The Cohen Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River

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TECHNICAL REPORT 8

Predation on Fraser River Sockeye Salmon

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Preface

Fraser River sockeye salmon are vitally important for Canadians. Aboriginal and non-Aboriginal communities depend on sockeye for their food, social, and ceremonial purposes; recreational pursuits; and livelihood needs. They are key components of freshwater and marine aquatic ecosystems. Events over the past century have shown that the Fraser sockeye resource is fragile and vulnerable to human impacts such as rock slides, industrial activities, climatic change, fisheries policies and fishing. Fraser sockeye are also subject to natural environmental variations and population cycles that strongly influence survival and production.

In 2009, the decline of sockeye salmon stocks in the Fraser River in British Columbia led to the closure of the fishery for the third consecutive year, despite favourable pre-season estimates of the number of sockeye salmon expected to return to the river. The 2009 return marked a steady decline that could be traced back two decades. In November 2009, the Governor General in Council appointed Justice Bruce Cohen as a Commissioner under Part I of the *Inquiries Act* to investigate this decline of sockeye salmon in the Fraser River. Although the two-decade decline in Fraser sockeye stocks has been steady and profound, in 2010 Fraser sockeye experienced an extraordinary rebound, demonstrating their capacity to produce at historic levels. The extreme year-to-year variability in Fraser sockeye returns bears directly on the scientific work of the Commission.

The scientific research work of the inquiry will inform the Commissioner of the role of relevant fisheries and ecosystem factors in the Fraser sockeye decline. Twelve scientific projects were undertaken, including:

Project	
1	Diseases and parasites
2	Effects of contaminants on Fraser River sockeye salmon
3	Fraser River freshwater ecology and status of sockeye Conservation Units
4	Marine ecology
5	Impacts of salmon farms on Fraser River sockeye salmon
6	Data synthesis and cumulative impact analysis
7	Fraser River sockeye fisheries harvesting and fisheries management
8	Effects of predators on Fraser River sockeye salmon
9	Effects of climate change on Fraser River sockeye salmon
10	Fraser River sockeye production dynamics
11	Fraser River sockeye salmon – status of DFO science and management
12	Sockeye habitat analysis in the Lower Fraser River and the Strait of Georgia

Experts were engaged to undertake the projects and to analyse the contribution of their topic area to the decline in Fraser sockeye production. The researchers' draft reports were peer-reviewed and were finalized in early 2011. Reviewer comments are appended to the present report, one of the reports in the Cohen Commission Technical Report Series.

Executive summary

Fishes live in the sea, as men do a-land;
the great ones eat up the little ones
William Shakespeare

Surviving in the ocean is living in a state of fear; fear of being eaten by birds, mammals and other fish. To the marine predator, it does not really matter what it consumes as long as the prey is about the right size. From this perspective, the Fraser River sockeye salmon is like many other species — an inviting mouthful swimming in the open water masses.

Sockeye salmon are repeatedly faced with making two choices throughout their life cycle. They can hide and limit risk of predation, but feed little and grow slowly—or they can stay in the open and risk being eaten, but feed a lot and grow quickly. It is a constant tradeoff where they are damned if they do and damned if they don’t. Sockeye salmon, like other fish, have successfully dealt with this dilemma through evolutionary time by developing a complicated life history that includes moving between ranges of habitats varying in the risks they represent. Minimizing predation forms an important part of this strategy.

Spawning in nutrient-poor streams and moving on to lakes has been an important part of the life-history strategy of sockeye salmon because neither of these habitats can maintain year-round predator populations that are abundant enough to severely impact varying numbers of sockeye salmon. A similar strategy may be at play for the larger sockeye in the open blue water ocean — where fish can hide at depth from predators during day, and feed at shallower depths from dawn to dusk under the cover of darkness. Between the lakes and the open ocean lies a dangerous stretch through the Fraser River and the Strait of Georgia, and along the British Columbia coast to Alaska. Predators are likely to gather to prey upon the ample and seasonal supply of outward bound and returning sockeye salmon. Making it through the gauntlet likely depends upon the size and speed of the migrating sockeye, the feeding conditions they encounter — and the species and numbers of predators that seek to eat them.

Naming the predators of sockeye salmon should not be a difficult task given that everyone likely loves sockeye—but scientifically supported ecosystem-level information about predator species (numbers, diets, trends, and distributions) is sparse throughout the sockeye salmon range. Research in freshwater has largely concentrated on fish species of interest to anglers, and has provided some information on stomach contents, but little to

no information about the abundance and trends of potential predators. More information is available from marine systems, but it is again almost exclusively for commercially important fish species, and largely absent for other predator species in the ecosystems.

A review of the available scientific literature reveals a wide range of species holding the remains of sockeye salmon in their stomachs, but only a few of these predators have specialized in targeting sockeye, and there are no studies showing that a predator has consumed sufficient numbers over the past three decades to pose a population threat to sockeye salmon. There is no sign of a smoking gun among the long list of potential predators of Fraser River sockeye salmon.

The list of prime predator suspects in the long term-decline in survival rate of Fraser River sockeye salmon as well as in the disappearance of the 2009 run of Fraser River sockeye is relatively short. Caspian terns and double-crested cormorants feed on sockeye smolts in freshwater and may be increasing in numbers, while lamprey may be a major factor in the Fraser River estuary. In the Strait of Georgia, the "usual suspects" among the fish predators (spiny dogfish, and coho and chinook salmon) have all declined in recent decades, and individually seems unlikely to have had any major impacts on sockeye salmon. Through the Strait of Georgia and Queen Charlotte Sound there are a number of potential predators of which sablefish is one of the more surprising. Sablefish is known as a deepwater species, but the juveniles are more coastal and known to feed on salmon smolts in the early summer months when supply is ample. Arrowtooth flounder is another potential predator, which has increased dramatically in recent decades, and could potentially be a predator on sockeye salmon during their first months at sea. Some species of marine mammals have been documented eating salmon smolts, but none have been seen taking sockeye salmon smolts.

Feeding conditions may have changed for the potential predators of sockeye salmon in the Northeast Pacific Ocean in recent decades. Previously abundant prey species such as walleye pollock and Pacific cod in the Gulf of Alaska, and Pacific jack mackerel, Pacific mackerel, and Pacific hake further south have declined, and could have potentially shortchanged the predators. Such a change could have increased predation pressure on sockeye, but data are unavailable to assess this possibility.

Once in the open ocean, sockeye salmon appear to draw the predatory attention of salmon sharks, blue sharks, and an obscure species fittingly called daggertooth. All three species likely increased in recent decades (after the 1992 UN ban on driftnet fisheries) — and two of them (salmon sharks and daggertooth) may favor sockeye. Unfortunately, data for these species is also too sparse to draw conclusions about their potential role in the poor return of Fraser River sockeye in 2009, but their life histories suggest relatively stable numbers that should not have exerted greater predation upon sockeye in any single year relative to others.

In addition to the daggertooth and sharks, marine mammals also consume adult sockeye salmon. However, sockeye are not an important part of marine mammal diets compared to the other species of salmon. No studies have reported marine mammals consuming sockeye salmon in the open ocean. However, small amounts of sockeye have been found in the stomachs or fecal samples collected from Steller sea lions, northern fur seals, harbour seals, killer whales, and white-sided dolphins feeding over the continental shelf and inside waters of British Columbia. Seal and sea lion populations have increased significantly in British Columbia and southeast Alaska since the late 1970s. However, the available data indicate that sockeye salmon is not a preferred prey species among marine mammals.

Overall, the list of potential predators of sockeye salmon is long, but only a few of these species might have individually been a major factor in the decline of Fraser River sockeye salmon based on their diets and indications of increasing population trends. Thus, the evidence that any single predator caused the decline of Fraser River sockeye salmon is weak or nonexistent. Instead, predation is more likely to be part of the cumulative threats that sockeye contend with. Cumulative threats are far more difficult to evaluate than a single factor. In the case of Fraser River sockeye salmon, stress from higher water temperatures, more in-kind competition due to increased escapement with resulting lower growth, and running the gauntlet through predators whose alternative prey may have diminished, may all have had cumulative effects. Assessing the cumulative effects of these and other stresses will require integrated evaluation.

Evaluating why the survival of Fraser River sockeye declined requires knowing what happened in each of the habitats the fish passed through. Finding correlations between survival rates and environmental indicators is not an explanation. An explanation requires uncovering the underlying mechanisms that affect survival, and calls for information about ecosystem resources and interactions. In theory, this information should have been available through the DFO Ecosystem Research Initiatives to study and evaluate ecosystem-level information instead of single species assessments, as has been the case until now. However, this initiative by DFO appears to have been little more than an intention supported with insufficient funding. Integrated management is seemingly at a standstill in British Columbia. This lack of a coordinated system to gather and assess ecosystem-level information limits the overall ability to better assess the effects of predation on Fraser River sockeye salmon.

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Introduction

The objective of this report is to provide the Cohen Commission with an overview of the current knowledge about potential predators of sockeye salmon and their impact across the geographical range of Fraser River sockeye salmon. This report summarizes the current knowledge about the role of predation by fish, birds and mammals on sockeye eggs, alevins, fry, and smolts in freshwater and on smolt, immature and maturing sockeye in marine systems.

The starting point for our analysis required evaluating a large body of scientific literature to judge which predators might be among the multitude of species that Fraser River sockeye salmon may encounter as they move from streams to lakes, to the river to the coast, through the Strait of Georgia, north to Queen Charlotte Sound and further out to the open North Pacific Ocean. Our efforts revealed little quantitative information to assess the impact of any of the potential predators on sockeye salmon in the ocean, save for a few species that are commercially caught. Similarly, there is little to no information about the abundance and trends in abundance for any potential predator in the freshwater. Thus, it is not possible to evaluate the cumulative effect of predation on Fraser River sockeye salmon with any degree of certainty.

Our assessment of the effects of predation on Fraser River sockeye was largely limited to single species assessments. This approach allowed a large number of potential predators to be ruled out in the sense that they were unlikely to have been a major or contributing factor in the decline in survival rate of Fraser River sockeye salmon over the last decades. This approach also identified potential predator species that require further study through an integrative fisheries research program to resolve their cumulative contribution to controlling the dynamics of Fraser River sockeye salmon.

Everybody loves sockeye

A state of fear

Living in the ocean is living in a state of fear (Bakun 2011). Fish eat fish. The first rule for species interactions is that when two fish meet—the smaller one tends to become the prey. What species it is does not really matter as long as the size is about right. From this perspective, there is nothing exceptional about Fraser River sockeye salmon. Through their life history Fraser River sockeye are a nice mouthful, mostly freely available in the open waters, be they limnetic (in lakes) or pelagic (in the ocean). Surviving this conundrum has evolved over millions of years.

All species have behavioral mechanisms and life history strategies that limits their predation risk (Walters and Martell 2004). Some species use refugia or feed under the cover of darkness to minimize predation risk. Other species of fish such as bluefin tuna may spawn where little food is available for the young larvae, but where predation risk is also low. It is better to eat less than to be eaten, or the hunter may become the hunted. The two processes are closely linked—to eat or be eaten? A fish can hide and most spend the most of the time doing so, but then it probably will not get food (unless it is an ambush predator). There is a constant tradeoff between eating and being eaten.

The successful life history strategy of sockeye salmon nicely illustrates the tradeoff between eating and being eaten. Sockeye spawns in low-nutrient streams, which can sustain only a limited number of predators on a year-round basis. Their strategy is to invest energy in large eggs that for months can sustain the emerging yolk sac larvae (or alevins as they are called by salmon scientists). The eggs and alevins stay hidden in gravel—which allows oxygen through, and keeps them out of harm's way from predators. Once the sockeye emerge from the gravel as fry, their parents will have been long dead, having fertilized the streams and the lakes below, and thus having seeded a food web that can sustain their offspring for the first year of life in otherwise nutrient-poor lakes.

A perilous journey begins once the smolt leaves for the ocean. The next two years of their life will take them along the border of the North American continent north to Alaska and then out in the open North Pacific Ocean (McKinnell and Dagg 2010). They will spend two years in the open sea, facing the constant tradeoff between finding food and avoiding predators—while simultaneously competing for resources (Figure 1). They may maintain growth by spending more time feeding in the face of increased competition, be it due to higher abundance of their year class or because of less food being available (Figure 1A). Spending more time feeding, however, means taking more risks, and will likely result in a linear increase in predation mortality. Alternatively, a fish may spend more time trying to feed when competition for food increases, but end up with reduced food intakes and lower growth rates (Figure 1B). This in turn would expose the young sockeye to predation for longer times (Lorenzen 1996).

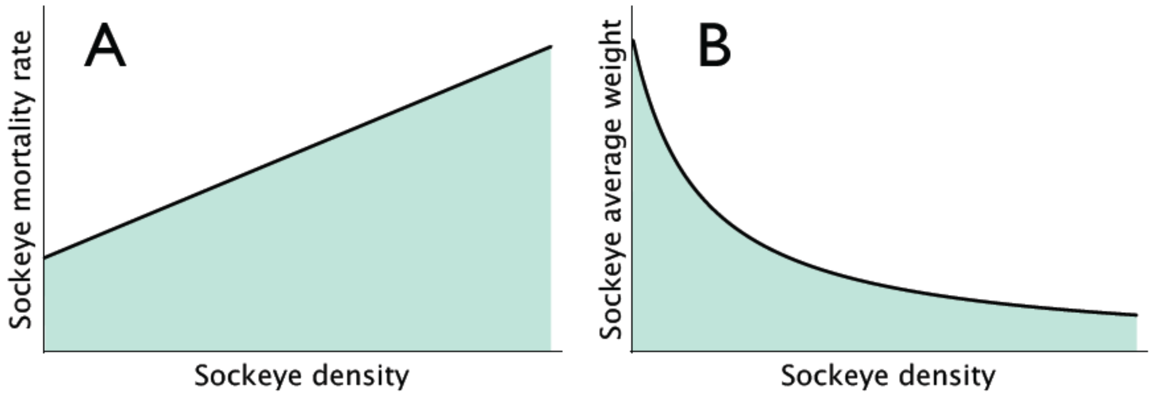


Figure 1. Two common strategies for dealing with competition between individual predators, such as for sockeye. (A) Predators vary the time spent feeding so as to maintain food intake. (B) Constant foraging time where increased competition leads to lower food intake and therefore lower predator weight.

Size and predation rates are closely related among fish (Lorenzen 1996). This growth–size–predation mortality tradeoff is known in general for sockeye (Ricker 1962), and has also been illustrated by fertilization experiments in sockeye lakes. Indications are that at Leisure Lake, smolt weights increased 112% and smolt-to-adult survival increased 25%. Similarly at Packers Lake, smolt weights increased by 100% and marine survival increased by 43%; and at Chilko Lake, each gram of increase in smolt weight was associated with a 14% increase in the rate of adult returns (Hyatt *et al.* 2004). These increases in size were due to fertilization, but the important aspect of the results is that this mechanism may provide stability over time. If there are more smolts one year, their freshwater growth is likely to be lower because increased predation associated with competition (for empirical sockeye data, see Fig. 5 in Hume *et al.* 1996). This in turn will lower the marine survival, and will drive the return towards an average value. Opposite, a low rate of spawning should be expected to result in higher growth (less competition, more food), higher growth and size of smolts, and higher marine survival.

Irrespective of strategy, avoiding predation is the key to survival. This involves short-term evolutionary adaptations such as avoiding predation by seeking an anti-predation window through daily vertical migrations (Clark and Levy 1988). Light diminishes through the water column, and many piscivores depend on sight. The daily vertical migrations of juvenile sockeye are thus closely related to light intensity, which allows them to feed in bursts on zooplankton during morning and evening, while spending the rest of the time hiding from visual predators in the dark (Scheuerell and Schindler 2003). Indeed, most fishes typically concentrate their feeding concentrated to short bursts in the course of the day, typically at dawn and dusk (Rickel and Genin 2005), and spend the rest of their time avoiding predators and living in a state of fear.

Competition or predation: are predators just executioners?

A lesson from ecosystem models is that fish such as salmon may survive well if there are no predators. They do not simply die because of food limitation. Something or someone must cause them to die. But is such a lesson an artefact of the ecosystem models or does it reflect reality? It may in fact be very real.

Competition alone is not a sufficient condition for species to die, although indications from freshwater systems on the impact of competion are not conclusive. For example, Beauchamp et al. (1995) concluded that competition was unlikely to be a limiting factor for sockeye production in Lake Ozette, Washington, even with an intensive enhancement program. Instead, predation impact was more likely to become a controlling factor, but total predation losses were (as tends to be the case) unknown due to lack of information about predator abundance. In another study, Sebastian et al. (2003) found an inverse correlation between kokanee (land-locked sockeye) and sockeye abundance in Adams and Quesnel lakes, and concluded that this was more than a coincidence—though one where sockeye seemed to outcompete kokanee.

It may not matter if the evidence for impact of competition is inconclusive, given that it is not likely to be a question of competition *or* predation. Rather it is more likely to be a question of how competition and predation interact. As described in the previous section, increased competition for food may manifest itself either by the competitors spending more time feeding, and therefore increasing their predation risk, or by the competitors avoiding the additional risk and instead limiting their food intake and hence growth rate. This in turn will have the same effect (i.e., a longer time exposed in the predation window results in an increased risk of being eaten). So, the results will likely be the same, with one twist— being doomed does not kill; there has to be an executioner.

The flipside of competition

Species such as sockeye salmon may be competing for food with many other species in the open ocean. It might therefore be intuitively assumed that reduced abundance of a competitor should benefit those remaining. But what if food is not a major limiting factor? What if it is predation pressure, such as hypothesized for Fraser River sockeye in lakes by Foerster and Ricker (1938) almost a century ago. The implications of this hypothesis may be that the reduction that has occurred in a number of the major, potential competitors of sockeye salmon in the North Pacific Ocean (see details later in this report) may result in increased predation pressure even if the predator biomass has not been increasing significantly. This could especially be the case where increasing numbers of smolts (with low body condition factors) have entered the open ocean as occurred for Fraser River sockeye in the last decade.

Impact of system productivity regimes

The ocean environment that Fraser River sockeye salmon encounters varies from year to year, typically with decadal changes being apparent, some decades are more productive, others less so. Climatic conditions vary, the productivity of plankton with it, and these changes are channeled through the food web to ultimately impact the higher trophic level species, such as sockeye salmon (Christensen and Walters 2011). A comprehensive overview providing a status for the North Pacific Ocean is published by PICES (McKinnell and Dagg 2010).

An implication of competition is that changes in system productivity impacting food conditions for sockeye salmon (and hence competition between individuals) is not likely to be a sufficient explanation for non-linear changes in sockeye productivity, such as the decline of sockeye salmon in the Fraser River.   This implication is supported by another lesson from modeling, based on foraging arena theory. Ecosystem models constructed to date indicate that predator and prey biomasses in marine systems tend to scale with changes in system productivity, though the impact on predators from productivity changes may be relatively bigger than for prey (Walters and Martell 2004). Higher-trophic level species such as salmon tend to do be relatively more impacted by system productivity changes than lower-trophic level species.

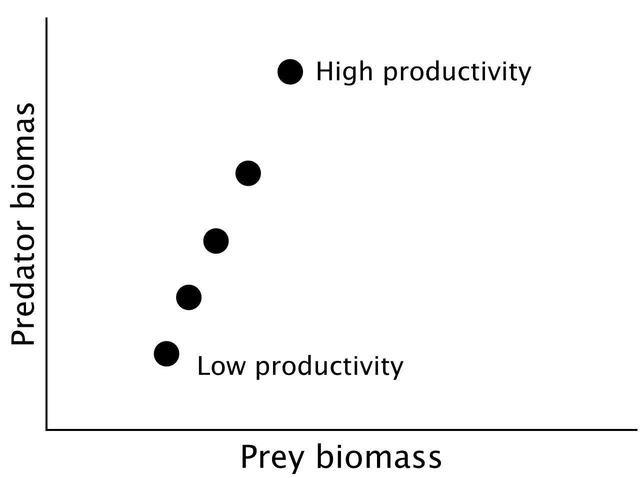


Figure 2. Impact of system productivity on predator and prey long-term (equilibrium) biomasses.

Foraging arena theory predicts a linear relationship between prey and predator biomass, but the impact of system productivity changes may be strongest for predators (Figure 2). Ecosystem models show that a reduction of 20% in primary productivity levels can be associated with an 80% drop in abundance of high trophic level fishes (Christensen and Walters 2011). There are indications that this may reflect actual conditions (Christensen and Walters 2011). Numerous studies that have tried to replicate ecosystem-wide population trends have had to incorporate both environmental factors (notably system productivity) and commercial fisheries (Christensen and Walters 2011).

Another aspect of environmental conditions relates to the impact of water temperature. While temperature will have a direct influence on metabolic rates of sockeye salmon it also impacts other parts of the ecosystem, including the risk of predation. This is illustrated by Petersen and Kitchell (2001), who used oceanic, coastal and freshwater climate indices and simulations of bioenergetics of key predators (e.g., northern pikeminnow), and predicted that warmer climatic conditions can lead to an increase in predation rates in the range of 26–31%.

Predator satiation and depensation

Predation is indeed an unavoidable risk in the marine environment, and different species have developed various evolutionary strategies to manage that risk. One, common strategy is for abundant species to overwhelm their predators by synchronous, localized spawning—as is done by corals, grouper associations, or the large sockeye salmon run to the Adams River. The subsequent large pulse of eggs, alevins, fry, smolt, immature, and adult sockeye moving in concert through a string of ecosystems will have the effect of saturating the predators, which in turn will result in declining predation mortality rates as sockeye abundance increases. Where predator saturation occurs, predation mortality is expected to be depensatory – i.e., decrease survival at low densities (Walters and Kitchell 2001).

Fresh and Schroder (1987) evaluated the predator-prey relationship of juvenile chum salmon (*Oncorhynchus keta*) and piscivores (≥100 mm FL rainbow trout, *Salmo gairdneri*, and ≥75 mm FL coho salmon, *O. kisutch*) in a coastal stream and a flow-channel. Their results indicate a saturating effect ("predator satiation") such as caused by handling time in functional response relationship (i.e. a type II relationship, Holling 1959). Similarly, Ruggerone and Rogers (1984) evaluated Arctic char, *Salvelinus alpinus* predation on migrating sockeye smolts in the Wood River lake system, Alaska, and also found evidence of predator satiation (type II functional relationship). At the smolt concentrations decreased, the mortality rate due to Arctic char increased. Predator satiation may indeed be a common phenomenon as also illustrated by the depensatory mortality described for mergansers (Wood 1987).

Salmon forests

Predator satiation is also a factor when sockeye reach the river on their spawning migration. At this stage, the year-class strength has been determined, and additional predation by predators such as bears is mainly of interest for ecological reasons, notably if there will be enough salmon to feed the bears. It is also an element in the discussion of whether increased sockeye escapement leads to more fertilization and faster growth of “salmon” forests due to bears transporting salmon into the forests, leaving parts of the carcasses behind (Helfield and Naiman 2001). Related to this, Quinn at al. (2003) evaluated effects of consumption by brown bears of spawning-run sockeye. Their study was based on 168 annual estimates of predation during 1986–2002 from 13 streams in the Woods River system, southwestern Alaska, to evaluate density-dependent effects of predation.

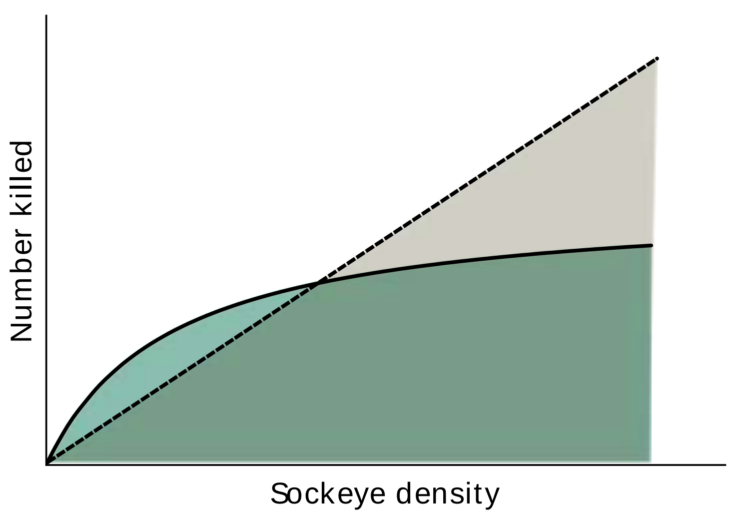


Figure 3. Hypothetical relationships between the number of sockeye and the resulting number of sockeye killed by bears. Quinn et al. (2003) found that the asymptotic relationship (solid line) fitted the available data better than the proportional model (dashed line), but the analysis was not conclusive. The study indicates that higher escapement of sockeye may not result in more marine nitrogen being added to the “salmon” forest systems around salmon streams.

The analysis of Quinn at al. (2003) showed that bears killed more sockeye on an annual basis as the salmon density increased, but that the rate of increase tended to decline at high densities so that the total number killed approached an asymptote (solid line in Figure 3). The number of sockeye killed by brown bears in the 17-year study was best explained by an asymptotic increase. They found that divergence from this relationship at some streams (dashed straight line in Figure 3) probably reflected variation in the undetermined numbers of bears using the streams (a numeric response *sensu* Holling), and variation in how much was consumed from each sockeye carcass. More observations at high densities would be needed for the analysis to be fully conclusive.

Potential predators

Many potential predators impact Fraser River sockeye salmon throughout their life history and range of environments. The following review identifies these potential predators along with an overview of their food habits (with focus on the role of salmon) and of what is known about the abundance and population trends for the predators. Our overview of potential predators is not exhaustive. We recognize that some rare species that are not specialized on salmon cannot potentially have any major impact on Fraser River sockeye salmon. We have therefore ignored rare potential predators.

Significance of predation

A number of factors have to be met before a potential predator can be deemed to have a significant impact on the decline in survival rate for Fraser River sockeye salmon over the last decades. These include:

- The prey and predator must overlap in time and space.
- The prey has to be eaten or preferred by the predator.
- There has to be a sufficient abundance of the predator for it to have an impact.
- The abundance of the predator must have been decreasing in recent decades, or there must be indications that the predator may have shifted to feed more on sockeye, e.g., because other prey have become less abundant.

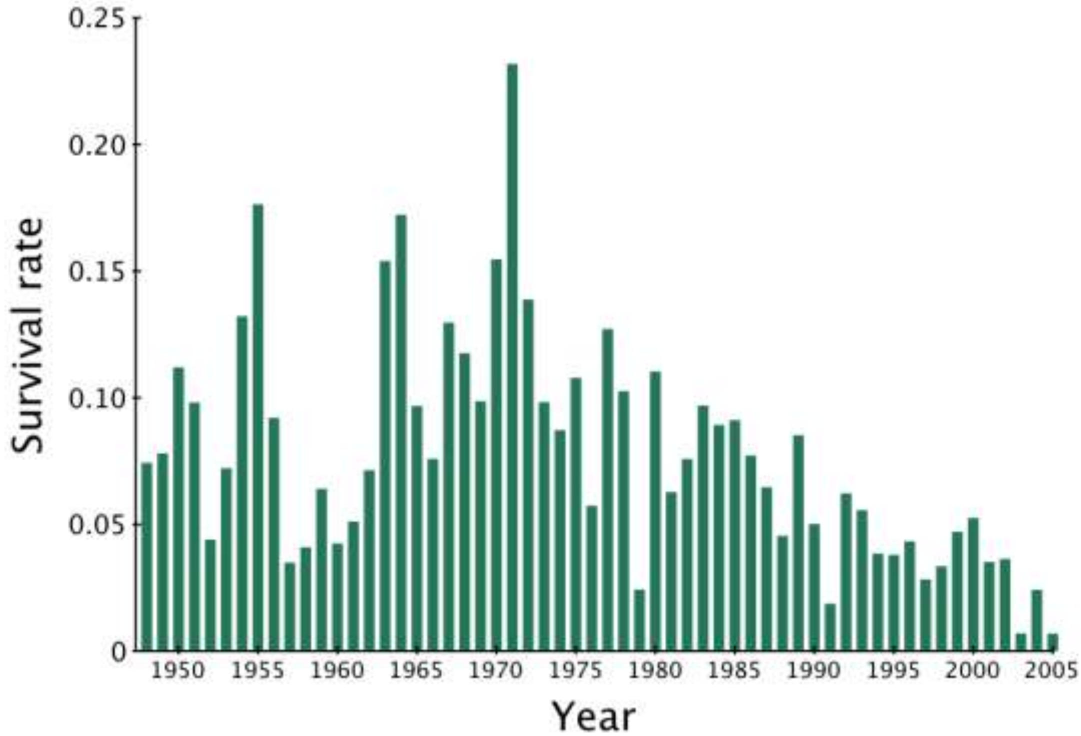


Figure 4. Weighted mean survival rates of Fraser River sockeye salmon by brood year. Based on estimates number of recruits (catch + escapement) and assuming 100 smolts per effective spawner, and 18 populations (Birkenhead, Bowron, Chilko, E.Stuart, Fennell, Gates, Harrison, L.Shuswap, L.Stuart, Nadina, Pitt, Portage, Quesnel, Raft, Scotch, Seymour, Stellako, and Weaver). Source: C. Walters, pers. comm.

An earlier review of 45 field studies demonstrated that predation is important for all life stages of Pacific salmon, though possibly less important in the marine post-smolt stage (Mather 1998). However, low incidence marine predation may be a significant factor even at (immature and maturing) stages given sustained exposure (Brodeur *et al.* 2003), and hence its impact cannot be ignored. Total mortality rate may vary between 0.4% and 0.8% per day for 410 days (Parker, 1968 cited by Beamish and Neville 2001), which translates into a difference between whether 3.7% or 19% of the smolts make it back from the ocean.

Time period of concern

When evaluation impact of predation, we are not just concerned with the low return of Fraser River sockeye in 2009, but rather with the gradual decrease in survival rate that appears to have taken place since around 1980 (see Figure 4).

We therefore set out to find time series information for predators going as far back in time as possible, and especially sought trend data that indicate that the predation pressure may have increased over the last three decades.

Freshwater and estuarine predators

Fish

Coho salmon (*Onchorhynchus kisutch*) and chinook salmon (*O. tshawytscha*)

Chinook and coho salmon both become highly piscivorous with age, and as they tend to have long residence time in freshwater they typically obtain a size where they potentially can prey on small sockeye fry, given co-occurrence.

Ruggerone and Rogers (1992) evaluated potential predation by juvenile coho on recently emerged sockeye salmon during three summers (1985-1987) in Chignik Lake, Alaska, and estimated that 59% of the sockeye fry was consumed by coho. The authors found that the juvenile coho reduced the return of sockeye to the lake, and recommended a fixed spawning escapement policy for coho to stabilize the predation impacts on sockeye.

The recent decline in population estimates for the chinook (Figure 12) and coho salmon (Figure 13) in the Strait of Georgia indicates that these species may not be behind the decline in survival of Fraser River sockeye salmon over the last decades.

Coastal cutthroat trout (*Oncorhynchus clarkii clarkii*)

Beauchamp et al. (1995) evaluated the predatory capacity of cutthroat in a study of Lake Ozette, Washington, and found that 40% of the spring and summer diet of large (≥300 mm FL), limnetic cutthroat consisted of age-0 and age-1 sockeye (40-140 mm FL). Further these authors concluded that the potential impact of large cutthroat trout by far exceeded the potential impact of northern pikeminnow. The consumption was thus estimated to 139 juvenile sockeye for each cutthroat, while the corresponding estimate was 5.6 juvenile sockeye per northern pikeminnow. The absolute impact on the juvenile sockeye could, however, not be estimated as the abundances of the larger piscivores were unknown.

Table 1. List of fish species with potential predation impact on Fraser River sockeye salmon in freshwater. Rare potential predators are excluded. The shading indicates status of knowledge: from nothing (no or light) to reliable estimates (dark).

Species		Abundance estimates	Trend estimates	Monitoring
Common name	***Scientific name***			
River lamprey	*Lampetra ayresi*			
Coho salmon	*Oncorhyncus kisutch*			
Chinook salmon	*Oncorhyncus tshawytscha*			
Coastal cutthroat trout	*Oncorhyncus clarkii clarkii*			
Rainbow trout/steelhead	*Oncorhyncus mykiss*			
Bull trout	*Salvelinus confluentus*			
Dolly Varden	*Salvelinus malma*			
Lake trout	*Salvelinus namaycush*			
Northern pikeminnow	*Ptychocheilus oregonensis*			
Burbot	*Lota Lota*			
Smallmouth bass	*Micropterus dolomieu*			
Largemouth bass	*Micropterus salmoides*			
Yellow perch	*Perca flavescens*			
Sculpin spp.	*Cottus* spp.			

In a February-May 1996 study of Lake Washington, Washington, Tabor and Chan (1997) found that cutthroat trout was the only species found to be an important predator on sockeye salmon fry. Only cutthroats less than 250 mm consumed sockeye. Yellow perch consumed a few sockeye fry, while the sampled individuals of juvenile coho salmon, mountain whitefish, brown bullhead, largemouth bass, and prickly sculpin had not consumed sockeye salmon fry.

Cutthroat trout are also known to specialize on salmon eggs during October to January in the Puget Sound area, Washington (Jauquet 2002; cited by Duffy and Beauchamp 2008; and Haque 2008).

Cartwright et al. (1998) evaluated predation by cutthroat trout on stocked sockeye salmon fry in Margaret Lake, Alaska during 1993 and 1994. Model results indicated that by

September, cutthroat trout consumed an estimated 34-51% and 32-100% of the sockeye salmon fry stocked in May 1993 and 1994, respectively. September hydroacoustic survey results estimated 82–87% decline for fry in 1993 and a 90–93% decline in 1994.

In 2001-2003, Duffy and Beauchamp (2008) sampled juvenile salmon and potential predators in Puget Sound, Washington, and found that coastal cutthroat trout were the most abundant potential fish predators though they were caught in low but consistent numbers only. The diet of cutthroats was dominated by Pacific herring, but juvenile salmon were important prey during April to June, making up around half of the fish prey consumed. Overall, the cutthroat predation, however, accounted for a minor amount of the early marine mortality for juvenile salmonids.

There is little available information about abundance and trend of cutthroat trout in the Fraser River system, which makes it difficult to quantify their eventual role in the decline of Fraser River sockeye salmon survival in recent decades. It is our subjective evaluation, however, that cutthroat trout are unlikely to be abundant enough to constitute a major factor for the decline.

Rainbow trout and steelhead (*Onchorhynchus mykiss*)

Rainbow trout feed on sockeye eggs in Quesnel Lake (Sebastian et al. 2003).

Rainbow trout. Photo: Eric Engbretson

Prompted by decline in freshwater survival of juvenile sockeye salmon in Lake Washington, Washington, Beauchamp (1995) estimated predation losses for sockeye smolt due to predation by wild steelhead, which during the study period, 1983-1985 was the primary riverine predator of sockeye fry migrating from the Cedar River into Lake Washington. The study indicated that wild steelhead consumed about 15% of the estimated emergent sockeye smolt production, and that the heaviest predation coincided with early and peak periods of the fry migration (February through mid-April). Hatchery-reared steelhead showed no evidence of preying on sockeye smolt.

Parkinson et al. (1989) evaluated feeding habits of rainbow trout related to prey availability in Quesnel Lake, and found that *O. nerka* (both sockeye and kokanee) fry constituted over 98% of midwater trawl catches in the lake, i.e. *O. nerka* was the dominant limnetic fish species. *O. nerka* also contributed significantly to the diet of rainbow trout, 55% of the trout stomachs contained fish and of the 113 identifiable fish the 112 were *O. nerka*. The study also showed that the largest prey taken by rainbow trout (>350 mm) were less than 1/3 of the predator length.

Evaluating available information about rainbow trout predation in lakes with sockeye and kokanee, Sebastian et al. (2003) concluded that piscivorous trout and char depend on kokanee as their primary forage species even though the abundance of juvenile sockeye is much higher than that of kokanee. This may be attributed to the larger size of the older kokanee or to a behavioral aspect related to fry distributions.

The study of Sebastian et al. (2003) provides a comprehensive overview of rainbow trout and kokanee/sockeye interactions and dynamics, reviewing information for Quesnel Lake, but does not give any indications of the abundance or trend in abundance for the rainbow trout.

Abundance and trend information does indeed not seem to be available for the Fraser River system. For Kootenay Lake (which has kokanee but no sockeye) there is, however, a recent evaluation of rainbow trout biomass covering 1953 – 2007 (Kurota *et al.* 2011). The indication from this analysis is that rainbow trout have been rather stable over the last decades. Taken jointly with the assumption that rainbow trout are unlikely to have increased during this time due to an overall increase in angler effort in the river system, the overall conclusion is that rainbow trout are unlikely to be a major factor for the decline of Fraser River sockeye salmon survival in recent decades. The same conclusion can be drawn for steelhead, whose population status is of concern through B.C., and notably so in the Fraser River.

Bull trout (*Salvelinus confluentus*)

Bull trout is considered a major piscivore species in Fraser system lakes (both in interior and much of the coast) and anadromous bull trout are abundant and efficient piscivores in the Fraser delta area (E. Taylor, UBC, pers. comm.) Indications are, however, that bull trout have declined in size and abundance in the Fraser River area over the last decades (http://www.env.gov.bc.ca/bcparks/planning/mgmtplns/tsilos/chilko_lake_bull_trout_population_status.pdf), and it is therefore unlikely that they can be a major factor for the decline in Fraser River sockeye salmon survival in recent decades.

Northern pikeminnow (*Ptychocheilus oregonensis*)

A very large proportion of the diet of northern pikeminnow may consist of juvenile sockeye. Beauchamp et al. (1995) thus found that in Lake Ozette, Washington, that 72% of the annual diet (by volume) of large (≥300 mm FL), limnetic northern pikeminnow consisted of age-0 and age-1 sockeye. The overall effect of northern pikeminnow was, however, estimated to be far less than that of cutthroat trout as only a very small proportion of the large northern pikeminnow (2-8%) co-occurred with juvenile sockeye in the limnetic zone of the lake.

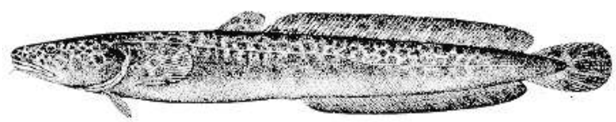
In a 1983-1986 study of northern pikeminnow predation on juvenile salmonids in the John Day reservoir of the lower Columbia River, Oregon, Petersen (2001) evaluated predation patterns based on 5,000 pikeminnow samples, and found evidence that northern pikeminnow is a significant predator on juvenile salmonids, which they tend to capture during brief feeding bouts. High percentages (>80%) of salmonids were found in pikeminnow diets, especially during April to May. They found a size difference, where the largest northern pikeminnow appeared to be more successful at capturing salmonids than smaller predators, though all were of a size (>250 mm) where they were capable of predating on the juvenile salmonids in the area (80-160 mm).

Brown and Moyle (1981) reviewed the impact of pikeminnow predation on salmonids and concluded that pikeminnow in lakes may prey extensively on young salmonids, but they found little evidence that this predation had much impact on year class strength. They also found that pikeminnow are unlikely to be significant predators on salmonids in streams, and that direct competition between pikeminnow and salmonids likely is limited. As a corollary on the importance of northern pikeminnow as predators on salmon smolt it can be mentioned that there was a "Pikeminnow Sport Reward Fishery Program" in 2010 in the lower Columbia River and funded by the Bonneville Power Administration, which pays anglers $4 to $8 for each large northern pikeminnow, and with a prospect of scoring $500 for tagged pikeminnow. The argumentation for the bounty is that "northern pikeminnow eat millions of salmon and steelhead juveniles each year in the Columbia and Snake River systems" (www.pikeminnow.org). The program is estimated to have removed over 3.5 million pikeminnow since 1990, and to have cut the predation on juvenile salmonids "by an estimated 37%", probably meaning that the abundance of the larger, piscivorous pikeminnow has been reduced by this amount.

There has also been concern about pikeminnow in the Fraser River, notably in Cultus Lake where an eradication program has been in place since 2005 (http://www.pac.dfo-mpo.gc.ca/science/habitat/cultus/updates-misesajour-eng.htm). A large number of pikeminnow has been removed from the lake, but its effectiveness has not yet been estimated, nor has the impact it may have had on Cultus Lake sockeye.

Pikeminnow may also be important predators of Fraser River sockeye salmon, but there does not seem to be abundance or trend estimates for the pikeminnow, and hence their importance cannot be quantified.

Burbot (*Lota Lota*)



Burbot is present in the Fraser River system, but there does not seem to be any information about its abundance or trend in abundance. It is active at night, and being slow moving, it is not favored by anglers (Froese and Pauly 2010). It was identified by Fresh (1997), but there is nothing to indicate that it should have played in role for the decline of Fraser River sockeye survival.

Sculpins (*Cottus* spp.)

Sculpins are predators on eggs, alevins, and young fry of sockeye salmon. Foote and Brown (1998) evaluated predation on sockeye eggs by two species of sculpins in Iliamna Lake, Alaska. The sculpins move actively to the spawning beaches before the onset of spawning and the largest individuals consume up to 50 fresh eggs in a single feeding and 130 over a 7-day period. The sculpins in the study area were estimated to consume about 16% of the total number of eggs spawned, primarily immediately after the eggs were spawned.
In the study, Foote and Brown (1998) concluded that there was evidence of "predator saturation", i.e. of density-dependent effect of spawner abundance and timing on the total egg consumption by sculpins. The spawning period is thus very short at the spawning beaches in Iliamna Lake and as the egg consumption predominantly is on newly spawned eggs this serves to limit the total predation rate.

In a series of studies in the lower Cedar River and Lake Washington, Roger Tabor and colleagues evaluated the impact of piscivores on juvenile salmon with emphasis on sockeye fry during their migration (Tabor and Chan 1996, 1997; Tabor *et al.* 1998; 2001). The studies showed that prickly sculpin (*Cottus asper*) were a major predator on sockeye salmon fry, and that several other sculpin species also consumed sockeye fry.

Fresh (1997) listed five sculpin species as predators on juvenile salmon. Given that there is nothing to indicate that sculpins should have increased in abundance in recent decades, and that sculpins only may be a factor on the youngest sockeye, it is not likely that sculpins should be of importance for the decline in the survival of Fraser River sockeye salmon over the last three decades.

Introduced fish species

There is special concern for introduced, exotic species in BC freshwater systems, and the potential threat they pose to native species, including to Fraser River sockeye salmon. Fisheries and Ocean Canada and the BC Ministry of Environment as a result have been conducting evaluations and monitoring of exotics to evaluate the risk they pose. Upon reviewing the available information we do not consider it likely that any of the exotics have had abundances over the last decade that indicate them to be major contributors to the population decline of Fraser River sockeye salmon.

Smallmouth bass (*Micropterus dolomieu*) and largemouth bass (*M. salmoides*)

Fresh (1997) identified these species as predators on juvenile salmon, and predation on smolt can potentially be considerable (Wydoski and Whitney 2003). Both species are considered potentially important predators that once established may be a threat for native fish species, notably for minnows. The risk is considered very high in small lakes and lower in larger water bodies, where there is less of the habitat preferred by basses (Tovey *et al.* 2009). This indicates that they may have had only limited potential overlap with Fraser River sockeye salmon smolts in the last decade.

We have not been able to find estimates of their abundance or trends in the Fraser River system, and we subjectively find it unlikely that these species were abundant enough to have had major influence on the decline in survival rate of Fraser River sockeye salmon over the last decades.

Yellow perch (*Perca flavescens*)

Yellow perch is an exotic species, which has spread in BC freshwater systems mainly through illegal introductions, e.g., in connection with use as live bait by anglers. It is potentially an important predator on and competitor with sockeye salmon fry in the Fraser River as described by Johnson (2009) "in the absence of natural predators yellow perch have been known to out-breed and out-compete native fish species, including salmonids, and can dominate smaller lake systems in just a few years."

Indeed, it has been speculated that yellow perch may directly be impacting sockeye abundance in the Fraser River, or "Missing sockeye – perhaps in the bellies of yellow perch?" (www.themonsterguide.com).

Yellow perch presence is confirmed for 78 water bodies in BC, including 59 lakes or ponds and 19 streams, while there are additional, unconfirmed records for three lakes and one stream (Runciman and Leaf 2009). The areas of confirmed presence include the Lower and Middle Fraser River watershed and the South Thompson River watershed.

A risk assessment conducted by Fisheries and Oceans Canada has concluded that the risk of yellow perch becoming established in BC water bodies is high or very high, while the potential ecological impact is considered very high in small water bodies and moderate in large lakes and rivers (Bradford *et al.* 2009).

Information about abundance or trends of yellow perch in the Fraser River system does not appear to be available, but it is noted that nine lakes within the upper Thompson watershed that had established yellow perch populations have been treated with rotenone over the last five years to eradicate the yellow perch and protect important salmon runs into Adams Lake and Shuswap Lake (Leif-Matthias Herborg, BC Ministry of Environment, pers. comm.) In conclusion, the available information provides little support for the hypothesis that yellow perch were a major factor for sockeye survival trends over the last three decades.

Table 2. List of bird species with potential predation impact on Fraser River sockeye salmon in freshwater and estuaries. Some less-common, potential predators are excluded. The shading indicates status of knowledge: from nothing (no or light) to reliable estimates (dark).

Species		Abundance estimates	Trend estimates	Moni-toring
Common name	***Scientific name***			
Double crested cormorant	*Phalacrororax auritus*			
Common merganser	*Mergus merganser*			
Gulls	*Larus spp.*			
Caspian tern	*Hydroprogne caspia*			
Bald eagle	*Haliaeetus leucocephalus*			
Osprey	*Pandion haliaetus*			

Birds

There are two main sources of bird counts with data available for British Columbia. The well-established Christmas Bird Count (CBC, http://birds.audubon.org/historical-results) held annually since 1900 under the auspices of the National Audubon Society, and the Great Backyard Bird Count (GBBC, http://www.birdsource.org/gbbc/). Of these, only the CBC gives information that is standardized for observer effort, and hence only this count can be used to evaluate trends in abundance. Even so, this is with the corollary that the CBC counts only cover the period from mid-December to early-January, and thus provide no information about notably bird species that do not overwinter in British Columbia.

Common merganser (*Mergus merganser*)

Common merganser occur year-round on the coast of British Columbia (both fresh and saltwater environments) with the densest concentrations from mid-November to March (Baron and Acorn 1997).

The merganser can be an important predator on juvenile salmon during the period of seaward migration. Wood (1987) evaluated the predation in two streams on Vancouver Island where the salmonid populations (chinook, chum, coho, and steelhead) were enhanced by spawning channels and hatcheries, and found that common merganser almost exclusively fed on juvenile salmonids. In contrast, mergansers in tidal waters rarely ate salmonids. Overall, the maximum mortality rate for any salmonid species showed a maximum level of 8% for the entire seaward migration due to merganser predation.

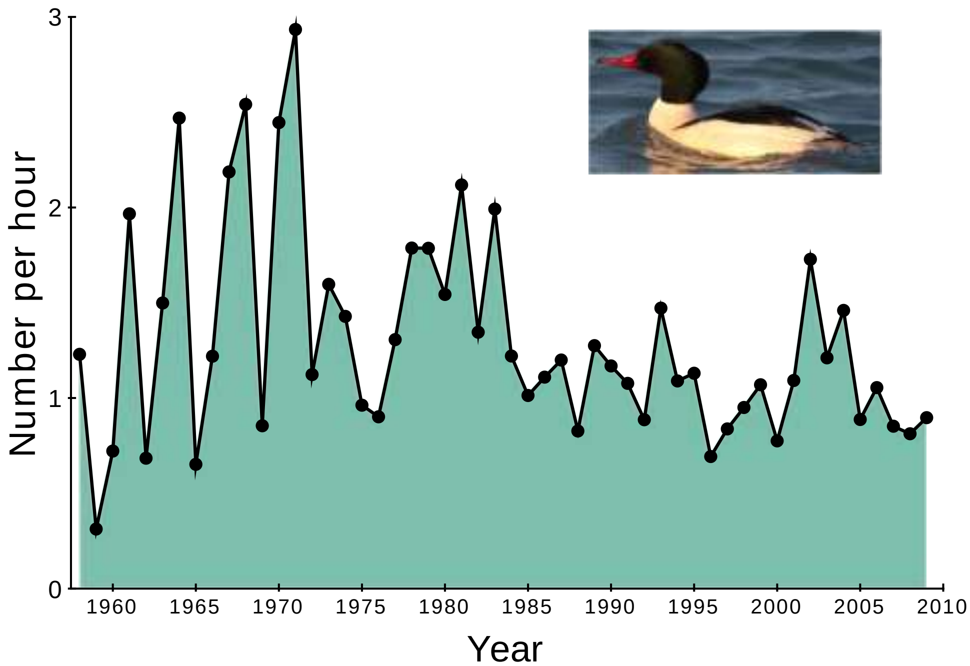


Figure 5. Number of common merganser per observer hour in Christmas Bird Counts (CBC) in British Columbia during 1958/1959-2009/2010.

Based on information from the Christmas Bird Counts for mergansers, there is no indication that mergansers have increased in abundance in abundance in recent decades. It is therefore unlikely that they have played a major role in the survival rate decline of Fraser River sockeye over the last decades.

Double-crested cormorant (*Phalacrocorax auritus*)

Double-crested cormorants are widely distributed in rivers and lakes and along the Pacific coasts of North America and have expanded since the 1960s. The colonies in the Columbia River estuary has, as an example, expanded rapidly from initial sightings in the 1980s to over 13,700 breeding pairs in 2006 (Ryan et al. 2007).

Studies at bird colonies in the Columbia River indicates that double-crested cormorants consume significant amounts of juvenile salmon in the Columbia River and estuary (Collis et al. 2001). The tags from around 3% of tagged sockeye were recovered from cormorant colonies.

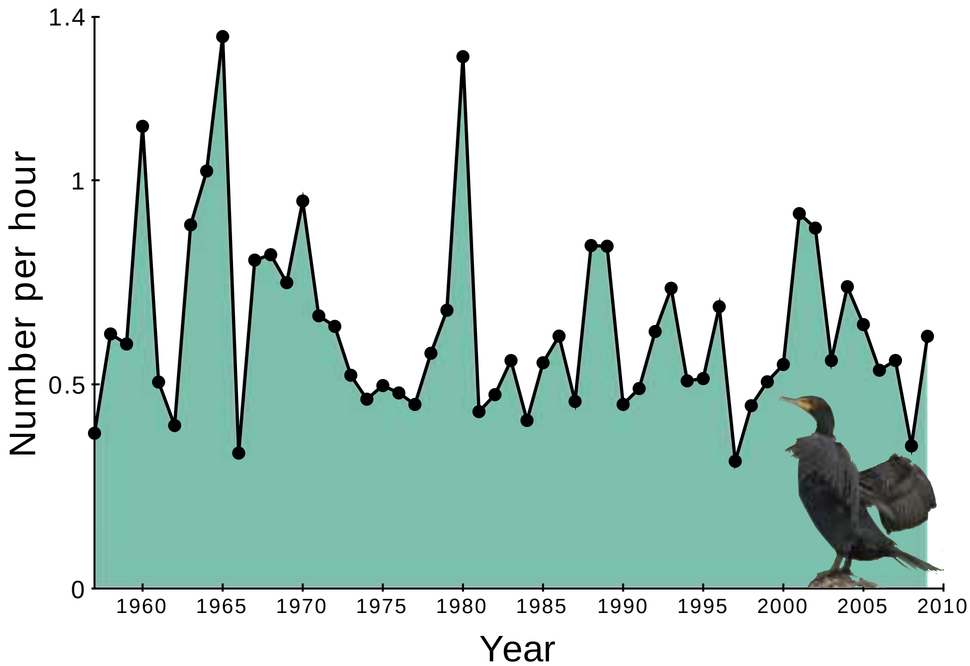


Figure 6. Number of double-crested cormorants observed in British Columbia per observer-hour during the Christmas Bird Counts 1957/1958 – 2009/2010.

The available data about abundance of double-crested cormorants in B.C. are sparse, with the indication from the Christmas Bird Count being that the population has been stable over the last decades (Figure 6). There is therefore no data to indicate that the cormorants may have impacted the decline in survival rate of Fraser River sockeye salmon over the last decades.

Caspian tern (*Hydroprogne caspia*)

Caspian tern was known as a vagrant summer visitor to B.C. before the mid-1940s, but has spread northward from California since the 1960s, breeding in Washington State since the 1980s, and now also with breeding locations in B.C., e.g., at Shuswap Lake (Campbell *et al.* 1997).

Roby et al. (2003) used bioenergetic modeling to evaluate the predation of juvenile salmon by Caspian terns in the Columbia River estuary and estimated the annual consumption to 8.1 million and 12.4 million smolt in 1997 and 1998, respectively.

PIT tags are used extensively in the Columbia River system to evaluate juvenile salmon survival through dams. Some 50,000 tagged salmon were released in 1987 increasing to over two million tags in 2003 (Ryan et al. 2007). Ryan and colleagues conducted a series of studies to evaluate the impact of piscivorous birds in the Columbia River system. They

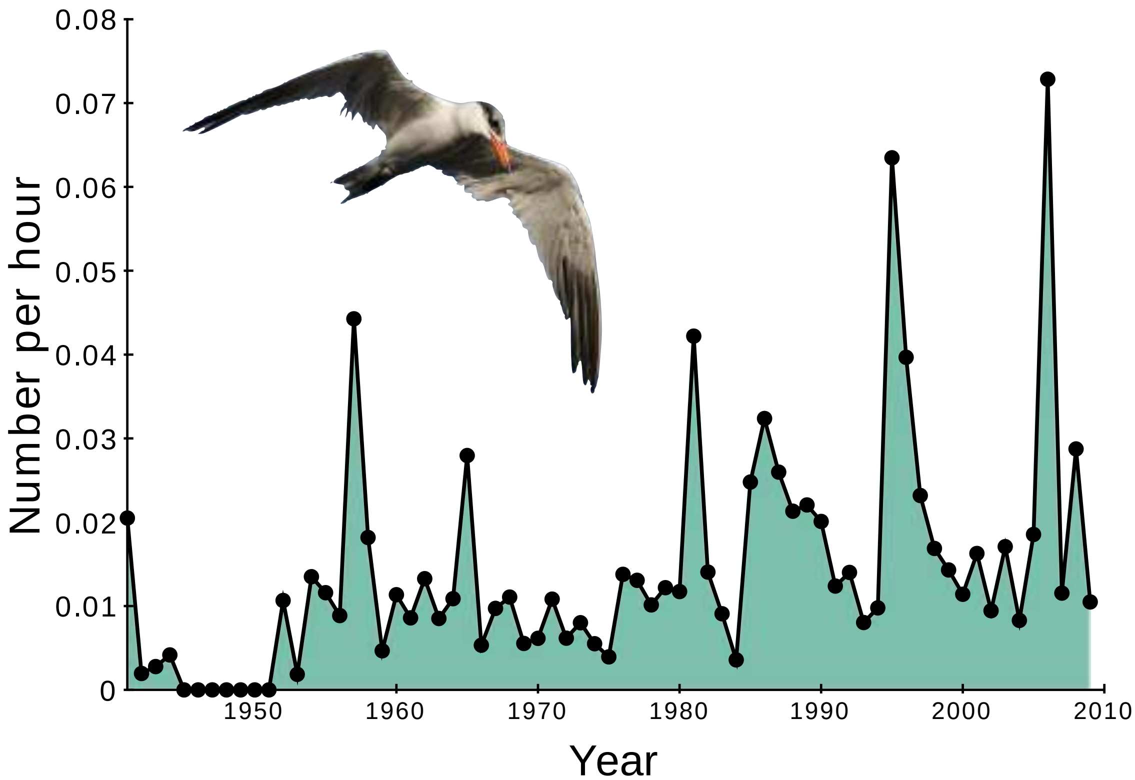


Figure 7. Trend in Caspian tern abundance in California from the Christmas Bird Counts, during 1900/1901 – 2009/2010. Caspian terns breeding in B.C. tend to overwinter in California.

quantified the number of passive integrated transponders (PIT) tags in bird colonies, and found more than 66,000 PIT tags on piscivorous bird islands in the Columbia system in 2006 with double-crested cormorants and Caspian terns being the dominant predators. Incorporating a tag detection efficiency of around 50%, this indicated that ~5% of the tagged salmon that were released in the system that year ended up in the bird colonies.

Caspian terns are not overwintering in B.C. as indicated by their abundance on the Christmas Bird counts during the last 110 years (none were registered). Nor has the species been registered during the Great Backyard Bird Count, generally held in mid-February since 1999. The Caspian terns migrate south mainly to overwinter in California during the winter, and Figure 7 therefore gives the trend in abundance for Caspian tern in California based on the CBC.

Based on the California trend data, the population of Caspian tern has increased since the 1970s, but the level for the last three decades is stable. There is no indication that the Caspian tern should be a major factor for the decline of Fraser River sockeye salmon survival rates, yet it may have a predation impact.

Bald eagle (*Haliaeetus leucocephalus*)

Bald eagles are widespread along the coast of British Columbia and are most concentrated in winter (Baron and Acorn 1997). They are fish eaters and scavengers, notably on spawned salmon carcasses during the winter months — thousands of bald eagles can regularly be observed at the Squamish and Harrison rivers in winter.

Estimates from the Christmas Bird Counts indicate that bald eagles increased strongly from the late 1950s up to the early 1980s, and that the population largely has been stable since then, i.e. during the time where sockeye survival rate has declined. This indicates that bald eagle is unlikely to be a major factor for the decline in survival rate of Fraser River sockeye salmon over these last three decades.

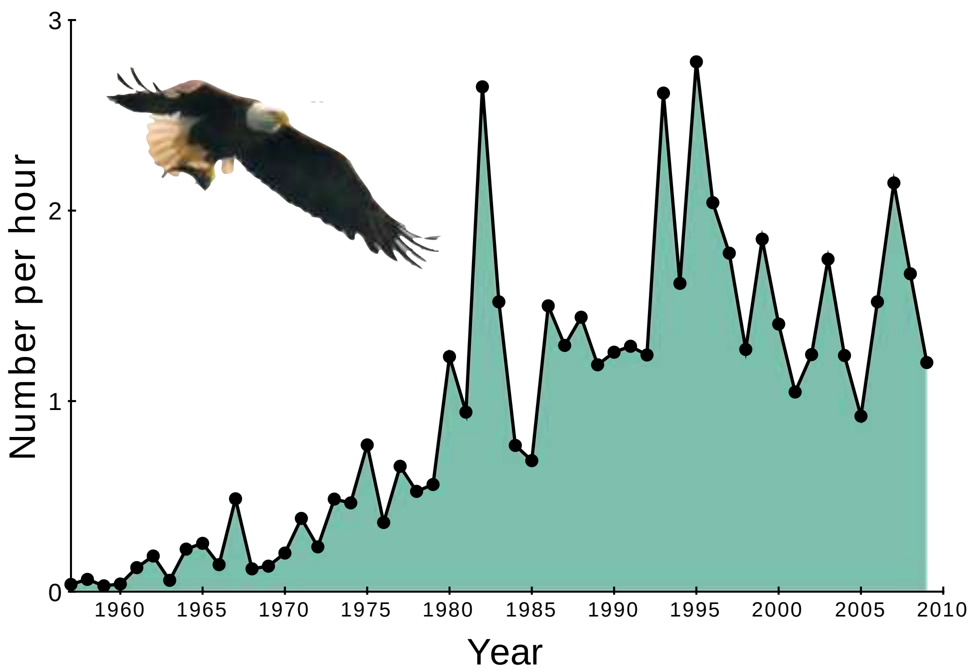


Figure 8. Abundance trend of bald eagle during Christmas Bird Counts in British Columbia during 1957/1958 – 2009/2010.

Osprey (*Pandion haliaetus*)

Ospreys are most common in the lower third of British Columbia, and migrate south for the winter, returning in April, when the ice is gone (Baron and Acorn 1997). They are piscivorous, and because of their migration, trend data are not available through the Christmas Bird Counts. Trend data for osprey does not seem available, only that the population declined in the 1950s and 1960s linked to pesticide impact, and since then has been recovering slowly. It is not likely that osprey has a major predation impact on sockeye in the Fraser River system.

Marine Mammals

Harbour seal (*Phoca vitulina richardsi*)

Of the 22 species of marine mammals known to occur in British Columbia, only the harbour seal has been documented feeding on salmon smolts in the freshwater and estuarine habitat (Olesiuk *et al.* 1990b; Olesiuk *et al.* 1995; Yurk and Trites 2000). Harbour seals are known to eat juvenile salmon outside of British Columbia, and there is a single report of California sea lions in Washington State consuming unidentified smolts (NOAA 1998; Laake *et al.* 2002). However, there are no reports of harbour seals eating sockeye salmon smolts.

Olesiuk et al. (1990b) collected ~3,000 harbour seal fecal samples from 58 sites in the Strait of Georgia from 1982-1988 and found smolt size remains at only two sites: Comox Harbour (May–July) and Port Moody (Sept–Nov). Neither of these two sites supported sockeye salmon runs. Direct observations in the Puntledge River (Comox Harbour) showed predation occurring on chum, coho and chinook fry between dusk and dawn with a nightly consumption by 10-20 seals averaging ~140,000 chum fry and ~13,000 coho smolts (Olesiuk et al. 1995). Chum and coho are also produced at Port Moody and were likely the species of juvenile salmon contained in the seal scats reported by Olesiuk et al. (1990b).

Predation by harbour seals on juvenile salmon in other systems has been looked at most intensively in the Columbia River (1995-97). During this time, harbour seals were found consuming juvenile steelhead (*Oncorhynchus mykiss*), chinook, and coho salmon—but no juvenile sockeye (Browne *et al.* 2002; Laake *et al.* 2002). Elsewhere, it has been speculated that resident harbour seals in Iliamna Lake, Alaska, might eat sockeye salmon smolts (Hauser et al. 2008)—but the speculation has not been supported with observations. It is conceivable that sockeye salmon smolts leave the Fraser River and other systems during a very narrow window that has been missed by the frequency of sampling or that their juvenile bones are too small and fragile compared to the other species of salmonids to be recovered (Olesiuk *et al.* 1990b; NOAA 1998). It is also possible that diets have changed since the 1980s when samples were last collected in British Columbia, or that only a small number of seals have learned to capture sockeye smolts and that their diets have not been sampled.

Despite the shortcomings of the data, they are the best that are available and show no indications that harbour seals are a significant predator of sockeye salmon smolts. Indeed, the available data indicate that harbour seal predation on Pacific salmon is confined almost exclusively to adult-sized fish (Olesiuk *et al.* 1990b). Harbour seal numbers increased through the 1980s and 1990s, but have been relatively constant for the past decade. Harbour seals should therefore have not posed an increasing threat to sockeye survival over the past decade.

Life and death in the ocean

The mortality of salmonids in the ocean can be substantial, and indications are that the early mortality is substantial (2-4% per day for the first 40 days) but also that there is substantial mortality afterwards, and that the total mortality is variable (0.4% - 0.8% per day for the 410 next days; Parker, 1968 cited by Beamish and Neville 2001).

A large number of species are known or believed to consume some sockeye salmon during their ocean phase. Of these, 25 species may impact sockeye salmon: one species of invertebrate (Humboldt squid *Dosidicus gigas*), 17 fish species and 7 species of marine mammals. Ackley et al. (1995) noted that predators on sockeye salmon smolts in the early marine phase include beluga whale, seals and porpoise, diving birds and adult chinook and coho salmon. The fish species identified by Sviridov et al. (2007) as the primary predators on Pacific salmon during the open ocean phase of their life history include: North Pacific daggertooth (*Anotopterus nikparini*), longnose lancetfish (*Alepisaurus ferox*), Pacific lamprey (*Lampetra tridentata*), Arctic lamprey (*L. camtschatica*), salmon shark (*Lamna ditropis*), spiny dogfish (*Squalus acanthias*), blue shark (*Prionace glauca*) and Pacific sleeper shark (*Somniosus pacificus*). To this list, we have added nine other potential predators (Table 3). Possible species of marine mammals that might prey on sockeye salmon during the ocean phase include: harbour seal (*Phoca vitulina richardsi*), Steller sea lion (*Eumetopias jubatus*), California sea lion (*Zalophus californianus*), northern fur seal (*Callorhinus ursinus*), killer whale (residents) (*Orcinus orca*), Dall's porpoise (*Phocoenoides dalli*), Pacific white-sided dolphin (*Lagenorhynchus obliquidens*), harbour porpoise (*Phocoena phocoena*), and humpback whales (*Megaptera novaeangliae*).

Table 3. List of marine species with potential predation impact on Fraser River sockeye salmon. Rare potential predators are excluded. The shading indicates status of knowledge: from nothing (light) to reliable estimates (dark).

Species		Abundance estimates	Trend estimates	Monitoring
Common name	***Scientific name***			
Humboldt squid	*Dosidicus gigas*			
River lamprey	*Lampetra ayresi*			
Spiny dogfish	*Squalus aconthias*			
Salmon shark	*Lamna diprosis*			
Blue shark	*Prionace glauca*			
Pacific sleeper shark	*Somniosus pacificus*			
Pacific herring	*Clupea harengus pallasi*			
Coho salmon	*Oncorhyncus kisutch*			
Chinook salmon	*Oncorhyncus tshawytscha*			
Daggertooth	*Anotopterus nikparini*			
Sablefish	*Anapoploma fimbria*			
Pacific cod	*Gadus macrocephalus*			
Tomcod	*MIcrogadus proximu*			
Walleye pollock	*Theragra chalcogramma*			
Pacific hake	*Merluccius productus*			
Arrowtooth flounder	*Atheresthes stomias*			
Pacific jack mackerel	*Trachurus symmetricus*			
Pacific mackerel	*Scomber japonicus*			
Harbour seal	*Phoca vitulina richardsi*			
Steller sea lion	*Eumetopias jubatus*			
California sea lion	*Zalophus californianus*			
Northern fur seal	*Callorhinus ursinus*			
Killer whale (residents)	*Orcinus orca*			
Dall's porpoise	*Phocoenoides dalli*			
Pacific white-sided dolphin	*Lagenorhynchus obliquidens*			
Harbour porpoise	*Phocoena phocoena*			
humpback whales	*Megaptera novaeangliae*			

Predators in the ocean

Invertebrates

Humboldt squid (*Dosidicus gigas*)

The Humboldt or jumbo squid is a large squid species (the mantle length can reach 1 meter), which occur in the eastern Pacific and which in recent years has had a biomass of the order of 10 million tonnes. The diet of jumbo squid is predominantly epipelagic lanternfish and squids. The prey sizes through the life cycle ranges between 5% and 15% of the squid total length (Nigmatullin et al. 2001).

Jumbo squids have over the last decades expanded northward from their previous northern range in the California Current, and also increased in abundance within their traditional range (Field *et al.* 2007). As an example, catches in Baja California Sur, Mexico were sporadic up to 1995, but has since then reached levels exceeding 100,000 tonnes in some years, making it one of the most important fisheries in the area (Rosas-Luis et al. 2008). Closer to the core of its distribution, the abundance of jumbo squid increased with more than an order of magnitude over the five years from 1999 to 2004 (Taylor et al. 2008).

The first recordings of Humboldt squid in the waters of British Columbia are from 2004 where the surface temperatures of the Northern Pacific that summer were the highest on record (Cosgrove 2005). The squids have spread northwards to Alaska (60˚N) and move north along California in early summer, appear in Oregon, Washington and B.C. during late summer and early fall, and are observed to move south again during fall (Bograd et al. 2010). They do not appear to spawn in the northern part of their range, and reports from the hake surveys indicate that the jumbo squids did not show up in B.C. in 2010.
Jumbo squid in the California Current primarily feed on small midwater and forage fishes, and adult groundfish such as Pacific hake, shortbelly rockfish (*Sebastes jordani*), and other semi-pelagic species (Field *et al.* 2007).

More recent, yet unpublished, joint studies by DFO and NMFS have over the last three years sampled jumbo squid over a broader range of space and time, and found two stomachs from Washington State in 2009 with salmon otoliths (mostly chinook and coho), while the common fish prey herring, anchovy, and some eulachon, capelin, and smelt, (J.C. Field, NOAA, pers. comm.) Jumbo squid thus clearly eat prey the size of sockeye smolt, but there is no direct evidence of jumbo squid predation on sockeye.

Likewise it is not clear to what degree there was spatial and temporal overlap of jumbo squid and the Fraser River sockeye smolts leaving the Strait of Georgia in 2007. There has been no targeted sampling program for jumbo squid in B.C. to provide estimates of abundance and distributions. Incidental information is available from, e.g., hake trawl surveys, but not conclusive with regard to degree of overlap with Fraser River sockeye smolts. If, however, the smolts have had to pass through an accumulation of jumbo squid it is entirely possible that they could have a strong predation impact on the sockeye.

Fish

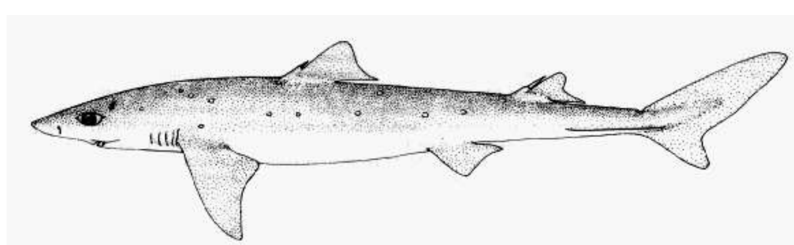
River lamprey (*Lampetra ayresi*)

Beamish and Neville (1995; 2001) estimated that river lamprey in the Strait of Georgia was a major predator on age-0 salmon and consumed an estimated 65%, 25%, and 2.3% of the smolt production for coho, chinook, and sockeye, respectively, in 1991. They consider the estimate conservative as river lamprey also feed in other areas outside the plume and the abundance estimates are conservative.

The study indicates that river lamprey may be an important predator on sockeye smolt, but there is very little additional information to use to quantify the effect. There are thus no estimates for trend in abundance of river lamprey in the Strait of Georgia and the rest of the areas where Fraser River sockeye salmon occurs.

Spiny dogfish (*Squalus acanthias*)

Spiny dogfish is a slow-growing, long-lived, low-fecundity small shark, which was fished extensively during the Second World War, and which now is subject to a small, directed fishery. It is a piscivore and known to be a substantial predator on Pacific herring as well as on juvenile salmon.



Beamish and Neville (2001) identify spiny dogfish as important predators on ocean juvenile (age-0) salmon in the Strait of Georgia with an estimated 7.7 million (or 100% of the release) of chinook and coho salmon killed by spiny dogfish within 4 weeks of the release, while the corresponding estimates for 1989-1991 were lower with 0.2, 0.1, and 0.2 million, respectively. The decline was related to estimated population trends for dogfish sharks decreasing from 1.4 million in 1988 to 0.3 million in 1990.

Based on ecosystem modeling, Beamish and Neville (2001) estimated that the annual consumption of juvenile sockeye/pink salmon (combined) in the Strait of Georgia amounts to 62 t for shorebirds, 50 t for river lamprey, 11 t for seabirds, 3 t for gulls, 55 t for coho, 345 t for chinook, 145 t for dogfish, and 5 t for lingcod. Beamish and Neville also report that the most abundant potential predators caught in 616 midwater trawl hauls in the Strait were Pacific hake, spiny dogfish, walleye pollock, chinook (age 1+), and coho (age 1+).

Do spiny dogfish then eat sockeye? Spiny dogfish are piscivorous with eleven of twelve diets in FishBase indicating fish as the main food, and as described above with reference to DFO studies in the Strait of Georgia. There is, however, little indication that salmonids form any major part of the dogfish diet. G.A. McFarlane (pers. comm.) thus indicates that of the 10,000 or so spiny dogfish stomachs he has sampled, he has never found any sockeye, and he finds it likely that the dogfish that were observed to feed heavily on chinook and coho smolts were specialized on dense hatchery releases. Overall, there are no clear indications that dogfish should have Fraser River sockeye as a diet item.

On the west coast of Vancouver Island, DFO stomach sampling further indicated that the main food of spiny dogfish was krill, with the majority of fish eaten being Pacific hake and herring (Tanasichuk et al. 1991). More recent studies show very similar results, with sardine showing up increasingly (G.A. McFarlane, pers. comm.).

Abundance and trend estimates for spiny dogfish in B.C. are sparse. Meanwhile a University of Washington thesis (Taylor 2008) indicates that population trends are uncertain; the population may have declined to 20-30% of its original biomass, or it may have rebuild to its historic level depending on parameter assumptions. Trawl surveys conducted by the Washington Department of Fish and Wildlife further indicates that spiny dogfish may have decreased significantly (~75%) in the southern Strait of Georgia during 1987 to 2001 (Palsson 2003), see Figure 9. In contrast, DFO research longline surveys do not indicate that the spiny dogfish in the Strait have declined over this period, but rather indicate a small increase from the late 1980s to 2005-8. Likewise, the average abundance trends (CPUE) from commercial fisheries in the Strait do not indicate any clear changes in abundance during 1980-2005 (King and McFarlane 2009).

DFO's last published assessment of spiny dogfish was in 1987, an updated assessment was done in 2010, and the report from this assessment was made available for this study in a pre-release version (Gallucci *et al.* 2010). Spiny dogfish in British Columbia is assessed as two populations: an inside stock in the Strait of Georgia (Statistical Area 4B), and an outside stock in all other coastal areas (Statistical Areas 3C through 5E). The new assessment indicates that the Strait of Georgia spiny dogfish population is in a stable state, without signs of recent increase, and that the population in the rest of B.C. is in "the healthy zone" (Gallucci *et al.* 2010). There are no indications of increase in abundance in recent decades for either stock.

The current DFO assessment for the outer BC stock, (Figure 10), illustrates the uncertainty with regard to the level of decline in spiny dogfish since the liver oil fishery started in the 1940s. Based on the most recent and other available information there does not seem to have been an increase in spiny dogfish over the last decades that would point toward an increased impact on Fraser River Sockeye Salmon.

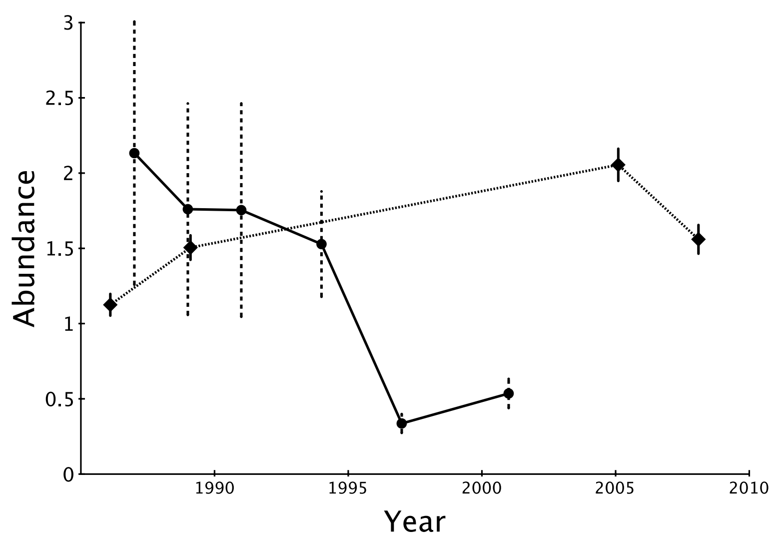


Figure 9. Full line: Spiny dogfish abundance (mean ± 1 std. dev.) in the southern Strait of Georgia as estimated by Washington Fish and Wildlife trawl surveys (Based on information in Palsson 2003). Dotted line: Spiny dogfish abundance (mean ± 1 std. dev.) in the Strait of Georgia from DFO longline surveys (Gallucci *et al.* 2010).

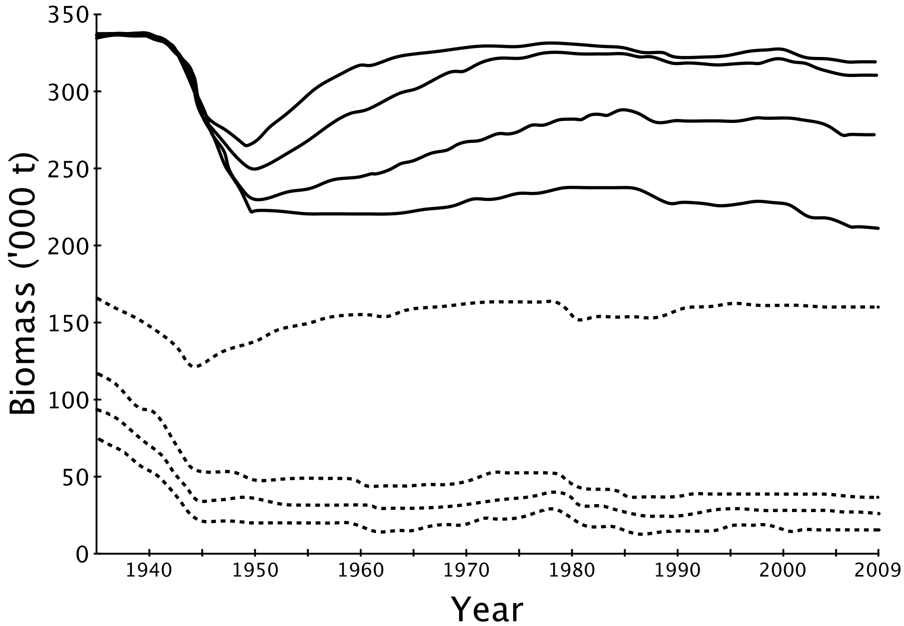


Figure 10. Biomass trajectories for spiny dogfish in the Strait of Georgia (dashed lines), and the rest of the coast of B.C (full lines). The trajectories indicate alternate assessment runs with different parameter settings selected to illustrate extreme and more average runs. While absolute abundances are uncertain, there is nothing indicating increasing trends in the recent decades. Based on Gallucci et al. (2010) and DFO (2010).

Overall, the conclusion for spiny dogfish thus is that they may be significant predators on juvenile salmonids, and as such also on Fraser River sockeye salmon, but that the available information is sparse. There are no indications that the abundance of spiny dogfish has increased in recent decades, and as such it is not likely that the spiny dogfish is a primary factor for the decline of Fraser River sockeye salmon.

Salmon shark (*Lamna diprosis*)

Salmon sharks are large, with a max length of 305 cm TL, and a common length of 180 cm. They feed on cephalopods and fish including salmon (Nagasawa 1998), with salmon being a preferred food during the summer months for salmon sharks that move to coastal areas (Brodeur et al. 1999). As an example, FishBase (Froese and

Pauly 2010) has diets for 10 salmon sharks, all of which contained bony fishes only. They are reported to feed primarily on Pacific salmon in spring and summer in the western North Pacific and Bering Sea, with sockeye averaging 40% of the stomach content in samples from 1958-59 (Nagasawa 1998). However, in the area of the North Pacific of most concern here, i.e. east of the Dateline, sockeye contributed 75% of the diet of salmon shark (Nagasawa 1998).

The salmon sharks are migratory and individuals have been found to move between Alaska and Hawaii. They mainly forage in highly productive ecoregions where they are likely to encounter higher prey densities (Weng et al. 2008). The salmon shark utilizes the Coastal Alaska Downwelling region mainly in summer-autumn coinciding with the return migration of Pacific salmon, notably of sockeye (Weng et al. 2008). Salmon are particularly vulnerable to predation by salmon sharks when holding, aggregated at river mouths, before beginning their upriver migration (Hulbert et al. 2005).

It is generally assumed that the salmon sharks were heavily impacted by driftnet fisheries up to 1992 when a UN General Assembly ban on driftnet went into effect. There are indications that salmon shark have increased in abundance since then. The CPUE for salmon shark was low in Japanese research vessel surveys from 1984 to 1993, but increased sharply in 1996, and have remained at a high level the following years (Nagasawa et al. 2002). Muto (2004, cited by Okey et al. 2007) found that Japanese CPUE increased 47% from 1992 to 2002.

Brodeur and Ware (1995) compared trends in research long line catches between 1958-59 and 1980-1989 and while the publication indicates a small increase in abundance of salmon shark, the abundance cannot be quantified based on the information they presented. Similarly, Okey et al. (2007) found non-quantifiable indications of increasing trends of salmon sharks from interviews with Aleutian fishers.

An interesting finding from the 1958-59 Japanese surveys in the North Pacific was that the catch rate of salmon shark varied with that of salmon (Nagasawa 1998). Days with higher salmon catch rates also yielded more salmon sharks. This indicates co-occurrence, with salmon sharks likely seeking out areas where its favored prey is more abundant.

The abundance of salmon shark is poorly known, with estimate of around 10,000 tonnes for each of several large areas of the North Pacific (Nagasawa 1998). The daily food consumption for salmon sharks is not known, but North Pacific sharks generally have a daily ration of 1-2% of their bodyweight. Based on this, Nagasawa calculated that the estimated number of salmonids eaten by salmon sharks corresponds to 12.6% to 25.2% of the total salmonid run for the study year, 1989.

Abundance trends for the areas of concern for Fraser River sockeye are thus very limited. There is only an indication that the abundance of salmon shark has increased in recent decades, and hence so has the predation impact on Fraser River sockeye probably. It is likely though, that the abundance is below the level it had more than 50 years ago.

Salmon shark population dynamics and ecology has not been monitored by DFO or other agencies since the 1980s. To reliably evaluate if salmon sharks have had increasing impact on Fraser River sockeye over the last decades would call for more information about the abundance and trend of salmon shark, including in the open ocean.

Blue shark (*Prionace glauca*)

There are other pelagic sharks in the open North Pacific Ocean that can have a predation impact on Fraser River sockeye salmon. Notably so blue shark, which Sviridov et al. (2007) found to be an important predator on salmon, though it is not specialized on eating salmon, rather its diet is diverse, with squids and small pelagics contributing a major proportion (Nakano and Stevens 2009). Markaida, and Sosa-Nishizaki (2010) further reviewed the available diet studies for blue sharks, and found that they tend to feed on a variety of passive pelagic prey, mainly mesopelagic cephalopods, that could be preyed upon as well as scavenged.

Blue sharks are, however, much more abundant than salmon shark. McKinnell and Seki (1998) thus reports that blue sharks accounts for 93.7% of the 1990-91 shark bycatch in the Japanese flying squid driftnet fishery, while salmon shark only contributed 5.2%.

The population trend for North Pacific blue sharks was reported by Siebert et al. (2006), who found that the adult population decreased approximately 18% from 1970 to 1990, and that they by 2004 had recovered to approximately 90% of the 1970 abundance. The trend for the total population was very similar, but with a slightly lower decline by 1990. A more recent NMFS assessment shows similar trends, but with a larger decrease in blue shark abundance by 1990, and a subsequent greater recovery (Kleiber et al. 2009).

Overall, there is no indication that blue shark thus may have increased substantially over the last decades, rather the population is estimated to be below the 1970-level, and it does not appear likely that blue shark trends by itself can explain the decline in Fraser River sockeye salmon survival rate, even if it may have contributed.

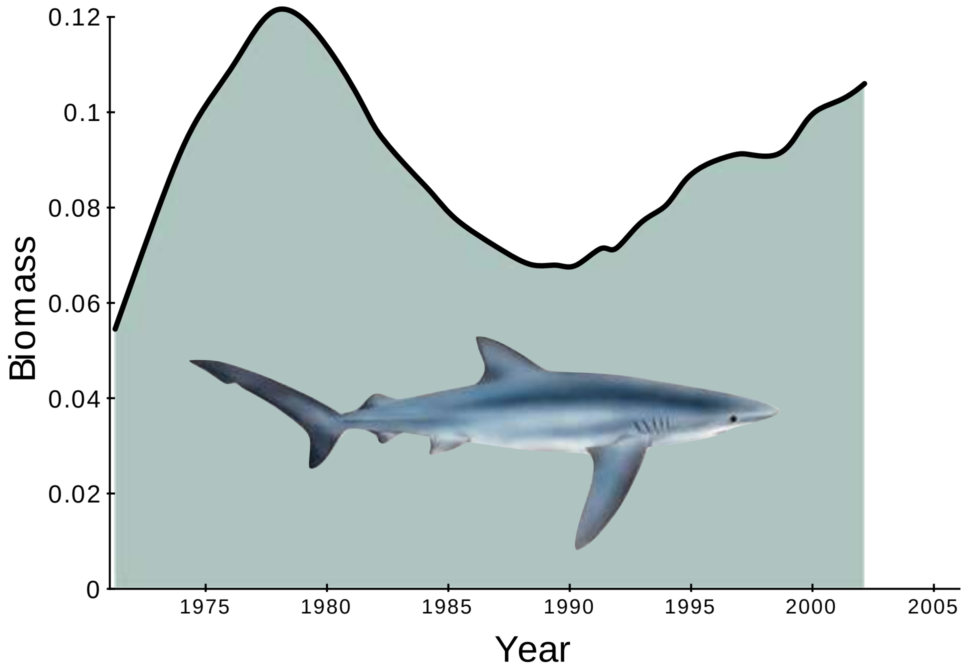


Figure 11. Total biomass trends (million t) trends for blue shark in the Northeast Pacific Ocean (Area 2; east of 180˚W, north of 30˚N), from 2009 NMFS assessment (Kleiber et al. 2009).

Pacific sleeper shark (*Somniosus pacificus*)

Sleeper sharks are large (up to 7 meters) pelagic sharks, which feed on a diverse range of food, typically bottom animals such as fishes, octopi, squids, crabs, tritons, harbour seals, and carrion (Compagno 1984).

A study (based on 13 sharks) indicated that immature salmon were part of the diet, with an estimated 4.5% by weight (Yang and Page 1999), while a later study (198 sharks, northern Gulf of Alaska) found that found that Pacific cod, walleye pollock, salmon, and halibut were the predominant fish prey. Salmon was a common prey (including sockeye), with 8.8% of the diet being identifiable as salmon (Sigler et al. 2006). There is limited information about the abundance of sleeper shark, and it is not considered likely that this species should be a direct factor for the decline of Fraser River sockeye salmon. There are no monitoring programs for the species.

Chinook salmon (*Oncorhynchus tshawytscha*)

There are resident chinook salmon populations in the Strait of Georgia and further up along the coast, and it is likely that these exert predation pressure on Fraser River sockeye smolt. Chinook are the most piscivorous of the salmon species, and Beamish and Neville (2001) estimated that the chinook in the Strait of Georgia could consume 345 tonnes sockeye smolt per year (or some 35 million smolt), if these constituted 0.5% of their diet.

The abundance of chinook salmon has, however, declined considerably over the last decades in the Strait making it unlikely that chinook is of importance for the decline of Fraser River sockeye salmon.

Coho salmon (*Onchyrhunchus kitsutch*)

Coho salmon are the second biggest fish eaters among the salmon, and they are also resident in the Strait of Georgia, with a potential predation impact on Fraser River sockeye salmon in the early ocean period where they may be most vulnerable. Beamish and Neville (2001) estimated that the coho could consume 55 tonnes of sockeye smolts (or perhaps 5 million individuals) if 0.1% of their diet was sockeye smolts.

Similarly to for chinook salmon it is, however, unlikely that the coho in the Strait of Georgia can have contributed much to the decline in Fraser River sockeye salmon given the serious decline the coho population has experienced over the last decades.

Pink salmon, (*Oncorhynchus gorbuscha*)

G. Ruggerone put forward a hypothesis that returning pink salmon in odd years may have a strong predatory impact on Fraser Rivers sockeye salmon smolt soon after the ocean entry (Peterman *et al*. 2010). The hypothesis is interesting given that pink salmon are now the most abundant salmon species in the Fraser River system.

To evaluate the hypothesis, we compared marine survival rates (Figure 4) to the number of returning pink salmon that the sockeye smolts might have encountered on ocean entry. We did not find any indication from this that the survival of sockeye was lower when the smolts might have encountered large numbers of returning pink salmon. The hypotheses was also deemed unlikely during discussions at the Cohen Commission Science workshop, November 29-30, 2010, as indications are that returning pink salmon have stopped eating by the time they reach the BC coast.

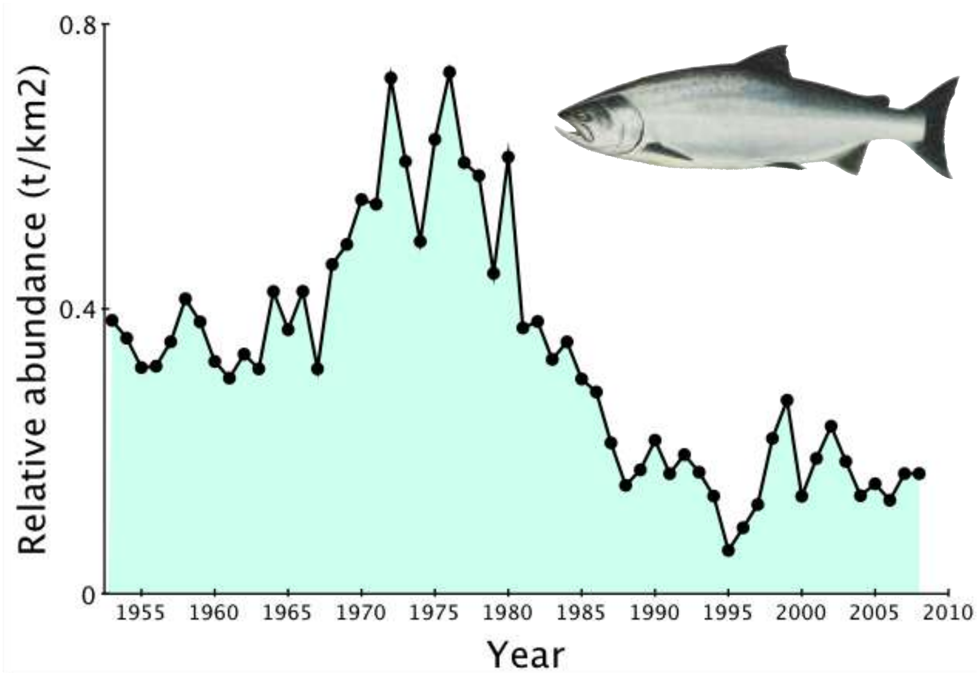


Figure 12. Abundance of chinook salmon (immature and maturing) in the Strait of Georgia, 1953 – 2008. (Based on information provided by D. Preikshot for DFO workshop, January 2010).

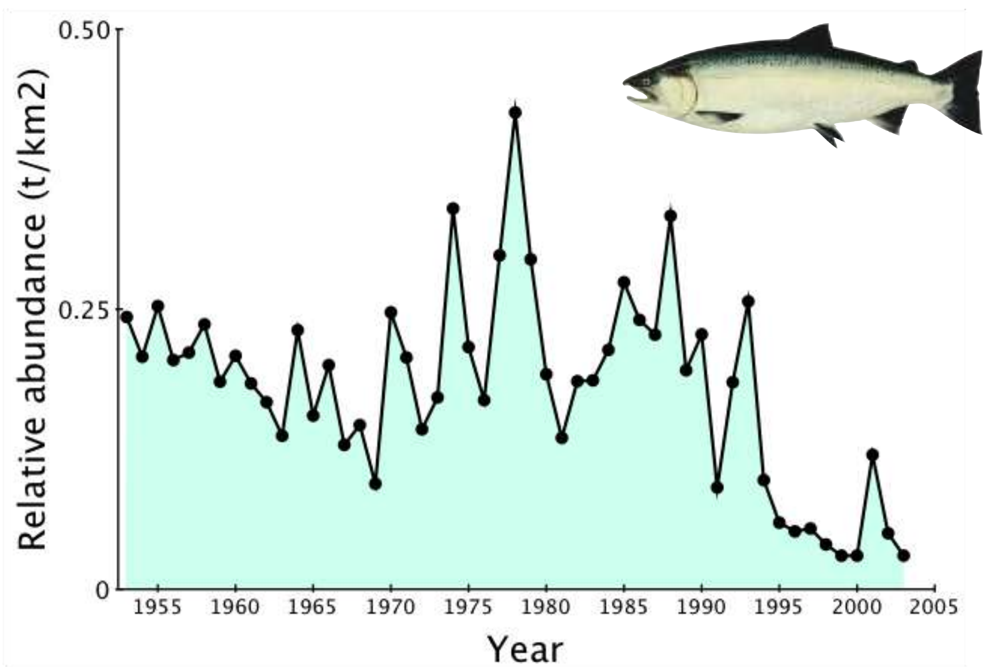


Figure 13. Abundance of coho salmon (immature and maturing) in the Strait of Georgia, 1953 – 2008. (Based on information provided by D. Preikshot for DFO workshop, January 2010).

Sablefish (*Anoplopoma fimbria*)

Brodeur et al. (2003) reports that Orsi et al. (2000) evaluated the diets of 19 potential fish predators in southeastern Alaska, and found only four species that consumed juvenile salmon. Of these only sablefish and adult coho salmon were judged to be important predators.

Sturdevant et al. (2009) evaluated predation by sablefish on juvenile salmon in Southeast Alaska in June and July 1999, and found that up to 63% of the sampled sablefish from trawl catches had each consumed one to four juvenile pink salmon, chum salmon, or sockeye salmon. They estimated that 0.8–6.0 million juvenile salmon were consumed by age-1+ sablefish in a 500-km^2 area during a 33-day period. The sockeye consumed were 145-167 mm, and on the average 46% of the length of the sablefish.

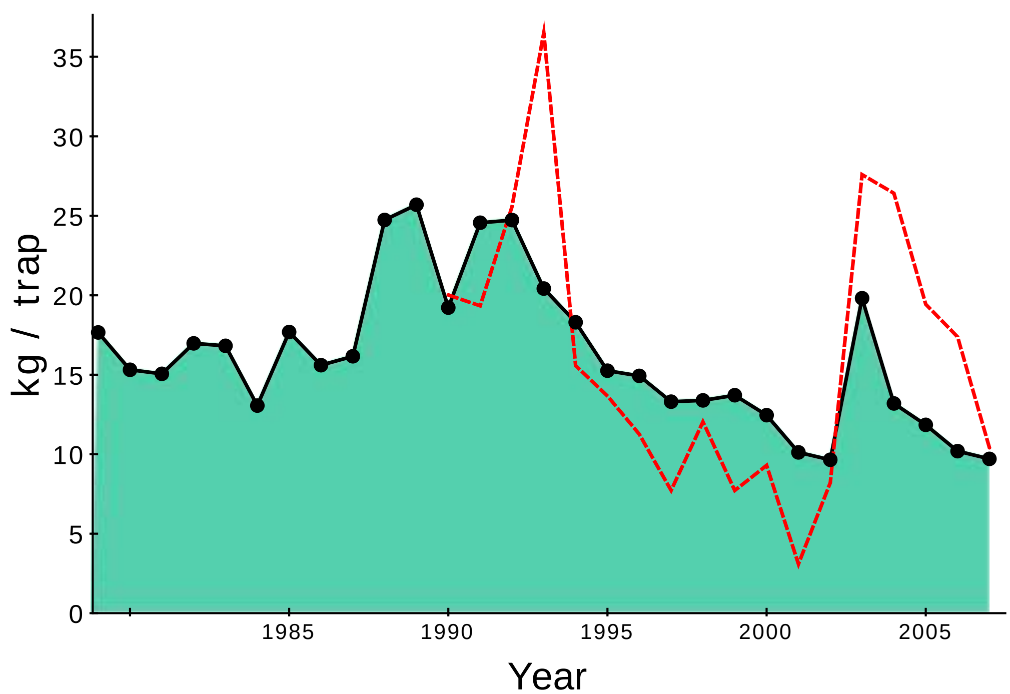


Figure 14. B.C. sablefish stock indices based on commercial trap CPUE (kg/hour), assumed to reflect relative changes in the population size. The red, stippled line indicates CPUE from research vessel surveys. (From Cox and Kronlund 2009).

Sablefish are opportunistic feeders known to prey on fish, (e.g., walleye pollock, eulachon, capelin, herring, sandlance, and Pacific cod), squid, krill, jellyfish (Yang and Nelson 2000).

The abundance of sablefish in B.C. as judged from nominal trap CPUE indicates that the sablefish have been in a decline since the late 1980s, see Figure 14**,** (Cox and Kronlund 2009). Further north in the Central and Eastern Gulf of Alaska, The sablefish has also experienced a decline since the late 1980s, but it has been relatively minor (see Figure 15) (Hanselman *et al*. 2009).

Sablefish could potentially impact Fraser River sockeye smolts during the outmigration, but given that there are no indications from the stock assessments that sablefish biomass has been increasing over the last decades, it is not likely that sablefish should be a direct major factor for the decline of Fraser River sockeye over the last decades.

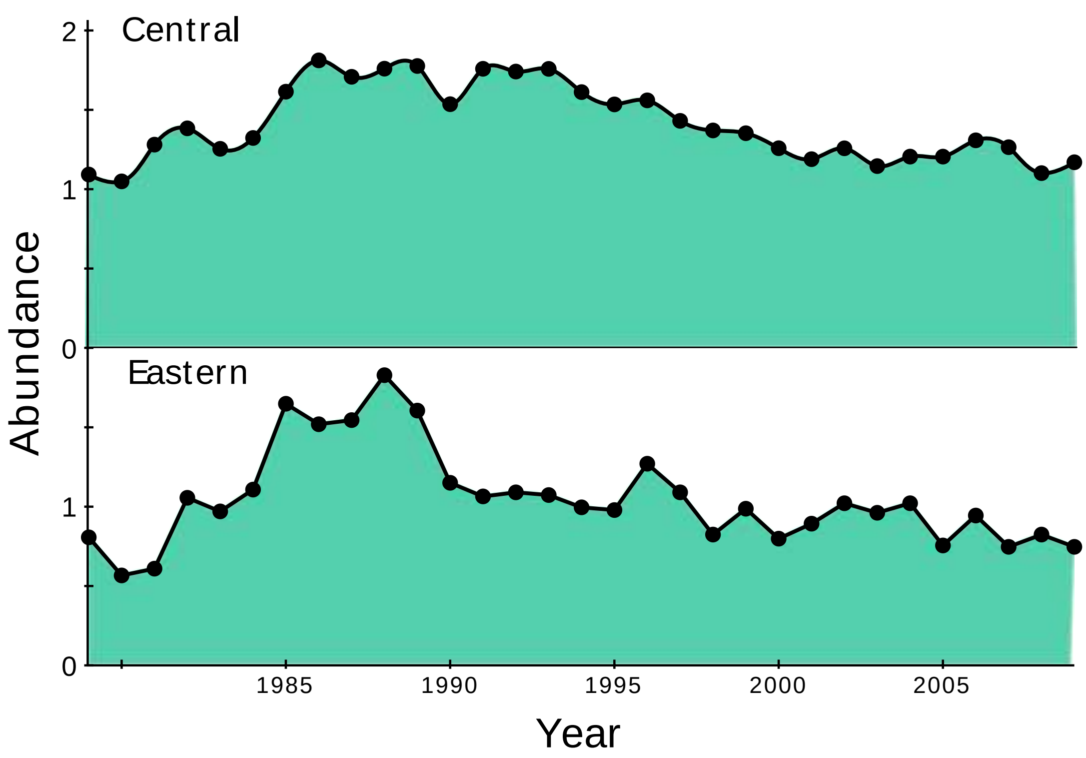


Figure 15. Abundance (relative, by weight) of sablefish in the Central and Eastern Gulf of Alaska based on surveys (based on Hanselman *et al.* 2009).

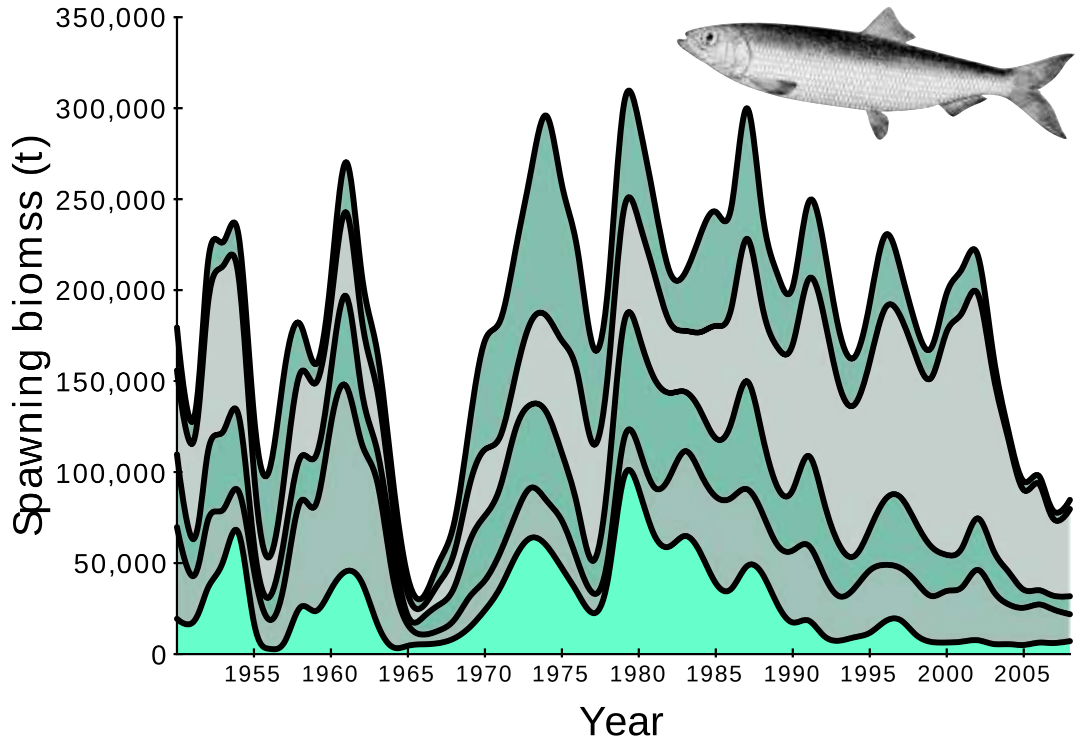


Figure 16. Spawning biomass (t) of Pacific herring in British Columbia from DFO assessment (Cleary *et al.* 2009). Covers five areas, Queen Charlotte Islands (lowest), Prince Rupert District, Central Coast, Strait of Georgia, and West Coast Vancouver Island (top).

<u>Pacific herring (*Clupea harengus pallasi*)</u>

Herring is a widely distributed and competitive species, which predominantly is planktivorous. It will, however, also feed happily on (at least juveniles of) small pelagics, but it is unlikely that it would prey on Fraser River sockeye smolt as these size-wise would be out of the predation windows for herring.

The herring in B.C. was fished down through a reduction fishery (for fishmeal and oil) over a few years in the early 1960s for then largely to recover between 1965 and 1975 (Figure 16).

The adult herring populations in B.C. have gradually declined since the early 1980s, with a sharp decline in spawning biomass in recent years. It is very unlikely that there will be any predation impact by Pacific herring on sockeye smolt; the sockeye are too big for herring when they enter the Strait, and at this time the adult herring will be out of the Strait after their spawning in early spring.

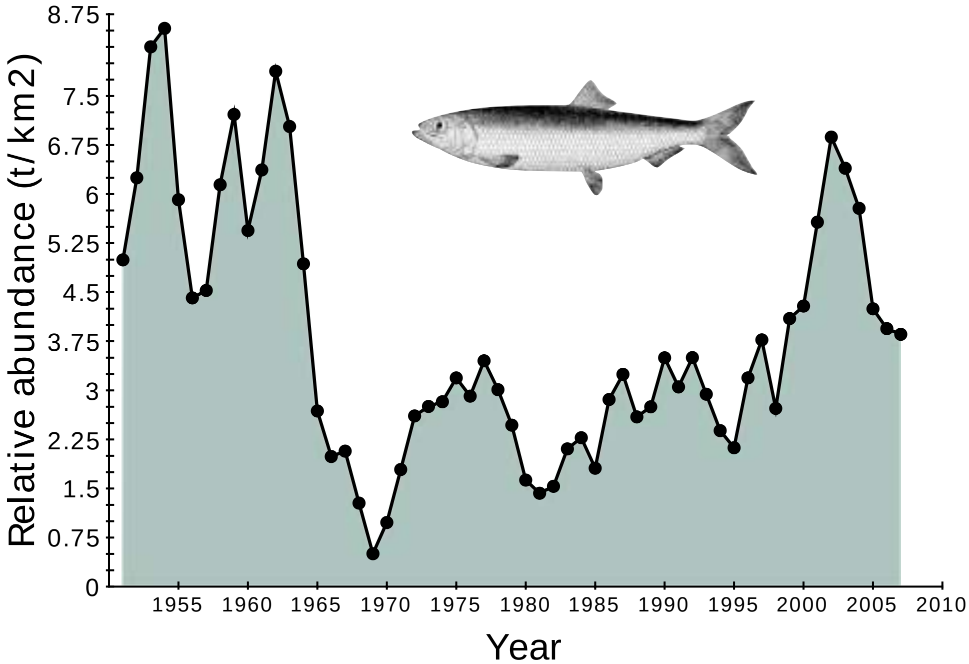


Figure 17. Abundance of juvenile herring in the Strait of Georgia, 1951 – 2007. (Based on information provided by Preikshot for DFO workshop, January 2010).

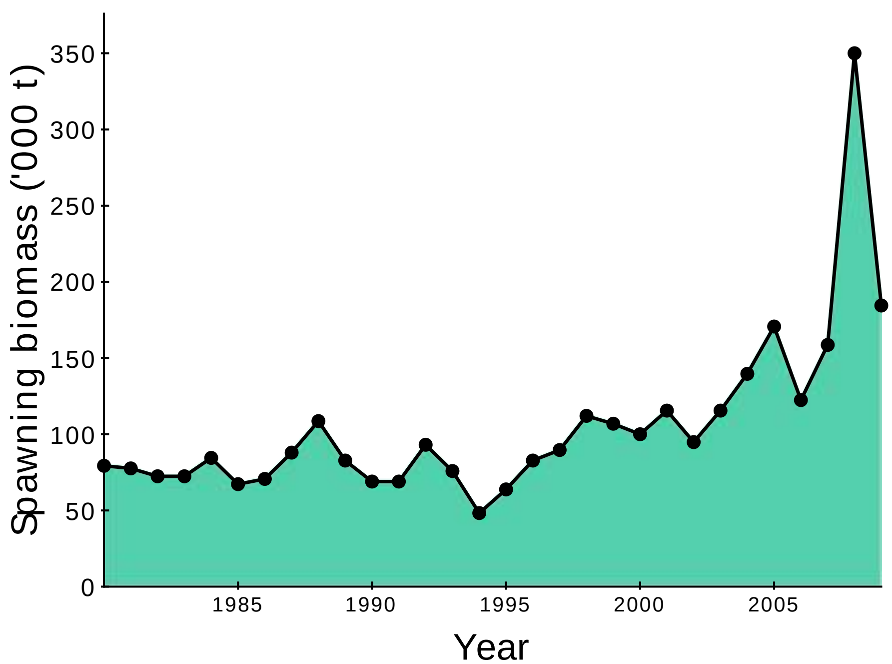


Figure 18. Combined spawning stock biomass (thousand tonnes) for all major stocks of Pacific herring in southeast Alaska (Hebert 2009).

Juvenile Pacific herring are abundant in the Strait of Georgia where they may compete with migrating sockeye smolt. The abundance of juvenile herring in the Strait has steadily increased since the late 1960s (Figure 17). It is therefore a fair assumption that competition between Fraser River sockeye smolt and Pacific herring may have increased through this time, assuming that the sockeye smolt stay long enough in the Strait to feed. Further north, in southeast Alaska the Pacific herring stocks the herring stocks have been steadily rebuilding since the mid 1990s, see Figure 18 (Hebert 2009).

Daggertooth (*Anatopterus nikparini*)

The daggertooth is a pelagic species that occurs through the North Pacific Ocean and California Current. It can reach a max length of 146 cm, and is found from the surface down to 2,000 meters (Froese and Pauly 2010). It has a distensible body and can take prey up to half of its own length. Its diet is varied and includes fishes, including sockeye salmon.

Angler with a Fraser River sockeye salmon with recent, presumed daggertooth slash wound, Aug. 2010.

Welch et al. (1991) demonstrated that slash wounds on the side of sockeye might be caused by daggertooth, and Nagasawa (1998) that salmonids with wounds of daggertooth are commonly found in stomachs of salmon sharks. Further, Sviridov et al. (2007) found in the western Bering Sea and North Pacific Ocean that 16.7% and 14.3% of maturing sockeye salmon in 2003 and 2004, respectively, had injuries caused by daggertooth.

Daggertooth. Photo: William van Orden

There is only very sparse information available on the abundance of daggertooth, and seemingly nothing about abundance trends. Russian pelagic research trawl surveys estimates the abundance in the northwestern Pacific Ocean to 0.6 to 3.4 individuals per km^2(Sviridov *et al.* 2007), which, however, seems low and may indicate that the pelagic trawls are inefficient for sampling daggertooth. The widespread occurrence of slash wounds caused by daggertooth rather indicates that the species may be abundant and that it may have some predation impact on salmonids, including on Fraser River sockeye. Without abundance trends, we cannot, however, conclude that daggertooth has been a factor for the decline in Fraser River sockeye survival over the last decades.

Pacific cod (*Gadus macrocephalus*)

Pacific cod is a common species in the North Atlantic where it may reach a size of up to 119 cm (Froese and Pauly 2010). There are an estimated nine Pacific cod stocks in British Columbia waters, distributed with four in the Strait of Georgia, one off the southwest coast of Vancouver Island, two in Queen Charlotte Sound, and two in Hecate Strait (Westrheim 1996).

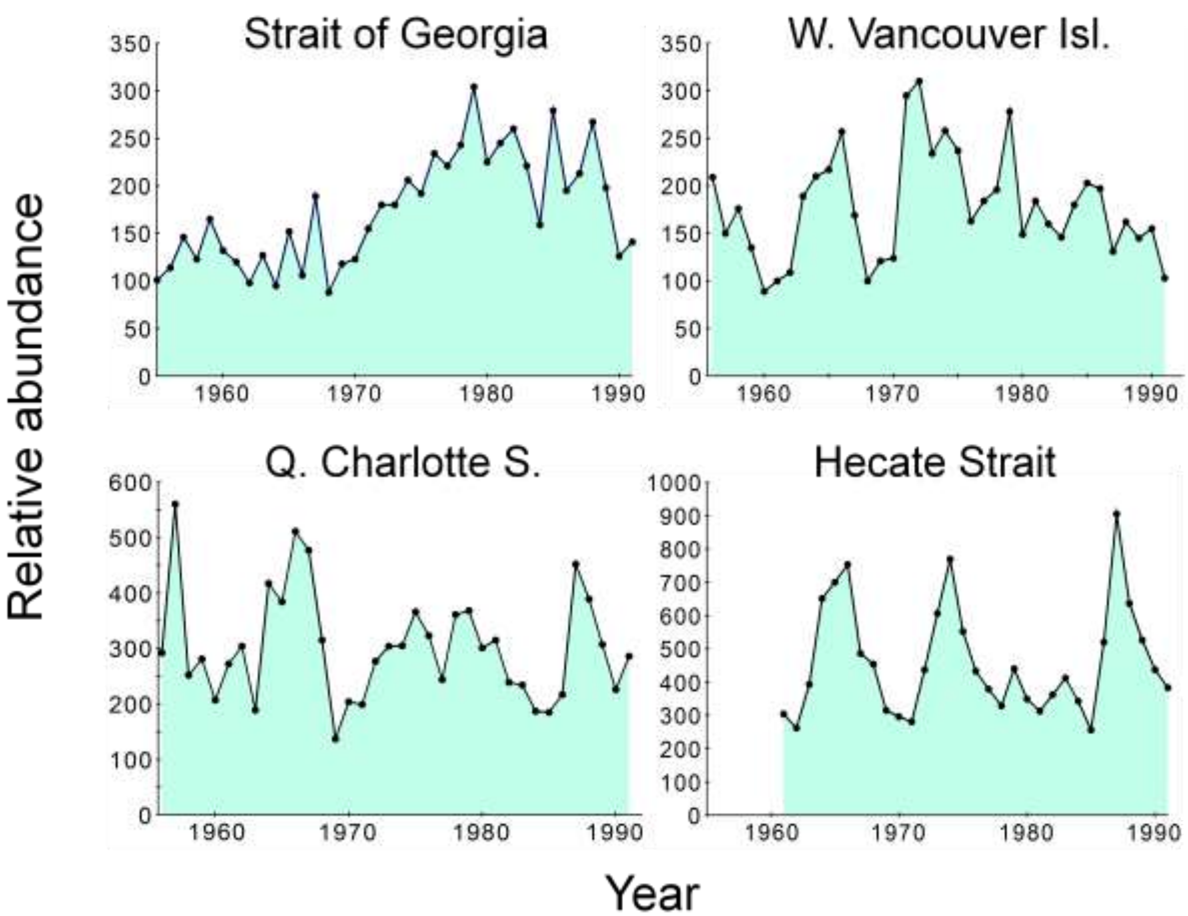


Figure 19. Relative abundance (CPUE, kg hour^{-1}) of Pacific cod based on commercial fisheries in B.C. (Westrheim 1996).

Pacific cod is not subject to regular assessments in B.C., but indications are that the stocks were rather stable from 1955-1991, see Figure 19 (Westrheim 1996). Research trawl surveys by the Washington Department of Fish and Wildlife in the Southern Strait of Georgia also indicate that the Pacific cod there were stable during 1987 – 2001, (Figure 20).

Pacific cod is widely distributed through the North Pacific Ocean, and there are major stocks in Alaska. Of interest here is the Gulf of Alaska population, which may overlap in distribution with Fraser River sockeye salmon. Pacific cod is assessed regularly in the Gulf of Alaska where NMFS conducts ground fish surveys every second or third year.

Based on the NMFS groundfish surveys it is indicated that the biomass of Pacific cod has declined some 45% over the last three decades, likely associated with increased fishing pressure (Thompson et al. 2006).

While Pacific cod is unlikely to play a role as predator on Fraser River sockeye it may be a competitor. And as a food source for other species, their decline could have led predators to seek alternative prey, such as for instance sockeye salmon.

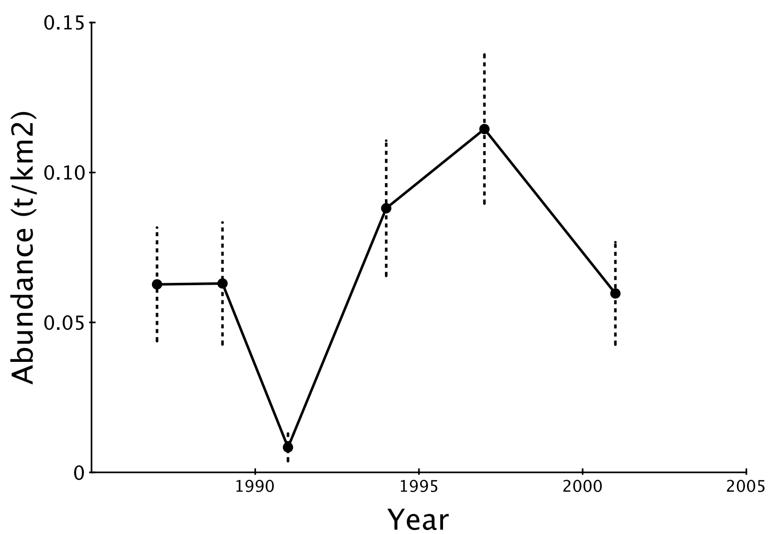


Figure 20. Abundance of Pacific cod (± 1 std. dev.) in the southern Strait of Georgia based on trawl surveys made by the Washington Department of Fish and Wildlife (Based on information in Palsson 2003).

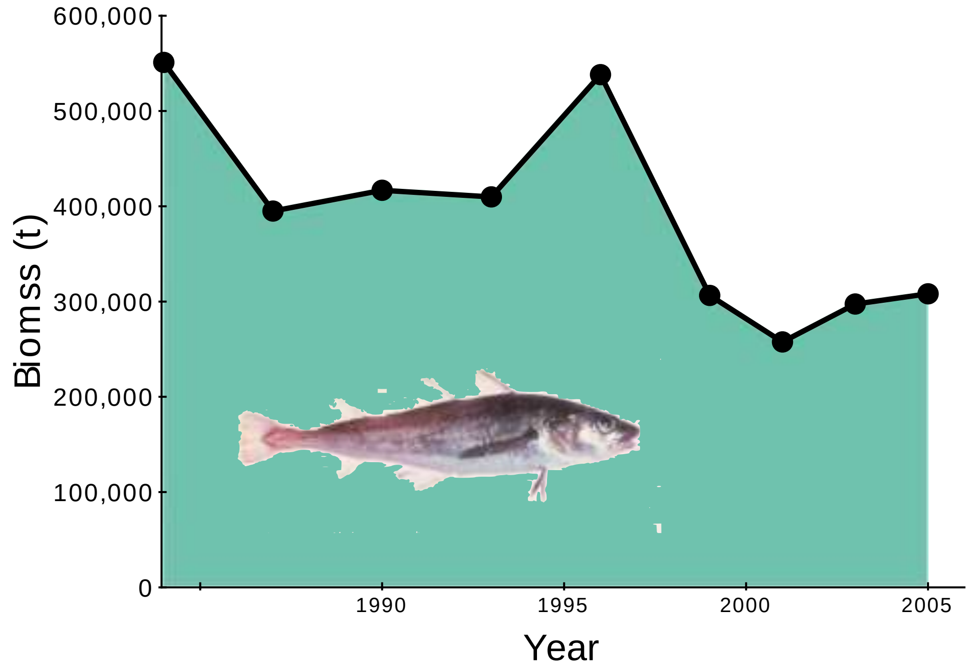


Figure 21. Biomass estimates (t) of Pacific cod in the Gulf of Alaska based on NMFS groundfish surveys (Thompson et al. 2006).

Pacific hake (*Merluccius productus*)

There are two stocks of Pacific hake of interest here, a smaller local stock in the Strait of Georgia, and a highly migratory and large stock occurring in the California Current.

The Pacific hake feed primarily on krill, but small pelagics such as Pacific herring, are also important components of their diet (King and McFarlane 2006), and they tend to become increasingly piscivorous with size (Buckley and Livingston 1997). It is expected that Pacific hake may feed on salmon smolt as well, but conclusive studies of this do not seem to be available.

The Strait of Georgia fishery for Pacific was established in the late 1970s, and it targets (or targeted) spawning concentrations in the central basin of the Strait. From the mid 1980s through to 2003 it varied around 4-8,000 tonnes, but has since declined, and there is currently no targeted fishery for hake in the Strait.

The abundance estimate of Pacific hake in the Strait based on DFO trawl surveys indicates that the population declined with approximately 50% from the early 1980s to the late 1990s (Figure 22).

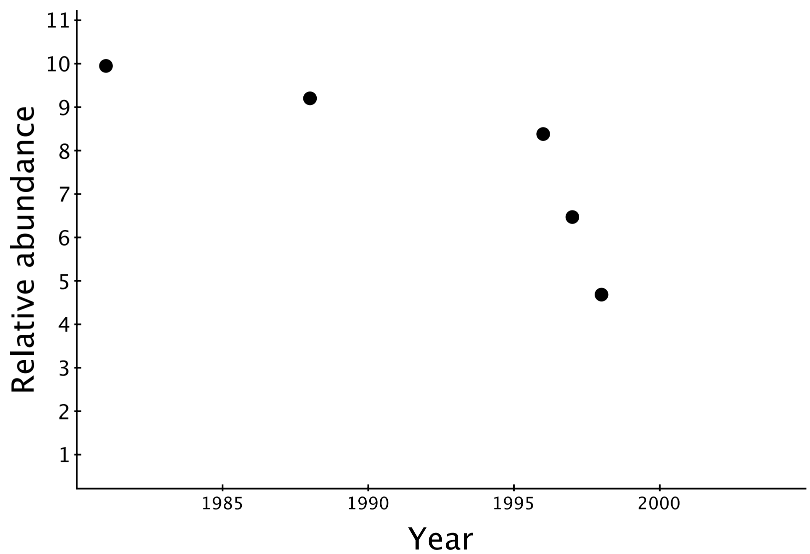


Figure 22. Relative abundance of Pacific hake in the Strait of Georgia based on trawl surveys (Preikshot, information distributed for DFO workshop, January 2010; Keiser *et al.* 1999).

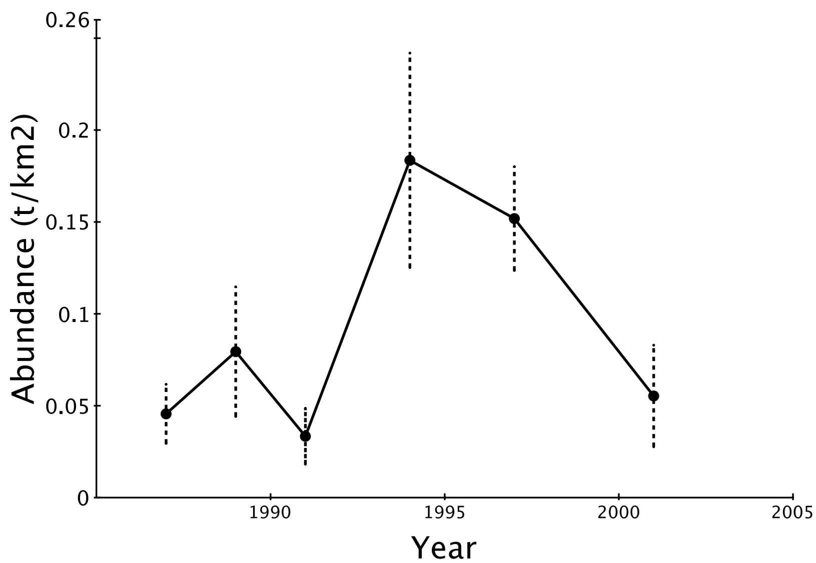


Figure 23. Estimated abundance (t, ±1 std. dev.) of Pacific hake in the southern Strait of Georgia (Based on information in Palsson 2003). Recent abundance estimates are not available for Pacific hake in the Strait of Georgia, but indications are that the population is now at a low level.

The Washington Department of Fish and Wildlife conducted a series of trawl surveys in the southern Strait of Georgia during 1987 – 2001, covering an area of 2,313 km^2. The surveys do not indicate a decline in southern Strait of Georgia hake abundance over the time period (Figure 23). There does not seem to be more recent abundance estimates for Pacific hake in the Strait of Georgia, but indications are that the population is now at a low level. Overall, the available information about Pacific hake in the Strait of Georgia point to a reduced abundance in the recent decades.

The Pacific hake stock in the California Current is migratory and a variable proportion of the population spends the warmer part of the year in the waters off Vancouver Island. This is very large population, measured in millions of tonnes (Figure 24), but indications from assessments are that the population overall has been declining since the 1980s. Martell (2010) also notes that the recent acoustic biomass estimates for Pacific hake may be biased upwards due to the large quantities of Humboldt squid present during the survey, it currently is not possible to distinguish hake from Humboldt squid using acoustics.

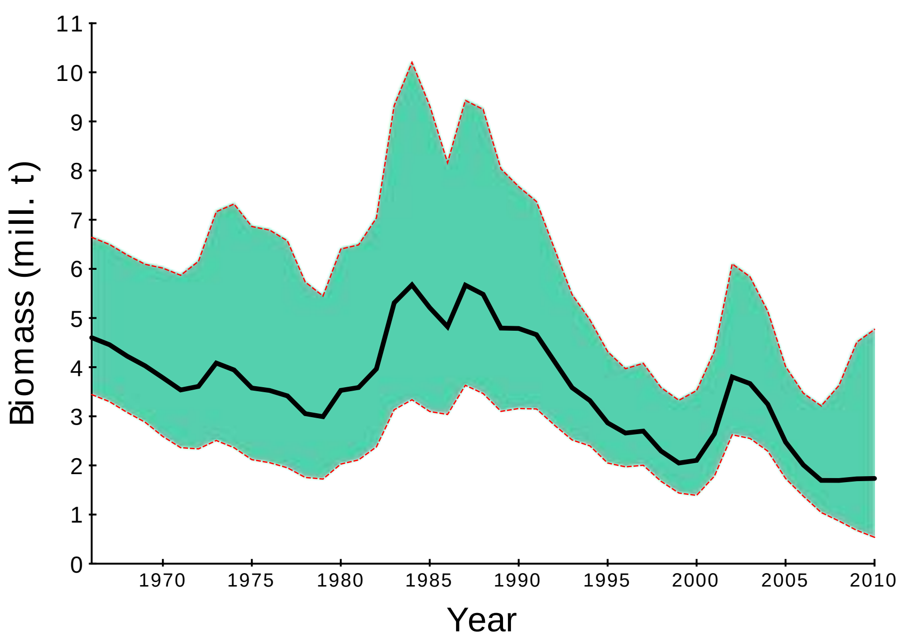


Figure 24. Estimated spawning stock biomass of Pacific hake (thick line). Dotted lines indicate 0.025 and 0.975 quantiles for the estimate (Martell 2010), i.e., there is 95% likelihood the stock is within the shaded area.

This overall decline in the California Current Pacific hake does not necessarily mean that the part of the population in B.C. waters has declined as the proportion of the population, (which is the largest and most piscivorous part) that moves north depends on water flow patterns (Agostini et al. 2006). There are some indications that this may have happened, as there has been a recent shift in the location of the fishery during 2006-9 to more northerly distribution in Queen Charlotte Sound and in the Strait of Juan de Fuca in comparison to the traditional fishing area off southwest Vancouver Island (Martell 2010). The aggregations of Pacific hake tend to coincide with dense distributions of krill, their main prey indicating that Pacific hake aggregate where the prey is (Mackas *et al.* 1997). If concentrations of outmigrating sockeye smolt can trigger something similar is not known.

Overall, there are, however, no indications that Pacific hake may have asserted increased predation pressure in B.C. waters in recent decades, and hence no indication that they should be a major factor for the declining survival of Fraser River sockeye salmon in recent decades.

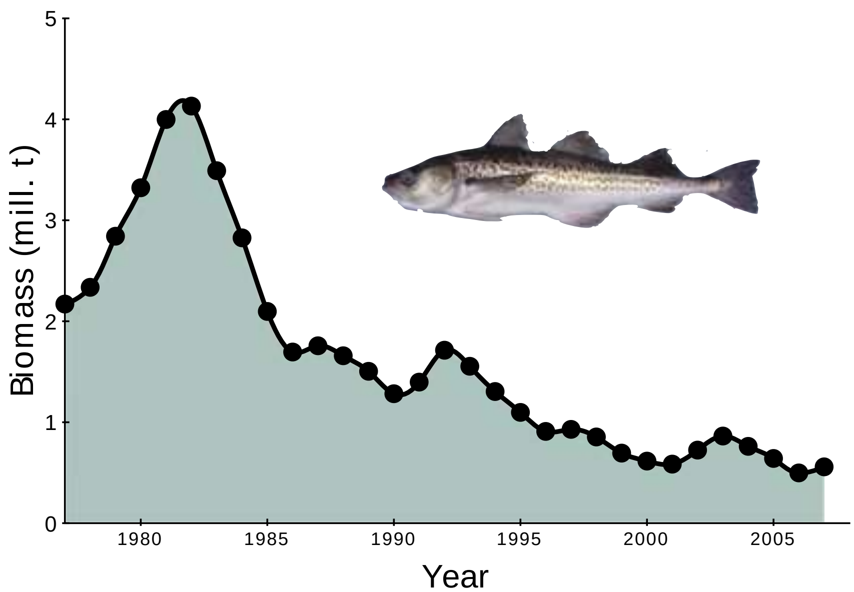


Figure 25. Biomass of walleye pollock (age 3+, million tonnes) in the Gulf of Alaska based on NMFS assessment (Dorn *et al.* 2009).

Walleye pollock (*Theragra chalcogramma*)

Walleye pollock is an abundant species in the North Pacific Ocean, of which the adults predominantly live close to the bottom, though they can also be found closer to the surface. They undergo diurnal vertical migrations, and mainly feed on krill, fishes and crustaceans.

Walleye pollock in the North Pacific Ocean is subject to one of the biggest fisheries in the world (2-3 million tonnes per year), and the species has been declining in recent years or decades. Of special interest here is the population in the Gulf of Alaska, which has experienced a steady decrease in abundance since the 1980s (Dorn *et al.* 2009).

Overall, there is no indication that the walleye pollock in the northern part of the Pacific Ocean should be a direct factor for the decline of Fraser River sockeye salmon. Noting the strong decline in walleye pollock, an interesting question is, however, what the predators that used to be eating walleye pollock are eating instead? Our best chance of answering that question is through a combination of diet studies and ecosystem-level modeling.

There is a local population of walleye pollock in the Strait of Georgia, which potentially could be a predator on the outmigrating Fraser River sockeye smolt. The population is not assessed but indications from surveys in the southern Strait do not indicate any clear trend during 1987-2001 (Figure 27). Overall, there is no indication that the rather scarce walleye pollock in the Strait of Georgia should me a major factor for the decline in survival of Fraser River sockeye salmon.

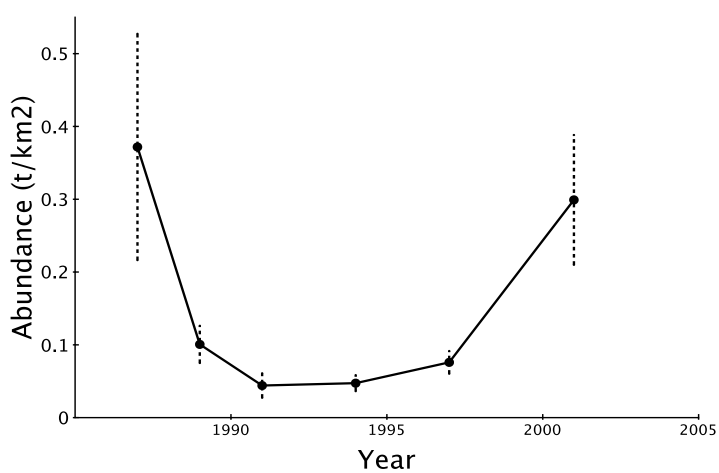


Figure 26. Walleye pollock in the southern Strait of Georgia based on Washington Department of Fish and Wildlife trawl surveys (Based on information in Palsson 2003).

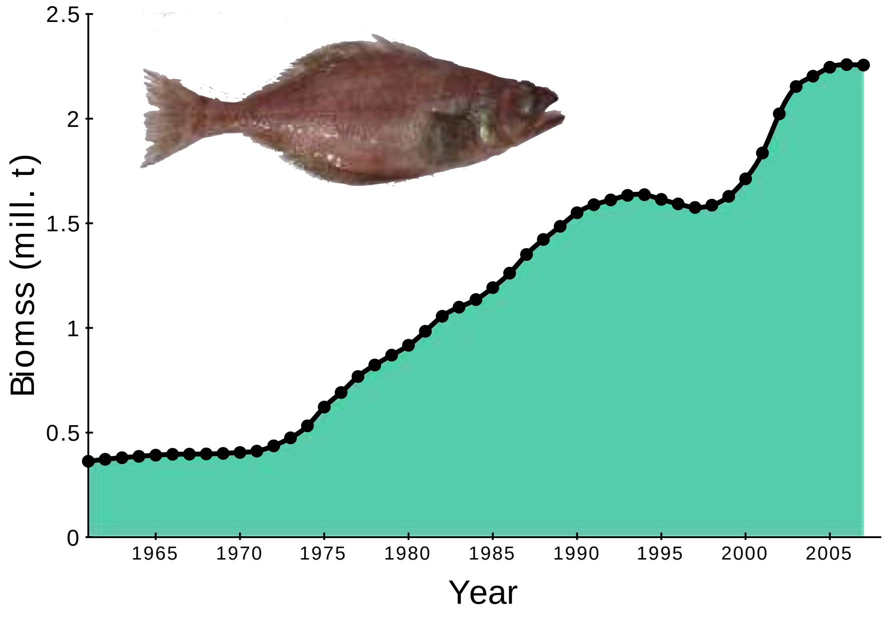


Figure 27. Biomass of arrowtooth flounder (age 3+, million tonnes) in the Gulf of Alaska from NMFS assessment (Turnock and Wilderbuer 2009).

Arrowtooth flounder (*Atheresthes stomias*)

Arrowtooth flounder is a large flatfish occurring from northern California to the Bering Sea. It can reach a length of 84 cm and feed predominantly on crustaceans and fish (notably cod, herring and pollock) (Froese and Pauly 2010).

It has seen a dramatic increase in biomass over the last four decades, and which now has a biomass in excess of 2 million tonnes in the Gulf of Alaska (Turnock and Wilderbuer 2009). It is caught during the NMFS groundfish surveys in Alaska, and it subject to regular assessments in Alaska. The population (or part of the population) in B.C. is not assessed regularly.

There is little information on the role arrowtooth flounder play as a predator on sockeye salmon, but Preikshot (2007a) in his ecosystem model of the Northeast Pacific Ocean assumed that sockeye contributed 0.1% to the diet of arrowtooth flounder. Given the biomass of arrowtooth flounder this potentially amounts to a considerable predation pressure. We can, however, not draw any conclusion about the role arrowtooth flounder may have played for the reduced survival of Fraser River sockeye given the lack of specific estimates for arrowtooth flounder in the areas that the smolt pass through, and given the lack of information about sockeye in the diet of arrowtooth in the area of concern.

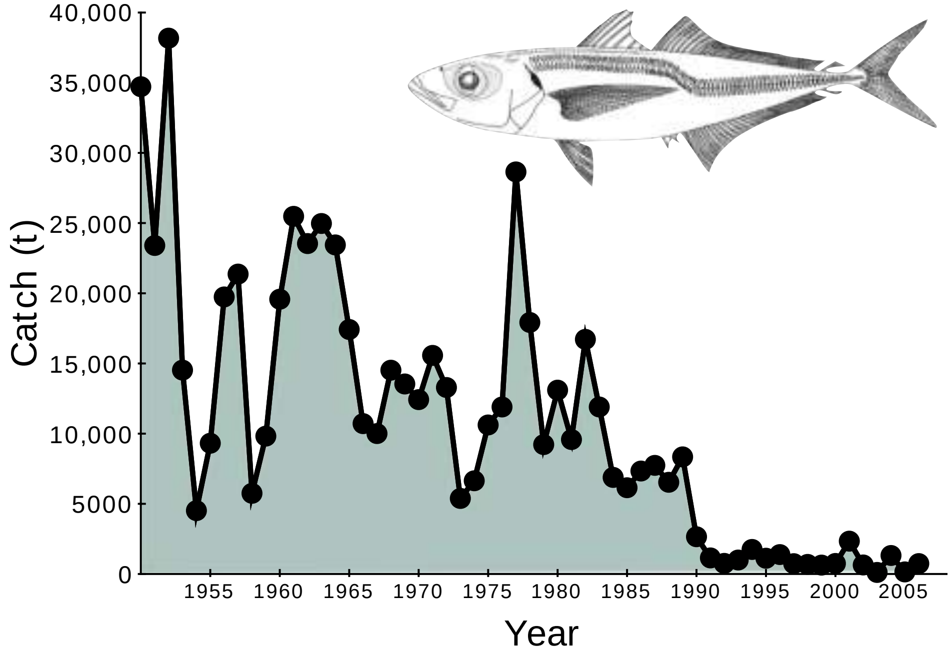


Figure 28. Catches (t) of Pacific jack mackerel in the California Current LME (Sea Around Us project).

<u>Pacific jack mackerel (*Trachurus symmetricus*)</u>

Jack mackerel occur from Mexico to southern Alaska, and is found up to 1000 km offshore. It is typically up to 55 cm long, but can obtain a maximum length of up to 81 cm (Froese and Pauly 2010). The diet is dominated by zooplankton.

Jack mackerel does not seem to be subject to assessments, the latest possibly being from 1983 and indicating a total biomass of up toward 2 million tonnes (Crone et al. 2009). Catches have shown a steady decline over the last half-century, and there is no indication available that the species should be building up.

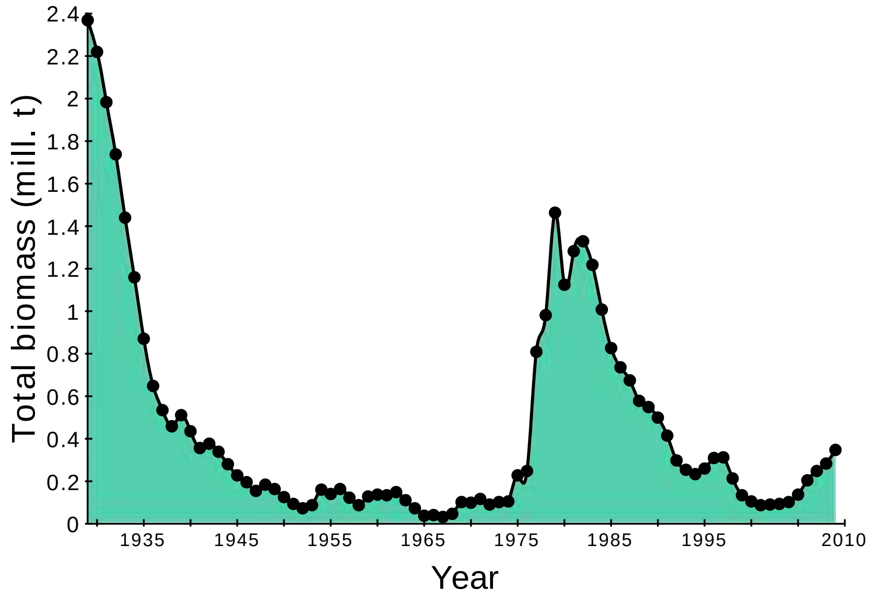


Figure 29. Biomass estimates for Pacific mackerel based on PFMC assessment (Crone et al. 2009).

Pacific mackerel (*Scomber japonicus*)

Pacific mackerel is a common pelagic species in the North Pacific ranging from Mexico to Alaska, with highest abundance south of Point Concepcion, California. The species is planktivorous and favored for fisheries compared to jack mackerel. However, Pacific mackerel collapsed after gaining attention with the collapse of the sardine fishery. The species recovered quickly in the late 1970s, and has since seen a gradual decline from a biomass high of 1.5 million tonnes. A Pacific mackerel stock assessment is conducted annually by the Pacific Fishery Management Council (PFMC), Portland, Oregon, the most recent published in 2009 (Crone et al. 2009).

Overall, there is nothing to indicate that Pacific mackerel should be a major competitor or predator on Fraser River sockeye salmon. The relevant question rather seems to be what the predators that once fed on mackerel eat now?

Table 4. List of bird species with potential predation impact on Fraser River sockeye salmon in saltwater. Some less-common, potential predators are excluded. The shading indicates status of knowledge: from nothing (light) to reliable (dark).

Common name	*Scientific name*	Abundance estimates	Trend estimates	Monitoring
Pelagic cormorant	*Phalacrororax pelagicus*			
Brandt's cormorant	*Phalacrororax penicillatus*			
Common merganser	*Mergus merganser*			
Gulls	*Larus spp.*			
Terns	*Sterna spp.*			
Common murre	*Uria aalge*			

Birds

Many juvenile fishes, including salmonids occur or spend some time in shallow coastal areas, e.g., in estuaries. This is a sensible behavior to minimize predation by larger fish that avoid the warmer coastal waters because of the associated constraints of available oxygen (Pauly 2010). Birds, however, are not constrained by the concentration of oxygen in water and have a definite advantage to catch prey in shallow water. It may well be therefore that bird predation is a major cause of mortality for salmon smolts in coastal areas.

Common tern (*Sterna hirundo*) and Arctic tern (*Sterna paradisaea*)

Terns are migratory, with Arctic tern well known for its migration between the Arctic and Antarctic. They are also highly piscivorous, and may potentially have an impact on Fraser River Sockeye during the early period when smolts are at sea. Unfortunately, there does not seem to be any measures of their abundance or abundance trends in the areas where terns overlap with Fraser Rivers Sockeye because the timing of migration does not overlap with the B.C. Christmas Bird Counts. Arctic terns predominantly migrate far offshore so they are not likely to be a major predator on Fraser River sockeye.

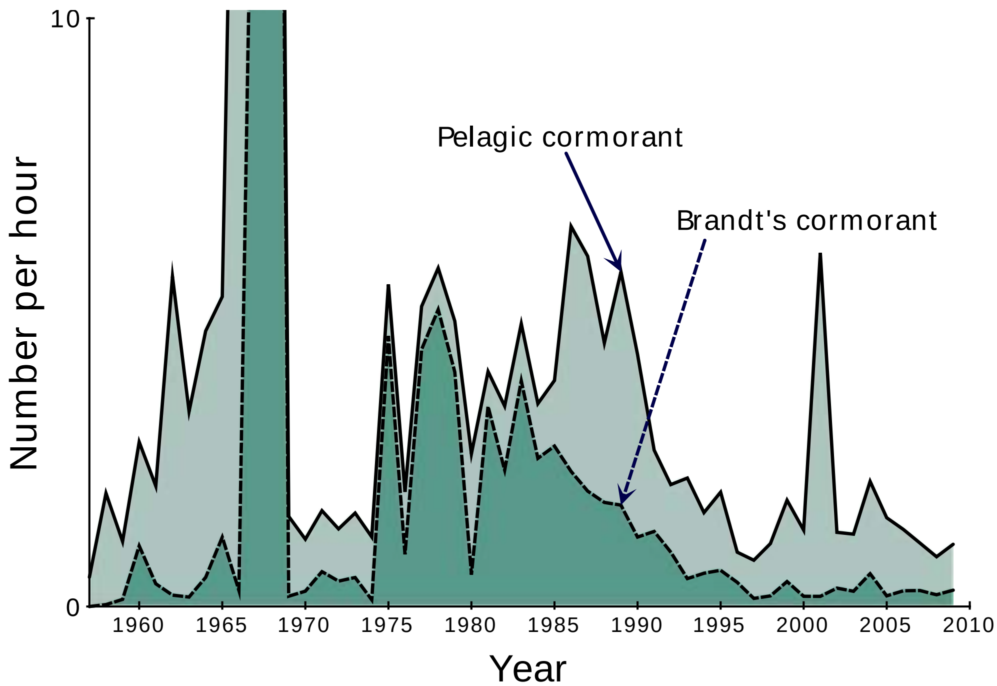


Figure 30. Cumulative numbers indicating trend of Brandt's and pelagic cormorants during the Christmas Bird Counts in British Columbia, 1957/1958-2009/2010.

Pelagic cormorant (*Phalacrororax pelagicus*) and Brandt's cormorant (*P. penicillatus*)

Cormorants are primarily piscivores, and pelagic cormorant and Brandt's cormorant are the two dominant species in the marine waters of British Columbia. They are only found in coastal waters, as they need to dry their feathers (and warm up) between dives. Brandt's cormorant tends to migrate north after breeding, and individuals from California overwinter in B.C. and Washington (Baron and Acorn 1997).

Based on complete surveys for the Strait of Georgia in 1987 and 2000, Chatwin et al. (2001) found that the numbers of nests of pelagic and double-crested cormorants decreased by 54% and 70%, possibly due to disturbance by bald eagles, changes in prey availability, and increased human disturbance at nest sites. This apparent decline in marine cormorants in BC as indicated by the winter counts, suggests that cormorants are unlikely to be a significant factor in the decline of Fraser River sockeye survival over the last decades.

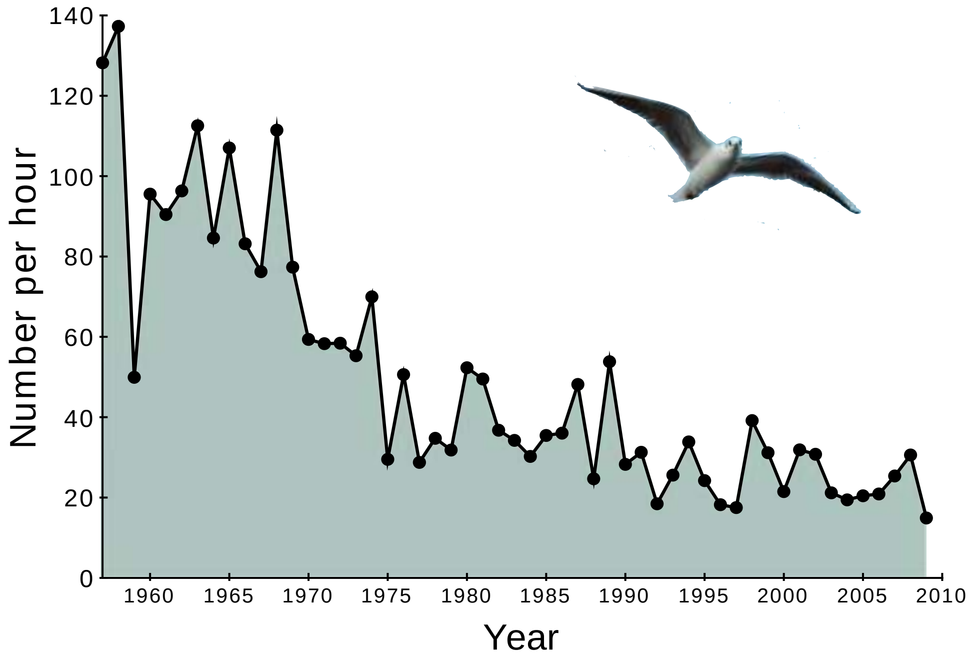


Figure 31. Abundance of gulls in B.C. based on the Christmas Bird Counts from 1957/1958 – 2009/2010. The majority of the gulls are Glaucous-winged gull (72%) followed by Mew gull (18%).

Gulls (*Larus spp.*)

A variety of gull species with diverse habits and diets occurs in British Columbia. The Glaucous-winged gull is the most common (78% of counts), and is coastal and omnivorous with fish being a common part of its diet. As such it is a potential predator on Fraser River sockeye, as indicated by the study of Beamish and Neville (2001), which indicated that gulls in the Strait of Georgia would consume 3 tonnes of juvenile sockeye and pink salmon annually if their diet included 0.1% of these prey. The abundance of gulls has, however, shown a strong decline over the last fifty years (Figure 31), and it is unlikely that they constitute a significant factor to the declining trend in survival of Fraser River sockeye over the last decades.

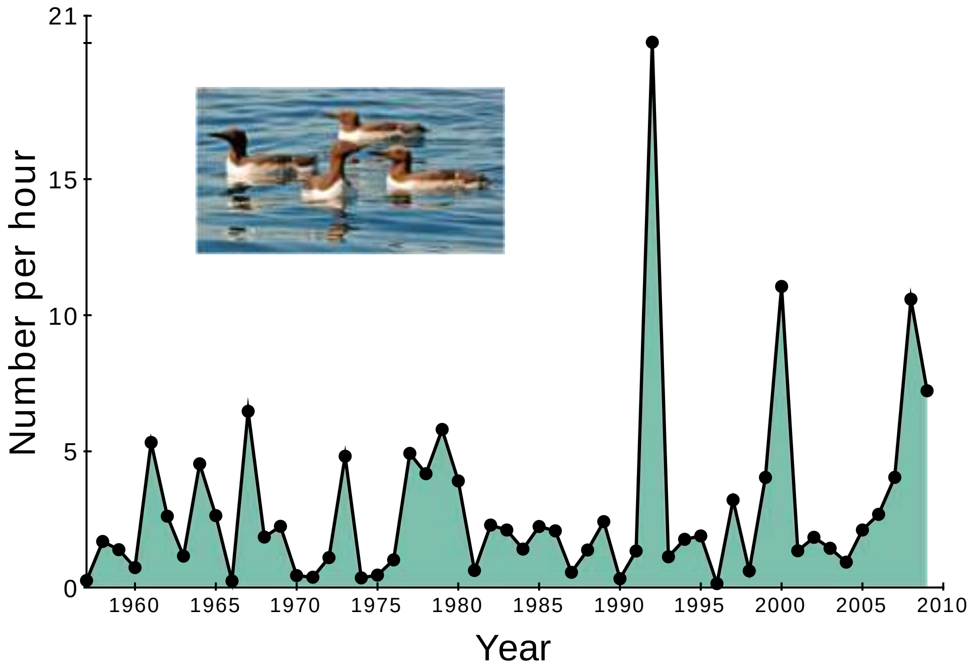


Figure 32. Abundance trend of common murres in British Columbia from Christmas Bird Counts, 1957/1958 – 2009/2010. Photo: T. Müller

Common murre (*Uria aalge*)

Common murres are true seabirds that only come ashore to breed during summer. The Strait of Georgia has major concentrations of these birds in late summer and fall (Baron and Acorn 1997).

Brodeur et al. (2003) noted that common murre aggregate and actively feed on smolts during release periods of hatcheries, and that salmonids can be an important part of the diet of common murres collected in coastal waters off-shore of several estuaries along the Oregon Coast.

Based on the Christmas Bird Counts the common murre contributes the vast majority of the numbers of alcids in British Columbia. The trends from the counts do not indicate any increasing trend over time, indicating that common murre may not be an important factor for the decline in survival of Fraser River sockeye salmon.

Marine Mammals

Harbour seal (*Phoca vitulina richardsi*)

Harbour seals occur primarily in coastal and estuarine habitats throughout British Columbia. They are considered non-migratory, but have been known to travel 300-500 km to find food or breeding sites. Harbour seals haul out on the mainland as well as offshore islands, sandbars, rocky shores, and beaches. Individuals show strong preferences for particular haulout sites (Pitcher and Calkins 1979; Pitcher and McAllister 1981), and show some seasonal movements towards estuaries when migrating adult salmon return to spawn (Bigg *et al.* 1990). Harbour seals tend to haul out near locations were prey are available (Montgomery *et al.* 2007) and may use tidal patterns to increase their foraging success (Zamon 2001). Increasing numbers of seals through the 1980s and 1990s have been associated with declines in the catchability of sockeye salmon in test fisheries (Forrest *et al.* 2009), and may be indicative of high rates of mortality of returning sockeye salmon.

The population of harbour seals in British Columbia was hunted (late 1800s) and then heavily culled (1913 to 1969) until protected in 1970 under the Fisheries Act. The population rebounded under protection at an annual rate of ~12.5% from 1973-1988 (Olesiuk *et al.* 1990a) and stabilized at a level believed to be on par with numbers in the late 1800s (Figure 31) (Olesiuk 2008a). In terms of numbers, harbour seals increased in British Columbia from ~9,000 in the early 1970s to ~108,000 today, with ~40,000 of this total occurring in the Strait of Georgia (Olesiuk 2008a). Harbour seals also increased in Washington State (NOAA 1998).

Knowledge about what harbour seals eat in British Columbia is limited. There are few records of stomach samples from the late 1950s and early 1960s (Fisher 1952; Spalding 1964). Diet was not considered important until the 1980s, when it was no longer considered appropriate to shoot animals to determine the last meal they had eaten. The system initiated in the 1980s and continued today to determine diet involves identifying hard parts of prey species recovered from fecal samples (scats) collected from seal resting sites (Pitcher 1980; Olesiuk *et al.* 1990b). Unfortunately, salmon bones have been particularly problematic to identify by species. Only recently have DNA techniques been developed to determine prey species contained within the scats of seals and sea lions, but it has not yet been applied to harbour seals in British Columbia (Purcell *et al.* 2004; Deagle *et al.* 2005; Tollit *et al.* 2009; Bowles *et al.* 2011).

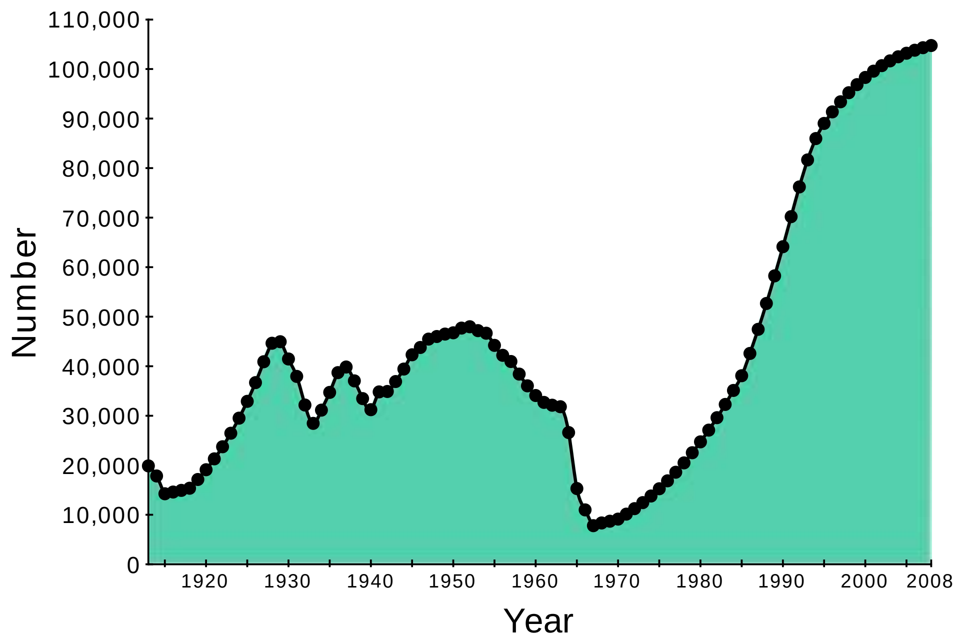


Figure 33. Estimated number of harbour seals in British Columbia (Olesiuk 2008a).

There are no data documenting what harbour seals have been eating for the past two decades in British Columbia. What information is available comes from ~3,000 fecal samples collected from 58 sites in the Strait of Georgia from 1982-1988. At that time, harbour seals were primarily eating Pacific hake (42.6%) and herring (32.4% of the overall diet, Olesiuk *et al.* 1990b). Hake were the primary prey consumed from April to November after spawning and moving to shallower water; while herring had the greatest prevalence in scat samples from December to March, coinciding with their annual emigration into the Strait of Georgia. Salmonids were a seasonal component of harbour seal diets and comprised only 4.0% of the overall diet (Olesiuk *et al.* 1990b). They were consumed in all months, but were most prevalent in estuaries from September to January.

Only 1.4% of the salmonids recovered from the scats of harbour seals collected during the 1980s could be keyed to species level (typically chinook), which prevents determining the proportion of sockeye eaten by harbour seals. However, it was noted that predation rates tended to be lower in estuaries supporting large sockeye and pink salmon runs (i.e., fewer seals congregated relative to the size of salmon runs in estuaries such as the Fraser River). In contrast seal numbers were highest in estuaries with large chum and coho runs (Olesiuk *et al.* 1990b). Overall, Olesiuk et al. (1990b) found the majority of samples containing salmonid remains were from estuaries where 5–17% of the harbour seals in British Columbia occurred. Some seals have been observed foraging in the

Fraser River well upriver of Yale, but it is not known what species they were targeting (Larkin 1992).

Mean daily per capita food requirements of harbour seals have been estimated to be 1.9 kg, or 4.3% of mean body mass (Olesiuk 1993). Assuming that seals ate all species of salmon equally, they would have consumed 2.8% of the mean escapement for the entire Strait of Georgia during the 1980s (Olesiuk *et al.* 1990b). However, there is no evidence that harbour seals have a preference for sockeye salmon (possibly preferring chum and coho salmon instead). Curiously, harbour seals in Alaska appear to haul out in greater numbers at sites that are further away from sockeye salmon streams compared to other runs of salmon (Montgomery *et al.* 2007). Numbers of seals have been relatively stable in British Columbia for the past decade and showed no changes that might indicate a disproportionate level of predation on the Fraser River sockeye salmon run over the past decade.

Steller sea lion (*Eumetopias jubatus*)

Sockeye salmon have a similar distribution to Steller sea lions in the North Pacific, and are hypothesized to have been isolated in Pleistocene glacial refugia in Beringia and the Pacific Northwest (see Baker *et al.* 2005). Allozyme and mtDNA data support the contention that the southernmost sockeye populations descended from the Pacific Northwest refugium, and the northern populations from the Beringian refugium (Bickham *et al.* 1995). Refugia may also explain the two genetically distinct populations of Steller sea lions in the North Pacific (Bickham *et al.* 1998), and might also have set the groundwork for Steller sea lions to be a significant predator of sockeye salmon.

There are two genetically distinct populations of Steller sea lions in the North Pacific (NMFS 2008). The western population from Japan to Prince William Sound, Alaska has declined by over 80% since the late 1970s and is listed as an endangered species in the United States. In contrast, the eastern population has increased dramatically over this same time period (Trites and Larkin 1996). In British Columbia, Steller sea lions were culled and the population declined into the 1960s (Figure 35). The population stabilized at about 10,000 once protected under the Fisheries Act (1971), but showed no signs of recovery until the mid 1980s. Since then it has grown by ~4% per year and numbers ~30,000 individuals (Olesiuk 2007; NMFS 2008; Olesiuk 2009).

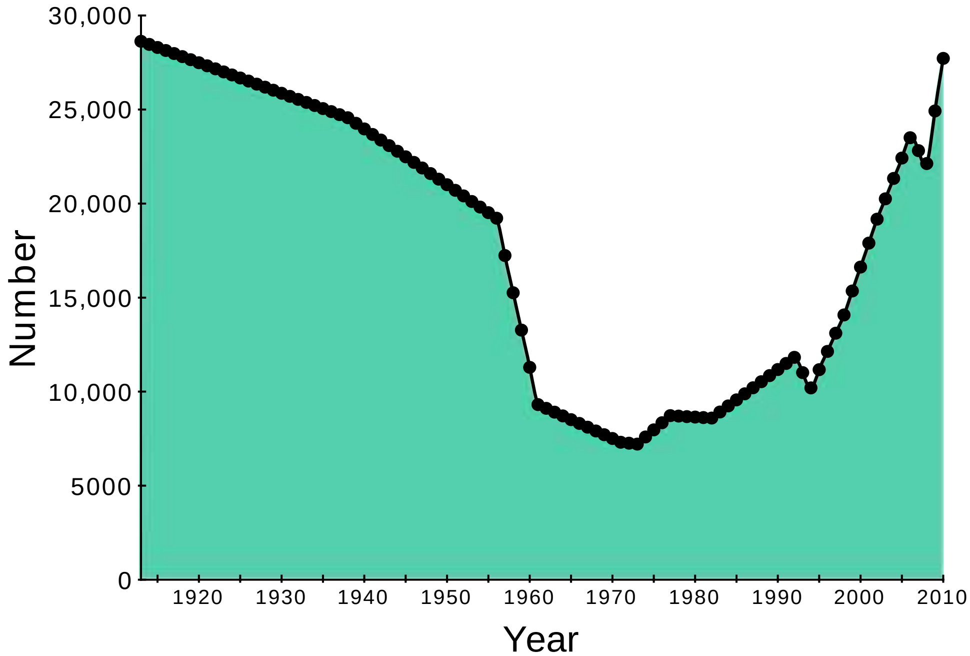


Figure 34. Estimated number of Steller sea lions in British Columbia (Olesiuk 2009).

Diets of Steller sea lions have been monitored intensively during summer in British Columbia and Southeast Alaska since the 1990s (Trites and Olesiuk, unpubl. data; Trites *et al.* 2007). Summer Steller diets in British Columbia have consisted of forage fishes (30% - mostly herring, sand lance and pilchard), gadids (18% - mostly hake), salmon (17%), rockfish (15%), flatfish (11%) and other species (9%) (Trites and Olesiuk, unpublished data). Seasonal samples collected in Southeast Alaska show that salmon were more often present in scats collected in the summer than during winter, as was true for demersal prey types (Trites *et al.* 2007). Winter samples contained greater proportions of gadids and cephalopods, while summer samples had greater numbers of salmon and small schooling species than winter samples.

It has only recently become possible to identify the recovered salmon bones by species using DNA techniques (Purcell *et al.* 2004; Deagle *et al.* 2005). It is also now possible to use DNA methodologies to identify prey species from the soft matrix of scats as well as determine the proportion of different prey species contained within each scat (Bowles *et al.* 2011). Tollit et al. (2009) identified species of salmon using DNA methods applied to 142 scats of Steller sea lions collected in the eastern Aleutian Islands (May 2005) and in Southeast Alaska and British Columbia (July 1997-2002). Of 150 salmonids identified to species, only 14 (9%) were sockeye salmon—the least frequently occurring species. The remaining salmonids consumed by Steller sea lions consisted of pink (36%), chum (30%), chinook (14%) and coho (11%).

Although sockeye salmon would appear to be the least favorite salmonid prey of Steller sea lions, they could still exert some impact on returning numbers of fish given their large body sizes and relatively high food requirements. Bioenergetic models estimate that male Steller sea lions (weighing 400-600 kg) consume about 30-35 kg per day (total of all prey species – including salmon) and that female Steller sea lions (weighing 200-300 kg) consume about 15-20 kg per day (Winship *et al*. 2002; Winship and Trites 2003).

California sea lion (*Zalophus californianus*)

The California sea lion occurs from southern Mexico to southern British Columbia. They breed in California and Mexico, and disperse along the coastline in the nonbreeding season to as far north as British Columbia. However, only the male California sea lions have a body size large enough to withstand the colder northern waters. Males typically arrive in British Columbia and will stay until May. They tend to haul out and feed along the outer coast of Vancouver Island and are most prevalent in the Strait of Georgia between January and May.

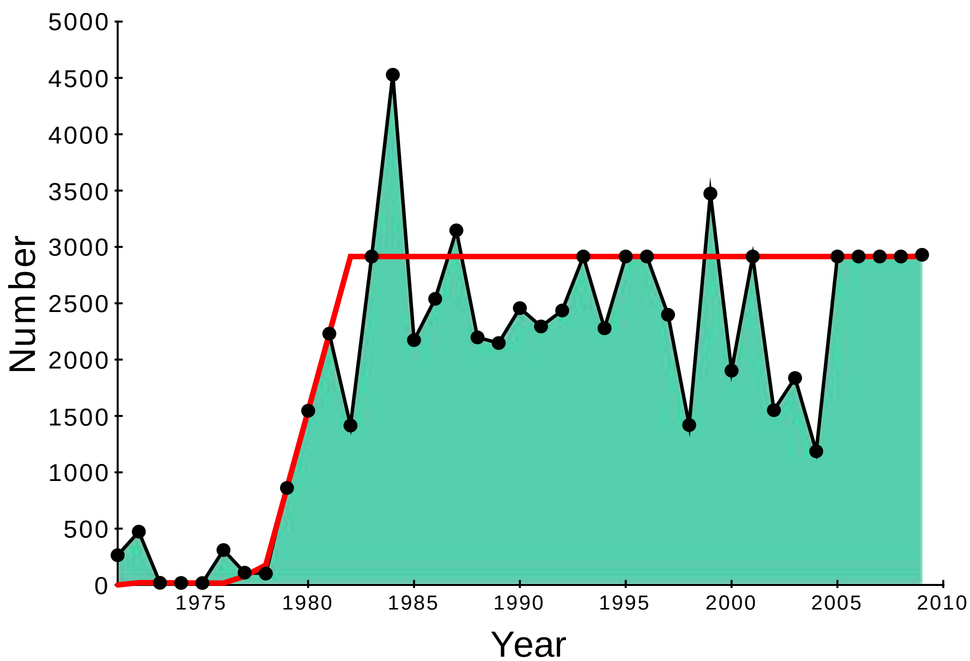


Figure 35. Estimated number of California sea lions in British Columbia.

The North America population of California sea lions numbers about 240,000 (Carretta *et al.* 2009), but only a small portion of this total migrates to British Columbia. The population has increased about 5 fold since the mid 1970s following protection from culling. In British Columbia, the few hundred males that were occasionally seen during the 1970s rose quickly through the 1980s with a peak count of 4,500 animals in 1984. Since that time, the BC population has stabilized at about 3,000 animals (Figure 36). Most of this population occurs at the southern end of Vancouver Island.

There are no diet data for California sea lions in British Columbia, although California sea lions have been observed hunting and eating salmon in Cowichan Bay (Bigg *et al.* 1990). Predation by California sea lions has been intensively studied on the Columbia River (Oregon) where males have been effectively feeding at the base of dams that restrict the movement of fish. Scars and wounds on sockeye salmon caused by seals and sea lions increased at the Bonneville Dam (Columbia River, 235 km from the ocean) from 3% in 1991 to 26% in 1996 (Fryer 1998). However, fewer than 3% of the fish were judged to have abrasions severe enough to adversely affect survival till spawning (Fryer 1998). Intercanine distances of seals and sea lions were compared with the spacing of scar marks on the bodies of chinook salmon. Based on the marking patterns, it appears that 10% were attributable to California sea lions and the remaining 90% were caused by harbour seals (Fryer 1998).

Northern fur seal (*Callorhinus ursinus*)

The northern fur seal is the most abundant and widely distributed pinniped in the North Pacific Ocean. It breeds in Alaska and in California and spends a large portion of the year at sea along the coast of North America and in the open North Pacific. The total population is believed to have dropped from about 2.5 million in the mid 1950s to under 500,000 in recent years (COSEWIC 2006). They are primarily found in BC waters from February to July (Trites and Bigg 1996; Olesiuk 2008b).

No research has determined the recent diets of northern fur seals in British Columbia or elsewhere in their range where they would overlap with Fraser River sockeye salmon. However, some insights can be gained from previous studies. For example, in 1935 a 2-year old sockeye salmon was recovered from a fur seal stomach on June 3, about 25 miles southwest of Flores Island near Barkley Sound (Clemens *et al.* 1936). This stomach also contained herring, flounder and a hexagrammid. A more extensive at-sea sampling program collected 10,743 fur seals along the west coast of North America from 1958-1974. Sockeye salmon occurred in the stomachs of northern fur seals off the coast of Washington and western Alaska, and in the Bering Sea (Kajimura 1984). But no sockeye were reported in any of the stomachs of fur seals caught in British Columbia, and sockeye was a rare prey species in the other regions (Kajimura 1984). Overall, salmon is part of a diverse fur seal diet (>70 species were identified), and contributed to 15% of the fur seal diet in Oregon and Washington, 16% in British Columbia, and 6% in Southeast Alaska. In British Columbia, the salmonids consumed were apportioned between pink (48%), coho (24%), chinook (14%), chum (10%), steelhead (5%) and sockeye salmon (0%).

Killer whale – resident form (*Orcinus orca*)

There are three forms of killer whales in British Columbia. One of them—the "resident" ecotype of killer whales—feeds predominately on salmonids (Ford *et al.* 1998; Ford and Ellis 2006). The "offshore" ecotype is believed to feed on sharks and large teleost fish such as tuna—while the "transient" ecotype feeds exclusively on marine mammals and seabirds (Ford *et al.* 1998; Saulitis *et al.* 2000; Krahn *et al.* 2007; Ford *et al.* 2011). The "resident" killer whale population has been subdivided into northern and southern groups based on geographic range, genetics, and similarities of underwater communication calls. In 2006 there were 329 resident killer whales in British Columbia (85 southern residents and 244 northern residents; COSEWIC 2008).

Nichol and Shackleton (1996) found a correlation between the movement of northern resident killer whales and the seasonal availability of salmon. They found that numbers of whales coincided with local runs of sockeye and chinook salmon. They also found correlations with killer whale presence and the abundance of pink and chum salmon.

Observations of feeding killer whales confirm that salmonids are the predominant food of resident killer whales in British Columbia (Ford *et al.* 1998). However, identifying the species of salmon consumed from scales and tissue fragments collected from kill sites reveals selective foraging. Unexpectedly, the sockeye, pink and chum salmon that correlated with the occurrence of killer whales form the minority of prey samples. Instead, the northern resident killer whales forage selectively for chinook salmon, probably because of the large size, high lipid content, and year-round availability of chinook (Ford *et al.* 1998; Ford and Ellis 2006; Ford *et al.* 2010b). Chum salmon were the second most frequently salmonid consumed, but smaller sockeye and pink were not significant prey despite their far greater seasonal abundance (Ford and Ellis 2006).

Hanson et al. (2010) recovered partial remains from 309 prey species taken by southern resident killer whales from Juan de Fuca Strait and the San Juan Islands. Of the 309 kills, only 4 were sockeye salmon (one taken in July and three in August). Most of the diet

(82%) consisted of chinook salmon. Pink salmon were noticeably absent, and sockeye was rarely eaten (Hanson *et al.* 2010).

The southern and northern resident killer whales in British Columbia are highly specialized and dependent upon chinook salmon (Ford *et al.* 2010b). Population trends and survival rates of these killer whale populations have been correlated with the availability of chinook salmon (Ford *et al.* 2010a). However, chinook salmon appear to be less frequently eaten by resident-type killer whales in Alaska (Worthy 2008). Sockeye salmon has been estimated to form 12.5% of the overall killer whale diet in the central Aleutians, 6.4% in the eastern Aleutians, and 10% in Gulf of Alaska (estimated using IsSource analysis, see Worthy 2008).

Dall's porpoise (*Phocoenoides dalli*)

Dall's porpoise are common across the entire North Pacific Ocean. They occur from Alaska to Baja, California on the west coast of North America and are among the most energetic and common small cetaceans. Dall's porpoise have been sighted throughout the coastal and deep oceanic waters of British Columbia in groups of two's and three's, to several hundred animals. Little is known about the biology and status of Dall's porpoise in British Columbia.

Stomachs of porpoise caught in high seas salmon and squid drift net fisheries (1984-1989) revealed that the porpoise fed mainly on myctophid fishes in the subarctic North Pacific and on gonatid squids as well as myctophid fishes in the Bering Sea (Ohizumi *et al.* 2003). Mizue et al. (1966) reported only one occurrence of sockeye salmon, from the stomachs of148 Dall's porpoise taken in conjunction with the high-seas salmon gill net fishery (from Stroud *et al.* 1981). Stomach contents of Dall's porpoise taken in the southern Sea of Okhotsk contained pilchard, gonatid squid and walleye pollock, but no salmon (Walker 1996). No information is available on the diet or numbers of Dall's porpoise in British Columbia, but the expectation is that they probably eat squids and species of prey pursued by salmon (Leatherwood and Reeves 1983; Turnock *et al.* 1995).

Pacific white-sided dolphin (*Lagenorhynchus obliquidens*)

The Pacific white-sided dolphin is believed to be the most abundant cetacean in the coastal waters of British Columbia (Heise 1997b). But it is only in recent years that they have been regularly sighted in the inside waters. Morton (2000) noted that white-sided dolphins were unreported in the Broughton's prior to 1984, but were known to have been historically present from the dolphin remains found in First Nations middens. She also reported a seasonal peak in the presence of dolphins in the Broughton Archipelago from October through January based on observations made from 1984 to 1998. A small population of dolphins numbering about 100 individuals took up year-round residency in the Strait of Georgia over the past 10 years, but nothing is yet known about their movements or diets.

The little information that is available about dolphin diets in British Columbia comes from the stomach contents of a few dead animals and from floating scraps and fragments of prey recovered during feeding events. In the Broughton Archipelago, prey species collected from 25 encounters with feeding dolphins indicated they ate herring, capelin and Pacific sardines (Morton 2000). None were reported eating salmon. Along the east coast of the Queen Charlotte Islands, the central mainland coast and Queen Charlotte Strait/Johnstone Strait, prey fragments and scales collected near actively foraging animals from 92 encounters with dolphins in 1994 and 1995 showed herring was the most commonly occurring prey species (59%), followed by salmon (30%), cod (6%), shrimp (3%) and capelin (1%) (Heise 1997a). The size of prey ranged from 15 to 60 cm. Of the 19 salmon pieces recovered, one could not be identified, one was a coho (age 1 y), four were sockeye (ages 1 to 4 y), and 13 were pink salmon (ages 0 and 1 y) (Heise 1997a). Prey species determined from fragment sampling were similar to those obtained from the stomach contents of 11 dolphins that stranded on the coast of British Columbia during the 1990s (Heise 1997a). Further south in Washington and California, no sockeye salmon have been reported in the diets of Pacific white-sided dolphins (Kajimura *et al.* 1980; Stroud *et al.* 1981; Black 1994).

The available data suggest that Pacific white-sided dolphins in British Columbia are opportunistic predators that feed on at least 13 different prey species. Salmon appear to be an important diet component of their diet from June through November, and may contribute 30-60% of their diet during this period (Heise 1997a). The majority of salmon consumed have been small (< 25 cm) though larger fish (> 50 cm) were occasionally taken. Herring was the most important year-round prey for these animals in British Columbia occurring in 59% of samples followed by salmon (30%), cod (6%), shrimp (3%), and capelin (1%) (Heise 1997a).

Pacific harbour porpoise (*Phocoena phocoena*)

Harbour porpoise occur in the eastern Pacific Ocean from the Bering Strait, Alaska, to central California. They are often seen in bays, estuaries, and occasionally freshwater rivers (Leatherwood and Reeves 1983; Hall 2004). Harbour porpoise occur year-round in

BC coastal waters (Baird and Guenther 1995), but little is known about their biology, numbers and population trends.

Little information is available on the diet of Pacific harbour porpoise. Stomach contents of incidentally caught animals in the Makah set-net fishery in Washington State from May to September, 1988-1990, contained primarily Pacific herring, followed by smelt, and squid (Gearin *et al.* 1994). Prey length varied from 6–18 cm depending upon species consumed. Of 15 stomachs of dead stranded porpoise recovered in British Columbia, only 5 contained single prey species consisting of sand lance, Pacific hake and Pacific herring (Hall 2004). There are reports of gadids (tomcod) being identified in their diet in other parts of the harbour porpoise range (Hall 2004), but no reports of them eating salmon.

Humpback whales (*Megaptera novaeangliae*)

Humpback whales are a migratory species that feed in high latitude areas from spring to fall—and winter in warmer tropical waters where calves are born and mating occurs (COSEWIC 2003; Clapham 2009). Humpback whales were hunted to near extinction in British Columbia (Gregr *et al.* 2000), and have increased significantly over the last few decades. The number of humpback whales in British Columbia during summer 2006 was estimated to be between 1,428-1,892 (Rambeau 2008).

Humpback whales filter feed tiny crustaceans, plankton and small fish (including herring, mackerel, capelin, and sand lance). They have recently been reported feeding on salmon fry and smolts released from salmon enhancement facilities at Baranof Island in Southeast Alaska (Chenoweth *et al.* 2010). Observers found a relationship between skiff activity near the fry and smolt release sites and the presence of whale—suggesting that the whales cued into increased skiff activity on release days to know when high concentrations of young salmon were available (Chenoweth *et al.* 2010). The whales used net pens, docks, the shoreline and bubbles to facilitate prey capture. The number of whales feeding at the release sites was one or two. Species of salmon raised on Baranof Island include pink, chum, coho and chinook salmon. These observations of humpback whales feeding on fry and smolt salmonids appear to be anomalous events related to human production and release of concentrated numbers of young salmon. No other reports have been made of humpback whales feeding on salmon, nor is the density of young salmon in BC likely to be high enough to support efficient predation by humpback whales.

Cumulative predation impact: no smoking gun, no butler

Hercule Poirot was once faced with a difficult case in the "Murder on the Orient Express". One night, a passenger sleeping alone in a cabin had been stabbed multiple times while the train was underway, and the murderer had to be onboard. M. Poirot interviewed everyone on the train, but there was no "usual suspect", no smoking gun and no butler. Rather, it seemed that all of the passengers (save M. Poirot) had a motive and an opportunity. That made for a difficult case indeed—who did it?

When facing a difficult case in science, the solution is often the same as on the Orient Express: all the suspects played a role and all are guilty. Individually, the tendency of scientists is to focus on a single suspect or cause—the one they know how to investigate. For the Fraser River sockeye, it may well be that the declining survival trend over the last decades was caused by a combination of effects, and not by any single one. If predation had been the smoking gun in the disappearance of Fraser River sockeye salmon, it should have been smelled by now. Another approach to resolving this open case may be to gather the bits and pieces, species by species, to evaluate how each may have contributed to the population trends of Fraser River sockeye salmon, similarly to what was done recently for the case of the missing Steller sea lions (Guénette et al. 2006).

Evaluating the cumulative predation impacts of Fraser River sockeye is hamstrung by the uncertainty in the raw data—not so much with regards to motive because everybody supposedly loves sockeye, but with regards to the opportunity to have committed the crime. Focusing attention on species that may have increased their predatory impact on sockeye salmon is a promising lead, but concluding a predator had the means and motivation to impact the sockeye population requires them to be found guilty on all charges—namely:

- There must be temporal and spatial overlap with Fraser River sockeye salmon.
- Sockeye (or at least salmon, if not specified) should be in the predator's diet.
- The predator should be abundant enough to have a significant predation impact.
- The abundance of the predator must have been increasing in recent decades, or there must be indications that the predator significantly increased their consumption of sockeye.

Table 5. Evidence level for potential predators that their diet includes sockeye salmon, that their abundance is high enough to have significant predation impact, that there is spatial and temporal overlap with Fraser River sockeye, and that there has been a positive trend in predator abundance over the last decades. The evidence levels scale from light (no evidence) to dark (strong evidence), and are not based on quantitative criteria. Predator habitats are denoted for freshwater (FW) and estuarine predators (ES), and marine predators (MA).

Habitat		Predator Species	Evidence for				
FW -ES	MA		Diet	Abun-dance	Overlap	De-crease	In-crease
		Northern pikeminnow					
		Rainbow trout/steelhead					
		Caspian tern					
		River lamprey					
		Coho salmon					
		Chinook salmon					
		Cormorants					
		Gulls					
		Bald eagle					
		Humboldt squid					
		Spiny dogfish					
		Salmon shark					
		Blue shark					
		Daggertooth					
		Sablefish					
		Arrowtooth flounder					
		Common murre					
		Harbour seal					
		Steller sea lion					
		California sea lion					
		Northern fur seal					
		Killer whale (residents)					
		Dall’s porpoise					
		White-sided dolphin					
		Harbour porpoise					
		Humpback whale					

Tabulating the list of prime suspects and the relative strength of the evidence against them on diets, numbers and population trends fails to reveal any obvious culprits (Table 5). Of the 26 listed suspects, only 6 are believed to consume significant amounts of sockeye. At the top of this short list is the salmon shark, followed in no particular order by blue sharks, daggertooth, sablefish, river lamprey and a seabird—the common murre. To date, none of the 9 species of marine mammals have been found to consume much if any sockeye salmon—with the possible exception of Pacific white-sided dolphins (for which the number of diet samples is extremely small).

In terms of overlap in time and space—sharks, seabirds and marine mammals have all had the opportunity to take Fraser River sockeye (Table 5). There is also overlap in the distribution of coho and chinook salmon with sockeye. But simple co-occurrence does not necessarily mean a crime occurred. Marine mammals, for example, appear to prey more on coho and chinook due perhaps to them being present for longer or being easier for marine mammals to catch than sockeye.

The survival rate of Fraser River sockeye has fluctuated significantly between years, but has declined overall from ~15% of the fish surviving in the early 1970s to a low of ~3% survival in the mid 2000s (Figure 4). The only predators that appear to have increased and consumed significant amounts of sockeye during this time were blue sharks and salmon sharks (Table 5). Of the other predators, harbour seals were the most visible predator that increased significantly from the 1970s to the 1990s, but their numbers have been stable for the past decade and there is no evidence that they consumed significant numbers of sockeye salmon (adults or smolts).

Table 6: Some estimates of predation mortality for sockeye salmon.

Life stage, habitat	**Predator**	**Mean loss (range)**	**Source**
Fry migrating to lakes	All	84% (67-97%)	Foerster (1968, cited in Fresh 1997)
Fry during May-Sep, lakes	Coho	59%	Ruggerone and Rogers (1992)
Fry, lakes,	Cutthroat	(82-93%)	Cartwright et al. (1998)
Smolt migrating to marine waters	All	63%	Rogers et al. (1972, cited in Fresh 1997)
Fraser River plume	River lamprey	2.5%	Beamish and Neville (1995)
Immature and maturing, open ocean	Salmon shark	(12.6-25.2%)	Nagasawa (1998)

Approximately 85-97% of sockeye smolt that leave the Fraser River die over a four-year period, with many of the missing salmon ultimately ending up in the stomachs of predators. Much of the mortality appears to occur early in life, but predation at later stages can also remove significant numbers of sockeye (Table 6). Unfortunately, assessing the cumulative effects of predation is not as simple as summing up all of the single-species assessments of predation removals. Non-linear interactions, competition among species, and consumption of other predators of sockeye salmon must all be taken into consideration using multispecies or ecosystem simulation models. Unfortunately the data are not available to construct such models and make reliable predictions at this time.

Sympathy for the predators?

Predators are not devils. They are important for the functioning of ecosystems, but their need to eat tends to be ignored by traditional fisheries management (unless they are marine mammals where it is easier to observe both the predators and the predation events). The usual assumption is that a predator will simply find an alternate prey if fisheries removes their target species. This then begs the question of whether the low ocean survival of Fraser River sockeye salmon might be because they became just such an “alternative prey”?

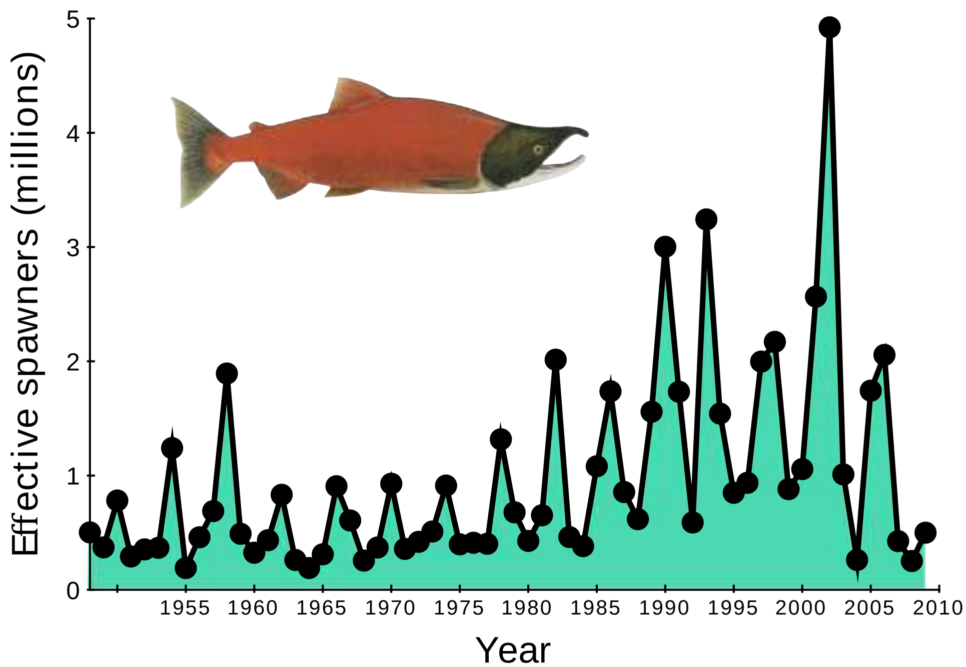


Figure 36. Number of effective spawners of Fraser River sockeye salmon. The number of spawners has increased in recent decades. Has this lead to more, but smaller smolts in poor feeding condition that will be more susceptible to predation?

Table 7. Evidence level for abundance trends in recent decades for potential, abundant competitors that Fraser River sockeye salmon may encounter. The evidence levels scale from light (evidence for weak trend) to dark (evidence for strong trend).

Area	Species	Abundance trend		
		Decrease	**No change**	**Increase**
Strait of Georgia	Herring, juvenile		[light]	[light]
	Pacific cod		[light]	
	Pacific hake	[medium]		
British Columbia	Herring, adult	[medium]		
	Pacific cod		[light]	
	Pacific hake	[medium]		
Northeast Pacific	Pacific jack mackerel	[dark]		
	Pacific mackerel	[dark]		
	Pacific sardine			[dark]
	Pacific herring			[medium]
Gulf of Alaska	Pacific cod	[medium]		
	Walleye pollock	[dark]		

Related to this is that the Fraser River sockeye may have become the unwitting victims of their own success. As shown in Figure 36, the numbers of effective spawners of Fraser River sockeye salmon have increased in recent decades, which in turn may have increased intraspecific competition and exposed smolts to higher rates of mortality. Previous studies have shown that increased sockeye fry abundance leads to lower average weight of smolts, and that the total biomass of a smolt year class may decrease with increasing number of spawners (Hume et al. 1996). The implication of this is that increased escapement may lead to higher predation mortality in the ocean where there is a strong positive correlation between size and survival (Lorenzen 1996).

An additional effect of increased production is that greater numbers of smolts may lead to predators focusing on such a food supply, especially if alternative prey species are decreasing. We evaluated this by examining abundant species that could be alternative prey for potential predators of Fraser River sockeye salmon, based on the assumption that a reduction in abundance of such alternative prey could lead to increased predation on sockeye even if the predator abundance was constant (Table 7).

Ecosystem food web modeling could be used to quantitatively evaluate the potential significance of an increase in predator biomass and a decline in alternative prey for the predators. Unfortunately, the available data (diets, abundance and trends) are insufficient at this time to construct such a model. In the meanwhile, models could be used to determine the resolution of diets needed and what abundance changes in predators are needed to explain the survival changes that Fraser River sockeye salmon have experienced over the past sixty years. While clearly feasible, time constraints prevented us from undertaking this task. The information needed for it is accessible through this report and from the Pacific Biological Station, notably as integrated in the modeling work of D. Preikshot (see Preikshot 2007b, and subsequent work at PBS).

Impact of hatchery programs

Kostow (2009) reviewed ecological risks associated with salmonid hatchery programs and found that hatchery fish may be linked to decreased wild fish survival. Of particular interest was the observation that decreased survival rates could be associated with increased predation by piscivorous fish, birds, and mammals. Release of hatchery fish often leads to high, localized concentrations of potential prey, which can attract predators. Given that wild fish often intermingle with hatchery fish, this could have in turn resulted in wild fish experiencing increased mortality due to the attraction of predators.

Large releases of hatchery fish may also impact ocean survival as demonstrated by Levin et al. (2001). Levin et al. found a significant impact on wild fish survival during years of poor ocean conditions, but did not find any effect during years of average conditions. They hypothesized that the effect was related to the marine environment, and related to increased competition, stress, and possibly predation.

There is some evidence of competition between hatchery and wild salmon, such as between pink and chum salmon (Fresh 1997), and pink salmon and other species (e.g., Hilborn and Eggers 2000). In comparison, less is known of potential predation impact of hatchery fish on wild salmon, with much of the information being circumstantial, but potentially important (Fresh 1997). An example is the study of Johnson (1973, cited by Fresh, 1997) which concluded that hatchery coho were responsible for the declines of a number of chum populations in Oregon and Washington states.

Discussion

Dominance cycles: role of predation?

The runs of several populations of sockeye salmon in the Fraser River system have in known history shown a four-year cycle with a dominant run, followed by a less abundant sub-dominant year class, and then two “off” years with very low abundance (Ricker 1950). Larkin (1971) described how this pattern can be derived in a model where predation is insufficient to influence the dominant year, but where this leads to a predator increase, which in turn has a strong impact on the following three years.

Considerable work has been done through the International Pacific Salmon Fisheries Commission (IPSFC) since the 1950s to identify the cause or causes of the dominance of one brood year over the others—but no clear answer is evident (Hume et al. 1996). Interestingly, IPSFC scientists in the 1950s believed that kokanee were responsible for the weak cycles because of competition for the same food, zooplankton, (Sebastian et al. 2003).

The incentives for building the “off” years is high (Walters and Staley 1987), but there is no indication that this is possible. It does indeed seem likely that there are inherent factors experienced by Fraser River sockeye salmon that induce the cyclic trends, which are not common elsewhere. Levy and Wood (1992), reviewed the alternative hypotheses for cyclic dominance in the Fraser River sockeye populations and concluded that only those that involve genetic effects on age at maturation, or on disease or parasite resistance, or involved depensatory predation soon after fry emergence, seem to have merit.

Without greater knowledge about freshwater and marine predators, it does not seem possible to add much to the discussion on what or who is behind the dominance cycles.

Availability of and need for diet studies

There are scores of potential predators on Fraser River sockeye salmon, and relatively few diet studies of potential predators. From experience, it is clear that specific information about who is causing predation mortality on a rare prey (such as sockeye may be once they leave the Fraser River and disperse in the ocean) is something one should not expect to find. Diet studies, which tend to involve stomach sampling and analysis, are typically restricted in time and space. They do well at determining what a species commonly eats, but are unlikely to be of much use for evaluating the effect of a predator on a species of prey that is rarely consumed.

As an example of the rare-prey phenomenon, Beamish and Neville (2001) estimated that spiny dogfish could annually consume 145 tonnes of sockeye smolts in the Strait of Georgia if sockeye salmon contributed a mere one-tenth of one percent of their diet (i.e., 0.1%). With an average ocean entry weight for sockeye smolt of 10 g (Table 16-3 in Quinn 2005), this corresponds to 14.5 million smolts and a highly significant level of predation. Given that 1) individual fish predators on a short time scale tend to specialize on a given prey, 2) only one type of prey is typically found in a given fish stomach, and 3) that a third or so of all predator stomachs are empty—more than one thousand dogfish would have to be sampled to find one that contains sockeye smolts. The dogfish would also have to be sampled when and where the sockeye smolts occurred. Overall, the odds are against finding rare prey in the stomachs of predators.

The conclusion of this simple calculation is not that diet studies are useless, but that caution needs to be exerted against having inflated expectations. Considerable lessons can be drawn from the tens to hundreds of thousands of stomachs that have been sampled in the areas where Fraser River sockeye salmon occur. Recent technology developments, such as identifying prey from DNA signatures opens the possibility to evaluate average diets integrated over time, instead of the single snapshot views that stomach sampling provides. Such methodologies may well enable predation rates of rare prey by common predators to be quantified, which is currently problematic.

Another problem with the diet studies is that they tend to be carried out as individual studies, and are not accessible through a central diet database for the Strait of Georgia. Nor is there a diet database for British Columbia or the North Pacific, unlike for the North Atlantic that began building their database in 1981 for the "Year of the Stomach" international study, coordinated by the International Council for Exploration of the Sea (ICES). The limited dietary data available for British Columbia comes from studies that are largely uncoordinated and are difficult and time consuming to access.

Toward ecosystem-based management

There has been a trend toward ecosystem-based management of fisheries over the last decades, as expressed through a large number of international agreements, most recently the Johannesburg and Reykjavik Declarations, and supported by the UN Food and Agricultural Organization through the Code of Conduct for Responsible Fisheries (FAO, 2003).

Canada has had a Fisheries Act since 1857 regulating fisheries, while the new Oceans Act, which passed in 1997 added a focus on the conservation of exploited species and their habitat, stating "conservation, based on an ecosystem approach, is of fundamental importance to maintaining biological diversity and productivity in the marine environment". The Oceans Strategy for Canada (DFO 2002) implementing the Oceans Acts introduced a nationally coordinated Integrated Management system for spatial management of marine ecosystems. The Ocean Strategy calls for "a commitment to planning and managing human activities in a comprehensive manner while considering all factors necessary for the conservation and sustainable use of marine resources and the shared use of ocean spaces". By and large, this corresponds to what elsewhere is called ecosystem-based management.

Related to the Ocean Strategy, Fisheries and Oceans Canada (DFO) launched a series of Ecosystem Research Initiatives (ERIs) in its five-year plan for 2008-2013 to introduce ecosystem-based management to its regions (http://www.dfo-mpo.gc.ca/science /publications/fiveyear-plan-quinquennal/index-eng.html#a3_2). The funding envelope for the ERI program is $2.3 million per year for the five priority large marine ecosystems distributed over the DFO Regions. This funding envelope severely limits the capacity of the ERIs to the point that the typical project being funded in the Pacific Region (where the ERI is focused on the Strait of Georgia) has a budget of $10,000-$20,000 per year (http://www.pac.dfo-mpo.gc.ca/science/oceans/detroit-Georgia-strait/projets-projects-eng.htm). This level of support is insufficient to ever meet the goals of Integrated Management.

Several years after establishing the Large Ocean Management Areas (LOMAs), the DFO website for "marine areas" (http://www.dfo-mpo.gc.ca/oceans/marineareas-zonesmarines /index-eng.htm) in November 2010 provided links to only two of the five LOMAs where Integrated Management is to be implemented. Integrated Management (IM) is indeed still in its initial stages. The Oceans Strategy of 2002 called for: 1) implementation of IM plans, 2) a national system of Marine Protected Areas (MPAs), and 3) Marine Environmental Quality (MEQ) guidelines, objectives and criteria. Progress for their moving forward is stalled as DFO continues to determine how to implement IM (PICES 2010).

While implementation of Integrated Management is wanting, there has been some progress on the scientific aspects of developing the required conservation objectives for integrated management. However, the corresponding socio-economic objectives have not yet been developed, at least not in Canada's Pacific Region (PICES 2010).

An important aspect of Integrated Management, or ecosystem-based management (EBM) as it is more commonly called, is the incorporation of ecosystem considerations in management. This is particularly relevant to salmon managers and their need to incorporate information on predator-prey relationships.

DFO's Wild Salmon Policy (DFO 2005) provides guidelines for management of Pacific salmon, including a Strategy 3 for "Ecosystem Values and Monitoring," which calls for integration of climate and ocean information into the annual salmon management processes. The Strategy calls for "maintaining species linkages" with focus on "minimizing fishing impacts on non-target, associated or dependent species, including predators and scavengers" and on "maintaining or restoring viable populations of associated or dependent species" (K. Hyatt, J. Irvine, J. Curtis and R. Lauzier, WSP Forum, March 27, 2008).

The Wild Salmon Policy (DFO 2005), however, only mentions predators once when stating that "salmon play an important role in marine ecosystems, with their bodies and waste products providing nutrients for organisms from microbes to top predators, such as killer whales". Concepts such as predation, prey, or food webs are not even mentioned.

The Pacific Salmon Commission (PSC) provides regulatory advice and recommendations to the Governments of USA and Canada on shared Pacific salmon stocks. There are no indications from the PSC website and publications (www.psc.org) that ecosystem-based management or food web considerations are factored into the advice they give.

Overall, Canada has not moved very far towards ecosystem-based management. This is clear from a recent comparison of US and Canadian management made by a PICES working group (PICES 2010). Of 21 components of integrated multi-sector ecosystem based management, Canada only scored on its policies for endangered species (SARA), while the US had made progress on 11 of the 21 components. Australia is possibly leading on implementation of ecosystem-based management, and has done so by initially "letting the policies move ahead of the science" (A.D.M. Smith, CSIRO, pers. comm.)

The focus of fisheries management on short-term tactical advice and setting annual quotas, while ignoring the longer-term strategic decisions that are fundamental for implementation of ecosystem based management, appears to be a global problem that has not capitalized on the progress made in developing the science needed to support ecosystem based management (Christensen and Walters 2011). Notably, ecosystem-based management calls for evaluating trade-offs, which may be severe, and which in turn have socio-economic consequences. Such trade-offs are seemingly ignored in the Wild Salmon Policy.

Would the implementation of ecosystem-based management have made a difference in understanding the effects of predators on sockeye salmon? Would an explicit ecosystem-based approach including predator-prey relationships make a difference for management of Fraser River sockeye? This is not just a question of whether the management incorporates consideration of the various players, be they in the ecosystem or relying on them, like humans. Rather, ecosystem-based management entails developing an understanding for how the environment, humans, and other ecosystem components impact ecosystems—which is exactly where the assessment of Fraser River sockeye salmon falls short. This should not be expected to be an easy process with shortcuts, and does not mean stopping the building of knowledge about individual species in ecosystems, notably through population dynamics. Ecosystem-based management involves conducting additional research to evaluate the questions that cannot be answered with traditional stock assessments—the kind of problems facing the Fraser River sockeye salmon.

Ecosystem manipulation: a scary concept

The discussion of whether fish predation can be a limiting factor for production of sockeye salmon was first raised by Foerster and Ricker in 1925 (Foerster and Ricker 1938; cited in Bradford *et al.* 2007). In the subsequent 15 years, they undertook two large-scale experiments to test their hypothesis, and found that the freshwater survival of juvenile sockeye could be increased through control of northern pikeminnow (Foerster and Ricker 1938, 1941). Similar results have been obtained from the Columbia River (Rieman and Beamesderfer 1990).

In general, the efficacy of a predator control program may depend on how important the given predator is for the target species, and whether it is possible to impact the size of the predator population, and whether there is public, institutional and legal acceptance of the control program (Beamesderfer 2000). Ecosystem manipulation is a scary concept, though one that once was applied rather freely in both freshwater and marine environments. Rotenone treatment, for example, is still being practiced, (e.g., to control exotic species such as yellow perch in Fraser River lakes), as is pikeminnow control. There was also the introduction in the 1960s of mysids to hundreds of lakes in North America, which has become a classic due to the unforeseen consequences. We have learned from such experiments to be cautious with ecosystem manipulations.

Manipulations in marine environments tend to be through commercial fisheries, which change the conditions for predators and prey, and have likely consequences that are rarely considered.

Attempts to control predatory species do not always have the intended outcome (Trites 2009). For example, harbour seals were culled in the 1960s in Alaska's Copper River delta to reduce the predation on salmon. However, the immediate result of the cull was not an increased number of salmon caught, but a decrease and failure of the razor clam (*Siliqua patula*) fishery. It turned out that the seals were primarily eating starry flounder (*Platichthys stellatus*), which fed on the razor clams. Without the seals, the predatory flounder population grew unchecked. Similarly, it has been postulated that harbour seals in British Columbia might have a net positive effect on the return of adult salmon by consuming species of fish that prey heavily on salmon smolts (Trites 1997). Similarly, Scheffer and Sperry (1931) proposed that pinnipeds produce a beneficial effect to salmon by consuming salmon predators and their parasites (lamprey). The biggest consumers of fish are other predatory fish and not marine mammals, but predation by fish is more difficult to quantify and observe (Trites *et al.* 1997).

The first step to moving beyond *ad hoc* experimentation with ecosystem manipulation is through analyzing the effects at the ecosystem level, be it through conceptual or quantified ecosystem modeling. It must further be recognized that there are limits to current empirical knowledge and modeling capabilities. Thus, experimental protocols need to be carefully developed as part of adaptive management schemes (Walters 1986).

State of the science

When fisheries science came of age in the early 20th Century there was considerable focus on understanding fish biology, with stomachs serving as a common currency of study. Diet studies have continued throughout the world to provide good knowledge about the major food types consumed by all major species in the sea. Unfortunately, much less is known about the minor food types and the sources and effects of predation on the less abundant and rarer prey, such as sockeye salmon might be once they are in the ocean. A dietary contribution of 0.01% or 0.10% sockeye salmon likely matters little for an abundant predator, but could make the difference between high or low survival of the sockeye salmon. Evaluating such differences in predation rates requires a sampling regime that integrates time and space—something that stomach sampling does poorly. Newer and better methodologies are increasingly being applied to do this.

Evaluating the importance of predators requires knowing the impact the predators may have, and even more importantly how this may have changed over time. Estimates of predator abundance are therefore needed, as well as information about their population dynamics (age structure, reproduction, and survival). While the methodologies for obtaining this information are well established, the data are poor for the areas of concern for Fraser River sockeye salmon. It is only for the fish species of considerable recreational or commercial interest that there is any information worth mentioning, and this has generally been collected with little consideration of ecosystem effects.

Estimating predation impact also requires knowing the consumption rates of the predators, which is generally obtained by combining the predictions of a population dynamics model with the age-specific energy requirements predicted from bioenergetics models. The procedures for this are well known. Consumption of marine organisms, expressed as a percentage of an individual's body weight per day, ranges from about 1–4% for cephalopods, 1–2% for fish, 3–5% for marine mammals and 15–20% for sea birds (Trites 2003). Immature age classes consume about twice as much (per unit of body weight) as do mature individuals. Furthermore, consumption is not constant throughout the year, but varies with seasonal periods of growth and reproduction.

Single factors rarely explain ecological phenomena and are equally unlikely to explain the recruitment patterns for Fraser River sockeye salmon over the last decades. More often than not, explanations are found by evaluating the interplay of a wide-range of cumulative impacts, including atmospheric and oceanographic conditions, environmental productivity, nutrient runoff, diseases and parasites, food webs with their prey, competitors, and predators, and human impact through fisheries or other effects. Doing so is possible, and is something that fisheries science is experienced in doing under the banner of integrated fisheries management. Unfortunately, this approach has not been actively pursued in British Columbia to the detriment of being able to evaluate the role of predation and other factors in the decline of Fraser River sockeye salmon.

Recommendations

Of the 26 potential predators we identified as possibly having an effect on sockeye salmon, only six appear to consume significant amounts (Table 5). Unfortunately, the available data were too sparse to make a definitive assessment about their impacts. We therefore recommend that data be gathered relative to sockeye salmon to better determine the diets and relative numbers and population trends of salmon sharks, blue sharks, daggertooth, sablefish, river lamprey and the common murre that may significantly impact the return of adult sockeye to British Columbia rivers.

Many diet studies are out of date (such as for harbor seals) or have not been conducted using technologies that can distinguish species of salmon from each other. Dietary studies through DNA, fatty acids, stable isotopes and morphometrics of tissue samples, stomach contents and prey remains in scats provide insights into the relative abundance of prey species and are a useful means to monitor ecosystem changes. It is a mistake to assume that diets do not change and do not need to be collected more than a few times a century. Food habits should be an integral part of fisheries management with a coordinated plan to keep the dietary information up to date. There is a joint responsibility for Fisheries and Oceans Canada and the BC Ministry of Environment to improve monitoring activities and update and maintain their inventory records.

We further recommend that a central diet database be created for British Columbia and the North Pacific The limited dietary data available for British Columbia comes from studies that are largely uncoordinated and are difficult and time consuming to access. Such a database would facilitate assessing the effects of predation on species such as Fraser River sockeye salmon, and would be integral to constructing ecosystem models and implementing ecosystem-based management. A starting place would be to create a central database for the Strait of Georgia.

Salmon research in British Columbia is focused on freshwater and habitat issues, but indications are that the problem of low survival may be explained by conditions encountered at sea. There has been little or no research into what happens to Fraser River sockeye after they leave fresh water and enter the ocean. We recommended that concerted actions be undertaken to evaluate the ecology of sockeye in the North Pacific during the marine half of their life cycle.

Finally, we recommend that a conceptual ecosystem model be built to assess the cumulative role that predators and other factors (e.g., food limitation) have on sockeye salmon as they leave the rivers and migrate through the North Pacific. Constructing the initial model will help to identify some of the important gaps in data and understanding, and would help to focus research so that science can better resolve questions pertaining to the low or high returns of sockeye salmon in future years.

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References

Ackley, D., C. Blackburn, K. Brix, D. Clausen, J. DiCosimo, R. Ferrero, L. Fritz, A. Grossman, J. Heifetz, p. Livingston, L.L. Low, R. Merrick, E. Varosi, and D. Witherell. 1995. Ecosystem considerations. North Pacific Fisheries Management Council. Anchorage, AK. The Plan Teams for the Groundfish Fisheries of the Bering Sea, Aleutian Islands, and Gulf of Alaska. 88 pp.

Agostini, V.N., R.C. Francis, A.B. Hollowed, S.D. Pierce, C. Wilson, and A.N. Hendrix. 2006. The relationship between Pacific hake (*Merluccius productus*) distribution and poleward subsurface flow in the California Current System. Canadian Journal of Fisheries and Aquatic Sciences 63:2648-2659.

Baird, R.W., and T.J. Guenther. 1995. Account of harbour porpoise (*Phocoena phocoena*) stranding and bycatches along the coast of British Columbia. Reports of the International Whaling Commission Special Issues 16:159-168.

Baker, A.R., T.R. Loughlin, V. Burkanov, C.W. Matson, R.G. Trujillo, D.G. Calkins, J.K. Wickliffe, and J.W. Bickham. 2005. Variation of mitochondrial control region sequences of Steller sea lions: the three-stock hypothesis. Journal of Mammalogy 86:1075-1084.

Bakun, A. 2011. The oxygen constraint. Pp. 11-23. *In* V. Christensen and J. Maclean (eds.). Ecosystem approaches to fisheries: a global perspective, Cambridge University Press, Cambridge.

Baron, N., and J. Acorn. 1997. Birds of coastal British Columbia. Lone Pine Publishing, Edmonton pp.

Beamesderfer, R.C.P. 2000. Managing fish predators and competitors: deciding when intervention is effective and appropriate. Fisheries 25:18-23.

Beamish, R.J., and C.E.M. Neville. 1995. Pacific salmon and Pacific herring mortalities in the Fraser River plume caused by river lamprey (*Lampetra ayresi*). Canadian Journal of Fisheries and Aquatic Sciences 52:644-650.

Beamish, R.J., and C.M. Neville. 2001. Predation-based mortality on juvenile salmon in the Strait of Georgia. North Pacific Anadromous Fish Commission Bulletin 2:11-13.

Beauchamp, D.A. 1995. Riverine predation on sockeye salmon fry migrating to Lake Washington. North American Journal of Fisheries Management 15:358-365.

Beauchamp, D.A., M.G. Lariviere, and G. Thomas. 1995. Evaluation of competition and predation as limits to juvenile kokanee and sockeye salmon production in Lake Ozette, Washington. North American Journal of Fisheries Management 15:193-207.

Bickham, J.W., T.R. Loughlin, D.G. Calkins, J.K. Wickliffe, and J.C. Patton. 1998. Genetic variability and population decline in Steller sea lions from the Gulf of Alaska. Journal of Mammalogy 79:1390-1395.

Bickham, J.W., C.C. Wood, and J.C. Patton. 1995. Variation in mitochondrial cytochrome b sequences and allozymes in sockeye (*Oncorhynchus nerka*). Journal of Heredity 86:140-144.

Bigg, M.A., G.M. Ellis, P. Cottrell, and L. Milette. 1990. Predation by harbour seals and sea lions on adult salmon in Comox Harbour and Cowichan Bay, British Columbia. *In* Canadian Technical Report of Fisheries and Aquatic Sciences. Pacific Biological Station. Nanaimo. Canadian Technical Report of Fisheries and Aquatic Sciences. 1769, 1-31 pp.

Black, N.A. 1994. Behavior and ecology of Pacific white-sided dolphins (*Lagenorhynchus obliquidens*) in Monterey Bay, California. MSc thesis, San Francisco State University, Pacific Grove, California. 147 pp.

Bograd, S.J., W.J. Sydeman, J. Barlow, A. Booth, R.D. Brodeur, J. Calambokidis, F. Chavez, W.R. Crawford, E. Di Lorenzo, R. Durazo, R. Emmett, J. Field, G. Gaxiola-Castro, W. Gilly, R. Goericke, J. Hildebrand, J.E. Irvine, M. Kahru, J.A. Koslow, B. Lavaniegos, M. Lowry, D.L. Mackas, M. Manzano-Sarabia, S.M. McKinnell, B.G. Mitchell, L. Munger, R.I. Perry, W.T. Peterson, S. Ralston, J. Schweigert, A. Suntsov, R. Tanasichuk, A.C. Thomas, and F. Whitney. 2010. Status and trends of the California Current region, 2003-2008. Pp. 106-141. *In* S. M. McKinnell and M. J. Dagg (eds.). Marine Ecosystems of the North Pacific Ocean, 2003-2008, PICES Special Publication 4.

Bowles, E., P.M. Schulte, D.J. Tollit, B.E. Deagle, and A.W. Trites. 2011. Proportion of prey consumed can be determined from faecal DNA using real-time PCR. Molecular Ecology Resources: *doi: 10.1111/j.1755-0998.2010.02974.x.*

Bradford, M.J., J. Amos, C.P. Tovey, J.M.B. Hume, S. Grant, and B. Mossop. 2007. Abundance and migratory behaviour of northern pikeminnow (*Pthchocheilus oregonensis*) in Cultus Lake, British Columbia and implications for predator control. Canadian Technical Report of Fisheries and Aquatic Sciences, Fisheries and Oceans Canada. Vol. 2723, 47 pp.

Bradford, M.J., C.P. Tovey, and L.-M. Herborg. 2009. Biological risk assessment for yellow perch (*Perca flavescens*) in British Columbia. Canadian Science Advisory Secretariat Research Document 2008/073.

Brodeur, R., S. McKinnell, K. Nagasawa, W. Pearcy, V. Radchenko, and S. Takagi. 1999. Epipelagic nekton of the North Pacific subarctic and transition zones. Progress in Oceanography 43:365-397.

Brodeur, R., K. Myers, and J. Helle. 2003. Research conducted by the United States on the early ocean life history of Pacific salmon. North Pacific Anadromous Fish Commission Bulletin 3:89-131.

Brodeur, R., and D. Ware. 1995. Interdecadal variability in distribution and catch rates of epipelagic nekton in the Northeast Pacific Ocean. Climate change and northern fish populations 121:329-356.

Brown, L.R., and P.B. Moyle. 1981. The Impact of squawfish on salmonid populations. North American Journal of Fisheries Management 1:104-111.

Browne, P., J. Laake, and R.L. De Long. 2002. Improving pinniped diet analyses through identification of multiple skeletal structures in fecal samples. Fisheries Bulletin 100:423-433.

Buckley, T.W., and P.A. Livingston. 1997. Geographic variation in the diet of Pacific hake, with a note on cannibalism. California Cooperative Oceanic Fisheries Investigations Report 38:53-62.

Campbell, R.W., N.K. Dawe, I. McTaggart-Cowan, G.W. Kaiser, and M.C.E. McNall. 1997. The birds of British Columbia. University of British Columbia Press, Vancouver, BC. 531 pp.

Carretta, J.V., K.A. Forney, M.S. Lowry, J. Barlow, J. Baker, D. Johnston, B. Hanson, M.M. Muto, D. Lynch, and L. Carswell. 2009. U.S. Pacific Marine Mammal Stock Assessments: 2008. *In* U.S. Department of Commerce, NOAA Technical Memorandum. NOAA Technical Memorandum. NMFS-AFSC-124, 340 pp.

Cartwright, M.A., D.A. Beauchamp, and M.D. Bryant. 1998. Quantifying cutthroat trout (*Oncorhynchus clarki*) predation on sockeye salmon (*Oncorhynchus nerka*) fry using a bioenergetics approach. Canadian Journal of Fisheries and Aquatic Sciences 55:1285-1295.

Chatwin, T.A., M.H. Mather, and T. Giesbrecht. 2001. Double-crested and pelagic cormorant inventory in the Strait of Georgia in 2000. British Columbia, Ministry of the Environment. (www.env.gov.bc.ca/wildlife/wsi/reports/4382_WSI_4382_RPT.PDF). 20 pp.

Chenoweth, E., J. Straley, E. McCauley, T. Sheridan, L. Garrison, J. Moran, H. Riley, F. Thrower, and B. Contag. 2010. Preliminary investigations of humpback whale predation at salmon enhancement facilities on eastern Baranof Island, Southeastern Alaska April 2010 to June 2010 [abstract], Alaskan fisheries in a changing world, American Fisheries Society, Alaska Chapter, 37th Annual Meeting, November 3-5, 2010, pp. 64, Juneau, Alaska.

Christensen, V., and C. Walters. 2011. Progress in the use of ecosystem modeling for fisheries management. Pp. 189-205. *In* V. Christensen and J. Maclean (eds.). Ecosystem approaches to fisheries: a global perspective, Cambridge University Press, Cambridge.

Clapham, P.J. 2009. Humpback whale *Megaptera novaeangliae*. Pp. 582-585. *In* W. F. Perrin, B. Wursig and H. G. M. Thewissen (eds.). Encyclopedia of Marine Mammals, Academic Press, San Diego.

Clark, C.W., and D.A. Levy. 1988. Diel vertical migrations by juvenile sockeye salmon and the antipredation window. American Naturalist 131:271-290.

Cleary, J.S., J.F. Schweigert, and V. Haist. 2009. Stock assessment and management advice for the British Columbia herring fishery: 2009 assessment and 2010 forecasts. Canadian Science Advisory Secretariat, Research Document 2009/079. 89 pp.

Clemens, W.A., J.L. Hart, and G.V. Wilby. 1936. Analysis of stomach contents of fur seals taken off the west coast of Vancouver Island in April and May, 1935. Pacific Biological Station. Nanaimo. 1-20 pp.

Collis, K., D.D. Roby, D.P. Craig, B.A. Ryan, and R.D. Ledgerwood. 2001. Colonial waterbird predation on juvenile salmonids tagged with passive integrated transponders in the Columbia River estuary: vulnerability of different salmonid species, stocks, and rearing types. Transactions of the American Fisheries Society 130:385-396.

Compagno, L.J.V. 1984. FAO Species Catalogue. Vol. 4. Sharks of the world. An annotated and illustrated catalogue of shark species known to date. Part 1 - Hexanchiformes to Lamniformes. FAO Fish. Synop. 125(4/1). 1-249 pp.

COSEWIC. 2003. COSEWIC assessment and update status report on the humpback whale *Megaptera novaeangliae* in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. vii + 25 pp.

COSEWIC. 2006. COSEWIC assessment and update status report on the northern fur seal *Callorhinus ursinus* in Canada. Committee on the Status of Endangered Wildlife in Canada, Ottawa. vii + 33 pp.

COSEWIC. 2008. COSEWIC assessment and update status report on the Killer Whale *Orcinus orca*, Southern Resident population, Northern Resident population, West Coast Transient population, Offshore population and Northwest Atlantic / Eastern Arctic population, in Canada. Committee on the Status of Endangered Wildlife in Canada, Ottawa. viii + 65 pp.

Cosgrove, J.A. 2005. The first specimens of humboldt squid in British Columbia. PICES Press 13, July:30-31.

Cox, S.P., and A.R. Kronlund. 2009. Evaluation of interim harvest strategies for sablefish (*Anoplopoma fimbria*) in British Columbia, Canada for 2008/09. Canadian Science Advisory Secretariat, Research Document 2009/042. 33 pp.

Crone, P.R., K.T. Hill, J.D. McDaniel, and N.C.H. Lo. 2009. Pacific mackerel (*Scomber japonicus*) stock assessment for USA management in the 2009-10 fishing year. Pacific Fishery Management Council. 197 pp.

Deagle, B.E., D.J. Tollit, S.N. Jarman, M.A. Hindell, A.W. Trites, and N.J. Gales. 2005. Molecular scatology as a tool to study diet: analysis of prey DNA in scats from captive Steller sea lions. Molecular Ecology 14:1831-1842.

DFO. 2002. Canada’s ocean strategy. Our oceans, our future. Policy and operational framework for integrated management of estuarine, coastal and marine environments in Canada. Fisheries and Oceans Canada. Oceans Directorate, Ottawa, ON. 43 pp.

DFO. 2005. Canada's policy for conservation of wild salmon. Fisheries and Oceans Canada, Vancouver, BC. 57 pp.

DFO. 2010. Assessment of spiny dogfish (*Squalus acanthias*) in British Columbia in 2010. *In* DFO Canaidan Science Advisory Secretariat Scientific Advisosry Report 2010/057. 11 pp.

Dorn, M., K. Aydin, S. Barbeaux, M. Guttormsen, B. Megrey, K. Spalinger, and M. Wilkins. 2009. Gulf of Alaska walleye pollock assessment. Alaska Fisheries Science Center, National Marine Fisheries Service. Seattle, WA. 104 pp.

Duffy, E., and D. Beauchamp. 2008. Seasonal patterns of predation on juvenile Pacific salmon by anadromous cutthroat trout in Puget Sound. Transactions of the American Fisheries Society 137:165-181.

Field, J.C., K. Baltz, A.J. Phillips, and W.A. Walker. 2007. Range expansion and trophic interactions of the jumbo squid, *Dosidicus gigas*, in the California Current. California Cooperative Oceanic Fisheries Investigations Report 48:131-146.

Fisher, H.D. 1952. The status of the harbour seal in British Columbia, with particular reference to the Skeena River. Fisheries Research Board of Canada, Bulletin 93:1-58.

Foerster, R.E., and W.E. Ricker. 1938. The effectiveness of reduction of predator control in decreasing the mortality of young sockeye salmon (*Oncorhynchus nerka* Walbaum). Verhandlungen des Internationalen Verein Limnologie 8:151-167.

Foerster, R.E., and W.E. Ricker. 1941. The effect of reduction of predaceous fish on survival of young sockeye salmon at Cultus Lake. Journal of the Fisheries Research Board of Canada 5:315-336.

Foote, C., and G. Brown. 1998. Ecological relationship between freshwater sculpins (genus Cottus) and beach-spawning sockeye salmon (*Oncorhynchus nerka*) in Iliamna Lake, Alaska. Canadian Journal of Fisheries and Aquatic Sciences 55:1524-1533.

Ford, J.K.B., and G.M. Ellis. 2006. Selective foraging by fish-eating killer whales *Orcinus orca* in British Columbia. Marine Ecology Progress Series 316:185-199.

Ford, J.K.B., G.M. Ellis, L.G. Barrett-Lennard, A.B. Morton, R.S. Palm, and K.C. Balcomb III. 1998. Dietary specialization in two sympatric populations of killer whales (*Orcinus orca*) in coastal British Columbia and adjacent waters. Canadian Journal of Zoology 76:1456-1471.

Ford, J.K.B., G.M. Ellis, C.O. Matkin, M.H. Wetklo, L.G. Barrett-Lennard, and R.E. Withler. 2011. Shark predation and tooth wear in a population of northeastern Pacific killer whales. Aquatic Biology *doi: 10.3354/ab00307*.

Ford, J.K.B., G.M. Ellis, P.F. Olesiuk, and K.C. Balcomb. 2010a. Linking killer whale survival and prey abundance: food limitation in the oceans' apex predator? Biology Letters 6:139-142.

Ford, J.K.B., B.M. Wright, G.M. Ellis, and J.R. Candy. 2010b. Chinook salmon predation by resident killer whales: seasonal and regional selectivity, stock identity of prey, and consumption rates. *In* DFO Canadian Science Advisory Secretariat Research Document 2009/101. iv + 43 pp.

Forrest, K.W., J.D. Cave, C.G.J. Michielsens, M. Haulena, and D.V. Smith. 2009. Evaluation of an electric gradient to deter seal predation on salmon caught in gill-net test fisheries. North American Journal of Fisheries Management 29:885–894.

Fresh, K., and S. Schroder. 1987. Influence of the abundance, size, and yolk reserves of juvenile chum salmon (*Oncorhynchus keta*) on predation by freshwater fishes in a small coastal stream. Canadian Journal of Fisheries and Aquatic Sciences 44:236-243.

Fresh, K.L. 1997. The role of competition and predation in the decline of Pacific salmon and steelhead. Pp. 245-275. *In* D. J. Stouder, P. A. Bisson and R. J. Naiman (eds.). Pacific salmon and their ecosystems: status and future options, Chapman and Hall, New York.

Froese, R., and D. Pauly. 2010. FishBase. World Wide Web electronic publication. www.fishbase.org, version (07/2010). Web [accessed December 2010].

Fryer, J.K. 1998. Frequency of pinniped-caused scars and wounds on adult spring-summer chinook and sockeye salmon returning to the Columbia River. North American Journal of Fisheries Management 18:46-51.

Gallucci, V., I. Taylor, J. King, G. McFarlane, and R. McPhie. 2010. Spiny dogfish (*Squalus acanthias*) assessment and catch recommendation for 2010. PBS, Fisheries and Ocean Canada. pp.

Gearin, P., S.R. Melin, R.L. DeLong, H. Kajimura, and M.A. Johnson. 1994. Harbor porpoise interaction with a chinook salmon set-net fishery in Washington state. Reports of the International Whaling Commission Special Issue 15:427-438.

Gregr, E., L. Nichol, F. Ford, G. Ellis, and A.W. Trites. 2000. Migration and population structure of northeast Pacific whales off the coast of British Columbia: an analysis of commercial whaling records from 1908-1967. Marine Mammal Science 16:699-727.

Guénette, S., J.J. Heymans, V. Christensen, and A.W. Trites. 2006. Ecosystem models show combined effects of fishing, predation, competition, and ocean productivity on Steller sea lions (*Eumetopias jubatus*) in Alaska. Canadian Journal of Fisheries and Aquatic Sciences 63:2495-2517.

Hall, A.M. 2004. Seasonal abundance, distribution and prey species of harbour porpoise (*Phocoena phocoena*) in southern Vancouver Island waters. MSc thesis, University of British Columbia, Vancouver. 108 pp.

Hanselman, D.H., J.T. Fujioka, C.R. Lunsford, and C.J. Rodgveller. 2009. Chapter 3: Assessment of the sablefish stock in Alaska. NPFMC Bering Sea, Aleutian Islands and Gulf of Alaska SAFE. 112 pp.

Hanson, M.B., R.W. Baird, J.K.B. Ford, J. Hempelmann-Halos, D.M. Van Doornik, J.R. Candy, C.K. Emmons, G.S. Schorr, B. Gisborne, K.L. Ayres, S.K. Wasser, K.C. Balcomb, K. Balcomb-Bartok, J.G. Sneva, and M.J. Ford. 2010. Species and stock identification of prey consumed by endangered 'southern resident' killer whales in their summer range. Endangered Species Research 11:69-82.

Haque, S.R. 2008. Movement patterns of coastal cutthroat trout (*Oncorhynchus clarki clarki*) in South Puget Sound, Washington 2006-2007. MSc thesis, Evergreen State College, Olympia, Washington. 46 pp.

Hauser, D.D.W., C.S. Allen, H.B. Rich, and T.P. Quinn. 2008. Resident harbor seals (*Phoca vitulina*) in Iliamna Lake, Alaska: summer diet and partial consumption of adult sockeye salmon (*Oncorhynchus nerka*). Aquatic Mammals 34:303-309.

Hebert, K. 2009. Southeast Alaska 2009 herring stock assessment surveys. Alaska Department of Fish and Game, Divisions of Sport Fish and Commercial Fisheries, Fishery Data Series No. 09-72. pp.

Heise, K.A. 1997a. Diet and feeding behaviour of Pacific white-sided dolphins (*Lagenorhynchus obliquidens*) as revealed through the collection of prey fragments and stomach content analyses. Report of the International Whaling Commission 47:807-815.

Heise, K.A. 1997b. Life history and population parameters of the Pacific white-sided dolphin (*Lagenorhyncus obfiquidens*). Report of the International Whaling Commission 47:817-825.

Helfield, J., and R. Naiman. 2001. Effects of salmon-derived nitrogen on riparian forest growth and implications for stream productivity. Ecology 82:2403-2409.

Hilborn, R., and D. Eggers. 2000. A review of the hatchery programs for pink salmon in Prince William Sound and Kodiak Island, Alaska. Transactions of the American Fisheries Society 129:333-350.

Holling, C.S. 1959. Some characteristics of simple types of predation and parasitism. Canad. Entomol. 91:385-398.

Hulbert, L.B., A.M. Aires da Silva, V.F. Gallucci, and J.S. Rice. 2005. Seasonal foraging movements and migratory patterns of female *Lamna ditropis* tagged in Prince William Sound, Alaska. Journal of Fish Biology 67:490-509.

Hume, J.M.B., and S.G. MacLellan. 2000. An assessment of the juvenile sockeye salmon (*Oncorhynchus nerka*) populations of Babine Lake. Can. Tech. Rep. Fish. Aquat. Sci. 2327. 37 p. pp.

Hume, J.M.B., K.S. Shortreed, and K.F. Morton. 1996. Juvenile sockeye rearing capacity of three lakes in the Fraser River system. Canadian Journal of Fisheries and Aquatic Sciences 53:719-733.

Hyatt, K.D., D.J. McQueen, K.S. Shortreed, and D.P. Rankin. 2004. Sockeye salmon (*Oncorhynchus nerka*) nursery lake fertilization: Review and summary of results. Environmental Reviews 12:133-162.

Jauquet, J.M. 2002. Coastal cutthroat trout (*Oncorhynchus clarki clarki*) diet in south Puget Sound, Washington 1999-2002. MSc thesis, Evergreen State College, Olympia, Washington. 79 pp.

Johnson, E.E. 2009. A quantitative risk assessment model for the management of invasive yellow perch in Shuswap Lake, British Columbia. MRM thesis, Simon Fraser University, Burnaby, BC. 105 pp.

Johnson, R.C. 1973. Potential interspecific problems between hatchery coho smolts and juvenile pink and chum salmon. Washington Department of Fisheries Management. Olympia. pp.

Kajimura, H. 1984. Opportunistic feeding of the northern fur seal, *Callorhinus ursinus*, in the eastern North Pacific ocean and Eastern Bering Sea. US Department of Commerce, NOAA Tech. Rep. NMFS SSRF-779. NOAA Technical Report. NMFS SSRF-779, 49 pp.

Kajimura, H., C.H. Fiscus, and R.K. Stroud. 1980. Food of the Pacific white-sided dolphin, *Lagenorhynchus obliquidens*, Dall's porpoise, *Phocoenoides dalli*, and northern fur seal, *Callorhinus ursinus*, off California and Washington; with appendices on size and food of the Dall's porpoise from Alaskan waters. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NMC-2. 30 pp.

Keiser, R., M.W. Saunders, and K. Cooke. 1999. Review of hydroacoustic methodology and Pacific hake biomass estimates for the Strait of Georgia, 1981 to 1998. Canaidan Science Advisory Secretariat Research Document 1999/15. 53 pp.

King, J.R., and G.A. McFarlane. 2006. Shift in size-at-age of the Strait of Georgia population of Pacific hake (*Merluccius productus*). California Cooperative Oceanic Fisheries Investigations Report 47:111.

King, J.R., and G.A. McFarlane. 2009. Trends in abundance of spiny dogfish in the Strait of Georgia, 1980–2005. Pp. 423. *In* V. Gallucci, G. McFarlane and G. Bargmann (eds.). Ch. 7. Biology and Management of Dogfish Sharks, American Fisheries Society.

Kleiber, P., S. Clarke, K. Bigelow, H. Nakano, M. McAllister, and Y. Takeuchi. 2009. North Pacific blue shark stock assessment. U.S. Dep. Commer., NOAA Tech. Memo., NOAA-TM-NMFS-PIFSC-17. 74 pp.

Kostow, K. 2009. Factors that contribute to the ecological risks of salmon and steelhead hatchery programs and some mitigating strategies. Reviews in Fish Biology and Fisheries 19:9-31.

Krahn, M.M., D.P. Herman, C.O. Matkin, J.W. Durban, L. Barrett-Lennard, D.G. Burrows, M.E. Dahlheim, N. Black, R.G. LeDuc, and P.R. Wade. 2007. Use of chemical tracers in assessing the diet and foraging regions of eastern North Pacific killer whales. Marine Environmental Research 63:91-114.

Kurota, H., M.K. McAllister, E.A. Parkinson, N.T. Johnston, and P.J. Askey. 2011. Progress report: Management reference points for kokanee and salmonid piscivores in large BC lakes. Province of British Columbia, Fisheries Project Report: *unpublished manuscript*.

Laake, J.L., P. Browne, R.L. DeLong, and H.R. Huber. 2002. Pinniped diet composition: a comparison of estimation models. Fisheries Bulletin 100:434-447.

Larkin, P. 1971. Simulation studies of the Adams River sockeye (*Onchorhynchus nerka*). Canadian Journal of Fisheries and Aquatic Sciences 28:1493-1502.

Larkin, P.A. 1992. Analysis of possible causes of the shortfall in sockeye spawners in the Fraser River - technical appendix. Pp. 62-67. *In* P. Pearse (ed.). Managing salmon in the Fraser - Report to the Minister of Fisheries and Oceans on the Fraser River salmon nvestigation, Vancouver, BC.

Leatherwood, S., and R.R. Reeves. 1983. Whales and dolphins. Sierra Club Handbook, San Francisco, CA. 302 pp.

Levin, P.S., R.W. Zabel, and J.G. Williams. 2001. The road to extinction is paved with good intentions: negative association of fish hatcheries with threatened salmon. Proceedings of the Royal Society of London. Series B: Biological Sciences 268:1153-1158.

Levy, D.A., and C.C. Wood. 1992. Review of proposed mechanisms for sockeye salmon population cycles in the Fraser River. Bulletin of Mathematical Biology 54:241-261.

Lorenzen, K. 1996. The relationship between body weight and natural mortality in juvenile and adult fish: a comparison of natural ecosystems and aquaculture. Journal of Fish Biology 49:627-642.

Mackas, D.L., R. Kieser, M. Saunders, D.R. Yelland, R.M. Brown, and D.F. Moore. 1997. Aggregation of euphausiids and Pacific hake (*Merluccius productus*) along the outer continental shelf off Vancouver Island. Canadian Journal of Fisheries and Aquatic Sciences 54:2080-2096.

MacLellan, S.G., and J.M.B. Hume. 2010. An evaluation of methods used by the freshwater ecosystems section for pelagic fish surveys of sockeye rearing lakes in British Columbia. Canadian Technical Report Fisheries and Aquatic Sciences 2886. v + 68 pp.

Markaida, U., and O. Sosa-Nishizaki. 2010. Food and feeding habits of the blue shark *Prionace glauca* caught off Ensenada, Baja California, Mexico, with a review on its feeding. Journal of the Marine Biological Association of the UK 90:977-994.

Martell, S. 2010. Assessment and management advice for Pacific hake in U.S. and Canadian waters in 2010. www.pcouncil.org/wp-content/uploads/E3a_ATT1 _HAKE_USCAN _MARCH_2010_BB.pdf. 80 pp.

Mather, M.E. 1998. The role of context-specific predation in understanding patterns exhibited by anadromous salmon. Canadian Journal of Fisheries and Aquatic Sciences 55:232-246.

McKinnell, S., and M.P. Seki. 1998. Shark bycatch in the Japanese high seas squid driftnet fishery in the North Pacific Ocean. Fisheries Research 39:127-138.

McKinnell, S.M., and M.J. Dagg. (eds.). 2010. Marine ecosystems of the North Pacific Ocean, 2003-2008. PICES Special Publication 4. 393 pp.

Mizue, K., K. Yosidda, and A. Takemura. 1966. On the ecology of the Dall's porpoise in Bering Sea and the North Pacific Ocean. [In Jpn., Engl. summ.]. Faculty of Fisheries Bulletin, Nagasaki University 21:1-21.

Montgomery, R.A., J.M. VerHoef, and P.L. Boveng. 2007. Spatial modeling of haul-out site use by harbor seals in Cook Inlet, Alaska. Marine Ecology Progress Series 341:257-264.

Morton, A. 2000. Occurrence, photo-identification and prey of Pacific white-sided dolphins (*Lagenorhyncus obliquidens*) in the Broughton Archipelago, Canada 1984-1998. Marine Mammal Science 16:80-93.

Nagasawa, K. 1998. Predation by salmon sharks (*Lamna ditropis*) on Pacific salmon (*Oncorhynchus* spp.) in the North Pacific Ocean. North Pacific Anadromous Fish Commission Bulletin 1:419-433.

Nagasawa, K., T. Azumaya, and Y. Ishida. 2002. Impact of predation by salmon sharks (*Lamna ditropis*) and daggertooth (*Anotopterus nikparini*) on Pacific salmon

(*Oncorhynchus* spp.) stocks in the North Pacific Ocean. NPAFC Technical Report No. 4. 51-52 pp.

Nakano, H., and J.D. Stevens. 2009. The biology and ecology of the blue shark, *Prionace glauca*. Pp. 140-151. *In* M. D. Camhi, E. K. Pikitch and E. A. Babcock (eds.). Sharks of the Open Ocean: Biology, Fisheries and Conservation, Blackwell Publishing, Oxford, UK.

Nichol, L.M., and D.M. Shackleton. 1996. Seasonal movements and foraging behaviour of northern resident killer whales (*Orcinus orca*) in relation to the inshore distribution of salmon (*Onchorhynchus* spp.) in British Columbia. Canadian Journal of Zoology 74:983-991.

Nigmatullin, C.M., K.N. Nesis, and A.I. Arkhipkin. 2001. A review of the biology of the jumbo squid *Dosidicus gigas* (Cephalopoda: Ommastrephidae). Fisheries Research 54:9-19.

NMFS. 2008. Recovery plan for the Steller sea lion. Eastern and western distinct population segments (*Eumetopias jubatus*). Revision. US National Marine Fisheries Service, Silver Spring, MD. 325 pp.

NOAA. 1998. Impact of sea lions and seals on Pacific Coast salmonids. NOAA-NWFSC Tech Memo-28. US Department of Commerce. 12 pp.

Ohizumi, H., T. Kuramochi, T. Kubodera, M. Yoshioka, and N. Miyazaki. 2003. Feeding habits of Dall's porpoises (*Phocoenoides dalli*) in the subarctic North Pacific and the Bering Sea basin and the impact of predation on mesopelagic micronekton. Deep Sea Research Part I: Oceanographic Research Papers 50:593-610.

Okey, T., B. Wright, and M. Brubaker. 2007. Salmon shark connections: North Pacific climate change, indirect fisheries effects, or just variability? Fish and Fisheries 8:359-366.

Olesiuk, P.F. 1993. Annual prey consumption by harbor seals (*Phoca vitulina*) in the Strait of Georgia, British Columbia. Fishery Bulletin 91:491-515.

Olesiuk, P.F. 2007. Abundance of Steller sea lions (*Eumetopias jubatus*) in British Columbia. Canadian Science Advisory Secretariat Research Document 2007/000:1-36.

Olesiuk, P.F. 2008a. An assessment of population trends and abundance of harbour seals (*Phoca vitulina*) in British Columbia. Canadian Science Advisory Secretariat Research Document 2008/XXX:1-170.

Olesiuk, P.F. 2008b. A preliminary assessment of the recovery potential of northern fur seals (*Callorhinus ursinus*) in British Columbia. Canadian Science Advisory Secretariat Research Document 2007/076:1-72.

Olesiuk, P.F. 2009. Abundance of Steller sea lions (*Eumetopias jubatus*) in British Columbia. Canadian Science Advisory Secretariat Research Document 2008/063:1-33.

Olesiuk, P.F., M.A. Bigg, and G.M. Ellis. 1990a. Recent trends in the abundance of harbour seals, *Phoca vitulina*, in British Columbia. Canadian Journal of Fisheries and Aquatic Sciences 47:992-1003.

Olesiuk, P.F., M.A. Bigg, G.M. Ellis, S.J. Crockford, and R.J. Wigen. 1990b. An assessment of the feeding habits of harbour seals (*Phoca vitulina*) in the Strait of Georgia, British Columbia, based on scat analysis. Ottawa. Ottawa: Department of Fisheries and Oceans, Canadian Technical Report of Fisheries and Aquatic Sciences (Report No. 1730), 135 pp.

Olesiuk, P.F., G. Horonowitsch, G.M. Ellis, T.G. Smith, L. Flostrand, and S.C. Warby. 1995. An assessment of harbour seal (*Phoca vitulina*) predation on outmigrating chum fry (*Oncorhynchus keta*) and coho smolts (*O. kisutch*) in the lower Puntledge River, British Columbia. PSARC Working Paper S95-10.

Palsson, W.A. 2003. Results from the 2001 transboundary trawl survey of the southern Strait of Georgia, San Juan Archipelago and adjacent waters. Washington Department of Fish and Wildlife. 117 pp.

Parkinson, E.A., J.M.B. Hume, and R. Dolighan. 1989. Size-selective predation by rainbow trout on two lacustrine *Oncorhynchus nerka* populations. Fisheries Management Report No 94. British Columbia, Ministry of Environment, Fisheries Branch. 17 pp.

Pauly, D. 2010. Gasping Fish and Panting Squids: Oxygen, Temperature and the Growth of Water-Breathing Animals. International Ecology Institute, Oldenburg/Luhe, Germany. 216 pp.

Peterman, R.M., D. Marmorek, B. Beckman, M. Bradford, N. Mantua, B.E. Riddell, M. Scheuerell, M. Staley, K. Wieckowski, J.R. Winton, and C.C. Wood. 2010. Synthesis of evidence from a workshop on the decline of Fraser River sockeye. June 15-17, 2010. A report to the Pacific Salmon Commission, Vancouver, BC. Pp. 123 + 25 pp. of appendices. Available from www.psc.org.

Petersen, J. 2001. Density, aggregation, and body size of northern pikeminnow preying on juvenile salmonids in a large river. Journal of Fish Biology 58:1137-1148.

Petersen, J.H., and J.F. Kitchell. 2001. Climate regimes and water temperature changes in the Columbia River: bioenergetic implications for predators of juvenile salmon. Canadian Journal of Fisheries and Aquatic Sciences 58:1831-1841.

PICES. 2010. Report of Working Group 19 on Ecosystem-based Management Science and its Application to the North Pacific. PICES Scientific Report No. 37 2010. pp.

Pitcher, K.W. 1980. Food of the harbor seal, *Phoca vitulina richardsi*, in the Gulf of Alaska. Fishery Bulletin 78:544-549.

Pitcher, K.W., and D.G. Calkins. 1979. Biology of the harbor seal, *Phoca vitulina richardsi*, in the Gulf of Alaska. Outer Continental Shelf Environmental Assessment Program, US Department of Interior Bureau of Land Management. Final Report. 78 pp.

Pitcher, K.W., and D.C. McAllister. 1981. Movements and haulout behavior of radio-tagged harbor seals, *Phoca vitulina.* Canadian Field-Naturalist 95:292-297.

Preikshot, D. 2007a. The influence of geographic scale, climate and trophic dynamics upon North Pacific oceanic ecosystem models. Ph.D. thesis, University of British Columbia, Vancouver. xv+208 pp.

Preikshot, D. 2007b. The influence of geographic scale, climate and trophic dynamics upon North Pacific oceanic ecosystem models. PhD thesis, University of British Columbia, Vancouver. xv+208 pp.

Purcell, M., G. Mackey, E. LaHood, H. Huber, and L. Park. 2004. Molecular methods for the genetic identification of salmonid prey from Pacific harbor seal (*Phoca vitulina richardsi*) scat. Fishery Bulletin 102:213-220.

Quinn, T., S. Gende, G. Ruggerone, and D. Rogers. 2003. Density-dependent predation by brown bears (*Ursus arctos*) on sockeye salmon (*Oncorhynchus nerka*). Canadian Journal of Fisheries and Aquatic Sciences 60:553-562.

Quinn, T.P. 2005. The behavior and ecology of Pacific salmon and trout. University of Washington Press, Seattle, WA. 378 pp.

Rambeau, A.L. 2008. Determining abundance and stock structure for a widespread migratory animal: the case of humpback whales (*Megaptera novaeangliae*) in British Columbia, Canada. MSc thesis, University of British Columbia, Vancouver, BC. 68 pp.

Rickel, S., and A. Genin. 2005. Twilight transitions in coral reef fish: the input of light-induced changes in foraging behaviour. Animal Behaviour 70:133-144.

Ricker, W. 1950. Cycle dominance among the Fraser sockeye. Ecology:6-26.

Ricker, W.E. 1962. Comparison of ocean growth and mortality of sockeye salmon during their last two years. Canadian Journal of Fisheries and Aquatic Sciences 19:531-560.

Rieman, B.E., and R.C. Beamesderfer. 1990. Dynamics of a northern squawfish population and the potential to reduce predation on juvenile salmonids in a Columbia River reservoir. North American Journal of Fisheries Management 10:228-241.

Roby, D., D. Lyons, D. Craig, K. Collis, and G. Visser. 2003. Quantifying the effect of predators on endangered species using a bioenergetics approach: Caspian terns and juvenile salmonids in the Columbia River estuary. Canadian Journal of Zoology 81:250-265.

Rosas-Luis, R., C.A. Salinas-Zavala, V. Koch, P.D.M. Luna, and M.V. Morales-Zárate. 2008. Importance of jumbo squid *Dosidicus gigas* (Orbigny, 1835) in the pelagic ecosystem of the central Gulf of California. Ecological Modelling 218:149-161.

Ruggerone, G.T., and D.E. Rogers. 1984. Arctic char predation on sockeye salmon smolts at Little Togiak River, Alaska. Fishery Bulletin 82:401-410.

Ruggerone, G.T., and D.E. Rogers. 1992. Predation on sockeye salmon fry by juvenile coho salmon in the Chignik Lakes, Alaska: implications for salmon management. North American Journal of Fisheries Management 12:87-102.

Runciman, J.B., and B.R. Leaf. 2009. A review of yellow perch (*Perca flavascens*), smallmouth bass (*Micropterus dolomieu*), largemouth bass (*Micropterus salmoides*), pumpkinseed (*Lepomis gibbosus*), walleye (*Sander vitreus*) and northern pike (*Esox lucius*) distributions in British Columbia. Canadian Manuscript Report of Fisheries and Aquatic Sciences 2882. Department of Fisheries and Oceans. Nanaimo. xvi+123 pp.

Ryan, B.A., M.C. Carper, B.P. Sandford, and G.M. Matthews. 2007. Detection of passive integrated transponder (PIT) tags on piscivorous bird colonies in the Columbia River Basin, 2006. Fish Ecology Division, Northwest Fisheries Science Center, National Marine Fisheries Service. pp.

Saulitis, E.L., C.O. Matkin, K. Heise, L. Barrett Lennard, and G.M. Ellis. 2000. Foraging strategies of sympatric killer whale (*Orcinus orca*) populations in Prince William Sound, Alaska. Marine Mammal Science 16:94-109.

Scheffer, T.H., and C.C. Sperry. 1931. Food habits of the Pacific harbor seal, *Phoca richardii*. Journal of Mammalogy 12:214-226.

Scheuerell, M., and D. Schindler. 2003. Diel vertical migration by juvenile sockeye salmon: empirical evidence for the antipredation window. Ecology 84:1713-1720.

Sebastian, D.C., R. Dolighan, H. Andrusak, J. Hume, P. Woodruff, and G. Scholten. 2003. Summary of Quesnel Lake kokanee and rainbow trout biology with reference to sockeye salmon. *In* Stock Management Report No 17. Province of British Columbia. 109 pp.

Sibert, J., J. Hampton, P. Kleiber, and M. Maunder. 2006. Biomass, size, and trophic status of top predators in the Pacific Ocean. Science 314:1773.

Sigler, M., L. Hulbert, C. Lunsford, N. Thompson, K. Burek, G. OíCorry Crowe, and A. Hirons. 2006. Diet of Pacific sleeper shark, a potential Steller sea lion predator, in the north east Pacific Ocean. Journal of Fish Biology 69:392-405.

Spalding, D.J. 1964. Comparative feeding habits of the fur seal, sea lion and harbour seal on the British Columbia coast. Fisheries Research Board of Canada Bulletin 146:1-47.

Stroud, R.K., C.H. Fiscus, and H. Kajimura. 1981. Food of the Pacific white-sided dolphin, *Lagenorhynchus obliquidens*, Dall's porpoise, *Phocoenoides dalli*, and northern fur seal, *Callorhinus ursinus*, off California and Washington. Fishery Bulletin, US 78:951-959.

Sturdevant, M.V., M.F. Sigler, and J.A. Orsi. 2009. Sablefish predation on juvenile Pacific salmon in the coastal marine waters of Southeast Alaska in 1999. Transactions of the American Fisheries Society 138:675-691.

Sviridov, V.V., I.I. Glebov, A.N. Starovoytov, A.V. Sviridova, M.A. Zuev, V.V. Kulik, and M.A. Ocheretyanny. 2007. Wounding of Pacific salmon in relation to the spatio-temporal variation in distribution patterns of important predatory fishes in the Russian economic zone. North Pacific Anadromous Fish Commission Bulletin 4:133–144.

Tabor, R., and J. Chan. 1996. Predation of sockeye salmon by cottids and other predatory fishes in the lower Cedar River, 1996. US Fish and Wildlife Service. Lacey, WA. 48 pp.

Tabor, R., and J. Chan. 1997. Predation on sockeye salmon fry by predatory fishes in southern Lake Washington, 1996. US Fish and Wildlife Service. Lacey, WA. 40 pp.

Tabor, R., J. Chan, and S. Hager. 1998. Predation of sockeye salmon by cottids and other predatory fishes in the Cedar River and southern Lake Washington, 1997. US Fish and Wildlife Service. Lacey, WA. 54 pp.

Tabor, R., S. Hager, A. Hird, and R. Piaskowski. 2001. Predation of juvenile salmonids by predatory fishes in the Lower Cedar River, 1999. US Fish and Wildlife Service. Lacey, WA. 38 pp.

Tanasichuk, R., D. Ware, W. Shaw, and G. McFarlane. 1991. Variations in diet, daily ration, and feeding periodicity of Pacific hake (*Merluccius productus*) and spiny dogfish (*Squalus acanthias*) off the lower west coast of Vancouver Island. Canadian Journal of Fisheries and Aquatic Sciences 48:2118-2128.

Taylor, I.G. 2008. Modeling spiny dogfish population dynamics in the Northeast Pacific. PhD thesis, University of Washington, Seattle, WA. 188 pp.

Taylor, M.H., J. Tam, V. Blaskovic, P. Espinoza, R.M. Ballon, C. Wosnitza-Mendo, J. Arguelles, E. Diaz, S. Purca, N. Ochoa, P. Ayon, E. Goya, D. Gutierrez, L. Quipuzcoa, and M. Wolff. 2008. Trophic modeling of the Northern Humboldt Current Ecosystem, Part II: Elucidating ecosystem dynamics from 1995 to 2004 with a focus on the impact of ENSO. Progress in Oceanography 79:366-378.

Thompson, G.G., H.H. Zenger, and M.W. Dorn. 2006. Assessment of the Pacific cod stock in the Gulf of Alaska. *In* Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Gulf of Alaska. National Marine Fisheries Service. 147-220 pp.

Tollit, D.J., A.D. Schulze, A.W. Trites, P.F. Olesiuk, S.J. Crockford, T.S. Gelatt, R.R. Ream, and K.M. Miller. 2009. Development and application of DNA techniques for validating and improving pinniped diet estimates. Ecological Applications 19:889-905.

Tovey, C.P., M.J. Bradford, and L.-M. Herborg. 2009. Biological risk assessment for smallmouth bass (*Micropterus dolomieu*) and largemouth bass (*Micropterus salmoides*) in British Columbia. Canadian Science Advisory Secretariat Research Document 2008/075.

Trites, A.W. 1997. The role of pinnipeds in the ecosystem. Pp. 31-39. *In* G. Stone, J. Goebel and S. Webster (eds.). Pinniped populations, eastern north Pacific: status, trends and issues, New England Aquarium, Conservation Department, Boston.

Trites, A.W. 2003. Food webs in the ocean: who eats whom and how much? Pp. 125-143. *In* M. Sinclair and G. Valdimarsson (eds.). Responsible Fisheries in the Marine Ecosystem, FAO, Rome and CABI Publishing, Wallingford, U.K.

Trites, A.W. 2009. Predator-prey relationships. Pp. 933-936. *In* W. F. Perrin, B. Wursig and H. G. M. Thewissen (eds.). Encyclopedia of Marine Mammals, Academic Press, San Diego.

Trites, A.W., and M.A. Bigg. 1996. Physical growth of northern fur seals (*Callorhinus ursinus*): seasonal fluctuations and migratory influences. Journal of Zoology, London 238:459-482.

Trites, A.W., D.G. Calkins, and A.J. Winship. 2007. Diets of Steller sea lions (*Eumetopias jubatus*) in Southeast Alaska, 1993-1999. Fishery Bulletin 105:234-248.

Trites, A.W., V. Christensen, and D. Pauly. 1997. Competition between fisheries and marine mammals for prey and primary production in the Pacific Ocean. Journal of Northwest Atlantic Fishery Science 22:173-187.

Trites, A.W., and P.A. Larkin. 1996. Changes in the abundance of Steller sea lions (*Eumetopias jubatus*) in Alaska from 1956 to 1992: How many were there? Aquatic Mammals 22:153-166.

Turnock, B., and T. Wilderbuer. 2009. Gulf of Alaska arrowtooth flounder stock assessment. Pp. 627-680. NPFMC Gulf of Alaska SAFE, North Pacific Fisheries Management Council, Anchorage, AK.

Turnock, B.J., S.T. Buckland, and G.C. Boucher. 1995. Population abundance of Dall's porpoise (*Phocoenoides dalli*) in the western North Pacific Ocean. Report of the International Whaling Commission (Special Issue 16) 38:1-397.

Walker, W.A. 1996. Summer feeding habits of Dall's porpoise, *Phocoenoides dalli*, in the southern Sea of Okhotsk. Marine Mammal Science 12:167-181.

Walters, C. 1986. Adaptive management of renewable resources. McMillan, New York [Reprint edition available from Blackburn Press, 2001]. 374 pp.

Walters, C., and J.F. Kitchell. 2001. Cultivation/depensation effects on juvenile survival and recruitment: implications for the theory of fishing. Canadian Journal of Fisheries and Aquatic Sciences 58:39-50.

Walters, C.J., and S.J.D. Martell. 2004. Fisheries ecology and management. Princeton University Press, Princeton. 399 pp.

Walters, C.J., and M.J. Staley. 1987. Evidence against the existence of cyclicdominance in Fraser River sockeye salmon (*Oncorhynchus nerka*). Pp. 375-384. *In* H. D. Smith, L. Margolis and C. C. Wood (eds.). Sockeye Salmon (*Oncorhynchus nerka*) Population Biology and Future Management, Canadian Special Publication of Fisheries and Aquatic Science, 96.

Welch, D., L. Margolis, M. Henderson, and S. McKinnell. 1991. Evidence for attacks by the bathypelagic fish *Anotopterus pharao* (Myctophiformes) on Pacific salmon (*Oncorhynchus* spp.). Canadian Journal of Fisheries and Aquatic Sciences 48:2403-2407.

Weng, K.C., D.G. Foley, J.E. Ganong, C. Perle, G.L. Shillinger, and B.A. Block. 2008. Migration of an upper trophic level predator, the salmon shark *Lamna ditropis*, between distant ecoregions. Marine Ecology Progress Series 372:253-264.

Westrheim, S.J. 1996. On the Pacific cod (*Gadus macrocephalus*) in British Columbia waters, and a comparison with Pacific cod elsewhere, and Atlantic cod (*G. morhua*). Canadian Technical Report Fisheries and Aquatic Sciences 2092:1-390.

Winship, A.J., and A.W. Trites. 2003. Prey consumption of Steller sea lions (*Eumetopias jubatus*) off Alaska: How much prey do they require? Fishery Bulletin 101:147-167.

Winship, A.J., A.W. Trites, and D.A.S. Rosen. 2002. A bioenergetic model for estimating the food requirements of Steller sea lions (*Eumetopias jubatus*) in Alaska, USA. Marine Ecology Progress Series 229:291-312.

Wood, C. 1987. Predation of juvenile Pacific salmon by the common merganser (*Mergus merganser*) on eastern Vancouver Island. I: Predation during the seaward migration. Canadian Journal of Fisheries and Aquatic Sciences 44:941-949.

Worthy, G.A.J. 2008. An investigation into the possible relationship between killer whale (Orcinus orca) predation and the continuing decline of the Steller sea lion (*Eumetopias jubatus*) population. Final Report to the Pollock Conservation Cooperative Research Center. PCCRC FP204077/. 82 pp.

Wydoski, R.S., and R.R. Whitney. 2003. Inland fishes of Washington State. University of Washington Press, Seattle, WA. 322 pp.

Yang, M.-S., and M.W. Nelson. 2000. Food habits of the commercially important groundfishes in the Gulf of Alaska in 1990, 1993, and 1996. NOAA Technical Memorandum, NMFS-AFSC-112. 174 p. pp.

Yang, M.S., and B.N. Page. 1999. Diet of Pacific sleeper shark, *Somniosus pacificus,* in the Gulf of Alaska. Fishery Bulletin 97:406-409.

Yurk, H., and A.W. Trites. 2000. Experimental attempts to reduce predation by harbour seals (*Phoca vitulina*) on outmigrating juvenile salmonids. Transactions of the American Fisheries Society 129:1243-1249.

Zamon, J.E. 2001. Seal predation on salmon and forage fish schools as a function of tidal currents in the San Juan Islands, Washington, USA. Fisheries Oceanography 10:353-366.

Appendix 1. Statement of work

"Effects of Predators on Fraser River Sockeye Salmon"

SW1 Background

1.1 The Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River (www.cohencommission.ca) was established to investigate and report on the reasons for the decline and the long term prospects for Fraser River sockeye salmon stocks and to determine whether changes need to be made to fisheries management policies, practices and procedures.

SW2 Objective

2.1 To prepare a technical report containing an evaluation of the effects of predators on Fraser River sockeye salmon.

SW3 Scope of Work

3.1 The Contractor will prepare a description of predation on sockeye salmon across the geographical range of the population, focusing on marine mammal predation on adults and smolts.

3.2 Another Contractor (Salmon-060 – Villy Christensen) will prepare an evaluation of freshwater fish predation on alevins, fry and smolts, and marine fish predation on smolts, sub-adults and adults. Dr. Christensen will prepare a report on fish predation that includes digital copies of figures and tables.

3.3 The Contractor will assume responsibility for integrating a fish predation assessment to be provided by the Commission prior to November 15, 2010, with the marine mammal predation assessment. An overall assessment of predation will be developed for the suite of predators that are encountered by juvenile and adult sockeye salmon.

3.4 The Contractor will evaluate the extent to which reductions in sockeye abundance are associated with predators in the Fraser River and in the marine areas frequented by Fraser sockeye.

SW4 Deliverables

4.1 The Contractor will organize a Project Inception meeting to be held within 2 weeks of the contract date in the Commission office. The meeting agenda will be set by the Contractor and will include a work plan for project implementation.

4.2 The main deliverables of the contract are 2 reports evaluating the effects of predators on Fraser River sockeye: 1) a progress report, and 2) a final report. The style for the Reports will be a hybrid between a scientific style and a policy document. An example of a document which follows this format is the BC Pacific Salmon Forum Final Report (www.pacificsalmonforum.ca).

4.3 A Progress Report (maximum 20 pages) will be provided to the Cohen Commission in pdf and Word formats by Nov. 1, 2010. Comments on the Progress Report will be returned to the contractor by Nov. 15, 2010.

4.4 A draft Final Report will be provided to the Cohen Commission in pdf and Word formats by Dec. 15, 2010. The draft Final Report should contain an expanded Executive Summary of 1-2 pages in length as well as a 1-page summary of the "State of the Science". Comments on the draft Final Report will be returned to the contractor by Jan. 15, 2011 with revisions due by Jan. 31, 2011.

4.5 The Contractor will make himself available to Commission Counsel during hearing preparation and may be called as a witness.

4.6 The Contractor will participate in a scientific workshop (tentatively November 30 – December 1, 2010) with the Scientific Advisory Panel and other Contractors preparing Cohen Commission Technical Reports to address cumulative effects and to initiate discussions about the possible causes of the decline and of the 2009 run failure.

4.7 The Contractor will participate in a 2-day meeting presenting to and engaging with the Participants and the public on the effects of predators on Fraser sockeye in (tentatively February 23-24, 2011).

“Fish Predation on Fraser River Sockeye Salmon”

SW1 Background

1.1 The Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River (www.cohencommission.ca) was established to investigate and report on the reasons for the decline and the long term prospects for Fraser River sockeye salmon stocks and to determine whether changes need to be made to fisheries management policies, practices and procedures.

SW2 Objective

2.1 Technical analysis is required to evaluate the effects of marine and freshwater fish predators on Fraser River sockeye salmon.

SW3 Scope of Work

3.1 The Contractor will prepare an description of predation on sockeye salmon across the geographical range of the population, focusing on fish predation on adults and smolts.

3.2 The Contractor will prepare an evaluation of freshwater fish predation on alevins, fry and smolts, and marine fish predation on smolts, sub-adults and adults. This evaluation will include a report that includes digital copies of figures and tables.

3.3 The Contractor will collaborate with Dr. Andrew Trites for integrating the fish predation assessment with the marine mammal predation assessment. An overall assessment of predation will be developed for the suite of predators that are encountered by juvenile and adult sockeye salmon.

3.4 The Contractor will evaluate the extent to which reductions in sockeye abundance are associated with fish predators in the Fraser River and in the marine areas frequented by Fraser sockeye.

SW4 Deliverables

4.1 The Contractor will organize a Project Inception meeting to be held within 2 weeks of the contract date in the Commission office. The meeting agenda will be set by the Contractor and will include a work plan for project implementation.

4.2 The main deliverables of the contract are 2 reports evaluating the effects of predators on Fraser River sockeye: 1) a progress report, and 2) a final report. The style for the Reports will be a hybrid between a scientific style and a policy document. An example of a document which follows this format is the BC Pacific Salmon Forum Final Report (www.pacificsalmonforum.ca).

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4.5 The Contractor will make himself available to Commission Counsel during hearing preparation and may be called as a witness.

4.6 The Contractor will participate in a 2-day scientific workshop on November 30 – December 1, 2010 with the other Contractors preparing Cohen Commission Technical Reports to address cumulative effects and to initiate discussions about the possible causes of the decline and of the 2009 run failure.

4.7 The Contractor will participate in a 2-day meeting presenting to and engaging with the Participants and the public on the effects of fish predators on Fraser sockeye on February 23-24, 2011.

Appendix 2. Reviews and responses

Reviewer: Sonja Saksida

1. Identify the strengths and weaknesses of this report.	
Reviewer's comments	Authors' response
This report was very well written and enjoyable to read. The document was very easy to follow.	None required
I found the first sentence in the executive summary a bit anthropomorphic but it does bring home the point.	None required
I also agree with the sentence on page 7 (Ln 27-28).	None required
The executive summary provides a very good summation of the document and solid approaches.	None required
The document provides interesting hypotheses regarding competition and predation (i.e. returning pink salmon consuming sockeye smolts?).	We have updated the hypotheses referred to
Author does a good job introducing the concept that multiple contributing factors are more likely at play than a smoking gun (single factor).	None required
Good use of tables and figures.	None required
Good summary of predators in both the marine and freshwater environments.	None required
Good discussion of SEP hatchery issue.	None required
Overall recommendations are solid and the issue of insufficient funding and the need to develop a systematic approach well presented.	None required

2. Evaluate the interpretation of the available data, and the validity of any derived conclusions. Overall, does the report represent the best scientific interpretation of the available data?	
Reviewer's comments	Authors' response
Good assessment of the data available.	None required

3. Are there additional quantitative or qualitative ways to evaluate the subject area not considered in this report? How could the analysis be improved?	
Reviewer's comments	Authors' response
Don't think there is much improvement needed.	None required

4. Are the recommendations provided in this report supportable? Do you have any further recommendations to add?	
Reviewer's comments	Authors' response
The recommendations are well supported and complete.	None required

5. What information, if any, should be collected in the future to improve our understanding of this subject area?	
Reviewer's comments	Authors' response
The authors provide a good summary of the information that needs to be collected.	None required

6. Please provide any specific comments for the authors.	
Reviewer's comments	Authors' response
Pg 44 Ln 16 - "the" not they sockeye Pg 45 Ln10 - in not In	Corrected
Pg 47 - rescale figure - axis difficult to read	Done
Pg 49 Ln 12 - word missing - should read Pacific Hake	OK as is

Pg 50 Ln 19 - missing word - it 'is' currently . . .	Corrected (but was OK)
Pg 64 – should this figure read California not Steller sea lions?	Corrected
Pg 65 Ln 10-12 - Sentence is confusing - a 2 year old seal not salmon?	The sentence has been clarified
Pg 72 Ln 12- spacing issues	Corrected
Pg73 Ln11 - Levin not Levein?	Corrected
Pg77 Ln 15 - incorrect date 2011? Also in references (or is this document in press?)	Year is correct, and reference is OK. Yes, the book was in press at the time.

Reviewer: Marc Labelle

1. Identify the strengths and weaknesses of this report.	
Reviewer's comments	Authors' response
Strengths: The draft report is an authoritative and extensive review of pertinent documents and data sets summarizing the possible impacts of known and hypothesized sockeye salmon predators, both in fresh water and marine environments.	None required
Weaknesses: The report does not provide estimates of total predator impacts on various life history stages, so one cannot determine if predation is a major factor that could account for the relatively low sockeye returns in 2009. However, this is largely due to the paucity of data on the abundance of predators, and is not the fault of the authors.	Given the very sporadic and incomplete knowledge of the abundance, trend and diet of potentially important predators, we found attempts to quantify the effect of predation to be too speculative.

2. Evaluate the interpretation of the available data, and the validity of any derived conclusions. Overall, does the report represent the best scientific interpretation of the available data?	
Reviewer's comments	Authors' response
This draft report provides little in terms of interpretation largely because of the paucity of data on some species.	Agree
But given the time constraints, the report can be considered as one of the best scientific review and summary that could be produced.	None required

3. Are there additional quantitative or qualitative ways to evaluate the subject area not considered in this report? How could the analysis be improved?	
Reviewer's comments	Authors' response
More rigorous and scientifically sound quantitative assessments could be conducted, but these would certainly require much more data than are currently available.	Data limitations is the key reason for this, and any analysis that goes into this report have to well-founded
The qualitative assessments of potential impacts could be improved by first obtaining more information on the abundance and spatio-temporal distribution of the main predators identified by the authors in Table 6, and possibly those of other potential predators mentioned by the current peer reviewer.	We fully agree, but we have not been able to obtain more information about abundance and spatial/temporal distributions. This is indeed called for, as considered in our recommendations
4. Are the recommendations provided in this report supportable? Do you have any further recommendations to add?	
Reviewer's comments	Authors' response
The authors provide few recommendations *per se*, and those provided are somewhat superficial and could be more explicitly written.	Agreed. We have added a recommendation section to our Discussion
Those provided by the current peer reviewer are given in the separate attachment. The authors can consider these, and include them in	Discussed below

their report if they support these or alternative ones based on these.	
5. What information, if any, should be collected in the future to improve our understanding of this subject area?	
Reviewer's comments	Authors' response
As noted above, the authors identify important data gaps for some key predators, mainly concerning abundance, distribution and consumption.	None required
Additional efforts should be made to provide greater insight into their possible impacts on survival rates of BC salmon stocks in general.	This would be interesting for a follow-up study, but was not part of the Statement of Work for our study
A few additional ones are suggested by the current peer reviewer in the attachment, with special emphasis on fresh water species that should be more actively monitored and managed by the BC Ministry of Environment.	Noted and incorporated as discussed below
6. Please provide any specific comments for the authors.	
Reviewer's comments	Authors' response
The draft report is an authoritative review of pertinent documents and data sets summarizing the possible impacts of known and hypothesized sockeye salmon predators, both in fresh water and marine environments. Despite the relatively short time available to conduct this review, the authors managed highlight pertinent data gaps that merit further investigation to better quantify the impacts of predators on Fraser River sockeye abundance over time. The following comments focus on perceived gaps and shortcomings of the draft report as written.	None required
Editorial issues The report covers much ground and is well-written, but some editorial changes seem justified. The writing style in some sections is	We have edited the text and updated the references.

somewhat verbose with several unnecessary comments. There are also some redundancies throughout, a few typographical errors, and incomplete references.	
<u>Content issues</u> Pages 17-23: The authors provide convincing arguments that juvenile coho and chinook salmon can affect pre-smolt sockeye survival that account for some of the variation in sockeye productivity. The Department of Fisheries & Oceans (DFO) has data on the abundance of these three species that could be used to investigate this issue.	We do not find it likely that these species are behind the decline of Fraser River sockeye as they have been declining in recent decades. Hence, no need to elaborate on this.
However, other fresh water species are known to prey upon (not "predate on" as stated on p.20) the early life history stages of sockeye.	We have used the term "predating on", which is acceptable. The term "predate on" is not in the report.
Ideally one should account for the combined impacts of all predatory fish species. Additional ones of concern include cutthroat trout, burbot, northern pikeminnow, smallmouth and largemouth bass, yellow perch and sculpins.	We are discussing what is known for these species, but cannot quantify their combined effect for lack of abundance information and of reliable quantitative information about the diets of these potential predators.
The authors highlight the paucity of data on the abundance of these species in the Fraser River watershed. The BC Ministry of Environment (MoE) is responsible for (i) monitoring these species, (ii) managing the supported sport fisheries, and (ii) help control (or eradicate) recently introduced species (e.g. perch).	No response required
The MoE authorized predator removal programs in the Shuswap drainage in recent years, but does not conduct periodical and scientifically defensible surveys of fish population assemblages throughout BC.	Discussed
The existing inventory database records are dated, incomplete, and of little use to help to quantify total impacts on pre-smolt sockeye production from the Fraser River drainage.	No response required

The authors should consider recommending that the MoE take the necessary steps to radically improve monitoring activities and update their inventory records.	This is highlighted in our Recommendations section
As is, the authors simply state there is not enough evidence to support the hypothesis that this predator species is 'a major factor'... Well, a distinction should be made about the lack of support given substantial data, and the lack of support given the absence of data.	We have gone through the conclusions for the various species with this in mind
The authors comment on the potential impacts of rainbow trout in Kootenay Lake, and draw attention to the trends shown in Fig. 4. That figure and associated passages should be removed, as they are not linked in any way to the Fraser River sockeye problems.	We have removed this Fig 4.
One potential fresh water predator not mentioned is sturgeon. In the early 1990s, Dr. Marvin Rosenau reported that several large sturgeons were found dead in the lower Fraser beaches, and further examination revealed they were gorged with pink salmon (among other preys). This led the BC Ministry of Environment Lands and Parks (MELP) to initiate surveys to determine the state of the sturgeon population in the Fraser River basin. Sturgeon surveys have since been subject to extensive investigations, in part via an extensive mark-recapture program. The results may contain information on the diet of sturgeon, and help determine if they prey substantially on live sockeye or simply scavenge opportunistically on salmon that die and settle on the bottom.	Sturgeon can only be a factor for returning sockeye, and by the time they reach the river the year class strength has already been determined. We therefore don't find it necessary to include sturgeon in the report.
Pages 32-55: The section on oceanic predators does not mention jellyfish as a potential killer of sockeye. BC fishermen mainly catch adult salmon in surface waters (used by migrating	This is very speculative and there are no quantitative time series data from BC waters that can be used to evaluate their trend in recent decades (L. Brotz, pers. comm.) We do

sockeye smolts earlier), and occasionally encounter high densities of jellyfish in coastal waters north of Queen Charlotte Strait. Even on-board observers likely record large concentrations when encountered. There were several unexplained major blooms of giant jellyfish (Nomura's jellyfish, *Nemopilema nomurai*) off the coast of Japan in recent years (including 2003, 2005, 2010), that clogged up nets of fishermen targeting salmon, and contaminated other species subject to harvest. Little is known about the abundance and spatio-temporal distribution of various species of jellyfish, so their impacts (if any) cannot be quantified with certainty. The authors might consider look into this issue, and determine if jellyfish should be considered as a potential killer of Fraser River sockeye.	not find it necessary to include jellyfish as predators on smolts as these likely are too big for the jellyfish occurring here.
P.70: Table 6 is a good summary of the main findings. As noted earlier, trends in abundance levels (or total predator biomass as recommended during the Vancouver workshop) should be in the table. Even crude figures would be helpful at this stage	We have included trend information in Table 5, while Table 6 has some sporadic estimates of mortality rates. We included all we could find.
Page 72-77: The authors note that 'Ecosystem food web modelling' could be used to quantitatively evaluate the potential significance of an increase in predator biomass....'. The outputs of such models are not always accurate or even helpful for day-to-day fishery management purposes. Some can have substantial data requirements that are not readily available, and rely heavily on assumptions that are not easily verifiable. The authors might consider stating they are 'qualitative' assessment methods that help identify future investigation priorities.	The first author, whose speciality this is, tend to disagree with regard to the models not being useful for management. The models need, however, to be based on data, and in the specific case of Fraser River sockeye the data material is to sparse to allow meaningful evaluation of predation mortality in notably the freshwater and open ocean stages. This is a clear result of how salmon research is prioritized with no to little concern for the ecosystems (apart from physical freshwater habitats) the sockeye encounter.
The authors then note the need for	We can only agree with the reviewer that

"Ecosystem-based management" approaches. It is important to make a clear distinction between Ecosystem-based assessments and Ecosystem-based management approaches, so the reader does not assume both are required. An Ecosystem-based management approach is not an all-encompassing do-it-all framework. Each needs to specify what is covered in terms of species mix, types of interactions, environmental variables, monitoring requirements, and etc. Many national fishery agencies and Regional Fishery Management Organizations (RFMOs) are still struggling with such issues, and have not yet adopted the same interpretations, standards, objectives and policies (see review by Currie for instance)[1]. One can progressively move towards an 'Ecosystem-based management' system simply by accounting for the effects additional variables in single species models (like recruitment losses to predators), by minimizing by-catch, protecting unique habitats, allowing for refuges, and etc. In fact, DFO is already moving in this direction, the authors might consider re-writing this section to better focus attention on the issues of concern.	introduction of EBM approaches is moving far too slowly. We do, however, not just call for ecosystem-based assessments but for ecosystem-based management, which is in line with the official DFO policy, but which is not making much headway. It is not just a question of gradually improving population dynamics models as the reviewers suggests, but even more a question of how to evaluate tradeoffs between alternative management scenarios.
P. 77: Ecosystem Manipulations. The authors seem to suggest that deliberately manipulating an ecosystem is "scary", and almost inevitably harmful. The term "scary' is hardly justified. Hunting and fishing activities have been conducted for centuries, and can be considered as deliberate manipulations of the ecosystem with undeniable impacts. However, more recent attempts to manipulate parts of some ecosystems in BC did not produce the results	We do find them scary as we have to understand the consequences, or at least evaluate those carefully if manipulations are part of adaptive management experiments. We think the term scary reflects that there is growing concern as we get more types of stakeholders involved. We do not suggest that manipulations "almost inevitably" are harmful. We have, however, modified the section to make clear the distinction between past and

[1] http://assets.panda.org/downloads/wwf_ecosystem_paper_final_wlogo.pdf

expected (including one by the junior author's Ph.D supervisor at UBC), but others such as fertilization, short term hatchery supplementation, non-native predator removals, and native species re-introduction have helped compensate for negative impacts (excessive exploitation, habitat loss, urbanization, pollution, etc.). So not all ecosystem manipulations should be considered (or termed) as harmful or scary.	present practices. Covering all aspects of manipulations is beyond the scope of the report.
Finally, the authors note the data and model limitations, and recommend carefully establishing the experimental protocols as part of the adaptive management process advocated by Walters (1986). The underlying assumptions used for modelling purposes may be wrong, and important links might not be included, so the predicted outcomes may not match the true outcomes. In fact, some deliberate ecosystem manipulations advocated by Walters (1986) can be considered as a simple way of learning by 'trial-and-error' to gain insight into the dynamics of the natural system under study, and in turn, help improve the model describing its dynamics (not necessarily vice-versa). So the authors might consider re-phrasing some passages.	We agree with the reviewer, and we could add a section on adaptive management, but it is really beyond the scope of the report.
In light of the above, it is recommended that the authors consider making adjustments to some sections and passages throughout the report, and then adjusting the executive summary accordingly.	We have made a large number of adjustments throughout the report, taking into consideration the suggestions from all reviewers.

Reviewer: Eric Taylor

1. Identify the strengths and weaknesses of this report.	
Reviewer's comments	Authors' response
Overall, this report is a useful, largely descriptive, summary of the issue of predation and how it may influence productivity of sockeye salmon. In general, it is well-written and presented and I think summarizes the state of affairs adequately.	None required
The issue of predation is a complicated one because even if one can demonstrate some kind of major change that could be responsible for major declines of sockeye salmon, deciding what to do about it is extremely difficult. Except in the rare case of an exotic (introduced) predator that has become invasive and seriously negatively affected sockeye salmon any kind of predator control program, even if one were feasible, can be very controversial and fraught with value judgements. Still, even knowing where the problem lies even if you cannot mitigate it would be useful. Several important revisions would help this report.	There are cases where mitigation through ecosystem manipulation may be possible, but such are indeed likely to be controversial.
1. **Better documentation**. I understand the difficulty in assessing role of predation with so little data, but the report reads as a bit "glib" in places – too easily dismissing the effect of predators without any real analyses or substantiation of some broad conclusions.	There is very little information about abundances, trends, and diets for most of the potential predators. If we are to conclude anything we have to use subjective perceptions (or professional judgment) to rule out some of what we consider to be unlikely candidates.
Some specific examples are given below, but in general I wonder if the conclusions might be more rigorous if the authors conducted some kind of "alternative scenarios" for trends in predator occurrence or abundance under the hypothesis of predator-induced declines in sockeye at least in verbal form to help structure their argument. The authors could derive a set of "expectations" under the hypothesis of predator effects. What patterns would be expected if predation was a major factor in the decline?	The form for modeling suggested by the reviewer is what the first authors is specialized in conducting. To develop such scenarios in a credible fashion, however, calls for much more data than is available, and we do not consider it feasible to conduct such an evaluation. Doing this in "verbal form" (i.e. qualitative, we presume) would call for a major re-writing of this report, which is beyond the time available to us. Predation is not a question of one or a few predators impacting Fraser River sockeye salmon. Rather, it is the cumulative impact that is important. We cannot predict an overall pattern based on a qualitative evaluation of this form.

Too often there are rather casual and vague statements about the potential, or not, role of predation. For example, page 18, line 34-35 ends the section with: "…but there is nothing indicating that cutthroat should be potentially important factor for the decline of Fraser River sockeye salmon". What is meant by "nothing"? What would you expect to see if cct were a factor in the decline of sockeye salmon? Are there specific data to test this expectation? How would it be tested? What info is needed to perform a critical test??	The reviewer poses good questions, which we dealt with elsewhere in our report. With regards to the cutthroat trout, rather than detailing the hypothetical contribution of cutthroat, we have chosen to reformulate the sentence quoted by the reviewer, to make it clear that is it our subjective evaluation that cutthroat are unlikely to be a major factor.
Also, some of the conclusions that authors make are rather poorly substantiated. For instance, in the section on possible roles of exotic predators the authors "conclude" that: "There are no estimates of their abundance or trends in the Fraser River system, and there is overall nothing that indicates they should be connected to the recent decline in Fraser River sockeye salmon." DFO has done some modelling of spread of exotics, at least in the lower Fraser and the province has a database tracking occurrence. The authors need to demonstrate that they have checked all these sources more thoroughly (via pers. comms with responsible gov't biologists - Bradford (DFO), Pollard (MoE))..	We have updated the information about exotics, consulted DFO/MoE colleagues, and added new material to these sections to accommodate the reviewer's concern.
The section on Yellow Perch is a much better effort in this regard. Their conclusions appear to be based on superficial "analysis" and rushed in places	We have tried to make it clearer where our conclusions are subjective, but given the number of potential predators, it was necessary to focus on predators that may be abundant enough to have had noteworthy impact.
2. Bioenergetics modelling. Related to the point above. The authors refer several times to bioenergetic models that have been generated to try and estimate the number of salmon eaten by various predators. Could this approach be exploited more generally to generate an expected "consumption level" of juvenile sockeye salmon at one or several life history stages and the number of single or combined	We made a model along the lines suggested by the reviewer with the purpose of evaluating potential impact. We concluded, however, that with the available information, it was a work of fiction rather than of science. The first author of this report has worked with this form of analysis for two decades, and has made a large number of such models, but rarely found as little information as is available about potential

predators that would <u>need</u> to be observed to account for a level of predation that <u>could</u> account for the observed declines in sockeye returns?? Yes, it would be "back of the envelope" and very crude, but it might provide a benchmark or ballpark figure of required abundance of predators to explain sockeye declines (and presumably to support their lack of effect). Right now, the presentation (at least for birds and fw fishes) is very *ad hoc* and vague and appears that the authors have rushed this part. At the very least, and if the authors feel that this approach is not worth pursuing, they should explain their rationale.	predators as for the freshwater and ocean environments that the Fraser River sockeye encounters.
3. Style. More of a stylistic point. I don't think that the analogy involving Poroit (page 68 line 17) is particularly effective – in fact, I think it is distracting. I won't go on here, but I think this analogy tends to trivialize, I am sure unintentionally, the sockeye problem and the biology. This is not an account of fiction, but an investigation into the instability of a crucial aspect of BC bioheritage.	The reviewer must remember that this report was supposed to be "a hybrid between a scientific style and a policy document". We don't agree that this analogy will trivialize the matter, but rather that it helps explain that we're likely dealing with several "culprits" when evaluating the role of predation.
4. Incompleteness. Tables 5 and 6 are a start at some kind of cumulative impacts "analysis" but it is never completed. The authors never put the pieces in the tables together. What is to be concluded from the info in Tables 5 and 6? If their data are too incomplete, the authors need to be explicit about that.	We have expanded the section on cumulative effects and provide some additional interpretation of Tables 5 and 6
5. Section on Dominance cycles seems peripheral. Why is this section included? The issues is not what causes dominance cycles, but what caused the apparent wildly unforeseen declines/increases of sockeye *within* the "normal" dominance cycles. How will understanding what causes dominance cycles help us understand why few fish showed up in 2009 and so many in 2010 when the opposite was predicted??	We included this section to illustrate that the discussion about the role of predation has been going on for a while and that predation is believed to be behind the cyclic dominance. Still, this has not been prioritized when deciding on what research/monitoring that should be conducted. Further, our study was not focused on 2009/10 but looked more generally at the trend for sockeye in the last decade.
6. Ecosystem management. This section sounds all good, but the problem is defining what it really means and if it is realistic in terms of predators. The authors section on "Ecosystem management" discusses one of the real issues. An ecosystem model that identifies	None required

a suite of predators as an important issue for salmon is one thing (and a good thing), what to do about is a quite another.	
The examples of predator control are misleading. Rotenone control, I doubt, is a “common happening” in BC lakes, quite the opposite. It is, in the absence of actual statistics cited by the authors, quite rare I would imagine and probably only, now at least, to control exotic species, not natural predators or in experimental manipulations. Pikeminnow control? How common is this in BC. Rare I bet. Did it work in Cultus Lake? Has it been rigorously assessed as a management tool from more than a “salmon-centric” viewpoint?? *Mysis*? A classic example of an exotic introduction with hugely unintended consequences and that was more than 40 years ago. Hardly correct to use it as an example of ecosystem manipulation that “…is applied very freely…” Not in today’s world at least in BC. This section needs to be revised to reflect current attitudes, not management attitudes of the 1960s.	We have revised the formulations to distinguish between past and current practices as suggested by the reviewer.
2. Evaluate the interpretation of the available data, and the validity of any derived conclusions. Overall, does the report represent the best scientific interpretation of the available data?	
Reviewer’s comments	Authors’ response
I think this is addressed above. Generally, yes, but see above. I think that the authors have it right, generally, but a bit more rigor is required.	None required
3. Are there additional quantitative or qualitative ways to evaluate the subject area not considered in this report? How could the analysis be improved?	
Reviewer’s comments	Authors’ response
See above re: bioenergetic modelling and better set-up of expectations of trends in predators and prey under “the predation hypothesis”.	Addressed above

4. Are the recommendations provided in this report supportable? Do you have any further recommendations to add?

Reviewer's comments	Authors' response
Yes, reasonable, esp. in terms of integrated ecosystem management or better understanding what of limits sockeye and other fishery resources. Not that we will be able (or necessarily should) to do much about natural constraints. Such info will be useful to better argue for prevention/mediation of things we can do something about – like habitat loss and degradation.	None required
The key issues influencing salmon persistence, outside of overexploitation, will be climate change and habitat loss and degradation.	None required
Predator limitation, except in the rare cases of an invasive predator or pathogen, are unlikely to be critical factors (or at least they will be overwhelmed by climate change and habitat loss/degradation).	This is the reviewer's opinion. If predation is a major factor and if the key predators could be identified (which would call for studies; hardly any have been conducted), we would be able to better prioritize where to allocate resources. The practice up to now has been to study where it is easy to do so, in freshwater and in coastal areas. Astonishingly little is known about the environment where Fraser River sockeye spend half of their lives, and where indications are that survival has declined in the decade of special concern.

5. What information, if any, should be collected in the future to improve our understanding of this subject area?

Reviewer's comments	Authors' response
Personally, I think not much as I do not believe that any real management action can come out of understanding predator interactions (or at least other factors in the ecology of salmon, like habitat protection, are more practical to understand and improve).	We disagree with the reviewer on this point, knowing many examples where understanding predator interactions are important for management. Even if habitat protection is easier to understand, it may not be of importance for improving the marine survival of Fraser River sockeye salmon.
Some ecosystem modelling to understand natural predator constraints (Ecosim-type modelling) would be good to interpret natural constraints on sustainability of salmon in light of other more human-imposed constraints (overharvest, habitat loss).	Yes, and this is where the first author has his expertise. We have concluded, however, that for the purpose of the Cohen Commission, the modeling would be too uncertain and hence too open to alternative interpretations to be defendable.

For instance, if we know that pelagic marine predators "regulate" sockeye salmon production in the ocean to, on average X millions of maturing adults per year, we better make sure that the freshwater environment of the Fraser River is in good enough shape (habitat, thermal regime) to "accept" those returnees each year.	The ocean carrying capacity is variable, marine survival is variable, so quite unclear where the reviewer is heading with this "build it and they will come" attitude. But yes, we shouldn't destroy the habitats that are critical for Fraser River sockeye, but do we know that those are limiting factors?
We probably can do nothing about the marine predators (nor should we necessarily), but we need info to account for their effects.	Yes, and this is one clear conclusion from this report: we need information about the abundance, trend, and diets of predators
The one exception would better monitor occurrence and spread of invasive species, largely, but not exclusively, in freshwater conduct research on how to minimize and eliminate exotic predators.	Invasive species is an example, but it is not an exception. We manipulate the marine environment as well, and the example of seal culling we provide with its unintended consequences gives a clear example.

6. Please provide any specific comments for the authors.

Reviewer's comments	Authors' response
Page 12, line 31. Examples of competitors that have decreased??	The section "Sympathy for the predators" described this
Page 12, line 33. Massive hatchery releases of salmon should moderate this potential effect to some extent	Even if the hatchery releases are massive, they do not compare to the several million tonnes of alternative prey that has disappeared
Page 14, line 19. Italicize sp. name	Corrected
Page 15. I am not sure what the general point is in the section "Salmon forests" (which seems like a distracting name – the report has nothing to do with salmon effects on forest productivity). I get the point of the figure, just not what general point the authors are trying to make given the mandate of the report.	It does deal with predation even if it is peripheral for the report, but it is of interest for the Cohen Commission, so we decided to include it.
Page 16, line 9. But what about the cumulative effects of rare predators??	In theory they may matter, but without numbers we will be unable to make a cumulative analysis. In general, (not just for rare species), this is what stops up from making such a cumulative analysis
Page 16, line 24. Is the Parker citation referring to sockeye salmon or pink salmon?	This is for salmon smolts in general – as far as we can tell, we do not have access to the original report, and quote it as cited by Beamish and Neville.
Table 1. Bull trout (*Salvelinus confluentus*) should be listed as they are major piscivores in Fraser system lakes (both in interior and much	We have included bull trout with a brief rebuttal of its potential importance. We have not been able to locate the monitoring data the

of the coast) and anadromous bull trout are abundant and efficient piscivores in the Fraser delta area. Likely much more important than Dolly Varden. Bull trout have been monitored extensively, for instance, in the Pitt Lake/River system by hatchery employees.	reviewer refers to even after extensive searches and consultation with a specialist on the Fraser River.
Some effort should be made to list *Cottus* species individually. Listing "spp." Is ambiguous, is it four species or 100 species? Also, don't italicize the "spp."	We corrected the last part of this, but do not go into details about a species complex. We provide details in the text about species that we think should suffice.
Page 18. Should be "Coastal cutthroat trout" (*O. clarkii clarkii*)	Corrected
Page 19, line 34. But Kootenay Lake is a very perturbed system and is fertilized annually and has kokanee spawning channels. Very difficult to conclude anything about rbtr predation here with such confounding effects. Still, I'd like to see a line superimposed on Figure 4 that shows estimates of kokanee (spawners	We have deleted the figure based on a recommendation from another reviewer
Page 19, lines 6-8. Statements about steelhead are vague here. Surely there is some trend info for the major populations?	If there is any trend information for steelhead we have not been able to locate it. Given the widespread concern of steelhead due to their decline in recent decades it really should be clear that they cannot be causing the decline in Fraser River sockeye.
Page 21, line 3. word missing ("study"?)	Couldn't find this, but changed the sentence.
Page 21, line 17. What about the great predator (pikeminnow) elimination "experiment" in Cultus Lake?? Did it work (did predation rates or returns of sockeye change)? If not, why not? What can be learned from it? What about Ricker's study of predators in Cultus Lake?	We rule pikeminnow out as a major contributor, and we are not able to cover all topics related to predation within the time allocated for this review. We have had to prioritize, which we hope the reviewer understands
Page 21, line 29. Are you sure about this?? DFO has done some work on spread or potential spread of these exotics? So has the province. The authors should provide some verification (pers. comms. From provincial, DFO biologists that these data do not in fact exist).	We contacted provincial and DFO biologists about this. It didn't lead to any information about abundance. Section is updated.
Page 22, line 27. This section on pike is a bit misleading. *Esox lucius* is not even found in the Fraser system (see McPhail 2007). The authors may be thinking of Alaskan systems where this species is can be an issue. The only issue wrt the Fraser is if pike were ever to be introduced (from the Peace system – again see	We have deleted the section on Northern pike

discussion in McPhail 2007).	
Page 35, line 23. This is an awkwardly-worded sentence – something isn't right.	Indeed, fixed.
Page 42, line 7. Why can't you test this? Was the poor 2009 return associated with a high pink return when 2009 brood sockeye were coastal-migrating immatures? Could you test across years lagging sockeye returning and pink returns. Another example of a rather meaningless speculation if untested/testable.	This was not meaningless speculation, but incomplete text. The hypothesis was put forward by G. Ruggerone at the 2010 PSC sockeye workshop. We have tested it now, and don't find supporting evidence. We have updated the text.
Page 44, line 15-18. This seems kinda' fanciful to even suggest for a primarily planktivorous fish. Why not investigate the alternative prey idea introduced earlier. Could declines of herring put more pressure in sockeye from predators? Much of the section deals with competition not predation.	Herring has been a species of focus for the first author. Herring can exert predation pressure on smaller species, e.g., sprat and capelin, but as described it is unlikely to be the case with sockeye smolt.
Page 52, line 6. This is an awkwardly-worded sentence – something isn't right.	Indeed, fixed.

Appendix 3. Terms and acronyms

CBC: Christmas Bird Counts, a standardized bird count held during mid-December to early January annually since 1900

CPUE: Catch per Unit Effort, a commonly used estimate for abundance trends, often standardized for changes in catchability

Depensation: Where decreased population size leads to reduced recruitment, e.g., through increased predation rates on juveniles. This is in contrast to the surplus production normally expected in such cases

DFO: Fisheries and Ocean Canada

Estuarine: Of or related to the border zone between freshwater and marine environments

FL: Fork length, a standard measurement of finfish taken from the snout to the middle of the caudal fin

Foraging arena: The leading theory for explaining predatory-prey interactions; incorporates prey behavior to reduce predation. Developed by Carl Walters over the last decades

GBBC: Great Backyard Bird Count, a bird count held during mid-February to early March annually since 1999

IM: DFO designation for Integrated Management; corresponds to what elsewhere is called Ecosystem-based Management

ICES: The North Atlantic International Council for Exploration of the Sea

IPHC: International Pacific Halibut Commission

IPSFC International Pacific Salmon Fisheries Commission

Limnetic: The open-water parts of a lake or body of freshwater where photosynthesis can occur

Littoral: The near-shore part of a body of water

LME: Large Marine Ecosystem, a designation used globally, notably by NOAA and the Global Environment Facility, for a large marine area that is candidate for introduction of ecosystem-based management. Canadian version is called LOMA

LOMA: Large Ocean Management Area, a DFO designation for ocean areas for development of integrated management plans, (http://www.dfo-mpo.gc.ca/oceans/marineareas-zonesmarines/loma-zego/approach-approche-eng.htm). Corresponds to what elsewhere is called LME, but with a single, coordinated management plan, which LMEs typically don't have. LOMA development involves four steps: (1) Initiation of the

	planning process, (2) Informing and reporting, (3) Setting of management objectives, (4) Development and implementation of IM plans
NMFS:	National Marine Fisheries Service in the US, forms part of NOAA, and is responsible for fisheries assessment and management outside state water
NPFMC:	North Pacific Fisheries Management Council, Anchorage, Alaska is one of eight regional councils established by the US Magnuson Fishery Conservation and Management Act in 1976, responsible for fisheries management in the Alaskan EEZ
NOAA:	The US National Oceanographic and Atmospheric Administration of the Department of Commerce
PFMC:	Pacific Fishery Management Council, based in Portland Oregon, and responsible for fisheries management of the US Pacific continental EEZ.
PICES	The North Pacific Marine Science Organization (a.k.a. the Pacific ICES)
Piscivore:	A fish eater
SL:	Standard length, a standard measurement of finfish taken from the snout to the end of the caudal fin

Appendix 4. Data sets and sources

Data set	File/description	Source/reference
Christmas Bird Counts	Conducted annually since 1900; standardized to observer-hours	http://birds.audubon.org/christmas-bird-count
DFO lake sockeye trawl surveys	DFO trawl sockey_summary.xls	Cohen Commission/PW; Sep. 21
Fraser River sockeye production	Frasersockeyedata 2010 Review.xls	Used for the August 30 PSC report (Peterman et al, 2010),
Great Backyard Bird Count	Abundance not standardized	http://www.birdsource.org/gbbc/
	Report	Palsson (2003)
Strait of Georgia ecosystem model data series	SoG ERI parameters and timeseries.csv	Compiled and distributed by Dave Preikshot, Jan. 26, 2010 for DFO workshop at PBS, Feb 21, 2010.

Appendix 5. Predator information from juvenile sockeye surveys

There have been hydroacoustic and trawl surveys conducted in a series of B.C. lakes since the mid 1970s to estimate sockeye numbers and size (Hume *et al.* 1996; Hume and MacLellan 2000). The surveys were done during the hours of darkness when fish tend to be dispersed and accessible to both hydroacoustic and trawl. The trawl used on the larger lakes was a 7 by 3 meter midwater trawl, which in principle should be able to catch at least some potential predators. On smaller lakes a 2 by 2 meter midwater trawl was used (MacLellan and Hume 2010).

There were a total of 422 trawl surveys conducted in 20 lakes in the Fraser River system (Table 8). The average catch was 3.8 fish per survey, including the target 0, 1, and 2-year old sockeye salmon. The low number of fish indicates that the midwater trawl, which mainly is used to identify targets on the acoustic transects (MacLellan and Hume 2010), is inefficient for sampling potential predators. This is best illustrated by there being no cases with four or more samples where the trend for non-target fish species was significant.

In conclusion, there does not seem to be any major datasets for potential fish predators from surveys in the Fraser River system.

Table 8. Bycatch species in sockeye midwater trawl surveys in the Fraser River system. Numbers after species names indicates the number of samples where the species occurred, in most cases with one individual. There were no significant abundance trends for species with 5 or more samples.

Lake	Surveys	Species caught
Adams	9	Cyprinid (1), other (1), lake trout (1)
Anderson	11	Sculpin (1), other (1), bull trout (3)
Bonaparte	1	Whitefish (1)
Bowron	1	Pigmy whitefish (1)
Chilko	37	Whitefish (2), cyprinid (2), other (1), sucker (1)
Cultus	89	Three-spine stickleback (42), chum salmon (1), coastrange sculpin (1), coho salmon (2), cyprinid (12), lamprey juvenile (2), largescale sucker (1), northern pikeminnow (6), other (13), redside shiner (14), river lamprey (1), sculpin (62)
East Barrière	2	Other (1)
Francois	10	Other (3), sculpin (4), whitefish (5)
Fraser	14	Chinook (1), cyprinid (1), northern pikeminnow (4), sculpin (6), whitefish (9)
Harrison	39	Three-spine stickleback (17), bull trout (1), chinook (4), chum (1), coho (5), longfin smelt (20), other (1), prickly sculpin (1), river lamprey (7), white sturgeon (1)
Kamloops	2	Whitefish (1)
Lillooet	4	Chinook (1), other (1), sculpin (3)
North Barrière	2	Other (1)
Pitt	41	Three-spine stickleback (34), longfin smelt (41), other (5), sculpin (16), whitefish
Quesnel	47	Burbot (1), lake trout (1), other (4), sculpin (2), whitefish (9)
Seton	13	Coastrange sculpin (1), other (1), sculpin (4)
Shuswap	62	Three-spine stickleback (1), burbot (1), bull trout (4), chinook (1), chiselmouth (1), cyprinid (4), lake trout (3), northern pikeminnow (3), other (19), pigmy whitefish (1), prickly sculpin (1), rainbow trout (1), redside shiner (1), sculpin (16), whitefish (15)
Stuart	13	Burbot (1), lake trout (1), other (5), redside shiner (1), sculpin (8), whitefish (11)
Takla	13	Chinook (1), lake trout (2), other (1), sculpin (3), whitefish (5)
Trembleur	12	Lake trout (1), sculpin (3), whitefish (8)