia in early July 2007 and very low abundances towards the end of the migration out of the Strait of Georgia are related to poor returns in two years.
- Juvenile sockeye salmon had very poor growth in 2007 and were small and in poor condition throughout their distribution from the Strait of Georgia to Hecate Strait.
- All other species of juvenile Pacific salmon that entered the Strait of Georgia in the spring of 2007 had very poor growth or very poor survival, or both. Juvenile coho salmon remain in the Strait of Georgia prior to the July surveys, indicating that their very poor condition was a result of reduced food availability in the strait.
- Juvenile Pacific herring had exceptionally poor survival in the Strait of Georgia in 2007, indicating that they also were not able to find food in their early development period.
- Hundreds of millions of juvenile sockeye salmon entered the Strait of Georgia from the Fraser River in early May 2007. By early July, only millions were still alive. It is well known in ecology that plants and animals that produce large numbers of seeds or offspring have very large mortality in their early development. Thus, it is to be expected that there will always be a large mortality of juvenile sockeye salmon in the Strait of Georgia. In years when food is scarce such as 2007, this mortality will be even larger.
- Winds and large flows of fresh water into the Strait of Georgia early in 2007 resulted in an ocean structure that was not suitable for normal plankton

- Juvenile sockeye salmon from major populations such as Chilko Lake are in the Strait of Georgia for about two months in some years, indicating that juvenile sockeye are influenced by conditions within the strait. Thus, the poor feeding conditions that affected the other species of Pacific salmon and Pacific herring would affect juvenile sockeye salmon.
- In 2009, a sample of juvenile sockeye salmon from Chilko Lake remained in the Strait of Georgia through to early July. Using average sizes, the daily rate of growth was about 0.5 mm / day which is similar to an average of 0.6 mm / day that is in the published literature. This indicates that some juvenile sockeye salmon remain and grow normally in the Strait of Georgia.
- The long-term declining trend in abundance of sockeye salmon was not unique to sockeye salmon. Coho and chinook salmon production declined at about the same time in the early 1990s. In contrast, pink and chum salmon production increased, indicating that the decline in sockeye salmon production is a consequence of a general change in the dynamics of the Strait of Georgia ecosystem.
- Populations of chinook and sockeye salmon that delayed their entry into the Strait of Georgia until early summer are surviving better than the populations that entered earlier in the year. This indicates that food is available for these populations later in the year either as a consequence of plankton production that is better in the summer than in the spring or because of reduced competition, or both. The survival of this unusual life history type is not a reason to believe that food was not limiting growth and survival early in the year in 2007.

Juvenile Pacific salmon surveys in the Strait of Georgia

Summary

Studies of the ocean ecology of juvenile Pacific salmon in the Strait of Georgia using trawls started in the mid-1990s with a standardized survey beginning in July 1998. These surveys continued through to the present, with juvenile sockeye salmon being captured in all surveys. Samples examined for DNA showed that virtually all sockeye salmon were from the Fraser River. DNA analysis also indicated that the juvenile sockeye salmon in the catches in the July survey were representative of the expected population composition based on the forecasted adult return in two years after the survey. This was an important observation as it showed that the survey was sampling a representative proportion of the population that was moving out of the Strait of Georgia toward the end of the migration. There was a positive relationship between the average catches of juvenile sockeye salmon in July and the abundances of adults that returned to the Fraser River two years later. In 2008, the relationship was used to show that the very low catches of juvenile sockeye salmon in 2007 could result in a very poor return of adults in 2009. The relationship that includes a preliminary estimate of a total return of about 29 million adult Fraser River sockeye salmon in 2010 indicates that the return in 2011 could be very good, perhaps as much as about one half of the 2010 return. The return in 2012 could be poor.

Sea-type juvenile sockeye salmon are abundant in the Strait of Georgia after most other juvenile sockeye salmon (lake-type) have died or left. Sea-type juvenile sockeye salmon enter the Strait of Georgia in their first year in fresh water after the fry emerge from the gravel. The major population of sea-type sockeye salmon in the Fraser River is from the Harrison River where the adults represent about 1% of the total production of all Fraser River sockeye salmon, historically. However, in the most recent five years, they represent about 9% of the total production. Harrison River juvenile sockeye salmon were rare in the open waters of the Strait of Georgia in July, although they were found in Howe Sound. They became abundant in the open Strait of Georgia in September. They leave the Strait of Georgia very late in the year, although it is not known precisely when and

where most leave. There is some evidence from other studies that most leave through Juan de Fuca Strait; however, some may also leave through Johnstone Strait. The catch of juvenile Harrison River sockeye salmon in September is positively related to the total return of adults indicating that the trawl surveys may provide a useful method of forecasting adult returns.

Our program conducted studies of the marine ecology of juvenile Pacific salmon in the Strait of Georgia in the mid 1970s through to the present. In the mid 1990s we experimented with a modified midwater trawl that was fished at a speed sufficient to capture all sizes of Pacific salmon in most areas of the coast and in most types of weather. The design of the trawl, the fishing methods and survey design were described in Beamish et al. (2000) and Sweeting et al. (2003). We established a standardized sampling grid and survey time that has been maintained in each survey in July and September since 1998, except for July 2003 when there was no survey (Figure 1). The exact dates of the surveys varied slightly according to the allocation of vessel time (Figure 2), but most surveys were about early July and mid September. In general, a survey takes 9-10 days with an average of 90, 30-minute sets. Fishing days may not be continuous because of crew issues or mechanical break downs. Sets are fished at different depths, with most sets in the top 15 m. Juvenile pink (*Oncorhynchus gorbuscha*), chum (*O. keta*) and sockeye (*O. nerka*) salmon are virtually all in the top 15 m. Coho (*O. kisutch*) salmon are found in the top 45 m and chinook (*O. tshawytscha*) salmon in the top 60 m. Catches are for a 30-minute set unless they are standardized as catch per unit effort (CPUE) which is the number of fish caught in 30 min, standardized to one hour. Abundances were calculated using the number of fish captured in a volume of water fished, compared to the total volume of water in the survey area according to the methods in Beamish et al. (2000). We use the term “population” to identify a genetically distinct group of Pacific salmon. We use the term “stock” to represent a fishable group or a group within a population.

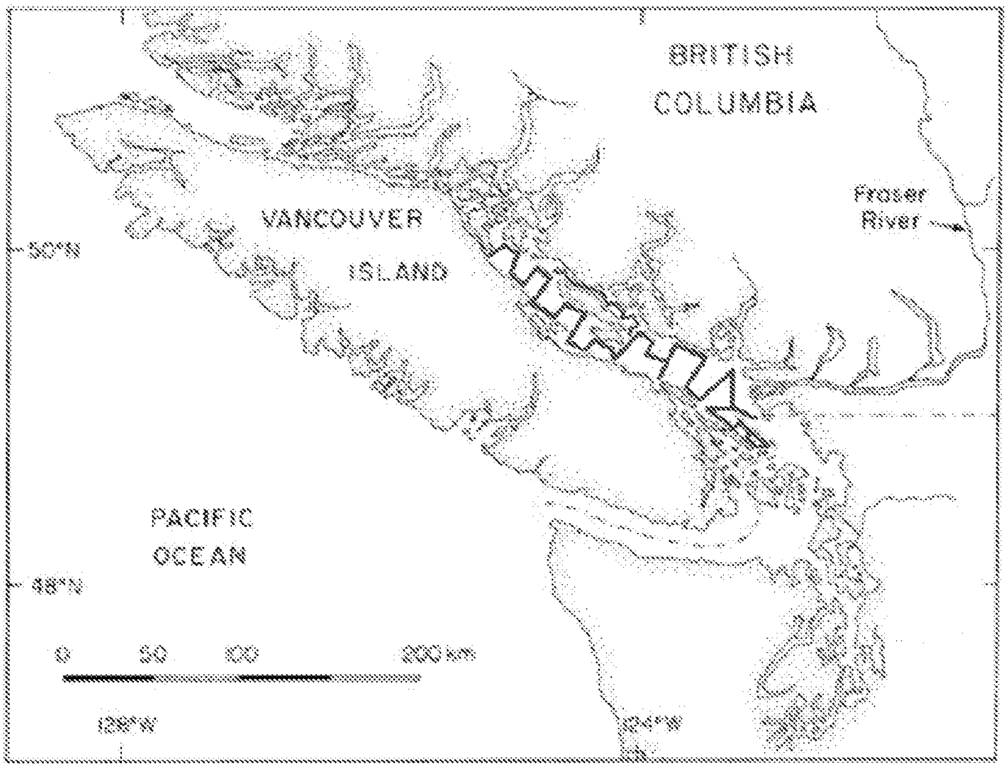


Figure 1. Standard track lines (red) for trawl surveys in the Strait of Georgia. Sets were evenly spaced along the track lines.

July trawl surveys and poor catches in 2007

Catches of juvenile sockeye salmon vary among years and among localities within years (Figure 4A-K). The catches of sockeye salmon in July in the 12 surveys from 1998 to 2009 (Figure 3, Figure 4A-4K) were lowest in 2007 (adult return year in 2009). In 2007, very few sockeye salmon were in the northern strait and virtually none were in the southern strait (Figure 4C). Low catches also occurred in 2000, 2002, 2005 and 2006. The largest catches were in 2004, 2008 and 2009 with 2004 being the largest among all years. In July 2008 and 2009, juvenile sockeye salmon were most abundant in the northern part of the Strait of Georgia (Figure 4A-4B). In July 1998, 2001, 2002 and 2005, juvenile sockeye salmon were distributed throughout the strait.

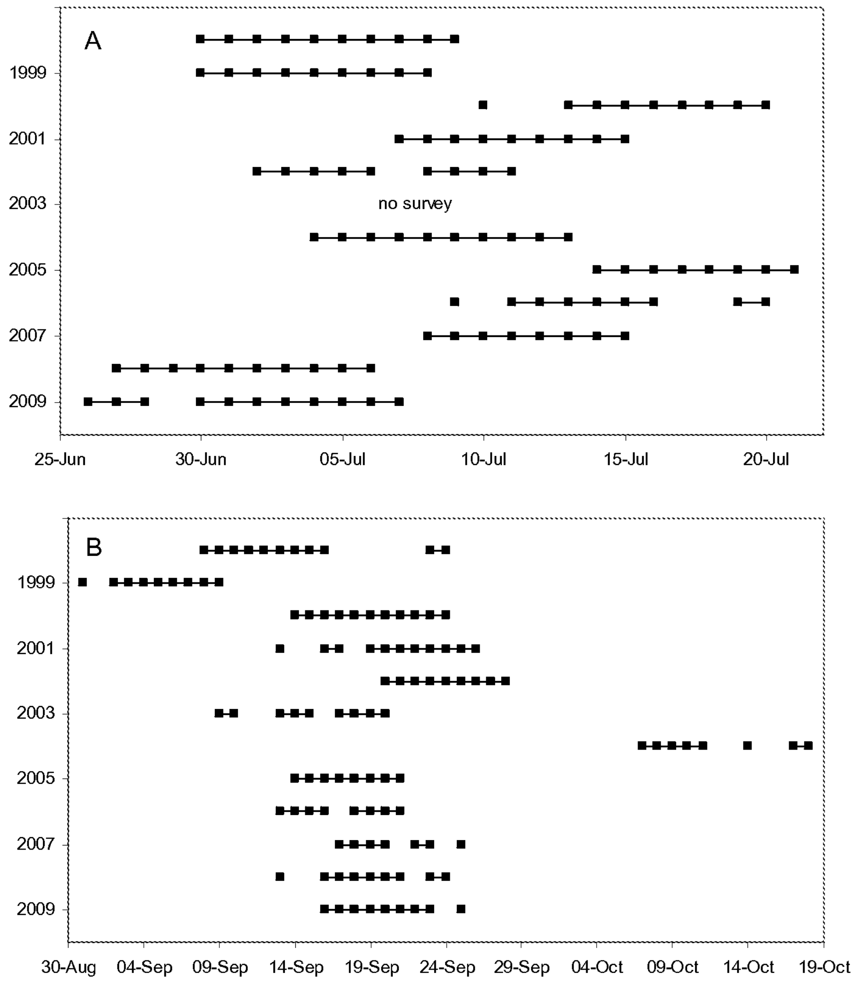


Figure 2. Date of trawl surveys in the Strait of Georgia in A) July and B) September from 1998 to 2009. There was no survey in July 2003.

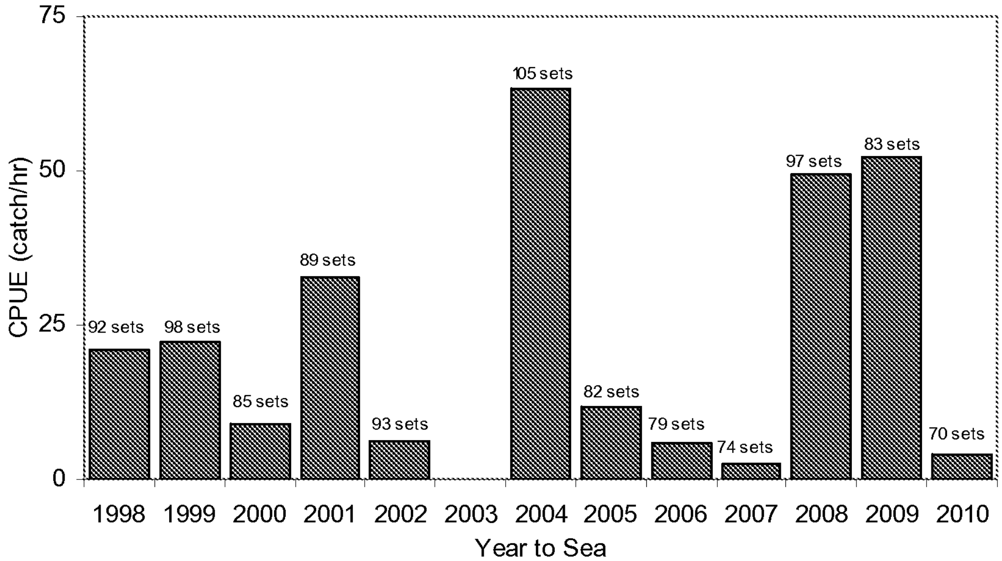


Figure 3. Average catch, standardized for one hour of effort or catch per unit effort (CPUE), for sockeye salmon in the trawl survey in July in the Strait of Georgia, 1998-2010, showing the very low catch in 2007. Some of the variation in CPUE relates to cyclic dominance of the various populations. Juveniles entering the ocean in 2007 came from a subdominant cycle and would be expected to be more abundant. Juveniles from the dominant cycle entered the Strait of Georgia in 2000, 2004 and 2008. There was no survey in 2003. The number of sets is shown for each year. The CPUE for the July 2010 survey is included, although the results are not discussed in this report except to indicate that there could be a poor return in 2012.

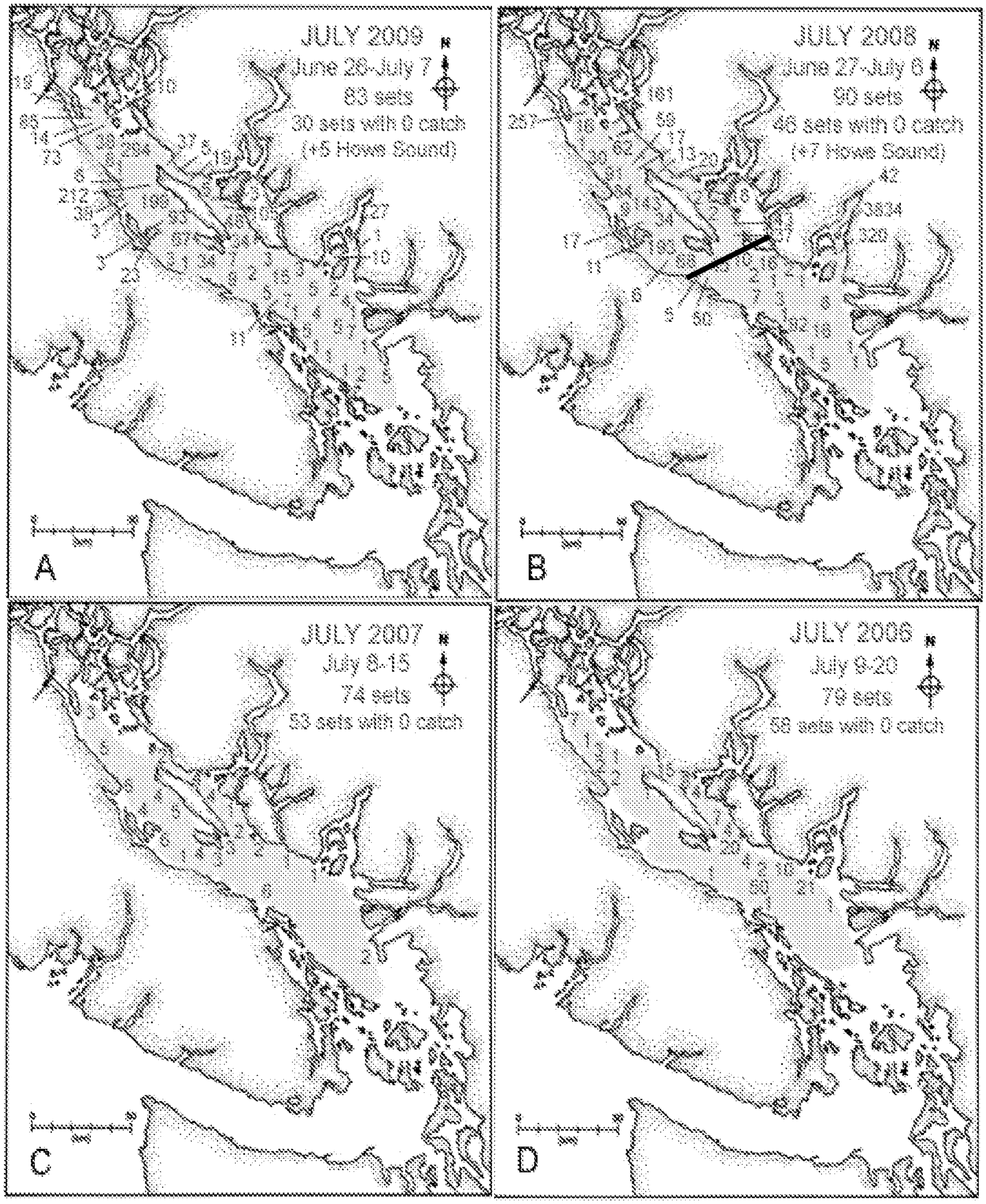


Figure 4. Sockeye salmon catches (in 30 minutes) in the July trawl surveys for A) 2009, B) 2008, C) 2007 and D) 2006. The survey area is shown in light blue. Zero catches are not shown to facilitate the comparison among years. The survey was identical to the track lines in Figure 1 in all years, with sets made in the same approximate location. The number of sets with 0 catch is identified.

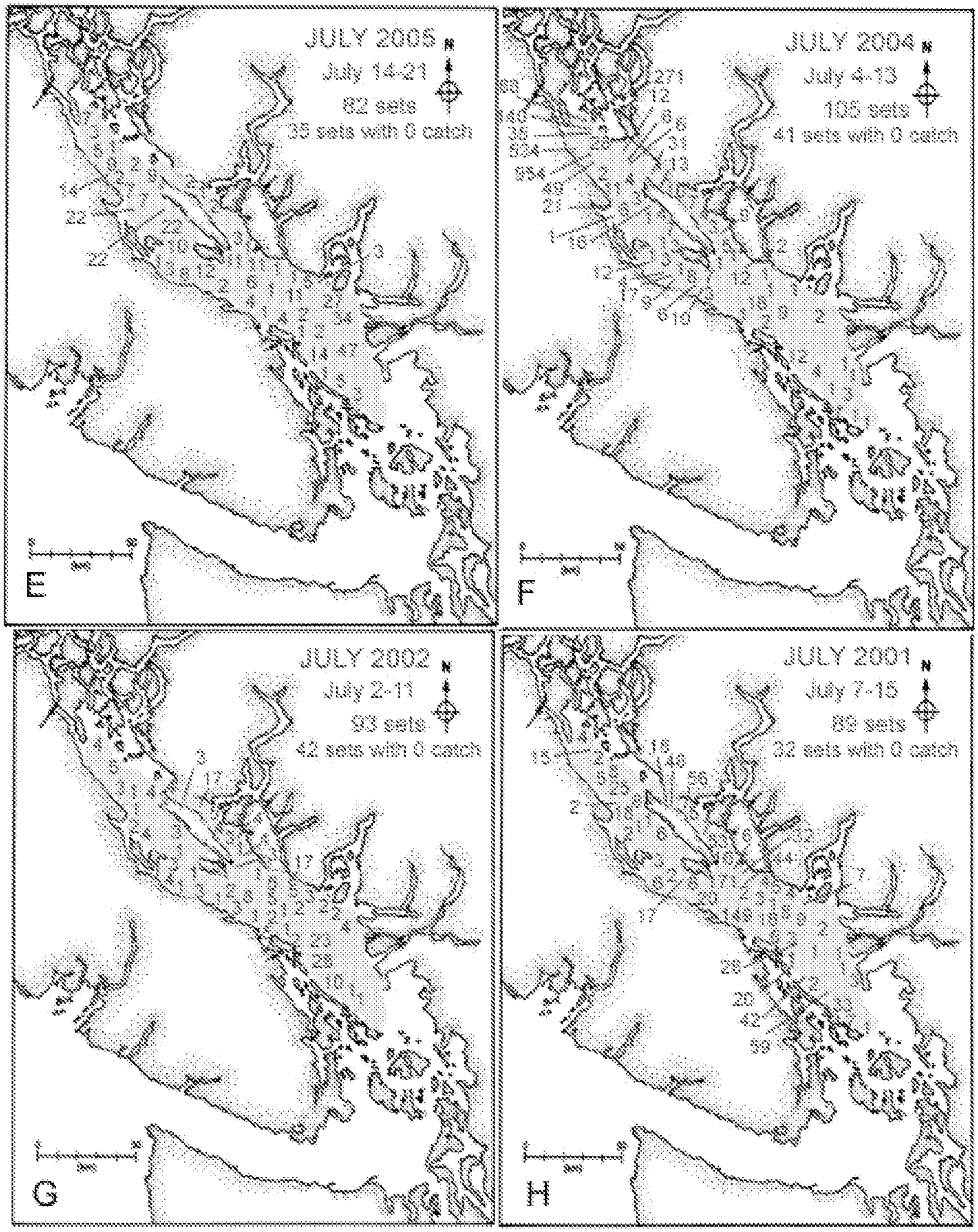


Figure 4 (Continued). Sockeye salmon catches (in 30 minutes) in the July trawl surveys for E) 2005, F) 2004, G) 2002 and H) 2001. The survey area is shown in light blue. Zero catches are not shown to facilitate the comparison among years. The survey was identical to the track lines in Figure 1 in all years, with sets made in the same approximate location. The number of sets with 0 catch is identified.

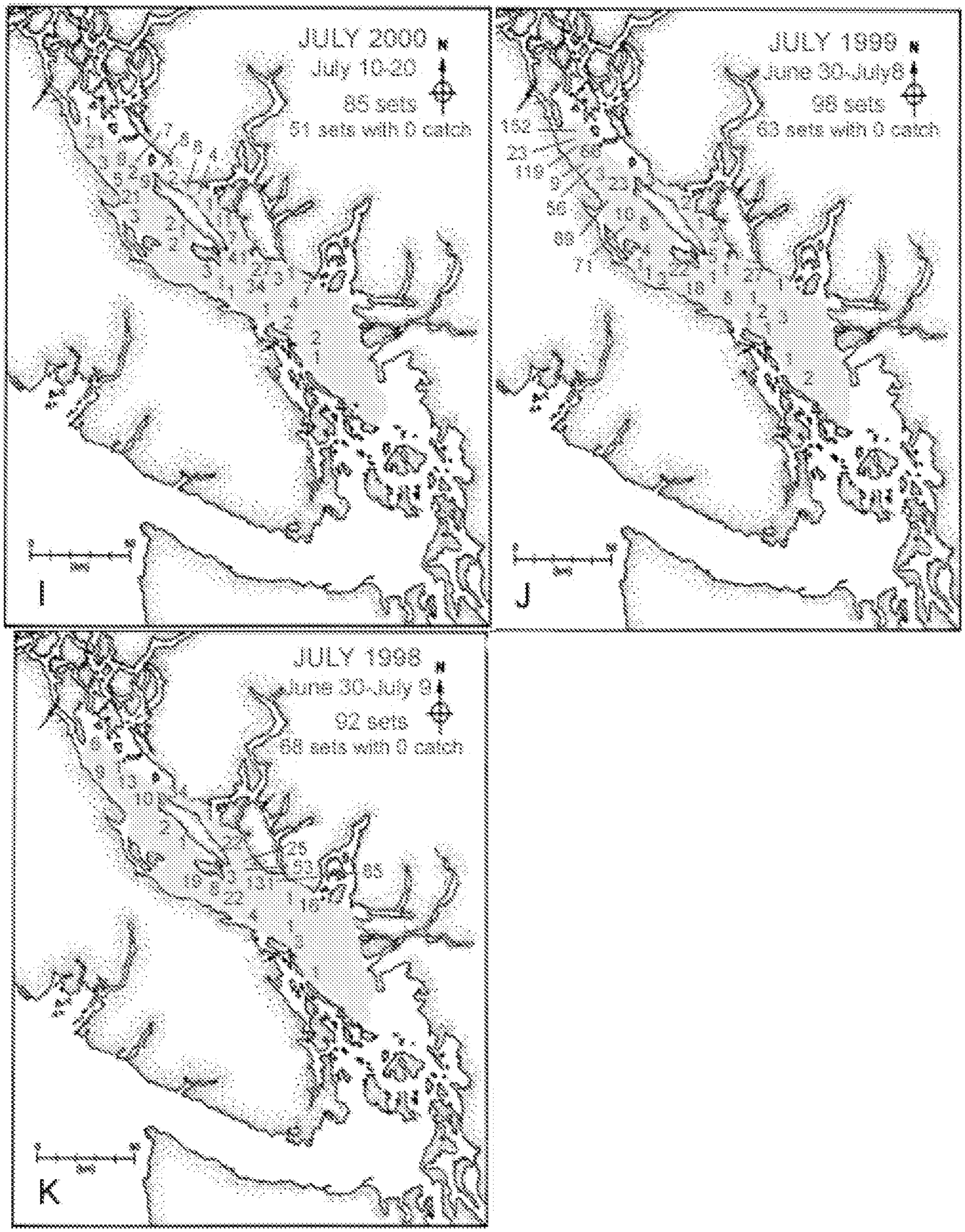


Figure 4 (Continued). Sockeye salmon catches (in 30 minutes) in the July trawl surveys for I) 2000, J) 1999, and K) 1998. The survey area is shown in light blue. Zero catches are not shown to facilitate the comparison among years. The survey was identical to the track lines in Figure 1 in all years, with sets made in the same approximate location. The number of sets with 0 catch is identified.

Relationship between catches of juvenile sockeye salmon and the total production of sockeye salmon in the Fraser River

In the 2008 "State of the Ocean" report, we reported that the returns of sockeye salmon to the Fraser River in 2009 could be extremely poor (Crawford and Irvine 2009). It is now known that the returns were extremely poor. The relationship between poor catches in the trawl survey and a poor adult return implies that adult production is influenced by conditions in the Strait of Georgia during the early marine feeding period.

Catches (CPUE) of juvenile sockeye salmon in mid July in the Strait of Georgia were related to the total return two years later (Figure 5A) with the exception of one aberrant year in 2000. Omitting 2000 from the relationship in Figure 5A produced a very strong correlation with an $R^2 = 0.84$ (Figure 5C). CPUE values were converted to natural logarithms (log) to account for the wide variation in the data (Figure 5C). The log converted CPUE data exhibited a pattern that showed that larger catches of juvenile sockeye salmon in the July surveys were an indicator (R^2=0.41) of adult returns two years later (Figure 5B). The log converted data were also examined using a jackknife analysis to test the effect of any one data point. The analysis re-samples the data by removing one data point at a time, to create a distribution of R^2 values. The 85% confidence interval for the R^2 value of the re-sampled data set was $R^2 = 0.21$ to $R^2 = 0.95$, indicating that the original relationship is strong and unlikely to be driven by data from any one year.

Preliminary results are available for the July 2010 trawl survey and the adult sockeye salmon return to the Fraser River. Trawl catches of juvenile sockeye salmon were poor in July 2010 indicating a poor return in 2012, as might be expected from this cycle (Figure 6A, B, C). When an estimated total adult return of 29 million fish for 2010 is included in the regression in Figure 6D, E, F, there is an improvement in the R^2 value for data from all years. Noteworthy is the estimate of a return of about 16 million sockeye salmon in 2011. This estimate could be considered in a relative sense, such as identifying very poor, poor, average, good and very good returns. Thus, the return in 2011 could be predicted to be very good. Adding another year (2010) to the data in Figure 5 not only improves the relationship slightly, it also reduces the influence of the "aberrant" value in 2000. If the adult returns in the next two years are good, poor in 2011, and poor in 2012, the relationship between catches in July and subsequent adult returns would be confirmed.

There is also a positive relationship between the CPUE of Harrison River sockeye salmon in the September survey and the total adult return (Figure 5D) as age 3 and age 4 fish. The large CPUE in the past three years in combination with the pattern of having a large percentage of age 4 returns when the juveniles from the Harrison River enter the strait in an even-numbered year could result in a series of very good total returns beginning in 2010.

Sets in Howe Sound were not part of the standard survey but were made in 2008 and 2009 (Figure 4A, B). In July 2008, there were large catches of juvenile sockeye salmon in Howe Sound. The fish lengths were much shorter than those captured in the open strait (Figure 7A). The smaller lengths and a DNA analysis (Figure 8) clearly distinguished these fish as Harrison River sockeye salmon. The catch in Howe Sound in July 2009 was smaller than in 2008 (Figure 4A).

The DNA samples for juvenile sockeye salmon collected in 2008 (Figure 9A) were aggregated according to the time adults entered the Fraser River to spawn in 2006 and expected to return in 2010. The samples contained 18 populations with adults that enter the river last or "late-run" populations dominating (Figure 10A). These late-run populations were estimated using DNA to be about 73% of the sample. The forecasted population composition for the major run timings for this brood year in 2010 indicated that late-run populations could be 82% of the total of all populations. Thus, our sample in July 2008 is representative of the population of juvenile sockeye salmon that would be expected to be migrating through the Strait of Georgia in 2008 (Figures 9, 10). "Summer" and "early summer" populations of sockeye salmon made up the remainder of the DNA sample. Catches in Howe Sound were 98% Harrison River sockeye salmon (Figure 8A). Only a few Harrison River sockeye salmon were found in the open strait in July and none were found in the DNA sample from the Gulf Islands in the June samples (Figure 9D).

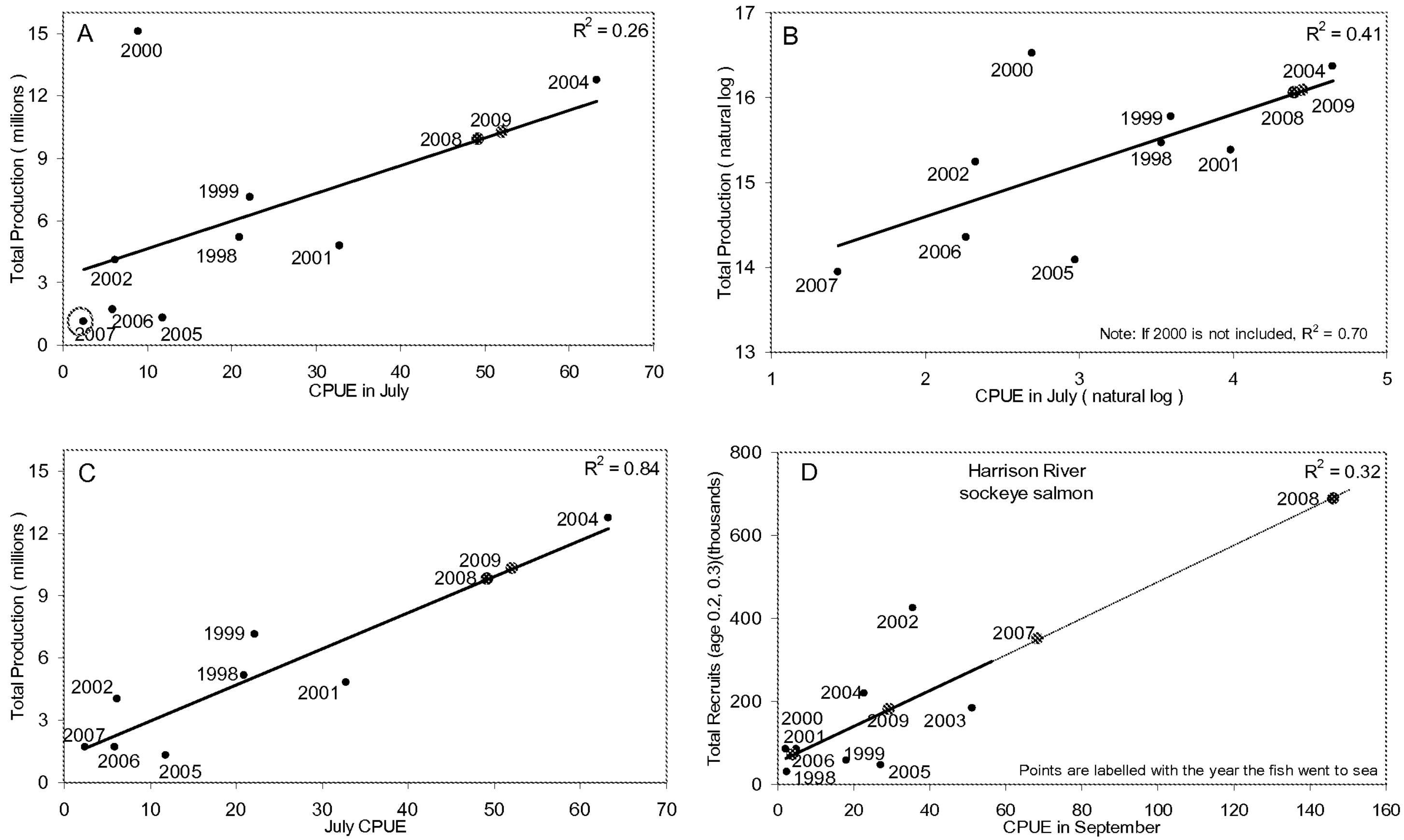


Figure 5. Relationship between catch of juveniles in July, standardized to one hour or CPUE, in July and the total production for adult sockeye salmon from the Fraser River. There was no survey in July 2003. A) The total production includes estimates of the mortality of adults in the Fraser River. The years are the ocean entry years and the return year will be two years later. The poor return in 2009 corresponds to the ocean entry year of 2007, circled in red. Catches in 2008 (blue dot) and 2009 (red dot) are not included in the R^2 estimate and are shown to indicate that the return in 2010 and 2011, respectively, would be about 10-11 million fish (it is known that the return was about 29 million fish). B) The relationship in Figure 5A shown using natural logarithms. C) The relationship in Figure 5A with ocean entry year 2000 omitted. D) The relationship between catch of juveniles and CPUE in September for sockeye salmon from the Harrison River. The years are the ocean entry years and the total production includes fish that return as age 3 (0.2) and age 4 (0.3). The ocean entry years of 2007 (green dot), 2008 (blue dot) and 2009 (red dot) will return as adults between 2010 and 2012 and are not included in the R^2 estimate. The values for 2007 and 2008 are included to show that returns in the next few years could be large.

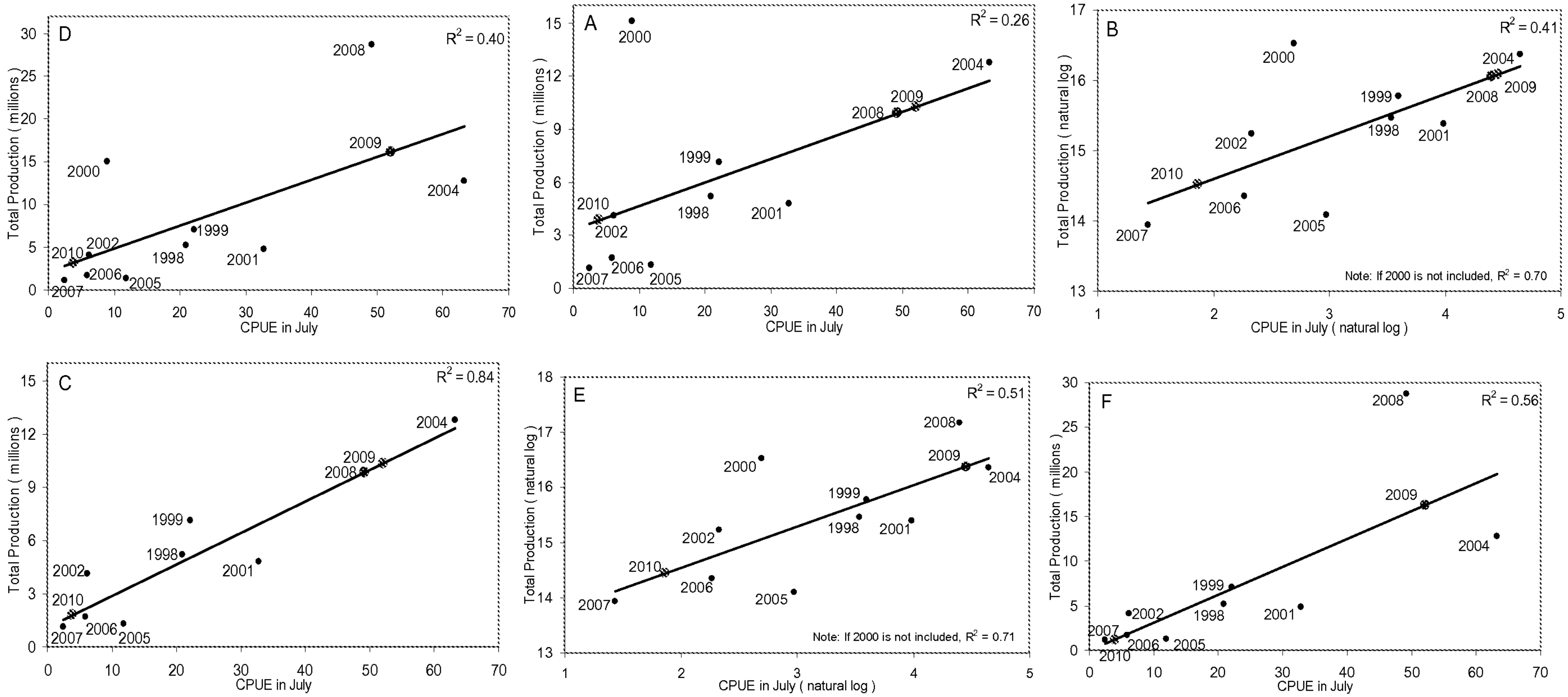


Figure 6. A,B,C are the same figure as Figure 5 A,B,C with the CPUE for July 2010 survey shown (green dot). The R^2 values do not include the values for 2008, 2009 and 2010. Figures D,E,F are similar to Figures 5 A,B,C, and 6 A,B,C except that they include an estimated total adult return in 2010 of about 29 million sockeye salmon and the CPUE in July 2008 in the regression. Figure D would indicate an adult return in 2011 of about 16 million sockeye salmon and about 2-3 million sockeye salmon in 2012.

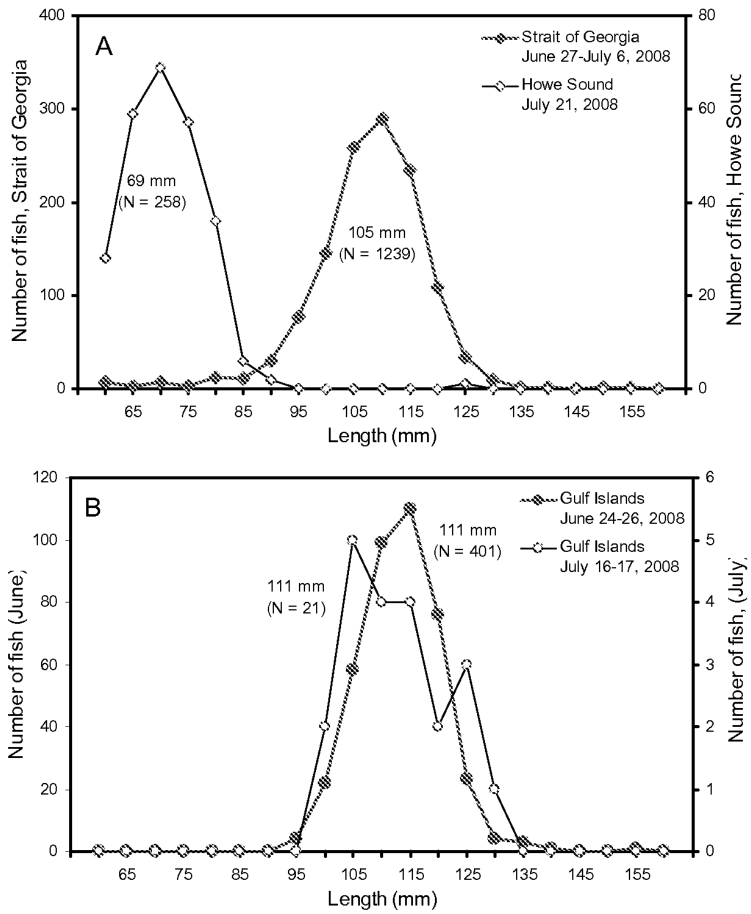


Figure 7. Lengths of juvenile sockeye salmon from the July survey in 2008. (A) Strait of Georgia (solid red diamonds) and Howe Sound (open diamonds) and (B) Gulf Islands in late June (solid circles) and late July (open circles). Howe Sound and the Gulf Islands are not part of the standard survey shown in Figure 3.

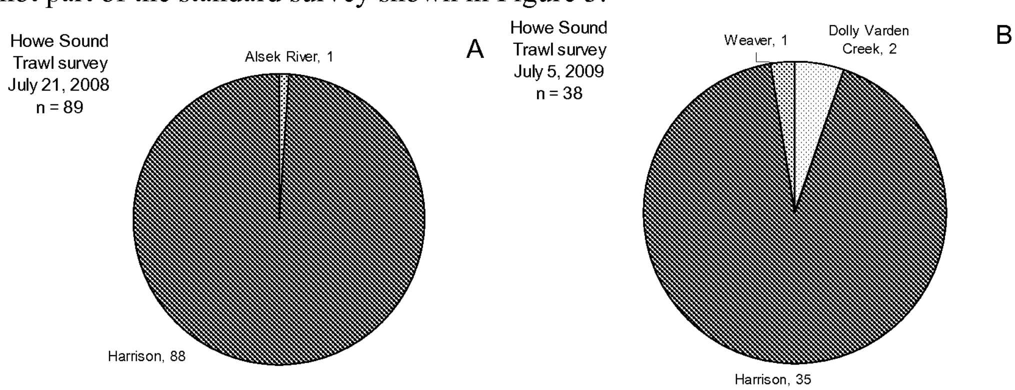


Figure 8. DNA composition of juvenile sockeye salmon captured in Howe Sound in A) July 21, 2008 and B) July 5, 2009, showing the dominance of Harrison River sockeye salmon in this area.

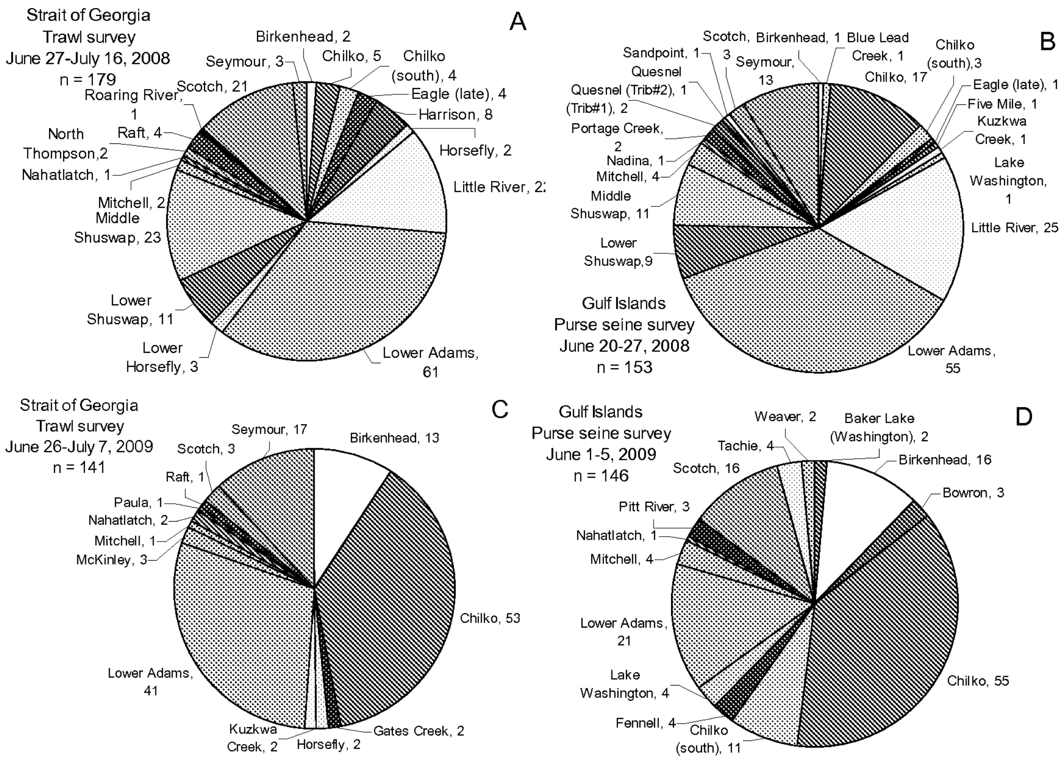


Figure 9. DNA composition of sockeye salmon captured in A) the Strait of Georgia trawl survey from June 27-July 16, 2008, B) the Gulf Islands purse seine survey from June 20-27, 2008, C) the Strait of Georgia trawl survey from June 26-July 7, 2009, and D) the Gulf Islands purse seine survey from June 1-5, 2009.

In 2009, there were 14 populations observed in the survey (Figure 9C) with the "summer-run" population dominant (Figure 10D). The escapement from the 2007 spawning in the Fraser River would represent the expected percentage of the populations that would enter the Strait of Georgia in 2009 and return in 2011. The expected percentages of the adult return in two years (Figure 10E) were similar to the observed percentages in Figure 10D. As in the 2008 samples, the composition of the catches in July 2009 is representative of the total of all populations leaving the Fraser River in 2009, indicating that the survey in July was catching a sample of fish that was representative of the population.

In the July 2009 survey, Chilko Lake sockeye salmon represented about 40% of the samples. If these fish entered the Strait of Georgia in mid May (see explanation on page 82), on average, they were resident in the strait for about two months, confirming that some juvenile sockeye salmon remain and feed in the Strait of Georgia for several

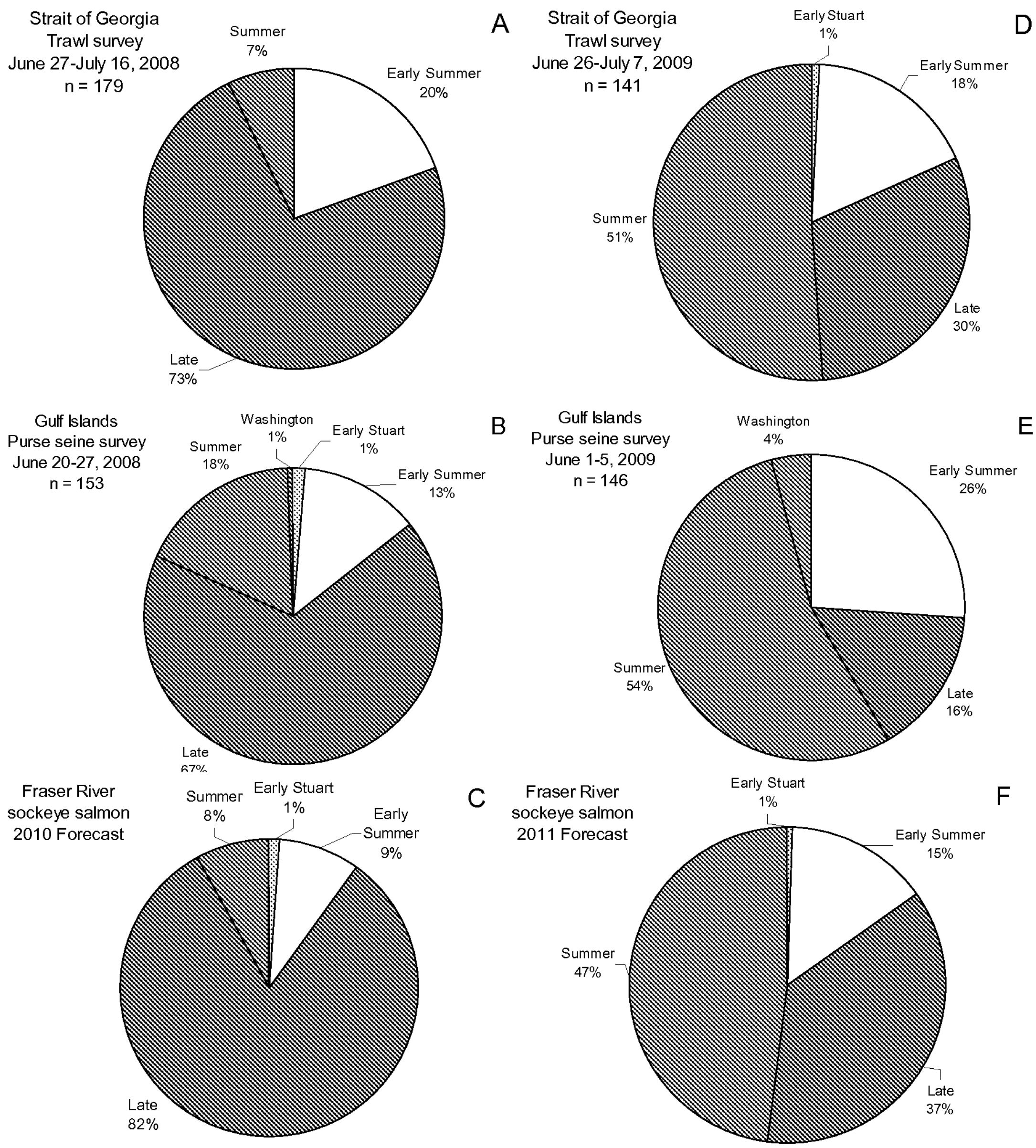


Figure 10. DNA composition of juvenile sockeye salmon captured in A) the Strait of Georgia July 2008 survey, B) the Gulf Islands survey from June 20-27, 2008, C) the expected proportions of the aggregate of specific run timings based on the stock assessment forecast for returns in 2010, showing that the samples in the survey are representative of the expected population composition, D) the Strait of Georgia July 2009 survey, E) the Gulf Islands survey from June 1-6, 2009, F) the expected proportions of the aggregate of specific run timings based on the 2011 stock assessment forecast showing that the samples in the survey are representative of the expected population composition. The populations are shown as aggregates of populations that are used in the management of sockeye salmon.

months. This confirms that these juvenile sockeye salmon do not move rapidly out of the Strait of Georgia. Chilko Lake sockeye salmon also dominated the catch in the Gulf Islands in June 2009, (Figure 9D) indicating that the dominant population was distributed throughout the Strait of Georgia and did not move rapidly out of the Strait of Georgia.

The percentage of age 3 and age 4 Harrison adult sockeye salmon alternated in relation to the presence or absence of juvenile pink salmon (Figure 11). In even-numbered years when there are large numbers of juvenile pink salmon in the Strait of Georgia, there is a higher percentage of fish that return as 4-year-olds. There were very large catches in September 2008 and because 2008 is an even-numbered year, there should be a large return of 4-year-olds in 2012 as well as a large return of 3-year-olds in 2011.

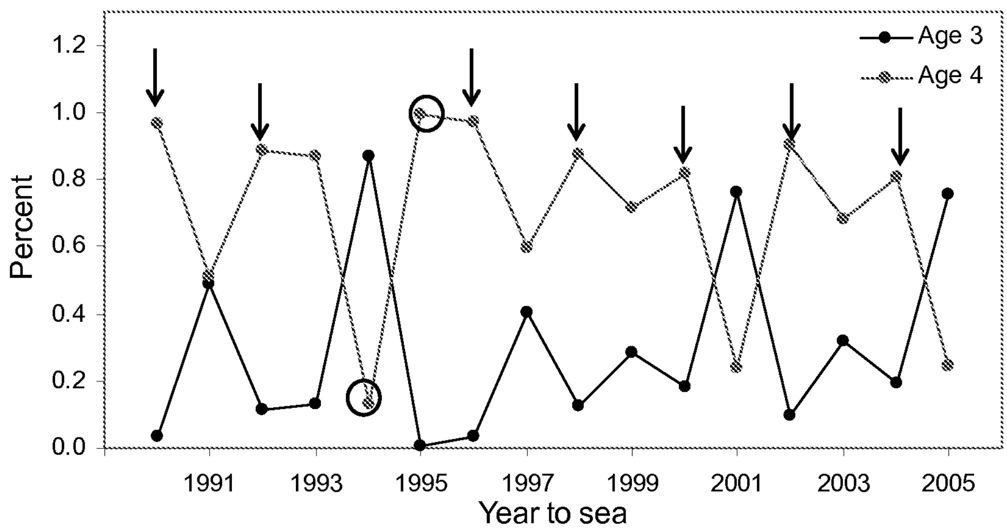


Figure 11. The percentage of Harrison River sockeye salmon returning as age 4 is higher when ocean entry of the brood year coincides with juvenile pink salmon entering the Strait of Georgia from the Fraser River. Arrows indicate the years in which the relationship holds and the circled years (1994, 1995) indicate that there is no relationship.

Juvenile sockeye, coho, chinook and chum salmon growth, diets and catches in 2007

Summary

In the spring and summer of 2007, juvenile sockeye salmon in the Strait of Georgia were the least abundant and had the poorest condition factor in the 11 years of trawl surveys in July. There was no question that the few juvenile sockeye salmon that survived through

to July in the Strait of Georgia were in poor condition. Catches of chum salmon were also the lowest in the 11 years of surveys. Juvenile coho salmon were the smallest in the 11 years of surveys with the lowest condition factor and highest percentage of empty stomachs. The health of juvenile chinook salmon was identical to juvenile coho salmon. Juvenile chinook salmon were the smallest in the 11 years with the lowest condition factor and highest percentage of empty stomachs. The similarity in the population ecology of all species of juvenile Pacific salmon in the Strait of Georgia in the spring and summer of 2007 is convincing evidence that low availability of prey in the Strait of Georgia was the reason for the generally poor condition and survival of all juvenile Pacific salmon in general and sockeye salmon in particular.

Evidence of poor growth and survival of juvenile Pacific salmon in 2007

Lengths of juvenile Pacific salmon in our catches in July are a measure of growth. It is important to recognize that these are measurements of fish that have survived and it is generally assumed that the surviving fish are the faster growing individuals. Individual fish are measured for length and weight, but accurate measurements of weight are only possible when the ship is stable. Consequently, we weigh fewer fish than we measure for length. We use a measure of the condition of a fish that is the standard W / L^3. This condition factor, or fitness of a fish, is a way of determining if an individual is "skinny" or "fat." A skinny fish with a low condition factor (<1.0) is generally considered to be less healthy than a heavier fish. A low condition factor or a skinny fish most likely is a consequence of reduced food or increased metabolic demands, or both. Poor condition of the surviving fish may eventually result in mortality in the first ocean winter according to the critical size critical period hypothesis (Beamish and Mahnken 2001). This hypothesis proposes that fish that grow rapidly in the early marine period begin to store energy as lipids early in the summer and it is these lipids that enable the fish to survive the harsh conditions in the first ocean winter. Stomach contents of all five species of juvenile Pacific salmon are routinely recorded from freshly caught specimens. A high percentage of empty stomachs of the fish that survived is additional evidence of reduced prey availability. There were very few juvenile pink salmon in the Strait of Georgia in July 2007, thus no measurements are available for pink salmon in 2007.

Sockeye salmon

The average length and weight of juvenile sockeye salmon in the catches in July 2007 (Figure 12A-B) resulted in the lowest condition factor in the 11 years of surveys (Figure 13). The percentage of fish with empty stomachs was about average (Figure 12C). The reduced abundance and poor condition of the few surviving juvenile sockeye salmon would be a consequence of very poor conditions for growth and survival in the Strait of Georgia early in 2007.

Later in this report (page 89) we show that the juvenile sockeye salmon that left the Strait of Georgia by early July 2007 were also very small relative to other years. This small size indicated that poor growth in the Strait of Georgia was the most likely explanation for the small sizes of the juvenile sockeye salmon in 2007. The condition of juvenile sockeye salmon in September 2007 (Harrison River sockeye salmon) was much better (Figure 13) than the sockeye salmon from other areas. We show later in this report that juvenile Pacific salmon that enter the Strait of Georgia later than the other populations were generally growing and surviving better.

Coho salmon

In July 2007, juvenile coho salmon were the smallest in length and weight in the 11 years of surveys (Figure 14A). The condition factor was also the lowest of all surveys, indicating that conditions for growth were poor. Furthermore, coho salmon had the highest percentage of empty stomachs in 2007 compared to all surveys from 1998 to 2009 (Figure 14C). Catches of coho salmon were about average in July 2007. However, the abundances of juvenile coho salmon in the Strait of Georgia have declined to low levels in recent years (Beamish et al. 2008a, 2010a), making it difficult to use these low abundances in July as a measure of productivity.

Chinook salmon

Juvenile chinook salmon in July 2007 were the smallest in length and in weight in the 11 years of surveys (Figure 15A-B) and, like coho salmon, had the lowest condition factor in 2007. Chinook salmon also had the second highest percentage of empty stomachs in July 2007 (Figure 15C). Catches of chinook salmon in July were about average. However, like coho salmon, the abundances of juvenile chinook salmon in July are now quite small, making it difficult to use the low catches as an indicator of production.

Chum salmon

Juvenile chum salmon are the most abundant of all juvenile Pacific salmon in our surveys. In July 2007 the catch was the lowest in all years (Figure 16D). Most chum salmon return to spawn as 4-year-olds. Thus, the juvenile chum salmon observed in the trawl surveys in 2007 would return to spawn in 2010. The very low catches in 2007 may indicate that the abundance of spawning chum salmon in rivers flowing into the Strait of Georgia could be very low in 2010. Juvenile chum salmon were relatively large compared to other years (Figure 16A); however, the low abundance in 2007 (Figure 16D) most likely indicates that a large number of juvenile chum salmon did not survive from ocean entry until July. Thus, the few fish that did survive and were in our samples were in about an average condition. There was also no indication of an abnormally high percentage of empty stomachs in 2007 (Figure 16C).

Discussion

The synchrony in the generally poor condition or poor survival, or both, of all juvenile Pacific salmon in the spring of 2007 in the Strait of Georgia is convincing evidence that food was severely limiting for these juveniles when they first entered the Strait of Georgia. Severely reduced food for juvenile Pacific salmon would decrease growth and increase mortality. Thus, it is to be expected that there would above average mortality of juvenile sockeye salmon in the Strait of Georgia in 2007.

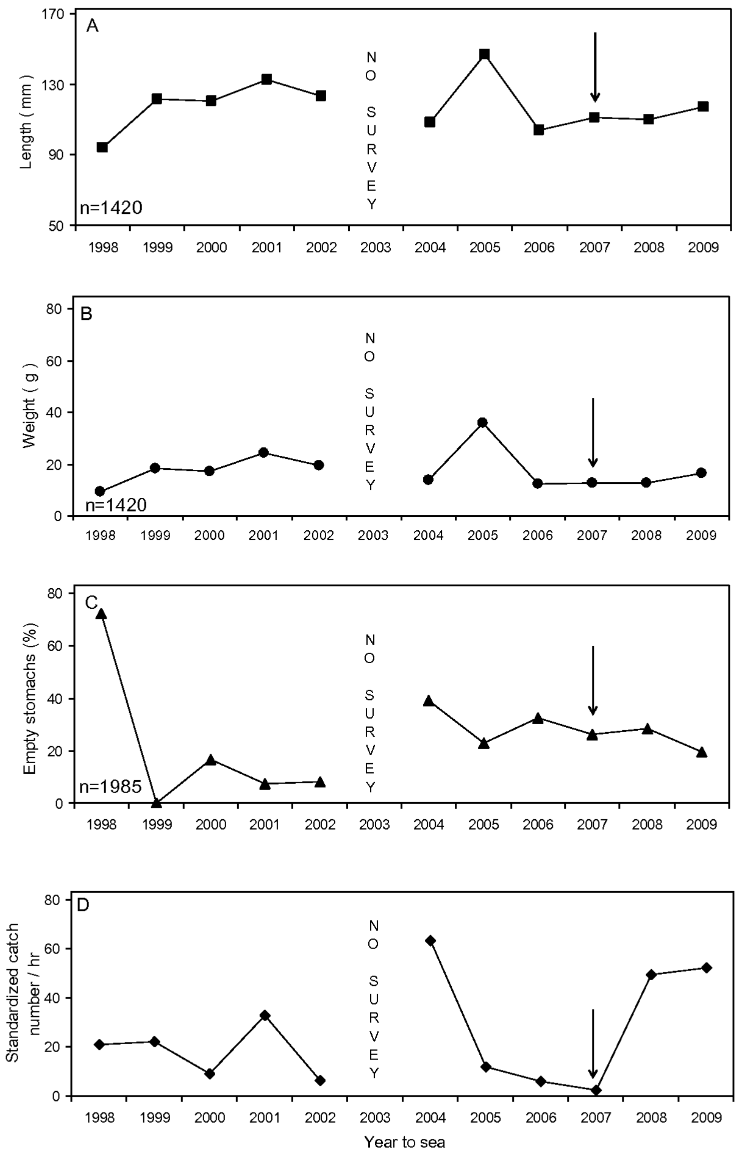
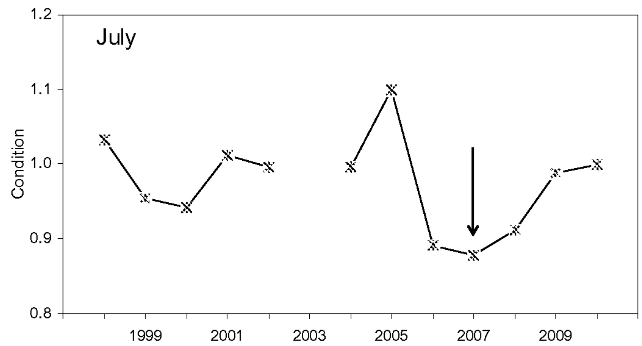


Figure 12. A) Average fork length (mm), B) weight (g), (C) percentage of empty stomachs, and D) catch for juvenile sockeye salmon in the July surveys in the Strait of Georgia 1998-2009. There was no survey in 2003. Arrows indicate the values for 2007. The lengths in A will differ slightly from the lengths in Figure 42A because the lengths here are only for the fish that were also weighed.



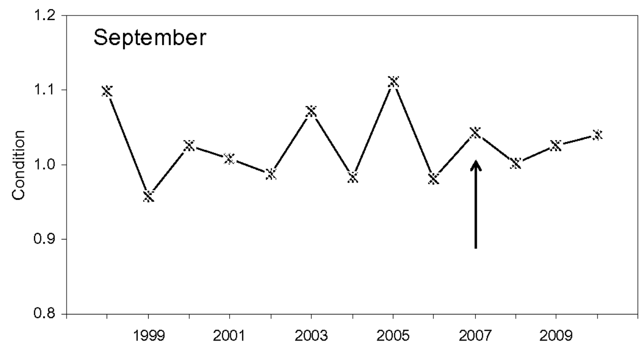


Figure 13. The average condition factor for samples of juvenile sockeye salmon collected in the Strait of Georgia in July and September, showing the low value in July 2007 and the higher values in September 2007. An estimate for July 2010 is included.

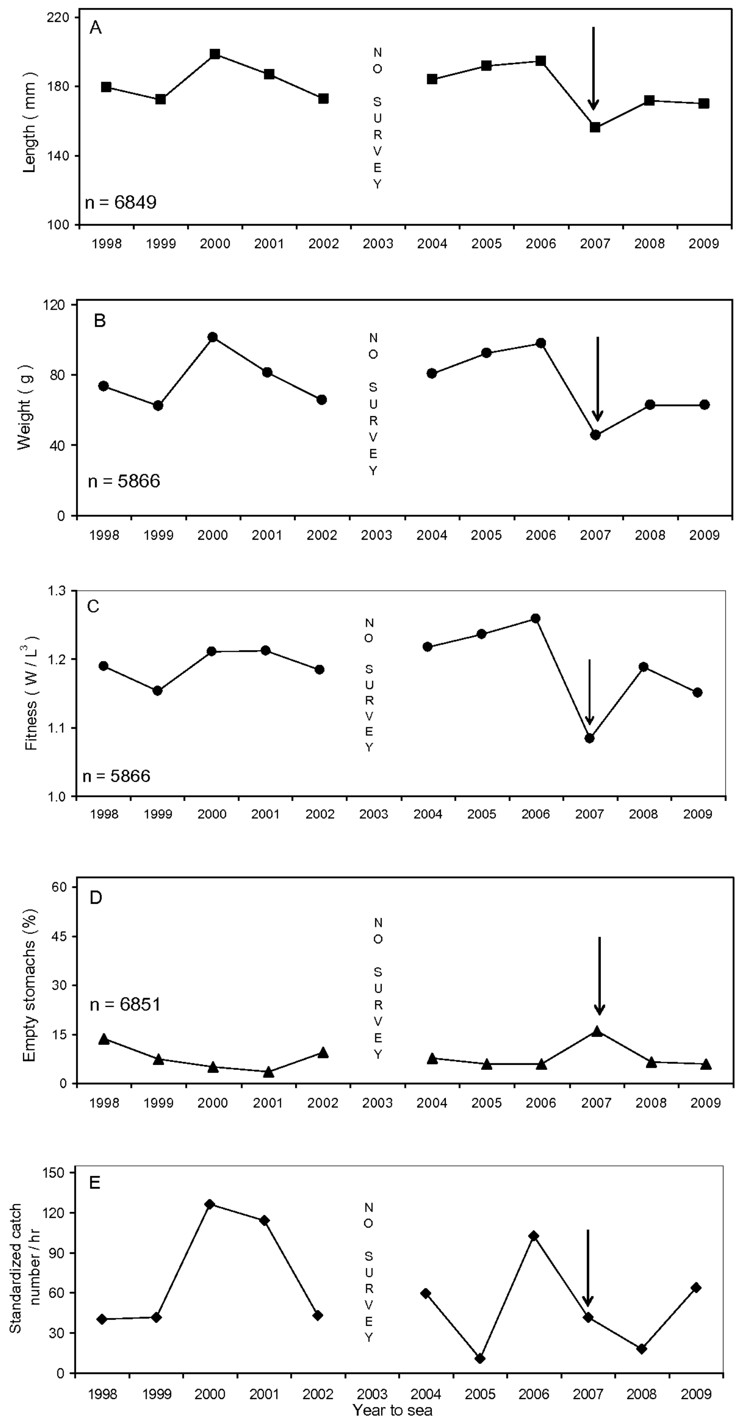


Figure 14. (A)Average fork length (mm), (B) weight (g), (C) fitness (W/L^3), (D) percentage of empty stomachs, and (E) catch of juvenile coho salmon in the July surveys in the Strait of Georgia. Arrows indicate the values for 2007.

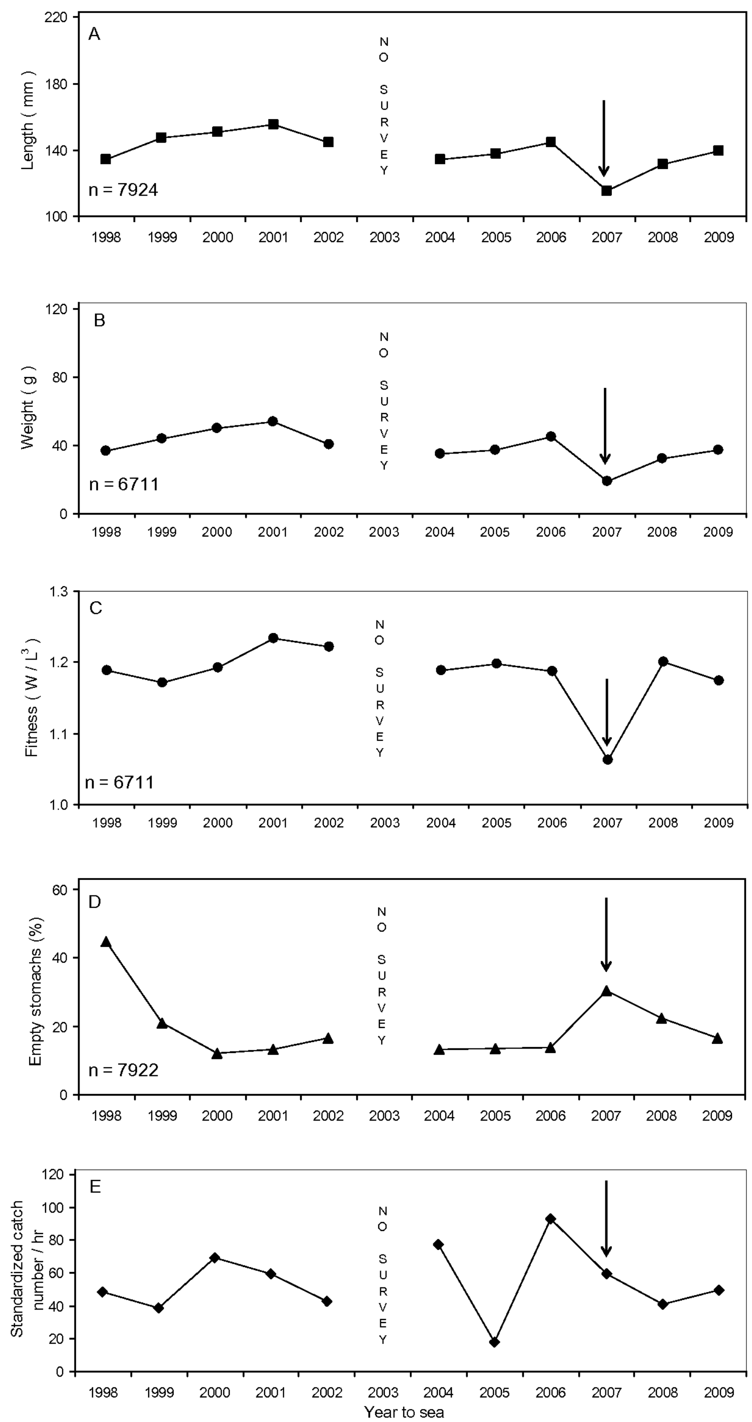


Figure 15. (A) Average fork length (mm), (B) weight (g), (C) fitness (W/L^3), (D) percentage of empty stomachs, and (E) catch of juvenile chinook salmon in the July surveys in the Strait of Georgia. Arrows indicate the values for 2007.

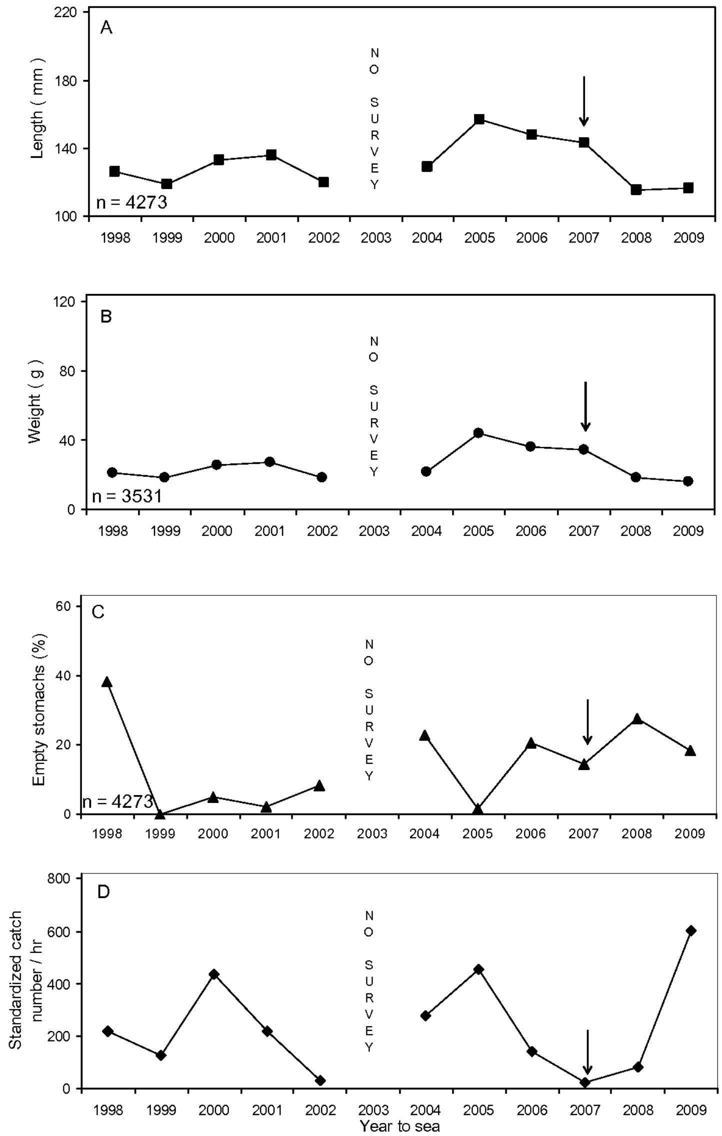


Figure 16. A) Average fork length (mm), B) weight (g), C) percentage of empty stomachs, and (D) catch of juvenile chum salmon in the July surveys in the Strait of Georgia 1998-2009. There was no survey in 2003. The arrows indicate values for 2007.

Impact of the environment on the growth and survival of juvenile Pacific salmon in the Strait of Georgia in 2007

Summary

The Strait of Georgia has warmed over the past 40 years. The average increase in temperature in the surface waters in May and June when juvenile Pacific salmon enter the Strait was about 1.5 °C from 1970 to 2005. Warmer ocean waters require that energy from food is used for metabolism and not growth or energy storage. If food consumption is also reduced because of competition or poor plankton production, growth is reduced even more.

Increases in plankton production in the Strait of Georgia in the spring begin when there is a stable surface layer that has an optimal depth for sunlight penetration. Wind and discharge from the Fraser River can combine to destabilize the mixing layer, reducing plankton production. The wind conditions in the spring of 2007 and high flows from the Fraser River and other rivers flowing into the Strait of Georgia resulted in an estimated mixing layer depth that was the shallowest in 30 years. Although there are no measures of plankton production in the spring of 2007, it is probable that plankton production was reduced or at least the preferred prey of Pacific salmon was reduced which would reduce growth. The fish that did not grow quickly most likely died during this early marine period, either from predation or disease, or both. Later in this report we show that hundreds of millions of juvenile sockeye salmon entered the Strait of Georgia in 2007. It is a basic principle in ecology that plants and animals that produce a large number of seeds or offspring will have a very large early mortality. Thus, it is to be expected that there will always be large mortalities of juvenile sockeye salmon in the Strait of Georgia. If conditions in the water column are not suitable for food production, even larger mortalities would be expected to occur and occur quickly.

Changes in the marine environment including a general warming

It is now recognized that conditions in the ocean can profoundly affect the production of Pacific salmon. The importance of ocean conditions may appear self evident; however, the impact of ocean conditions was considered by early researchers to be random. This interpretation resulted in relatively little attention to ocean impacts on juvenile Pacific salmon survival until the 1970s and 1980s.

An important change in the trend in climate occurred in 1977, resulting in ocean conditions that were generally much more favourable for Pacific salmon production. For example, the dramatic increases in Pacific salmon production in Alaska are a consequence of the ocean changes after 1977. Sockeye salmon production from the Fraser River also improved at this time, resulting in larger abundances. Other known trend changes occurred in 1989 and 1998 (McFarlane et al. 2000, King 2005). Beamish et al. (2004c) showed that the production of Fraser River sockeye salmon followed distinct climate regimes. The climate regime shift in 1989 resulted in a period of reduced production for sockeye salmon in the 1990s. These recent changes since 1989 have also not been favourable for most coho and chinook salmon that enter the Strait of Georgia. At the same time that shifts in climate-ocean trends occurred, there has been a general warming of the Strait of Georgia (Figure 17). The increased temperatures have been particularly large in the surface waters at the time most juvenile Pacific salmon enter the Strait of Georgia (Figure 18), although there has been some cooling in recent years. If the warming trend since the early 1970s is a consequence of global warming, the warming would be expected to continue. Thus, although there will be year-to-year variation in climate, it might be expected that the current temperature trends will persist over the long term.

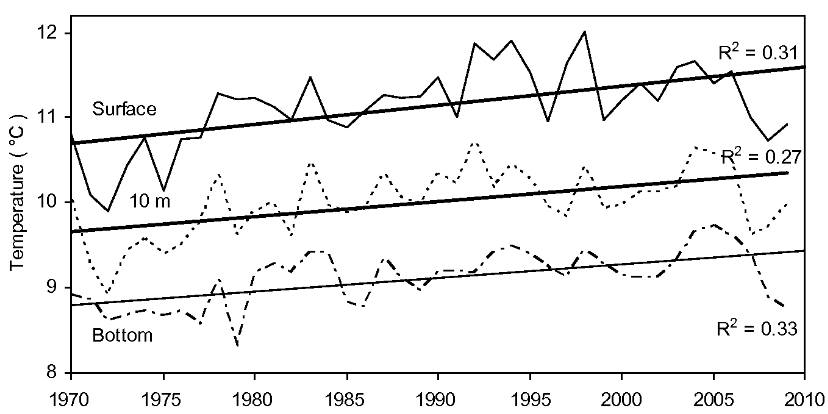


Figure 17. Average annual temperatures at the surface, 10 m and bottom in the Strait of Georgia, showing the increasing warming from 1970 until 2005.

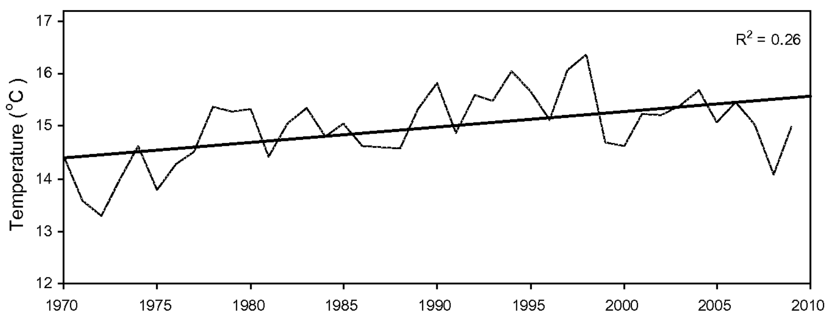


Figure 18. The increasing warming in the surface waters from 1970 to 2005 during the time that juvenile Pacific salmon enter the Strait of Georgia from May to September.

Winds, Fraser River flows and plankton layer depth

Monthly mean wind data from the Met Buoy C46146 (49°20.4N, 123 ° 43.6W) located on Halibut Bank were used to identify the mean wind stress (wind speed squared in the alongshore direction) from April, May and June. The May 2007 values were anomalously weak winds (Figure 19).

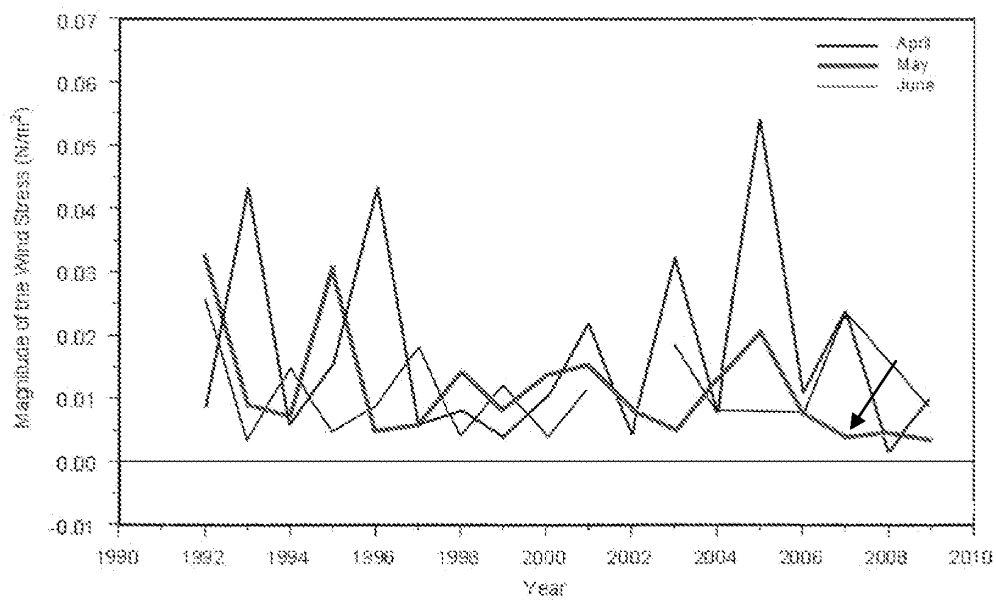


Figure 19. Average wind stress magnitude at the Met Buoy (C46146) located on Halibut Bank (49°20.4N, 123 ° 43.6W) for April, May and June, from 1992 to 2009. The arrow shows the value for May 2007.

Plankton production increases in the spring when waters stratify, forming a less dense surface mixed layer. A stable surface layer retains phytoplankton at an optimal depth range that ensures that the sunlight penetrates to the bottom of the layer (Yin et al. 1997). The depth and stability of the mixing layer can affect the amount of phytoplankton produced (Gargett 1997). The optimal stability of the layer is related to the amount of freshwater discharge, the amount of wind and the intensity of solar radiation. Climate effects have been linked to the production of biological organisms through variation in the mixed layer depth (Polovina et al. 1995). Plankton production requires a supply of nutrients, sunlight and surface layer of water that stabilizes the process of optimizing the delivery of sunlight and nutrients to the rapidly growing plankton. If there is a brackish surface layer in the strait, and if this layer is stable and shallow because of high river discharge and weak wind mixing, plankton will be constrained to a thin, highly opaque layer incapable of entraining nutrients from the underlying marine waters. The layer will greatly diminish light penetration, and eventually will result in insufficient nutrients for plankton growth. This differs from open ocean regions where optimal plankton production occurs when there is optimal stability of the surface mixing layer (Gargett 1997). Gargett (1997) describes optimal plankton production as a balancing act between processes such as freshwater flows and warming that stabilize the layer and processes such as strong winds that can destabilize the layer.

In the Strait of Georgia, the depth of the mixed layer is a balance between the stabilizing effect of freshwater input, solar heating that produces buoyant surface waters and the destabilizing effect of winds that promote mechanical mixing within this surface layer. Freshwater discharge is an important contribution to the establishment of the mixing layer in the Strait of Georgia, but wind mixing is the major factor affecting the stability of the mixing layer (St. John et al. 1993). In March and April of 2007 there was exceptionally large discharge from the Fraser River (Figure 20) and other rivers flowing into the Strait of Georgia.

The Thomson and Fine (2009) method for calculating mixed layer depth was used to estimate the average mixed layer depth in the Strait of Georgia from 1979 to 2008. The estimate is not an actual measure of the depth, but a proxy for the measurement. The average depth for the combined months March, April, May was the shallowest in 2007 (Figure 21). This is an indication that plankton production would be reduced at the time of ocean entry of juvenile sockeye salmon and most other Pacific salmon in the spring of 2007. Thus the winds and flows from the Fraser River appear to have combined to prevent the formation of an optimal and stable mixing layer in the spring of 2007.

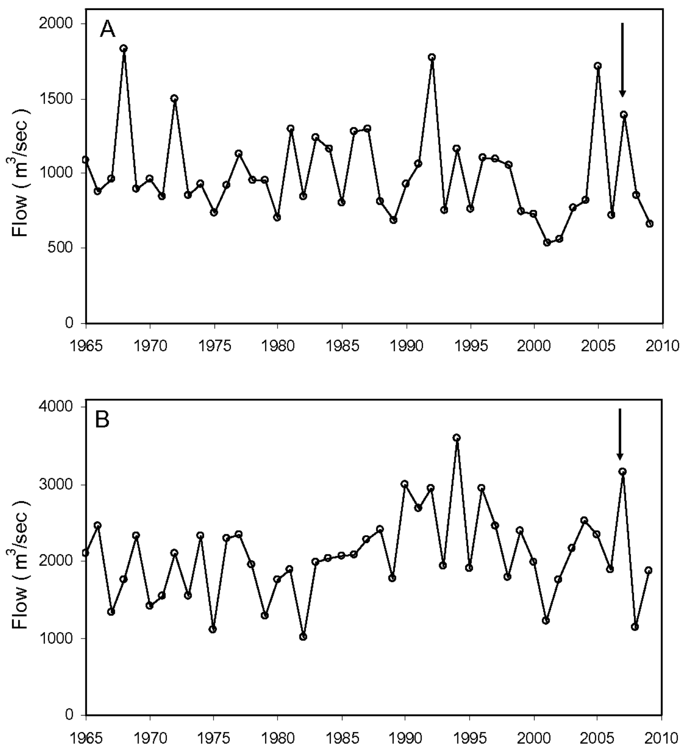


Figure 20. Average daily Fraser River flows (in cubic meters per second), (A) March and (B) April from 1965-2009. Arrows identify the large flows in 2007. Data obtained from Environment Canada for station number 08MF005 at Hope.

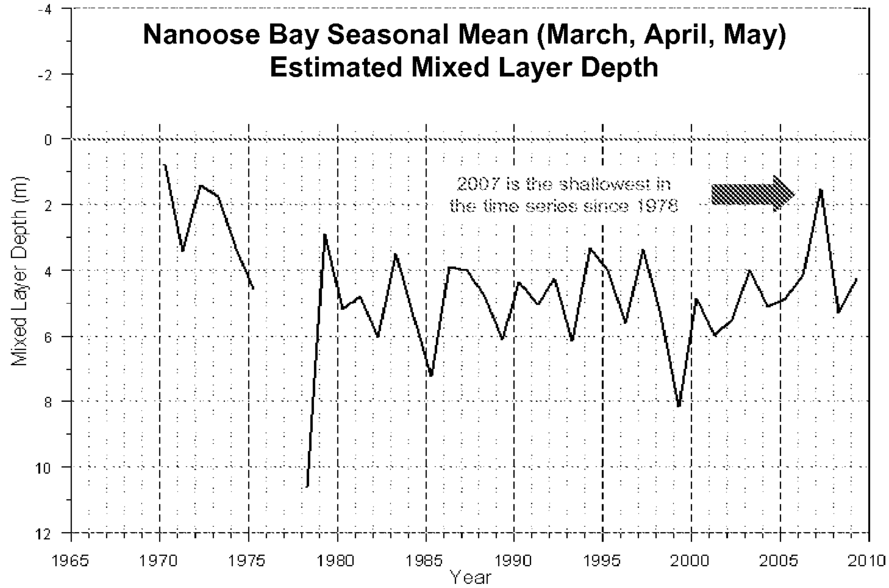


Figure 21. The monthly mean mixed layer depth at Nanoose Bay in Spring (March-April-May) from 1978 to 2009. The arrow identifies the extremely shallow mixing layer depth in 2007.

September trawl surveys and the abundance of Harrison River sockeye salmon

Summary

Juvenile sockeye salmon were commonly captured in most years in the southern Strait of Georgia in September. In 2007, there were 24 times more juvenile sockeye salmon in the catches in the September survey than in the July survey. In the years that DNA analysis was available, virtually all of these juveniles were from the Harrison River. These sockeye salmon in September were in much better condition than the juvenile sockeye salmon captured in July. Juvenile Harrison River sockeye salmon were not abundant in the Gulf Islands in September but were there in a November 2008 survey, possibly indicating that they were moving out of the Strait of Georgia through a southern route. The fish captured in November were about 2 times the size of juveniles entering the strait four months earlier, indicating that they were resident in the Strait of Georgia over this period. In the winter of 2004, a trawl survey in the northern Strait of Georgia captured sockeye salmon from Harrison River. This could indicate that some migrate north out of the Strait of Georgia or that in some years small numbers of juvenile sockeye salmon

remain in the strait over winter. The late ocean entry into the Strait of Georgia relative to all other populations of sockeye salmon most likely results in better feeding conditions and improved growth and survival.

Sockeye salmon typically have a “lake-type” life history in which they rear in a lake after emerging from the gravel for about one year. Less common are the “sea type” (Gilbert 1914) that remain in the river for several months after emergence from the gravel and then enter the ocean in their first year. Some authors recognize a “river type” which are fish that remained in a river for a prolonged period, but Wood et al. (2008) consider that river-type sockeye salmon are a special case of the sea-type life history as both do not rear in lakes.

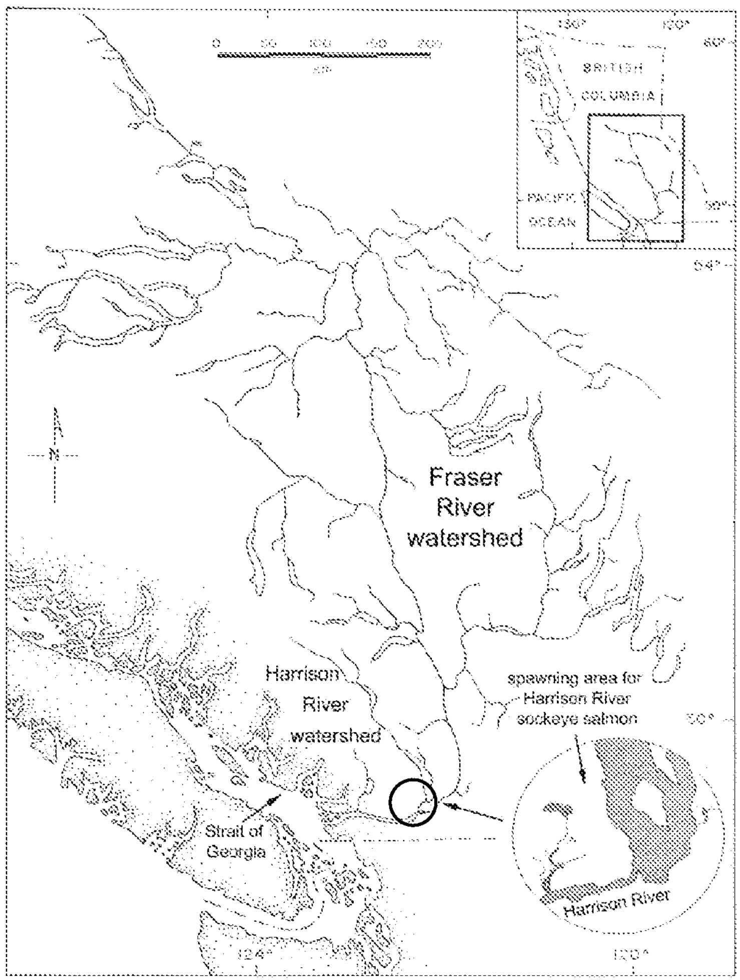


Figure 22. Map of Fraser River drainage area showing the Harrison River drainage.

In the Fraser River, the largest population of sea-type sockeye salmon occurs in the Harrison River (Figure 22). From 1950 to 2004, the Harrison River sockeye salmon accounted for an average of 1% of the total sockeye salmon return to the Fraser River. In the last five years, from 2005 to 2009, the Harrison River sockeye salmon accounted for an average of 9% and up to 21% of the total production of Fraser River sockeye salmon. Lake-type sockeye salmon also occur within the Harrison River drainage. The percentage that the Harrison River sockeye salmon contribute to the total production of all sockeye salmon in the Harrison River drainage was high in the 1950s and 1960s, decreased through to the early 1990s and in the last five years is at historic high levels (Figure 23). The total returns to the Harrison River averaged 69,600 individuals from 1952 until 2009 (Figure 24). The largest return of 421,000 occurred in 2005 and the second largest return occurred in 2009 (Figure 24).

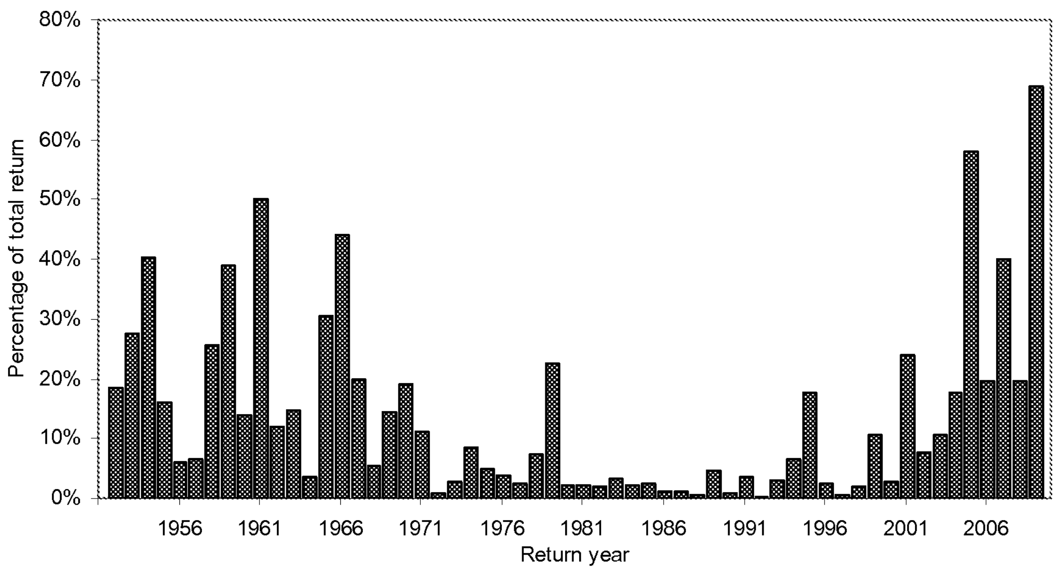


Figure 23. Percentage of sockeye salmon returning to the Harrison River (sea-type) in relation to the total return to all major spawning areas within the Harrison River drainage (Harrison, Weaver and Birkenhead rivers).

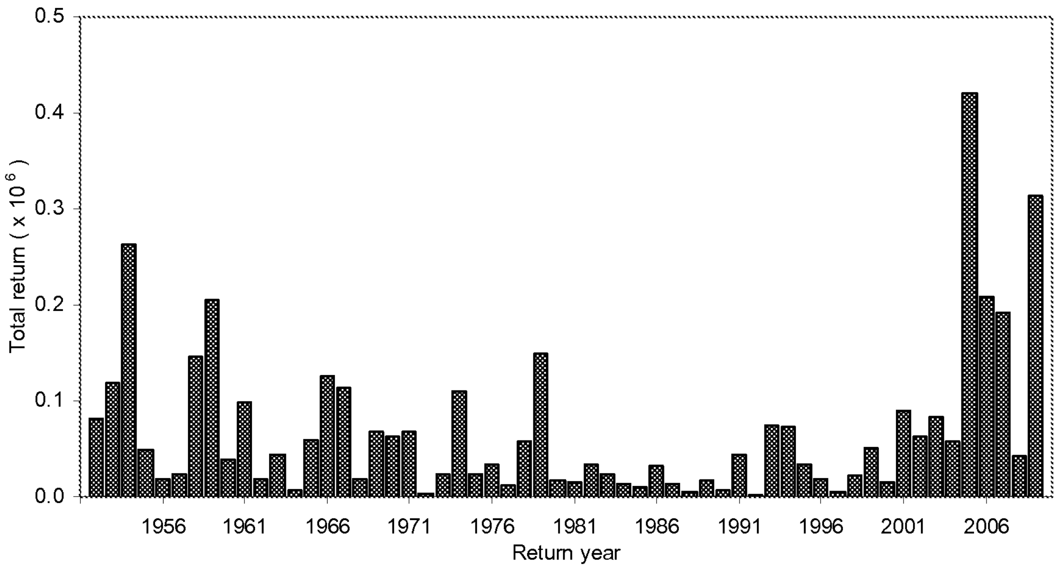


Figure 24. Total return of sockeye salmon to the Harrison River, 1952-2009.

Juvenile sockeye salmon were commonly captured in the September trawl surveys in all years except 2006 when they were rarely found. The CPUE increased beginning about 2002 and was the highest in 2008 (Figure 25). DNA stock identification in 2008 and 2009 showed that virtually all the sockeye salmon captured in these September surveys were from the Harrison population (Figure 26). However, a bimodal length distribution in some years and the capture of some lake-type sockeye salmon in February probably indicates that, in some years, lake-type sockeye salmon remain in the Strait of Georgia past July. Harrison sockeye salmon tend to be more abundant in the southern areas of the strait, although their distributions varied among years (Figure 27, 2009 to 1998). Years with large catches in September were 2007 and 2008. Average catches were in 1999, 2002, 2003, 2004, 2005 and 2009. The lowest catches occurred in 1998, 2000, 2001 and 2006 (Figure 27). A comparison of the distributions of juvenile sockeye salmon in July and September 2007 (Figure 28) highlights the difference in abundances and in behaviour of the sea-type (Figure 28B) and lake-type (Figure 28A) life histories. The CPUE in September 2007 was 24 times higher than observed in July. This indicates that the conditions for juvenile sockeye salmon survival were better in early summer 2007 when the Harrison River sockeye salmon entered the strait than in the spring when the lake-rearing sockeye salmon entered. The size of Harrison River sockeye salmon in September was about double the size when they entered the ocean indicating that a substantial amount of growth occurs in the Strait of Georgia. Previously, (Figure 13) it was shown that the condition of the juvenile sockeye salmon captured in September 2007 was much better than the condition of the sockeye salmon captured in July, showing that the Harrison River sockeye salmon are generally growing better than all other juvenile sockeye salmon.

The average Juvenile Harrison River sea-type sockeye salmon enter the ocean approximately six weeks after the average lake-type sockeye salmon (see pages 83-84). It appears that Harrison River sockeye salmon are moving into the open waters of the Strait of Georgia about the time when most other juvenile sockeye salmon are leaving or have left the southern areas of the strait. They begin to aggregate in Howe Sound, about mid July, but gradually move into the Strait of Georgia by September.

Very few juvenile sockeye salmon were captured in the Gulf Islands in the September surveys in 2008 (13 sockeye salmon in 44 sets) and 2009 (4 sockeye salmon in 48 sets). The larger catch of juvenile sockeye salmon in the Gulf Islands in November 2008 (see next section of this report) that were virtually all Harrison River sockeye salmon (Figure 29) indicates that these fish move into the Gulf Islands area late in the year. This may indicate a movement out of the Strait of Georgia through Juan de Fuca Strait.

The recent improved survival of the Harrison River population compared to the other populations of sockeye salmon appears to be a result of their late entry into the ocean. The production of fry in fresh water is important, but it appears to be the availability of prey in the summer that improves their marine survival and is increasing their productivity. The success of the sea-type life history compared to the lake-type life history emphasizes the importance of recognizing the different life history strategies within a population. In a period of expected climate change, it would seem logical that these life history strategies need to be protected.

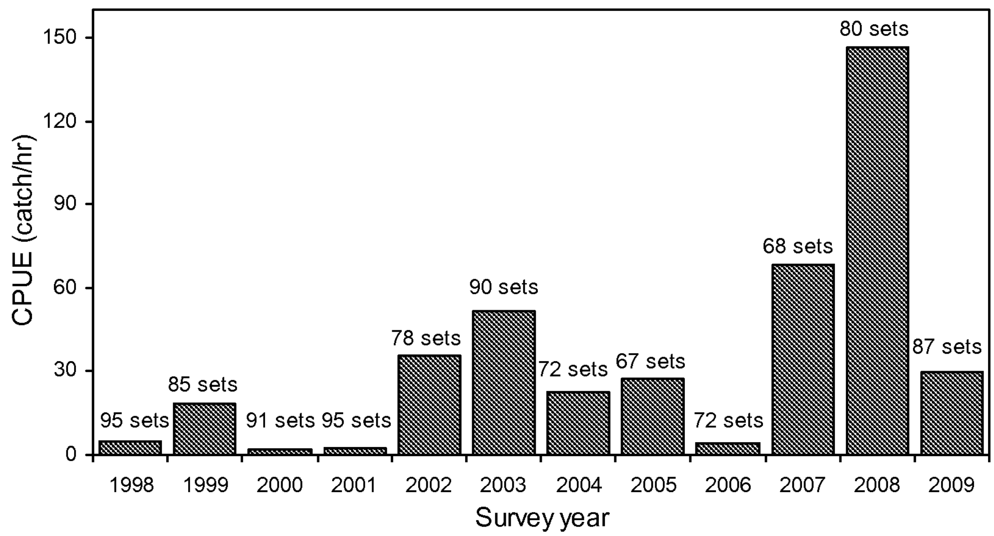


Figure 25. Catch standardized to one hour or catch per unit effort (CPUE), for sockeye salmon in the trawl survey in September in the Strait of Georgia, 1998-2009.

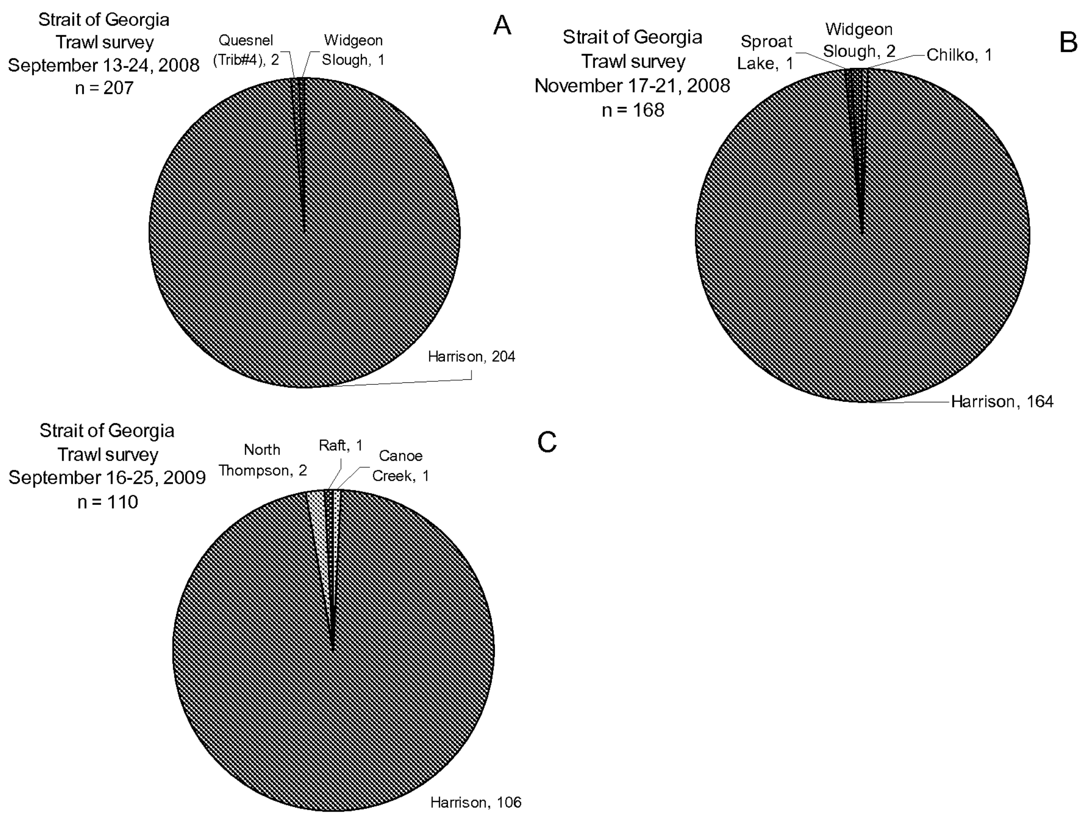


Figure 26. Population composition of juvenile sockeye salmon captured in the Strait of Georgia trawl survey as indicated by the DNA analysis in A) September 13-24, 2008, B) November 17-21, 2008 and September 16-25, 2009.

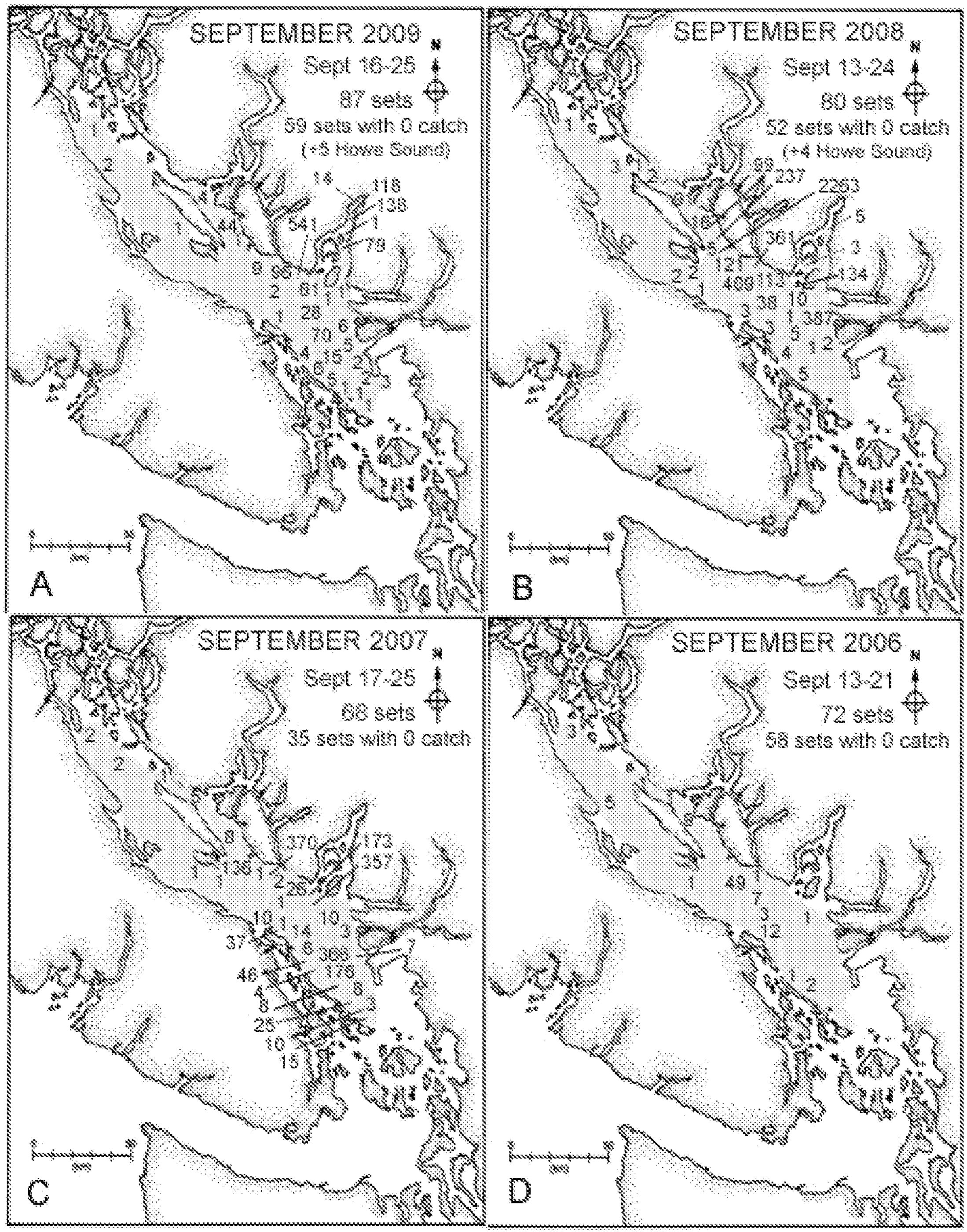


Figure 27. Sockeye salmon catches (in 30 minutes) in September trawl surveys for A) 2009, B) 2008, C) 2007, D) 2006. The survey area is shown in light blue. Zero catches are not shown to facilitate the comparison among years. The survey was identical in to the track lines in Figure 1 in all years, with sets made in the same approximate location. The number of sets with 0 catch is identified.

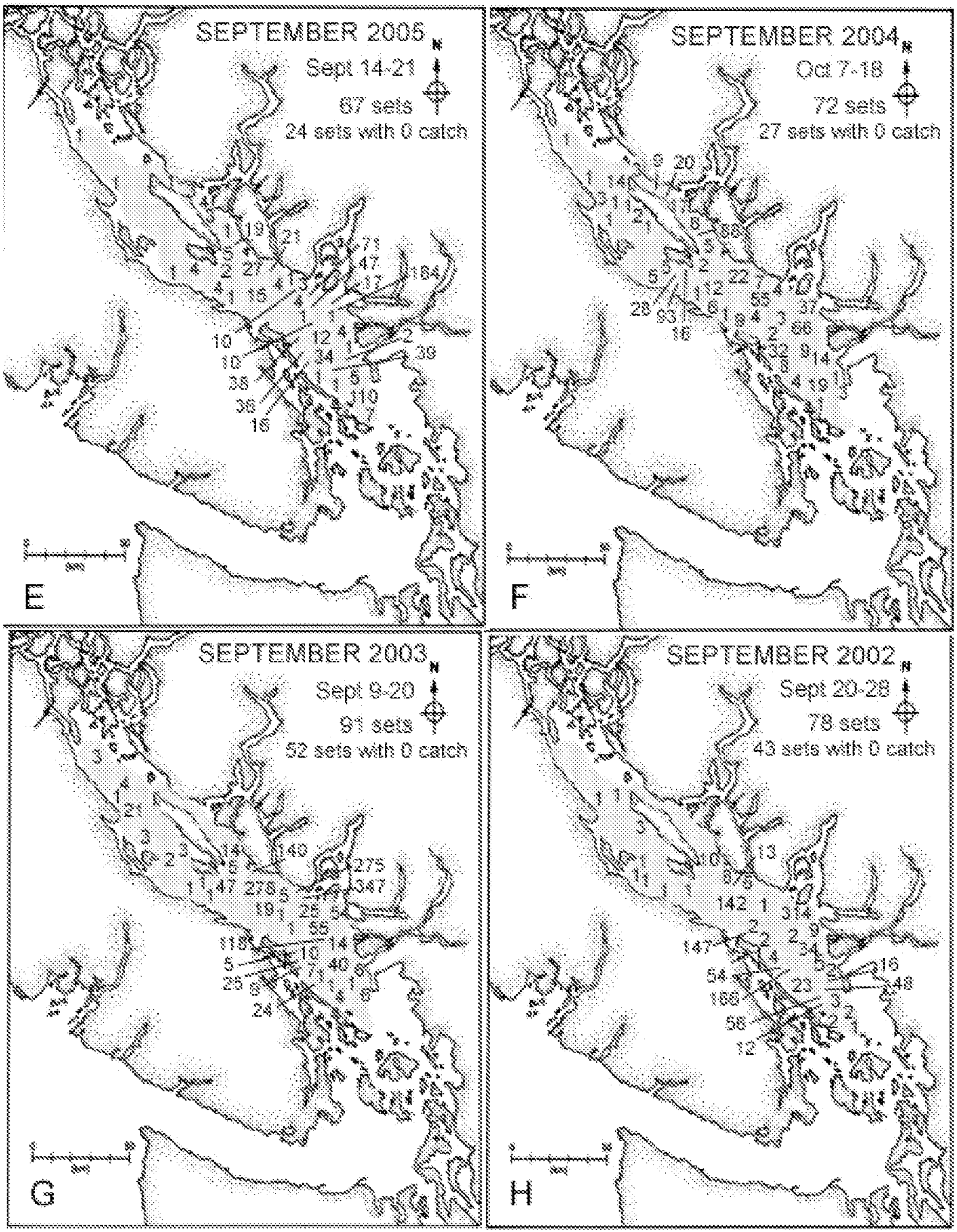


Figure 27 (Continued). Sockeye salmon catches (in 30 minutes) in September trawl surveys for E) 2005, F) 2004, G) 2003 and H) 2002. The survey area is shown in light blue. Zero catches are not shown to facilitate the comparison among years. The survey was identical to the track lines in Figure 1 in all years, with sets made in the same approximate location. The number of sets with 0 catch is identified.

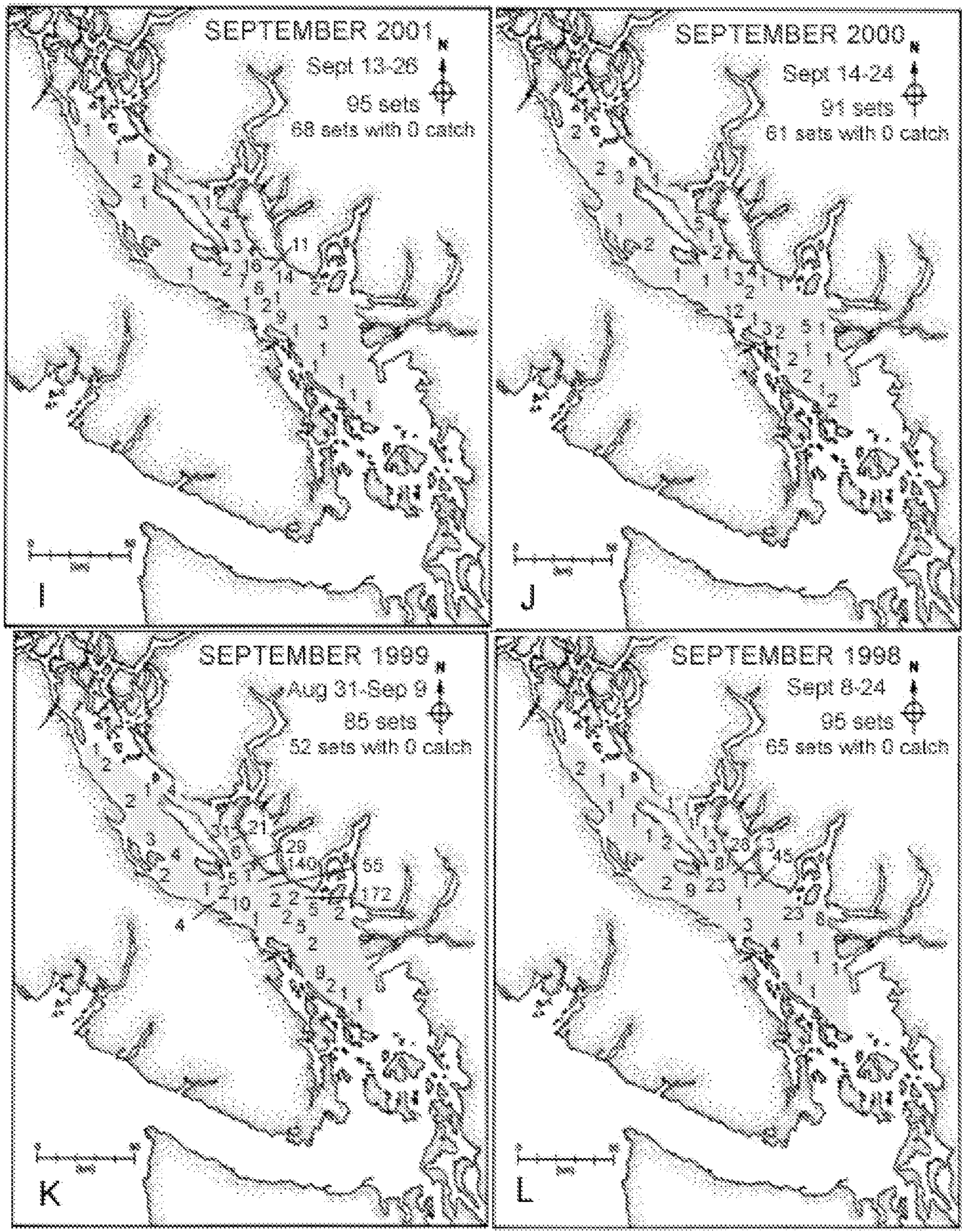


Figure 27 (Continued). Sockeye salmon catches (in 30 minutes) in September trawl surveys for I) 2001, J) 2000, K) 1999 and L) 1998. The survey area is shown in light blue. Zero catches are not shown to facilitate the comparison among years. The survey was identical to the track lines in Figure 1, with sets made in the same approximate location. The number of sets with 0 catch is identified.

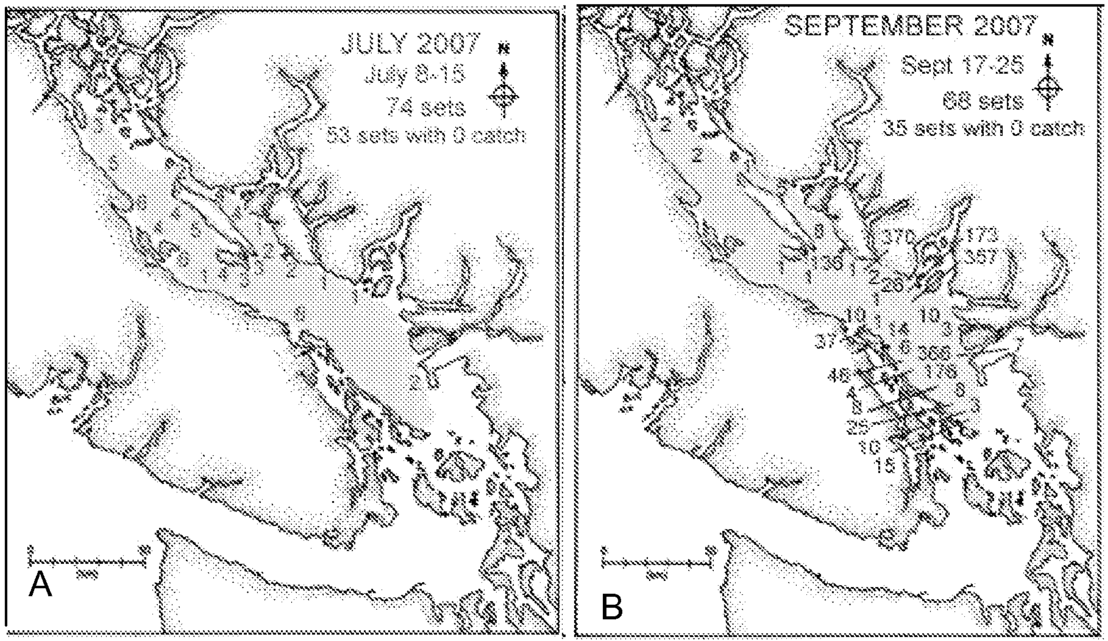


Figure 28. Sockeye salmon catches (in 30 minutes) in the trawl surveys in A) July 2007 and B) September 2007, showing the large increase in catches in September compared to July in 2007. Juvenile salmon in the July catches were virtually all in the northern area of the strait and in the southern area in September.

November 2008 trawl survey and sockeye salmon catches

A trawl survey of the Gulf Islands, southern Strait of Georgia and Howe Sound was completed from November 17-21, 2008. The Gulf Islands region was surveyed from November 17-19 and 23 sets captured 108 juvenile sockeye salmon (CPUE = 10.3). The average length of these sockeye salmon was 149 mm (S.D. = 12.6). The results of the DNA analysis showed that 98% of these sockeye salmon originated from the Harrison River (Figure 29). The southern Strait of Georgia was surveyed on November 19 and 21, and 14 sets captured 103 juvenile sockeye salmon (CPUE = 15.8). The average length was similar to the fish captured in the Gulf Islands at 150 mm (S.D. = 9.54) and 96 % these fish originated from the Harrison River. The mean length of about 150 mm indicated that the Harrison River sockeye salmon probably remained in the Strait of Georgia and grew from the average length of approximately 69 mm observed in late July in 2008 (Figure 7A). There were 9 sets in Howe Sound on November 20, 2008 but no sockeye salmon were captured. Thus, it appeared that juvenile Harrison River sockeye salmon remained in the Strait of Georgia for about four months and left by November by migrating through the Gulf Islands and out through Juan de Fuca Strait.

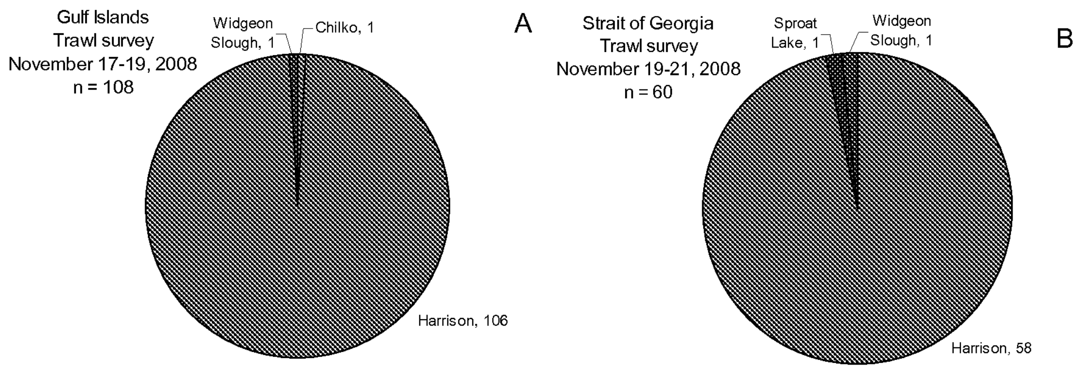


Figure 29. Population composition from the results of the DNA analysis of juvenile sockeye salmon captured in A) the Gulf Islands from November 17-19, 2008 and B) the Strait of Georgia from November 19 and 21, 2008.

February 2004 trawl survey and sockeye salmon catches

From February 11-13, 2004, 34 sockeye salmon were captured in the trawl that was fished just off the bottom between French Creek and Cape Lazo (Figure 30). These sockeye salmon ranged in length from 205 to 270 mm and averaged 235 mm (Figure 31). Ages were not determined, but their lengths indicated that these fish were spending their first ocean winter in the Strait of Georgia. DNA was analyzed for 33 sockeye salmon and 5 were identified as Harrison River sockeye salmon (Figure 31). The catches are included in this report to indicate that some sockeye salmon remain in the Strait of Georgia in their first marine winter. In particular, some Harrison River sockeye salmon were still in the strait. The catches in the northern Strait of Georgia may indicate that some Harrison River sockeye salmon might eventually exit the Strait of Georgia through Johnstone Strait.

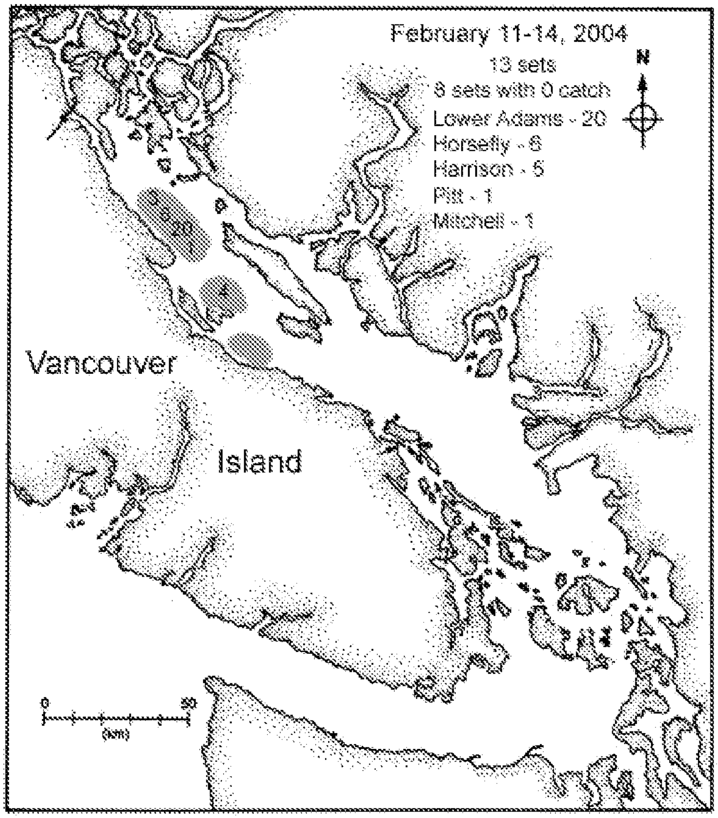


Figure 30. Location of trawl survey conducted from February 11-14, 2004. The populations represented in the sample are shown in the upper right. Harrison sockeye salmon represented 15% of the sample. The survey area is shown in light blue.

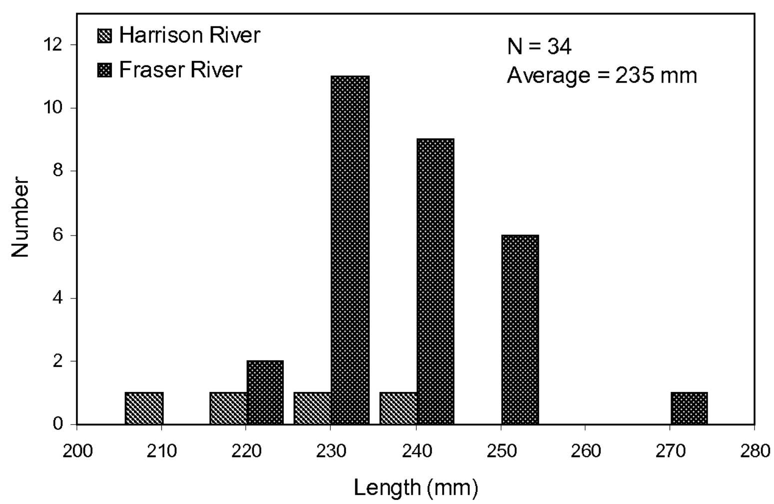


Figure 31. Lengths of sockeye salmon captured in the Strait of Georgia in February 2004. Red bars indicate length of Harrison River sockeye salmon and blue bars indicate lengths of all other Fraser River sockeye salmon.

Gulf Islands surveys and sockeye salmon catches

Summary

The Gulf Islands area has traditionally been a major rearing area for juvenile sockeye salmon. In 2008 and 2009, we surveyed the area using the trawl net and using a purse seine with a small mesh bunt. Results are reported to show that many more juvenile sockeye salmon moved into the Gulf Islands area in June to July 2008 than in 2009, indicating that the movements of juvenile sockeye salmon within the Strait of Georgia differ among years. There also is evidence that in some years juvenile sockeye salmon are resident for about a month in the Gulf Islands area.

Trawl surveys

Trawl surveys in the Gulf Islands were carried out in June 24-26 and July 16-17, 2008 and June 24-26 and July 17-19, 2009. In 2008, the CPUE of lake-type, juvenile sockeye salmon in the Gulf Islands in June and in the Strait of Georgia in July was similar, but the lengths were larger in the Gulf Islands (Table 1). This similarity indicates that the population of juvenile sockeye salmon was distributed throughout the northern and southern areas, including the Gulf Islands area. The larger individuals in the Gulf Islands may indicate that fish had been resident here longer and had grown. The CPUE of juvenile sockeye salmon in the trawl survey in the Gulf Islands later in July 2008 decreased substantially, indicating the juvenile sockeye salmon were moving out of the area (Table 1). Catches were smaller in 2009 compared to 2008. In late June 2009, the catches of juvenile sockeye salmon in the Gulf Islands were about four times smaller than at the same time in 2008 (Table 1). The catches were also substantially smaller than in the open Strait of Georgia. The survey later in July 2009 caught only three sockeye salmon. There were major differences in the pattern and timing of movements of juvenile sockeye salmon in the southern Strait of Georgia between 2008 and 2009, but in both years the catches in the Gulf Islands declined by mid July. Unfortunately, we were not able to fish in the exit areas of the Strait of Georgia later in July, so we are not able to identify if the juvenile sockeye salmon in the Gulf Islands left through Juan de Fuca Strait. We believe that they moved north and out through Johnstone Strait, as our survey in Juan de Fuca Strait in mid July caught very few juvenile sockeye salmon (see Figure 50).

Table 1. Juvenile sockeye salmon catches in the trawl surveys in the Gulf Islands in June and July 2008 and 2009. Catches in the Strait of Georgia are included for comparison.

2008	Date	June 24-26, 2008	June 27-July 6, 2008	July 16-17, 2008
	Location	Gulf Islands	Strait of Georgia	Gulf Islands
	Catch	672	1,662	21
	CPUE	59.3	49.3	2.5
	Mean fork length (mm)	111	106	111
	(SD)	(7.3)	(11.0)	(9.0)
	Number measured for length	401	1,239	21

2009	Date	June 24-26, 2009	June 26-July 7, 2009	July 17-19, 2009
	Location	Gulf Islands	Strait of Georgia	Gulf Islands
	Catch	131	1,585	3
	CPUE	15.7	53.0	0.4
	Mean fork length (mm)	108	116	116
	(SD)	(9.2)	(10.3)	(11.1)
	Number measured for length	131	1,183	3

Purse seine surveys

Purse seine surveys were conducted on June 20-27, 2008 and June 1-5, 2009. The location of the sets and the methods used are summarized in Beamish et al. (2010b). In 2008, the catches of juvenile sockeye were larger than in 2009 (Figure 32). The survey in June 2009 was about three weeks earlier than in 2008. We did not observe a reduction in CPUE in the trawl survey in the open Strait of Georgia in 2009, thus, it is possible that juvenile sockeye salmon from the Fraser River were still migrating into the Gulf Islands area in June 2009 as observed by Healey (1980) in the late 1970s. In 2009, the average lengths of the fish from the purse seine were smaller compared to those collected in the trawl study about 22 days later (Figures 33). This is evidence that the fish had grown an average of 8 mm over these 22 days and that these juvenile sockeye salmon most likely were resident in the Gulf Islands over this period. Although we cannot prove that the same fish remained in the Gulf Islands for about a month, it is the most likely explanation and an important observation because it shows that some juvenile sockeye salmon will remain in the Strait of Georgia and not migrate quickly out of the strait.

In late June 2008, populations of late-run juvenile sockeye salmon dominated the catch in the trawl and purse seine surveys (Figures 10B, 34A-B). The approximate percentages of the expected proportion of late-run populations (Figure 10C) closely matched the observed percentages in the sample analyzed for DNA, indicating that the populations of all juvenile Pacific salmon were distributed throughout the Gulf Islands as well as throughout the Strait of Georgia (Figures 9A, 10A, 34A-B). In 2009, the composition of the catch in the June 24-26 survey was dominated by the Chilko Lake population (Figure 34D), as was expected from the forecast for the adult return in 2011 (Figure 10C). Despite the differences in abundances in the Gulf Islands between 2008 and 2009, the general conclusion was that the populations of juvenile sockeye salmon were distributed in their expected proportions throughout the Strait of Georgia, including the Gulf Islands, through to the middle of July.

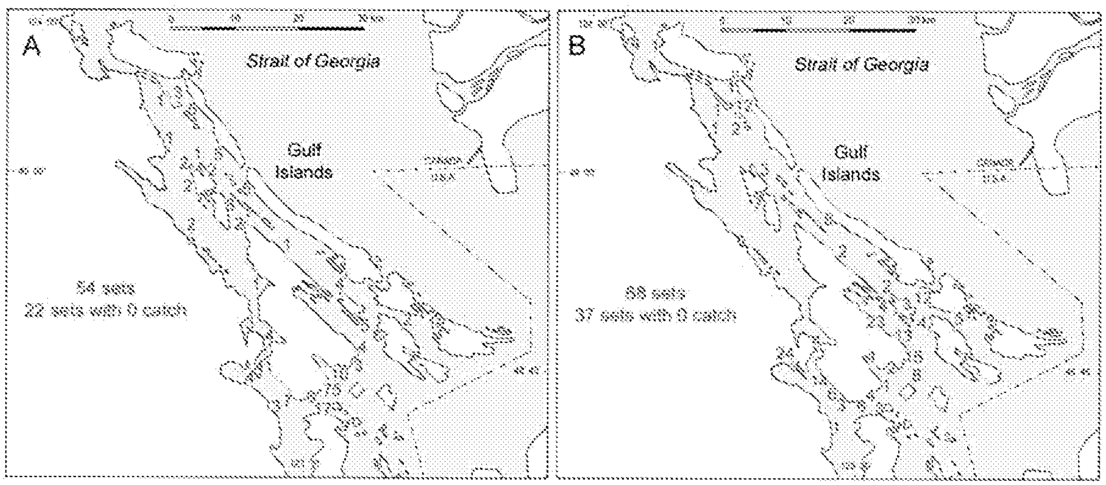


Figure 32. Catch of juvenile sockeye salmon in purse seine surveys in the Gulf Islands for A) June 1-5, 2009 and B) June 20-27, 2008.

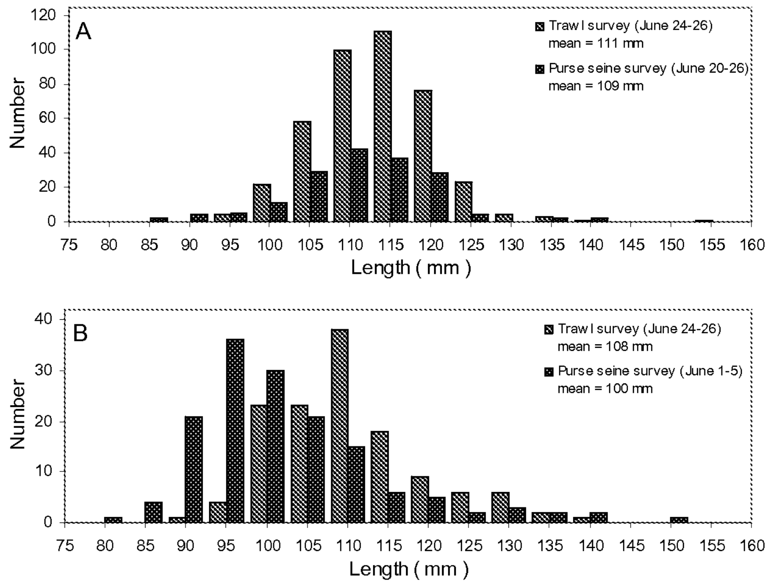


Figure 33. A comparison of lengths of sockeye salmon captured in the trawl and purse seine surveys in the Gulf Islands in A) June 2008 and B) June 2009.

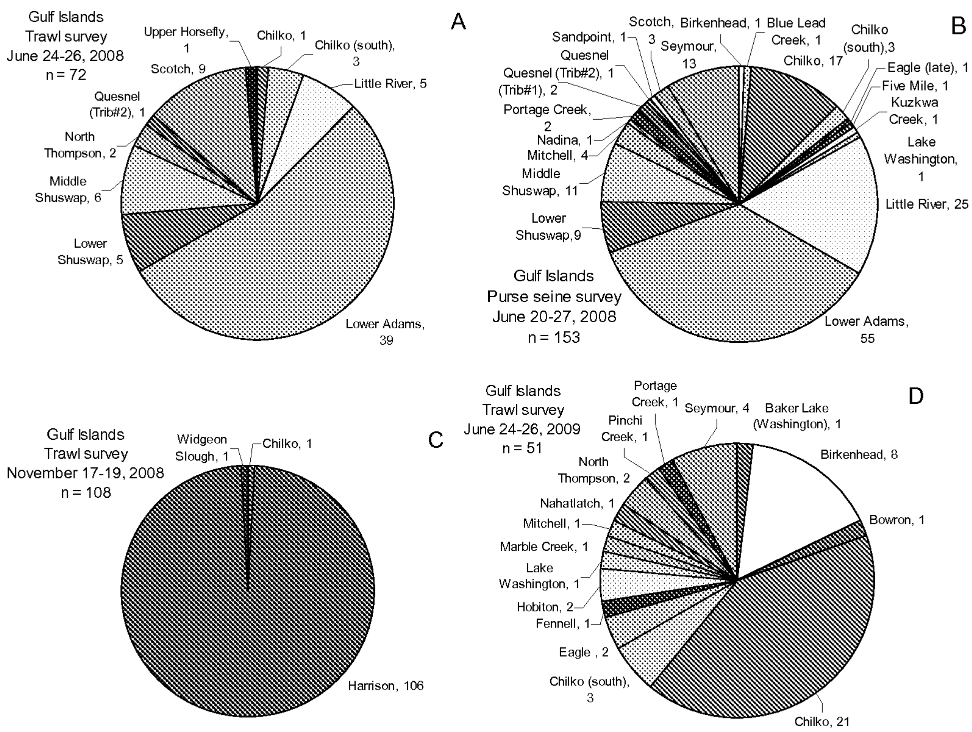


Figure 34. DNA composition of juvenile sockeye salmon captured in the Gulf Islands in A) in the trawl survey June 24-26, 2008, B) in the purse seine survey June 20-27, 2008, C) in the trawl survey November 17-19, 2008, and D) in the trawl survey June 24-26, 2009.

Responses of other species to conditions in the Strait of Georgia in the spring 2007

Summary

The virtual absence of age 0 juvenile Pacific herring in surveys in September 2007 indicates that there was a major mortality of the larval and juvenile age 0 Pacific herring. It is likely that the poor survival of juvenile Pacific herring resulted from a reduction in plankton availability early in 2007. The mortality that led to the poor survival most likely occurred when the larval Pacific herring first started feeding, which would be before mid May when most juvenile sockeye salmon entered the Strait of Georgia.

Juvenile chinook salmon that entered the Strait of Georgia later than most other chinook salmon stocks had very good marine survival. These South Thompson summer chinook salmon entered the Strait of Georgia in July and August, about eight weeks after most other chinook salmon stocks entered the strait. These chinook salmon mixed with the Harrison River sockeye salmon that also entered the strait about the same time and much later than most other sockeye salmon. The good survival of both Harrison River sockeye salmon and South Thompson summer chinook salmon indicated that a life history type of late ocean entry is currently surviving better than other populations of the same species, most likely because feeding conditions are better fro these species in the early summer.

Pacific herring

Most Pacific herring (*Clupea harengus pallasi*) in the Strait of Georgia spawn in March. Their eggs are deposited on aquatic plants in the nearshore areas and hatch in about 2-3 weeks. First feeding, therefore, would occur about mid to late April. Metamorphosis (when larval fish first look like adults) occurs about 10 weeks after hatching at a length of 24-40 mm (Hourston and Haegele 1980).

Pacific herring remain in the Strait of Georgia for their first ocean year after which they are reported to move offshore (Schweigert et al. 2009). Most Pacific herring return to spawn in the Strait of Georgia when they are age 3. It is during the spawning period that a percentage of the population is fished for their roe. Mature Pacific herring are reported to migrate back offshore after spawning. The biomass of the spawning fish may be made up of about 50% of the first-spawning, age 3, Pacific herring (Schweigert et al. 2009). There is a purse seine survey by the Pacific herring assessment group that fishes 10 transects and 48 stations throughout the Strait of Georgia to determine the relative abundance of juvenile Pacific herring in their first ocean year in the Strait of Georgia (Schweigert et al. 2009). In recent years, this survey occurred in late September. In 2007, the mean catch of 0.006 kg of Pacific herring was the lowest catch in the 19 years of the surveys (Figure 35A, Schweigert et al. 2009). The second lowest catch was in 2005. Recruitment to the fishery from the 2005 year class occurred in 2008 and was one of the lowest on record (Schweigert et al. 2009). This indicates that there was a very large mortality of the larval herring in the spring of 2007 and that recruitment from the 2007 year class could also be poor in 2010.

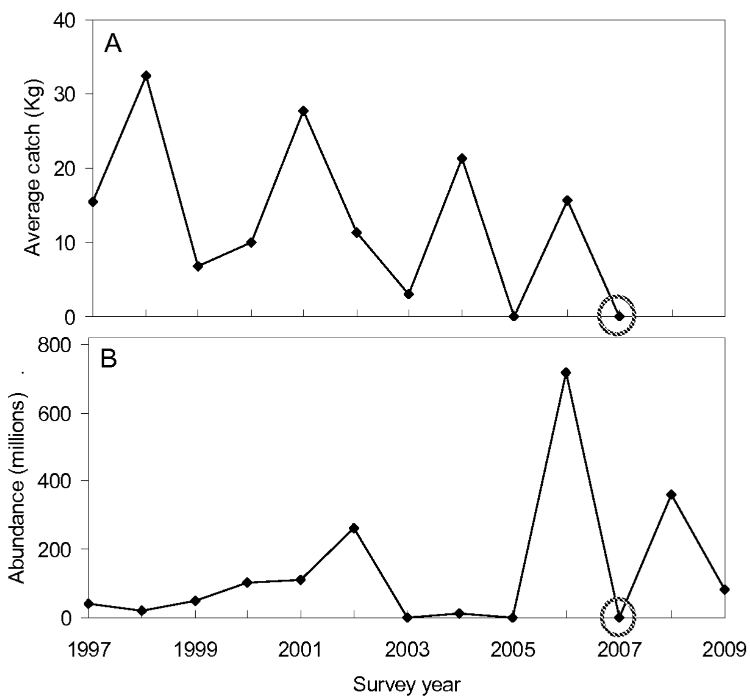


Figure 35. (A) The average catch of juvenile (age 0+) Pacific herring from the Pacific herring assessment purse seine survey in September in the Strait of Georgia. (B) Estimated abundance of juvenile (age 0+) Pacific herring from the September trawl survey. In September 2007 there were virtually no age 0+ Pacific herring caught in the trawl survey. Abundance was estimated using the top 45 m as the area that contained age 0+ Pacific herring.

Our trawl survey in September catches juvenile (age 0+) Pacific herring at an average length of about 95-100 mm in length. Our surveys are for the entire strait and more offshore, compared to the closer to shore purse seine sampling by the Pacific herring assessment group. Despite the different gear and the areas sampled, our survey also identified very poor catches of juvenile (age 0+) Pacific herring in 2007 (Figure 35B). The very low catch of juvenile Pacific herring in their first ocean year in 2007 indicates that larval and juvenile mortality was exceptionally high. It is probable that a lack of food was the major cause of exceptional early marine mortality.

South Thompson chinook salmon

Summary

There are 14 populations of chinook salmon from the South Thompson drainage. These fish spawn in the summer and after the juveniles emerge from the gravel they enter the Strait of Georgia about mid July or about eight weeks later than the average ocean entry time for all other chinook salmon populations. By September, most other populations of chinook salmon have left the strait or died and about 70% to 80% of the remaining chinook salmon are from the South Thompson drainage. The South Thompson chinook salmon probably leave the Strait of Georgia through Juan de Fuca Strait in October and November. This late ocean entry life history type is similar to the life history type of Harrison River sockeye salmon that are also surviving very well. This indicates that conditions in the Strait of Georgia in July and August appear to be suitable for this life history type and an indication of the importance of managing to protect the naturally evolved diversity within populations of a particular species.

There are 14 populations of chinook salmon (summer chinook) that make up the South Thompson summer chinook salmon DNA baseline (Figure 36). Juvenile chinook salmon from these populations have a life history that is similar to the ocean-type, except that they remain in fresh water longer (about six months) in the spring than most other chinook salmon. Adults return to spawn in the summer. In general, South Thompson summer chinook salmon stocks have been very productive in recent years as indicated by the increasing escapements since the mid-1990s (Figure 36). Six stocks (Lower Adams, Little River, Lower Shuswap/Upper Adams, Lower Shuswap, Middle Shuswap and South Thompson River) have been particularly productive.

We examined the DNA of about 4,000 juvenile chinook salmon collected in the Strait of Georgia in 2006, 2007, 2008 and 2009 (Figure 37). These analyses show that juvenile chinook salmon from the South Thompson group begin to increase in abundance in the Strait of Georgia in July after most other juvenile chinook salmon have entered the strait. The percentages of all other chinook salmon that enter the Strait of Georgia (shown in six major DNA groupings) indicate that in late June to early July 2008 and 2009 the percentage of South Thompson populations (Figure 37, Table 2) is less than 10%. In 2006 and 2007 the percentages were about 20% to 40%. By September the percentages of South Thompson chinook salmon in 2006, 2007, 2008 and 2009 ranged from 63 to 79% (Figure 37, Table 2). In mid July, the South Thompson chinook salmon in the Strait of Georgia averaged about 100 mm (Figure 39). These late ocean entry chinook salmon are much smaller than the chinook salmon that entered the ocean earlier. Despite their small size, they survive very well. By mid September, the average length was about 150 mm, indicating that the fish were feeding and growing in the strait (Figure 40). The relatively few chinook salmon from the South Thompson population in November were much smaller than the other chinook salmon (Figure 41) possibly indicating that movement out of the strait was size related. We estimated the abundance of juvenile chinook salmon in the Strait of Georgia during our surveys in July and September using the methods described by Beamish et al. (2000). These abundance estimates indicated that in 2006 and 2007, there were about the same number of South Thompson chinook salmon in the Strait of Georgia from about late July to late September. In 2008 the abundance was almost 30 times larger in September than in early July (Table 2). These abundances of South Thompson chinook salmon in September were substantially larger than the population aggregates from all other chinook salmon populations within the Fraser River watershed. A survey in November 17-21, 2008 completed 14 sets only in the southern Strait of Georgia and is not representative of the distribution throughout the Strait of Georgia. However, the DNA from the sample of 55 chinook salmon indicated that South Thompson chinook salmon represented only 5% of the sample (Figure 38). It is possible that this indicates that South Thompson chinook salmon had left the Strait of Georgia by November or died or both. A study in September 2008 placed 78 acoustic tags in juvenile chinook salmon that were shown to be from the South Thompson drainage by their DNA (Neville et al. 2010). Seven of these fish were detected leaving the Strait of Georgia through Juan de Fuca Strait in October and November, confirming that this is the time and place that they migrate offshore.

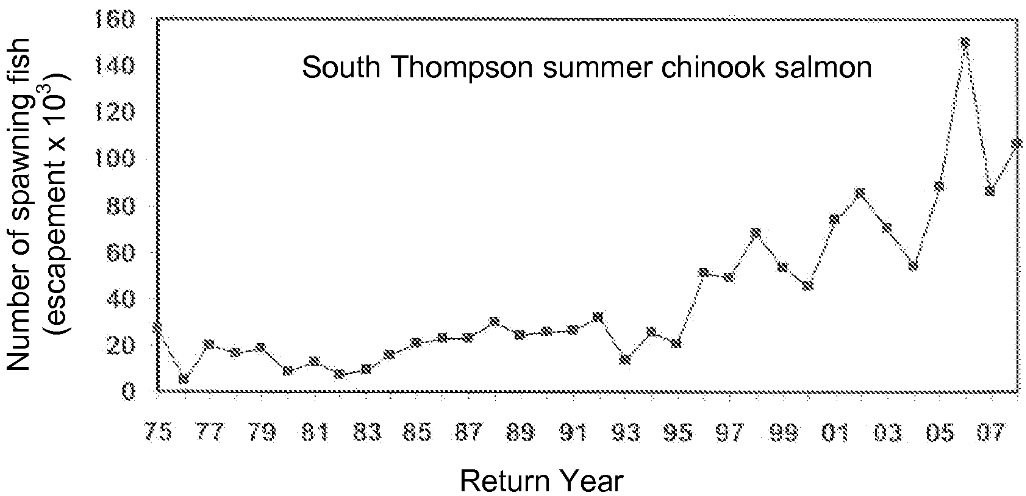


Figure 36. Abundance of spawning Fraser River summer-run populations (escapement) including five stocks that spawn in the South Thompson watershed - Middle Shuswap, Lower Shuswap, Lower Adams, Little River and South Thompson River. Also included are escapements to the Maria Slough located in the Lower Fraser River watershed, but have the same life history as the South Thompson chinook salmon. Other South Thompson stocks are the Lower Adams, Bessette, Duteau Creek, Eagle River, Harris Creek, Lower Thompson, Salmon River, Seymour River @ Thompson River and Scotch Creek.

Earlier in this report we showed that virtually all juvenile sockeye salmon in the Strait of Georgia in September in most years were from the Harrison River. Thus, the sockeye and chinook salmon that entered the Strait of Georgia in July and much later than other populations of the same species survived very well in the Strait of Georgia. This indicates that feeding conditions in the Strait of Georgia in July and August appear to be suitable for the survival of juvenile salmon with a life history strategy of late entry into the ocean.

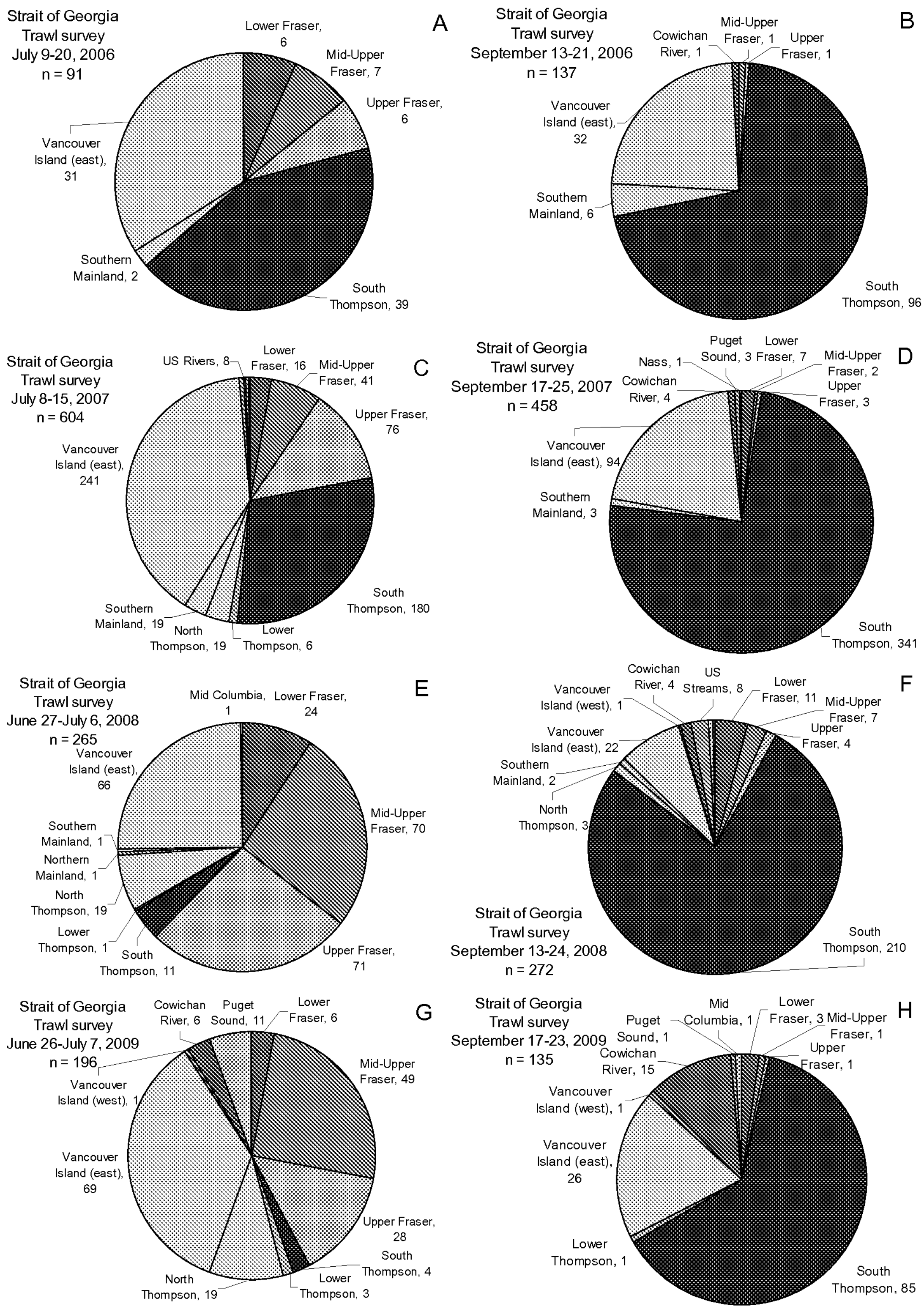


Figure 37. DNA stock composition of chinook salmon captured in the Strait of Georgia in the July and September surveys from 2006-2009.

Table 2. Abundance estimates of chinook salmon populations in July and September 2006-2008.

Survey	Total Abundance	South Thompson		Upper Fraser		North Thompson		Mid-Upper Fraser		Lower Fraser	
		%	Abundance	%	Abundance	%	Abundance	%	Abundance	%	Abundance
July 9-20, 2006	6,907,000	43	2,670,000	7	483,000	0	0	8	553,000	7	483,000
Sept 13-21, 2006	4,085,000	70	2,859,000	1	41,000	0	0	1	41,000	0	0
July 8-15, 2007	5,915,000	21	1,242,000	13	769,000	3	177,000	7	414,000	3	177,000
Sept 17-25, 2007	2,606,000	73	1,902,000	1	26,000	0	0	0	0	2	52,000
June 27–July 6, 2008	3,260,000	4	130,000	27	880,000	7	228,000	26	848,000	9	293,000
Sept 13-24, 2008	4,853,000	79	3,834,000	1	49,000	0	0	2	97,000	4	194,000

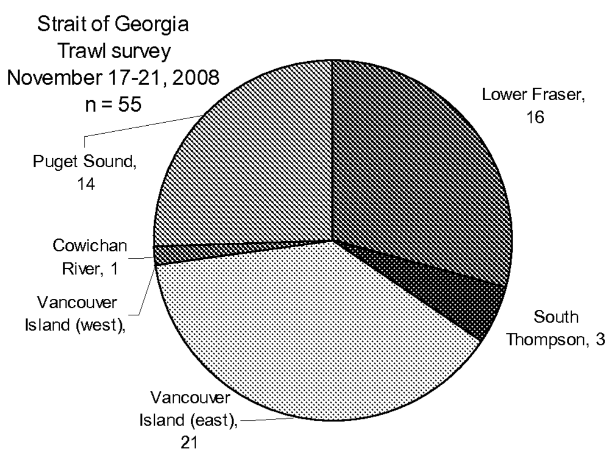


Figure 38. Population composition of chinook salmon captured in the trawl surveys in the Strait of Georgia, November 2008.

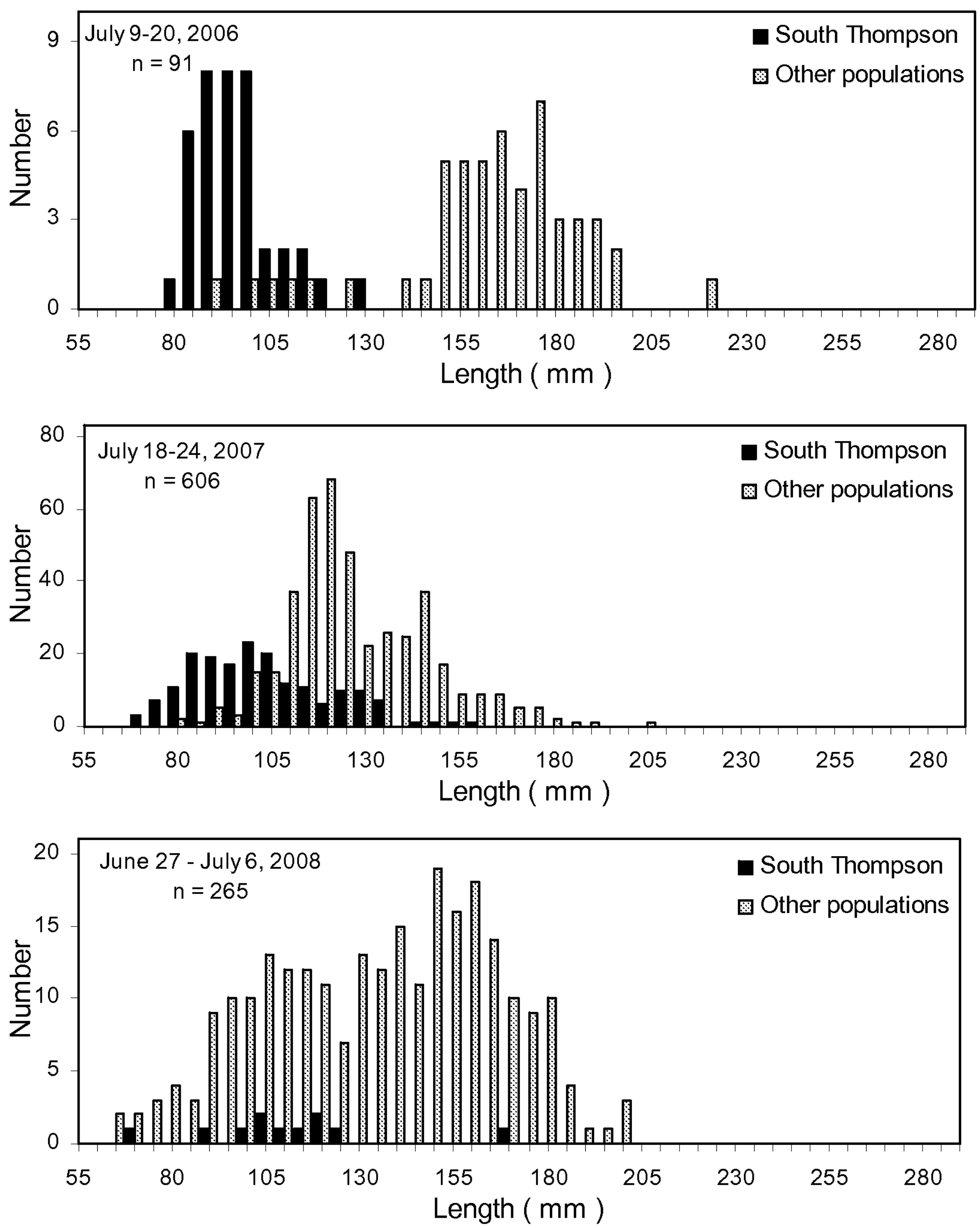


Figure 39. Lengths of South Thompson summer chinook salmon and other populations of chinook salmon captured in the Strait of Georgia during July surveys, 2006-2008.

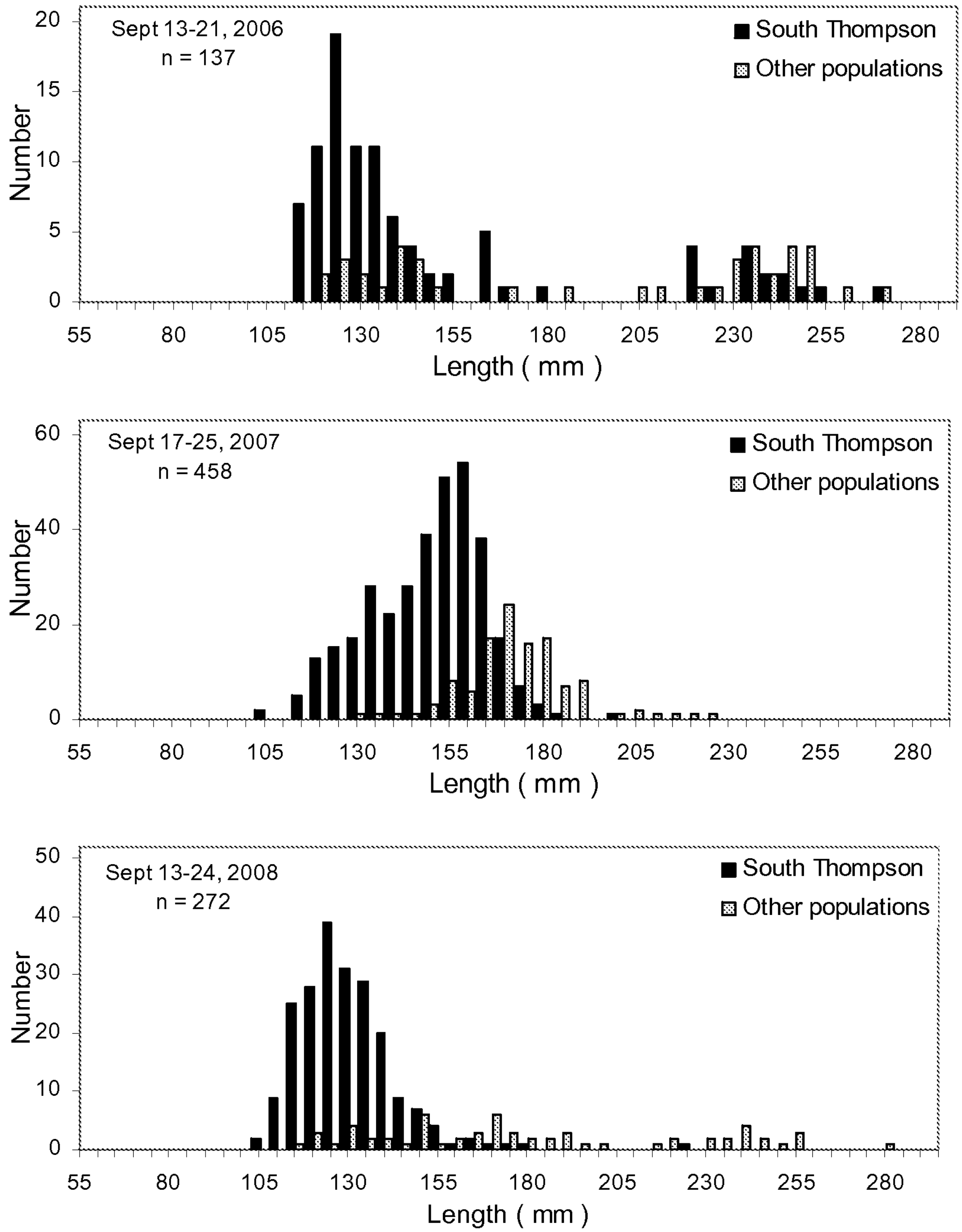


Figure 40. Lengths of South Thompson summer chinook salmon and other populations of chinook salmon captured in the Strait of Georgia during September surveys, 2006-2008.

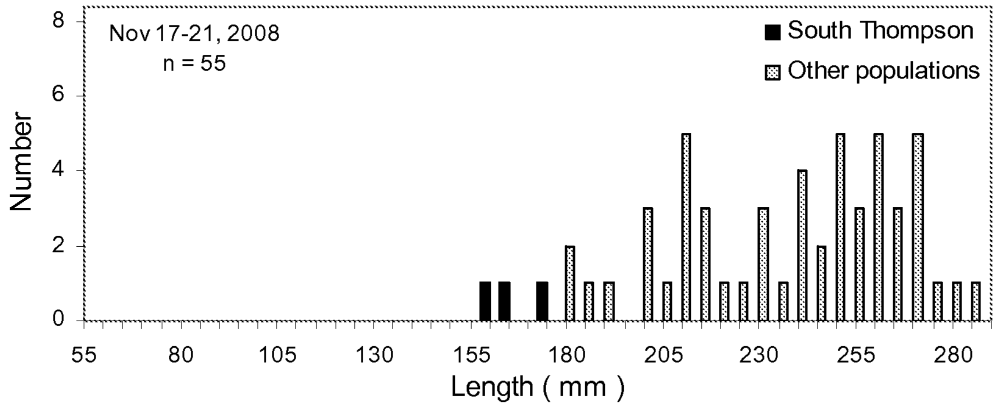


Figure 41. Lengths of South Thompson summer chinook salmon and other populations of chinook salmon captured in the Strait of Georgia during the November 2008 survey.

Impact of juvenile pink salmon on the growth of juvenile sockeye salmon

Summary

Juvenile pink salmon from the Fraser River enter the Strait of Georgia in the spring in even-numbered years and return to spawn in the next year. Virtually no pink salmon from the Fraser River spawn in even-numbered years or enter the Strait of Georgia in odd-numbered years. These juvenile pink salmon reduce the growth of juvenile sockeye salmon and increase the age of return of Harrison River sockeye salmon. This impact on growth or age of returning adults, or both, indicates that there is competition for food between pink and sockeye salmon. This competition also identifies a linkage between juvenile sockeye salmon production and plankton availability in the Strait of Georgia. It is also important evidence of impacts on juvenile sockeye salmon while they are in Strait of Georgia.

The mean fork length of juvenile sockeye salmon in the July surveys followed an alternating pattern of being larger in odd-numbered years and smaller in even-numbered years (Figure 42A). Pink salmon spawn in the Fraser River in odd-numbered years and the resulting juvenile pink salmon enter the Strait of Georgia in even-numbered years. The alternating mean length of juvenile sockeye salmon in July indicates that the pattern is related to the abundance of juvenile pink salmon that are virtually only in the Strait of

Georgia in even-numbered years. The reduced growth of juvenile sockeye salmon is most likely due to competition with pink salmon for food as pink and sockeye salmon eat similar food in July. We examined several thousand stomachs of these two species and found that about 80% of their diet in July consists of the same prey (Figure 43). This is an important illustration of the impact of food availability on the growth and survival of juvenile Pacific salmon in the Strait of Georgia in general and sockeye salmon in particular. It is important to note that the measured effect of pink salmon occurs within the Strait of Georgia during the residence period of juvenile sockeye salmon. The alternating pattern of smaller and larger average lengths also occurs for juvenile Harrison River origin sockeye salmon in September (except for 1999; Figure 42B). This indicates that the competition between juvenile pink and sockeye salmon extends through the summer into September. It is proposed that the survival of juvenile Pacific salmon in the early marine period is related to how fast they grow (Beamish and Mahnken 2001). Thus, the competition for food that affects the amount of growth could also reduce the survival in the early marine period.

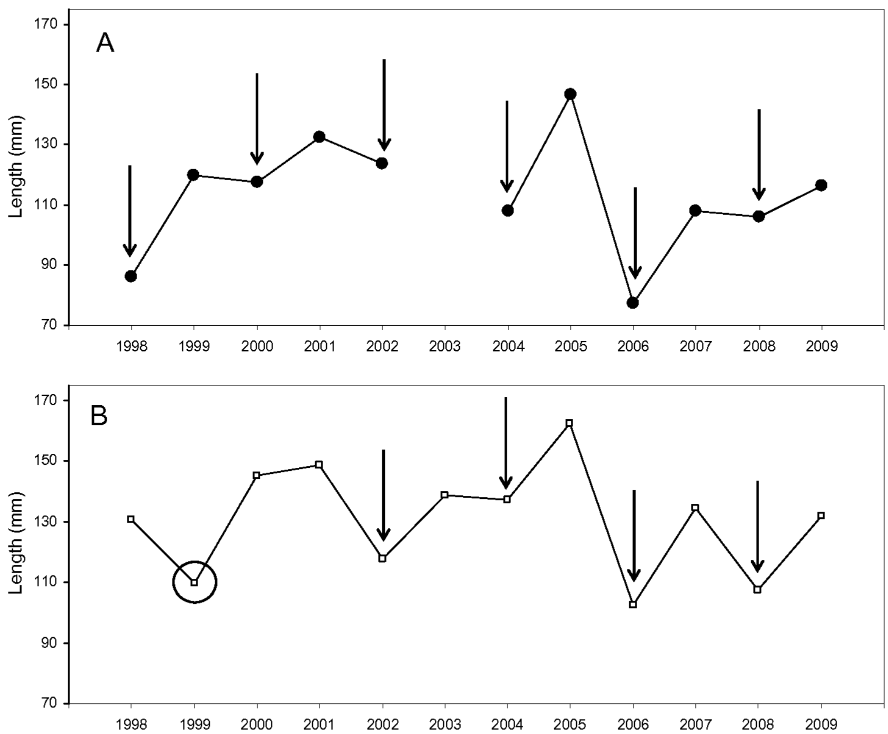


Figure 42. Average fork lengths for juvenile sockeye salmon caught in (A) July and (B) September surveys in the Strait of Georgia, 1998-2009. The average lengths in (A) will differ slightly from Figure 12A because all lengths are included and not only the lengths of fish that were also weighed. There was no survey in July of 2003. Arrows indicate the years when juvenile pink salmon from the Fraser River were in the Strait of Georgia. The circle indicates when the pattern does not occur. Virtually all juvenile sockeye salmon captured in September were in most years probably from the Harrison River.

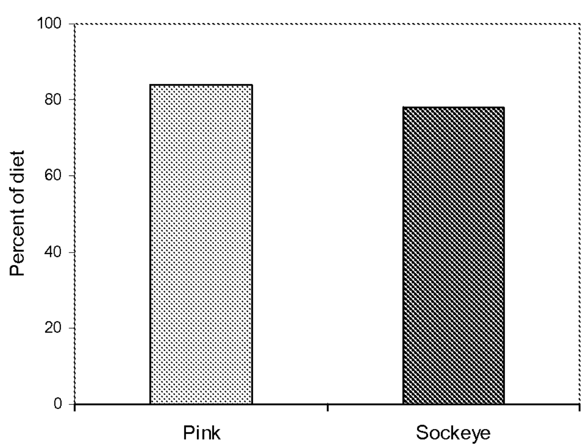


Figure 43. Percentage of amphipods and euphausiids in the stomachs of juvenile pink and sockeye in our July surveys from 1998 to 2009.

Evidence that there was a change in ocean conditions in the Strait of Georgia in the early 1990s that affected both sockeye and coho salmon production

Summary

The production of sockeye salmon from the Fraser River began a steady decline in the early 1990s. The early marine survival of coho salmon also exhibited a precipitous decline from the late 1990s that appears to have started earlier in the 1990s. The synchrony between the trends in sockeye and coho salmon is an indication that the factors causing the trends are in the Strait of Georgia and probably associated with a change in the ocean ecosystem.

Fraser River sockeye salmon production trends

The total production from all populations of sockeye salmon in the Fraser River drainage is known because the numbers are needed to manage the Pacific Salmon Treaty between Canada and the United States. The total production expressed as total numbers (Figure 44) and as recruit per spawner (Figure 45) show a distinct declining trend beginning in the early 1990s. The cause of the recent declining trend is most likely a result of the impact of a large-scale change in climate, possibly resulting from a change in atmospheric circulation (Beamish et al.1999a). Beamish et al. (2004a) published an analysis that showed that the productivity of Fraser River sockeye salmon could be partitioned into distinct regimes that matched climate regimes as identified by specific years when regimes shifted abruptly. In this paper, they identified the 1990s as a period of poor productivity. In their discussion they wrote "the regime in the 1990s was characterized by significantly reduced marine survival and reduced recruitment per spawner. It was the contrasting trends between regimes that exposed the importance of trends in climate on recruitment. The next regime most likely will also provide a level of productivity that will stand out when it ends and the results are compared with past regimes." Thus, the declining trend in the total returns shown in Figure 44 was known in the scientific literature.

Coho salmon production trends

Coho salmon production and behaviour in the Strait of Georgia changed about the same time that sockeye salmon production declined. Beginning about 1994, virtually all coho salmon remaining in the Strait of Georgia left in the fall and did not return until they were migrating back to their spawning rivers (Beamish et al. 1999b). Prior to about 1994, some coho salmon remained in the Strait of Georgia and supported a small winter fishery. There were brief periods around 2000 when some coho salmon returned, but the behavioural change about 1994 has persisted. Early marine survival, from ocean entry until September, has also declined (Beamish et al. 2008a). We do not know when the decline started, but from 1998 to 2007, an index of early marine survival declined from about 15% to about 2% (Figure 46). The total marine survival (Figure 47) dropped below 5% in the early 1990s, possibly indicating that the changes in sockeye and coho salmon production occurred at about the same time. The total marine survival of coho salmon from ocean entry until the fish return as adults, calculated using CWTs (Beamish et al. 2008a), declined from about 15% in the early 1980s to about 1% at present (Figure 48). The reasons for the increased mortality of coho salmon are not known, but it is possible that the mortality is related to poor growth. There is a good relationship between our catches of coho salmon in September and the total marine mortality (Figure 48), indicating that the factors that affect coho salmon production are within the Strait of Georgia and occur within the first four months after they enter the ocean. According to the relationship in Figure 48, the return in 2010 could be good and better than has been seen in the past seven years.

Conclusion

The changes in behaviour of coho salmon and the declining production of sockeye and coho salmon occurred at about the same time in the early 1990s. It is possible that these changes were associated with the regime shift in 1989 (Beamish et al. 2004c). Because coho salmon remain in the Strait of Georgia through to the fall (Chittenden et al. 2009), the factors causing the changes most likely are in the Strait of Georgia. The consequences of the impacts may continue after the fish leave the strait, but the original impacts are most likely in the Strait of Georgia.

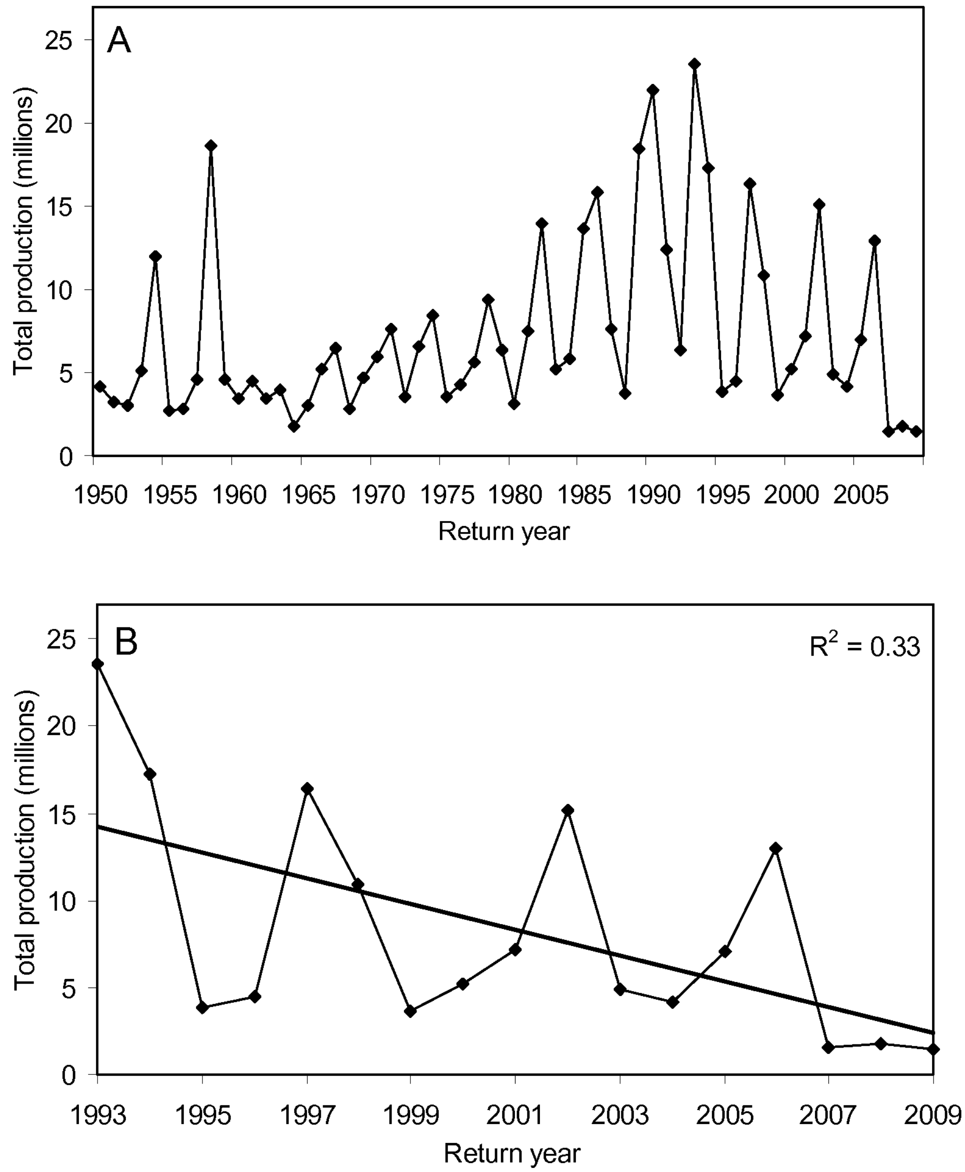


Figure 44. The total production of A) all Fraser River salmon populations from 1950-2009 and B) Fraser River sockeye salmon from 1993-2009, showing a declining trend beginning in about 1994. Total production includes an estimate of adult mortalities within the Fraser River.

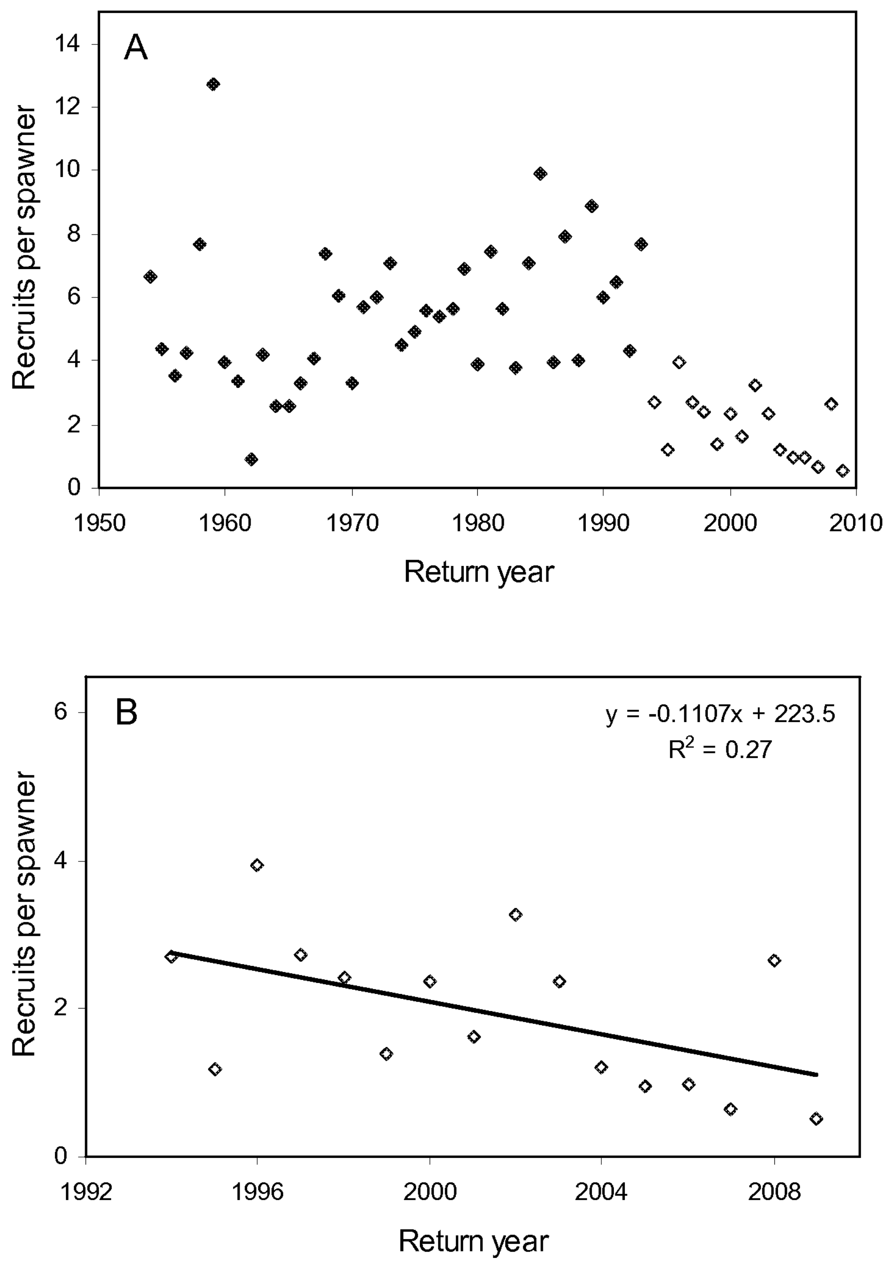


Figure 45. Recruits per spawner index for sockeye salmon in the Fraser River. A) The values 1952-2009, with 1994-2009 shown in open diamonds. B) The expanded data from 1994-2009. The recruit per spawner index relates the production of sockeye salmon to the number of fish that actually spawn.

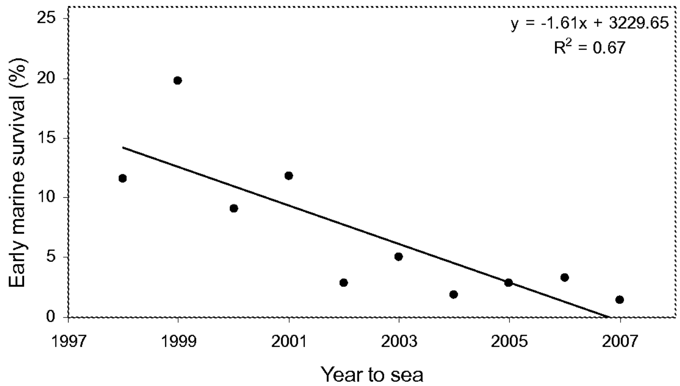


Figure 46. Early marine survival of coho salmon from an average ocean entry time in mid May to September of their first marine year in the Strait of Georgia.

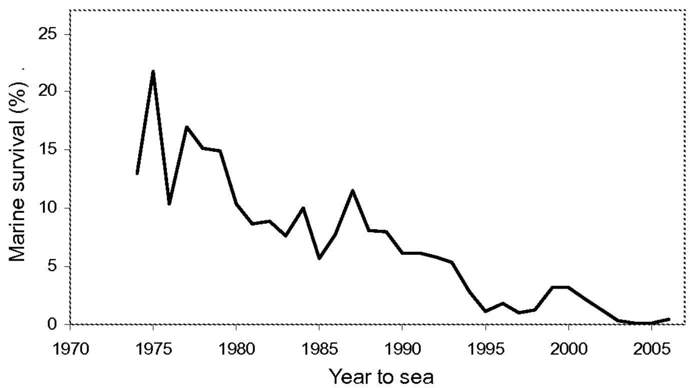


Figure 47. Total marine survival of coho salmon entering the Strait of Georgia from year to sea 1974-2006.

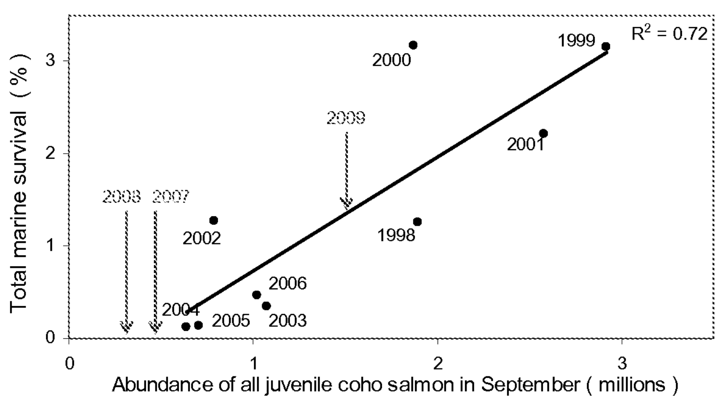


Figure 48. Relationship between total marine survival of coho salmon calculated using CWTs and abundance of juvenile coho salmon determined from the September trawl surveys. The red values indicate the expected marine survival for coho returning one year later in 2008, 2009 and 2010. Note that the return in 2010 could be better than observed in the past seven years. Final estimates for 2007 and 2008 are not available until all CWT information is available. Years are the year to sea.

Previous studies of juvenile sockeye salmon in the Strait of Georgia

Summary

Studies of the early marine life history of juvenile Pacific salmon did not begin in British Columbia until the 1950s. Consequently, it was not until the late 1960s and 1970s that detailed information about the movement of juvenile sockeye salmon in the Strait of Georgia became available. Initial studies by Healey reported that sockeye salmon smolts that reared in lakes that drained into the Fraser River entered the Strait of Georgia in late April and early May. These juveniles migrated across the Strait of Georgia and into the waters around the Gulf Islands. By June, they were reported to leave through Juan de Fuca Strait. In the late 1970s this behaviour changed, with most leaving through Johnstone Strait. There are no published records that document when the change occurred, but it is possible that it was in 1977 at the time of a major regime shift. There are reports that juvenile sockeye salmon took an average of about four weeks to move through the Strait of Georgia, although these estimates are based on catches and not tagging. The studies by Groot and colleagues in the 1980s have been interpreted to indicate that sockeye salmon left the Strait of Georgia through Johnstone Strait around the end of June. However, very little sampling was done in the northern strait in June in their study, resulting in uncertainty about when the majority of juveniles left. Juvenile Pacific salmon surveys by Beamish and colleagues in the 1990s and 2000s showed that relatively large catches of juvenile sockeye salmon occurred in July in the Strait of Georgia. This would indicate that it takes about eight weeks for the majority of juvenile sockeye salmon to migrate through the Strait of Georgia. However, these studies also did not indicate when the majority of juvenile sockeye salmon left the Strait of Georgia. Surveys in 1997 indicated that there were large abundances of juvenile sockeye salmon in the Strait of Georgia in mid June and it is likely that most juvenile sockeye salmon left the Strait of Georgia through Johnstone Strait. A proper study that documents the movement of the major populations of sockeye salmon in and out of the Strait of Georgia, however, remains to be done.

First juvenile Pacific salmon surveys

It was not until the mid 1950s that a sustained effort was made by Canadian researchers to find and catch juvenile Pacific salmon during their first few months in the ocean. Up to this time, the common view was that density-related processes in fresh water determined the abundance of returning adults. Research on juvenile Pacific salmon in the ocean was generally considered to be unnecessary. Foerster (1968), in his book on sockeye salmon, reported that juvenile sockeye salmon from the Fraser River were considered to leave the Strait of Georgia through Juan de Fuca Strait, but it was not until the late 1960s and early 1970s that researchers studied the movements of juvenile Pacific salmon through the Strait of Georgia. Studies of the ecology of juvenile sockeye salmon in the Strait of Georgia began with work in the 1960s reported in Barraclough and Phillips (1978), continuing with the studies by Healey (1978) and Groot and colleagues in the early 1980s. More recently the ecology of juvenile sockeye salmon has been studied in the Strait of Georgia using trawl surveys described in this report. Early studies of the movements of sockeye salmon in the Strait of Georgia focused on the duration of stay and the exit of the Strait of Georgia to access the North Pacific basin. The research on juvenile Pacific salmon during their early marine period off British Columbia has been summarized by Beamish et al. (2004a) and will be briefly summarized in this report.

Migration of sockeye salmon through Juan de Fuca Strait in the 1970s

Healey (1980) reported that the majority of juvenile sockeye salmon from the Fraser River entered the Strait of Georgia in late April as smolts after spending one year in fresh water. As mentioned previously, this life history type is referred to as “lake type” and is the most common life history representing an average of about 99% of all populations in the Fraser River until recently. In May, in these early studies, juvenile sockeye salmon were observed to concentrate in the lower strait along the outer Gulf Islands. By June, they were within the Gulf Islands and apparently began to migrate out of the Strait of Georgia through Juan de Fuca Strait. Smaller abundances remained within the strait through August and September.

Barraclough and Phillips (1978) summarized information on the distribution of all five Pacific salmon species in the southern Strait of Georgia from surveys conducted in spring and summer of 1966, 1967, 1968 and 1969. They presented a conceptual model of salmon movement through the Strait of Georgia to the southern Gulf Islands and out of Juan de Fuca Strait to the Pacific Ocean. The migration through Juan de Fuca Strait was thought to be a consequence of salmon following the physical movement of water in tidal currents and estuarine flow. Foerster (1968) also suggested that juvenile sockeye salmon used the southern route to the Pacific. However, his conclusion was based on unpublished work by W.A. Clemens who described beach seining in the San Juan Islands during the 1950s in which no sockeye salmon were actually sampled. The lack of juvenile sockeye salmon in the surveys was reasoned to be due to a preference for deeper water or having already passed through the sampling area to the Pacific Ocean, or both. Despite the rather weak evidence for a migration route through Juan de Fuca Strait, it is most likely that this was how juvenile sockeye salmon left the Strait of Georgia. None of these early works suggested that sockeye salmon might leave by the northern route.

Healey (1980) and others also reported that some juvenile sockeye salmon migrated directly to sea after emergence from the gravel without spending one year in fresh water. These fish were observed in the Fraser River delta about July at a fork length of 60-70 mm. Their small size readily distinguished them as the equivalent of ocean-type chinook salmon that went to sea in their first year in fresh water. Foerster (1968) referred to those fish as ocean type but this life history was originally described by Gilbert (1914) as sea-type sockeye salmon, which is the terminology used previously in this report. Birtwell et al. (1987) found that the maximum abundance of juvenile sea-type sockeye salmon in the Fraser River estuary was in late June and early July. Healey (1980) reported that these sea-type sockeye salmon from the Harrison River remained in the strait through to September. He did not know when they left, but suggested that it might be in September. Healey (1980) reported that most lake-type sockeye salmon left the Strait of Georgia in late June and July through Juan de Fuca Strait. This is the first instance that we could find of a field data derived interpretation of a southward migration through Juan de Fuca Strait.

Migration of sockeye salmon through Johnstone Strait

Groot et al. (1984) and Groot and Cooke (1987) hypothesized that the return route of adult sockeye salmon might be a consequence of the route taken by juveniles out of the Strait of Georgia. They conducted a study of the distribution of juvenile sockeye salmon in the Strait of Georgia from 1982 to 1985. In their results, Groot and Cooke (1987) summarized data from 3 (1982, 1983 and 1984) of 4 years (1982-1985) of juvenile sockeye salmon surveys (Groot et al. 1985). The last year (1985) had surveys in Johnstone Strait and Queen Charlotte Strait, but was not included in their paper.

Groot et al. (1984) reported that the juvenile sockeye salmon left the Fraser River in two directions. One route was across the Strait of Georgia toward the Gulf Islands and then out of the Strait of Georgia through Juan de Fuca Strait. The other movement was north and eventually through Johnstone Strait. By amalgamating survey data from 1982-1984, they proposed that in late April juveniles were northwest and west of the Fraser River mouth. By early May most were east of Texada Island and the rest were in the Gulf Islands. In late May most were in the north end of the Strait of Georgia. By early June, many were in Johnstone Strait. Some were in the western Gulf Islands and around Texada Island. Very few were moving south in late June. According to the Groot and Cooke (1987) report, there were none in the Gulf Islands in late June and a few were off Texada Island. Their general conclusion was that sockeye salmon smolts oriented themselves northwards upon entering the Strait of Georgia and exited through the north of the Strait of Georgia. It is important to note that Groot and Cooke (1987) reported that, "no sampling was done in the northern Strait of Georgia during June; thus it is not certain when the majority of smolts left these waters."

We combined the data from the studies of Groot and colleagues for 1982 to 1984 into three zones; south (Victoria to Lasqueti Island), middle (Lasqueti Island to Savary Island) and north (Savary Island to Sonora Island). Juvenile sockeye salmon catches were converted to the number caught per set for each zone. The majority of their sampling occurred in the south and middle of the Strait of Georgia and relatively little in the north (Figure 49). The report that in early May most juveniles were east of Texada Island does not appear to be consistent with the higher standardized catch in the southern strait in Figure 49. The observation that by early June many juveniles were in Johnstone Strait while some remained in the middle and southern Strait of Georgia is partly a reflection of their sampling regime. For example, the highest recorded standardized catches were in the middle Strait of Georgia in early June and the reported standardized catch in the southern strait appear to be as high as any time in May. However, sampling in the southern strait was irregular after early June so there was no clear basis to conclude there were none there. The Groot and Cooke (1987) paper omits the survey results from 1985 which suggest high catches of juvenile sockeye salmon in Queen Charlotte Strait and Johnstone Strait in late June, perhaps because the origin of these sockeye salmon was unclear. In general, the studies of Groot and colleagues identify a movement of juvenile sockeye salmon north and out of the Strait of Georgia through Johnstone Strait, but the date that the majority of the smolts left the Strait of Georgia was not determined.

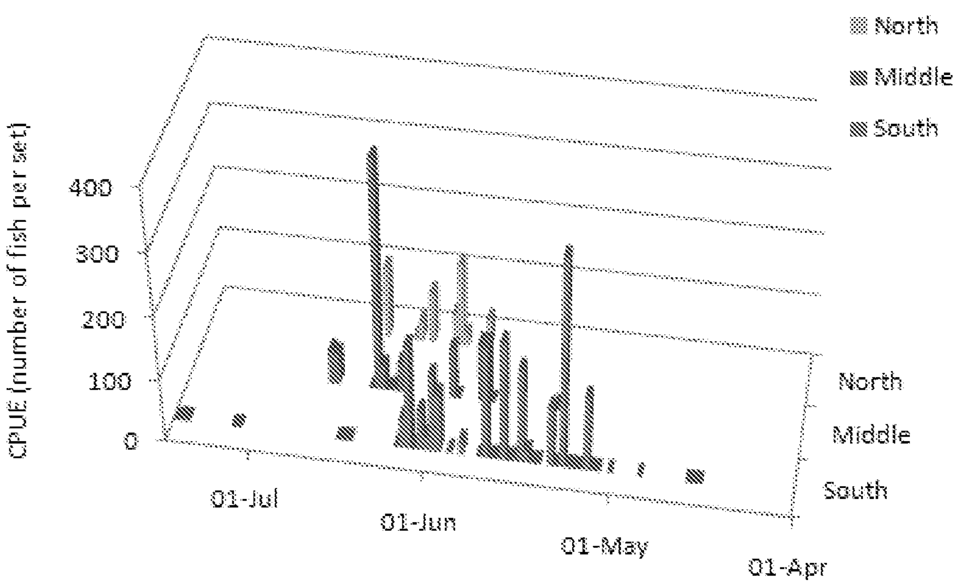


Figure 49. Juvenile sockeye salmon catches in the Strait of Georgia reported by Groot and Cooke (1987). Surveys were conducted over the months of April to July in 1982, 1983, and 1984. The graph shows the total catch, standardized for catch, for all three years for each day, for three geographic divisions of the Strait of Georgia: North, Middle and South (see text for location of regional boundaries). The results show that there is a movement north from early May to mid-June. The x axis has the months shown with April at the far right to correspond to the orientation of the Strait of Georgia.

It is clear that most juvenile sockeye salmon changed their migration route out of the Strait of Georgia between the years that Healey and Groot did their studies. It is possible that this change occurred about the time of the 1977 regime shift (Beamish et al. 1997, 2004b, 2008b). The reason for the change and the percentage of juveniles that continued to migrate through Juan de Fuca Strait are not known.

We do not regularly survey in Johnstone Strait or Queen Charlotte Strait. Thus we are not able to compare catches in the migration route outside of the Strait of Georgia with catches in the Strait of Georgia. We do survey regularly in Juan de Fuca Strait. We catch some juvenile sockeye salmon in Juan de Fuca Strait in July (Figure 50) but the numbers are small relative to catches in the Strait of Georgia (Figure 3), suggesting that most juvenile sockeye salmon are not migrating through Juan de Fuca Strait at this time. Until there is a survey in Juan de Fuca Strait in May and June, it is not possible to be certain that the percentage leaving through Juan de Fuca Strait is low.

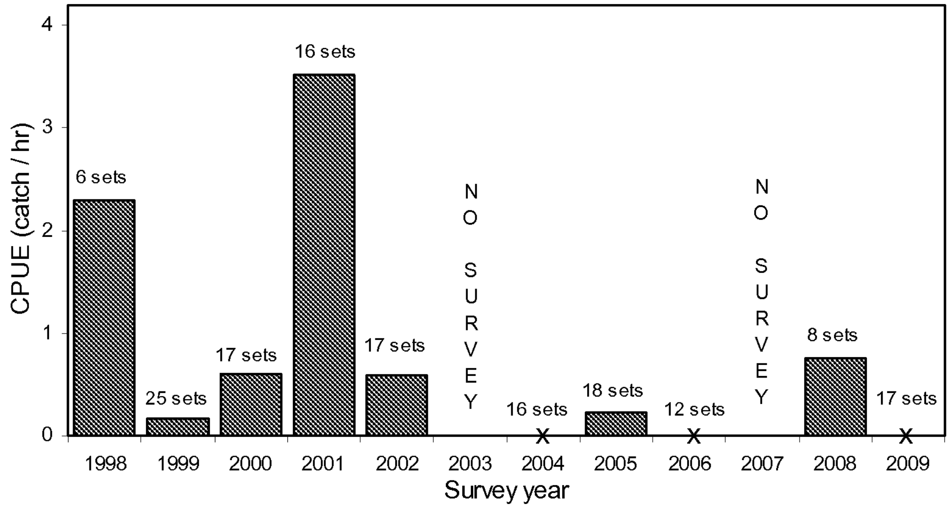


Figure 50. Catch, standardized for one hour of effort or catch per unit effort (CPUE), for juvenile sockeye salmon in Juan de Fuca Strait in the July trawl surveys 1998-2009. Note the very low values compared to values in Figure 3. The number of sets is shown for each year. An x indicates that no juvenile sockeye salmon were caught.

Early beam trawl and rope trawl surveys

Prior to our standard trawl surveys, we used a beam trawl (Hargreaves and Hungar 1990) to study the population ecology of juvenile Pacific salmon in the Strait of Georgia. These studies began in 1992. In 1995 we changed the fishing gear to a rope trawl because the beam trawl could not be towed at speeds that would catch all sizes of Pacific salmon. From 1995 to 1998 we completed 19 surveys in the Strait of Georgia and surrounding area (Table 3). Over this period there were surveys in February, March, April, May, June, July, September, October and November (Table 3). The surveys were initially designed to determine if the gear could sample Pacific salmon in a manner that would allow us to study the response of populations to factors that affected their early marine survival, such as climate. These early studies led to a focus on a standardized survey in July and September in the Strait of Georgia. During this exploratory period, we captured juvenile sockeye salmon. A total of 15,200 juvenile sockeye salmon were sampled for lengths and a smaller sample for stomach contents. Most juvenile sockeye salmon in the Strait of Georgia (89%) were captured in June and early July. The second largest catches (8.6%) occurred in September. We now know that juvenile sockeye salmon captured in September would most likely be Harrison River sockeye salmon. Catches in November were 2% of the total and these might also have been Harrison River sockeye salmon. Catches of less than 1% occurred in February, April and October. Catch distributions from the May 27-June 7 and June 17-July 11, 1997 surveys are included in this report (Figure 51). The surveys were not designed to identify the migration pattern of juvenile sockeye salmon out of the Strait of Georgia, but the catches can be used to provide some information about distributions of juvenile sockeye salmon in 1997.

In 1997, we conducted seven trawl studies in and around the Strait of Georgia (Table 3). No juvenile sockeye salmon were captured in the Strait of Georgia in the surface waters in late February and only two juveniles were captured in 70 sets in April (Table 3, Figure 51). Large catches were made in late May and early June (Table 3, Figure 51) and again in mid to late June (Table 3, Figure 51). These large catches showed that there were large abundances of juvenile sockeye salmon in the Strait of Georgia in June. This would indicate that most juvenile sockeye salmon should not be considered to migrate quickly out of the strait. Unfortunately, the survey in early July was only in the southern strait where moderate catches of juvenile sockeye salmon were made (Table 3, Figure 51). However, the series of surveys showed that juvenile sockeye salmon remained in the

Strait of Georgia into July. In late June and early July 1997 we fished in Juan de Fuca Strait and off the west coast of Vancouver Island. We captured only three juvenile sockeye salmon in 85 sets (Table 3). These surveys appear to confirm that juvenile lake-type Fraser River sockeye salmon were not leaving through Juan de Fuca Strait. However, we had relatively large catches of juvenile sockeye salmon in Queen Charlotte Strait and Queen Charlotte Sound at the same time. The origin of the sockeye salmon in Queen Charlotte Strait was not determined, but they may have originated from the Fraser River. There were 200 sets in September and October that captured moderate numbers of juvenile sockeye salmon throughout the Strait of Georgia. The sockeye salmon captured in September and October were most likely from the Harrison River. The catches of these presumed Harrison River sockeye salmon in September and October were distributed throughout the Strait of Georgia (Figure 51). In particular, there were catches north of Texada Island, possibly indicating that these fish would leave through Johnstone Strait. However, the identity of the populations was not determined.

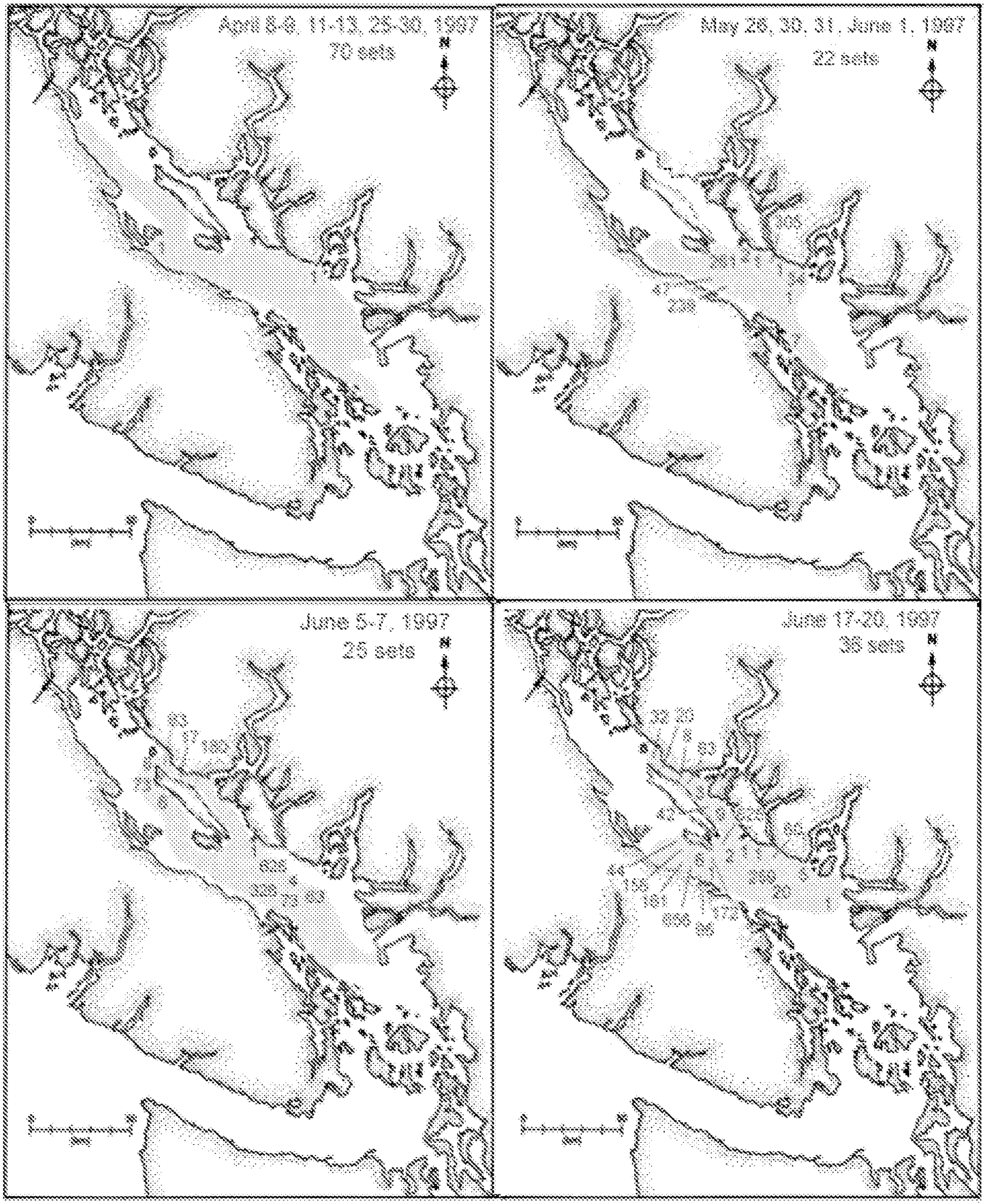


Figure 51. Juvenile sockeye salmon catches (in 30 minutes) in the trawl surveys in 1997. The survey area is shown in light blue. Zero catches are not shown.

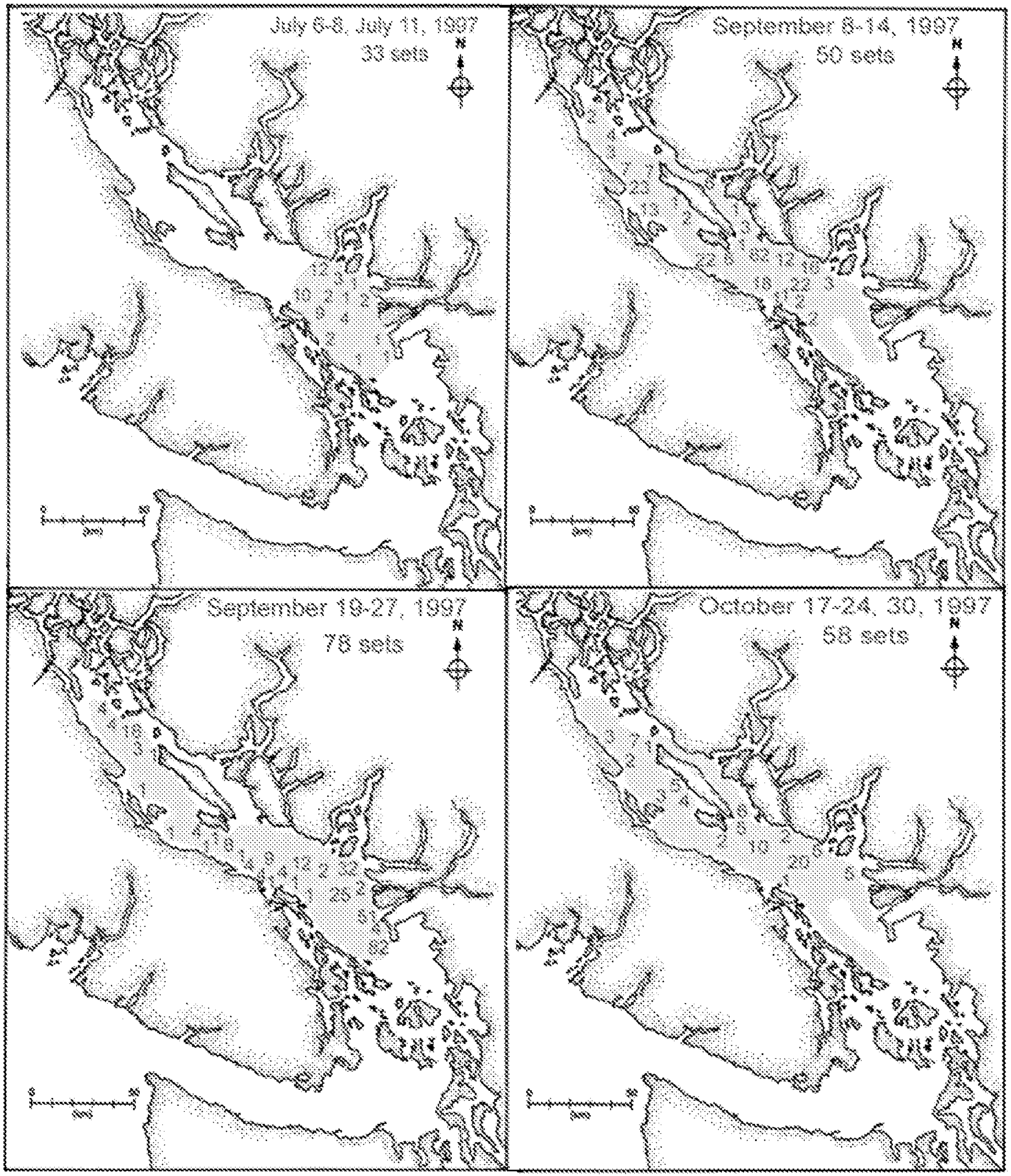


Figure 51 (Continued). Juvenile sockeye salmon catches (in 30 minutes) in the trawl surveys in 1997. The survey area is shown in light blue. Zero catches are not shown.

Table 3. Summary of juvenile (ocean age 0+) sockeye catch from cruises from 1995 to 1998 using the rope trawl.

Date		Number of Sets	Strait of Georgia		Juan de Fuca Strait		West Coast Vancouver Island		Johnstone Strait		Queen Charlotte Strait		Queen Charlotte Sound		Puget Sound	
			Catch	# of Sets	Catch	# of Sets	Catch	# of Sets	Catch	# of Sets	Catch	# of Sets	Catch	# of Sets	Catch	# of Sets
Apr 21-27	1995	41	1	33	0	5	0	3								
Sep 11-15	1995	35	1	20			0	15								
Nov 15-17	1995	69	123	40			0	14	0	8	0	7				
Feb 26-Mar 7	1996	54	0	54												
Apr 9-26	1996	107	71	47	6	8	1	52								
Sep 8-20	1996	82	790	64	0	18										
Nov 4-15	1996	82	39	57	9	9			0	9	0	7				
Feb 20-23	1997	55	0	39	46	7	8	9								
Apr 8-May 2	1997	180	2	70	15	15	53	56			0	8	0	8	4	23
May 26-Jun 7	1997	85	2,357	47	9	21	4	17								
Jun 17-Jul 11	1997	187	2,512	69	1	30	2	55			399	6	331	13	4	14
Sep 8-14	1997	50	260	50												
Sep 19-27*	1997	92	281	78	0	3									0	11
Oct 17-30	1997	95	81	58			8	37								
Feb 10-Mar 7	1998	130	0	44	0	25	0	61								
Apr 6-23	1998	124	0	43	3	14	0	67								
Jun 24-Jul 13	1998	157	487	96	6	5	0	32	29	9			2	5	28	10
Sep 8-24	1998	160	177	95	3	24	0	21	1	11					3	9
Nov 17-28	1998	117	109	95	36	22										

* Second survey using MV *Frosti*

Migration of juvenile sockeye salmon out of the Fraser River and the ecology of juvenile sockeye salmon in the Strait of Georgia

Summary

Juvenile sockeye salmon that rear in lakes before entering the Strait of Georgia leave their freshwater rearing areas from early April to late May. The average first feeding day in the Strait of Georgia for these lake-type sockeye salmon was May 25, for one sample collected in early July 2008 or about three weeks after most smolts begin their migration out of fresh water. A sample of Harrison River sockeye salmon collected in the Strait of Georgia in September 2008 had an average first feeding day of July 7, about six weeks after the other lake-type sockeye salmon enter the ocean. An average of about 250 million juvenile sockeye salmon enters the Strait of Georgia each year with a range from perhaps 44 million to 740 million smolts. It is a basic principle in ecology that plants and animals that produce large numbers of seeds or offspring will have a large early mortality. Thus, it is to be expected that there will be large mortalities of these juvenile sockeye salmon in the Strait of Georgia even under favourable ocean conditions. Abundance estimates of juveniles in the Strait of Georgia in early July and catches in Queen Charlotte Sound and Hecate Strait about the same time confirm that very large mortalities occur in the Strait of Georgia. In 2007, between 467 and 491 million sockeye salmon smolts may have left their freshwater rearing areas and most of these probably entered the Strait of Georgia. It is possible that very few fish survived the first few months in the Strait of Georgia. Certainly, the abundances went from hundreds of millions to millions by early July. Harrison River sockeye salmon, however, survived relatively well in 2007. In fact, abundances of juvenile Harrison River sockeye salmon in September 2007 were relatively large compared to other years.

Juvenile sockeye salmon around the subarctic Pacific have the most restricted diet of all Pacific salmon. Juvenile sockeye salmon in the Strait of Georgia fed heavily on decapods when they first enter the Strait of Georgia and on amphipods later. Amphipods are also the main diet items of juvenile Harrison River sockeye salmon. The percentage of higher-energy amphipods was unrelated to either length or recruit per spawner for the lake-type

or Harrison River sockeye salmon. Thus, it was the quantity of prey that was available rather than the quality of prey available that probably was related to the growth and survival in the early marine period.

Harrison River sockeye salmon remain in the Strait of Georgia for approximately five months. All other juvenile sockeye salmon appear to stay in the Strait of Georgia for up to two months. In 2008 and 2009, juvenile sockeye salmon from the Fraser River may be found in equivalent densities in the Strait of Georgia, Hecate Strait and Queen Charlotte Sound at about the same time in late June and early July. It is not known if the rate of migration through the Strait of Georgia varies among years, but it is known that the proportion of stocks in the population in July is the expected composition of adults that will return in two years, indicating that the later migrating fish are not specific to particular stocks.

Our studies did not identify the sources of the very large early marine mortality. Predation is an obvious source of mortality, but evidence of predation was difficult to find. It is possible that reduced growth and poor condition increases the susceptibility of individuals to common diseases. There is evidence of competition for prey with pink and chum salmon, which reduces growth. This is important as it is possible that early marine survival is better for faster-growing individuals, however there are no estimates of early marine survival for juvenile sockeye salmon.

Downstream migration and first feeding in the Strait of Georgia

The timing of the migration of sockeye salmon smolts from the freshwater rearing lakes within the Fraser River drainage into the Fraser River is known only for two populations and for an aggregate of all lake-type populations. Smolts leaving Cultus and Chilko lakes are enumerated as are lake-type sockeye salmon smolts that are caught during the enumeration of pink and chum fry at Mission. These enumerations indicate that most sockeye salmon smolts migrate down the Fraser River in early May with the migration period extending two months from early April until the end of May (Figure 52).

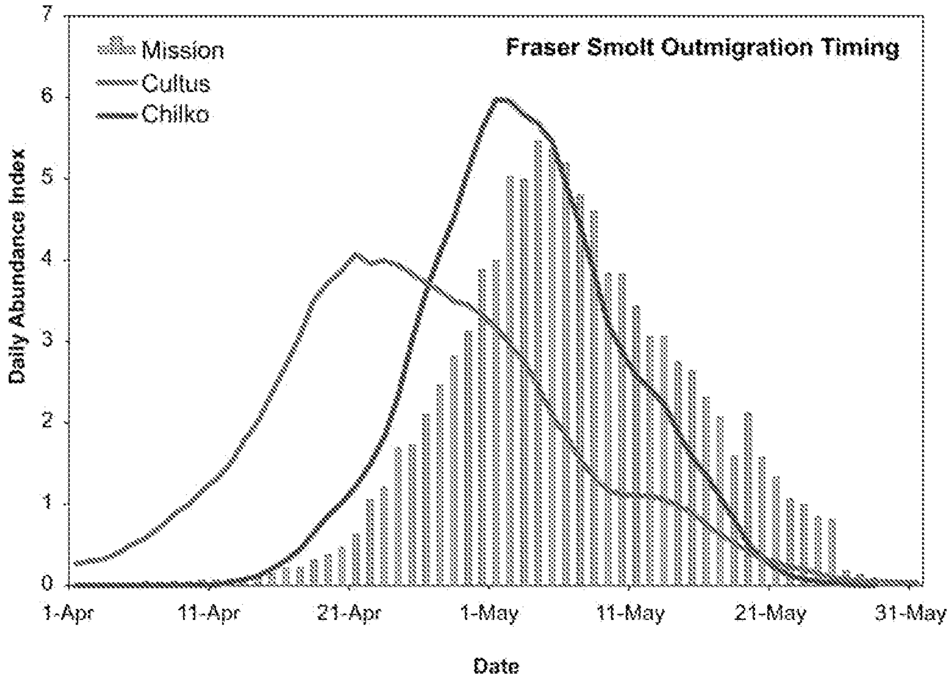


Figure 52. Numbers of juvenile sockeye salmon smolts leaving Chilko and Cultus lakes and counted at the Mission site (Data from Fisheries & Oceans Canada and the Pacific Salmon Commission; analysis (7-day running average) and figure provided by Daniel Selbie and David Peterson). Cultus and Chilko enumeration occurs at smolt fences, and the Mission estimates arise from bycatch in the downstream trap used to count pink salmon fry migrating out of the Fraser River.

The timing of entry into the ocean would be expected to occur shortly after smolts pass the enumeration site at Mission, approximately 80 km from the Strait of Georgia. There is very little information about either the exact time of ocean entry or the exact time that the smolts begin feeding in the ocean. An estimate of the average first ocean feeding day was made in our study for the lake-rearing life history type of juvenile sockeye salmon collected in the Strait of Georgia in early July 2008. The otolith in the ear of a fish has been shown to grow in daily increments. Daily growth rings in the otolith of juvenile sockeye salmon that formed in the ocean were distinguished from rings formed in fresh water by their wider spacing and more robust structure. Daily growth rings that formed in the otolith in the Strait of Georgia were counted from the day of capture back to the first ocean daily growth ring. The sample of 24 lake-type juvenile sockeye salmon came from 7 populations (according to the DNA stock identification) and averaged 105 mm in fork length. The mean first day of feeding in the ocean was May 25 and the range was from May 14 to June 19. If most smolts begin to leave fresh water in early May, this would indicate that average feeding in the ocean begins about three weeks after the fish start their downstream migration.

The first ocean feeding day was also examined from a sample of 36 Harrison River sockeye salmon collected in September 2008 in the Strait of Georgia and averaging 116 mm in fork length. The mean first day of feeding in the ocean was July 7 and the range was from June 6 to July 24. Thus, it appears that juvenile Harrison River sockeye salmon enter the Strait of Georgia, on average, about 6 weeks after smolts from the other lake-type populations enter. A sample of 7 juvenile Harrison sockeye salmon collected in Howe Sound on July 3, 2008, averaged 63 mm in fork length. These fish started feeding in the Strait of Georgia from June 9-29 with an average date of June 18. However, it is evident from the September sample that most Harrison sockeye salmon had not entered the Strait of Georgia at the time of the July 2008 survey. Thus, both of the estimates of the average first feeding day may underestimate the actual average first feeding day which may be between mid and late July.

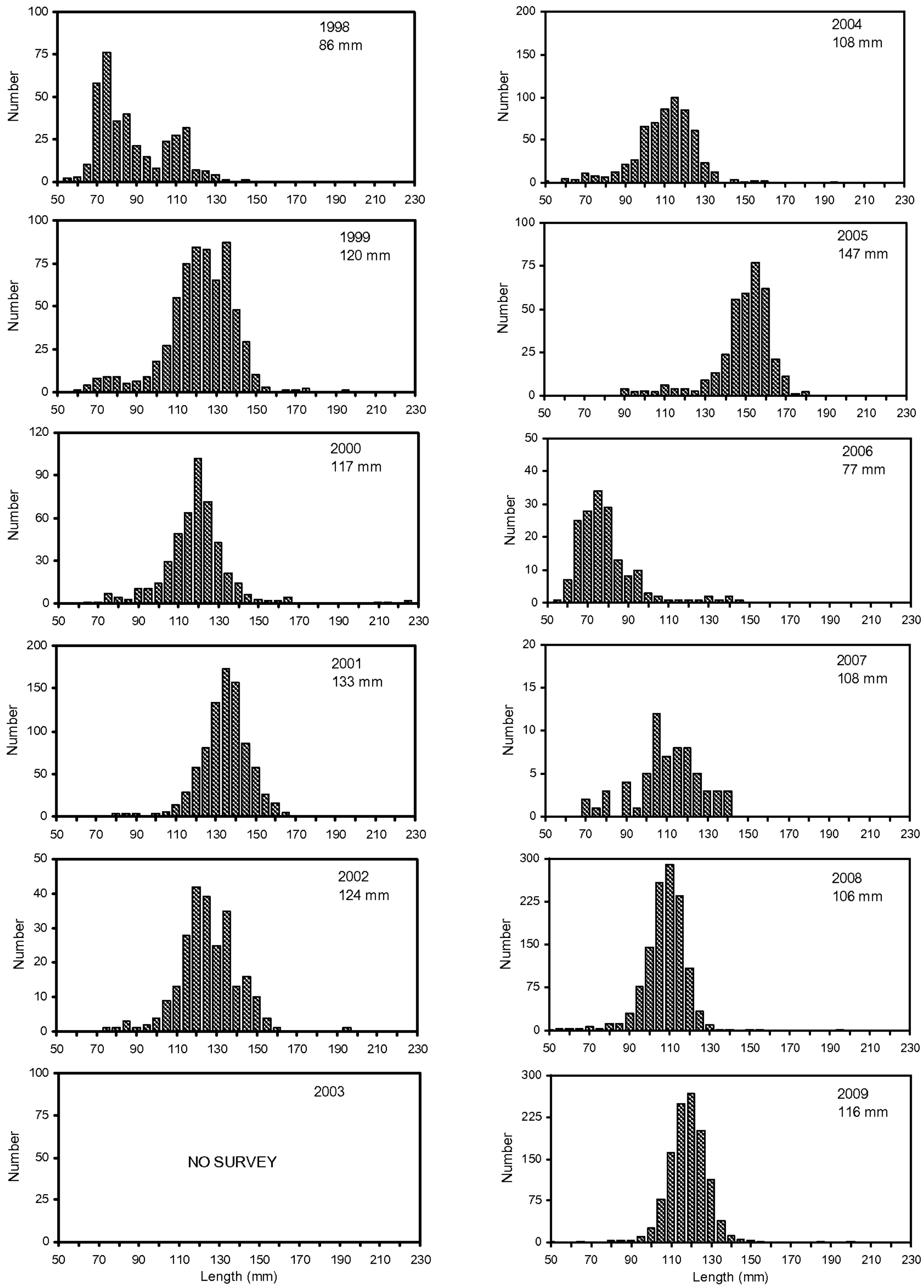


Figure 53. Lengths (mm) of juvenile sockeye salmon captured in July surveys in the Strait of Georgia, 1998-2009. The average length for each survey is shown. No survey was conducted in 2003.

Ocean ecology of lake-type juvenile sockeye salmon

Our trawl studies show that juvenile, lake-type sockeye salmon remain in the Strait of Georgia through to the end of our surveys in about mid July (Figure 4). However, there is variation among years that may result from the four-year production cycles and from ocean conditions (Figure 54). The average length of juvenile sockeye salmon in the July trawl surveys ranged from 86 mm to 147 mm (Figure 53). From June 26 to July 7, 2009, a sample of 77 Chilko Lake sockeye salmon (determined from DNA analysis) was obtained from four locations in the northern Strait of Georgia. The average length was 113 mm, which compares to an average length of 116 mm from a total sample of 1,183 juvenile sockeye salmon that were measured for fork length. The smolts leaving Chilko Lake in early May were approximately 83 mm with 50% leaving the smolt-counting area by about May 3. Thus, over a period of about two months in the Strait of Georgia, these fish increased an average of about 30 mm in length. There will be a short period the freshwater migration down the Fraser River, but if the length at which 50% leave the lake is compared to the average survey lengths about the middle of the survey then there is an average increase of about 30 mm in about 60 days or about 0.5 mm / day. This is similar to an average daily growth during the early marine period of 0.6 mm / day reported in Burgner (1991). Thus, if the difference in sizes is representative of Chilko Lake growth and behaviour in the Strait of Georgia, the length of residence and rate of growth indicates that some juvenile sockeye salmon remain and grow in the Strait of Georgia at rates consistent with the published literature. Also, it is apparent that to achieve this growth, the juvenile sockeye salmon do not leave the Strait of Georgia quickly.

It is known from surface trawl studies by Trudel and colleagues that juvenile sockeye salmon from the Fraser River are in Queen Charlotte Sound and Hecate Strait in late June and early July (Tucker et al. 2009). Their surveys completed 8 to 21 sets, in late June and early July from 2004 to 2009. Their average catch of juvenile sockeye salmon from the Fraser River was 35 in 2008 and 18 in 2009 (Figure 55). In the Strait of Georgia trawl survey, we completed 47 sets at the surface in 2008 and 40 sets in 2009 (Figure 4A,B). Our average catch of juvenile sockeye salmon in early July for the same fishing time (30 min) was 34 in 2008 and 34 in 2009, respectively. Without an estimate of the abundances of juvenile sockeye salmon in Queen Charlotte Sound or Hecate Strait it is difficult to compare the catches in Queen Charlotte Sound and Hecate Strait with our surveys. However, in 2008 and 2009, the average catch in the Strait of Georgia was either similar to the catches farther north or higher, indicating that a portion of the total population of juvenile Fraser River sockeye remained in the Strait of Georgia in July and that juvenile sockeye salmon from the Fraser River were distributed from the Strait of Georgia to Hecate Strait in early July.

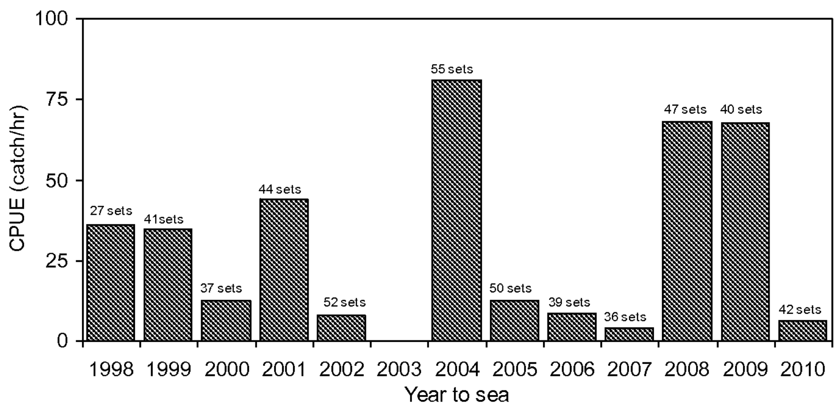


Figure 54. The average catch per unit effort of juvenile sockeye salmon in the July trawl surveys, 1998 to 2009, from sets made throughout the Strait of Georgia at the surface (0-15 m). There was no survey in 2003.

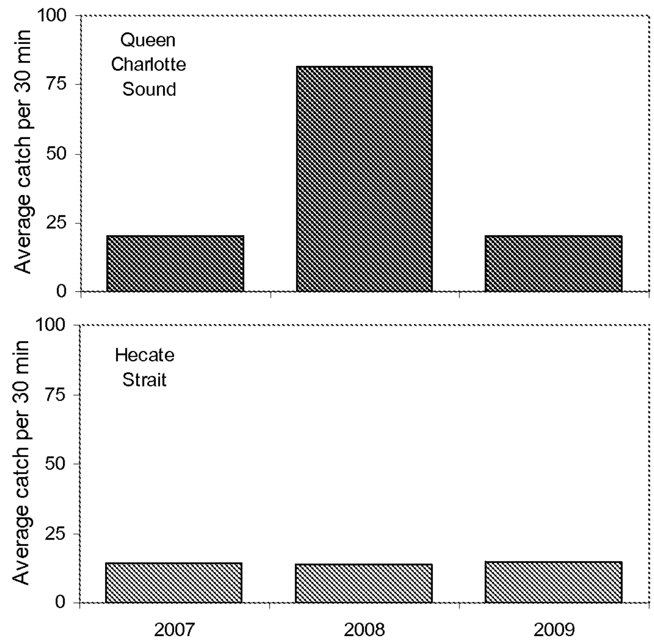


Figure 55. The average catch per 30 minute set of sockeye salmon from the Fraser River in Queen Charlotte Sound and Hecate Strait.

In 2007, the average catch of juvenile sockeye salmon in our standard trawl survey was 1.8 fish for 36 surface sets throughout the Strait of Georgia. We report only the catches in the surface sets as the surveys in Hecate Strait and Queen Charlotte Sound fished only in the surface 15-20 m. This compares to an estimate of 15.7 juvenile sockeye salmon for 18 sets in Queen Charlotte Sound and Hecate Strait at about the same time in late June and early July (Figure 55). Clearly, there were more juvenile sockeye salmon outside of the Strait of Georgia at the time of our trawl survey in July 2007. The surveys in Hecate Strait started in 2004 and the catches in 2007 represented the lowest percentage of juvenile Fraser River sockeye salmon in the time series (Table 4). The proportion of juvenile west coast of Vancouver Island (Barkley Sound) and Fraser River sockeye salmon in Hecate Strait, an area where both stocks mix, may be used as an index to evaluate the relative mortality of these stocks. Assuming that Barkley Sound and Fraser River sockeye salmon entered the marine environment at about the same time and migrated northward at about the same speed based on the relative abundances in the two areas, it is possible that juvenile Fraser River sockeye salmon would be more abundant than Barkley Sound sockeye salmon where these stocks mix in Hecate Strait in 2007.

Yet, the ratio was close to 1:1 in June 2007 (Table 4) which implies that Fraser River sockeye salmon were disproportionally under-represented in this area, possibly because they sustained high mortality prior to reaching Hecate Strait. In contrast to 2007, the proportion of Fraser River sockeye salmon relative to Barkley Sound in 2008 and 2009 was 2:1 and 4:1, respectively. One interpretation is that in 2007 there were fewer juvenile sockeye salmon leaving the Strait of Georgia compared to the observations in the years 2004 to 2009 (Table 4).

Table 4. Percentage of Fraser River juvenile sockeye salmon in Hecate Strait compared to the percentage of sockeye salmon from sites on the west coast of Vancouver Island.

Year	Percentage (%) of West Coast Vancouver Island sockeye salmon in Hecate Strait, June 17-July 3	Percentage (%) of Fraser River sockeye salmon in Hecate Strait, June 17-July 3
2004	2.9	94.3
2005	0	82.4
2006	20.0	60.0
2007	47.1	45.4
2008	30.3	63.0
2009	15.8	63.2

The lengths and weights of the juvenile sockeye salmon from the Fraser River in the Hecate Strait and Queen Charlotte Sound surveys are available from 2004 to 2009. The average length and weight was the lowest in 2007 in the six years of data (Figure 56). This is similar to the observations of the poor condition of juvenile sockeye salmon sampled in the Strait of Georgia in 2007 (Figure 12). Clearly, poor condition and small size of juvenile sockeye salmon in 2007 from the Strait of Georgia through to Hecate Strait is evidence of poor growth in the early marine period in the Strait of Georgia.

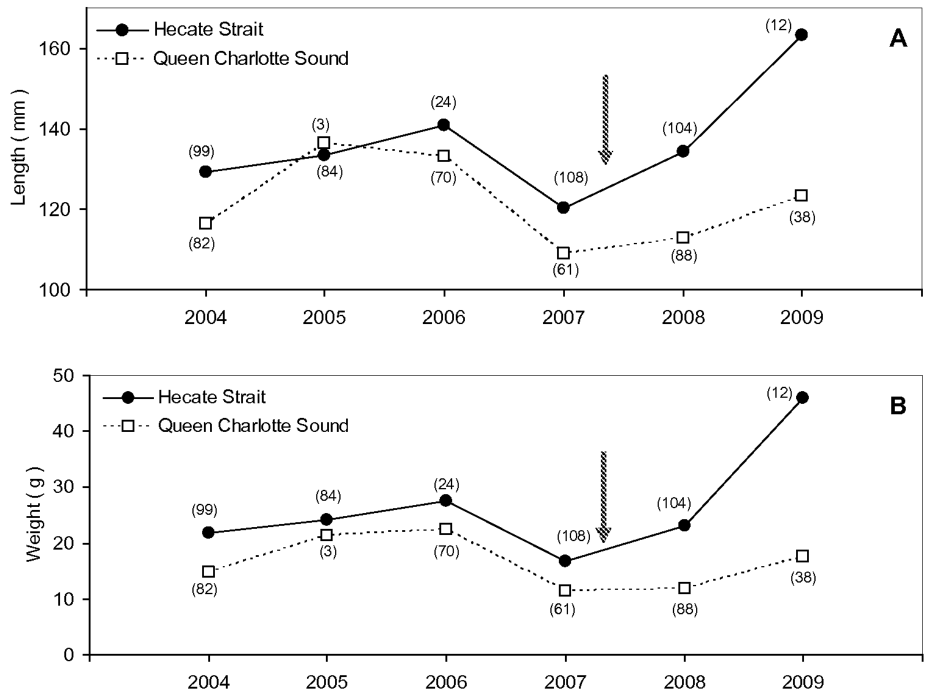


Figure 56. Average length and weight of sockeye salmon in surveys in Hecate Strait and Queen Charlotte Sound from 2004-2009; (n) = number of fish. The arrow identifies sizes in 2007.

In July 2009, the abundance of juvenile sockeye salmon in the Strait of Georgia was estimated to be 2.6 million using the methods in Beamish et al. (2000). This estimate uses a catchability of 1.0 which assumes that all fish in front of the net opening are retained in the net. There are no reliable estimates of catchability except for some Russian estimates of 0.3 for a much larger net (Shuntov et al. 1993). If we use a conservative catchability estimate of 0.5, the abundance of juvenile sockeye salmon in early July would be double, or approximately 5.2 million. In comparison, the abundance estimates from the standard trawl surveys in the Strait of Georgia in 2007 were 130,000 or 260,000 if the catchability is 0.5. It is apparent that in 2007 there were substantially fewer juvenile sockeye salmon in the Strait of Georgia in July 2007 compared to 2009. It is informative to compare these abundance estimates with the estimates of abundance of sockeye smolts that enter the Strait of Georgia, as an estimate of the number of juvenile sockeye salmon entering the Strait of Georgia provides a perspective of where and when most marine mortality is occurring. We estimated the numbers of juvenile salmon entering the strait using two methods. The first method used an estimate of the marine survival to estimate the actual number of smolts entering the Strait of Georgia from all Fraser River sockeye salmon populations. We used the marine survival calculated for the Chilko Lake population and applied the survival to the all Fraser River populations. Thus, if 2% survived to return as adults, 98% must have died. The total number of dead fish, therefore, can be estimated using the number that survived. The second method was based on the counts of juvenile sockeye salmon leaving Chilko Lake. Chilko Lake is one of the major sockeye salmon producing systems on the Fraser River. This population represents from 10% to over 50% of the Fraser River sockeye salmon depending on the years. We used the estimate of smolts leaving the Chilko system and expanded the number by the proportion of the total return in two years that was represented by the Chilko Lake escapement. Thus, for example, if 20% of all smolts were from Chilko Lake, 80% of the smolts would be from other lakes. These estimates of total smolt production are approximate and do not consider mortalities during the downstream migration. However, the estimates provide a perspective of the amount of mortality that occurs in the early marine period. In 2007, the two estimates indicated that between 467 million and 491 million juvenile sockeye salmon entered the Strait of Georgia (Table 5). Figure 52 indicates that it takes an average of about seven weeks for juvenile sockeye salmon to migrate out of the Fraser River. Our studies indicate that it takes about eight weeks for all of these juveniles to leave the Strait of Georgia as we are still catching juvenile sockeye salmon in July. A simple model that assumes that juvenile sockeye salmon migrate through the Strait of Georgia in proportion to their ocean entry timing and finish the total migration out of the strait by mid July shows that about 18% of the juveniles remain by July 1 and 10% by July 4. Our surveys in the first two weeks of July, therefore, could be sampling the juveniles that are last to leave fresh water. Therefore we use an estimate of 10% as a conservative estimate of the percentage of the population of juveniles in the Strait of Georgia at the time of our surveys. Our estimate of the number surviving in the Strait of Georgia by early July using a catchability of 0.5 was 260,000. The catches of juvenile Fraser River sockeye salmon in Queen Charlotte Sound and Hecate Strait indicate that many juveniles had left the Strait of Georgia by the time of the July trawl surveys. The number that left is unknown but using a scenario that 90% left, the 10% abundance remaining in the Strait of Georgia would indicate that only a small percentage of this 10% survived in the Strait of Georgia by early July. If 260,000 represents 10% of all the surviving juvenile sockeye salmon, then the rest of the surviving population could be about 2.6 million juvenile sockeye salmon. Compared to the estimates of total smolt production of 467 or 491 million, the remaining abundances are less than 1% of this total smolt production. It is a common principle in ecology that plants and animals that produce large numbers of seeds or offspring have a very large early mortality (Colinvaux 1978). It is also a fundamental hypothesis in fishery science that the availability of prey when larval fish begin feeding is related to the variability in production in freshwater and marine fish populations (Hjort 1914; Lasker 1975; Cushing 1990; Houde 2008). Thus, it is to be expected that there will be a large mortality within the Strait of Georgia over the two month period of movement out of the strait. Although it is not known where the mortality occurs, we proposed previously that much of the mortality occurred in the Strait of Georgia because of the poor growth or survival or both of the other species of Pacific salmon and Pacific herring. Obviously, the estimate of mortality is very approximate; however, it illustrates the very important point that very large mortalities are occurring and it is likely that a substantial mortality occurs in the Strait of Georgia. This also indicates that relatively small changes in the mechanisms that cause the mortality could result in large changes in the final abundances.

Table 5. Estimates of the number of juvenile sockeye salmon entering the Strait of Georgia from the Fraser River.

Year to Sea	Return in two years	Percentage (%) of Chilko Lake population	Chilko Lake smolt count	Total number of smolts using the percentage of Chilko Lake smolts method	Chilko Lake marine survival (%) used to estimate smolt production (year to sea +2)	Total number of smolts using the marine survival method
2000	15,132,000	4.3	11,746,000	274,937,000	7.3	207,281,000
2001	4,889,000	31.9	20,247,000	63,520,000	3.9	125,369,000
2002	4,183,000	13.1	19,257,000	151,260,000	5.5	76,058,000
2003	7,025,000	15.3	36,841,000	241,634,000	7.7	91,228,000
2004	12,967,000	10.0	21,003,000	212,815,000	2.8	463,117,000
2005	1,508,000	29.0	23,536,000	81,260,000	1.9	79,356,000
2006	1,752,000	25.6	11,318,000	44,148,000	4.0	43,808,000
2007	1,400,000	15.7	77,145,000	491,116,000	0.3	466,667,000
2008	29,000,000	15.2	73,046,000	740,128,000	4.2*	693,780,000

*Average of 2000-2007

Juvenile sockeye salmon prey consumption in the Strait of Georgia

Previous studies

Sockeye salmon smolts in the Strait of Georgia captured in late April 1968 fed mainly on copepods and crab megalops (Robinson 1969a). However, when these raw counts were converted to volume, larger items such as fish and euphausiids became dominant diet constituents. Fish were as much of 50% of the stomach volumes with crab megalops, euphasiids, copepods, amphipods, and “other” species evenly contributing to the other 50%. In surveys conducted during July 1967, Robinson (1969b) reported that while copepods and crab megalops were important diet items, the diet was more varied, including many other types of zooplankton and land-derived insects. When converted to volume, the majority, i.e. 60%, of stomach contents were “other” species, largely terrestrial insects, while crab megalops, eupahausiids, copepods, amphipods and fish were approximately 8% each. Healey (1978) presented summaries of juvenile sockeye salmon stomach analyses from 1975 and 1976 with amphipods contributing 50-60% of stomach volumes in both years and the remainder of stomach contents being roughly distributed between copepods, amphipods, fish, euphausiids and “other” species. Burgner (1991) suggested that copepods in general, and *Neocalanus* in particular, were a crucial component of the diet of sockeye salmon smolts in the Strait of Georgia, but this may be an impression from count data rather than contribution to stomach volume or mass of prey consumed.

Figure 57 summarizes reported juvenile sockeye diet composition from surveys conducted in the Strait of Georgia during the 1960s, 1970s and 1990s. For the Robinson diet compositions, prey count data were converted to volumes using assumptions about the relationship of length to weight. Haegele (1997) reported prey counts and used size conversion factors for each prey group to create an importance index for different prey items. Haegele’s size index was used to generate the approximate volume estimates in Figure 57. Healey reported diet compositions as volumes but did not separate his data into months, opting to aggregate data for the summer. Therefore, it is important to note that the different results are comparable only in a qualitative sense. Diet data averaged over the entire sampling season for each year sampled can also be used to assess the qualitative decadal-scale changes in juvenile sockeye salmon diets from the late 1960s to 2009 (Figure 58).

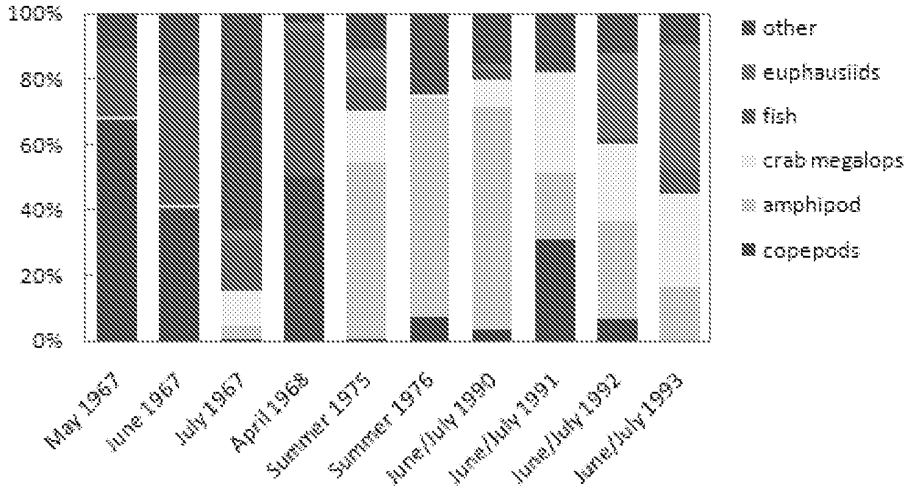


Figure 57. Summary of percentage volumes of juvenile sockeye salmon diet items from early studies in the Strait of Georgia. Data sources; May, 1967 – Robinson *et al*. (1968a), June, 1967 – Robinson *et al*. (1968b), July 1967 – Robinson (1969a), April 1968 – Robinson (1969b), Summer 1975 and Summer 1976 – Healey (1978), June/July 1990-1993 – Haegele 1997.

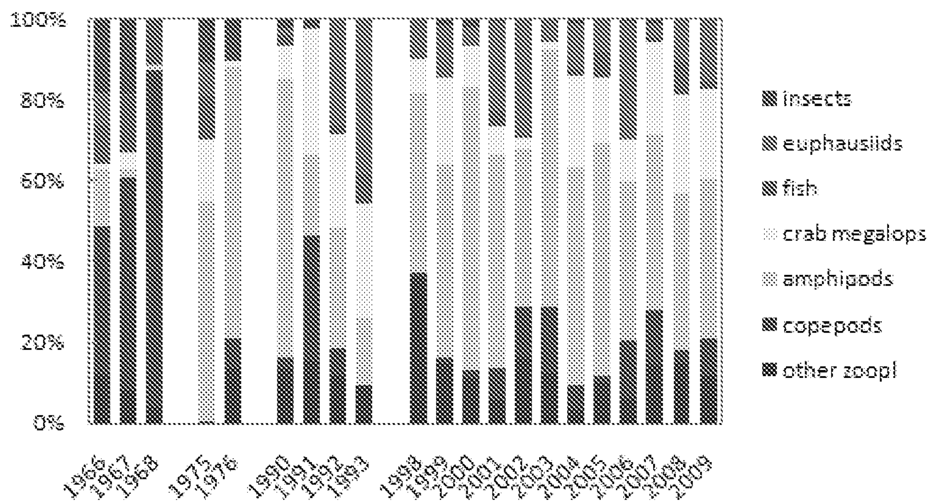


Figure 58. Juvenile sockeye diet data, from studies in the Strait of Georgia, converted to percentage of volume and averaged over all months reported for years surveyed. Data includes all years with available data, and includes information in this report; July diets reported in Figure 56, September diets reported in Figure 57 and information in Table 8. Data sources; 1967 – Robinson *et al*. (1968a and 1968b) and Robinson (1969a). 1968 – Robinson (1969b). 1975 and 1976 – Healey (1978), 1990-1993 – Haegele (1997). 1998-2009 (this report, Figure 56, 57, Table 8).

Copepods appear to decrease in importance from the 1960s to the early 2000s. Euphausiids and crab megalops increased in importance from the 1960s to the 1990s, adding to about a third of all diet by volume. Amphipods were almost absent in diets in the early years but were important in the 1970s, decreased in the early1990s, and have been a large contributor in recent years. Terrestrial insects appear to have been a significant diet item in the 1960s and 1970s but have been a very small contributor to diet since the 1990s. The fish and "other" zooplankton groups have no obvious trends and vary greatly in the reported data, though "other" zooplankton usually has made up about 10% of the volume of juvenile sockeye diets.

A Russian study of juvenile Pacific salmon diets from 1966 to 2002 looked at the diet of 3,935 juvenile sockeye salmon (Karpenko et al. 2007). The main item in the diet was hyperid amphipods, followed by euphausiids, copepods, larval crabs and juvenile fish. Juvenile sockeye salmon had the most restricted diet of all Pacific salmon with only 5 to 11 items over most of the study period.

A trawl survey from May 29 to June 8, 2010, completed 69 sets along the standard survey track lines. The stomach contents of 357 juvenile sockeye salmon were examined throughout the Strait of Georgia. Figure 59 shows the location and number of sockeye salmon examined for stomach contents. Crab megalops and crab zoea were 27% of the diet (Figure 60). Hyperid amphipods, fish remains and euphausiids represented 20%, 18% and 18%, respectively. This diet is very similar to the diet observed for juvenile sockeye salmon in the previously reported study by Russian scientists (Karpenko et al. 2007).

In all of the July trawl surveys, 1851 juvenile sockeye salmon stomachs have been examined for diet since 1998 (Figure 61). Amphipods, decapods and euphausiids were the dominant items in the diet. The two most common items in the "other" category were calanoid copepods and *Oikopleura*. In July 2007, there was an anomalously low percentage of euphausiids, perhaps indicating that euphausiids were less available. However, euphausiids were represented in average proportions in the diet of sockeye salmon sampled in September (Figures 62). Amphipods are a high-energy diet item that reflects the prey quality of a fish diet. There was a very weak relationship between the percentage of amphipods in the diet in July and length (Figure 63) and no relationship between the percentage of amphipods and recruits per spawner (Figure 64). However, there was a strong relationship between the amount of prey in the stomach and length (Figure 65). Thus, the conditions affecting the growth of juvenile sockeye salmon appear to be more related to the quantity of prey and not the quality of prey.

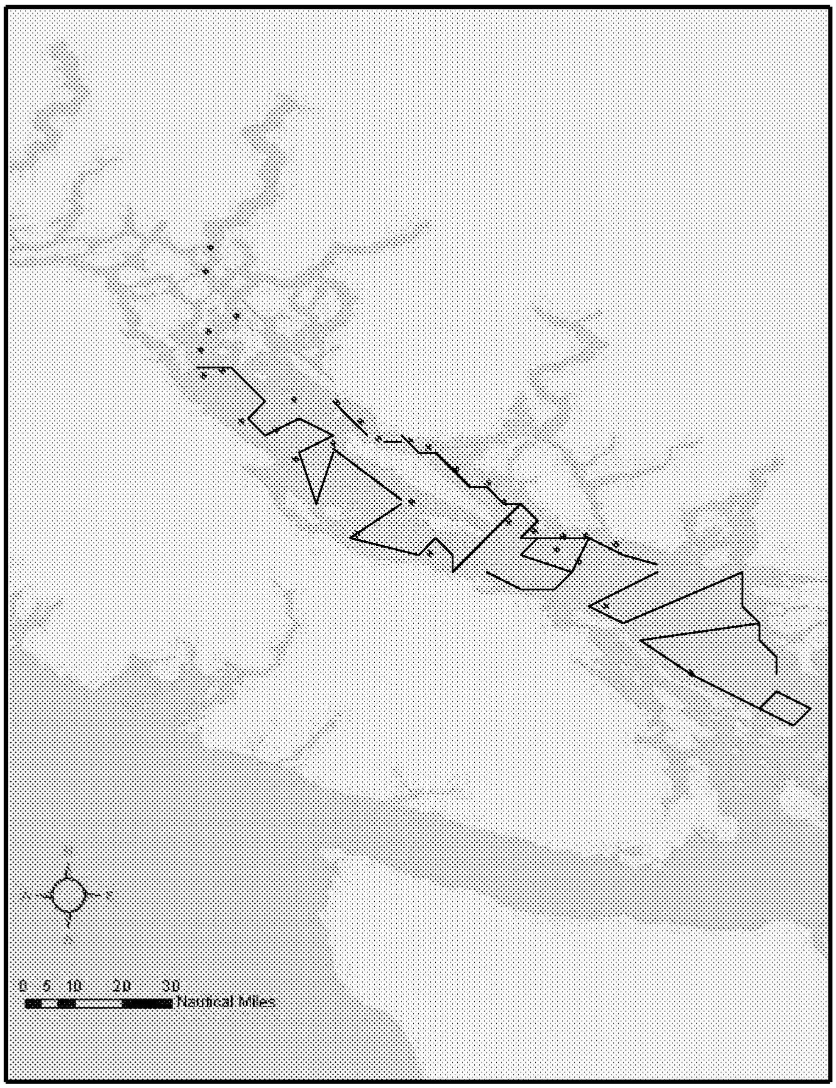


Figure 59. Location of diet samples (black circles) collected from juvenile sockeye salmon in the May 29 to June 8, 2010 trawl survey. Black lines show the standard survey track lines.

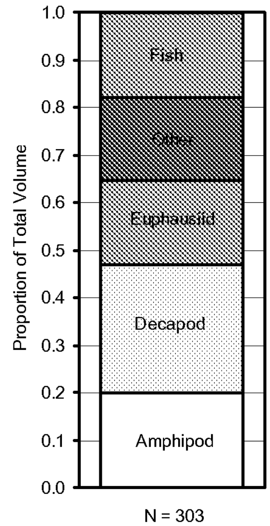


Figure 60. Items in the diet of juvenile sockeye salmon sampled May 29 to June 8, 2010.

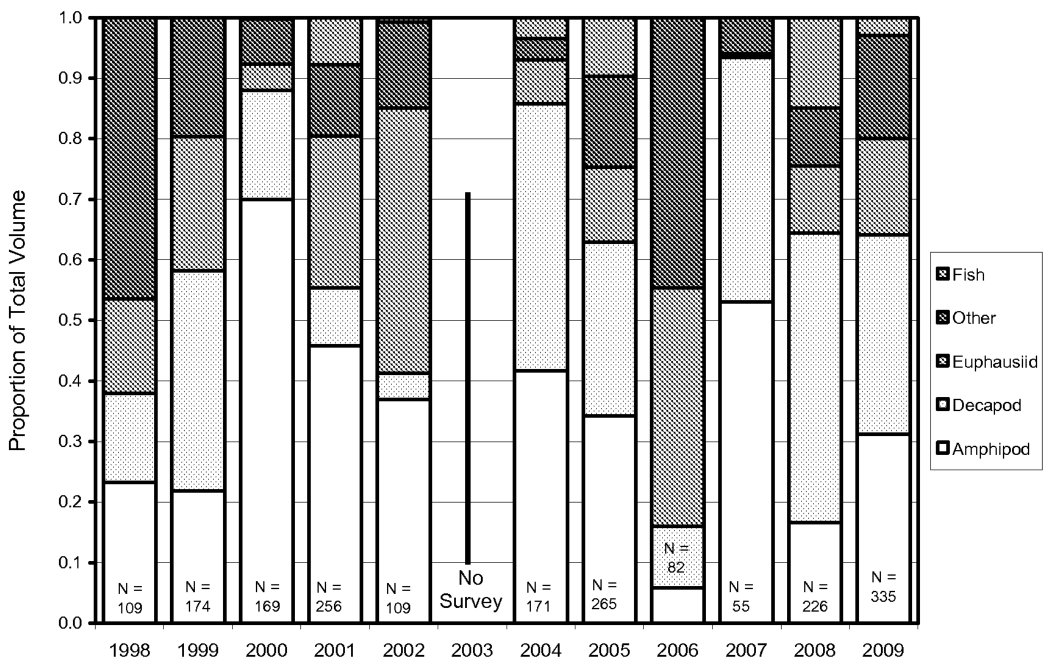


Figure 61. Items in the diet of juvenile sockeye salmon sampled in the trawl surveys, July 1998 to 2009.

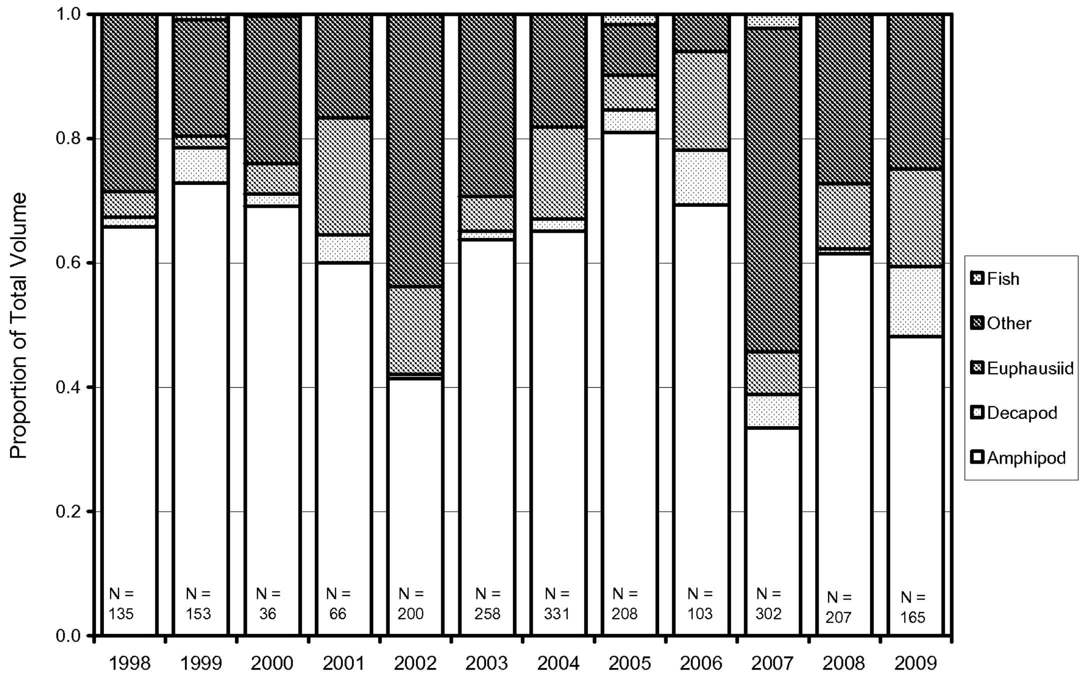


Figure 62. Items in the diet of juvenile sockeye salmon sampled in the trawl surveys, September 1998 to 2009.

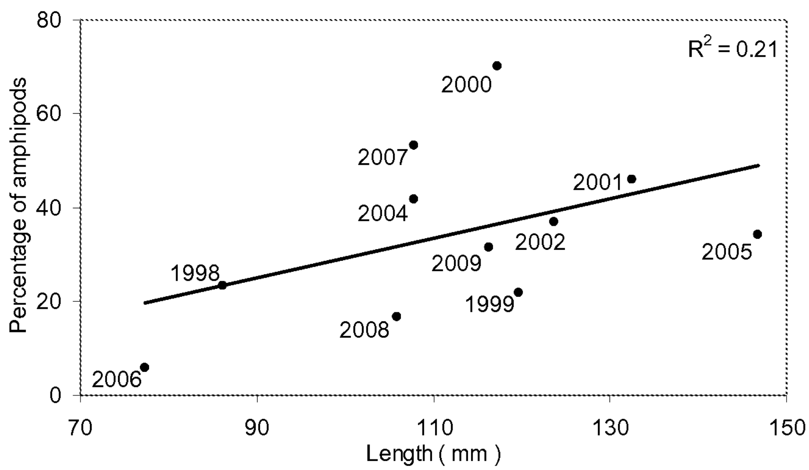


Figure 63. Relationship between the average length of juvenile sockeye salmon and the percentage of amphipods in the diet of juvenile sockeye salmon sampled in the trawl surveys in July, 1998 to 2009. The years are survey years or the year-to-sea for juvenile sockeye salmon. There was no survey in 2003.

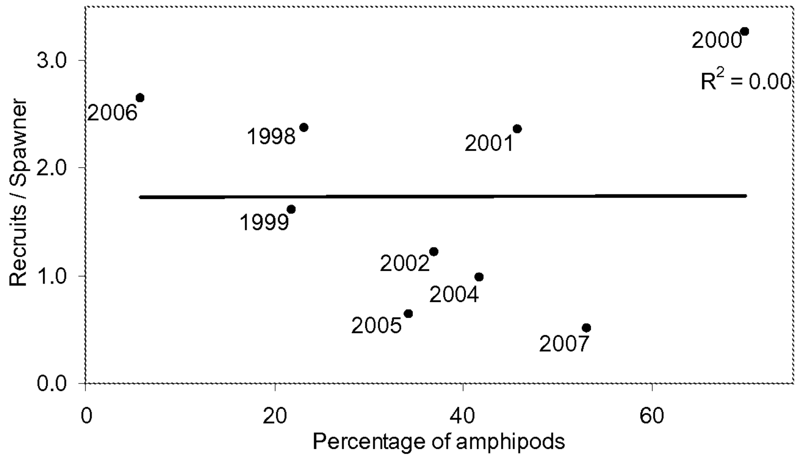


Figure 64. The percentage of amphipods in the diet of juvenile sockeye salmon from the July trawl survey and the recruits per spawner for the fish that returned as adults in two years.

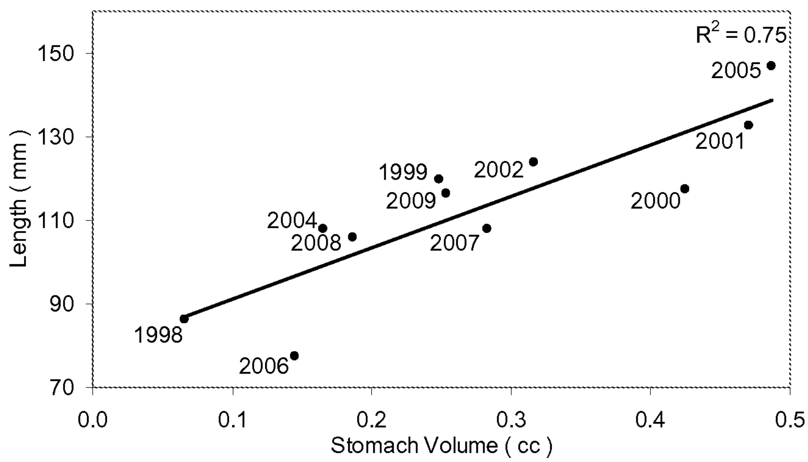


Figure 65. Relationship between average length and stomach volume for juvenile sockeye salmon captured in the July trawl survey, 1998 to 2009. Years are the survey year or the year to sea for juvenile sockeye salmon.

Predation on juvenile sockeye salmon in the Strait of Georgia

Studies traditionally report that the major cause of early marine mortality in juvenile sockeye salmon and other juvenile Pacific salmon is predation. Thus, juvenile fish that grow as rapidly as possible are thought to be able to avoid predation. Large numbers of fish, birds, and mammals in the proper location, in both time and space, are traditionally thought to feed on these juvenile salmonids as they reside in the estuaries, the shallow nearshore marine areas and the deeper mid-water locations of the Strait of Georgia. However, there are very few studies that document this predation. We also point out that the smaller Harrison River sockeye salmon and South Thompson chinook salmon are surviving better than the larger fish that enter the ocean earlier. We are unable to discuss avian or mammalian predation, other than to acknowledge its existence and we focus, therefore, on piscine predation. A quick list of the qualifications for a given fish species to be a potential major predator on juvenile salmon assumes that the species must exist in large enough numbers throughout the Strait of Georgia to have a measurable impact on the juvenile sockeye salmon population. They must exist at a size range sufficient to feed on juvenile salmon for several weeks to months and they must overlap in their distribution throughout the water column enough to promote interaction rates sufficient enough to have impacts. Applying these assumptions to the species commonly resident in the Strait of Georgia leads to a rather short list of potential fish predators on juvenile sockeye salmon: spiny dogfish (*Squalus acanthias*), Pacific hake (*Merluccius productus*), walleye pollock (*Theragra chalcogramma*), other salmon (e.g., adult chinook) and various species of rockfish (*Sebastes* spp.). These fish are in the bycatch data from our surveys in the Strait of Georgia.

Pacific hake, which may be at historic or near-historic high population levels in the Strait of Georgia, have population sizes big enough and certainly have the size range capable of feeding on juvenile sockeye. From 1998-2002 we examined some 257 hake stomachs from spring and summer surveys in the Strait of Georgia for the presence of juvenile sockeye salmon. The size of these fish ranged from 125-569 mm, covering at least three year classes. Juvenile sockeye were not found in any of these stomachs. Other studies in the 1970s, 1980s and 1990s have examined the diet of thousands of Pacific hake in the Strait of Georgia and juvenile Pacific salmon were absent in virtually all of the stomachs (G.A. McFarlane, personal communication). Thus, Pacific hake are not a predator of sockeye salmon or any other species of Pacific salmon.

Spiny dogfish, like Pacific hake, appear to have population levels sufficiently high to have a population-level impact, even at low levels of predation. Some early work suggested that, at certain times and locations (e.g., smolt emigration from the Big Qualicum River in May), spiny dogfish do appear to school to take advantage of the influx of high numbers of juvenile salmon into the ocean (Beamish et al. 1992). However, this observation was not only inconsistent at this site across years, but has not been reported for other major salmon river outlets. Spiny dogfish that feed on fish also tend to be deeper in the water column than the vast majority of juvenile sockeye. While spiny dogfish are commonly caught as shallow as 30-45 meters, most of these fish are juveniles that feed mostly on plankton. An examination of approximately 500 spiny dogfish stomachs from our trawl surveys (1998-2002) revealed that while fish and euphausiids do comprise a significant proportion of the spiny dogfish diet, juvenile sockeye were only found in two fish (3 - chinook, 13 - chum, 16 -coho, 2 - pink, 3 - unknown juvenile salmon). Thus, while the opportunity exists, spiny dogfish in the Strait of Georgia do not appear to be major consumers of juvenile sockeye salmon.

Walleye pollock are large, omnivorous fish that are resident in the Strait of Georgia. Fish do not generally comprise a major portion of their diet, but larger fish are capable of catching and eating small salmon. However, these larger fish tend to be very deep in the water column and most unlikely to feed on juvenile sockeye salmon. Our catch of larger walleye pollock in the Strait of Georgia is mostly from sets deeper than 60 m. This indicates that there is physical separation within the ecosystem that precludes walleye pollock from being major predators on juvenile sockeye salmon. Of 269 walleye pollock stomachs examined from the trawl surveys in the Strait of Georgia (1998-2002), a single chinook smolt was the only juvenile salmon observed in the stomach. The walleye pollock diet was mainly composed of euphausiids and amphipods.

Millions of adult salmon return to the Strait of Georgia every year, on the way to their various natal rivers. Most of the returning fish are in the Strait of Georgia after mid June, when much of the early marine mortality has already occurred. In addition, resident coho and especially resident chinook salmon are potential predators on juvenile salmonids. The regime shift in the late 1980s appears to have impacted coho salmon behaviour such that the once-common "blueback" coho fishery in the Strait of Georgia essentially has collapsed. These coho salmon, instead of returning to the Strait of Georgia in early January to February, now seem to prefer to remain outside of the Strait of Georgia and only return in the late summer, just prior to moving back into freshwater. Thus, their potential as major predators has declined considerably. Similarly, the population levels of adult and sub-adult chinook in the Strait of Georgia are just not sufficient to explain the extremely low rate of early marine survival of juvenile sockeye salmon. An examination of adult and subadult chinook salmon taken in July surveys in the Strait of Georgia from 1998-2002 reveal that, of 204 stomachs examined, juvenile sockeye were never observed. Only one juvenile chinook salmon was found in a stomach.

There are 16 rockfish species found in the Strait of Georgia. However, most rockfish tend to be very territorial, bottom-dwelling residents. While population levels of rockfish as a whole in the Strait of Georgia used to be high, individual species population levels no longer appear to be large enough to be considered as having potential for impact at the population level. Furthermore, rockfish are rarely caught in our surveys suggesting that these species are not a major predator of juvenile sockeye salmon.

Competition between juvenile sockeye salmon and other fish

In any ecosystem, direct competition infers that another fish species either is feeding on the same diet items as juvenile sockeye salmon or is occupying the preferred niche within the habitat for juvenile sockeye salmon. Pink and chum salmon abundances are currently at historic highs throughout the North Pacific region. Juvenile chum salmon catches over the course of the Strait of Georgia summer surveys consistently are 3-8 times larger than the other juvenile Pacific salmon catches except for pink salmon. Juvenile pink salmon only enter the Strait of Georgia in large numbers in even-numbered years, but have high catch numbers in those years. In contrast, the catch of juvenile pink salmon in odd years averages only 30 fish. Additionally, juvenile pink and chum salmon both enter the marine environment in the late spring (April-May) and are present in the marine environment when juvenile Fraser River sockeye salmon enter. Coho and chinook salmon enter the strait from about mid May to June. Additionally, the average sizes of juvenile chum and pink salmon in the July surveys are approximately equal to that of juvenile sockeye salmon. Thus, pink and chum salmon seem to be capable of being direct competitors for food within the Strait of Georgia habitat.

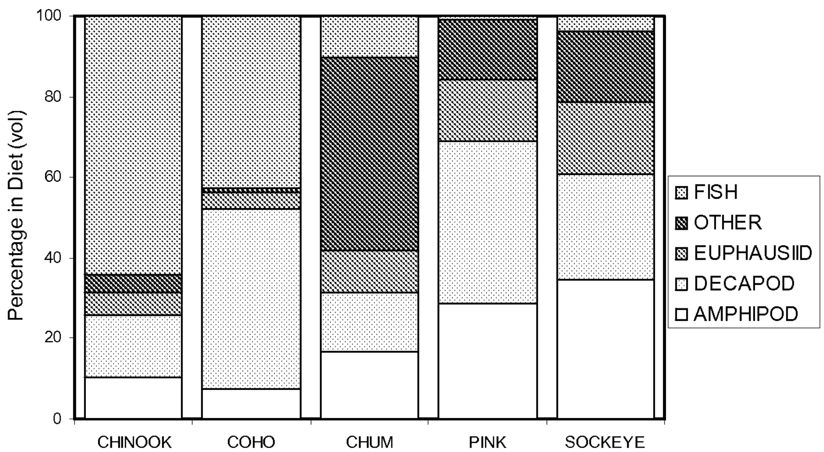


Figure 66. Average diet for juvenile salmon captured in July trawl surveys in the Strait of Georgia, 1998-2009.

An examination of diet items from the trawl survey demonstrates that juvenile pink and chum salmon both have significant diet overlaps ($Chi^2 = 0.95$ and 0.74, respectively; $P \leq 0.05$, Horn Index) in July. Coho and chinook salmon do not significantly overlap with sockeye salmon diets. In the July surveys from 1998-2009, the major diet items for juvenile sockeye salmon rearing in the Strait of Georgia were amphipods and items in the "other" category (Figures 61, 66). Hyperids generally make up over 98% of the amphipods in the diet of juvenile sockeye, chum and pink salmon. Similarly, the dominant items in the generalized "other" category of juvenile sockeye; chum and pink salmon tend to be dominated by calanoids and chaetognaths, with *Oikopleura* also contributing consistently over the years of our study. Even though juvenile chum salmon also feed heavily on ctenophores (the only salmon to do so), their diets overlap considerably with juvenile pink salmon. Thus, juvenile pink and chum salmon appear to be direct competitors with juvenile sockeye salmon rearing in the Strait of Georgia. Previously in this report, we showed that the growth of sockeye salmon is reduced when pink salmon are abundant in the Strait of Georgia (Figure 42), confirming that it is probable that competition for food affects the growth of juvenile sockeye salmon. If reduced early marine growth is associated with increased early marine mortality as observed in studies of other Pacific salmon, then it is possible that competition for food among pink, chum and sockeye salmon increases the mortality of juvenile Fraser River sockeye salmon.

Ocean ecology of sea-type Harrison River sockeye salmon

Virtually all juvenile sockeye salmon caught in the September trawl surveys in most years are likely from the Harrison River as shown previously in this report. In several years, the length distribution was bimodal indicating that some lake-type sockeye salmon probably remained in the Strait of Georgia. The average lengths ranged from 103 mm to 163 mm for the surveys from 1998 to 2009 (Figure 67). The CPUE ranged from 2.1 fish / hr to 146.2 fish / hr (Figure 25). Abundance estimates of about 2,738,000 to 7,502,000 were observed in 2007 and 2008, respectively. The abundances in September 2007 were substantially larger than observed for the juveniles in July. Thus, conditions within the Strait of Georgia were substantially better for juvenile sockeye salmon later in the summer of 2007. Harrison River sockeye salmon tended to be concentrated more in the southern areas of the Strait of Georgia (Figure 27). The one survey in November 2008 captured Harrison River sockeye salmon (Figure 29), indicating that some fish remained within the Strait of Georgia for about four months. No ocean age 1+ Harrison River sockeye salmon have been caught in July, but a few age 1+ fish were caught in the northern part of the Strait of Georgia in February 2004 (Figure 31). This indicates that most fish leave the Strait of Georgia very late in their first marine year. As reported previously, catches on the west coast of Vancouver Island in February (Tucker et al. 2009) may indicate that the movement is through Juan de Fuca Strait. It is not known where these fish rear in the open ocean.

In the Strait of Georgia in September, juvenile Harrison River sockeye salmon fed heavily on amphipods (Figure 62). Euphausiids, interestingly, were consistently a relatively minor part of the diet. Items in the "Other" category are listed in Table 8, with calanoid copepods and *Oikopleura* being the dominant food items. There was no relationship between the percentage of high-energy amphipods and length (Figure 68). Thus, there is no evidence that the prey quality was a major factor affecting growth. As shown previously (Figure 5D), there is a relationship ($R^2 = 0.32$) between the catches in September and the total return.

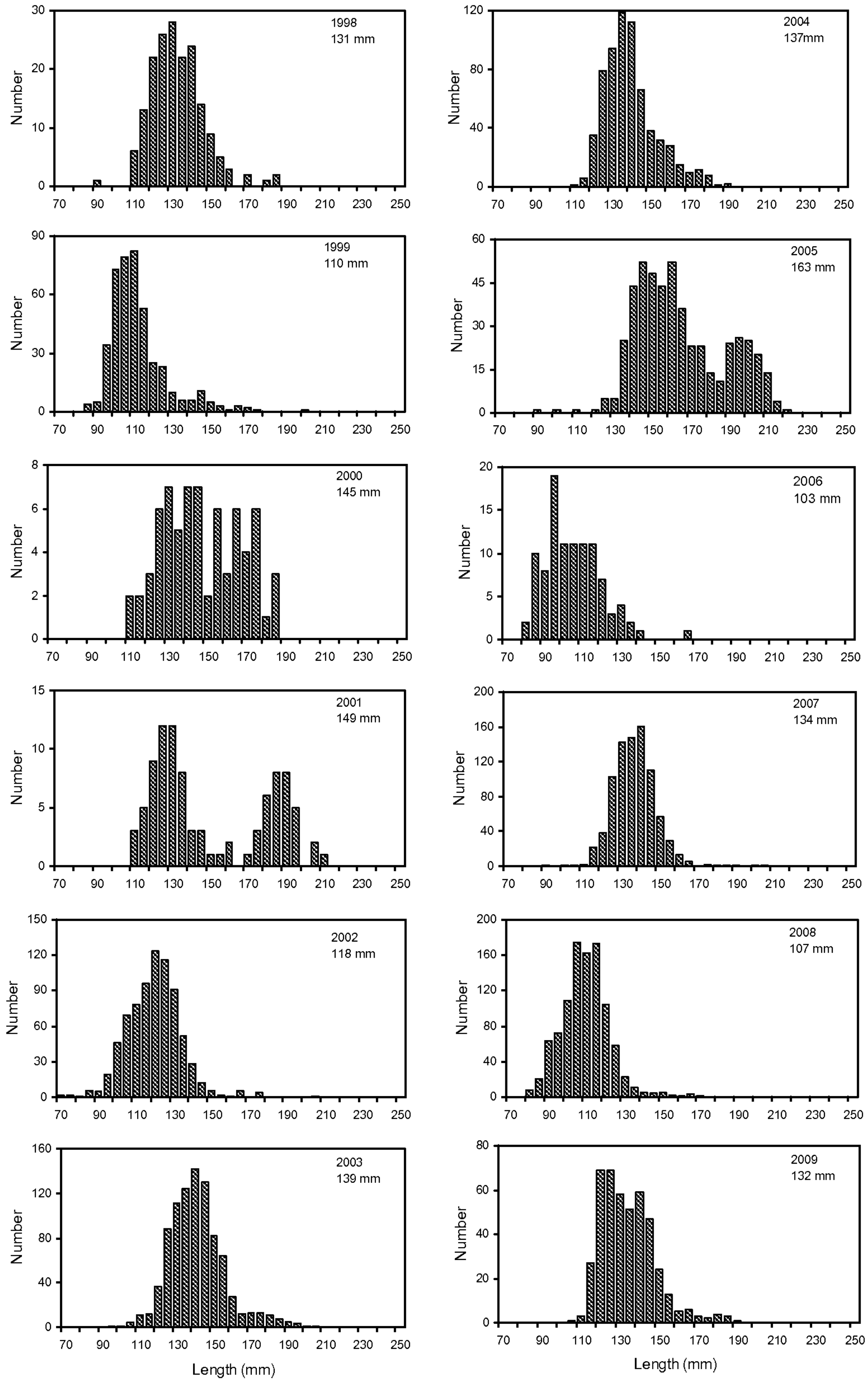
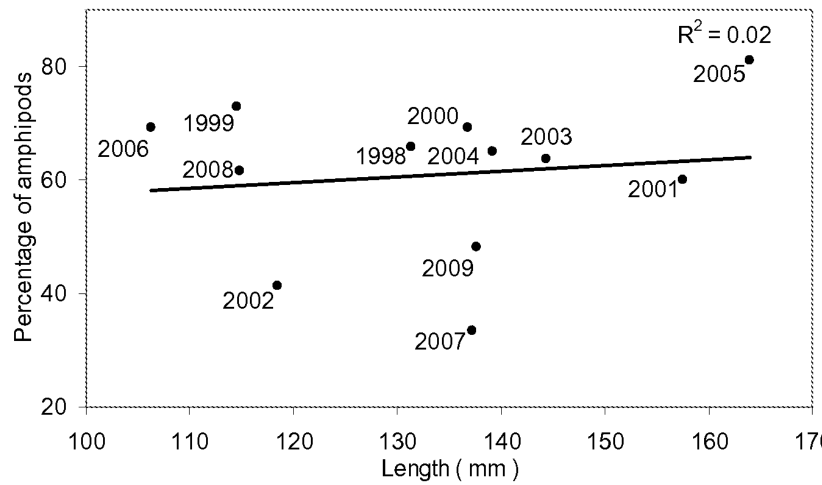


Figure 67. Lengths (mm) of juvenile sockeye salmon captured in the September trawl surveys in the Strait of Georgia, 1998-2009. The average length for each survey is shown.

Table 8. Species in "OTHER" category in diet of juvenile sockeye salmon captured in the September trawl surveys in the Strait of Georgia, 1998-2009. Values are shown as total volume (cc).

"OTHER" diet	Year											
item	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Calanoid	0.27	0.53	0.385	3.295	17.315	22.88	20.325	1.44	1.225	31.92	3.34	7.985
Chaetognath	0.07		0.155	0.74	6.38	1.47	1.26	8.35	0.155	3.525	1.11	5.655
Clione												0.36
Ctenophore					1.3	0.32	0.18					
Digested matter	1.945	0.09	0.52	0.55	1.2	0.64	3.79	0.4	0.37	0.72	0.07	
Gastropod					0.28						0.06	2.17
Harpacticoid	0.5											
Insect		1.26	0.52	0.36	0.21		4.96		0.52	2.99	0.16	0.19
Mysids							0.32					
Octopus (juv.)											0.16	
Oikopleura	28.49	5.68	0.71	1.15	11.36	13.89	4.795	0.08	0	29.475	14.435	0.18
Ostracod			1.05		2.29		1.255	0.2		0.525	0.1	1.415
Polychaete					0.49	0.98		0.21		0.82	0.04	0.785
Waste/debris				0.06								0.04

Figure 68. Relationship between length and the percentage of amphipods in the diet of juvenile sockeye salmon sampled in the trawl surveys in September, 1998 to 2009. The years are survey years or year-to-sea for juvenile sockeye salmon.



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