Bioeconomics of Fraser River Sockeye Salmon Fisheries

by

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Abstract

Sockeye salmon (*Oncorhynchus nerka*) in the Fraser River are immensely important to British Columbia's culture and economy. Despite centuries of exploitation and decades of intensive study there remain several key uncertainties about the biological system, including those around dramatic four-year cycles of abundance and pre-season projections of how many fish will return in a given year. Recent years have seen declines in the productivity of some stocks as well as broader conservation concerns, leading to closure of some commercial fisheries, and it appears that greater economic benefits may only be obtained if greater conservation risks are incurred. However, the existing literature contains no analysis focused on bioeconomic analysis of trade-offs between economic and conservation objectives in such complex multi-stock, multi-fleet fisheries.

This dissertation develops a bioeconomic simulation model to examine these trade-offs. The model is applied to the Fraser River sockeye salmon fishery and parameterized using historical biological, fishery and economic data. In the first set of analyses, the fishery is simulated retrospectively from 1952 through 1998 and the economic outcomes of several management strategies are examined. In the remaining analyses the fishery is simulated 24 years into the future in a prospective analysis, assuming either that the long-term average productivity regime is still valid, or that recently observed changes in productivity are permanent. Given the outcomes of these simulations the trade-offs between economic benefits and conservation risk are described.

The retrospective analysis showed that if relatively simple harvest rules had been implemented historically, the fishery could have been 20-200% more profitable, depending on the particular harvest rule applied and the mechanism underlying stock dynamics. The prospective analysis under the long-term average productivity regime found that there is a policy region that would yield significantly greater economic benefits than the currently applied policy while only minimally increasing conservation risk. Under the modified productivity regime, however, conservation risk is uniformly and unavoidably higher, and the trade-offs become more difficult in the sense that relatively more conservation risk must be incurred to obtain greater economic benefit.

Preface

I completed some of this dissertation while employed with the federal public service of Canada. However, this work is in no way a reflection of any policy position of the Government of Canada or any of its departments, agencies, or personnel. The analysis conducted and views expressed are entirely my own. Furthermore, none of this work was conducted during paid working hours, or using any computers or other equipment or resources provided for official government business. All official government data used as cited in the dissertation are publicly available.

Portions of Chapter 2 and the majority of Chapter 3 were published in 2009 in *Fisheries Research* (published by Elsevier B.V.) volume 97, pages 32-41, as "Retrospective bioeconomic analysis of Fraser River sockeye salmon fishery management" by A. Dale Marsden, Steven J.D. Martell and U. Rashid Sumaila. I identified the research questions and designed the research program in consultation with my co-authors (both members of my supervisory committee at the time). Steve Martell provided the biological data set that he had obtained from Fisheries and Oceans Canada for previous research, while I gathered all remaining data. I conducted all analyses, and prepared and submitted the manuscript, with input from my co-authors.

An earlier version of the work published in *Fisheries Research* was presented under the title "Retrospective economic analysis of Fraser River sockeye salmon fishery management" at the 2006 conference of the International Institute of Fisheries Economics and Trade in Portsmouth, UK, and published in the proceedings of that conference. Contributions for that paper were as for the journal article as described above.

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List of Acronyms

AIC	Akaike Information Criterion
BC	British Columbia
CAD	Canadian dollars
COSEWIC	Committee on the Status of Endangered Wildlife in Canada
CPUE	Catch per unit effort
CU	Conservation unit
CV	Coefficient of variation
EFS	Effective female spawners
ER	Exploitation rate
FRSSI	Fraser River Sockeye Spawning Initiative
MEY	Maximum economic yield
MSE	Management strategy evaluation
MSY	Maximum sustainable yield
NPV	Net present value
OLS	Ordinary least squares
PSC	Pacific Salmon Commission

TAC	Total allowable catch
TAM	Total allowable mortality
WSP	Wild Salmon Policy, more formally "Canada's Policy for Conservation of Wild Pacific Salmon"

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During the 2006 sockeye fishery, my uncle, Allan Marsden, was generous enough to allow me to come aboard his seine vessel, the Snow Drift, and see how the fishery actually happened on the water during a 15-hour opening. He and his crew explained a great deal about the fishery past and present, and that knowledge and the opportunity to watch first-hand improved my understanding of the fishery.

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I would inevitably forget someone important and would likely break the page limit on this section. I will say only that one of the best parts of being a graduate student is the amazing people with whom one has the privilege to work, live and travel, and I've been truly, truly blessed in this respect. So, thank you to you all.

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Dedication

To my parents and grandparents,
all of whom, at one time or other,
made their living from the sea.

Chapter 1

Introduction

Salmon in the Fraser River have been an important part of British Columbia's (BC) economy and culture for millennia. First Nations people traditionally caught salmon as the fish were returning to spawn, with the fish being consumed locally as well as traded with other groups. Commercial fisheries by non-natives began in the 1860s and rapidly expanded over the following five decades. Fraser River sockeye were a major focus of these fisheries, which in the early days focused on producing canned product for export (Henderson and Graham, 1998). Disaster struck Fraser sockeye stocks in 1912-1915 when obstructions in the main arm of the river prevented most fish from reaching the spawning grounds (Ricker, 1950), but most stocks gradually recovered over the following decades to eventually produce record catches in the 1980s and early 1990s (Henderson and Graham, 1998), while one stock declined to the point of being declared endangered (COSEWIC, 2003). By the mid 1990s abundance again began to decline, to the point that the commercial fishery for Fraser sockeye was closed in 2005, 2007 and 2008 to allow enough returning fish to reach the spawning grounds to ensure that conservation goals would be met. In 2009 returns were much lower than even the most pessimistic projections for that year, and after several months of discussion following the end of another lost commercial fishing season, on November 6, 2009, the Government of Canada appointed The Honourable Bruce Cohen, Justice of the Supreme Court of British Columbia, as a Commissioner to conduct "...an inquiry into the decline of sockeye salmon in the Fraser River" (hereafter referred to as the 'Cohen Commission'). Remarkably, as the Commission was beginning its hearings during the following year, Fraser sockeye runs returned in numbers that were much *higher* than the most optimistic predictions and higher than the majority of active harvesters had ever seen. However, 2011 and 2012 again provided very modest returns and minimal fishing opportunities.

This story of dramatic highs and lows raises a number of biological questions: Why does production in some parts of the system vary cyclically, with abundance changing by more than one-thousand-fold within a four-year cycle? Why is an ecological system that has been resilient enough to produce such abundance for so long, including in the face of multiple human stresses and occasional catastrophe, suddenly failing to meet expectations?

There are also policy questions that arise from these biological questions: Has management performed as well as it might have, or has a lack of information hindered past management performance? How should management proceed from now on given more recent learning about the system, while allowing for biological variability and uncertainty? What are the trade-offs between management objectives implied by the choices that must be made, and how do these trade-offs change depending on the answers to the biological questions above?

And finally a technical, methodological question arises in trying to address these biological and policy questions: what methods can be used to explore these issues, and what are the advantages and disadvantages of different methods?

This dissertation addresses these policy and methodological questions in the context of continuing concerns about both conservation of Fraser sockeye stocks and the future of the BC commercial salmon fishery, as well as the evolving nature of the federal government's mandate with respect to fisheries and conservation.

1.1 Overview of Fraser sockeye

1.1.1 Biology

Much of the basic biology of sockeye salmon (*Oncorhynchus nerka*) is well known from decades of study (Burgner, 1991). Mature salmon return to their natal streams during summer and autumn at ages ranging from three to six years, although in the Fraser system the vast majority of fish return at age four. These salmon spawn in tributary streams, trunk streams between lakes, and at lake outlets. The eggs hatch in winter or spring, and the juveniles then spend the following summer and winter feeding and growing in lake and stream habitats before migrating to the ocean the following spring. The juveniles migrate to the Gulf of Alaska, where they typically spend the next two (or rarely, one, three or four) years growing, and finally return to spawn.

Fraser sockeye can be grouped or classified at several hierarchical levels. The release in 2005 of "Canada's Policy for Conservation of Wild Pacific Salmon," usually known as the Wild Salmon Policy (WSP; DFO, 2005) has spurred much research aimed at assessing the diversity of all salmon in BC, including sockeye in the Fraser River system. The WSP specified that salmon would be "...maintained by identifying and managing 'conservation units' (CUs) that reflect their geographic and genetic diversity." Given this guidance, Holtby and Ciruna (2007) produced the first list of putative salmon CUs based on three broad types of information: ecology, life history, and molecular genetics. For sockeye more specifically, this included information on: whether the population rears in a lake or in a river during its freshwater phase; the timing of the population's migration back to its spawning grounds from the ocean (known as 'run timing'); and freshwater and oceanic geographic locations. Based on these characteristics, they found that in all of BC there are 24 river-type sockeye CUs and 214 lake-type sockeye CUs, only some of which are in the Fraser system. This putative list of CUs was further revised over subsequent years, and the most current list as of August 2011 included, for sockeye, 22 confirmed CUs in the Fraser River system,

Table 1.1: The 19 major stocks that are the focus of management of the Fraser sockeye fishery. All stocks are used in Chapters 4 and 5, while only the nine stocks designated with * were used in Chapter 3.

Management unit	**Stock name**	**Management unit**	**Stock name**
Early Stuart	Early Stuart*	Summer	Chilko*
Early Summer	Bowron		Late Stuart*
	Fennell		Quesnel*
	Gates		Stellako*
	Nadina	Late	Cultus
	Pitt		Harrison
	Raft		Late Shuswap*
	Scotch		Portage
	Seymour*		Weaver*
			Birkenhead*

along with two *de novo* CUs (derived from transplanted hatchery fish), six CUs that required further validation, and eight CUs that are considered to be extirpated (Grant et al., 2011). These CUs correspond quite closely to the 19 major stocks that are used for the purposes of fisheries management (Grant et al., 2011; MacDonald and Grant, 2012). These stocks are the only ones for which sufficient data exist to conduct quantitative analyses, but they account for 98% of the long-term annual average returns, and 89-100% of single-year returns (Pestal et al., 2011). These 19 stocks are grouped into four larger aggregations known as management units based on their run timing (Table 1.1; more information about run timing is in section 1.1.2). The approximate locations of the spawning grounds of the stocks are shown in Figure 1.1.

Like almost all fished species, these stocks are characterized by variability and uncertainty. The abundance of a few of the largest stocks have exhibited regular, extreme cycles of abundance of returning spawners, varying in some stocks by two to four orders of magnitude in any four-year period (Schnute

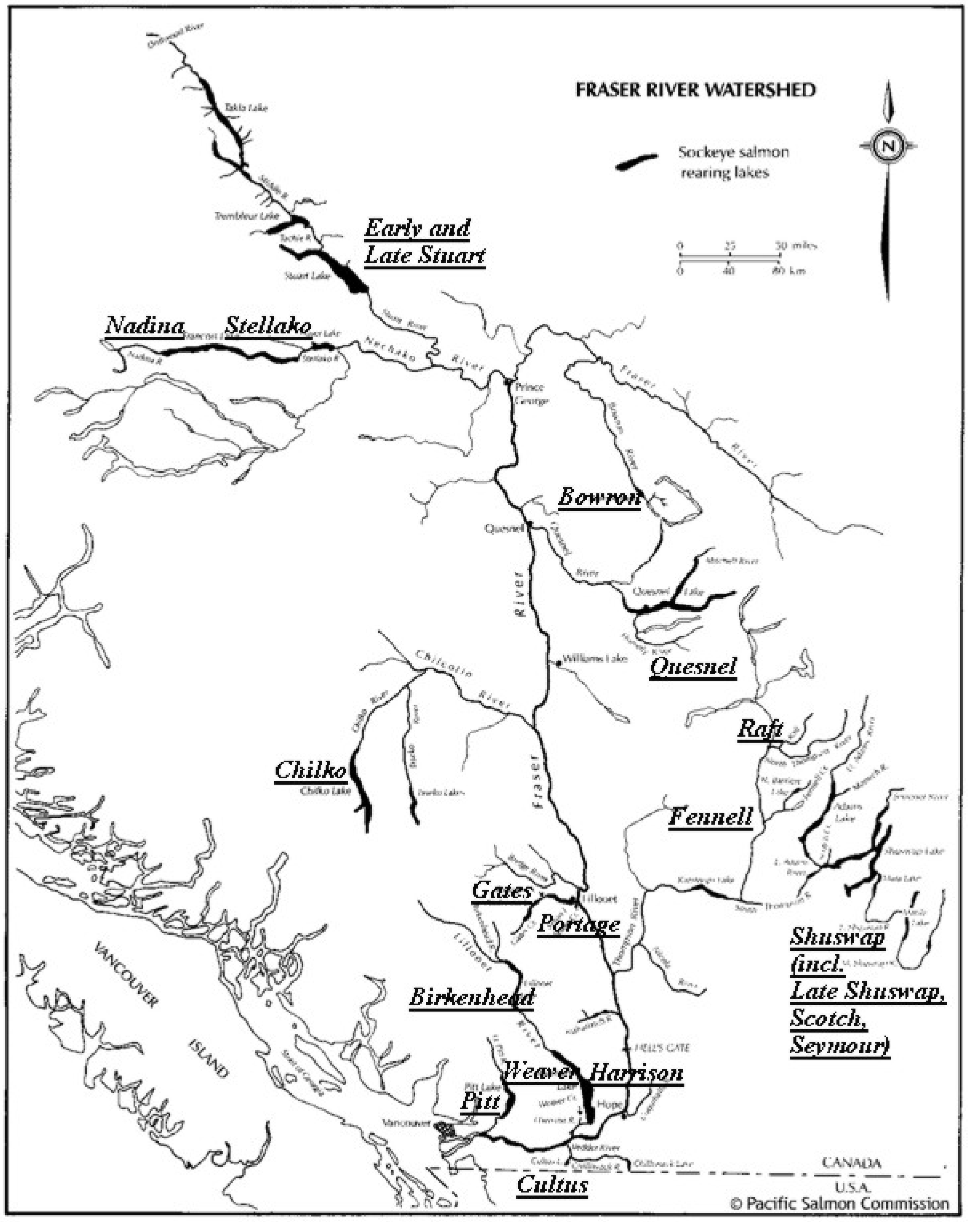

Figure 1.1: Locations of spawning grounds of the 19 main stocks of Fraser River sockeye salmon. Base map from the Pacific Salmon Commission. Locations marked based on information in Holtby and Ciruna (2007) and Grant et al. (2011).

et al., 2000). In the 1800s and early 1900s there was typically one year with a large number of recruits (the 'dominant' run), followed by three years with much smaller abundances (Ricker, 1950; Ward and Larkin, 1964). At this time, the cycles of the various stocks were synchronized so that the dominant run for all stocks occurred in the 1901 cycle line (i.e., in 1901, 1905, 1909, etc.). Upon recovery from obstructions in the river in 1912-1915, however, the dominant run was no longer synchronized across stocks; for example, the dominant run of the Late Shuswap stock is now in the 1902 cycle line, while that of the Late Stuart and Quesnel stocks is in the 1901 line (Ricker, 1997). As well, after the recovery there appeared in many stocks a 'subdominant' cycle line, of a size smaller than the dominant line but substantially larger than the 'off' cycle lines, in the year immediately following the dominant line.

The underlying mechanism causing the cycles has been the subject of considerable study and debate in the biology literature (reviewed by Levy and Wood, 1992). The predominant hypotheses can be roughly divided into two main lines. The first, and perhaps more prevalent, is that the ecology of the sockeye's spawning and rearing grounds generates and maintains the cycles through some form of delayed density-dependence. Suggested mechanisms have included: (1) build-up of predator or parasite populations supported by large numbers of sockeye juveniles rearing in lakes, with the predators/parasites then depressing populations of subsequent year-classes; (2) satiation of predators at high densities of juveniles, resulting in proportionally lower mortality rates during years with high juvenile abundance; (3) depletion of food resources by strong year-classes; and (4) a genetic mechanism where age-at-maturity is strongly heritable, many of the spawners in small cycle lines are age-5 fish from previous generations, and this production is 'lost' to the cycle in the next generation because the fish again spawn at age 5 (Ricker, 1950; Ward and Larkin, 1964; Larkin, 1971; Levy and Wood, 1992; Walters and Woodey, 1992). The second major explanation that has been put forward is the depensatory fishing mortality hypothesis, which argues that the cycles may simply be a result of historical randomness causing variation in abundance, and this variation then being amplified by higher exploitation rates on smaller cycle lines (Walters and Staley, 1987). A workshop in 2006 that examined the phenomenon of cycles in Fraser sockeye (Cass and Grout, 2006) produced a consensus that delayed density-dependent interactions are "a biological reality," but to varying degrees across the different systems, and that high fishing pressure is required to establish and maintain cycles. Thus there is still considerable uncertainty about what causes the observed abundance cycles.

The mechanisms underlying the cycles may have important management implications. If depensatory fishing mortality alone is responsible for the cycles, adjustments in fishing rates should allow the 'off' years to rebound and, in the long run, allow greater and/or more stable yields. However, if delayed density-dependence on rearing grounds causes the cycles, depending on the specific mechanism(s) at play, it may be more difficult to obtain greater yields from the 'off' years; it may be necessary to implement more aggressive approaches, such as predator removals or lake fertilization. Since all management approaches imply costs (forgone catch, cost of ecosystem manipulations, etc.), taking an 'incorrect' management approach would not only leave the problem unresolved, but would be costly as well.

Another important type of uncertainty in the Fraser sockeye fishery concerns the potential biological productivity of the system. There are several distinct but related aspects of this limitation. First, sockeye stocks are limited to some extent by the total productive capacity of their rearing lakes, but the degree and nature of this limitation is not known with a great deal of precision. There have been attempts to assess these limits indirectly (e.g., Hume et al., 1996), but it has been argued that the only way to minimize this uncertainty is through "adaptive management" experiments, where stocks would be allowed to rebuild to clarify limits (Walters and Hilborn, 1976; Walters, 1981). Such experiments were begun in the late 1980s once it became apparent that many stocks were actually over-exploited, and because Canada, under the 1985 Pacific Salmon Treaty, was entitled to most of the increased catch that might arise from a stock rebuilding program (Welch and Noakes, 1991; Huppert, 1995). This so-called rebuilding plan lowered harvest rates from 80-90%, which was typical at the time, to 60-70%, depending on the particular stock, with the aim of allowing an increase in escapement and therefore abundance, which would then allow for learning about the true productive capacity of the system. The outcome of this plan was not as predicted, for several reasons: productivity of many stocks declined (see below), leading to fishery-independent decreases in abundance; harvest opportunities on some abundant stocks were limited by the desire to protect weaker stocks that migrated at the same time; and market conditions became less favourable to rebuilding (Cass et al., 2004). Nevertheless, this effort to rebuild has yielded better information about the productivity of the system (Martell et al., 2008).

A second type of uncertainty about productivity is closely related to that about cyclic dominance: if density-dependent interactions among cycle lines actually exist in the forms hypothesized, they will reduce total potential productivity. If these interactions do not exist, however, then total production could be substantially increased by allowing rebuilding of off-cycle lines (Walters and Staley, 1987; Welch and Noakes, 1990, 1991). Some such rebuilding of off-cycle lines has been attempted in the Fraser River, and in some cases has caused the cyclic patterns in returns to begin breaking down (Cass and Grout, 2006). There is still some question, though, of whether this pattern will be repeated on other stocks that have not yet rebuilt, and whether productivity might still be somewhat suppressed by weak cycle-line interactions.

A third uncertainty about productivity that has been of particular concern in recent years is about the cause of declines in the overall productivity of many stocks. Productivity is usually measured as the number of recruits (i.e., adult fish that migrate back toward the spawning grounds) per spawning adult, and this value for the whole Fraser sockeye system decreased substantially starting in the early 1990s (DFO, 2012d). This decline was one of the focal points of the Cohen Commission, and hypotheses about its cause or causes were extensively examined as one component of the Commission's work (Marmorek et al., 2011; Nelitz et al., 2011; Peterman and Dorner, 2011). Peterman and Dorner (2011) examined changes in productivity in Fraser sockeye stocks as well as in other sockeye stocks both north and south of the Fraser system. They found that productivity has declined since the late 1980s not only in Fraser River stocks but also in many other areas, including Washington State, the west coast of Vancouver Island, the northern and central coast of BC, and the Alaskan panhandle; however, productivity in western Alaska has increased during this period. These researchers also examined the life stages at which productivity changes have occurred in the Fraser system, and found that declines in productivity overall have mostly been associated with declining survival from juvenile to adult, but not from spawner to juvenile, suggesting that the cause(s) of declining productivity exert their influence after juveniles leave their freshwater rearing grounds.

In another component of the Cohen Commission's work in this area, Nelitz et al. (2011) examined a range of possible factors related to sockeye's freshwater habitat that may have contributed to declines in productivity, including logging, hydro-electrical development, urbanization, agriculture and mining, and concluded, in keeping with Peterman and Dorner (2011), that freshwater factors are unlikely to explain the observed declines. A third Cohen Commission study (Marmorek et al., 2011) integrated evidence from the above studies and from others (e.g., Peterman et al., 2010). Their conclusion was that the most likely causes of declining productivity are poor marine conditions in the Strait of Georgia as juvenile salmon migrate from the river mouth toward their ocean feeding grounds, and that these conditions were being exacerbated by climate change. Other research further supports the hypothesis that Fraser sockeye productivity is decreasing because of low early marine survival. Beamish et al. (2012) found similar declines in juvenile production of both salmon and herring in 2007, and they and Thomson et al. (2012) suggest that this similar pattern is due to a common cause, most likely poor food production. Thomson et al. (2012) also point to much higher marine survival in 2008 and the associated favourable oceanic conditions. Finally, as a contribution to the Cohen Commission's research, two other reports outlined evidence regarding the possible role of salmon farms in causing declines in Fraser sockeye productivity. Noakes (2011) reviewed peer-reviewed literature, technical documents, and data submitted to the Commission by industry and government, and interviewed individuals from government, industry, academia and elsewhere, and generally concluded that there was no relationship between salmon farms and declines in Fraser sockeye. In contrast, Dill (2011) concluded that the quality and quantity of the data available were not sufficient to draw any conclusions about the possible role of salmon farms in sockeye declines. He noted with concern that there are negative correlations between farm production and wild sockeye production, and suggested that if there is a causative link it is most likely disease, sea lice, or both.

Whatever is causing these declines, they are having significant impacts on stock abundance as noted above. One particularly severe case is the Cultus Lake sockeye stock, which in 2003 was proposed by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) for listing as Endangered under the *Species at Risk Act* because of the extent of the decline in its abundance since the 1970s, to about 5% of historical levels (COSEWIC, 2003; DFO, 2010a). Cultus sockeye was not listed as Endangered under the *Species At Risk Act*, however, despite this assessment. Instead, DFO established the Cultus Sockeye Recovery Team, which developed a conservation strategy for the stock (Bradford et al., 2010). The key elements of this strategy have been to reduce the harvest rates on the stock, to control predators in Cultus Lake, and to undertake a captive breeding program to supplement production. As of 2010, however, there was no evidence that this population had recovered substantially (DFO, 2010a), and conservation efforts continued into 2012 (DFO, 2012c). However, the reduction in harvest rates on Cultus sockeye has had strong implications for the fishery as it is part of the Late management unit that also contains one of the largest stocks, the Late Shuswap stock. This means that reducing the harvest rate on Cultus sockeye to 20-30%, as has been standard practice, has required imposing this same low harvest rate on Late Shuswap and other Late stocks, leading to greatly reduced revenues through forgone catch.

1.1.2 Fisheries

Major fisheries

The Fraser sockeye commercial fishery, like the other BC salmon fisheries, is conducted by three fleets. *Trollers* are relatively small vessels that pull a number of hooks through the water to catch individual fish. They operate over a wide area along both sides of Vancouver Island and mostly focus on fishing chinook and coho salmon, but also catch some sockeye. Trollers have typically accounted for 10-20% of total sockeye catch, but in recent years their percentage has declined to 5%. *Gillnetters* suspend a fine-mesh net in the water to entangle salmon by the gills as they attempt to swim upstream. Most gillnet operations occur in Johnstone and Juan de Fuca Straits, near the mouth of the Fraser River, and in the lower part of the river itself, and they have historically taken anywhere from 20 to 90% of the total annual sockeye catch (mean for 1952-2002 = 50%), with their recent allocations being 45-50%. *Seiners*, or purse seiners, are the largest vessels in the salmon fishery, and encircle large groups of fish with a bag-like net. These vessels operate chiefly in Johnstone and Juan de Fuca Straits, and annually account for 10-70% of sockeye catch (mean for 1952-2002 = 40%), with recent allocations similar to those of gillnets.

Total commercial landings of Fraser sockeye (Figure 1.2) increased fairly steadily, albeit with a great deal of year-to-year variation, from the 1950s through the early 1990s, but then decreased in the late 1990s and early 2000s. Sockeye landings represented about 15% of all salmon landed value in BC in the 1950s. This proportion increased to 55% in the 1990s because of increases in sockeye catches as well as decreases in the catch of other species. However, the share of sockeye in total salmon catch has again declined in recent years due to low abundance.

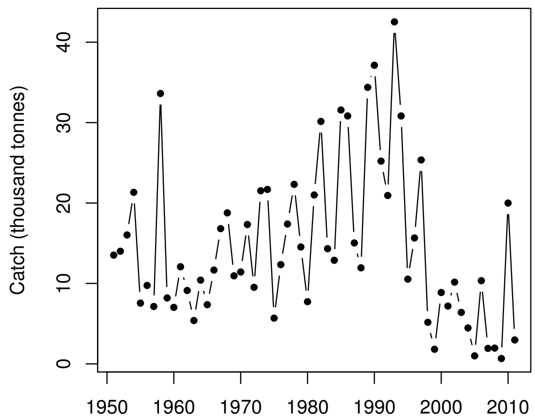

Figure 1.2: Annual commercial landings of Fraser River sockeye salmon from 1951 to 2011, in thousands of tonnes.

There are several other fisheries that catch Fraser River sockeye. After conservation of spawning stocks, the government of Canada's highest priority is allocation of salmon to US fisheries, which is required to satisfy obligations under the Pacific Salmon Treaty. Many Fraser sockeye historically returned from their oceanic phase through Juan de Fuca Strait, where they were subject to harvest in US waters. From 1937, with the ratification of the Fraser River Convention, harvests of Fraser sockeye and pink salmon were equally divided between the two countries (Miller and Munro, 2004). A climatic regime shift in the late 1970s, however, changed the migratory behaviour of sockeye, and many more fish began diverting through Johnstone Strait and bypassing the US fisheries south of Vancouver Island. This strengthened Canada's bargaining position in negotiations about salmon allocation, and the terms of the 1985 Pacific Salmon Treaty have allowed Canadian fisheries to typically take about 80% of the Fraser sockeye catch each year (Huppert, 1995; Miller and Munro, 2004). Disputes in the 1990s disrupted the allocations somewhat, but a renewed agreement in 1999 restored the US catch share to under 20%.

The other significant fisheries on Fraser sockeye are First Nations fisheries for food, social and ceremonial purposes, which are given the highest priority in domestic allocations of catch (i.e., after meeting escapement goals and international treaty obligations). These fisheries have historically comprised a relatively small proportion of the total Canadian sockeye catch, averaging about 4-8% before the 1990s. However, in the early 1990s pilot sales programs were implemented under the Aboriginal Fisheries Strategy, allowing First Nations fishers to sell some of their catch. This increased the legal catch by First Nations, and there were allegedly large illegal catches during the same period (Pearse and Larkin, 1992; Government of Canada, 2005). In more recent years, First Nations fisheries have taken greater proportions of the total catch than was historically the case; for example, in 2004 First Nations fisheries in the Fraser River took about a quarter of the total Canadian sockeye catch (Government of Canada, 2005).

There is some recreational fishing on Fraser sockeye but it has typically been very limited, usually representing less than 1% of the total catch (Pestal et al., 2008). Furthermore, many of these fisheries are catch-and-release depending on timing and location (e.g., DFO, 2012c), further mitigating any impacts they might have on the stocks.

Economics of the fisheries

A variety of publications over the years has addressed the economics of the BC salmon fishery, generally falling into three categories. The first category is a set of surveys of industry stakeholders with respect to a variety of economic variables, or compilations of data gained through various means (Department of Fisheries, 1964; Buchanan and Campbell, 1957; Campbell, 1969a; Hunter, 1971; Hsu, 1974; DPA Group Inc., 1988; DFO, 1992; Gislason, 1997). The variables considered include the number and value of vessels of different gear types, variable and fixed costs per vessel, number of days fishing, and prices of sockeye by gear type. Several financial profiles of BC commercial fishing fleets have also been developed much more recently by consultants to DFO, with the analysis being based on data provided by DFO and industry, as well as on interviews conducted by the consultants with industry participants (Gislason, 2011; Nelson, 2009, 2011). Analyses of both the 2007 and 2009 fishing years presented a very bleak picture of the fleets targeting Fraser sockeye: in most cases revenues were insufficient or barely enough to cover direct fishing costs, and inclusion of fixed costs (i.e., those that would be incurred irrespective of fishing activity) resulted in most fleets showing a substantial net loss in both years.

The second major type of literature that has addressed the economics of the fishery is a number of reports from government-mandated commissions and enquiries, which at a variety of times have tried to figure out 'what's wrong' with the fishery, and find solutions. These have included: the Sinclair (1960) report, which recommended license limitation and fleet reduction (a policy that was not implemented until 1969); the Pearse (1982) report, which recommended further reductions in fleet capacity; the Mifflin plan (reviewed by Muse, 1999), which implemented substantial buyback programs to reduce fleet capacity; and a report by McRae and Pearse (2004) which recommended the establishment of an individual quota system in BC's fisheries. The recurring theme in this set of reports has been that there is overcapacity in the fishery, and that this must be reduced to ensure the long-term viability of the fishing industry.

The third set of literature, which is most closely related to this dissertation, is bioeconomic modelling of Pacific salmon fisheries, of which there has been relatively little. As mentioned above, there is a great deal of data available but most analysis has been qualitative. There are, however, some studies which took a more quantitative approach and integrated economics with biology. Rothschild and Balsiger (1971) examined intra-season temporal allocation of catch to maximize the value of the catch in the Bristol Bay, Alaska, sockeye fishery. Loose (1979) constructed a bioeconomic model of the sockeye fishery in the Skeena River in northern BC. Link and Peterman

(1998) used a cost-benefit analysis to examine the value of data from a fishwheel for improving management of the sockeye fishery on the Nass River, also in northern BC. Sands and Hartman (2000) built a simulation model of the fisheries for sockeye and pink salmon in northern BC and southern Alaska, and mostly examined issues of allocation between Canadian and US fishers. Finally, Routledge (2001) used a bioeconomic model to examine incentives to drive weak salmon stocks to extinction in either mixed-stock fisheries or terminal fisheries, where salmon would be caught close to their spawning grounds.

Thus, while there has been some modelling work on similar fisheries on the Pacific coast, there has been no empirical bioeconomic simulation modelling of the Fraser sockeye fishery. There has also been little integration of biological issues, such as the uncertainty about stock-recruitment dynamics, with economic considerations. Some work on Fraser sockeye has taken proxies for economic objectives into account; for example, objective functions used in analyses by Schnute et al. (2000) and Cass et al. (2004) included penalties for years in which catch fell below some predetermined level, which presumably would incur serious economic losses. However, examining policy implications in more precise economic terms requires a fuller specification of the economics of the fishery, integrated with a biological model that accounts for key characteristics of and uncertainties about the system. This is a gap that this dissertation will help to fill.

1.1.3 Fisheries management

Management of the Fraser sockeye fishery occurs in two main phases: pre-season planning and in-season management. The first of these is primarily the responsibility of DFO, while the latter, under the terms of the Pacific Salmon Treaty, is the responsibility of the Fraser Panel of the Pacific Salmon Commission (PSC).

Pre-season planning consists of three main sets of activities. The first is to develop forecasts of the number of sockeye returning in each stock (e.g., DFO, 2012d). These forecasts are made using a number of different models of varying complexity, with the model used for a particular stock determined by the performance of that model for that stock (details in Grant et al., 2010). The resulting forecasts are probabilistic in nature, meaning that they specify a range of likely stock abundances, with a probability attached to each level. For example, in 2010: the 50% forecast for the Early Stuart stock was 41,000 fish, meaning that there was a 50% chance that 41,000 or more fish would return to spawn; the 10% forecast was 101,000 fish; the 90% forecast was 17,000 fish; and similar forecasts were made for 25% and 75% probabilities. These forecasts are developed several months before the fishery begins, and outline the range of stocks sizes that, based on past observation and recent ocean and river conditions, can be expected in that year. These probabilistic forecasts can be thought of – at least conceptually – as confidence intervals on the expected return. For example, the 80% confidence interval on the Early Stuart stock in 2010 was 17,000 to 101,000 fish. This is a remarkably large range with an almost six-fold difference between the lower and upper bounds. Moreover, even with this large range there remains a 20% probability that the actual abundance of returns will fall outside this range.

The second activity that takes place during pre-season planning is the determination of the expected harvest from each stock, based on harvest rules established in the general framework of the Fraser River Sockeye Spawning Initiative (FRSSI; Cass et al. 2004; Pestal et al. 2011; DFO 2012c). This initiative was begun in 2002 to develop a new approach to setting escapement policies for Fraser sockeye following on some of the concerns that had arisen with the previous 'rebuilding' approach (Cass et al., 2004). FRSSI also represents an effort to address one of the principles outlined in the WSP: that decisions about the fishery should be made in structured, public consultative processes (DFO, 2005; Pestal et al., 2008). At the core of FRSSI is a detailed simulation model of sockeye stocks and the management system that incorporates a wide range of uncertainties and allows for testing of different management approaches and exploration of their implications (Pestal et al., 2008, 2011). The model has been developed iteratively over the last 10 years through a process of consultation with a range of stakeholders and incorporation of their comments into the model where appropriate.

Currently, the main application of the FRSSI model is in the annual development of escapement strategies for Fraser sockeye stocks (DFO, 2012c). The model is used in a consultation process with stakeholders to explore the implications, both for harvest and for conservation risk, of different harvest levels given the pre-season forecasts of run size, and on this basis a strategy is selected and recommended to the federal Minister of Fisheries and Oceans, who under the *Fisheries Act* has decision-making authority in these matters.

The third component of pre-season planning is the development of a pre-season fishing plan by the PSC. Given the run-size forecasts and escapement strategies provided by DFO, the PSC uses a spatial simulation model of the various stocks and fisheries (Cave and Gazey, 1994) to propose a set of fishery openings that will meet these objectives if the forecasts turn out to be accurate. However, it is acknowledged in developing this plan that substantial changes are likely to be required in-season given the great deal of uncertainty about the abundance and timing of different management units.

While a great deal of planning is conducted pre-season, most of the key decisions about how many fish will be harvested in a given place and on a given day are made during the fishing season itself. Once Fraser sockeye stocks begin their migration from ocean feeding grounds toward the rivers, the PSC takes over primary responsibility for managing the fishery. This in-season management process has several key components (PSC, 2012). The three primary sources of data are: (1) test fisheries conducted along the length of the coast and into the lower parts of the Fraser River that provide data on abundance of sockeye by area and time, along with information about stock composition; (2) a hydro-acoustic facility in the Fraser River at Mission, approximately 70 km upstream from the mouth of the river, that counts the fish passing that point in the river; and (3) visual observers at Hell's Gate, a narrowing of the river approximately 200 km upstream from the mouth. These data are supplemented with information obtained from commercial and First Nations fisheries. Samples taken from fish caught in test, commercial and First Nations fisheries are used to determine the stock to which each fish belongs, using two techniques: scale pattern analysis, which relies on differences between circuli patterns seen on the scales of sockeye from different stocks (Gable and Cox-Rogers, 1993); and genetic analysis, which compares genetic patterns in the samples with those known to exist in each of the various stocks.

These data sources and analyses provide managers with the means to develop a detailed, albeit imperfect, picture of the abundance and distribution of each stock at various points in time using an in-season run-timing model (PSC, 2006, 2012). This model is based on the historical observation that sockeye stocks migrate in groups that are roughly normally distributed in space/time; that is, if we monitored the abundance of a given stock as it approaches the first test fisheries, we would initially see low densities of fish, but these densities would increase as the peak concentration of the run approached our observation point, before tailing off again as the peak passed[1]. At the early stages of each run, the in-season model attempts to use only the leading part of each migration to estimate both its timing and abundance. This can be problematic as any particular test fishing result could signify a number of different underlying occurrences. For example, large test-fishery catches early in the run could indicate that the abundance of the run is indeed large, or it could indicate that a small- or moderate-sized run is coming but is arriving earlier than expected. These issues pose challenges for in-season management and can in some cases lead to uncertainty about whether fishery openings – especially early in the run and further from the river – should be allowed, or if they may pose risks to some stocks, e.g., if the run is indeed smaller than anticipated. However, as the run continues to arrive and enter test fisheries, more data are gathered and managers become more

[1] Alternatively, if we conducted test fisheries on a single day over a wide range of areas, we would see a similar roughly normal distribution of the same fish stock in space, with the bulk of the stock at some point on the migration route and then progressively lower densities as we move away from the centre of the run.

confident of total run sizes. Furthermore, estimates based on hydro-acoustic data obtained at Mission are considered more reliable than those from test fisheries, so the former data replace the latter in the model as the run begins to pass Mission, further reinforcing confidence in the estimates.

Actual fishery openings are allowed based on an integrated consideration of all available information. Managers meet two or more times per week to review available data, and if an opening is to be allowed harvesters are informed of the exact location(s) and time of the opening, often only days in advance. The fishery is opened at a time and place that, according to modelling and available data, will result in harvests that are consistent with the stock-by-stock escapement strategies established by DFO before the season. While significant uncertainty about run size and timing remains deep into the fishing season, the process as a whole is relatively effective at controlling harvest at quite a detailed temporal and spatial scale, allowing fisheries of various types to proceed if and only if these are consistent with management objectives.

There are several post-season steps in the management process (PSC, 2012). Data on the stock composition of catches are collected and refined by the PSC after the season closes. DFO collects a variety of data on stocks once they reach the spawning grounds, including estimates of abundance and spawning success of each stock (summarized by Pestal et al., 2011), and estimates of abundance of juveniles of the next generation that leave freshwater systems one to three years later on their way to ocean feeding grounds. Many of these data are critical for developing pre-season forecasts of returns in the following years.

1.2 Policy objectives for Fraser sockeye

As the above overview demonstrates, there are a number of serious challenges facing the fishery and potentially compromising the benefits it provides. The very poor recent financial performance of fishing fleets is in sharp contrast to current and past federal governments' economic objectives for these fisheries; this objective is reflected in the first of DFO's current strategic objectives[2]: "economically prosperous maritime sectors and fisheries" (commonly expressed as 'economic prosperity'; DFO, 2012a). Biological variability and uncertainty, declines in productivity, and conservation concerns all present challenges in the management of the fishery that affect these economic benefits, but also pose difficulties with respect to the conservation of at least some of the stocks concerned. Incidentally, these difficulties have the potential to affect DFO's ability to support its second strategic objective: "sustainable aquatic ecosystems." Perhaps more worrisome is the stark trade-off between conservation and economic benefits, particularly when considering the situation around the Cultus Lake sockeye stock, where conservation and rebuilding efforts have required large reductions of harvest rates on stronger stocks. Indeed the importance of this trade-off is recognized by fisheries managers (DFO, 2012c).

Canada's official policy in this area was laid out in 2005 in the Wild Salmon Policy (WSP; DFO, 2005). The overall goal of the WSP is to "...restore and maintain healthy and diverse salmon populations and their habitats for the benefit and enjoyment of the people of Canada in perpetuity." The Policy outlines three objectives that support this goal: safeguarding genetic diversity, maintaining habitat and ecosystem integrity, and managing fisheries for sustainable benefits. While these objectives might in some cases conflict with one another, the Policy clearly establishes priorities: "...conservation of wild salmon and their habitat is the highest priority for resource management decision-making..." and "...resource management processes and decisions will honour Canada's obligations to First Nations." In other words, conservation is given the highest priority, then First Nations' opportunities for harvests, and finally commercial and recreational fisheries.

[2]Strategic objectives are very general statements about the long-term, overarching objectives of the government for federal departments, usually stated (among other places) in each department's annual "Report on Plans and Priorities," a submission to Parliament outlining that department's spending plans for the year and the rationale for those plans.

Having established its goal, objectives and guiding principles, the WSP outlines a set of six strategies that together comprise the substance of the policy, along with actions that support each of these strategies. These six strategies are: (1) standardized monitoring of wild salmon population status, using the concept of conservation units (outlined in section 1.1.1); (2) assessment of habitat status; (3) inclusion of links to the wider ecosystem in wild salmon management, such as the possible role of salmon in fertilizing terrestrial environments, and consideration of the effects of climate change on wild salmon; (4) a planning process that integrates the outputs of the first three strategies; (5) the annual delivery of programs related to population monitoring, fisheries planning and management, habitat management, and enhancement; and (6) regular reviews of the performance of these programs and of the Policy overall. A key component of the WSP with respect to managing the trade-off between conservation and economic benefits is the framework under which population status is assessed (strategy 1). This framework establishes three status zones denoted red, amber and green, with the zones being delimited by an upper and a lower abundance benchmark. The green zone, above the upper benchmark, is where the population is considered healthy; the amber zone, between the two benchmarks, is where there is some concern about the population and thus caution in its management; and the red zone, below the lower benchmark, indicates serious conservation risk, although not necessarily the level of concern associated with COSEWIC Endangered or Threatened status (DFO, 2005). Importantly, the Policy states that this status will affect the relative weight given to different objectives in making management decisions: in the green zone "social and economic considerations will tend to be the primary drivers" of management, while in the red zone conservation will be the primary driver.

Since the WSP was released in 2005 much has been done to implement its provisions. Progress has been made in identifying CUs (Holtby and Ciruna, 2007; DFO, 2009; Grant et al., 2011), in developing standardized methods to assess these CUs (Holt et al., 2009; Holt, 2009), and in preliminary applications of these methods in some cases, including Fraser sockeye (Grant et al., 2011). There has also been significant progress with respect to the other five strategies in the Policy (DFO, 2012e). However, of particular interest in the context of this dissertation is how the Policy is being implemented with respect to commercial fisheries, more specifically regarding how the priority given to conservation is being interpreted and applied in situations where this priority might conflict with economic benefits. This can be seen most clearly in the approach being taken to the management of depleted populations such as Cultus Lake sockeye (see section 1.1.1), where several parallel actions are being undertaken to rebuild the stock (DFO, 2010a). The recovery action of most interest here is the significant reduction in harvest rates from historical levels that were typically 70-90% to 20-30%. The timing of the Cultus stock's migration means that this harvest rate must also be applied to all other stocks in the Late management unit, regardless of their abundance. In other words, for any given abundance level for the Late stocks, potential harvest and revenue have been reduced to less than half of what they would have been without this constraint. Perhaps not surprisingly, this reduced access to sockeye has been cited as one of the key reasons for the poor performance of commercial salmon fleets in recent years (Nelson, 2009; Gislason, 2011).

While the current approach to implementation is well-established, there remains within the basic framework of the WSP much room to navigate in order to balance trade-offs among policy objectives. While conservation has been specified as the highest priority and the Policy is currently being implemented in keeping with this priority, conservation outcomes are inherently uncertain; for example, research and analysis in this area almost universally refers to probabilities of particular events such as extirpation (e.g., COSEWIC, 2003; Pestal et al., 2008; DFO, 2010a). Thus policy decisions are not being made about whether or not "to conserve" populations and species, but rather the amount of effort and resources that are to be expended, or the benefits that are to be forgone, to decrease conservation risk to acceptable levels. Extreme policies might close fisheries altogether and spend many millions of dollars on enhancement and habitat protection activities to reduce conservation risk to the lowest level possible, or conversely manage fisheries so as to maximize the present value of vessel profit obtained from the fishery while only attaining the bare minimum of acceptable conservation outcomes (e.g., as set out in law, such as the *Species at Risk Act*). However, there is a large set of policies between these extremes, and a subset of these would be consistent with the basic tenets of the WSP.

Another reason to examine Fraser sockeye management under the WSP is that most of the published research and planning documents cited above do not directly and quantitatively deal with economic benefits in monetary terms. For example, the FRSSI model and process includes a great deal of detail in biological aspects of the fishery, but economic values are captured primarily through the stability of harvest and avoiding catches so low that the fleet would no longer be viable. A consultant conducted a pilot socio-economic analysis of three FRSSI scenarios during the early stages of development of the model (Gislason, 2006), but while socio-economic analysis has been noted as an area to pursue it has not been followed up in further developments of the model to this point (Pestal et al., 2011). The lack of economic analysis of the fishery is somewhat at odds with the federal government's primary objective of economic prosperity in fisheries, especially given the high-profile nature of this fishery since the establishment of the Cohen Commission in 2009. In recent years the federal government has placed a strong emphasis on economic benefits and development, with some critics arguing that not enough attention has been paid to environmental and conservation concerns. In this context it would be informative to have some explicit, quantitative analysis of what the implications would be of different approaches. This dissertation will provide some of this analysis.

A final note on terminology is required with respect to the use of the term "economic" when referring to values, benefits, and outcomes. The term is used throughout this dissertation in keeping with its colloquial and common policy use, that is, to refer to benefits derived in markets by the buying and selling of goods and services. However, economics as a discipline is much broader than these transactions, and economic analysis can incorporate a wide range of values and benefits, including many that have no market mechanism associated with them (see TEEB, 2010, for an overview). While it might be possible to attribute dollar values to some of the non-market and non-use values associated with sockeye salmon and then integrate these values into the economic analysis, this would require a much larger and more varied data set than I had at my disposal. Thus, when discussing "economic benefits" I have focused on market benefits, but this should not be interpreted as a dismissal of the importance of non-market benefits.

1.3 Quantitative modelling of fisheries

1.3.1 Bioeconomic modelling

The preceding sections describe a deeply complex and variable system involving interacting biological and economic components about which there are varying types and levels of uncertainty. Given the stated intent to address a set of policy questions about this system, a methodological question arises regarding what techniques are appropriate for addressing these questions. The nature of the questions posed in general terms at the beginning of this dissertation – particularly about trade-offs between objectives and the contingency of these trade-offs on uncertain and variable conditions – suggests that a quantitative model is required if useful predictions are to be made (Walters and Martell, 2004).

More specifically, given that these questions involve both biological and economic components, what appears to be called for is a bioeconomic model that combines techniques and insights from the two disciplines. Bioeconomic models and bioeconomic theory have long been used to inform fisheries policy and management. Almost 60 years ago Gordon (1954) published what is often cited as the first bioeconomic model of a fishery, arguing that the open-access nature of the industry would lead to the dissipation of economic rent and that "this is why fishermen are not wealthy...." Schaefer (1957) added to this a logistic growth function for the fish stock, giving rise to what has come to be known as the Gordon-Schaefer model (Larkin et al., 2011). This model provided several important findings: it introduced the concept of maximum economic yield (MEY), which is the maximum net revenue that can be obtained by the fishery given the characteristics of the fish stock and vessels, and demonstrated Gordon's contention about the dissipation of economic benefit. Another major development in fisheries bioeconomics followed when Clark and Munro (1975) extended this basic model to a dynamic context using capital theory, arguing that a fish stock could be thought of as a stock of natural capital, and that the owner(s) could 'invest' (disinvest) in the stock by harvesting at a rate less than (greater than) the stock's growth rate. This dynamic approach allowed them to examine not only optimal states, but also optimal strategies for making the transition from any given state to another.

These studies taken together established the groundwork for much of the analysis of fisheries economics that has followed. Many of these studies have provided further insights into economic issues around fisheries and their management, including: the "malleability" of built capital in the fishery (e.g., vessels, gear), meaning the degree to which it can be easily applied to other uses (Clark et al., 1979; Charles and Munro, 1985; Sumaila, 1995); the form of the production function that describes the relationship between the fish stock, the amount of effort, and the amount of harvest that is likely to be obtained at different levels of these variables (Hannesson, 1983); international trade and its likely effects on natural resources (Brander and Taylor, 1997; Hannesson, 2000); the utility of marine protected areas in economic terms (Hannesson, 1998; Sumaila, 1998); and a great number of other issues.

Two particularly extensive and prominent areas of the fisheries economics literature have been quite influential in shaping policy. The first of these concerns the quasi-open-access nature of many fisheries due to the lack of property rights that exist in most other areas of market economies, and potential solutions to this challenge, mostly focused on instruments such as catch shares and individual quotas (e.g., Arnason, 2010, 2012). The second area is the application of game theory to understand strategic interactions between fisheries stakeholders (Sumaila, 1999; Kaitala and Lindroos, 2007; Bailey et al., 2010), particularly in international fisheries (Munro, 1979, 2009). Both of these topics are beyond the scope of this dissertation and are thus not addressed here.

Many of the above noted studies have focused on theoretical analysis of fisheries, often developing some model that can be solved analytically. Such an approach is appealing for a number of reasons. A rigorous theoretical model will be relatively transparent in its form and its assumptions, at least for those with the mathematical training and ability required to understand the model. In cases where analytical solutions are possible, the model will usually yield quite general conclusions, or at least a clear indication of the bounds within which some particular conclusion applies (e.g., conditional on the value of some parameter, or the relative values of multiple parameters such as the ratio of prices to costs). Empirical applications of the model can then be quite straightforward, as parameter values can be estimated from available data and used to calculate the outputs of interest. This approach is limited, however, especially in the case of particularly complex fisheries that might involve multiple target stocks, multiple fishing fleets, stochastic variables, uncertain or changing parameters, non-linear constraints imposed by management, and so on. A purely theoretical model of such a fishery could quickly become unwieldy and analytical solutions would become impossible to obtain if the model tried to capture the full complexity of the system. This is not to say that theoretical approaches to these complexities are impossible – many published studies have done so (e.g., Charles and Munro, 1985; Sethi et al., 2005) – but when many or all of these conditions exist in the same fishery a primarily theoretical approach seems limited in its ability to address detailed questions.

Ultimately, the selection of the approach must be driven by the questions that are to be answered. A theoretical model of even a very complex system might provide very useful predictions about the broad nature of a system and outcomes of particular policies. For example, no matter the complexity of the fishery, the general prediction of rent dissipation under conditions of open access is likely to hold. However, making more precise quantitative predictions in relatively complex systems will be very difficult with a primarily theoretical model. On the other hand, a more complex model reflecting as much biological and economic detail as possible will not necessarily be more useful in making policy predictions (Walters and Martell, 2004). At best, the effort required to develop a complex, detailed model will be wasted if a simpler model could have yielded equally valid and useful insights; at worst, a more complex model might lead to erroneous conclusions and recommendations, or to a greater risk of undesirable outcomes if its complexity compromises its accuracy, precision, or both (Walters and Martell, 2004).

In cases where specific quantitative predictions about particular outcomes are required, an alternative to a model focussed on theory is an empirical bioeconomic model. With this approach, the model still has a solid theoretical grounding but the focus is on applying the model with empirical data. Predictions about the implications of policy and management approaches can then be explored using numerical and simulation approaches, ranging from relatively abstract where realistic parameters are assumed and their implications explored (e.g., Larkin et al., 2006; Smith, 2008; Costello et al., 2012) to more specific, applied cases where actual fisheries are modelled, sometimes with a great deal of complexity, and outcomes are explored through simulation modelling.

This simulation approach is of particular interest in the context of this dissertation, and there are many examples of and variations on this theme. Sylvia and Enriquez (1994) developed a bioeconomic model of harvesting and processing in the Pacific whiting fishery in the US, and examined the effects of three policy instruments (harvest quotas, limits on fleet capacity, and allocation between fleets) on both economic and conservation objectives. Their results showed trade-offs between present value of profit, physical output of the processing industry, and conservation risk. Larkin and Sylvia (1999) developed a model of the same vertically integrated fishery, incorporating such considerations as fish quality, harvest schedule on a seasonal basis, and allocation among user groups, and used the model to find a management plan that would maximize the economic benefits of the fishery. They found that focusing harvesting at the point in the season when fish quality was highest was critical to maximizing net present value (NPV), while quota allocation between user groups was much less important. Holland (2000) developed a spatial model of fleet dynamics of groundfish fisheries near New England to examine the implications of different marine sanctuary designs for harvester behaviour and thus economic outcomes. He concluded that properly designed sanctuaries could increase harvest and revenue in areas where fishing effort had been excessive prior to the implementation of the closure, mainly by decreasing the efficiency of fishing effort, and questioned whether – at least from an economic perspective – this was a suitable way to attain management objectives. Holland et al. (2005) evaluated the biological and economic performance of a variety of management strategies in a New Zealand rock lobster fishery, using the standard stock assessment model for this fishery and an economic sub-model to convert catch and effort into revenue and cost. Like Sylvia and Enriquez (1994), they did not attempt to identify an 'optimal' strategy, but instead compared the performance of different strategies, and noted the importance of including economic factors in the analysis. Smith et al. (2008) developed and estimated a bioeconomic model of the Gulf of Mexico gag (a type of grouper) and found that harvesters' behaviour more than offset the intended protective effects of a fishery closure during the spawning season. A great number of other studies have built bioeconomic models of various kinds to examine the existing and potential economic benefits that could be obtained if MEY were to be pursued as a management objective, often in comparison to MSY: Dalton and Garber-Yonts (2010) for north Pacific crab; Kompas et al. (2009) for the Australian southern and eastern scalefish and shark fishery; Milon et al. (1999) for the Florida spiny lobster fishery; and Punt et al. (2010) for the Australian northern prawn fishery are only a few examples of these studies.

One system that has been the subject of substantial empirical bioeconomic modelling is the Baltic Sea salmon fishery, in the northern Gulf of Bothnia. Laukkanen (2001) developed a steady-state bioeconomic model of the fishery, where salmon are caught in four sequential fisheries: offshore, inshore, estuary and river. The wild salmon populations in this area are quite weak but are caught in the same fisheries as hatchery-reared stocks, meaning that conservation efforts have required limiting harvest on both sets of stocks. Laukkanen solved this model analytically, and then used separately-derived parameters to determine empirical outcomes. She found that the optimal management regime would close the offshore and inshore fisheries and allocate more fish to the recreational river fishery, and suggested that this regime would improve economic outcomes while preserving wild stocks. Kulmala et al. (2008a) developed a dynamic model that incorporated age-structure in the fish stock as well as random recruitment variability, and used a numerical simulation to find an optimal solution. They applied the model to the Simojoki River salmon stock, and their findings echoed those of Laukkanen (2001) for the overall fishery: that closing the offshore and inshore fisheries would yield better economic outcomes than the status quo. Kulmala et al. (2008b) developed a bioeconomic simulation model of 15 wild stocks and six hatchery-reared stocks that incorporated the fisheries of four countries (Finland, Sweden, Denmark and Poland). They used the model to conduct a retrospective analysis of management performance under the historical regime, and compared the outcome to those that would have occurred with economically optimal management and either cooperation or non-cooperation by the four countries involved. They found that the fishery overall had incurred economic losses of 3.7 million EUR, that historically only the Polish fleet had been profitable, and that optimal management under a cooperative regime would have yielded 3.3 million EUR in net economic benefits. The last two studies incorporated uncertainty in biological dynamics using a Bayesian stock assessment method developed elsewhere (Michielsens et al., 2006, 2008).

There are similarities between the body of work on Baltic Sea salmon and this dissertation. However, the focus of much of the former research, in keeping with much bioeconomic work in general, has been on finding economically optimal strategies (while satisfying a conservation constraint) and comparing these strategies to other options. Relatively little attention has been given to quantifying trade-offs between economic benefits and conservation risk, as is the focus of this dissertation.

Empirical bioeconomic modelling thus provides a framework within which a wide array of policy questions can be explored. However, there are a number of drawbacks to this approach. First, the data requirements for bioeconomic modelling can be quite heavy, especially with greater levels of model complexity (Larkin et al., 2011). In particular, economic data, especially cost data, can be quite difficult to obtain. Any empirical model will only be as reliable as the underlying data used for parameter estimation and simulations. Given the complexity of many such models, transparency of the model and the underlying assumptions can also be a concern as the details can be quite cumbersome to present, especially in the limited space available in primary journals. However, as demonstrated in the literature reviewed above this empirical approach has much to offer, particularly in terms of exploring quantitatively the implications of different management regimes.

1.3.2 Retrospective versus prospective modelling

In developing a model of a fishery to address policy questions, one choice that must be made is the time period in which to base the analysis. There are two basic options here: to base the analysis in the past, i.e., to conduct a *retrospective* analysis; or to base the analysis in the future, i.e., to conduct a *prospective* analysis. Each of these approaches has advantages and disadvantages that are worth exploring both from a general point of view and more specifically in the context of the analyses conducted in this dissertation.

Retrospective analysis

A retrospective analysis consists of building a model that is based in the past and using it to address research questions. There are three broad types of analysis that are often referred to as “retrospective” in the literature. The first refers to an examination (Hamon et al., 2009) or reconstruction of the past, for example, in situations where historical data about variables of interest are limited (e.g., Cheung and Sadovy, 2004) – in these cases a reconstruction can provide estimates of these variables. The second type involves validation of an analytical technique using a retrospective model. For example, one approach has been to use the first half of the available time-series of data to estimate model parameters, and then use the second half of the times series to test the model's performance at predicting the actual historical time series (Grant et al., 2010), while another approach has been to remove one year of data at a time (Quinn, 2003). There are many such analyses in the literature, including many regarding Pacific salmon (Flynn and Hilborn, 2004; Holt and Peterman, 2004; Haeseker et al., 2005; Grant et al., 2010; MacDonald and Grant, 2012).

What is of greater interest in the context of this dissertation is a third type of retrospective analysis, which is a retrospective *policy* analysis. A typical approach to such an analysis in a fisheries context might be to consider many variables (e.g., climate, ocean conditions, fuel prices, etc.) as exogenous and fixed, and then use the model to examine how the trajectory of other variables of interest – e.g., catch, revenue, profit – would have changed if some decision or policy variable was different. Such an analysis can then give insight about the implications of policies that might then be applicable to current and future management. This type of analysis appears to be less common in the literature than the methodological analyses described above, but there has been some retrospective assessment of Fraser sockeye management. Schnute et al. (2000) conducted a retrospective Bayesian decision analysis of four Fraser sockeye stocks, examining how mean catch and variability of catch would have changed if management had proceeded differently. Martell et al. (2008) examined the performance of management of Fraser River and Bristol Bay, Alaska, sockeye salmon fisheries, using a very similar framework to that used in Chapter 3 of this dissertation. One of the studies on the Baltic Sea salmon fishery described above also conducted a retrospective policy analysis of an international fishery (Kulmala et al., 2008b). From this point forward in this dissertation, I will use the term "retrospective analysis" to refer to this type of analysis, i.e., a policy analysis.

Retrospective policy analysis is particularly beneficial because it incorporates information about how some variables did in fact change historically, and is thus not dependent on assumptions about how these variables might have changed. For example, to the extent that data are available, ocean conditions that occurred near the BC coast in the 1990s and 2000s are known, so there is no need to simulate or assume anything about this potential determinant of fish productivity. The modelling exercise can then incorporate these data and focus on assessing the implications of changes in management. Retrospective analysis also allows for comparison with actual outcomes. For example, assuming that the available data are reliable, run sizes, catches, and spawning escapements of salmon over the last decades are known, so outcomes that are modelled in a retrospective analysis can be directly compared to those that were observed (Cass et al., 2004).

However, the retrospective approach also has drawbacks. The fact that some variables are held constant imposes a degree of rigidity on the analysis as the model is essentially locked into a single outcome of what are normally considered to be stochastic processes. There may be some particular aspect of the time series that came to pass that introduces a bias into the analysis that makes it inappropriate for use when answering questions about the future (Cass et al., 2004). For example, the large run size of Fraser sockeye observed in 2010 was completely unexpected and ran counter to all expectation (Grant et al., 2010). Any retrospective analysis that incorporates this unusually high return may be unduly biased toward optimism about the state of sockeye stocks and the prospects for future returns. Another concern with retrospective analyses is the risk that some variables will be inappropriately assumed to be exogenous and held constant, when in fact they may be endogenous to the model and may not have behaved as they did in the past if the policy approach had been different. One particular area of risk here may be in the economic components of a model. Fish harvesters are well known to change their behaviour in space and time in response to regulation (Walters and Martell, 2004; Grafton et al., 2006), and such changes in behaviour may lead to changes in the structure of their costs, in their production function, and perhaps also in the prices that they obtain for their catch. If these changes are not accounted for in a model this may introduce bias into the analysis. Perhaps most critically, using impacts of policies tested in models of the past do not necessarily yield useful information about these impacts in the future, as one or more of the parameters or structures in the system may change over time (Schindler et al., 2008); if this were the case, policies derived from the results of retrospective analyses might be erroneous or even dangerous.

Prospective analysis

In contrast to retrospective approaches, prospective analysis involves setting a model in the future, using expectations about variables and parameters to simulate the fishery and the likely outcomes of different policies. This approach will almost always require some data from the past, as without such data there would be little basis for our expectations about the future. However, in a prospective analysis many other variables and parameters can be modified according to expectations, some of which may be exogenous to the system. For example, a model that includes fishing costs might include assumptions about changes in fuel prices over time, or a model that includes environmental variables as exogenous determinants of fish population dynamics might include the expected effects of climate change on these variables (e.g., Cheung et al., 2008, 2009; Healey, 2011). Prospective analysis is the most typical approach used in management strategy evaluation (MSE), a general framework being increasingly used in analyses of fisheries. In an MSE, several inter-related components of a fishery system are simulated – including the dynamics of the fish stock, harvesting, and components of management such as data gathering, stock assessment, etc. – and the outcomes of different “management procedures” compared (McAllister and Pikitch, 1997; Holland, 2010).

The advantages and disadvantages of a prospective analysis are essentially the complements of those of retrospective analysis. A prospective analysis obviously does not allow for comparisons with actual outcomes, and assumptions must be made about how all variables and parameters will change (or not change), whether exogenously or in response to the control variables in the model. However, this approach allows a greater degree of freedom in modelling, allowing for exploration of a wider range of assumptions and possibilities about the current state of the fishery, as well as about what may unfold in the future. This is possible because the model is not bound to the probability space defined by historical observation (Cass et al., 2004). This also avoids the risk that any bias in the observed time series of variables that are normally considered to be stochastic may in turn introduce bias into the model.

These two approaches to policy analysis of natural resource systems each have benefits and costs, and each will be applied in this dissertation. In each case, part of the discussion will include consideration of both the value and the potential drawbacks of the approaches taken.

1.3.3 Trade-offs

As noted briefly above, policy decisions about fisheries – or in any other area – inevitably involve trade-offs (Walters and Martell, 2004). Perhaps the largest scale trade-off in fisheries management is at a societal level, between the different objectives that society wishes to see attained with respect to its natural resources. Such objectives are often characterized along three lines: economic, social and environmental. Each of these objectives are reflected in discussions and literature about fisheries in general, and about sockeye salmon fisheries in particular: how much profit the industry will generate (Clark, 1985); how much employment and how many small, resource-dependent coastal communities the fishery will support (Brown, 2005); and how great the risks are of a variety of ecological losses (Walters, 1995). Unfortunately, in many cases such objectives are diametrically opposed; for example, catching more fish will usually imply somewhat greater risks of ecological losses.

One approach to examining trade-offs in contexts such as this is to formulate a utility function for the situation in question that combines the different objectives (in this case, societal objectives) into a single value (Keeney and Raiffa, 1976; Lindley, 1985; Belton and Stewart, 2002). This approach has been applied to British Columbia sockeye fisheries in the past (Keeney, 1977), but mostly as a demonstration of the approach, since the author elicited responses from only two experts on the fishery and excluded the stakeholders themselves. More recently, other authors have developed objective (they used the term "value") functions for the Fraser sockeye fishery. Schnute et al. (2000) considered only two components to the function (total catch, and number of years with catch below some minimum threshold), while the FRSSI work described above (Cass et al., 2004; Pestal et al., 2008, 2011) has considered total catch, the number of years below two different benchmarks, and the number of years with low escapement, and has experimented with a variety of other objectives. These last two studies also experimented with the implications of different weights applied to each component of the objective function.

Rigorous formulation of a full objective function suitable for use in actual policy-making is a complex and demanding task (Keeney and Raiffa, 1976; Keeney, 1977). Such a formulation at the level of social policy requires extensive interviews with different groups of stakeholders to assess: their objectives; how to quantify these objectives in the form of "attributes;" how the utility or value that they derive from these objectives is related to the attributes (i.e., the shape of the individual components of the objective function); the relative importance that they attach to each component of the objective function; and how the components might be combined into a single value (Keeney and Raiffa, 1976; Keeney, 1977; Belton and Stewart, 2002).

Formulating a full societal objective function appropriate to the scale being examined here is beyond the scope of this study.

There are other approaches to decision-making with multiple objectives (Belton and Stewart, 2002). The "satisficing" model describes a decision-maker who eliminates all alternatives that do not meet some minimum standard with respect to what s/he judges to be the most important criterion. The decision-maker then considers the second-most important criterion in a similar fashion, and so on until only one alternative remains. However, this approach still requires relative importance (at least in an ordinal sense) to be assigned to the various criteria. The "outranking" approach seeks to rank alternatives with an emphasis on the strength of evidence that the ranking is appropriate, rather than on the strength of the preference itself.

Rather than attempting to develop a formal objective function for societal objectives and decision-making in the fishery and then seeking to maximize that function, trade-off analysis in this dissertation will focus on revealing the shape and magnitude of trade-offs between economic and conservation objectives, and how these trade-offs change under different assumptions about the underlying conditions of the fishery. This approach has been recommended by Walters and Martell (2004) as an appropriate role for quantitative modelling of fisheries policy issues. Developing an objective function with weights attached to particular components runs a high risk of introducing the researcher's own value judgements into the outcomes, while focusing solely on describing trade-offs reduces this influence. Other researchers have also taken this type of approach. Sylvia and Enriquez (1994), in their model of Pacific whiting harvesting and processing, showed policy frontiers that represented the best possible outcome for different combinations of their policy variables, and examined how these outcomes were related to each of the policy variables. Cheung and Sumaila (2008) used an ecosystem model of the northern South China Sea to examine a range of policies and their outcomes in conservation and socio-economic terms, and in similar fashion to Sylvia and Enriquez (1994) showed policy frontiers that represented Pareto-optimum[3]

[3]Cheung and Sumaila (2008) defined a state as Pareto-optimal in this context if the

outcomes.

1.4 Dissertation theme and research questions

1.4.1 Overarching theme and contributions

The main theme of this dissertation is *trade-offs among objectives*. The idea of trade-offs is central to economics as a discipline, which is often defined in terms of the 'allocation of scarce resources,' and as noted above it is possible to integrate a wide variety of values (e.g., market and non-market values) into an economic analysis. Nevertheless, trade-offs among these values are often neglected in the fisheries economics literature. Instead, many fisheries economics studies use profit or NPV as an objective function, with the focus being on the allocation of resources (labour versus capital, different types of capital, or spatial allocation) in order to maximize NPV. Likewise, much of the non-economic fisheries management literature focuses on the maximization (long- or short-term) of physical yield as an objective, or at least omits explicit consideration of economics. However, trade-offs among objectives in fisheries management are even more pervasive than uncertainties, and will most likely remain so since we can never 'reduce' trade-offs with more research: we can only reveal them. An important contribution of the dissertation, then, is to reveal quantitatively the trade-offs among management objectives in a complex multi-stock, multi-fleet fishery where there is significant uncertainty about stock dynamics.

A secondary theme of the dissertation is *resource management under uncertainty*. Renewable natural resource management is inherently uncertain, making this theme something of a truism, but the dissertation incorporates several specific uncertainties and examines their implications for policy and management. The central uncertainties are: (1) the cause(s) of dramatic

outcome in terms of one objective can only be improved at the expense of the outcome in terms of another objective.

cycles in the abundance of some populations; and (2) changes in the productivity of some sockeye stocks in recent years. Other uncertainties and types of variability are also incorporated – for example, year-to-year randomness in abundance, and variability in river conditions that affect migration success – but the focus for assessing policy implications is on the two central uncertainties noted above.

1.4.2 Research questions

This dissertation examines a subset of these issues from a high-level policy perspective, examining quantitatively some of the biological and economic implications of a range of policy approaches that place varying degrees of emphasis on conservation and economic benefits, while considering uncertainty about population dynamics and environmental conditions that affect these populations. The approaches explored will generally remain within the constraints of the existing legislative and policy framework (i.e., staying within the broad constraints of the *Fisheries Act*, the requirement for access for First Nations, and the WSP priority of conservation and sustainable management), but will in some cases vary from the particular way in which some of this framework is currently being implemented. The aim will not be to make specific recommendations about which approaches are 'optimal,' but rather to reveal the trade-offs between objectives that follow from different choices.

More specifically three general questions will be addressed in the context of the Fraser sockeye fishery:

1. How would different management approaches have affected the economic benefits obtained historically from a fishery, if other aspects of that fishery had remained the same? To what extent would the benefits of these approaches have depended on the mechanisms that generated fish stock dynamics, and how would the outcomes have differed if erroneous assumptions had been made about the underlying dynamics?

2. What is the trade-off between economic benefits and conservation risk in the fishery from this point forward? In other words, how much economic benefit must be forgone to reduce conservation risk?; or conversely, how much must conservation risk be increased in order to pursue greater economic benefits?
3. How is this trade-off between economic benefits and conservation affected by different assumptions about future trends in stock productivity?

In answering each of these questions, a fourth methodological question about retrospective and prospective analysis as discussed in section 1.3.2 will also be considered:

4. What are the advantages and disadvantages of retrospective and prospective analysis for examining fisheries policy issues?

The lessons learned with respect to this last question will be discussed in each chapter, and drawn together in the concluding chapter.

The remainder of this dissertation is organized as follows: Chapter 2 describes the general simulation modelling approach I used to examine each of the research questions. Chapters 3 through 5 then address in turn the first three research questions noted above. Chapter 3 uses a retrospective version of the simulation model to examine past management and its implications. Chapter 4 describes a stochastic forward-projection version of the model that I used to examine question 2. Chapter 5 uses the same model to expand the analyses in Chapter 4 along the lines noted in question 3. Chapter 6 concludes the dissertation by synthesizing the results, noting some potential weaknesses in the analysis, and briefly outlining some policy implications of the work.

Chapter 2

A simulation model for Fraser sockeye

This chapter describes the general simulation model used for most of the analysis contained in the core analytical chapters of the dissertation, Chapters 3 through 5. There is a fundamental difference between the analysis in Chapter 3, a retrospective analysis of the historical fishery, and Chapters 4 and 5, a prospective analysis. However, the underlying model structure is essentially the same in all chapters, consisting of three interlinked components: (1) a stock dynamics model describing how the fish stocks change over time; (2) a catch function describing how the amount of catch by different types of commercial fishing vessels changes over time, and with changes in fishing effort and fish abundance; and (3) an economic model describing the revenue and costs associated with different levels of catch. These components are described in this chapter in general terms that are applicable in each of the applications. The specifics of each application are then described in the appropriate chapters, including any changes that are made to the general framework described here.

2.1 Stock dynamics model

The model begins with a group of mature sockeye salmon from stock s with abundance or 'run size' $Q_{s,t}$, entering the fishing grounds in year t on the way from the ocean to their spawning stream. The fishery takes a catch numbering $Y_{s,t}$, which is some proportion $u_{s,t}$ of the run, leaving an escapement $S_{s,t}$:

$$Y_{s,t} = u_{s,t} Q_{s,t} \tag{2.1}$$

$$S_{s,t} = Q_{s,t} - Y_{s,t} \tag{2.2}$$

This escapement of fish then makes its way up the river to spawn, generating some number of recruits $R_{s,t}$:

$$R_{s,t} = f(S_{s,t}) \tag{2.3}$$

where f is one of the two recruitment functions described below. Note that the time subscript refers to the brood year (i.e., the year in which the fish spawn); recruits subscripted t do not actually recruit until three to six years after the brood year ($t + 3$ to $t + 6$), depending on how many years they spend in freshwater and in the ocean. When they do return, they become part of the next run of migrating fish entering the fishing grounds:

$$Q_{s,t} = \sum_{a=3}^{6} \kappa_{a,s,t-a} R_{s,t-a} \tag{2.4}$$

where $\kappa_{a,s,t}$ is the proportion of recruits from stock s and brood year t that return at age a.

Recruitment models

To model the hypothesized mechanisms underlying cycles in sockeye abundance (see section 1.1.1), I used two different stock-recruitment functions. The first, corresponding to the depensatory fishing hypothesis, is the classic

Ricker (1954) model:

$$R_{s,t} = S_{s,t}\alpha_s \exp(b_{s,0}S_{s,t} + w_{s,t}) \tag{2.5}$$

where $b_{s,0} < 0$. In the current context it is best to transform the model to a log-linear form:

$$ln(R_{s,t}/S_{s,t}) = a_s + b_{s,0}S_{s,t} + w_{s,t} \tag{2.6}$$

where $ln(R_{s,t}/S_{s,t})$ can be thought of as a productivity index, $a_s = ln(\alpha_s)$ is the productivity at low spawning stock sizes, $b_{s,0}$ is the density-dependence parameter that determines how quickly productivity decreases with increasing escapement, and $w_{s,t}$ is a recruitment 'anomaly,' i.e., the deviation of log recruits per spawner in year t from the long-term average relationship. Note that with the Ricker model there is nothing inherent in the stock-recruitment function to cause cyclic behaviour.

The second stock-recruitment model corresponds to the delayed density dependence hypothesis, and is typically referred to as the Larkin (1971) model. This is a variation on the Ricker model that allows for decreases in productivity due to interactions with previous spawning stocks $S_{s,t-i}$, where i =1 to 3:

$$ln(R_{s,t}/S_{s,t}) = a_s + b_{s,0}S_{s,t} + b_{s,1}S_{s,t-1} + b_{s,2}S_{s,t-2} + b_{s,3}S_{s,t-3} + w_{s,t} \tag{2.7}$$

where all $b_{s,i} \leqslant 0$. The $b_{s,i}$ are parameters for density dependence operating at lags of i years; if $b_{s,i} < 0$, spawners in year $t - i$ will have a negative impact on productivity in year t.

Either equation 2.6 or equation 2.7 is used as the recruitment function f in equation 2.3, completing the dynamic biological model of the system. These two models have been widely used in assessments and simulations of salmon populations, and in particular Fraser sockeye (e.g., Cass et al., 2000; Schnute et al., 2000; DFO, 2012d). A workshop held in 2006 to discuss causes of the cyclic behaviour of some stocks recommended that the Larkin model be used for the purposes of simulation, since it collapses to the Ricker model if the data do not suggest interactions between cycle lines (Cass and Grout, 2006). This approach has been taken in the FRSSI work (Pestal et al., 2011), although some others have estimated both models and used the one that best fits the data (Peterman and Dorner, 2011, 2012). In Chapter 3 both models are used in order to examine how the outcomes of different management regimes depend on the model. However, in Chapters 4 and 5 only a single model is used, based on model fit.

2.2 Catch model

To model catch in the fishery, the substantial spatio-temporal overlap among the stocks on the fishing grounds must be accounted for: fish from some stocks migrate from the ocean to their spawning grounds at the same time, so it is not practical to exert a particular intensity of fishing effort on one stock without affecting other stocks that are migrating at the same time (see section 1.1.1 and Table 1.1). Following current management practice (DFO, 2010b, 2012c) I assumed that a single exploitation rate u is set for each group of stocks (called a management unit and indexed τ) migrating during each period.

To model how catch changes with fishing effort and stock size, I used a modification of the Cobb-Douglas function that allows catchability (the constant of proportionality between inputs and catch) to vary over time. Given the long periods of time over which I simulated the fishery and the technological changes in the fishery that would be likely occur over such an extended period, I assumed that catchability would increase over time. More specifically, I assumed that it would increase by the same percentage each year. I also allowed catchability to differ between the three fleets that target sockeye: gillnetters, seiners and trollers (see section 1.1.2). Catchability for fleet f in year t is then

$$q_{f,t} = \rho_f \exp(\phi_f t) \tag{2.8}$$

where the parameters are specific to a given fleet: ρ_f is catchability in the first year of the data set being used for estimation, and ϕ_f is the percentage increase in catchability each year. The catch function, incorporating this time-varying catchability, is then

$$Y_{f,\tau,t} = q_{f,t} E_{f,\tau,t}^{\beta_f} Q_t^{\gamma_f} \tag{2.9}$$

where the exponents β_f and γ_f are fleet-specific elasticities reflecting the percentage increase in catch with a 1% increase in effort and stock size, respectively. Parameter values of $\beta > 1$ or $\gamma > 1$ would indicate increasing returns to effort and stock size, respectively; $\beta = 1$ or $\gamma = 1$ would indicate constant returns to the respective factors, while $\beta < 1$ or $\gamma < 1$ would indicate diminishing returns.

Note that in equation 2.9, catch Y in a given year is calculated for each fleet and management unit as a function of (1) fishing effort E applied by that fleet to that management unit and (2) the run size Q for that year aggregated across *all* management units. While it would be ideal to use run size data that are specific to management units, the data used to estimate these parameters were not specific enough to allow this approach. Overall run size was used as an approximation to allow for some incorporation of this variable into the model. Further details are presented in the appropriate chapters.

To drive the stock dynamics the model must allow for catch that is taken not only by the Canadian commercial fleet, but also by United States and First Nations harvesters as well as the recreational fishery. Different approaches were taken in the retrospective and prospective analyses, so details of these calculations are presented in the appropriate chapters. In general, the total catch taken from each management unit is calculated as

$$Y_{\tau,t}^{\text{total}} = Y_{\tau,t}^{\text{other}} + \sum_{f=1}^{3} Y_{f,\tau,t} \tag{2.10}$$

where $Y^{\text{other}}_{\tau,t}$ is catch other than by the commercial fleet. The total catch $Y^{\text{total}}_{\tau,t}$ is assigned to the stocks within each management unit in proportion to each stock's abundance in year t, and these removals from the population then drive the stock dynamics as in equation 2.2.

2.3 Economic model

Many of the specifics of the economic model differ between the retrospective and the prospective analyses, so only the most general aspects of the model are presented here.

With fleet f exerting $E_{f,\tau,t}$ vessel-days of effort during period τ in year t, the cost of fishing in a given year is

$$C_t = \sum_f \sum_\tau c_{f,t} E_{f,\tau,t}$$

where $c_{f,t}$ is the variable cost of fishing per vessel-day.

Note that this cost function does not include any fixed costs or capital costs. Fixed costs are omitted in some bioeconomic analyses because they are considered sunk costs in the short run, meaning that they will not affect decision-making by harvesters. However, given that the analyses conducted here cover 24-47 years, which is likely to be longer than the life span of many vessels, it would not be reasonable to consider fixed costs to be sunk in this context. Nevertheless, I assumed that the Fraser sockeye fishery has played a relatively small role in decisions about investment in BC salmon fleets, on the following basis: (1) the fleets exploit five species of Pacific salmon, with Fraser River sockeye salmon accounting for on average 30% of the total annual BC salmon catch between 1950 and 2000, and an even lower proportion since 2000; and (2) at various times in the history of the fishery, many salmon vessels have obtained a substantial portion of their revenue from species other than salmon (e.g., seiners catch herring; Nelson, 2009; Gislason, 2011). Since

I infer that most investment decisions are based primarily on factors outside the Fraser River sockeye fishery, it is reasonable to ignore fixed and capital costs when assessing the profitability of this particular fishery.

The total revenue generated in year t is

$$V_t = \sum_f \sum_\tau p_{f,t} Y_{f,\tau,t} \tag{2.11}$$

where $p_{f,t}$ is the price per fish received by fleet f for sockeye in year. I assume that price in any given year is perfectly elastic with respect to quantity, since most BC salmon is exported, and comprises a relatively small portion of global salmon production (DFO, 1992). Furthermore, a linear regression of price (in real dollars; data set described in Chapter 3) on BC sockeye landings from 1962 through 2002 showed no statistically significant effect of landings on price ($p > 0.31$).

Finally, the current value of profit in each year of the fishery is calculated as:

$$\Pi_t = V_t - C_t \tag{2.12}$$

This value can then be used as is, or used in a discounting equation to account for time preference and opportunity cost (as in section 3.2.3).

2.4 Conclusion

The three components of the basic model outlined above provide the framework with which I simulate the dynamics of the fishery, including historical or randomly generated variability in recruitment, and historical or projected values of the other variables and parameters. Given this framework, I now proceed with the retrospective and prospective analyses.

Chapter 3

Retrospective analysis of Fraser sockeye fisheries

3.1 Introduction

This chapter[4] examines the historical management of the Fraser sockeye fishery to assess how economic outcomes would have differed if alternative management regimes had been applied in the fishery. The retrospective model incorporates known information about annual variability in recruitment and assumes one of two explanations for the cyclic behaviour of the stocks. The analysis then examines simulations of the fishery from 1952 through 1998 and describes the economic outcomes of four management regimes: the regime that was actually applied historically; a target escapement regime; a fixed exploitation rate regime; and a hypothetical "omniscient manager" that optimizes exploitation rates over the full course of the simulation, assuming full knowledge of the time series of productivity.

This chapter is an analysis in its own right that yields insights about the historical management regime and how it could have been improved, but also provides motivation for the prospective analyses presented in Chapters 4 and 5. The chapter is an application of the retrospective policy analysis approach discussed in section 1.3.2, having much in common in particular with the

[4] An earlier version of this chapter was published in 2009. Details can be found in the Preface.

analysis of Martell et al. (2008) but adding an economic component to the model. This application will serve to demonstrate some of the strengths and weakness of the retrospective approach to policy analysis.

The research questions addressed in this chapter are: How would different management approaches have affected the economic benefits obtained historically from a fishery, if other aspects of that fishery had remained the same? To what extent would the benefits of these approaches have depended on the mechanisms that generated fish stock dynamics, and how would the outcomes have differed if erroneous assumptions had been made about the underlying dynamics?

The remainder of the chapter is organized as follows: section 3.2 describes the data and empirical approach used to parameterize the model, and the simulation approach that was used; section 3.3 describes and discusses the results; and section 3.4 summarizes the results and their implications in the context of the dissertation as a whole.

3.2 Model, parameter estimation, and simulations

The raw data necessary for the parameter estimations were obtained from a variety of sources (outlined in Table 3.1), and parameters were estimated as described below. All economic data are in Canadian dollars (CAD) and were adjusted to real 2000 dollar values using the Consumer Price Index. Some of the data, especially economic data, required some analysis before they could be used in the simulations. Where the details of these analyses are particularly lengthy, they are included in Appendix A so as not to disrupt the flow of the main text.

Table 3.1: Data sources for parameter estimation and simulations. The years listed are those for which data were available; the data were used as described in the text to estimate values for missing years.

Variable/Parameter to be estimated	Year(s)	Source
Run size (Q_t), recruitment (R_t), escapement (S_t)	1948-2002	A. Cass, Fisheries and Oceans Canada, pers. comm. Described by Schnute et al. (2000).
Catch and effort data for catch model coefficients: intercept (ρ_f) and year (ϕ_f). (Run-size data for γ_f as above).	1952-1996 2000-2006	DFO (1995a) B. Patten, Fisheries and Oceans Canada, pers. comm.
Variable cost of fishing effort ($c_{f,t}$)		
Labour	1950-1984	Government of Canada (1986)
	1986-2002	Statistics Canada (2006)
Non-labour	1953-1954	Buchanan and Campbell (1957)
	1968	Campbell (1969a)
	1976-1995	Gislason (1997)
Price ($p_{f,t}$)		
By Species	1952-1995	DFO (1995a)
	1996-2002	DFO (2012b)
By Species and Gear	1976	Shaffer (1979)
(for calculation of	1986-1990	DFO (1992)
troll premium)	1996-2005	DFO (2012b)
Consumer price index	1948-2002	IMF (2005)

3.2.1 Stock dynamics model

For each of the hypothesized recruitment functions (Eq. 2.6 and 2.7), I estimated the parameters a_s and $b_{s,i}$ for each of the nine major stock complexes in the Fraser River using data from 1948-2002. I used ordinary least squares (OLS) to estimate the parameters of the Ricker and Larkin models as shown in equations 2.6 and 2.7 (Tables 3.2 and 3.3). A numerical search routine ("optim" in R; http://www.r-project.org) was used to estimate the Schnute and Kronlund (1996) non-linear formulation of the Larkin model by minimizing $\sum_t w_{s,t}^2$, subject to the constraint $b_{s,i} \leqslant 0$. Recruitment anomalies, $w_{s,t}$, were calculated as the difference between the observed and predicted $ln(R/S)$ values for each recruitment model, i.e., the residuals from the regressions. I used the OLS Ricker estimates and non-linear Larkin estimates as the basis for the biological simulations, but provide the linearly-estimated Larkin parameters for their comparability to the Ricker parameters.

Note that there is likely to be some correlation in the $w_{s,t}$ values across stocks as all stocks spend several years in overlapping areas in the ocean, and migrate through some of the same river and ocean waters. However, Peterman et al. (1998) found that these correlations are for the most part small in the stocks being modelled (median correlation coefficient for 36 pairwise correlations = 0.19), so I chose to disregard this correlation in the estimations. I also examined the residuals for temporal autocorrelation by regressing $w_{s,t}$ on $w_{s,t-1}$ for each stock (Wooldridge, 2003). There was statistically significant (at $\alpha = 0.05$) autocorrelation for two stocks when using the Ricker model, and only one stock when using the Larkin model. Thus, autocorrelation did not appear to be an overly common problem in this data set, and I proceeded without correcting for its effects. The parameter estimates are similar to those of Cass et al. (2000), who conducted an official stock assessment of Fraser River sockeye using data covering roughly the same period.

These stock-recruitment parameters then allow calculation of two key management parameters: $u_{\text{MSY},s}$ and $S_{\text{MSY},s}$, the exploitation rate and escape-

Table 3.2: Stock-recruitment and management parameter estimates for the Ricker model. S_{MSY} values are in millions of fish. For each a and b value the coefficient estimate is shown with the standard error below it. Asterisks indicate statistical significance at $\alpha = 0.05$ (one asterisk) and 0.01 (two asterisks).

	a_s	$b_{0,s}$	$u_{\mathrm{MSY},s}$	$S_{\mathrm{MSY},s}$	$u_{\mathrm{MSY},\tau}$	$S_{\mathrm{MSY},\tau}$
Early Stuart	1.55	-1.96	0.61	0.31	0.61	0.31
	0.14**	0.80*				
Late Stuart	1.99	-1.45	0.72	0.49	0.71	3.45
	0.20**	0.70*				
Stellako	1.96	-3.46	0.71	0.21		
	0.13**	1.09**				
Quesnel	1.94	-0.30	0.71	2.35		
	0.13**	0.22				
Chilko	2.17	-1.90	0.76	0.40		
	0.15**	0.35**				
Seymour	1.66	-6.38	0.64	0.10	0.67	2.31
	0.15**	2.65*				
Late Shuswap	1.77	-0.34	0.67	1.93		
	0.15**	0.13*				
Birkenhead	2.14	-6.89	0.75	0.11		
	0.17**	1.55**				
Weaver	1.93	-4.19	0.71	0.17		
	0.21**	3.54				

Table 3.3: Stock-recruitment and management parameter estimates for the linear Larkin model (equation 2.7). S_{MSY} values are in millions of fish. Standard errors are shown below the parameter estimates. Asterisks indicate statistical significance at $\alpha = 0.05$ (one asterisk) and 0.01 (two asterisks).

	a_s	$b_{0,s}$	$b_{1,s}$	$b_{2,s}$	$b_{3,s}$	$u_{\mathrm{MSY},\tau}$	$S_{\mathrm{MSY},\tau}$
Early Stuart	2.11	-2.14	-3.26	-1.59	-0.91	0.75	0.09
	0.18**	0.79**	0.80**	0.70*	0.70		
Late Stuart	2.29	-1.72	-1.55	-1.10	0.33	0.76	1.20
	0.28**	0.71*	0.71*	0.80	0.79		
Stellako	2.14	-3.03	-1.20	0.83	-2.15		
	0.22**	1.10**	1.15	1.14	1.28		
Quesnel	2.13	-0.31	-0.09	-0.48	-0.39		
	0.16**	0.22	0.22	0.24	0.24		
Chilko	2.30	-1.61	-0.85	-0.14	0.24		
	0.22**	0.40**	0.42*	0.42	0.43		
Seymour	2.09	-5.71	-5.54	-4.31	-4.78	0.77	0.86
	0.19**	2.77*	2.86	2.88	2.76		
Late Shuswap	2.35	-0.58	-0.32	-0.40	-0.04		
	0.31**	0.16**	0.16*	0.16*	0.16		
Birkenhead	2.22	-6.68	-1.37	1.04	-0.60		
	0.22**	1.77**	2.08	2.11	2.00		
Weaver	1.84	-5.45	2.07	3.70	-2.18		
	0.30**	3.95	3.96	3.96	4.03		

ment, respectively, that produce the maximum sustainable yield (MSY). In the case of the Ricker model these are functions of a_s and $b_{s,0}$ (Schnute and Kronlund, 1996), while in the Larkin model they are a more complicated function of a_s and $b_{s,i}$. Given the mixed stock nature of the fishery, though, it is not possible to harvest individual stocks at rates that will produce MSY, no matter which biological model is used. I therefore used a numerical search to find a set of exploitation rates ($u_{\mathrm{MSY},\tau}$, $\tau = 1, 2, 3$) or target escapements ($S_{\mathrm{MSY},\tau}$, $\tau = 1, 2, 3$) that, when applied every year in a deterministic system with no recruitment variability, would yield the maximum total sustainable yield over the long term from the set of stocks that migrate during that period. I used a numerical approach to find $u_{\mathrm{MSY},\tau}$ and $S_{\mathrm{MSY},\tau}$ under the Larkin model for each set of stocks in a similar way (Tables 3.2 and 3.3).

It is worth noting that the use of the Larkin model in simulations does not impose cycle-line interactions on the simulated population. If there is no evidence of interactions in the data, the $b_{s,i}$ ($i > 0$) parameters will be estimated to be very small or even zero, in which case the Larkin model reduces to the Ricker model. This allows for variation among stocks in both the existence and the strength of cycle-line interactions.

3.2.2 Catch model

The catch and effort data were broken down by year, month, fleet, and statistical area. Most of the monthly data provide effort for the entire salmon fleet without differentiating by target species. To obtain data for sockeye only, I selected those catch-effort records for which sockeye comprised >80% of the total catch in that month and area for the gear type in question. The resulting data set contained 145 observations for gillnets, 101 observations for seiners, and 42 observations for trollers, with each observation consisting of the total sockeye catch during a particular month in a particular statistical area, as well as the number of vessel-days of fishing effort exerted by the fleet in question.

A key component of the catch function (equation 2.9) that is missing from this data set is the stock size Q. While data were available on the *annual* stock sizes of each of the nine stocks modelled, it is not possible to match these stock sizes with the catch data in a particular area and month to allow estimation of the stock effect on catch (i.e., the γ_f parameters). To try to crudely assess the stock effect, I used data on the total sockeye run size in the year in question, i.e., $Q_t^{\text{total}} = \sum_{s=1}^{9} Q_{s,t}$. I modified equation 2.9 by substituting in equation 2.9 and taking logarithms to obtain:

$$ln(Y_{i,t}) = ln(\rho_f) + \phi_f t + \beta_f ln(E_{i,t}) + \gamma_f ln(Q_t^{\text{total}}) \tag{3.1}$$

which is to be applied to one fleet at a time. OLS estimates of the parameters for each fleet using equation 3.1 found roughly constant returns to effort: the mean estimates ($\pm$ standard error) of β_f were 0.92 ± 0.03 for gillnetters, 0.81 ± 0.07 for seiners, and 0.94 ± 0.12 for trollers. Given that these values are very close to 1, and for the sake of simplifying the analysis, I assumed that $\beta_f = 1$ for all fleets, and instead estimated two catch per unit effort (CPUE) functions:

$$ln(Y_{i,t}/E_{i,t}) = ln(\rho_f) + \phi_f t + \gamma_f ln(Q_t^{\text{total}}) \tag{3.2}$$

which is called model A; and a similar function with the $\ln(Q)$ term omitted, called model B. The estimates of these parameters produced mixed results (Table 3.4). For gillnetters and trollers the estimate of γ_f is quite small, and omitting this variable from the model appears to make little difference to the fit; indeed, for trollers, the Akaike Information Criterion (AIC; Hilborn and Mangel, 1997) is lower when Q is omitted, i.e., the fit is better.

For seiners it appears that the model including Q fits better, and that the stock effect on CPUE is substantial. This stock effect may be a reflection of the fact that seiners have significantly higher catching power and efficiency than the smaller gillnetters and trollers, and seiners are therefore less likely to reach their maximum catching capacity (i.e., reach saturation) even with very large runs[5]. However, as noted above, the run size data used to estimate these parameters do not match the temporal or spatial scale of the catch-effort data, so including the γ parameter for seiners might introduce bias into the simulations. For this reason, and for consistency with the approach used for the other fleets, I used model B for seiners for the base analysis. However, I also conducted a sensitivity analysis to examine the effect of using model A for seiners; the results of this analysis are presented with the other results.

Table 3.4: Estimates of parameters of two CPUE models, model A (equation 3.2) and model B (same as A, but without $\ln(Q)$). Parameter estimates are given as mean $\pm$ standard error, with asterisks indicating statistical significance at $\alpha = 0.05$ (one asterisk) or 0.01 (two asterisks).

Fleet	Model	ϕ_f	γ_f	n	R^2	F	AIC
Gillnetters	A	0.025 ± 0.004**	0.114 ± 0.075	145	0.285	31.5	276
	B	0.028 ± 0.004**	-	145	0.275	29.9	277
Seiners	A	0.0043 ± 0.0078	0.657 ± 0.149**	101	0.233	14.1	255
	B	0.020 ± 0.008**	-	101	0.073	3.63	272
Trollers	A	0.057 ± 0.016**	0.045 ± 0.179	42	0.332	6.95	58.1
	B	0.058 ± 0.015**	-	42	0.330	6.90	56.2

To correct for bias introduced by the logarithmic estimation (Kennedy, 1983), the catch per unit effort values for each year, $\text{CPUE}^*_{f,t}$, were predicted as

$$\text{CPUE}^*_{f,t} = \widehat{\text{CPUE}}_{f,t} \cdot \exp\left[-\frac{\sigma^2}{2}(1 - \mathbf{z}'(\mathbf{Z}'\mathbf{Z})^{-1}\mathbf{z})\right] \tag{3.3}$$

where $\widehat{\text{CPUE}}$ is the CPUE value predicted by the OLS parameters, σ^2 is the variance of the residuals, $\mathbf{z} = (1, t)$, and $\mathbf{Z}$ is the variance-covariance matrix

[5]Note that this point refers to active vessels' ability to capture large numbers of fish in a short period of time, e.g., one day. It does not refer to issues of latent harvesting capacity where some vessels will decline to fish in years with low fish abundance.

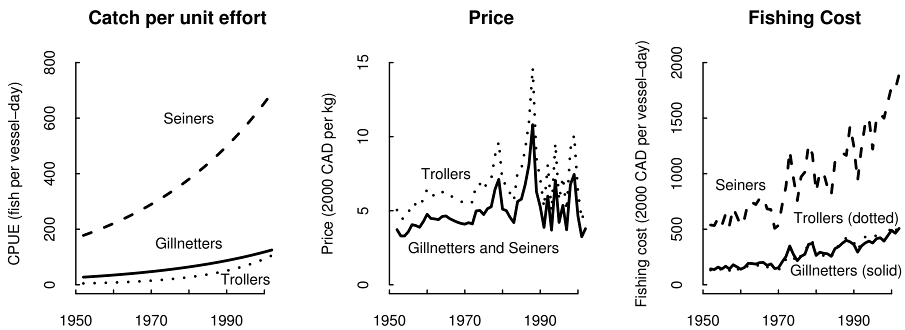

Figure 3.1: Estimates of time-variant parameters for simulation models: CPUE, landing price for sockeye, and fishing cost. Note that costs for trollers and gillnetters are similar and overlap substantially.

from the regression for model B. The resulting annual estimates of CPUE are shown in Figure 3.1.

It was also necessary to calculate the catch taken by fleets other than the Canadian commercial fleet ($Y^{\text{other}}_{\tau,t}$ in equation 2.10). US harvesters have been allocated varying proportions of the total Fraser sockeye catch at different points in time according to international treaty, and First Nations harvesters along the banks of the river have also taken significant catches, in keeping with a variety of treaty and constitutional rights. In the simulation model, catch by US and First Nations fishers in each year was estimated using the historical proportion of the total run each group took in that year, i.e., $Y^{\text{US}}_{\tau,t} = u^{\text{US}}_t Q_{\tau,t}$, and similar for First Nations catch. The total catch taken from each run-timing group was then calculated as

$$Y^{\text{Total}}_{\tau,t} = (u^{\text{US}}_t + u^{\text{A}}_t)Q_{\tau,t} + \sum_{f=1}^{3} Y_{f,\tau,t}$$

This equation was used in place of equation 2.10 to determine the total catch taken from each management unit.

3.2.3 Economic model

Variable cost[6]

Since the objective is to examine the profit obtained from the fishery from a societal perspective, I took variable cost to be the opportunity cost of labour, plus any other costs associated with running the vessel on a daily basis. Capital costs, as well as fixed costs such as insurance, maintenance, etc., were omitted for reasons discussed above (section 2.3).

To estimate labour costs, I obtained average annual incomes for BC fishermen (1950-1984) and workers in BC resource industries (1986-2002), and then adjusted these values using census data to account for higher earnings by captains compared to deckhands (Table 3.1). Average crew sizes were then used to estimate total labour cost per vessel-day of effort for each fleet. The single year with missing data (1985) was estimated as the average for 1982-84 and 1986-88.

I used several studies of costs in this fishery over the study period (Buchanan and Campbell, 1957; Gislason, 1997; Sinclair, 1960) to estimate non-labour variable cost per vessel-day in 1953-54, 1968 and 1976-95 for each fleet. In general, these reports gave cost data as an average per vessel for the fishing season, or for the entire fleet along with the number of vessels in the fleet. It was then straightforward to calculate average cost per vessel-day of fishing. This provided a data set with many gaps, i.e., years without estimates of costs. To fill these gaps, I assumed, given the clear pattern in the time series, that non-labour costs had increased exponentially over the study period, and fit an exponential curve to the raw data. For the simulations, I used raw data for the years in which they were available, and the interpolated values for the other years. Finally, the sum of labour and non-labour variable costs provided estimates of total variable cost per vessel-day for each year ($c_{f,t}$, shown in Figure 3.1).

[6]More details on this analysis and the compilation of the underlying data can be found in Appendix A.

Note that this approach to variable costs, specifically to fuel cost, omits the possibility that the fishery is being subsidized by fuel tax exemptions. As noted in the next chapter (section 4.3.3), in recent years British Columbia has granted a partial exemption to fish harvesters on fuel excise taxes, amounting to 12.5 cents per litre of diesel (Martini, 2012). I had no data on whether such exemptions were in place during the time period of the retrospective analysis, so this is not considered here. However, if data were available, it would be ideal to include the value of this exemption as an implicit subsidy to the fishery (Sumaila et al., 2008, 2010).

Prices

Most official statistics report price by fleet or by species, but rarely by gear and species. Such a distinction is important because troll-caught sockeye often command a higher price than net-caught (gillnets and seines) sockeye. Where possible (see Table 3.1), I obtained prices for sockeye for each gear. I found that there was no trend in the price premium for troll-caught sockeye, so I used the average of this premium (the ratio of troll-caught to net-caught sockeye) as the premium obtained in all years. I used the overall average sockeye price as the price for gillnet- and seine-caught sockeye, and this average multiplied by the troll premium as the price for troll-caught sockeye (Figure 3.1). Prices were obtained on a per-kilogram basis, so I used the ratios of historical catch in kilograms and in numbers to calculate the mean weight of sockeye salmon in each year, and multiplied the price per kilogram by this weight to obtain a price per fish as required in equation 2.11.

The final step in the economic model was to calculate the NPV of the stream of profits obtained during 1952-1998 (the time span of that analysis) from the perspective of a manager looking back in time from 1998. Using the current profit Π_t in year t shown in equation 2.12, the NPV is

$$\pi = \sum_{t=1952}^{1998} \Pi_t (1+\delta)^{1998-t} \tag{3.4}$$

This equation appears somewhat different from the more common discounting equation. Discounting is typically used to decrease the relative importance attached to future values, to reflect the opportunity cost of forgone values in early years, as well as time preference more generally. However, in the current case I am looking backward in time, so the equation used increases the importance of past values. This accounts for the fact that profit obtained in 1952 could have been invested elsewhere in the economy, and this investment would have earned a return, thereby increasing the relative value of earlier profits when compared to later ones.

3.2.4 Management simulations

To evaluate the consequences of various harvest rules I started with the assumption that either the Ricker or the Larkin model, with the parameters estimated above (a_s, $b_{s,i}$, $w_{s,t}$ for all s and t), accurately represents the underlying biological system. For each assumed model, I then simulated four scenarios:

1. application of the historical time series of exploitation rates, $u_{\tau,t}$, for comparison with the simulated outcomes below;
2. application of a fixed harvest rate policy in every year, where the harvest is $Y_{\tau,t} = u_{\mathrm{MSY},\tau} Q_{\tau,t}$;
3. application of a target escapement policy, where harvest is $Y_{\tau,t} = \max\{0, Q_{\tau,t} - S_{\mathrm{MSY},\tau}\}$ and $S_{\mathrm{MSY},\tau}$ is the target escapement set by managers for period τ; and
4. application of an 'omniscient manager' routine, as described by Martell et al. (2008). For these simulations, the manager is assumed to have known in 1951 the value of all parameters, including the annual recruitment anomalies $w_{s,t}$, for the entire 47-year period and set annual harvest rates $u_{\tau,t}$ so as to maximize either discounted profits (π in equation 3.4) or Canadian commercial catch summed over all years. This

approach is sometimes referred to as an "open-loop" policy simulation (Walters and Martell, 2004).

I initialized each simulation with historical data from the first four years of the data set (1948-1951). For the simulation of the historical time series, effort levels were set for 1952-1998 to produce annual catches equal to the historical ones. For the fixed harvest rate and target escapement policies, effort levels were set so that the resulting harvest rate or escapement was equal to the target level. For the omniscient manager scenario, a numerical search routine (again "optim" in R) was used to find the time-series of annual effort levels that maximized the total discounted profit (equation 3.4) with a range of discount rates (0.03, 0.07, 0.11, 0.25, 0.50 and 1.0). For all simulations, the time series of effort levels by management unit $E_{\tau.t}$ were allocated among fleets ($E_{\tau,f,t}$) so that each fleet had a proportion of the total harvest equal to the one it obtained historically. These effort levels were then combined with CPUE, price and cost estimates to calculate profits over the study period.

Note that I included no stochastic elements in the simulations, for example, in the implementation of harvest strategies, which can sometimes be problematic (Holt and Peterman, 2006). The deterministic approach taken here leaves aside some potentially important implementation difficulties, but the overall issue of long-term profitability in the fishery can still be examined with this relatively simple model.

3.3 Results and discussion

The general pattern seen when comparing any of the simulated policies to the historical series is similar under both the Ricker and the Larkin models: all policies call for forgoing some profit in the very early years (until about 1957) to allow the stocks to rebuild (Figure 3.2). Profits are then, on average,

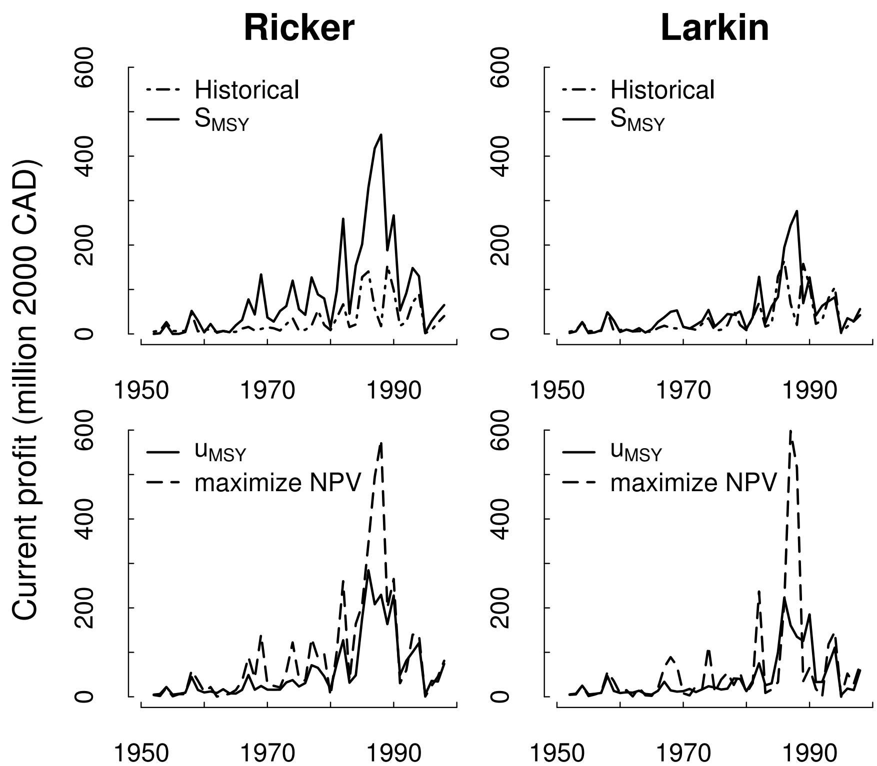

Figure 3.2: Time series of current-value profit (Π_t) from simulations where the Ricker (left panels) or Larkin (right panels) model was assumed to be the true biological model. The top panels show a simulation of the historical fishery, and a fishery managed using a target escapement policy (S_{MSY}), while bottom panels show simulations of a fishery managed using a fixed harvest rate (u_{MSY}) and a NPV-maximizing omniscient manager with $\delta = 0.07$. The catch-maximizing omniscient manager is omitted for the sake of clarity, and because the pattern is quite similar to that for the NPV maximization.

somewhat greater in the late 1950s and early 1960s, and much greater from the mid-1960s onward when compared to the historical values.

For the NPV maximization scenario, this temporal pattern is mildly sensitive to moderate variations in the discount rate: in simulations using the Ricker model with discount rates higher than the default ($\delta = 0.07$), discounting at 0.25 produced only a small deviation from the trajectory obtained with lower rates, and a loss of 9% of current-value profit over the study period. A discount rate of 0.50, however, resulted in very little rebuilding of stocks and yielded a total 47-year profit only slightly greater than the historical scenario, while a discount rate of 1.0 resulted in almost complete elimination of all stocks within four years. This result is in keeping with expectations based on previous results (e.g., Clark, 1973). The rest of the results presented were obtained in simulations where the discount rate was set to 0.07, the standard federal government of Canada rate at the time that the analysis was conducted.

The mean current-value profit over the 47-year period for each scenario is used to examine the overall result of each management approach and biological model (Table 3.5). While there is great variation around the mean from year to year, the mean is nevertheless useful in providing an intuitive value with which to discuss the relative benefits in each scenario. Assuming the Ricker model is the 'true' model underlying the biological dynamics, almost twice as much profit (relative to the historical outcome) could have been obtained from the fishery if a simple fixed exploitation rate harvest policy had been applied (i.e., three different exploitation rates, $u_{\mathrm{MSY},\tau}$, applied every year, one to each management unit τ). Furthermore, almost three times as much profit could have been obtained if a target escapement policy had been applied, with target escapement in each period set to the value of $S_{\mathrm{MSY},\tau}$ as calculated above. However, under the Ricker model, using an 'omniscient' policy (i.e., knowing a_s, $b_{s,0}$ and all $w_{s,t}$ in advance) would produce only about 3-4% more profit than the target escapement policy.

As noted in section 3.2.2, the choice of catch model for the seine fleet may have an important effect on the economic outcomes simulated here. To examine this effect I repeated the analysis for the Ricker model using a catch model for seiners that included the effect of run size on CPUE (i.e., model B in Table 3.4). These analyses yielded mean annual current-value profits of 31, 61 and 93 million CAD for the historical, fixed harvest rate, and target escapement simulations, respectively. Thus, ignoring the effect of run size on CPUE has a minimal effect on the findings.

Table 3.5: The mean, SD and coefficient of variation (CV) of annual current-value profit over the entire study period in different simulations. Mean and SD are in millions of CAD. Note that the 'historical' values are not observed values, but are simulated as described above, producing slightly different results with the Ricker and Larkin models.

	Ricker model			Larkin model		
Simulation	mean	SD	CV	mean	SD	CV
Historical	30	37	1.22	33	40	1.22
Fixed harvest rate	58	69	1.19	41	51	1.25
Target escapement	88	106	1.20	49	59	1.20
Omniscient yield maximization	91	114	1.26	62	94	1.52
Omniscient NPV maximization	92	124	1.35	63	117	1.85

If the Larkin model, with the parameters estimated, is the 'true' model underlying the stock dynamics, the most apparent difference from the Ricker model is that the fishery has substantially less capacity to generate profit: depending on the management approach taken, profit under the Larkin model is 56-70% of that obtained with the same management approach under the Ricker model (Table 3.5). If the Larkin model is the 'true' model and a fixed exploitation rate policy had been applied, 24% more profit could have been obtained than the historical case, while 48% more profit could have been obtained with a target escapement policy.

In a substantial divergence from the results obtained with the Ricker model, the omniscient yield- and profit-maximizing policies applied under the Larkin model yield 27% and 30% more profit, respectively, than the target escapement approach, and produced almost twice as much profit as the historical case (Table 3.5). This greater improvement in performance obtained with omniscient manager policies under Larkin relative to Ricker occurs because of the cyclic nature of populations under the Larkin model, and the fact that the cycles are not synchronized. Under the Ricker model, each $S_{\mathrm{MSY},\tau}$ is the optimal escapement every year, while under the Larkin model each $S_{\mathrm{MSY},\tau}$ represents a compromise between four different optimal escapements, each one applicable during a different year in the four-year cycle. The omniscient manager is not constrained in this manner and can therefore set escapements closer to an optimum level. An additional difference between results with the Ricker and Larkin models is that profits generated under the Larkin model are generally more variable, with higher coefficients of variation in the fixed harvest rate and omniscient manager simulations. This variability also arises from the cyclic behaviour of stocks under the Larkin model.

Another question that might be asked is, what are the consequences of making an incorrect assumption about the underlying biology? For example, if the Ricker model is the 'correct' model but the manager chooses the $u_{\mathrm{MSY},\tau}$ values that are appropriate under the Larkin model, how much profit is lost? The consequences of a management error are qualitatively similar whether a fixed exploitation rate or a target escapement approach is used (Figure 3.3). If the Larkin model is assumed to be correct, there is much more certainty about the outcome of either management approach: if the manager is mistaken in the choice of model, the fishery would make 12-13% more profit. In contrast, if the Ricker model is assumed to be correct but the Larkin model is in fact the correct model, 34% or 73% of total profit is lost if a fixed exploitation rate or target escapement policy, respectively, is employed.

The results here, like those of Martell et al. (2008), suggest that better knowledge of the biology of the system, i.e., the degree of knowledge that we have today about the parameters of the stock recruitment relationships, could have substantially increased the benefits obtained in the fishery; the exact

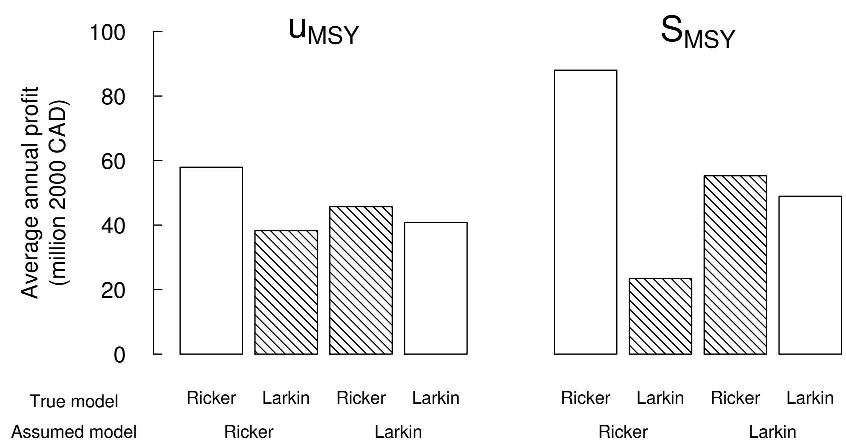

Figure 3.3: Average annual current-value profit obtained in simulations when the 'correct' (open bars) or 'incorrect' (hatched bars) model is used to determine the fixed harvest rate (left) or target escapement (right) to be applied. The "assumed model" labels on the bottom denote the model that is assumed when calculating the management parameters to be applied, while the "true model" labels just above denote the model that is actually used to run the simulation. For example, the left-most open bar shows the profit if the Ricker model is used to calculate u_{MSY} values (assumed model = Ricker), and these values are used in a simulation of the fishery that actually uses the Ricker model (true model = Ricker).

amount of the increase would have depended on the harvest rule employed, and the true biological model (Ricker or Larkin) underlying the system. Of course, a substantial data set would have been required before it would have been possible to estimate all parameters with any degree of certainty. Since the value of S_{MSY} is a function of the a and b_i parameters (Schnute and Kronlund, 1996), application of this target would have required a long time series of stock-recruitment data. However, u_{MSY} is a function of a only, i.e., of productivity at low stock sizes. Since the stocks were actually quite small in the early 1950s, it would have been possible to roughly estimate u_{MSY} at that time. To demonstrate this, I estimated, using only the first few years of data, the a parameter for each stock (a_s), either as the average of $\ln(R/S)$ or by estimating equation 2.6 and using the resulting a estimate. I then calculated each $u_{\mathrm{MSY},s}$ iteratively using $a_s = u_{\mathrm{MSY},s} - \ln(1 - u_{\mathrm{MSY},s})$ (Schnute and Kronlund, 1996), and took $u_{\mathrm{MSY},\tau}$ as the average of $u_{\mathrm{MSY},s}$ weighted by the size of the stock. Mathematically,

$$u_{\mathrm{MSY},\tau} = \sum_s u_{\mathrm{MSY},s} \frac{\sum_t Q_{s,t}}{\sum_s \sum_t Q_{s,t}}$$

where s only includes stocks running during period τ, and t includes only the years used to estimate a. As the results show (Table 3.6), we could have made a reasonable estimate of each $u_{\mathrm{MSY},\tau}$ even with only four years of data.

Table 3.6: Values of $u_{\mathrm{MSY},\tau}$ estimated using the first few years of data, by (1) taking the mean of $ln(R/S)$ over several years and (2) using the intercept of equation 2.6. Each estimate uses only the first years of the stock-recruitment time series as specified in the first column.

	Early (true = 0.609)		**Mid** (true = 0.711)		**Late** (true = 0.672)	
Years used	$\overline{ln(R/S)}$	intercept	$\overline{ln(R/S)}$	intercept	$\overline{ln(R/S)}$	intercept
1948-51	0.545	0.649	0.701	0.795	0.628	0.640
1948-53	0.528	0.607	0.699	0.779	0.604	0.684
1948-55	0.528	0.655	0.680	0.789	0.616	0.673
1948-57	0.591	0.654	0.702	0.771	0.644	0.658

In contrast with the great value of knowledge of the a and b_i parameters, the ability to predict recruitment anomalies, $w_{s,t}$, would have had relatively little value (3-4 million CAD annually) if the Ricker model was the 'true' model, but substantially more (13-14 million CAD annually) if the Larkin model was a better description of the system. This finding, at least under the Ricker model, is similar to that of Walters and Parma (1996), who found that there was little to be lost in a wide variety of fisheries by applying a fixed exploitation rate policy as opposed to trying to take advantage of recruitment variability. Efforts to better understand and predict recruitment anomalies should thus be weighed against the cost of these efforts, especially if the Ricker model is seen as more credible. However, the substantial gains from projecting recruitment anomalies under the Larkin model might justify further research.

The findings here agree largely with those of Martell et al. (2008). In the current case, incorporation of economic considerations has not resulted in qualitatively different conclusions from those obtained when considering physical yield alone. This lack of a difference might result partly from the simple linear cost and catch models used, which unlike many economic models of fisheries do not include increasing costs of fishing as stocks decrease. Nevertheless, it is desirable to incorporate economic considerations into quantitative analyses of fisheries policy whenever possible to allow the explicit examination of economic questions.

An issue that I do not tackle directly, but which is relevant in all cases considered, is the relative costs and risks associated with each management approach. The costs of management failure (Figure 3.3) are one aspect of this, and the analysis suggests that, at least for the harvest policies simulated here, assuming that the Larkin model is the true model can be seen to be a precautionary approach to management. Indeed, this is consistent with the current approach of setting escapement strategies based on simulations with the Larkin model (Cass and Grout, 2006). However, the implementation of each management approach has direct costs as well as the benefits shown here. A fixed harvest rate policy yields more stable profit over time

(Hannesson, 1993) and is relatively easy for managers to implement because it is relatively independent of the total returns. There are, however, conservation risks associated, since there is a fishery even in years with very small runs – given other uncertainties not modelled here, this policy might result in a higher probability of stock collapse due to overfishing. A target escapement policy, in contrast, yields more variable profit but is safer from a conservation perspective, since in years with runs smaller than S_{MSY} there is no fishery. However, such a policy is more difficult to implement than the u_{MSY} policy because it is heavily dependent on knowing how many fish will be running in a given year (Cass and Grout, 2006), information that is notoriously uncertain in this fishery until well into the fishing season (see section 1.1.3). A more complete analysis of this management problem, then, would consider not only the potential benefits of management approaches, but also the costs and risks associated, and try to estimate the probabilities of various possible outcomes for each management approach. It would also be helpful to consider implementation error and other stochastic factors in the analysis. Inclusion of stochasticity would allow the examination of conservation risks due to random variability, an issue that cannot be examined with approach taken here as there is no random process error included in the model. These improvements would help provide a more sound basis for informed decision-making. Some of these issues are addressed in the following chapters.

3.4 Conclusions

This chapter has presented a retrospective analysis of the Fraser sockeye fishery during the second half of the 20th century. The analysis revealed that, given additional information, the fishery could have provided significantly more economic benefit, but the scale of these benefits and the relative strengths and weaknesses of different management regimes depend on the assumed stock-recruitment relationship.

The retrospective approach applied here has several advantages, along the lines of those proposed in section 1.3.2. Many parameters and variables needed for the model are taken to be known, including recruitment anomalies, prices, costs, and CPUE. This allows much of the variability in the system to be held constant, in effect allowing a *ceteris paribus* analysis in the remainder of the model. There is an intuitive appeal to this because the historical outcome provides a solid benchmark against which to compare the simulated results. However, as noted previously, it is impossible to know if the results here would hold if the outcomes of what are usually assumed to be stochastic processes (e.g., ocean conditions) had been different. As a specific example, in Figure 3.2 there are several years during the 1980s and early 1990s with extremely large profits, corresponding to the high productivity of sockeye stocks observed during this period and as captured in the model by the recruitment anomalies $w_{s,t}$ applied in the simulations. Productivity has since declined, raising the question of whether the high productivity observed in the 1980s and 1990s is caused by (1) an inherent property of some or all stocks, (2) random variation that can be expected to recur on a regular basis, or (3) random variation that is extremely unlikely given the inherent properties of the system. While the first two hypotheses would suggest that this high-productivity period is appropriate to include in considerations about future management, the third suggests that it should be disregarded as it is not representative of the 'true' nature of the system.

These are some of the limitations associated with the retrospective analysis. The next two chapters will move to a prospective analysis framework that overcomes some of these problems, but introduces others. The relative merits of the two approaches will be revisited in Chapter 6, drawing lessons from each analytical chapter.

Chapter 4

Prospective analysis of trade-offs between management objectives

4.1 Introduction

The preceding chapter showed how significantly more economic benefit could have been obtained from the Fraser sockeye fishery during the second half of the 20th century, depending on the particular management approach employed and the mechanism underlying stock dynamics. However, while that analysis showed some implications of past management, there are some challenges with respect to whether or not those lessons would be applicable to current and future management, or whether they are to some extent dependent on the particular time series of random variables that existed in the past but may not be representative of what can be expected in the future. One way to further explore this issue, both from the perspective of Fraser sockeye management specifically and the methodological issue of backward- versus forward-looking analysis, is to conduct a prospective analysis of the fishery and compare the findings with those from the retrospective analysis.

This chapter uses a prospective analysis of the Fraser sockeye fishery to examine the economic benefits that would be attainable from the fishery under different management regimes, while also examining the trade-offs between these benefits and the risks to stock conservation that would be posed by the different regimes. As detailed in later sections, the analytical approach in this chapter is different in a number of important ways from that used in Chapter 3, in addition to the shift from retrospective to prospective analysis. In general, these changes make the model more consistent with the approach currently applied in the fishery. This shift comes with some costs, such as the inability to compare to historical outcomes, but also with benefits, such as the flexibility to examine a wider range of assumptions about underlying conditions. The analysis bears some resemblance to a management strategy evaluation (MSE; Holland, 2010) in that it examines the outcome of different harvest rules, but should not be considered an MSE as there is no simulation of the management process, such as gathering of stock and economic data, stock assessment techniques, or other aspects of management; rather, the analysis here is focused on the harvest rule.

This chapter addresses the following research question: What is the trade-off between economic benefits and conservation risk in the fishery from this point forward? In other words, how much economic benefit must be forgone to reduce conservation risk?; or conversely, how much must conservation risk be increased in order to pursue greater economic benefits?

The remainder of this chapter is organized as follows: section 4.2 outlines the model used and the approach taken to simulation in the prospective analysis; section 4.3 details the data and approach used to parameterize the model; section 4.4 presents and discusses the results of the analysis; and section 4.5 provides conclusions.

4.2 Model and simulations

The equations in the general model outlined in Chapter 2 remain applicable here, but the approach taken in the current chapter is quite different from that in Chapter 3, both conceptually and in terms of the data used to parameterize the model. This section outlines in detail the model and simulation approach used in this chapter, and how it differs from that in the preceding chapter.

The following sections introduce a great deal of terminology, much of which may seem interchangeable (e.g., target escapement, escapement goal, escapement strategy). I have included in Table 4.1 a summary of the key terms that will be used below in describing the model and the results. These terms and abbreviations are used consistently through the text to avoid confusion where possible, and are also consistent with the use of terminology in current management documents (e.g., Pestal et al., 2011; DFO, 2012c).

4.2.1 Stock dynamics model

The stock dynamics model framework laid out in section 2.1 is applied without modification here. In contrast to Chapter 3, the 19 stocks currently used for the purposes of fisheries management (MacDonald and Grant, 2012) are modelled here. These 19 stocks are grouped into four management units on the basis of their migration timing as noted in Chapter 1. All stocks belonging to the same management unit migrate at the same time, so for the purposes of modelling it is assumed that fish in a given management unit will be caught by fisheries in proportion to their contribution to the management unit during that year. In other words, a harvest rate of 0.5 (half the run) will catch 50% of the fish in each stock that is part of the run.

Instead of assuming that all stock dynamics follow the Ricker model, or all follow the Larkin model, the model that best fits the data (as determined by the AIC) for each stock is used to model that stock. This approach is consistent with that applied by others in recent research (Peterman and Dorner, 2011, 2012). Rather than use data on total spawners to estimate stock-recruitment relationships, as was the case in Chapter 3, here I used the number of "effective female spawners" (EFS). This approach accounts for both the sex ratio and for the fact that not all females that reach the spawning grounds will succeed in spawning, and is consistent with current

Table 4.1: Definitions of key terms used in modelling.

Term	Definition
Exploitation rate	The fraction of the run that is caught by all harvesters, including US, First Nations, recreational and commercial fisheries.
ER floor	The minimum exploitation rate applied by all harvesters combined, regardless of run size.
Total allowable mortality (TAM)	The total mortality to the run that is allowed by management, from when the run approaches the fishing grounds until it reaches the spawning grounds, due to both harvesting and in-river natural mortality. TAM varies with run size.
TAM cap	The maximum TAM at large run sizes.
Target escapement	The number of fish that are allowed to pass the fishing grounds before harvesting is allowed.
Harvest rule	The framework that establishes escapement goals and TAM based on three management parameters: ER floor, TAM cap and target escapement. Also refers to any given application of this framework, i.e., for particular selected values of the parameters.
Escapement goal	The number of fish that management would aim to allow onto the spawning grounds for any given run size, as determined by the harvest rule.
Escapement strategy	The actual number of escapees that managers attempt to allow onto the spawning grounds in any given year, as a function of the escapement goal and the observed run size. This value is decided by the Minister, based on advice from managers, which in turn is developed with stakeholder input.

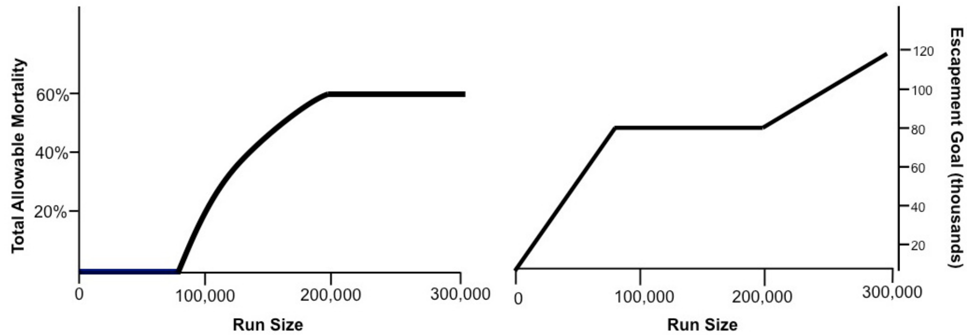

Figure 4.1: A sample harvest rule for the purpose of discussion. On the left is the total allowable mortality (TAM) rule, and on the right is the corresponding escapement goal. Based on Pestal et al. (2011).

practice in management and stock assessment (MacDonald and Grant, 2012; Peterman and Dorner, 2012). Since this model is simulating the fishery forward in time, actual recruitment anomalies are unknown. Therefore, these are generated randomly in multiple simulations, and each harvest rule is simulated many times using a Monte Carlo approach to quantify probable outcomes. The variance in the simulated recruitment anomalies was equal to the variance of the observed residuals in the stock-recruitment analysis for each stock.

4.2.2 Harvest rule and catch model

While the model incorporates catch into the overall dynamics as outlined in section 2.2, the method used to determine the allowable catch is quite different here than in the retrospective analysis. This section outlines the harvest rule, which is conceptually the same as that used in current management, and the discussion here is based on several official documents outlining the system (Pestal et al., 2008, 2011; DFO, 2012c). For the purpose of discussion, a sample harvest rule is shown (Figure 4.1).

The figure shows two key values, and how they change with the size of the run approaching the fishing grounds: (1) the total allowable mortality (TAM), which is the total proportion of the run that is 'allocated to' mortality, whether because of fisheries by US, First Nations or Canadian recreational or commercial harvesters, or because of natural mortality during their migration up the river to the spawning grounds[7]; and (2) the escapement goal, which is the number of fish that management will attempt to allow safe passage to the spawning grounds.

Each harvest rule has three distinct segments delimited by particular run sizes. In the example in the figure, the first segment of the TAM (for run sizes up to 80 thousand fish) there is no allowable mortality, meaning that all fish are permitted to pass by the fishing grounds and swim up river. In the second segment, from 80 to 200 thousand fish, all additional fish beyond the first 80 thousand are "allocated" to mortality (how this allocation is dealt with is described below). These two segments together define what is usually referred to as a target escapement policy. However, the harvest rule as it is currently applied deviates from target escapement in the third segment, from 200 thousand fish upward. This is where a cap on the TAM is implemented to prevent very high exploitation rates. In the example shown here if the run size was 1080 thousand fish, 1000 thousand of them, or about 93% of the total run, would be harvested *if* a true target escapement policy were in place. While the larger more productive stocks may be able to withstand such heavy fishing pressure there is a substantial risk that other stocks, or sub-populations within some stocks, may be seriously depleted. So, for run sizes above some upper limit (200 thousand fish in the example), the TAM is capped, typically at 60% under the current management regime.

The shape of the rule as described above is thus defined by two parameters: (1) the target escapement, which is where the first segment above meets the second segment, and where TAM starts increasing from zero; and (2) the TAM cap. In some contexts it is useful to refer to another value, the "cut-back point," which is the run size at which the TAM cap is reached, but the value

[7]The use of the word "allowable" may seem odd when some of the mortality included in TAM is beyond management control. However, this is the terminology used in current management, and the implications of the TAM are clarified below.

itself is redundant because once we know the first two parameters above, we can also calculate the cut-back point. In the current implementation, there is a third parameter that is used for some stocks and that provides additional flexibility: (3) the exploitation rate (ER) floor, which is an ER (distinct from TAM; see below) that is applied even at very low stock sizes. It should be clear that the TAM in the left panel of Figure 4.1 and the escapement goal in the right panel are interchangeable, i.e., that either one can be derived from the other. All of this information taken together – the TAM, the escapement goal as a function of run size, and the ER floor – is referred to as the *harvest rule*. A different harvest rule is specified for each management unit, with the expectation that the rule will be applied over many years to determine how much harvest should be taken, contingent on the run size that approaches the fishing grounds in that year.

In reality, the implemented harvest rule has changed from year to year (DFO, 2012c, and similar documents from preceding years). Each year DFO staff meet with stakeholders to review in a consultative process the simulated performance of a variety of candidate harvest rules using the FRSSI model (see section 1.1.3). On the basis of these discussions and other internal deliberations, DFO resource managers recommend an escapement strategy and corresponding harvest rule to the Minister of Fisheries, who makes the final decision on implementation (A-M. Huang, DFO, pers. comm.).

Given the harvest rule and a run size in any particular year, the run must then be partitioned as follows. To start, there is the escapement goal specified by the harvest rule. Continuing with the sample harvest rule described above, suppose that in a particular year there is a run size of 120 thousand fish. This falls in the second segment of the escapement goal in the graph, so the actual escapement goal in this year will be 80 thousand, making the TAM $(120 - 80)/120 = 0.333$. However, this does not mean that 40 thousand fish may be harvested: a safety factor, called a management adjustment, is applied to allow for expected mortality during the up-river migration. This adjustment is specified as a percentage of the escapement goal, and can range from less than ten percent to more than 200 percent of the escapement goal. A pre-season adjustment is specified based on long-term average river conditions (A-M. Huang, DFO, pers. comm.), but like other pre-season projections is used for planning purposes only. The magnitude of the management adjustment to be implemented is decided in-season based on observed conditions in the Fraser River. In our example with a run size of 120 thousand fish and an escapement goal of 80 thousand, if the management adjustment were 25% the adjusted escapement goal would be $1.25 \cdot 80 = 100$ thousand, making the total allowable catch (TAC) $120 - 100 = 20$ thousand fish. However, if due to harsh river conditions the adjustment was 100%, the escapement goal would be 160 thousand. This goal is clearly not attainable given the run size of 120 thousand, but regardless of this the TAC will be set to zero.

The final step in the process, which is independent of the harvest rule, is to partition this TAC among the various fisheries. The approach taken here to this partitioning is the same as that used in the FRSSI model (Pestal et al., 2008), which is a close approximation of the actual, but somewhat more complex, procedure (outlined in DFO, 2012c). Under the terms of the Pacific Salmon Treaty, US fisheries receive 16.5% of the TAC[8], and First Nations fisheries are allocated the first one million fish in the remaining TAC. Any fish beyond those allocated to these priorities are then subdivided among the First Nations economic opportunity fishery (3.7%), the recreational fishery (5%), and commercial fisheries (the remainder). Finally, the commercial allocation is divided among gillnetters (46.5%), seiners (48.5%) and trollers (5%). This allocation among the three fleets sometimes varies slightly from year to year subject to negotiation among representatives of each fleet, but was stable from 2010-12 (DFO, 2012c, and preceding IFMPs). Therefore, I assume here that it is constant through time.

[8]The TAC used for this calculation only is adjusted downward by 400 thousand fish to account for First Nations fisheries.

4.2.3 Economic model

The economic portions of the model are much the same in the prospective analysis as they were in the retrospective chapter. Fixed costs are disregarded, for the same reason as outlined in section 2.3. Indeed, given repeated recent closures of the Fraser sockeye fishery and its poor performance in recent years, it seems likely that this particular fishery is playing an even smaller role in investment decisions than it did historically. Net revenue is apportioned between fuel and other costs, labour costs, and vessel profits according to average costs and payment schemes outlined by Nelson (2009; 2011, details below). Note that the calculation of labour costs is approached differently here than it was in the retrospective analysis, given the data available in recent publications. In the prospective analysis, crew members are paid as a share of gross or net revenue, with the remainder of the revenue considered profit for the vessel. The details of this partitioning require discussion of the data themselves, so this is left to the next section.

4.3 Data and parameter estimation

Data for parameterizing the model were obtained from a variety of sources (outlined in Table 4.2), and parameters were estimated as described below. All economic data are in Canadian dollars (CAD) and where necessary were adjusted to real 2011 dollar values using the Consumer Price Index.

Table 4.2: Data sources for parameter estimation and simulations.

Variable/Parameter to be estimated	Year(s)	Source
Run size (Q_t), recruitment (R_t), escapement of EFS (S_t)	Brood years 1948-2004	S. Grant, Fisheries and Oceans Canada, pers. comm.
Catch and effort data for catch model coefficients: intercept (ρ), year (ϕ), and effort (β). (Run-size data for γ as above).	2001-2011	B. Patten, Fisheries and Oceans Canada, pers. comm.
Variable cost of fishing effort ($c_{f,t}$)	2007, 2009	Nelson (2009, 2011)
Price of sockeye ($p_{f,t}$)	2007-2011	DFO (2012b)
Consumer Price Index	1998-2011	Statistics Canada, 2012

4.3.1 Stock dynamics model

The estimations conducted here are quite similar to those for the retrospective analysis, as outlined in section 3.2.1. For each of the hypothesized recruitment functions (Eq. 2.6 and 2.7), I estimated the parameters a_s and $b_{s,i}$ for each of the 19 stocks listed in Table 1.1. For many stocks data were available for the brood years 1948-2004, but for some of the smaller stocks data sets are missing data for the earlier part of the time series. The data for spawners were provided as EFS, rather than as the total number of spawners.

OLS was used to estimate the parameters of the Ricker and Larkin models (Tables 4.3 and 4.4). A numerical search routine ("optim" in R; http://www.r-project.org) was also used to non-linearly estimate the Larkin model by minimizing $\sum_t w_{s,t}^2$, subject to the constraint $b_{s,i} \leqslant 0$. I used the OLS Ricker estimates and non-linear Larkin estimates as the biological basis for the simulations, but provide the linearly-estimated Larkin parameters for their comparability to the Ricker parameters. Standard errors and indications of statistical significance of individual parameters are not presented here for the sake of simplicity of presentation; the emphasis is instead placed on the goodness of fit of the model, and the comparison of the Ricker and Larkin models.

The parameter estimates derived here match quite closely those of other authors, as do the findings of which model is the best fit to the data based on AIC (Peterman and Dorner, 2011). On the basis of the AIC findings, the Larkin model was used for all stocks except Bowron, Raft, Cultus and Harrison; the Ricker model was used for these four stocks.

Following Pestal et al. (2011) and the rationale outlined in section 3.2.1, I chose to disregard potential cross-correlation between stocks in the residuals, $w_{s,t}$. I examined the residuals for temporal autocorrelation as in the retrospective analysis, by regressing $w_{s,t}$ on $w_{s,t-1}$ for each stock (Wooldridge, 2003). There was statistically significant (at $\alpha = 0.05$) autocorrelation for five stocks when using the Ricker model (coefficients of $0.29 - 0.45$ for the stocks with 'significant' autocorrelation), and six stocks when using the Larkin model (coefficients of $0.28 - 0.41$). However, the primary effect of temporal auto-correlation will be to bias significance tests, as opposed to the estimates of the parameters themselves (Wooldridge, 2003). Since the focus here is on the parameters themselves and not on testing hypotheses with respect to their statistical significance, I will proceed without further addressing auto-correlation. This is also in keeping with the approach taken in the FRSSI model (Pestal et al., 2011).

Finally, within the simulations, an approach was required to estimate the proportion of the total escapement that would become EFS, which is a function of both sex ratio and spawning success. I used the long-term average of $EFS_{s,t}/S_{s,t}$ for each stock to estimate this proportion, using data in the stock-recruitment database obtained for the full estimations in the retrospective analysis (A. Cass, Fisheries and Oceans Canada, pers. comm.).

Table 4.3: Stock-recruitment parameter estimates for the Ricker model (equation 2.6). n is the number of observations and $\hat{\sigma}^2$ is the variance of the residuals in the regression. Horizontal lines separate stocks from different management units (see Table 1.1). The last column shows the ratio of the AIC of the Ricker model to that of the Larkin model estimated in Table 4.4.

	a_s	$b_{0,s}$	n	$\hat{\sigma}^2$	AIC	AIC ratio
Early Stuart	2.08	-2.56	57	0.611	132.3	1.06
Bowron	2.46	-71.56	57	0.616	133.7	0.96
Fennell	3.15	-232.99	38	0.720	99.3	1.09
Gates	2.80	-58.74	37	0.846	102.8	1.17
Nadina	2.15	-11.65	32	0.679	82.3	1.03
Pitt	2.34	-45.53	57	0.560	127.1	1.02
Raft	2.36	-44.65	57	0.608	131.0	0.98
Scotch	2.37	-234.80	25	1.089	80.2	1.43
Seymour	2.30	-12.08	57	0.860	149.1	1.05
Chilko	2.74	-3.62	57	0.496	121.4	1.04
Late Stuart	2.56	-2.06	57	1.744	188.3	1.02
Quesnel	2.58	-1.07	57	1.061	162.8	1.17
Stellako	2.61	-7.69	57	0.431	112.0	1.13
Cultus	1.87	-26.99	57	0.973	158.6	0.97
Harrison	2.87	-123.09	57	1.089	164.1	0.97
Late Shuswap	2.08	-0.31	57	0.979	157.1	1.05
Portage	3.27	-168.48	51	1.192	154.6	1.31
Weaver	3.07	-16.43	39	0.782	105.0	1.07
Birkenhead	2.77	-13.80	57	0.900	153.5	1.00

Table 4.4: Stock-recruitment parameter estimates for the Larkin model (equation 2.7). $\hat{\sigma}^2$ is the variance of the residuals in the regression, and numbers of observations (not shown) are the same as for the Ricker model. Horizontal lines separate stocks from different management units (see Table 1.1).

	a_s	$b_{0,s}$	$b_{1,s}$	$b_{2,s}$	$b_{3,s}$	$\hat{\sigma}^2$	AIC
Early Stuart	2.48	-2.32	-4.70	-3.13	-1.34	0.531	124.8
Bowron	2.47	-75.40	-0.18	-0.21	-0.14	0.699	139.0
Fennell	3.45	-181.25	-53.98	-53.45	-31.62	0.681	91.5
Gates	3.71	-71.54	-33.45	-75.56	-81.65	0.655	87.7
Nadina	2.48	-18.50	-0.00	-14.21	-17.28	0.754	79.6
Pitt	2.56	-30.27	-4.21	-23.76	-7.33	0.530	124.7
Raft	2.47	-39.74	-0.12	-31.43	-9.34	0.633	134.1
Scotch	3.02	-0.00	-56.60	-31.16	-60.76	0.620	56.0
Seymour	2.77	-9.95	-16.52	-9.99	-9.37	0.723	141.5
Chilko	2.91	-2.43	-2.17	-0.00	-0.00	0.462	117.0
Late Stuart	2.77	-2.21	-2.00	-1.30	-0.00	1.729	185.1
Quesnel	3.00	-0.91	-0.74	-0.99	-0.90	0.690	139.0
Stellako	3.10	-7.04	-2.42	-1.06	-7.11	0.328	98.9
Cultus	1.88	-28.61	-0.01	-1.53	-0.01	1.110	163.9
Harrison	2.90	-128.80	-0.00	-0.01	-0.00	1.228	169.4
Late Shuswap	2.85	-0.78	-0.80	-0.82	-0.40	0.836	149.3
Portage	3.64	-154.68	-126.26	-0.18	-0.13	0.919	118.4
Weaver	3.45	-15.74	-4.39	-0.00	-11.73	0.786	98.0
Birkenhead	3.02	-12.02	-6.83	-0.00	-0.00	0.902	153.1

Note that this approach to estimating the stock-recruitment relationships assumes that the stock-recruitment relationships observed during 1948-2004 still apply and that the parameters have not changed over time (i.e., that the parameters are stationary; Hilborn and Walters, 1992). There is some evidence (Peterman and Dorner, 2011; DFO, 2012d) that this is not the case: that productivity has varied over years and in particular has declined in recent years. I do not address this contention in this chapter, and instead take the parameters estimated over the full range of the data to be indicative of the long-term productivity of the system. However, in the next chapter I examine the possible implications of changed productivity.

4.3.2 Harvest rule and catch model

As noted above, there is no single harvest rule that has been applied in each year of the fishery, as is usually the intent with harvest rules of the kind used in this fishery. The ER floors and TAM caps have been relatively consistent, but the target escapements have been quite variable. As an approximation of the current approach, which I will use as a baseline rule to which different trials will be compared, I used the ER floors and TAM caps planned for the actual fishery in 2012, and used the mean of the target escapements used from 2009 through 2012 (shown in Table 4.5). I took these values as indicative of the current policy approach and intent, i.e., implying a particular attitude toward the trade-off between conservation risk and economic benefits.

Another part of the harvest rule routine is the management adjustment, which allows for poor river conditions that in some years will kill many fish before they reach the spawning grounds. To simulate the variability in this value, I used the adjustments that have been estimated before the season for the last four years (2009-12; DFO, 2012c, and similar documents). For the first three management units, the mean and standard deviation of adjustments have been: 0.623 ± 0.022 for Early Stuart; 0.436 ± 0.054 for Early Summer; and 0.078 ± 0.015 for Summer. The values for the Late management unit were 6.04, 0.66, 0.69 and 1.27, suggesting positive skewness. I chose to

Table 4.5: Approximation of current harvest rule parameters used for each management unit. This approximation is used as a baseline in the simulations. The baseline target escapement is the mean of values from 2009-2012. Data from DFO (2012c) and similar management plans in preceding years.

parameter	Early Stuart	Early Summer	Summer	Late
ER floor	0.1	0.1	0.1	0.2
TAM cap	0.6	0.6	0.6	0.6
Target escapement	118	200	592	673

represent this using a log-normal distribution, where the mean and SD in log space are 0.31 ± 1.03. Variability was then generated by pulling random draws from these distributions during the Monte Carlo simulations.

To estimate the parameters of the catch model, data on salmon fisheries catch and effort were obtained from DFO's Fisheries Operations System (FOS) database. Each record in the database represented one observation, with each observation consisting of the catch of each species of salmon, the amount of fishing effort being applied (in vessel-days), along with the date of the observation, the fleet that was fishing, and the management area. To select only observations that pertained to sockeye-specific fisheries, I omitted any observations where sockeye was $<90\%$ of the total salmon catch. Given the need here for a general, broad-based model of how catch will change with fishing effort and run size (equation 2.9), I aggregated the remaining observations across dates, but retained the separation by month and license area, which is an aggregation of management areas (see DFO, 2012c). The resulting data set included 62 data points, which are shown in Figure 4.2. As in the retrospective analysis, to crudely incorporate the effect of run size I used historical data on annual run size.

To begin the estimation I used a logarithmic form of equation 2.9, but given the relatively small data set I included the estimation for the three fleets in a single model, rather than estimating separate models for each fleet as in the retrospective analysis. To account for potential differences in gears I

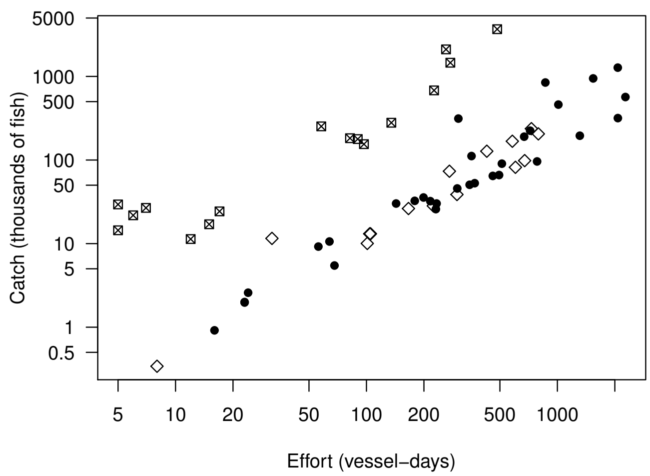

Figure 4.2: Catch-effort data used for estimating the catch function, by fleet: gillnetters (filled circles), seiners (crossed squares), and trollers (open diamonds). Note that both the vertical and horizontal axes are shown on a logarithmic scale.

included dummy variables for seiners and trollers, and included dummies on license area and month to see if these would be affect the estimation. Finally, to allow for possible interactions between the effects of different variables, I examined the importance of several interaction terms.

I experimented with many combinations of variables and dummies in the model with the ultimate goal of finding a model that parsimoniously (as defined by AIC) explained variability in catch. Throughout all models, effort and run size were consistently important variables, in terms of both the p-value attached to their coefficients and the absolute size of their coefficients.

The first model run included all fleet, area and month dummies, and compared this to the same model but with fleet-effort interactions. This addition increased AIC, the p-values for the coefficients on both interactions were >0.39, and visual examination of the data gives no indication that the catch-effort relationship has different slopes between fleets, so I omitted these interaction terms from further consideration. The area and month dummies were also not significant, and in any case would not be possible to deal with in the modelling framework outlined above, so I also omitted these, again lowering the AIC. The resulting model included log of effort, log of run size, year and the two fleet dummies as explanatory variables:

$$ln(Y_{i,t}) = ln(\rho) + \phi t + \beta ln(E_{i,t}) + \gamma ln(Q_t^{\text{total}}) + \delta_{\text{S}} dum_{\text{S}} + \delta_{\text{T}} dum_{\text{T}} \quad (4.1)$$

where the dum_f and δ_f are the dummies and coefficients for fleet f. Table 4.6 shows the parameter estimates. Note that some of the coefficients were not statistically significant, but were nevertheless retained as there is a theoretical rationale to consider them important. Also, the approach taken here differs somewhat from that taken in the retrospective analysis, where I assumed that the returns to effort were constant. I retained the estimate of β in the current analysis (rather than assuming $\beta = 1$) because I tested for but found no significant interactions between effort and gear, and because I

Table 4.6: Estimates of parameters for the catch model in equation 4.1. The model was estimated with 62 observations, and the variance of the residuals $\hat{\sigma}^2$ was 0.278.

Variable	Coefficient	Estimate	SE	p-value
(intercept)	ρ	-49.99	39.4	0.21
year	ϕ	0.0268	0.0197	0.18
ln(effort)	β	1.157	0.053	<0.01
ln(run size)	γ	0.297	0.095	<0.01
seiners	δ_{S}	3.00	0.19	<0.01
trollers	δ_{T}	-0.051	0.171	0.76

had greater confidence in the estimates as they were derived from a higher quality data set, which was obtained from a single integrated database and covered a shorter time period.

When these parameters are used to simulate catch levels, the predicted catches must be corrected for the log-normal bias that arises in estimating this logarithmic form of the model. In the retrospective analysis I used Kennedy's (1983) method (equation 3.3) to correct for this bias. However, the second part of that correction, to account for bias when projecting in time outside the range of the data set, was much less than 1% of the overall correction. Therefore, for the sake of simplicity here I corrected only for log-normal bias (Hilborn and Mangel, 1997):

$$Y_i^* = \hat{Y}_i \cdot \exp\left(-\frac{\hat{\sigma}^2}{2}\right) \tag{4.2}$$

where Y_i^* is corrected catch, $\hat{Y}_i$ is the catch estimated using the catch function, and $\hat{\sigma}^2$ is the variance of the residuals in the estimation of the catch function.

4.3.3 Economic model

The DFO Pacific Region statistics web site (DFO, 2012b) includes data on sockeye landed quantities and values by fishing fleet, so it was straightforward to calculate average prices for each fleet.

Cost calculations follow closely on Nelson's (2009; 2011) financial profiles of BC's commercial fishing fleets. Of the costs outlined in those publications, three are appropriate to include here. First, fuel use (in litres) is estimated for each fleet using: (1) Nelson's estimates of aggregate fuel cost for the fleet for the full fishing season; (2) an online database of fuel prices (Kent Marketing Services, 2012) that includes the price of diesel in BC coastal ports in the years of Nelson's estimates; (3) data from the OECD (Martini, 2012) showing that BC fish harvesters receive an exemption from the 12.5-cent excise tax on diesel fuel; and (4) the number of vessel-days of fishing effort exerted by each fleet, from DFO statistics (DFO, 2012b). These data combined allow the estimation of fuel consumption per vessel-day of effort. Fuel prices for the simulations were then estimated as the average of the real (2011 CAD) price of diesel fuel at these same BC coastal ports during 2007-2011. Finally, given the amount of effort estimated in each year using the catch function, fuel cost can be calculated using these data and then subtracted from the gross revenue.

The second cost to include was that of sockeye license fees for each fleet. This is a cost imposed by the government, and it is a cost directly related to this particular fishery, so it is included here by subtracting the aggregate license cost (across all vessels) for each fleet from the total revenue in the fishery.

The third cost to include is for crew and captain. Given average crew sizes in these fleets and typical arrangements between vessel owners, captains and crew, Nelson (2009; 2011) provided approximate shares of revenue that are allocated to the captain and crew: 62% of net revenue for seiners (i.e., gross revenue minus fuel and license costs), and 17% of gross revenue for trollers. Gillnetters typically have no crew, and so no labour costs.

Once fuel, license and crew costs are deducted, the remaining revenue is considered private profit to the vessel owner.

4.3.4 Simulations and outputs

For each harvest rule to be tested I conducted 1000 simulations, which was enough to produce quite stable results. Each simulation was initialized with historical data and the parameters estimated above, and then run for 24 years (six spawning cycles). The FRSSI model is typically run for 48 years, but I decided on shorter simulations for two reasons: (1) it seems unreasonable to assume that predictions about economic parameters can be made with even a remote degree of confidence much beyond two decades; and (2) some of the trials outlined below took 10 hours to complete, so 48-year simulations would have taken nearly twice as long. For practical reasons I simulated for 24 years only.

The research questions addressed in this chapter concern the trade-offs between conservation and economic benefits, so I extracted the following indicators from the simulations to represent these objectives:

- Mean and year-to-year variability (standard deviation) of vessel profit. The mean profit is referred to here interchangeably as *economic benefit*. Note that it could be argued that crew shares also provide an economic benefit, especially in rural communities where there may not be many other economic opportunities. In keeping with standard economic practice, labour is considered a cost here, and thus deducted from gross economic benefits. However, given the function used to calculate the crew share – a constant proportion of revenue – this subtraction of the crew shares will change the magnitude of the economic benefit indicator, but will not change its relationship with other variables, most notably the shape of the trade-off with conservation risk. Thus, at least qualitatively, the results here would for the most part hold if one wanted to consider crew shares as a benefit;

- The proportion of times during each 24-year simulation that the four-year average of the number of spawners fell below BM2, a low-abundance benchmark used in the FRSSI process that is derived based on historical lows in spawner abundance, as well as expert judgement in some of the FRSSI workshops (Pestal et al., 2008; DFO, 2010b). This proportion is referred to here as *conservation risk* and, while it is not intended to represent a chance of extirpation, it is used as a flag in current management activities, and high values for this proportion suggest that there may be cause for concern about a particular harvest rule with respect to its tendency to depress stock levels below acceptable levels.

- In addition to the above by-stock conservation indicator, in order to combine the measures of conservation risk I took the cross-stock sum of the squares of conservation risk. That is, if conservation risk for a given stock is ψ_s, this indicator is $\sum_s \psi_s^2$. I used squares, rather than the straight proportions, in order to give relatively more weight to higher levels of conservation risk. I refer to this value as *aggregate conservation risk*.

Sets of simulations were conducted to assess how several forms of change in the baseline harvest rule would affect these indicators. The changes tested were as follows:

- Moving the ER floor from 0 to 0.90;

- Moving the TAM cap from 0.10 to 1.0;

- Moving the target escapement from 0 to 3 times the baseline target escapement. In the text I refer to target escapements by these multiplier values.

- A combined test that involved changing all three harvest rule parameters within the above ranges.

4.4 Results and discussion

The first three sets of results below (sections 4.4.1 through 4.4.3) show how economic benefits and conservation risk change with one of the three harvest rule parameters, holding the other two parameters constant. These results are shown mostly as a preliminary exploration of the relationships between these parameters and the outcomes. This exploration gives insight into the changes we see in the more comprehensive analysis, which involves exploring the full policy space at once, i.e., trying many different combinations of the harvest rule parameters in turn and examining the results. The last section examines the sensitivity of the analysis to the choice of stock dynamics model.

4.4.1 ER floor

Trials that involved varying the ER floor from 0 to 0.9 showed a smooth increase in the current value of profit for much of this transition, from about 8 million CAD to a peak of about 19 million CAD with an ER floor of 0.8, before profit falls off rapidly with higher ER floors (Figure 4.3). Recall that the ER floor is a *minimum* exploitation rate that is mostly applied at low run sizes; in terms of the harvest rule shown in Figure 4.1, it is an exploitation rate that overrides the TAM, which is a function of run size, and also overrides the management adjustment that allows for in-river mortality. For example, even if the run size was 10,000 fish (which in our example in section 4.2.2 and Figure 4.1 would call for TAM = 0) and the management adjustment was 400% (due to expected in-river mortality of 80% of the run), an ER floor of 10% would still allow for the harvest of 1000 fish.

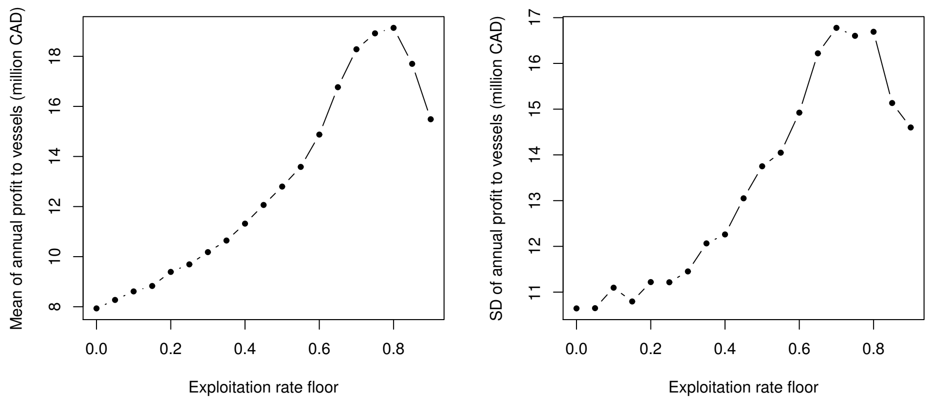

Figure 4.3: Mean and standard deviation of vessel profit over 24 years as the ER floor is increased from 0 to 0.90. The profit value used here and below is current value (i.e., with no discounting).

There is, however, high variability of profitability from year to year, and a strong correlation between mean profit and standard deviation of profit. This is a consequence of the harvest rule, which approximates a target escapement policy at low and moderate stock sizes; target escapement policies are known to generate relatively large inter-annual variability in catch (Hilborn and Walters, 1992), and therefore in revenue and profit. In my implementation of the harvest rule the ER floor overrides the TAM cap. Therefore, as the ER floor is increased from 0 to 0.6, the harvest rule as a whole becomes closer to a fixed exploitation rate policy; and for ER floors $\geqslant 0.6$, the applied policy is a true fixed exploitation rate, i.e., the same exploitation rate is applied at all run sizes. This is why the coefficient of variation (CV, defined as SD divided by mean) is about 1.3 for low ER floors, but decreases to about 0.9 at higher ER floors.

Another result to note is that the profits obtained in these scenarios are markedly lower than those seen in the retrospective analysis (e.g., compare to Figure 3.2 and Table 3.5). For example, the target-escapement simulation with the Larkin model yielded an annual average of 62 million CAD (in 2011 dollars, converted from 49 million CAD in Table 3.5 using total inflation from 1998 to 2011 of 25.7%; Statistics Canada, 2012), while the analyses here yield only 8-19 million CAD. There are three primary reasons for this difference. First, prices of sockeye used in the current analysis are lower than those in the retrospective analysis, 16.59 CAD per fish for gillnetters and seiners, and 22.50 CAD for trollers in the retrospective analysis (again converted here to 2011 CAD); 9.35, 8.22 and 15.72 CAD for the three gears in the current analysis.

Second, fishing costs in the prospective analysis are substantially higher, particularly for seiners. As an example, consider the revenues and costs that would be expected for seiners in the two analyses assuming a run size of one million fish: in the last year of the retrospective analysis (1998) one vessel-day of effort would be expected to yield a catch of 700 fish (see Figure 3.1), and thus 11,600 CAD in revenue. Cost for this effort would be 1900 CAD, so profit would be 9700 CAD, or 12,192 CAD in 2011 dollars. In contrast, in the prospective analysis one vessel-day in 2011 would yield a catch of about 2000 fish and thus revenue of 16,440 CAD. However, fuel would cost 811 CAD and, more importantly, crew members would receive 62% of the revenue (net of fuel). Thus only 5939 CAD remains as profit for the vessel.

Third, note that the mean profit levels seen under the Larkin model in the retrospective analysis are strongly influence by a few years of extremely high profits in the 1980s and early 1990s (Figure 3.2, right-hand panels) due to very high productivity in those years. In the retrospective analysis that high productivity is passed directly into the simulation (through the recruitment anomalies, $w_{s,t}$) and is thus reflected in the outputs. In contrast, in the prospective analysis those years will have increased both the mean estimates of productivity of each stock and the variability in that productivity through their influence on the stock-recruitment parameters estimated with historical data. However, random variability in stock dynamics in this analysis is simulated with random draws from a log-normal distribution, meaning that productivity and profit observed over many simulations will tend to reflect the mean stock-recruitment relationship, rather than particular extreme events or periods of time. Note that this is an illustration of a weakness of retrospective analysis, as discussed in previous sections: that analysis is bound to the *observed* outcomes of stochastic processes that may not be good predictors of outcomes of those processes that we will see in the future.

The second set of results for this analysis show changes in the conservation risk to each stock as the ER floor increases from 0 to 0.9 (Figure 4.4). In most stocks conservation risk is reasonably low and stable until the ER floor exceeds about 0.6 to 0.7, at which point the risk to many stocks starts to increase quite rapidly. This should not be surprising, as the exploitation rate that generates MSY, u_{MSY}, for these stocks is in the area of 0.75 (Table 3.3), so exploitation above these rates will lead to depletion. These outcomes also reflect the fact that a high ER floor overrides the TAM cap (set at 0.6) and imposes a high exploitation rate even when stocks are at low levels. The exception to this pattern is the Cultus Lake stock, for which conservation risk is uniformly high, averaging almost 1 for most policies.

Finally, we can examine the trade-off of aggregate conservation risk against mean annual profit as the ER floor is changed (Figure 4.5). Starting at low ER floor values in the top left, we can see that increasing the ER floor significantly increases profit without significantly increasing[9] aggregate conservation risk until about 0.70, when aggregate risk starts to increase quite sharply. Note that the minimum aggregate risk is approximately 1, which represents the fact that risk to the Cultus stock is nearly 1 regardless of the ER floor employed.

This is quite clearly a dramatically convex trade-off (Walters and Martell, 2004), where performance with respect to one of the objectives can be improved while incurring only minimal losses with respect to the other objective. Note also that ER floors above 0.75 are clearly 'dominated' (Walters

[9]As noted in the figure legend, for these trade-off plots conservation risk is reversed on the vertical axis, i.e., with high values of risk at the bottom of the axis. The results are presented this way to make it clear that moving away from the origin (the bottom left) is desirable on both axes, and discussions of convex versus concave trade-offs will be much more intuitive. However, throughout the text reference is still made to *increasing* conservation risk.

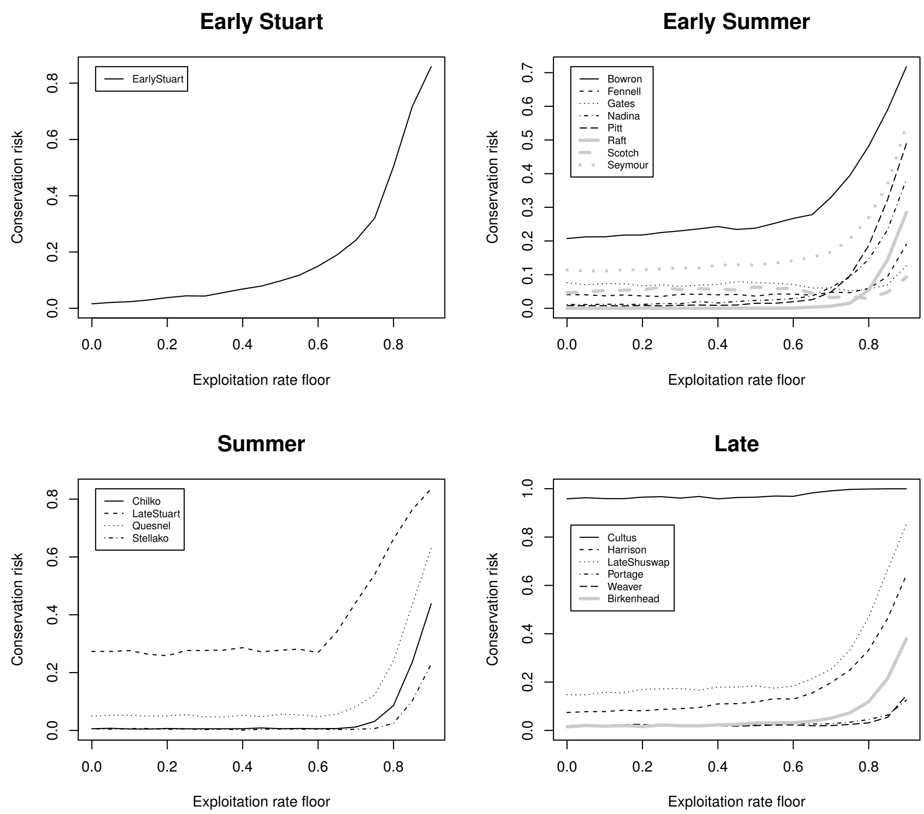

Figure 4.4: Conservation risk by stock (individual lines) and management unit (panels) with changing ER floor.

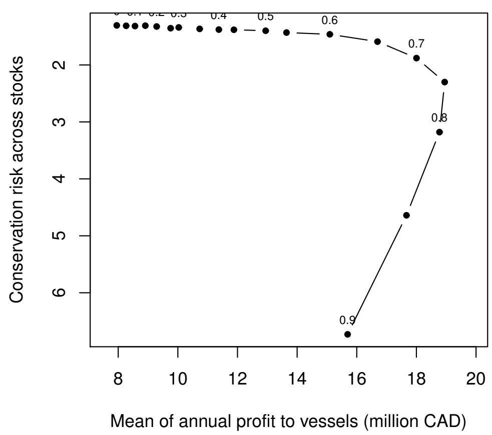

Figure 4.5: Trade-off of aggregate conservation risk against mean vessel profit as ER floor is increased from 0 (top-left) to 0.9 (bottom-right). Note that here, as in all trade-off plots of this type, conservation risk is reversed on the vertical axis.

and Martell, 2004) by the other ER floors, meaning that moving from an ER floor $\geqslant 0.8$ to an ER floor of 0.75 implies improvements with respect to *both* objectives. This result suggests that – for this harvest rule parameter only – there may be a suitable region around 0.7-0.75. However, consideration must be given to the effects of other parameters.

4.4.2 TAM cap

In the next set of trials, as the cap on total allowable mortality (TAM) is increased from 0.1 to 1 (Figure 4.6), mean annual profit in the fishery increases from just less than zero at a TAM cap of 0.1, to 15 million CAD at a TAM cap of 1. The lack of profit at very low TAM caps (<0.20) is not surprising: when the TAM cap is low the commercial fishery will be closed in many years as any small amounts of fish that may be harvestable because of the ER floor of 0.1 will be allocated to US and First Nations fisheries.

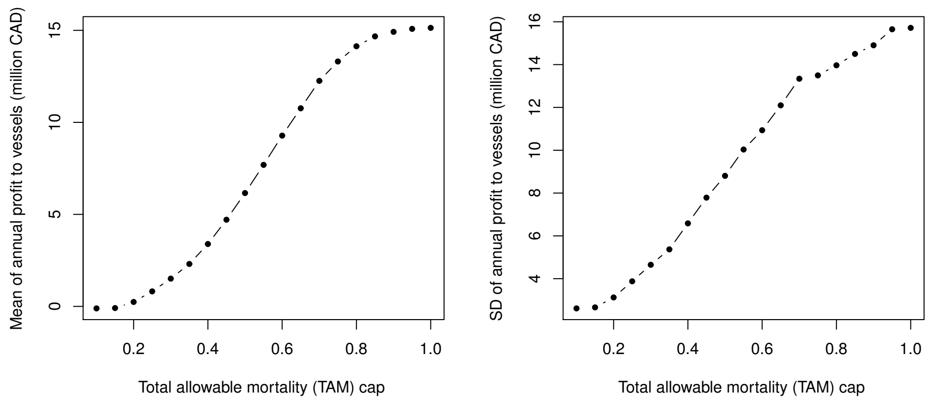

Figure 4.6: Mean and standard deviation of vessel profit over 24 years as the TAM cap is increased from 0.1 to 1.

However, there will be a few years where, due to random variation, run sizes will be large enough to allow a small commercial fishery. This serves to counteract the negative profits incurred when the fishery is closed and vessels must still pay license fees. The net effect is an estimated mean profit near zero, but with a positive standard deviation. As with the ER floor, we see a strong correlation between mean and SD of profit. Note that the CV of profit at the highest TAM cap (1.07) is higher than that for the highest ER floor (0.9, above), as setting the TAM cap at 1 means that the harvest rule replicates a target escapement policy at high run sizes, leading to more variability.

When we examine how conservation risk changes with the TAM cap (Figure 4.7) we see a much more complex set of patterns than when we changed the ER floor. The Early Stuart stock is not sensitive to the TAM cap because it is managed as its own unit; therefore, only its abundance is used in the harvest rule to set the escapement goal.

In contrast, several of the Early Summer stocks (Fennell, Gates and Scotch) appear to have higher conservation risk at *lower* TAM caps, which would

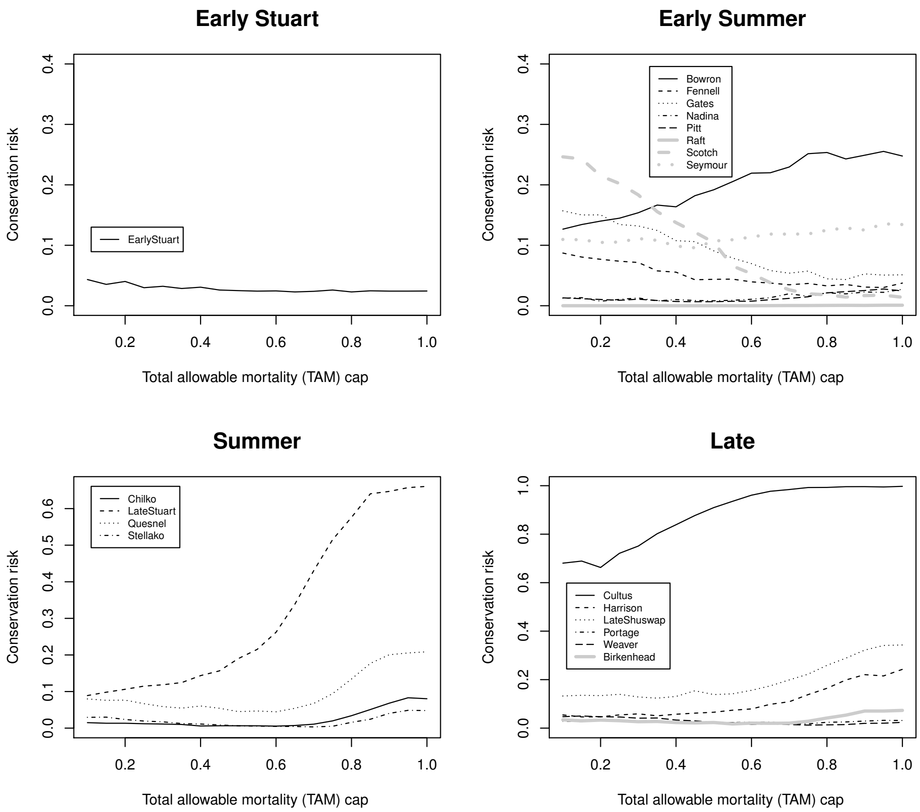

Figure 4.7: Conservation risk by stock (individual lines) and management unit (panels) with changing TAM cap. Note that the scale of the vertical axes differ between panels.

seem counterintuitive. These are heavily cyclic stocks, i.e., with relatively high density-dependence in the lags, so at low settings of the TAM cap the heavy density dependence depresses the population in subsequent years enough to push the four-year mean population below the benchmark. Note that this may also suggest that the benchmark level for these stocks is higher than it should be to represent true conservation risk. Finally, the time series of stock-recruit data used to estimate the stock dynamics of these three stocks are somewhat shorter than those of most other stocks (see Table 4.3). Martell et al. (2008) showed how the estimates of the scale parameters (b_s) can change significantly as more data are used in the estimation; thus, these findings with respect to conservation risk at low TAM caps may suggest some concern is warranted about the parameters estimated. However, the conservation risk in all of these cases is <0.25, so this is unlikely to be a serious concern.

For other Early Summer stocks, conservation risk is generally relatively low (<0.10). The exception is Bowron, which is one of two non-cyclic (i.e., modelled with Ricker) stocks in this management unit (along with Raft). While Bowron falls below its benchmark about 25% of the time at higher TAM caps, Raft does so $<1\%$ of the time. This is also likely due to the benchmark for Bowron perhaps being higher than it should be: the benchmarks for Bowron and Raft are roughly the same (4900 and 5200) even though the smallest observed four-year average for Bowron is much smaller than that for Raft (1600 versus 2600; Pestal et al., 2008), and the scale parameter on the Ricker model for each stock (-71.6 vs -44.6) suggests that Bowron's equilibrium stock size should be significantly smaller.

Similar patterns are seen in most of the plots for Summer and Late stocks: low conservation risk for low TAM caps, with increases starting at higher TAM caps, with the start point of the increase depending on the particular stock. In general, the stocks with the lowest productivity (the a_s parameter in Table 4.4) are those for which conservation risk begins to increase at lower TAM caps (e.g., Late Stuart in Summer, Late Shuswap in Late), and which reach a higher level of risk at the highest TAM caps. The exception here

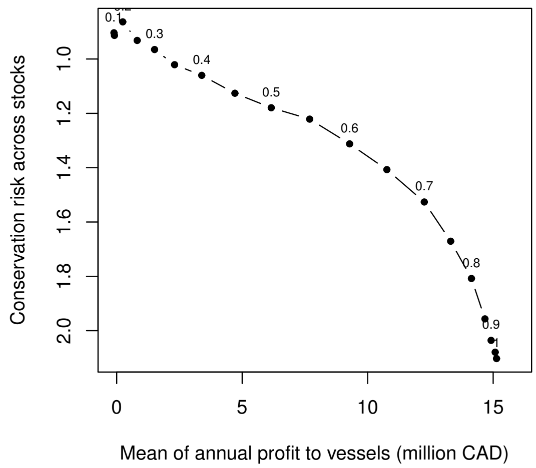

Figure 4.8: Trade-off of aggregate conservation risk against mean annual profit as TAM cap is increased from 0.1 to 1.

is again the Cultus stock, which has relatively high conservation risk at all TAM caps. However, unlike our trials with different ER floors, low TAM caps do relieve some of this risk. Note, though, that to reduce conservation risk to its lowest possible level requires a TAM cap of about 0.20, which as we saw above (Figure 4.6) essentially eliminates all profit in the fishery.

The trade-off plot of conservation risk against profit makes this conflict relatively clear (Figure 4.8). For example, the lowest aggregate conservation risk at the top left allows for zero or slightly negative profit. Profit can be increased to about 8 million CAD per year at a TAM cap of 0.55 before conservation risk starts to increase more rapidly. However, while this TAM cap keeps conservation risk on most individual stocks below 0.20, the risk to the Cultus stock is >0.90 (Figure 4.7). Note also that in the region where TAM cap $\geqslant 0.5$ the trade-off is reasonably convex, but much less so than the trade-off seen above when varying the ER floor.

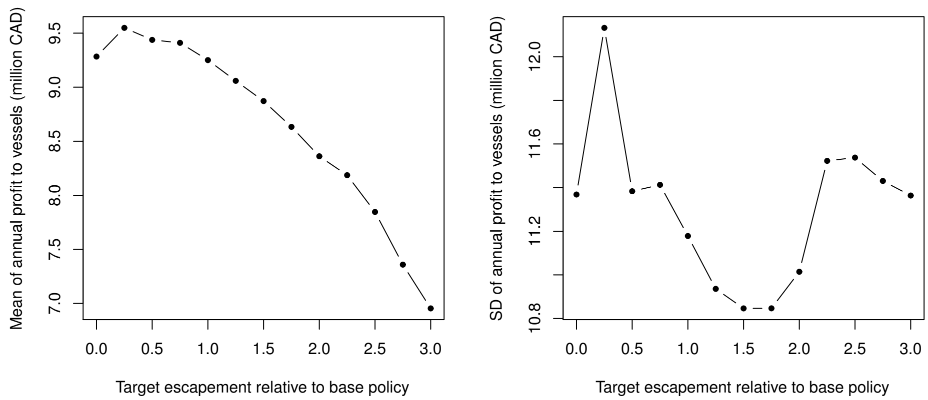

Figure 4.9: Mean and standard deviation of vessel profit over 24 years as the target escapement is changed from 0 to 3 times its baseline level.

4.4.3 Target escapement

Changes in the target escapement, from zero to three times the baseline described above, results in less marked changes in profitability than the other harvest rule parameters (Figure 4.9). A target escapement of zero in the harvest rule context used here is the equivalent of applying a fixed exploitation rate equal to the TAM cap[10]. In general the lowest target escapements lead to the highest profits, but as target escapements are increased above the baseline, profit starts to decline, albeit slowly (note the small range of the y-axes in both panels in Figure 4.9). The SD of profit is relatively stable across the range of target escapements tried.

Conservation risk generally decreases as target escapement increases (Figure 4.10) because greater target escapements allow more fish onto the spawning grounds before allowing fisheries. Conservation risk to the Early Stuart stock

[10]Under a pure target escapement policy, a target escapement of zero would lead to extinction, as the full run would be harvested (exploitation rate = 1). However, the harvest rule uses the TAM cap to limit the exploitation rate, making the exploitation rate = TAM cap at all run sizes. Also, the management adjustment procedure will limit the actual harvest rate to be less than the TAM.

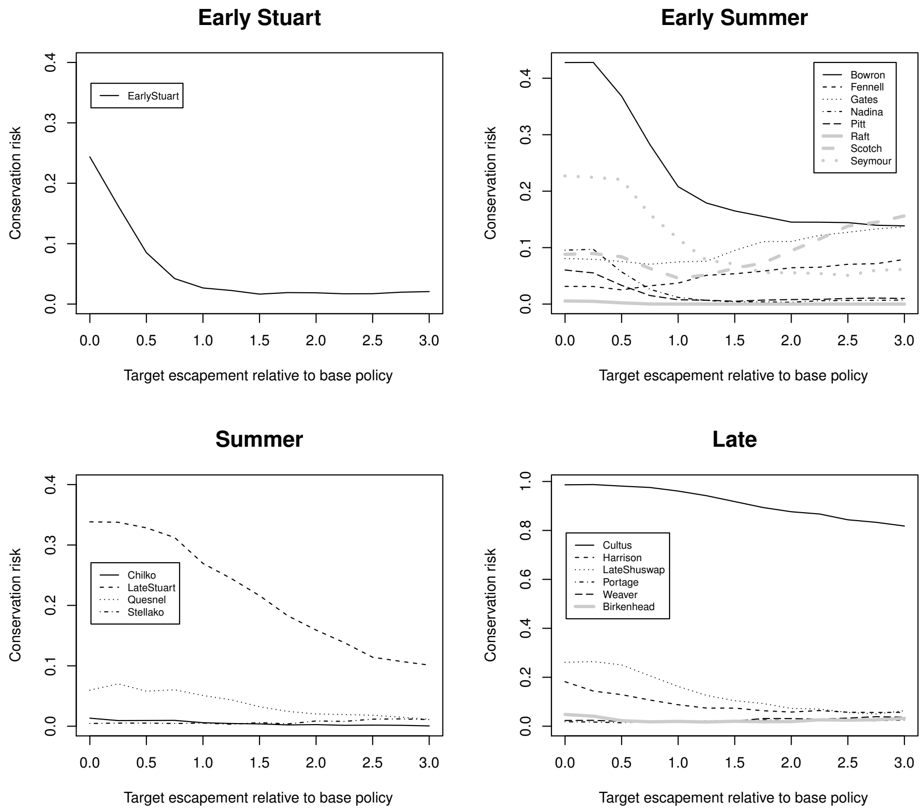

Figure 4.10: Conservation risk by stock (individual lines) and management unit (panels) with changing target escapement.

is a relatively simple function of the target escapement, again because this target is set solely based on that stock as opposed to on an aggregate of multiple stocks. However, small target escapements still pose a small risk to this relatively unproductive stock.

The patterns seen in conservation risk when increasing the target escapement in the Early Summer stocks match some of those seen when *decreasing* the TAM cap, as both of these changes lead on average to lower implemented exploitation rates. High target escapements, like low TAM caps, will tend to push the Fennell, Gates and Scotch stocks below their benchmarks from time to time for the reasons noted in the previous section. However, as in that analysis, the level of risk observed is quite low for these stocks.

Conservation risk to the remaining Early Summer stocks, as well as most Summer and Late stocks, as we would expect, declines with increasing target escapements. The patterns here are generally the same as for the TAM cap trials, with less productive stocks showing greater risk and requiring higher target escapements before risk begins to decline. The exception is again the Cultus stock, where even with a target escapement three times the current level there is still >0.8 conservation risk.

In the trade-off plot (Figure 4.11) we can see again that profit changes relatively little when increasing the target escapement from 0 to 1 times the baseline (moving up from the bottom-right), while aggregate conservation risk declines from 1.9 to 1.3. From that point onward, however, increasing amounts of profit must be given up for ever-decreasing conservation gains. Like the trade-off relationship when varying the ER floor, this trade-off is strongly convex with target escapements in the 1-2 range appearing to strike a balance between the two objectives. For example, increasing the target escapement beyond 2 decreases profit while yielding only very small decreases in conservation risk, while decreasing the target escapement beyond 1 has the opposite effect: increasing conservation risk while not significantly changing profit.

4.4.4 Multiple harvest rule parameters

The results in the previous three sections give some insight into how we can expect the outcomes with respect to our management objectives to change with each of the harvest rule parameters, while keeping the other parameters at their baseline levels. What is of greater interest, however, is the outcomes when all harvest rule parameters are allowed to vary. To examine this full range of options, I simulated each possible harvest rule within the following 'policy space': ER floor between 0.1 and 0.6; TAM cap between 0.1 and

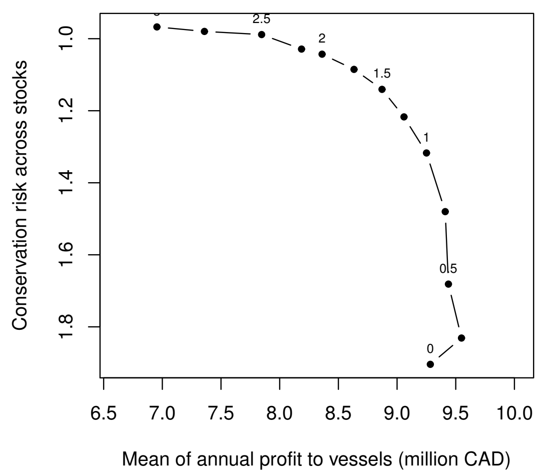

Figure 4.11: Trade-off of aggregate conservation risk against annual profit with changing target escapement.

0.95; and target escapement between zero and three times the baseline. The results are then presented as sets of contour plots, where the contours show mean annual profit (Figure 4.12) and aggregate conservation risk (Figure 4.13). Within each figure, a single panel shows results for one ER floor value, with the vertical and horizontal axes showing changes in the TAM cap and target escapement, respectively.

To begin, I examine the outcomes when ER floor is held at its baseline level of 0.1, i.e., the top-left panel in each of the figures. Several patterns emerge in the contour plot of profit (Figure 4.12). First, recall that very low target escapements impose a fixed exploitation rate equal to the TAM cap, so as we move up the left-hand side of the plot we see profit increase gradually to a maximum, then decrease because of stock depletion at very high exploitation rates. Second, for lower TAM caps (<0.7, the bottom half of the plot), changes in target escapement do not lead to significant changes in profits. However, at higher levels of the TAM cap (the top of the plot), increasing

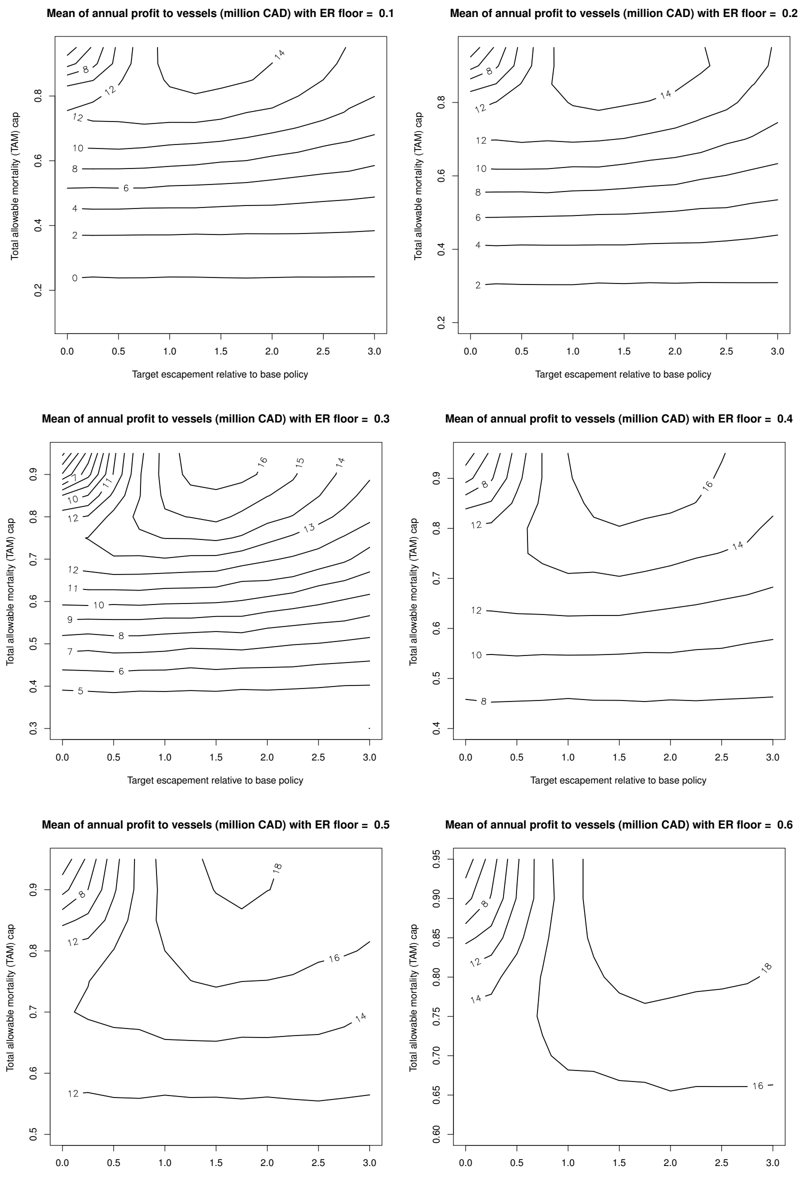

Figure 4.12: Mean annual profit of vessels when all three harvest rule parameters are changed. Each panel shows results with a different ER floor, ranging from 0.1 to 0.6. Note that the ER floor overrides the TAM cap, which can be seen in the compression of the TAM cap axis as ER floor increases from panel to panel.

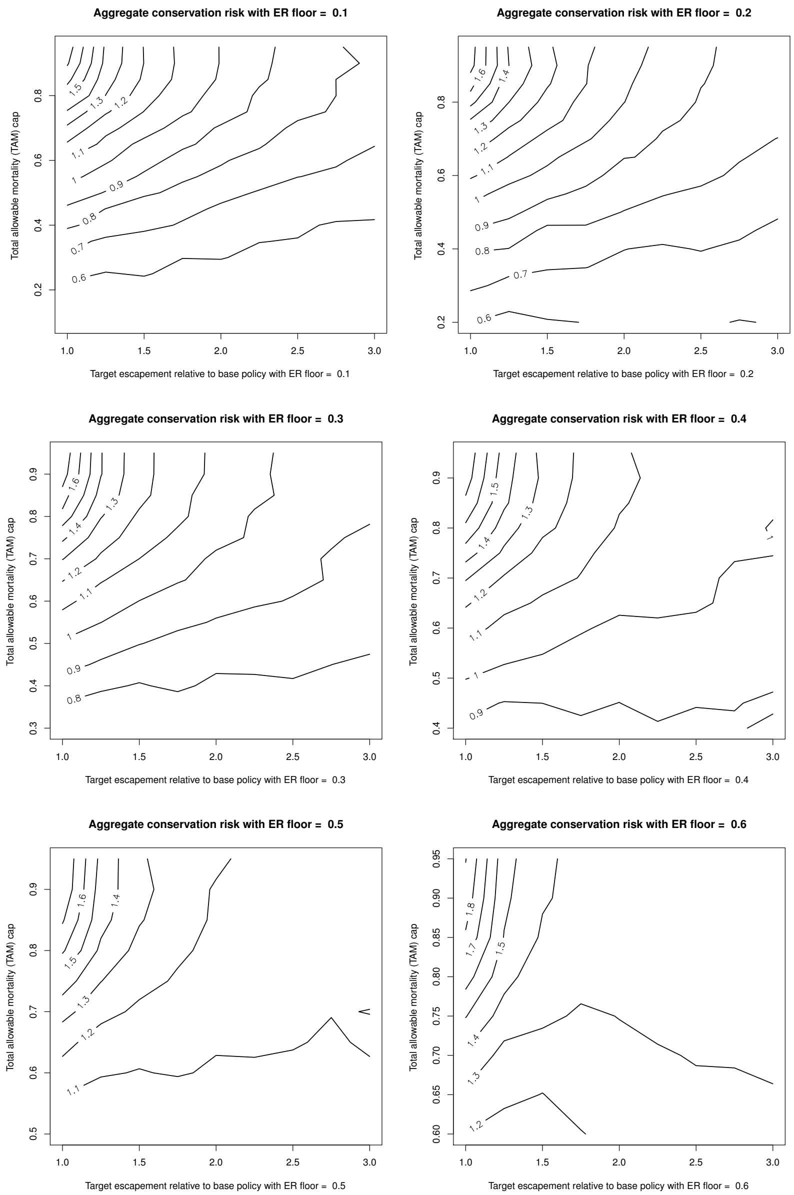

Figure 4.13: Aggregate conservation risk when all three harvest rule parameters are changed (for target escapements >1.0 only). Each panel shows results with a different ER floor, ranging from 0.1 to 0.6.

the target escapement from zero leads first to increases in profit, but then to decreases again once we pass target escapements of 1.5-2. This is because when the TAM cap is high, the lowest target escapements lead to stock depletion while the highest target escapements allow so many spawners that there are few fishing opportunities. Overall, the highest profits are generated by a combination of moderate target escapement (1-2) and high TAM cap (>0.85). Recall that the current harvest rule applied in the fishery is ER floor = 0.1, TAM cap = 0.6, and target escapement = 1; at this position in the figure we see profitability of about 9 million CAD.

Moving to aggregate conservation risk (Figure 4.13), note that the panels show only conservation risk for target escapements $\geqslant 1$. This is because when TAM cap is greater than 0.65, decreasing the target escapement below 1 very rapidly increases conservation risk to such an extent (at the extreme to > 18) that patterns in other regions of the policy space are completely obscured. The contour with ER floor set to 0.6 shows this most clearly (Figure 4.14), but other values of ER floor (not shown) demonstrate essentially the same pattern. For clarity of presentation the main results are only shown for target escapements $\geqslant 1$.

The patterns in aggregate conservation risk when ER floor is set to 0.1 (Figure 4.13, top-left panel) are more straightforward than those for profit. We see, quite intuitively, that increasing target escapement and decreasing TAM cap will decrease conservation risk, and that in the area of the current harvest rule aggregate conservation risk is about 1.1 (with most of this risk accounted for by the Cultus stock, as previously noted). However, some harvest rules at the top of the plot in the area of maximum profit noted above keep conservation risk the same as or only slightly greater than it is under the current harvest rule. For example, if we start at the current harvest rule and move along the contour indicating conservation risk of 1.1, we see that target escapement of about 1.5 and a TAM cap of 0.95 produce the same risk as the current rule. Thus it seems that this alternative harvest rule could generate substantially more profit while keeping conservation risk the same.

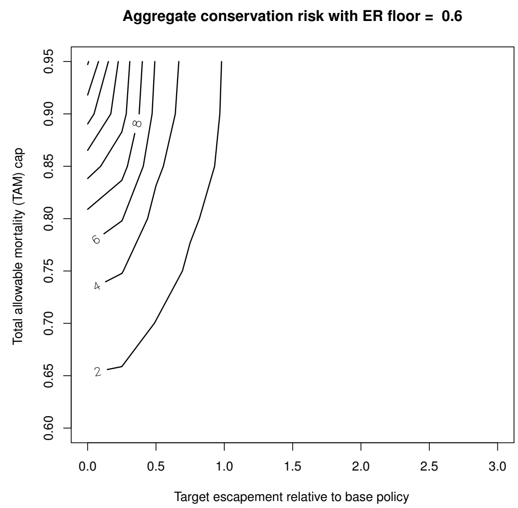

Figure 4.14: Aggregate conservation risk when ER floor = 0.6 and other harvest rule parameters are varied in the full range of the trials. Included only to demonstrate the rapid increase in conservation risk in the high-TAM-cap, low-target-escapement region.

In examining the remaining panels in each of these figures, it is clear that for a wide range of ER floors, TAM caps approaching 0.95 and target escapements 1.5-2 times current levels appear to maximize profit, and that higher ER floors will further increase profits, from a maximum of about 15 million CAD at ER floor = 0.1 to >18 million CAD at ER floor = 0.6. In the full set of plots of aggregate conservation risk (Figure 4.13), we see broadly similar patterns in conservation risk as the ER floor increases. Note that increasing ER floor leads to increased conservation risk overall, but that these increases are not dramatic in numerical terms. For example, in the policy region noted above (target escapement = 1.5-2, TAM cap = 0.95) conservation risk increases from 0.9-1.0 at ER floor of 0.1, to about 1.3-1.4 at ER floor of 0.6.

Another analysis that combines the two objectives is to examine the ratio of the two, that is, mean annual profit divided by aggregate conservation risk (Figure 4.15). This provides a rough indicator of the net benefit of a particular harvest rule with respect to both objectives. This analysis supports the findings above: the highest profit-risk ratios are found in the region of maximum TAM cap and target escapements around 2, for each of the ER floors tried. The highest value attainable for the profit-risk ratio is 15.5, which occurs with an ER floor of 0.4.

Finally, to assess the outcomes across all harvest rules, we can plot a trade-off plot that is analogous to those used to examine outcomes when changing only one harvest rule parameter (e.g., Figure 4.5). In this case, the plot presents the combination of mean annual profit and aggregate conservation risk associated with each of the harvest rules tested (Figure 4.16). The plot shows that the current harvest policy is dominated by many others that provide higher profits, lower aggregate conservation risk, or both. The two policies noted above are at the right-hand edge of the trade-off plot, providing the maximum or near maximum profit possible but, at least in the case of ER floor $= 0.6$, incurring somewhat higher conservation risk. The other point to note on the graph is that there is some degree of convexity in the trade-off.

On the basis of this examination there seems to be suitability of the policy region at TAM cap $\simeq 0.95$, target escapement 2 times current levels, and ER floor $\simeq 0.4 - 0.6$. Given this finding, it is worth examining the results of this policy region in a bit more detail with respect to more specific outcomes.[11]

With an ER floor of 0.6, mean conservation risk (Figure 4.17)[12] to most stocks is below 0.2, with the exceptions of Bowron, Late Stuart and Cultus. The risk to all stocks except Cultus could be decreased, some quite significantly, by moving to an ER floor of 0.4. The base policy produces somewhat lower conservation risk than either of the above cases, but generally speak-

[11] Detailed numerical results for the selected set of harvest rules outlined in this section, as well as the baseline harvest rule, are presented in Appendix B.

[12] The box plots in this figure and others show the distributions of variables for all 1000 simulations. The top and bottom of each box indicate the 75th and 25 percentiles, respectively; the thick line in the middle indicates the median value; the 'whiskers' (vertical broken lines) encompass all points within 1.5 times the height of the box; and open circles indicate outliers, i.e., observations outside the range of the whiskers.

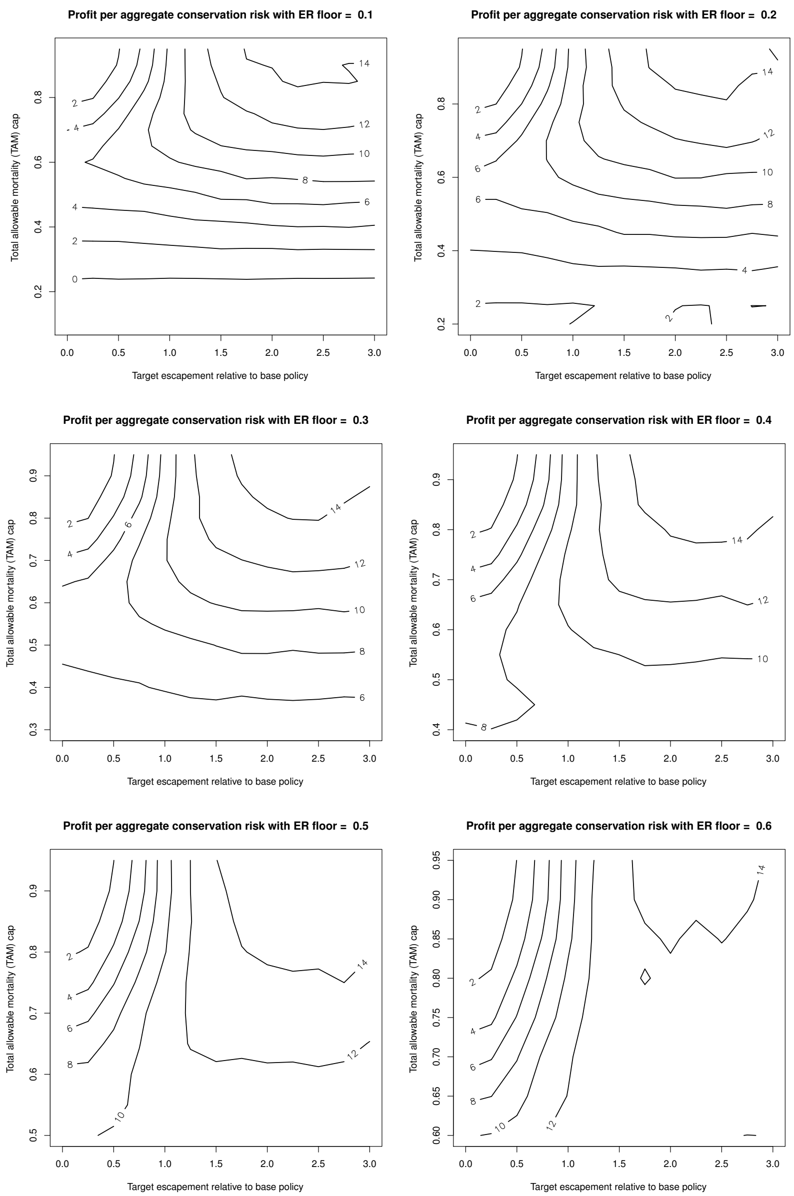

Figure 4.15: Mean annual profit divided by aggregate conservation risk, for ER floors of 0.1-0.6.

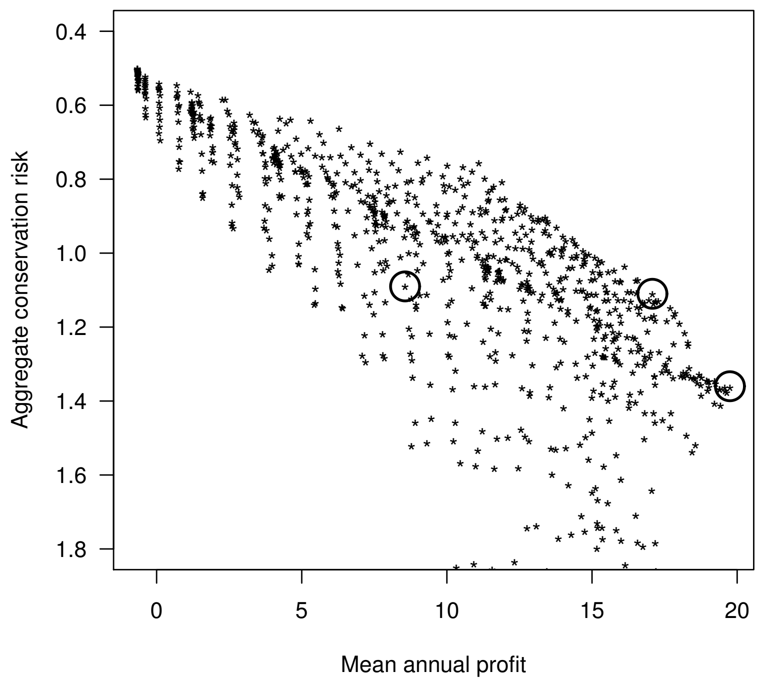

Figure 4.16: Trade-off plot showing the range of possible outcomes in terms of mean annual profit and aggregate conservation risk. Each symbol represents the outcome of one harvest rule. The circles denote, from left to right: (1) the currently applied harvest rule; (2) a harvest rule with ER floor = 0.4, TAM cap = 0.95, and target escapement twice the current level; and (3) as for 2 but with ER floor = 0.6. Some harvest rules with conservation risk >1.8 are omitted because they are dominated by the other policies shown.

ing, mean conservation risk to individual stocks here is quite similar to that when ER floor is 0.4.

When examining time series of profit to fishing vessels for these policies (Figure 4.18) we get further insight into the implications of these harvest rules over time. In general, the relatively high target escapement allows the majority of stocks to build up over time. In early years, this involves heavy fishing on large runs and closure or near closure of the fishery on small runs. However, in later years, stock sizes have built up enough that catches and therefore profits are, on average, much more stable. There is still significant variation (e.g., from 14.6 to 25.5 million CAD between years 20 and 22), but clearly much less dramatic than in earlier years. The main difference between ER floor 0.4 and 0.6 is simply of scale, with ER floor 0.6 allowing on average somewhat higher profits, but with slightly more variability over the four-year cycle than with the lower ER floor.

4.4.5 Sensitivity analysis

The analysis as conducted above assumed a single stock-recruitment model – Ricker or Larkin – based on the fit of each model to the data for each stock. This involved using the Larkin model for 15 stocks and the Ricker model for four, based on the fit of each model to data for each stock (see section 4.3.1). However, to test the sensitivity of the analysis to this selection of stock-dynamics model, I ran the analysis using (1) the Larkin model for all stocks, and (2) the Ricker model for all stocks.

The results using the Larkin model for all stocks were indistinguishable from those in the main analysis above. This is not surprising, as in the main analysis the Larkin model was used for all of the largest stocks that will tend to dominate any patterns observed. Given this result, I do not present plots here of outcomes using only the Larkin model.

Results of the analysis assuming the Ricker model for all stocks are shown below, and several features stand out (Figures 4.19 and 4.20). The decline

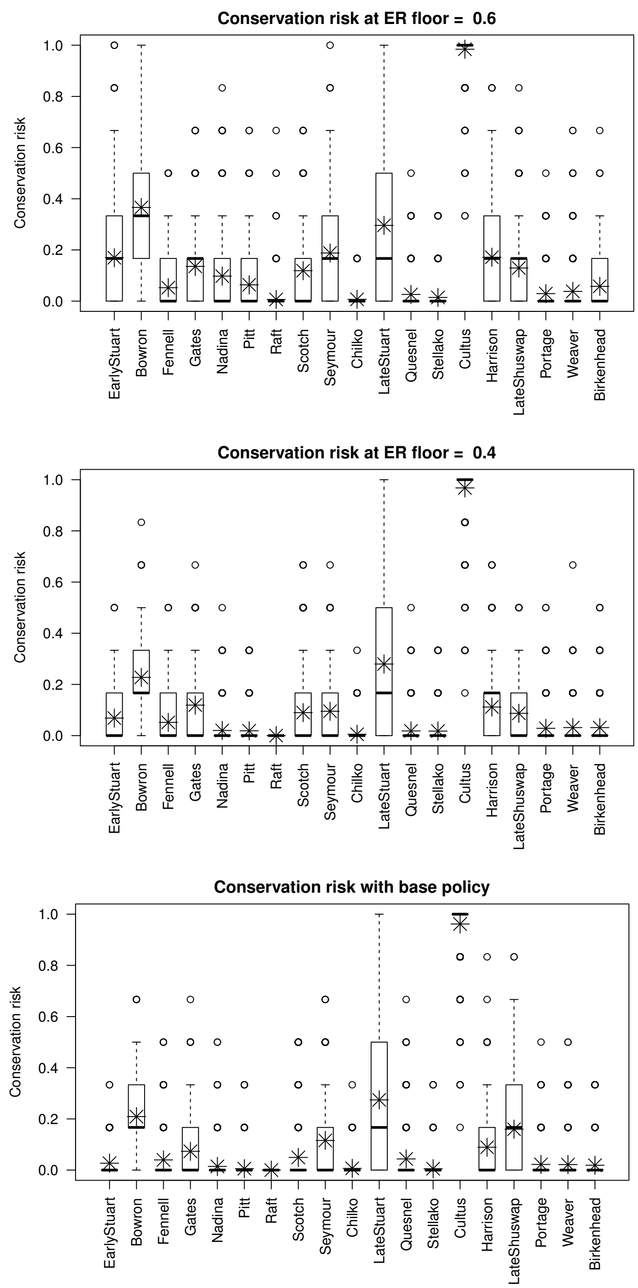

Figure 4.17: Conservation risk by stock with: (1) Top: TAM cap = 0.95, target escapement = 2, and ER floor = 0.6; (2) Middle: as for 1 but ER floor = 0.4; (3) base policy of TAM cap = 0.6, target escapement = 1, ER floor = 0.1 (0.2 for Late). The mean of 1000 simulations is shown with an asterisk for each stock.

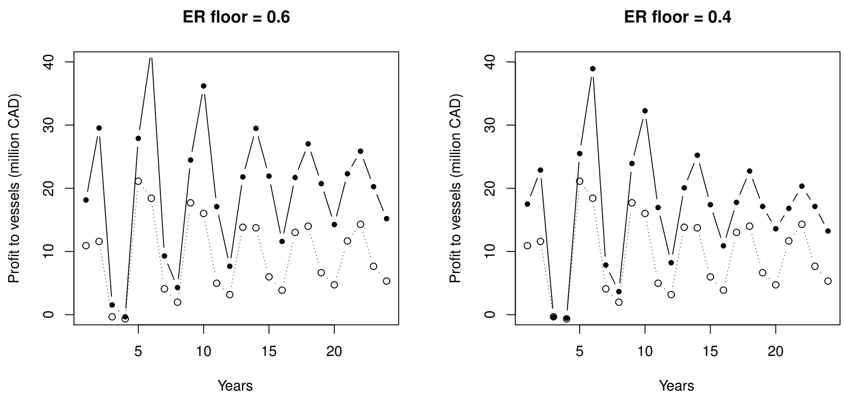

Figure 4.18: Time series of vessel profit with TAM cap = 0.95, target escapement = 2, and ER floor = 0.6 (left panel) or 0.4 (right panel, both with filled symbols). The base policy of TAM cap = 0.6, target escapement = 1, ER floor = 0.1 (and 0.2 for Late) is shown on each graph (with open symbols) for comparison. Values for each year are averages over 1000 simulations.

in profit at high TAM caps and very low target escapements occurs here as it did in the main analysis. Otherwise, it appears that with the Ricker model the most profitable harvest rules will be those that involve high target escapements, high TAM caps and high ER floors. The result of such a rule would be to build up the stock over time due to the high target escapement, but very heavy exploitation of large runs.

The patterns in conservation risk with harvest rule changes (Figure 4.20) vary depending on the ER floor applied. For ER floors up to 0.3 the pattern in conservation risk with the Ricker model is essentially the same as in the main analysis, although the conservation risks involved are marginally higher with the Ricker model. For ER floors of 0.4 and higher, however, the conservation risks involved increase quite substantially as ER floor increases, and the risk at any given ER floor is much greater under the Ricker model than under the Larkin model. For example, at ER floors of 0.5 and 0.6, conservation risk in the top-right quadrant of the respective panels averages 1.15 and 1.35 in the main analysis, but the corresponding risks under the Ricker model are

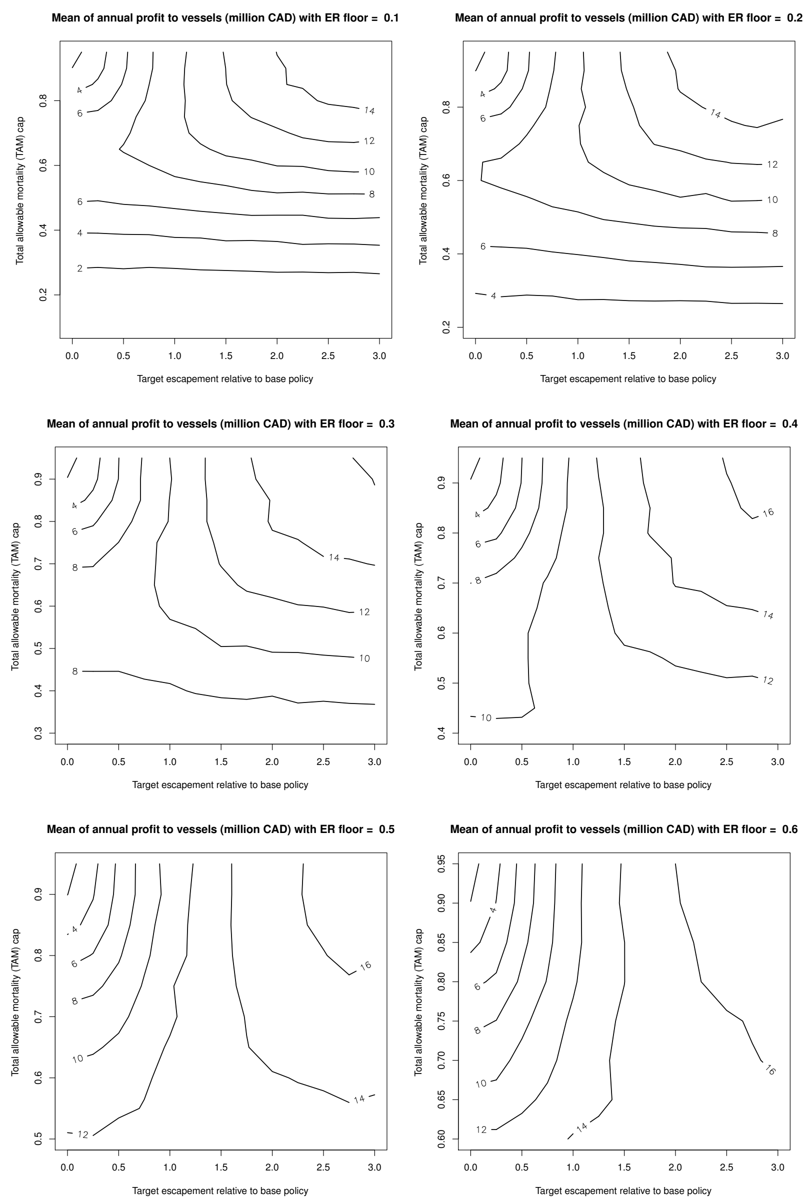

Figure 4.19: Mean annual profit of vessels when all three harvest rule parameters are changed, assuming the Ricker model for all stocks. Other details as in Figure 4.12.

about 1.5 and 2.2.

Perhaps the most crucial question in this sensitivity analysis is whether our conclusion about viable alternative harvest rules above in the preceding section (target escapement $\simeq 2$, TAM cap = 0.95, ER floor = 0.4 or 0.6) would be seriously undermined if the Ricker model was indeed appropriate. Comparing the relevant figures suggests that this would not be the case: under the Ricker model, moving from the current baseline harvest rule, with its mean profitability of 7 million CAD and aggregate conservation risk of 1.5, to the above noted alternative harvest rules would increase mean profitability to over 15-16 million CAD while either decreasing aggregate conservation risk slightly to 1.4 with ER floor = 0.4, or increasing risk to about 2.0 with ER floor = 0.6. This suggests that the former rule, with ER floor = 0.4 may be more appropriate than the latter as it appears to be more robust to uncertainty about the underlying stock dynamics.

4.5 Summary and conclusions

The analysis in this chapter has revealed and quantified the trade-offs between the economic benefits obtained from the fishery and conservation risk to the stocks that support the fishery, as examined through simulations of a wide range of harvest rules that could conceivably be applied in the fishery. Any trade-off between these types of objectives is potentially difficult, but the analysis has shown that there is a set of harvest rules that provides significantly greater economic benefits than those obtained under the base policy, while not overwhelmingly increasing conservation risk. In particular, a rule where (1) a moderate exploitation rate of 0.4 is applied at stock sizes up to (2) a target escapement approximately twice that currently employed, after which (3) all fish returning in excess of the target escapement are caught. I now refer to this harvest rule as the 'alternative' harvest rule. As can be seen in Figure 4.21, the alternative harvest rule places more emphasis than

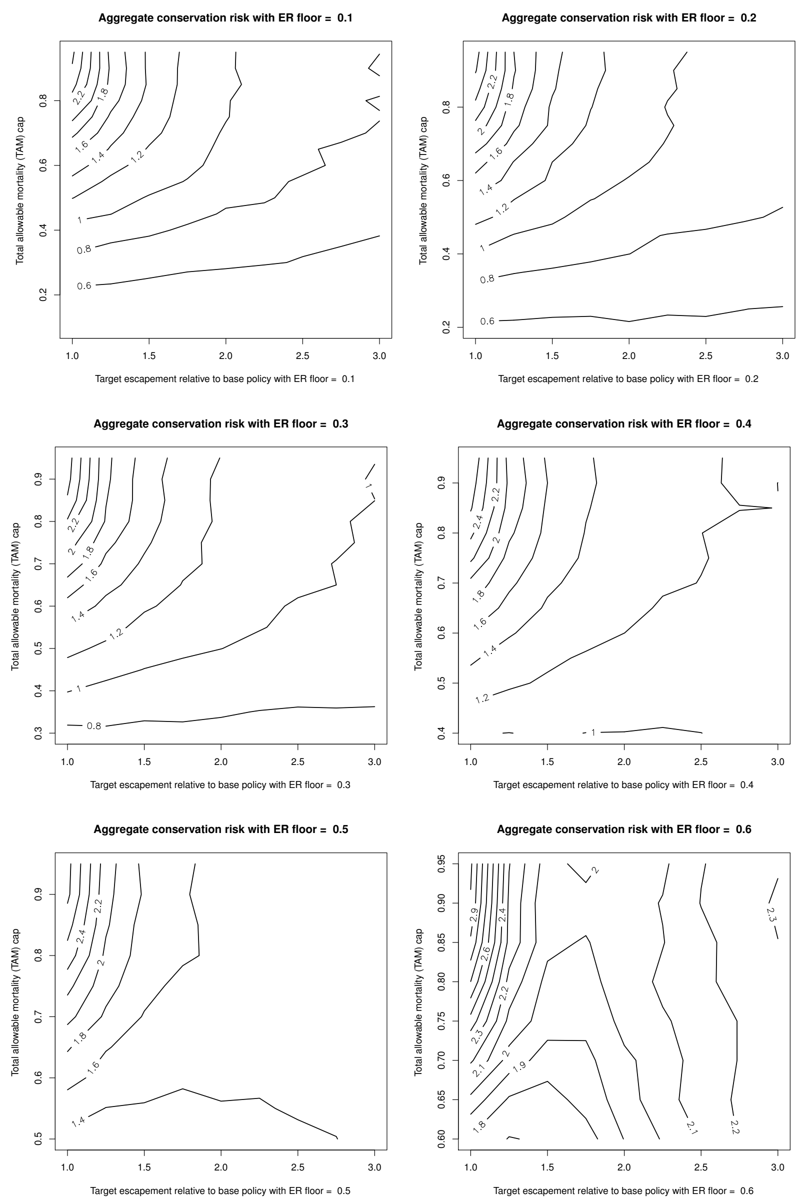

Figure 4.20: Aggregate conservation risk when all three harvest rule parameters are changed (for target escapements >1.0 only), assuming the Ricker model for all stocks. Other details as in Figure 4.13.

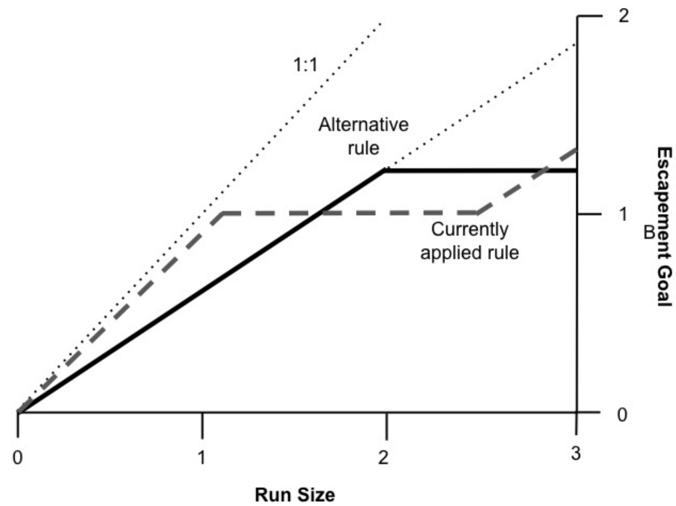

Figure 4.21: Escapement goal implied by a harvest rule with ER floor = 0.4, TAM cap = 0.95, and target escapement equal to twice the current baseline levels. Run sizes are defined relative to the baseline target escapement (set to 1). The solid line shows the escapement goal for the alternative harvest rule, while the thick broken line is the harvest rule currently applied in the fishery. The dotted lines are for reference. The vertical distance between the 1:1 line and the escapement goal is the allowable harvest.

the baseline rule on allowing some harvest (40%) at low run sizes (<1.5), but then allowing greater escapement at moderate run sizes (1.5-2.75).

A peculiarity of the terminology used here – and in other literature around these harvest rules for sockeye salmon – and of the relationships between the components of the rule is that if ER floor is >0, the target escapement used in the definition of a harvest rule (i.e., the value used as a harvest rule parameter above) is not a true target escapement in the sense of the definition in Table 4.1. To see this, note that Figure 4.21 shows the escapement goal associated with the alternative harvest rule. In the figure, the first segment of the alternative rule represents the 60% of the run that is allowed to escape – the remaining 40% is harvested in keeping with the ER floor. The second segment begins at a run size that is twice the baseline target escapement, because the alternative harvest rule calls for this. The point here is that what we have called the "target escapement" in the harvest rule is not the target escapement in the true sense. Rather, at run sizes of 2, managers allow an escapement of $(1 - \text{ERfloor})$ times the target escapement, in this case 1.2 units of fish. Thus, the true 'target' is 1.2, not 2. It is therefore more suitable to think of what we call target escapement as a reference point that denotes when the exploitation rate may be increased above the ER floor.

The prospective analysis conducted here allows a flexible approach to examining the management of the Fraser sockeye fishery and trade-offs between objectives. I have used historical data to estimate many of the properties of the biological and economic systems, and then used assumptions about how these properties will evolve over time to allow simulation of a variety of harvest rules. Such an analysis encounters some of the same challenges encountered in the retrospective analysis – e.g., uncertainty about the structure of some relationships, such as the stock-recruitment function, and has one additional disadvantage: that it is not possible to compare outcomes seen in the prospective analysis with outcomes actually observed. However, this can also be seen as an advantage in the sense that we can explore possible futures more fully, as we are not bound to the particular outcomes of stochastic processes that actually came to pass. One issue that may be of interest to examined given recent observations is the implications of changes in stock productivity for the analyses and outcomes explored above. This issue is addressed in the next chapter.

Chapter 5

Trade-offs between objectives under declining productivity

5.1 Introduction

To this point, I have demonstrated how significantly greater economic benefits could have been generated from Fraser sockeye in the past, and how, depending on which harvest rule is applied in the future, greater benefits could also be derived from this point forward. As I have shown, there are trade-offs between the profit of commercial vessels and conservation risk to many of the sockeye stocks, with the particular details of the trade-off depending on how the harvest rule is modified. However, the preceding chapter demonstrated that there are some possible harvest rules that increase economic benefits with minimal change in conservation risk; indeed, at least one of these rules slightly *lowers* conservation risk while almost doubling mean annual profit.

Both the retrospective and prospective analyses conducted thus far have assumed that long-term average biological conditions have remained constant over the period from which historical data were drawn in order to estimate parameters. These analyses have also assumed – through the use of stationary parameters estimated based on those historical data – that these conditions will prevail throughout the period of the simulations. However, recent evidence discussed in the introductory chapter has suggested that productivity of many Fraser sockeye stocks has changed significantly since the early 1990s, more specifically that average productivity has declined. Such a decline would, depending on its permanence, have dramatic consequences for the management of the Fraser sockeye fishery, and may significantly affect the trade-offs discussed above. To the extent that this decline in productivity is related to climate change, this is a specific instance of a broader trend being seen in many other fisheries worldwide as the effects of climate change become more pronounced (Cheung et al., 2010; Sumaila et al., 2011).

This chapter examines this issue using the same prospective analysis approach used in Chapter 4. In the current chapter, productivity of the stocks under examination is modified in keeping with published estimates from other researchers, and the effects of these changes on economic benefits from the fishery, conservation risk to sockeye stocks, and the trade-offs between these objectives is examined, and compared to the outcomes of the previous analyses.

The research question examined in this chapter is: How is this trade-off between economic benefits and conservation affected by different assumptions about future trends in stock productivity?

5.2 Model and simulations

The modelling approach and parameters used in this chapter are almost identical to those used in Chapter 4. The stock dynamics model, the catch model, the economic model, and all of their parameters are as described in sections 4.2 and 4.3, with the exception of the productivity parameters (described below). Likewise, the simulation framework is the same as above.

To examine changes in productivity, Peterman and Dorner (2012), using stock-recruit data quite similar to mine, estimated for either the Ricker or the Larkin model a time-varying a_s parameter for each stock (i.e., $a_{s,t}$). This is the productivity parameter in both stock-recruitment models in that it estimates the logarithm of the number of recruits per spawner at very low spawner abundance. Their choice of whether to present the Ricker or Larkin estimates was determined by the fit of each model to the data, but the models in these cases included the time-variance in the a_s parameters, meaning that their model choice did not necessarily match those in my analysis. I therefore took the following steps to estimate a standardized recent a_s parameter for each stock that could be applied to my models. I first extracted the estimates of $a_{s,t}$ in the last four years of their time series, 2001-2004. I then took the mean of these four values, and subtracted the long-term average of their $a_{s,t}$ estimates over time. I considered the resulting value to be an indicator of how productivity had changed from the long-term average to 2001-04; since these were the most recent data available, they will have to suffice as an indicator of current productivity, even though my simulations start in 2009. These changes are shown in Figure 5.1, and were added to the appropriate a_s parameters estimated in the preceding chapter to generate a set of parameters defining what I call the "modified productivity regime," while the productivity regime used to calculate results in the preceding chapter is referred to as the baseline productivity regime. The modified parameters were then used in simulations to explore the impacts of different harvest rules under this regime.

5.3 Results and discussion

5.3.1 ER floor

The first trials involved changing the ER floor from its baseline of 0.1 (0.2 for Late stocks) to anywhere from 0 to 0.95 (Figure 5.2). The shapes of the changes in mean and standard deviation of profit as the ER floor is changed are essentially the same in the higher productivity regime (Figure 4.3). One important difference is visible, however, as mean profit is reduced by 20-25% under modified productivity. This decrease in profits should not be surprising, as the overall net change in productivity between the baseline and modified regimes is negative.

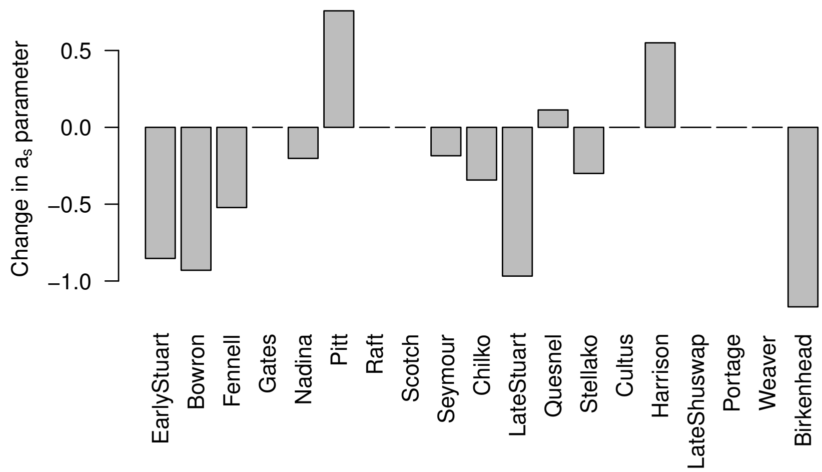

Figure 5.1: Changes in the a_s parameter from the long-term average to 2001-04, as derived using the method described in the text.

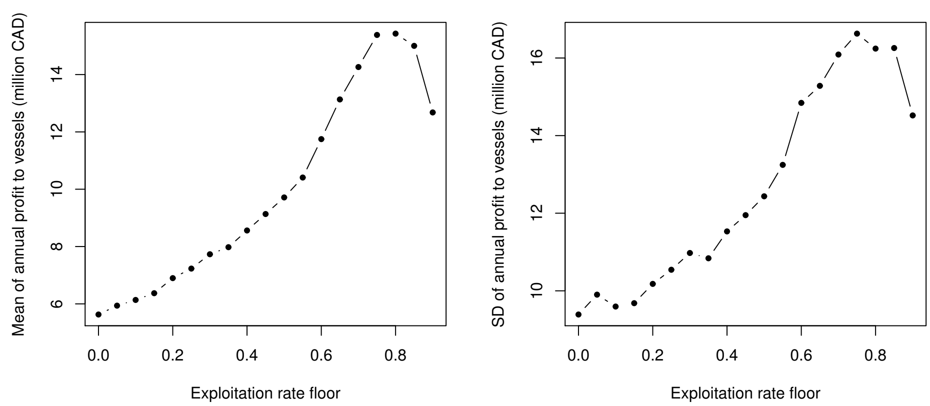

Figure 5.2: Mean and standard deviation of vessel profit over 24 years as the ER floor is increased from 0 to 0.90, with modified productivity parameters.

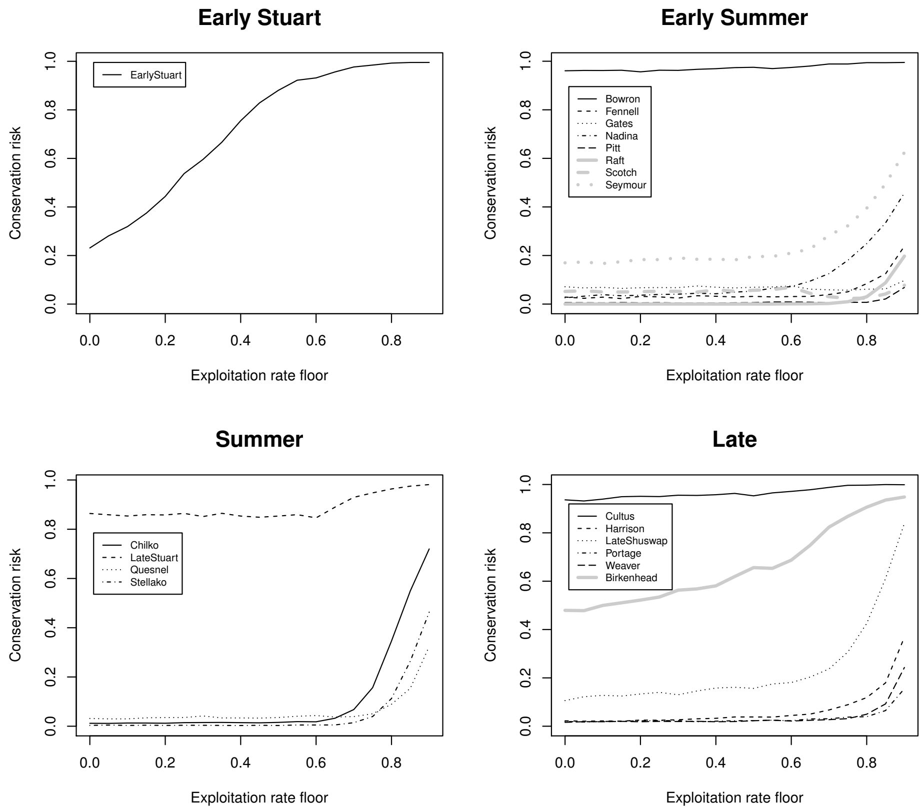

Figure 5.3: Conservation risk by stock (individual lines) and management unit (panels) with changing ER floor, with modified productivity parameters.

However, the modified productivity regime apparently has serious consequences for the conservation risk to some stocks (Figure 5.3). In particular, where only the Cultus stock had uniformly high conservation risk with the base parameters and most other stocks had reasonably low risk at ER floor values <0.6 (Figure 4.4), several additional stocks have relatively high conservation risk at a wide range of ER floor values, including Early Stuart, Bowron, Late Stuart, and Birkenhead. Perhaps not surprisingly, these four stocks are those with the greatest decreases in productivity in recent years (Figure 5.1).

These comparisons between conservation risk under the modified regime and the baseline regime can be seen more clearly if we plot the ratio of the conservation risk under the different regimes (Figure 5.4). Here we can clearly see the much higher risk to Early Stuart, Bowron, Late Stuart and Birkenhead stocks at low ER floors, as noted above. We can also see that risk under the modified regime is somewhat higher for a number of other stocks for a range of ER floors, in particular Nadina, Seymour and Chilko; and risk is in general lower for Pitt, Quesnel and Harrison. These patterns match quite closely the changes in the a_s parameters when moving from the baseline productivity regime to the modified regime (Figure 5.1).

The trade-off between aggregate conservation risk and profit with a changing ER floor under modified productivity (Figure 5.5) differs from that under base productivity (Figure 4.5, also included in Figure 5.5 for comparison) in several respects. First, for any given ER floor, conservation risk is higher and profits lower under the modified regime. Second, the trade-off is 'more difficult' when ER floor is increased from 0 to about 0.7, in the sense that significant additional risk must be incurred in order to increase profits; this can be seen by comparing the slope of the top-left portion of the trade-off curve under the modified regime with that under the baseline. The result here is that, while an argument could be made that under the baseline regime an ER floor in the region of 0.7-0.75 might be suitable, it is more difficult to make this argument under the modified regime as these ER floors imply a substantial increase in aggregate conservation risk.

5.3.2 TAM cap

The second set of trials involved changing the TAM cap from the baseline level of 0.6 to a range of values from 0.1 to 0.95 (Figure 5.6). As with ER floor, the shape of the relationships between mean and SD of profit and changes in the policy are similar under the different productivity regimes, with profit again being about 20-30% lower under the modified productivity

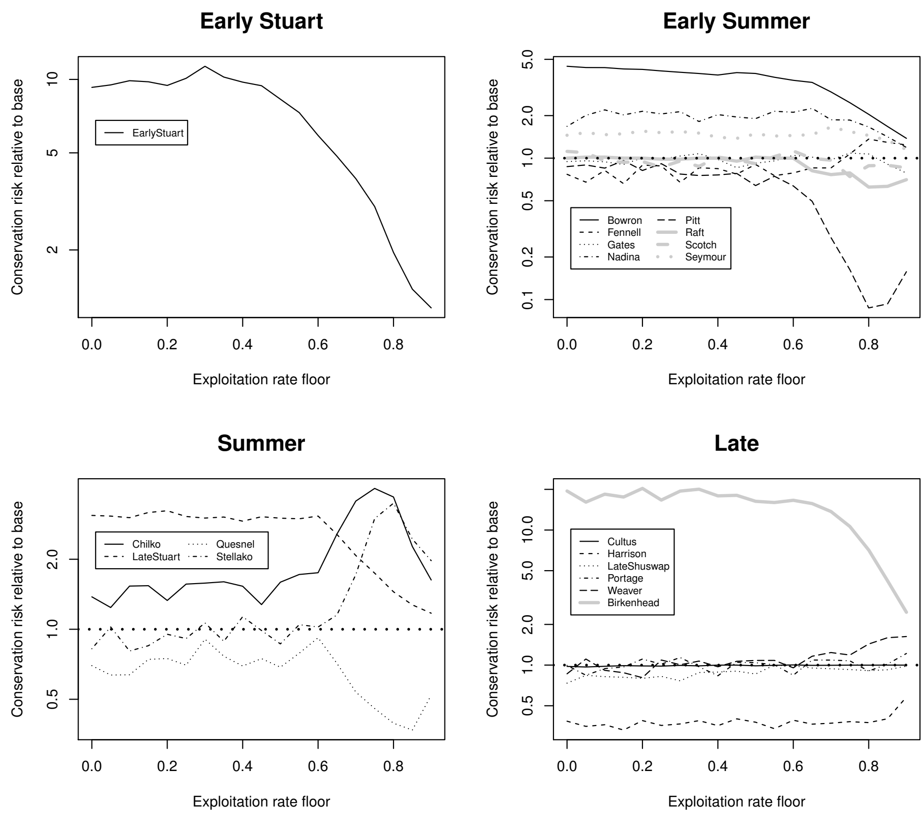

Figure 5.4: Ratio of conservation risk under the modified productivity regime to that under the base regime, with changing ER floor. The vertical axis is on a logarithmic scale to allow easier differentiation of widely different values. The broken horizontal line shows where the conservation risk is equal under the two regimes.

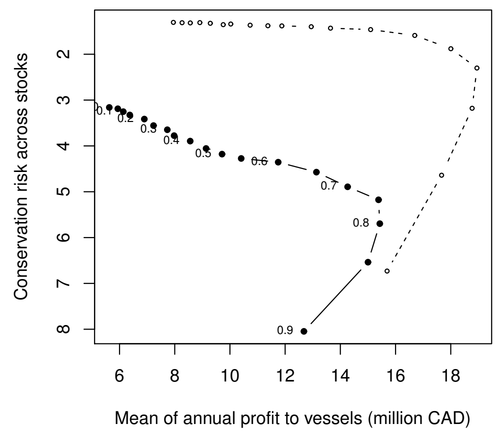

Figure 5.5: Trade-off of aggregate conservation risk against mean vessel profit under the modified productivity regime (filled circles) as ER floor is increased from 0 (top-left) to 0.9 (bottom). The result under the baseline regime is included (broken line) for comparison.

regime compared to under the base regime (Figure 4.6). However, variability of profit is quite similar between the two regimes.

As under the baseline productivity regime, conservation risk generally increases with the TAM cap (Figure 5.7). Conservation risk in the Early Stuart stock is essentially independent of the TAM cap, albeit at a much higher level of risk than under the base productivity regime (Figure 4.7). For several other stocks, including Bowron, Late Stuart, Cultus and Birkenhead, conservation risk increases to very high levels at higher TAM caps. Risk for most other stocks remains at relatively low levels.

When we examine these conservation risks compared to those under the base regime (Figure 5.8), we see some of the same patterns as we did when changing ER floor. The risk to Early Stuart is quite high relative to that under the baseline, as is risk to Bowron, Late Stuart and Birkenhead. As with ER floor, several stocks that have mildly reduced productivity under the

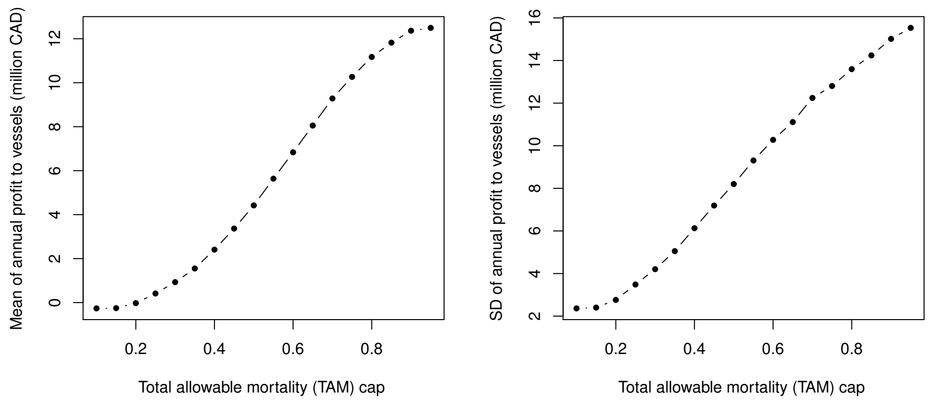

Figure 5.6: Mean and standard deviation of vessel profit over 24 years as the TAM cap is increased from 0.1 to 0.95, with modified productivity parameters.

modified regime – Nadina, Seymour and Chilko – tend to have higher conservation risks at high TAM caps than they did under baseline productivity, while most other stocks are close to their baseline risk levels, or have lower risk in cases where their productivity is higher under the baseline regime, especially in the case of Harrison.

The trade-off between conservation risk and profit under the modified productivity regime (Figure 5.9) differs from that under the base regime in two important respects. First, as with changes in ER floor, any given TAM cap implies more aggregate conservation risk and less profit under the modified regime when compared to the baseline regime. The second difference is that that while the trade-off under the baseline regime was convex, the trade-off under the modified regime is mostly concave (Walters and Martell, 2004; Cheung and Sumaila, 2008). In other words, on the scale chosen (i.e., the sum of squared stock-level conservation risks), a relatively large amount of profit must be given up in order to lower conservation risk under the modified regime. In contrast, under the base regime there was a range of TAM caps (0.5-1) over which much more profit could be earned without increasing

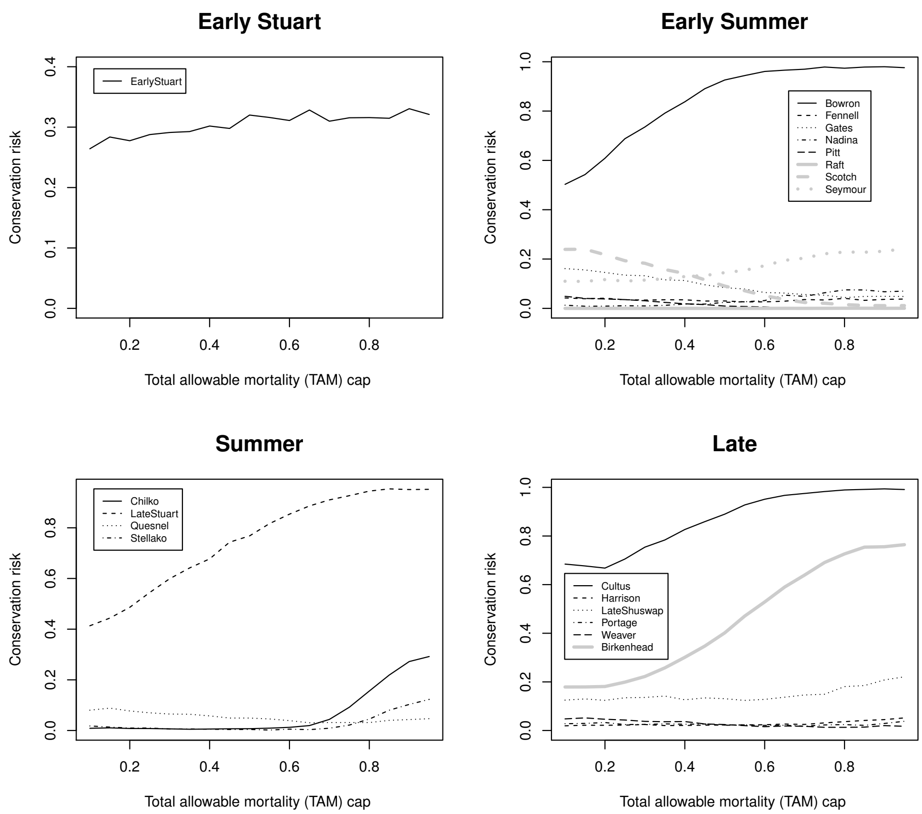

Figure 5.7: Conservation risk by stock (individual lines) and management unit (panels) with changing TAM cap, with modified productivity parameters.

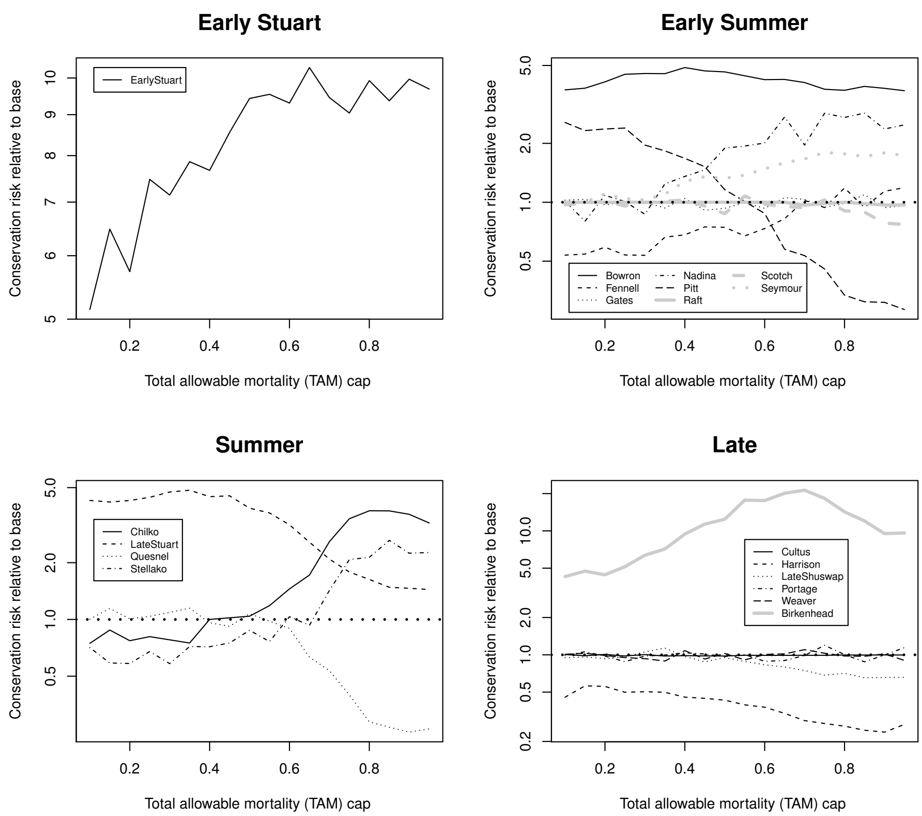

Figure 5.8: Ratio of conservation risk under the modified productivity regime to that under the base regime, with changing TAM cap.

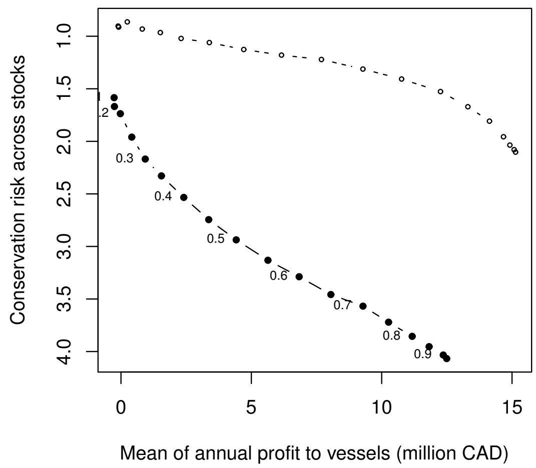

Figure 5.9: Trade-off of aggregate conservation risk against mean vessel profit as TAM cap is increased from 0.1 (top-left) to 0.95 (bottom-right), under the modified productivity regime. The result under the baseline regime is included (broken line) for comparison.

conservation risk significantly. Note also that aggregate conservation risk varies over a larger range of values under the modified regime. For example, changing the TAM cap from 0.2 to 0.6 under the base regime increases aggregate conservation risk from 0.9 to 1.3; in contrast the same change in TAM cap under the modified regime increases risk from 1.75 to 3.25, which is a much larger increase in both absolute and relative terms. In contrast, the increase in profit when making these changes in TAM cap is quite similar: 9 million CAD in the base regime compared to about 7 million CAD under the modified regime.

5.3.3 Target escapement

The final single-variable trial is to vary target escapement (Figure 5.10). As with previous trials, the relationship between mean and standard deviation

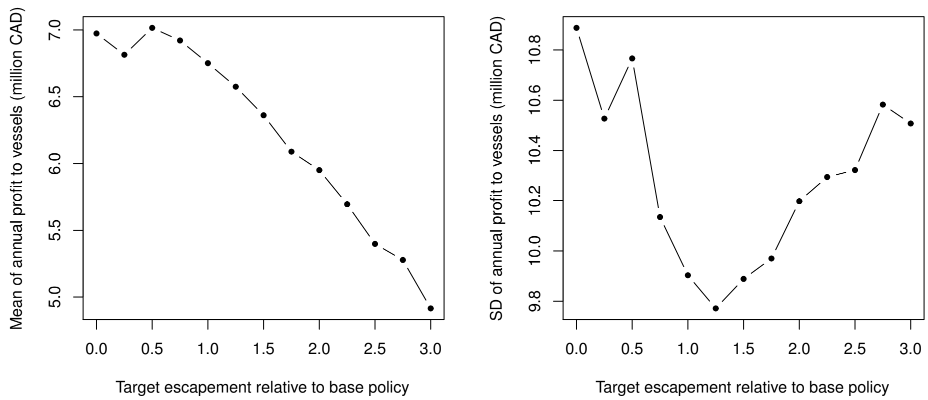

Figure 5.10: Mean and standard deviation of vessel profit over 24 years as the target escapement is changed from 0 to 3 times its baseline level, under modified productivity.

of profit and target escapement is quite similar under the two productivity regimes, but again with lower profit under the modified regime. However, as with the base regime, even tripling the target escapement decreases mean profit only by about 25%.

There are some parallels between the change in conservation risk with target escapement and with other harvest rule parameters. For the stocks with the most significantly decreased productivity – Early Stuart, Bowron, Late Stuart and Birkenhead – conservation risk is dramatically higher under the modified regime (Figures 5.11 and 5.12) than under the base regime (Figure 4.10; note in particular the different scales on the two sets of graphs), in particular at low target escapements. The patterns for the other stocks are generally similar between the two regimes.

Varying the target escapement under the modified productivity regime yields a concave trade-off between aggregate conservation risk and profit (Figure 5.13), and as with the previously tested harvest rule parameters outcomes are unambiguously worse under the modified regime with respect to both

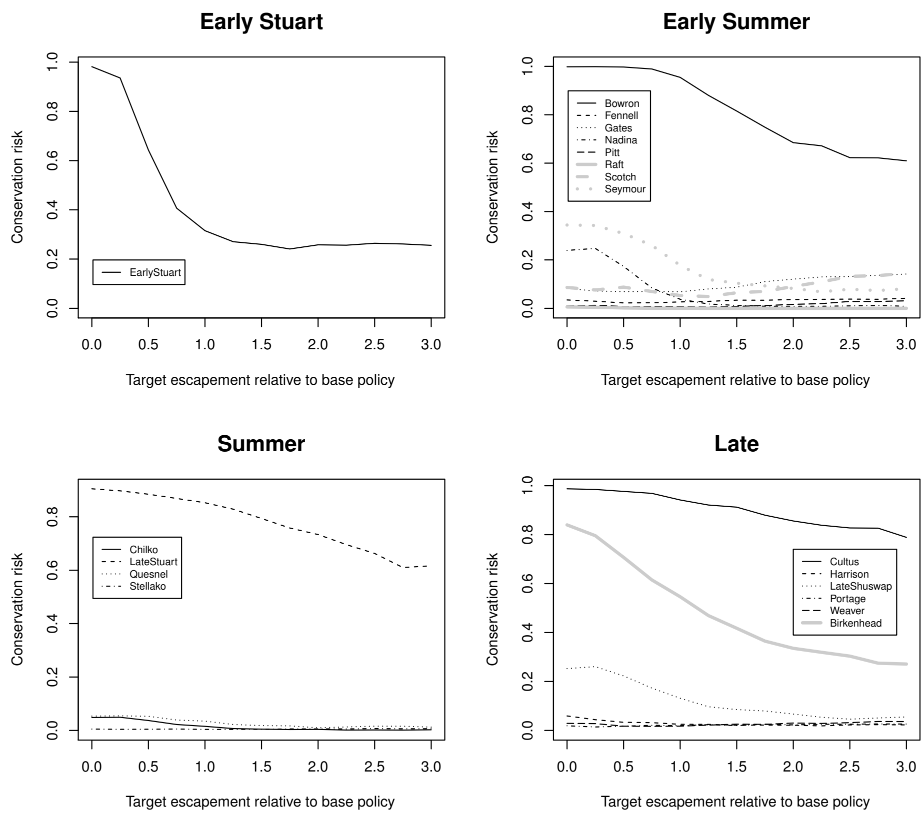

Figure 5.11: Conservation risk by stock (individual lines) and management unit (panels) with changing target escapement, under modified productivity.

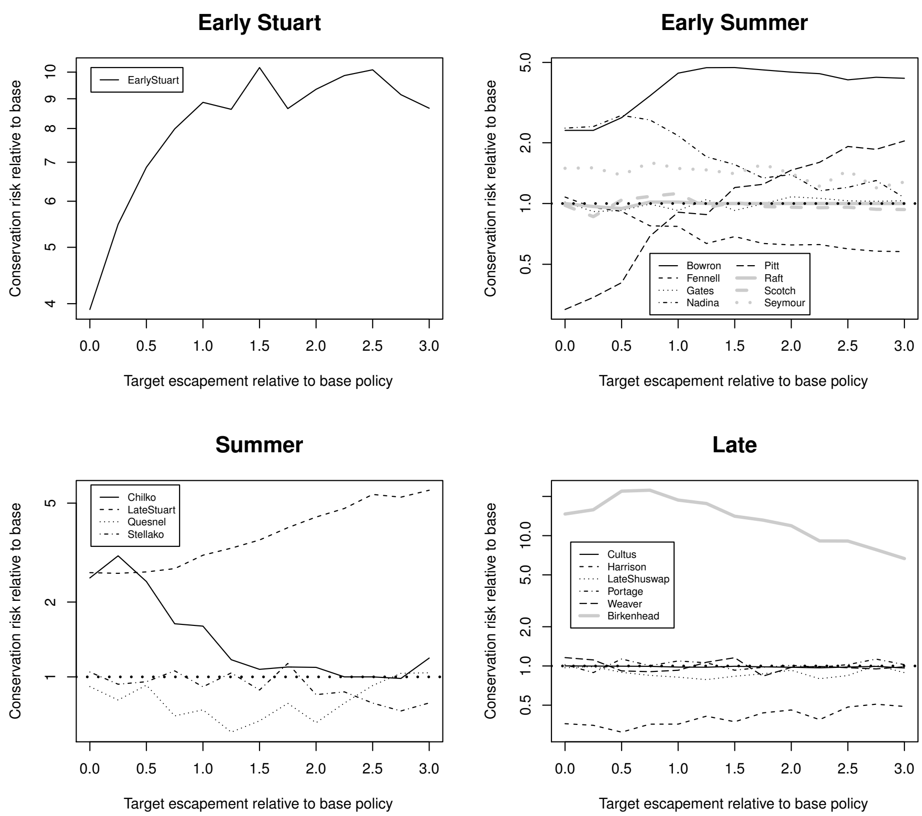

Figure 5.12: Ratio of conservation risk under the modified productivity regime to that under the base regime, with changing TAM cap.

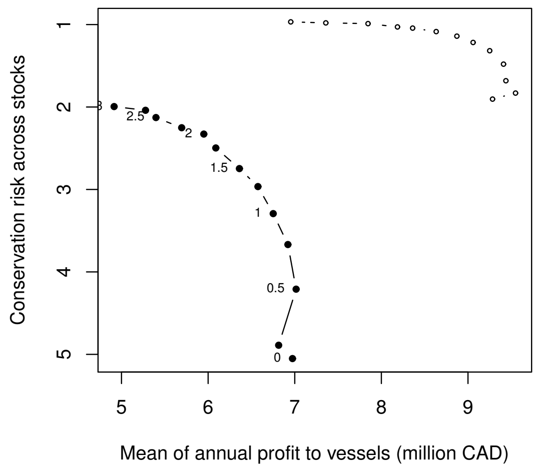

Figure 5.13: Trade-off of aggregate conservation risk against annual profit with changing target escapement, under modified productivity. The result under the baseline regime is included (broken line) for comparison.

objectives. Also, in comparison to the base regime the slope of the trade-off is relatively steep in the region of target escapements 1-2, implying a slightly more difficult trade-off under the modified regime. Finally, the relative and absolute range of aggregate conservation risk encountered over the range of target escapements explored is greater than that under the base regime, meaning that policy changes will have a greater impact on conservation under the modified productivity regime than under the baseline regime.

5.3.4 Multiple harvest rule parameters

The single-variable trials described above present some troubling first indications about the modified productivity regime, with a tendency toward lower profits, higher conservation risk, and more difficult choices and sharper trade-offs when compared to the baseline regime. To explore these further, rather than fix one variable and vary the other two, I have varied all three harvest rule parameters in turn and observed the range of outcomes. I again simulated with ER floors of 0.1 through 0.6 (stepping by units of 0.1), with TAM cap and target escapement varied over the ranges in the single-variable trials above.

The broad pattern in the relationship between profit and the three harvest rule parameters under the modified regime (Figure 5.14) is similar to that found under the base productivity regime (Figure 4.12), with the exception (as in the single-variable trials) that profit under modified productivity is somewhat reduced compared to the base regime, by approximately 25-30%. Additionally, the region of highest profits at high TAM caps appears to be centred closer to target escapements of 1.0-1.5, compared to 1.5-2.0 under the base productivity regime. However, increasing the ER floor to 0.5 and 0.6 shifts this region to the right, i.e., to higher target escapements, in keeping with the results under the base regime. Finally, the highest profits are again associated with ER floors of 0.5-0.6.

As with the pattern in profit, the relationship between aggregate conservation risk and the harvest rule parameters is quite similar in shape between the modified productivity regime (Figure 5.15) and the base regime examined above (Figure 4.13). The most notable difference, as would be expected from the results of the single-variable trials, is that conservation risk is substantially higher under the modified regime, and the gradients in aggregate conservation risk as we change harvest rule parameters are much steeper. For example, moving from an ER floor of 0.1 to 0.6 within the region of maximum profit (TAM cap = 0.9, target escapement = 1.5) implies increasing aggregate conservation risk from 2.9 to 4.4, while the same transition under the base regime involved an increase from 1.1 to 1.5. This is clearly a greater absolute increase in conservation risk, but also a slightly greater relative increase (52% compared to 36%).

Remembering that the base policy is a TAM cap of 0.6, ER floor of 0.1, and target escapement of 1, the aggregate conservation risk associated with this policy is approximately 3.0 (Figure 5.15), while profit is about 6.5 million

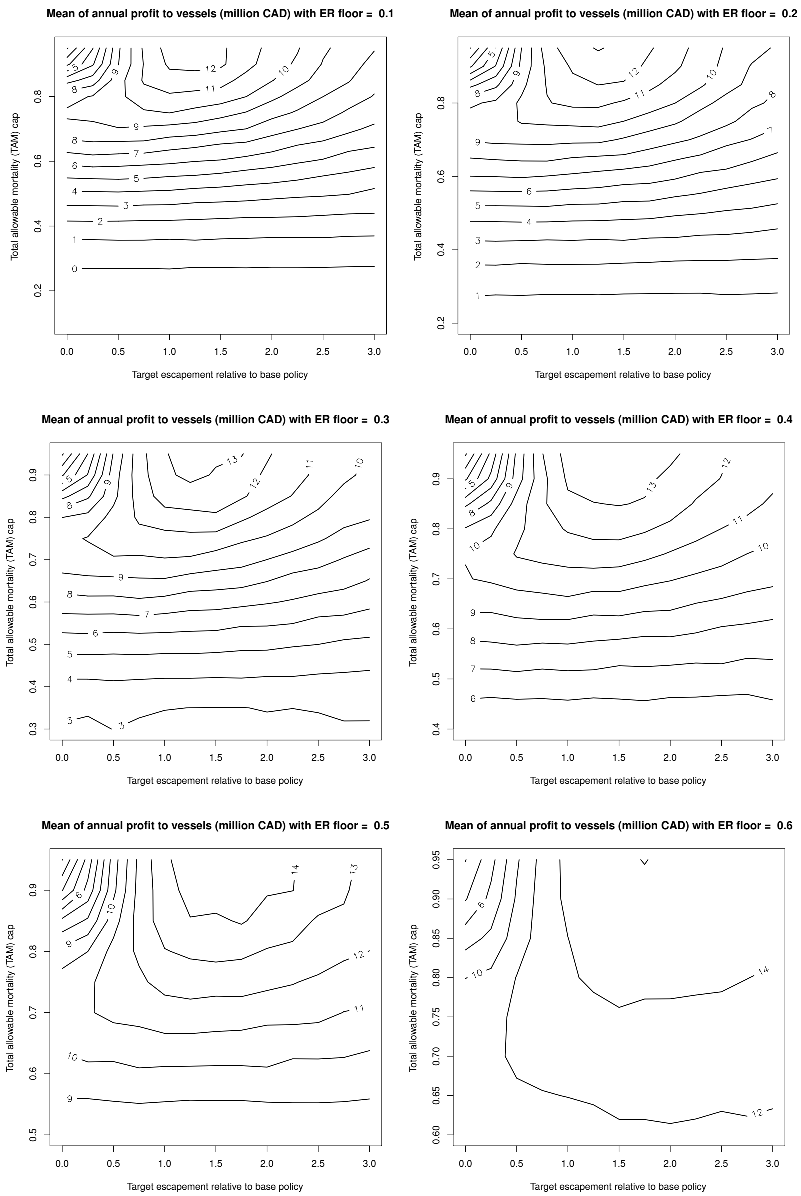

Figure 5.14: Mean annual profit of vessels when all three harvest rule parameters are changed under the modified productivity regime. The panels show results with different ER floors, ranging from 0.1 to 0.6 (trials at 0 and 0.7 are excluded for simplicity).

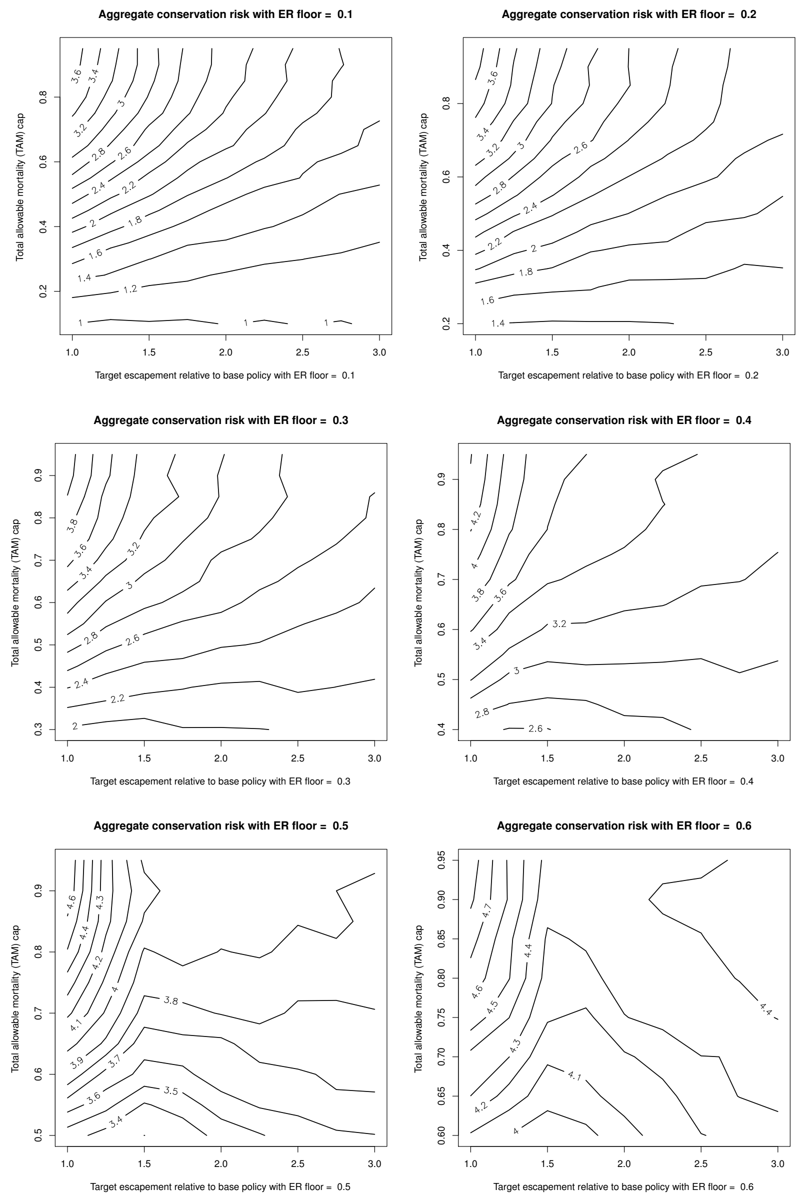

Figure 5.15: Aggregate conservation risk when all three harvest rule parameters are changed under the modified productivity regime, for target escapements >1 only. Each panel shows results with a different ER floor, ranging from 0.1 to 0.6.

CAD (Figure 5.14). Moving to a higher TAM cap of 0.95 and target escapement of 1.5 while keeping ER floor at 0.1 increases profit substantially, to about 12 million CAD, while decreasing aggregate conservation risk slightly, from 3.0 to 2.8. Further increases in ER floor within this TAM cap-target escapement region could yield just over 13 million CAD in profit at an ER floor of 0.3, and about 15 million at an ER floor of 0.5. These last harvest rules, however, would lead to substantial increases in aggregate conservation risk, from 3.0 under the current rule to 3.4 and 4.0 under the alternatives at ER floors of 0.3 and 0.5, respectively.

To examine these results and compare the outcomes in terms of the two objectives in a more integrated fashion, I again calculated the ratio of profit per aggregate conservation risk, as in Figure 4.15. We see that higher ER floors lead to progressively lower profits per unit of aggregate conservation risk, and that in keeping with the discussion above a suitable region appears to be at low ER floors (0.1-0.3), high TAM caps (0.9-0.95) and moderate target escapements (1.5-2.5; Figure 5.16).

As in the preceding chapter and in the trials above that involved changing single harvest rule parameters, I plotted the outcomes of all harvest rules examined in terms of both objectives (Figure 5.17). In this figure we can see, as in the analysis with baseline productivity, that the currently applied harvest rule is dominated by many other possible rules[13]. The two 'alternative' harvest rules noted above are circled in the figure, and we can see that the alternative rule with ER floor = 0.1 dominates the current rule. The second alternative rule, with ER floor = 0.3, is somewhat further down the frontier from the first, providing slightly more profit but increasing aggregate conservation risk substantially. In comparison to the current rule, this second alternative rule provides almost twice as much profit while incurring roughly the same aggregate conservation risk.

As with the single-parameter trials above, outcomes under modified produc-

[13]Detailed numerical results for the selected set of harvest rules outlined in this section, as well as the baseline harvest rule, are presented in Appendix B along with results for the baseline productivity regime discussed in Chapter 4.

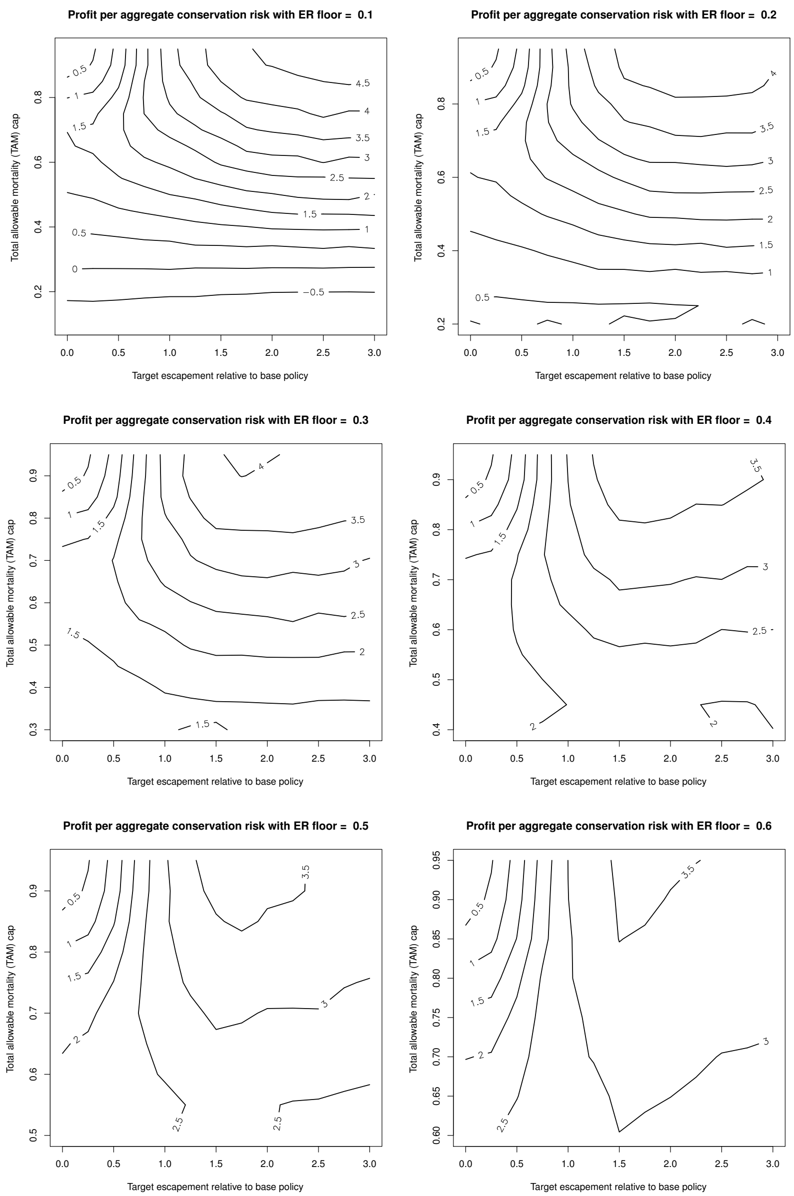

Figure 5.16: Mean annual profit divided by aggregate conservation risk, for ER floors of 0.1-0.6.

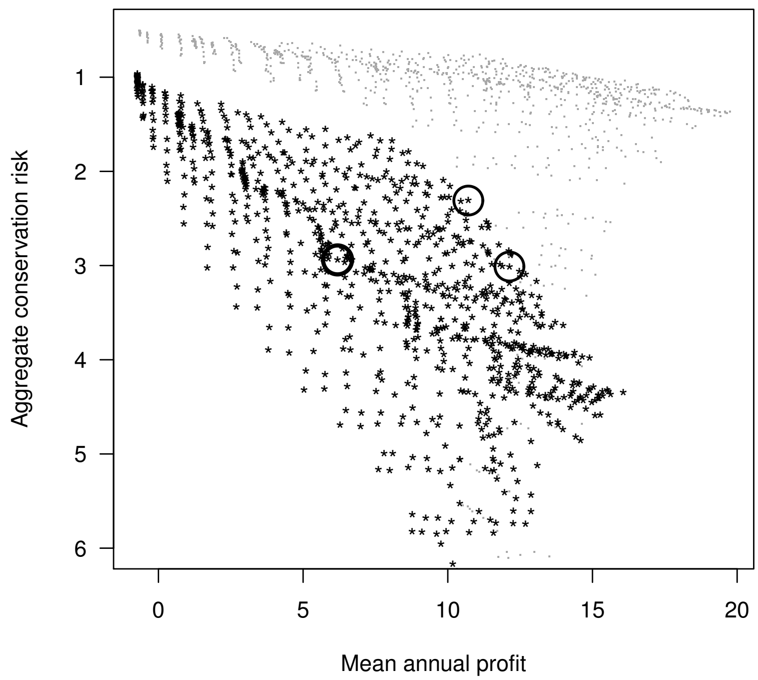

Figure 5.17: Trade-off plot showing the range of possible outcomes in terms of mean annual profit and aggregate conservation risk, under modified productivity. Each symbol represents the outcome of one harvest rule: asterisks show outcomes in the modified-productivity analysis, while small dots show outcomes under baseline productivity (originally presented in Figure 4.16) for comparison. The circles denote, from left to right: (1) the currently applied harvest rule; (2) a harvest rule with ER floor = 0.1, TAM cap = 0.95, and target escapement 1.5 times the current level; and (3) as for 2 but with ER floor = 0.3. Some harvest rules are omitted because they are dominated by the other policies shown.

tivity are dominated by those under the baseline productivity regime. We also see, based on the slope of the Pareto frontier (Cheung and Sumaila, 2008) that could be drawn along the top-right edge of the points, that under modified productivity more conservation risk must be incurred in order to increase profit, especially if we wish to increase profit above about 8 million CAD per year. The overall trade-off is still convex, unlike that when varying the TAM cap, but is not convex to the same extent as that under the baseline productivity regime. Overall, this plot supports the contention that the trade-off between conservation risk and mean annual profit is significantly more difficult under modified productivity than under baseline conditions.

I examined three of these harvest rules in more detail, as in section 4.4.4: (1) the high-profit region at a TAM cap of 0.95, target escapement of 1.5, with ER floor at 0.1; (2) as for 1, but with ER floor elevated to 0.3; and (3) the base policy, where ER floor is 0.1 (0.2 for Late), TAM cap is 0.6 and target escapement is 1 (Figure 5.18). The ER floors tested here are substantially lower than those tested under the base productivity regime as, based on the analyses above, higher ER floors lead to quite dramatic increases in conservation risk that are unlikely to be acceptable. In comparison to the base harvest rule, an ER floor of 0.3 (combined with TAM cap of 0.95 and target escapement of 1.5) increases conservation risk to many stocks, both those that have reduced productivity under the modified regime (especially Early Stuart, Late Stuart and Birkenhead) but also most other stocks. An ER floor of 0.1 also increases conservation risk on some stocks, but not to the same extent as the ER floor of 0.3; furthermore, risk to many stocks (Bowron, Nadina, Scotch, Quesnel, Late Shuswap) is decreased relative to the base policy, with the net effect that, as noted above, aggregate conservation risk is slightly lower with an ER floor of 0.1 compared to the base policy.

To examine how conservation risk changes based on the assumed productivity regime, Figure 5.19 shows the difference between mean conservation risk incurred by the ‘alternative’ harvest rule under the modified regime (asterisks in top panel in Figure 5.18) and that incurred by the alternative rule under the baseline regime (asterisks in middle panel in Figure 4.17). As would be

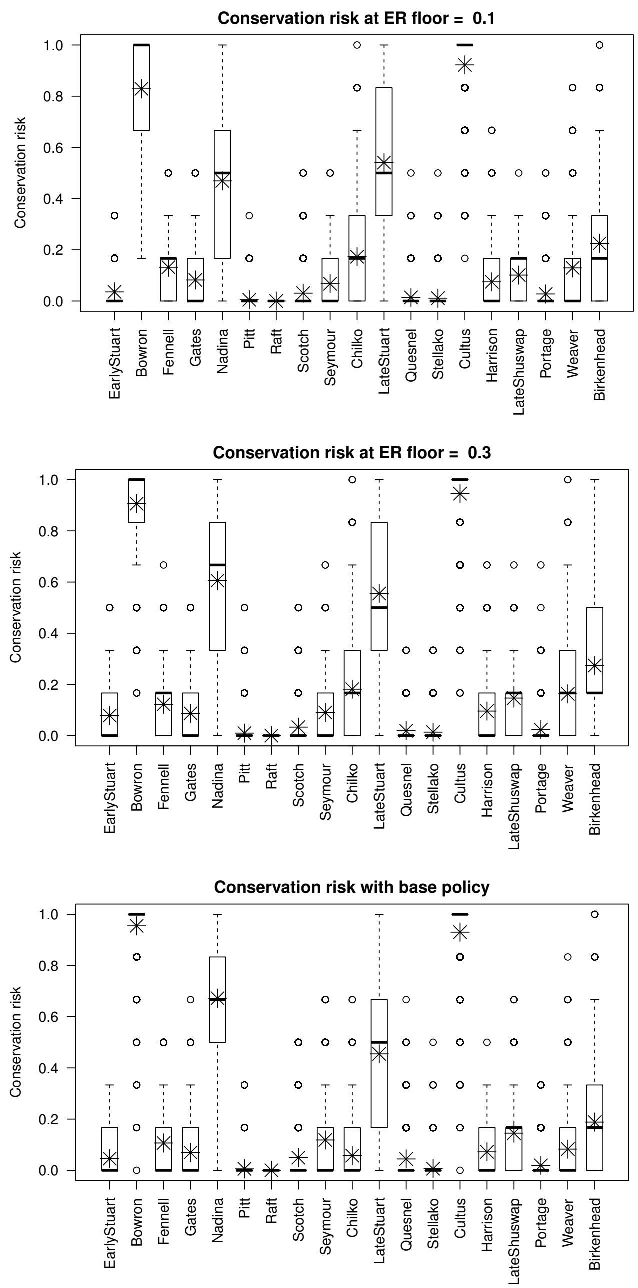

Figure 5.18: Conservation risk by stock under modified productivity, with: (1) Top: TAM cap = 0.95, target escapement = 1.5, and ER floor = 0.1; (2) Middle: as for top but ER floor = 0.3; (3) base policy of TAM cap = 0.6, target escapement = 1, ER floor = 0.1 (0.2 for Late). The mean of 1000 simulations is shown with an asterisk for each stock.

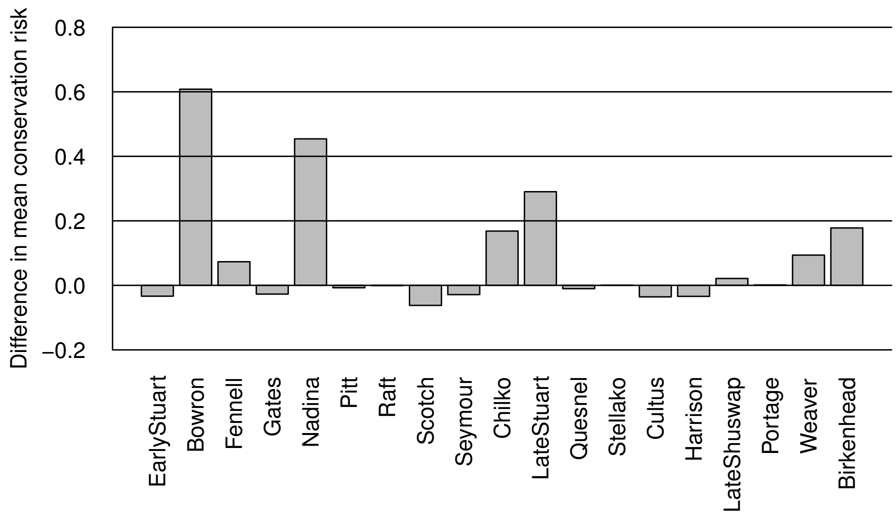

Figure 5.19: Difference between the mean of conservation risk by stock (mean over 1000 simulations) incurred by the alternative harvest rule under the modified productivity regime (ER floor = 0.1, TAM cap = 0.95, target escapement = 1.5) and that under the baseline regime (ER floor = 0.4, TAM cap = 0.95, target escapement = 2). Positive values indicate higher risk under the modified regime.

expected, and in line with the results above, the differences in risk are mostly aligned with changes in productivity under the modified regime (Figure 5.1): stocks with lower productivity have higher conservation risk, and vice versa. One notable example is Early Stuart, which faces much lower productivity but slightly lower conservation risk. This occurs because Early Stuart is managed on its own rather than as a multi-stock fishery, so the TAM is determined only by the status of that single stock; and since the ER floor chosen under the modified productivity regime is 0.1, as opposed to 0.4 under the baseline regime, the Early Stuart stock is somewhat better protected under the modified regime.

Finally, we can examine the time series of profit throughout the simulation period, where profit is represented as the mean of 1000 simulations under a given harvest rule (Figure 5.20). The ER floors of 0.3 and 0.1 when applied

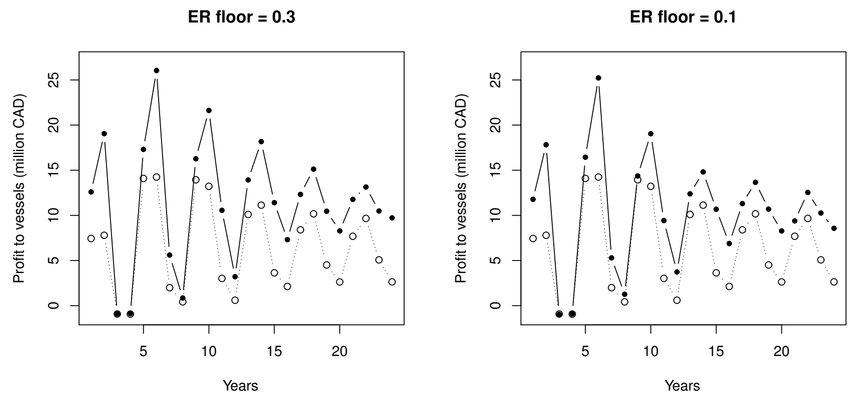

Figure 5.20: Time series of vessel profit with TAM cap = 0.95, target escapement = 2, and ER floor = 0.6 (left panel) or 0.4 (right panel, both with filled symbols). The base policy of TAM cap = 0.6, target escapement = 1, ER floor = 0.1 (and 0.2 for Late) is shown on each graph (with open symbols) for comparison. Values for each year are averages over 1000 simulations.

in the 'high profit' area (TAM cap 0.95, target escapement = 1.5) yield quite similar results. All three harvest rules lead to some rebuilding of the fisheries and gradual stabilization of profits over time, albeit with some remaining variability over the cycle. Significantly, however, the base harvest rule yields much lower profit than the two alternatives, but also much more variable profit, in both relative and absolute terms.

5.4 Summary and conclusions

The fishery under the modified productivity regime examined here is faced with new policy challenges compared to the baseline regime examined in the preceding chapter. This modified regime imposes increased conservation risk to many stocks while also decreasing the profits that are attainable in the commercial fishery. The analysis outlined above suggests that a harvest rule with ER floor = 0.1, TAM cap = 0.95 and target escapement set to 1.5 times the baseline level may be a suitable policy to balance conservation and economic objectives as they are defined here. This harvest rule, to which I will refer as rule C, is shown in Figure 5.21 and compared to: (1) the harvest rule that was considered suitable under the baseline regime, which I will call rule B; and (2) the harvest rule currently applied in the fishery, called rule A. At run sizes < 1, rule C is the same as rule A, i.e., 10% of the run is harvested. For run sizes of 1-1.5, this harvest rate is still applied, meaning that in this range rule C places more emphasis on escapement than either rule A or rule B. However, the target escapement in rule C is 1.5, so escapement beyond this level will be harvested, except at exceedingly high escapements where the TAM cap will limit allowable mortality. In general, harvests (seen as the vertical distance between the 1:1 dotted line in the figure and the escapement goal) under rule C will be lower than those under either of the previous rules discussed, especially when compared to rule B at low escapements. This emphasis on escapement is a consequence of reduced productivity in many stocks, and reduced average productivity, meaning that low harvest rates must be applied in years when escapements are low in order to prevent serious conservation concerns from arising.

The outcomes under this modified productivity regime are unambiguously less desirable in terms of the two objectives than under the baseline productivity regime. Perhaps more challenging from a policy and management perspective, however, is that the trade-offs between these objectives are more difficult under the modified regime than in the baseline analysis. In the cases of the ER floor and the target escapement (when varying only one harvest rule parameter), this is a change in the slope of the trade-off, while in the case of the TAM cap there is a qualitative change from a slightly convex trade-off to a concave one, where performance in terms of one objective cannot be improved without disproportionate losses in performance with respect to the other objective. These cases of concave trade-offs can be particularly difficult to negotiate as there is unlikely to be an easy 'middle ground' or compromise state that will satisfy all stakeholders (Walters and Martell, 2004). Some possible ways to navigate this situation will be explored in the final chapter. The trade-off when we tested harvest rules through the full policy space showed

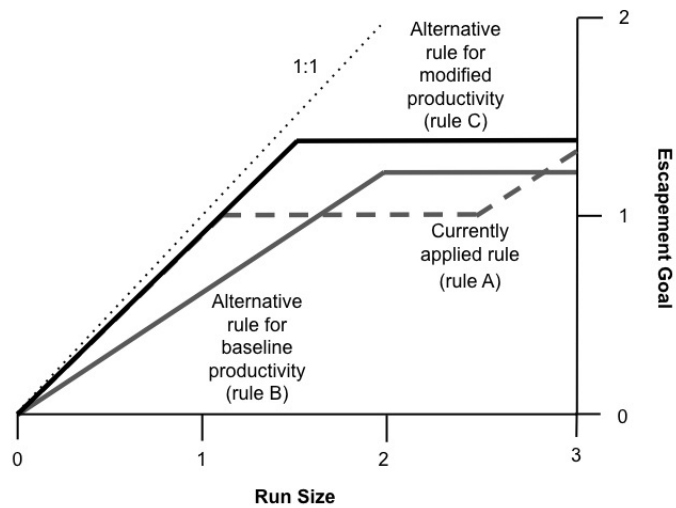

Figure 5.21: Escapement goal implied by a harvest rule with ER floor = 0.1, TAM cap = 0.95, and target escapement equal to 1.5 times the current baseline levels (solid black line, labelled rule C). Run sizes are defined relative to the baseline target escapement (set to 1). The solid grey line shows the escapement goal for the alternative harvest rule under baseline productivity (rule B, the same as Figure 4.21), while the thick broken line is the harvest rule currently applied in the fishery (rule A). The vertical distance between the 1:1 line and the escapement goal is the allowable harvest.

convexity under both productivity regimes, which is less troubling than the concavity observed with TAM cap. However, the Pareto frontier under the modified regime was much less convex than that under the baseline regime, suggesting a more difficult trade-off under modified productivity.

This chapter has served to illustrate another particular benefit of prospective policy analysis in comparison to retrospective analysis, as this approach has allowed me to examine the impacts of a particular change in the underlying biology of the system. While such an analysis could possibly be conducted in a retrospective setting, it would have less intuitive appeal because assuming altered historical productivity would impose a change on the underlying system that was not actually observed. There seems to be little reason to choose to conduct a simulation in the past when such dramatic changes must be assumed in fundamental aspects of the ecosystem.

Despite the important differences in outcomes and the selected harvest rule imposed by the modified productivity regime, the overall conclusion in this chapter is broadly similar to that in the preceding chapter that analyzed the baseline productivity regime: that a policy involving high TAM caps and somewhat higher target escapement could substantially increase average annual profit, decrease the variability in profit, and to a small extent even decrease aggregate conservation risk. However, it may be that this rule, and the alternative rule proposed in Chapter 4, both overlook some other objective that is driving policy in the fishery. This issue will be addressed in the next and final chapter.

Chapter 6

Conclusion

This concluding chapter begins by revisiting the research questions posed in Chapter 1 and examining the findings of the dissertation in this context. It then goes on to address some of the strengths and weaknesses in the analyses presented, before examining some policy implications of the findings.

6.1 Synthesis of findings and contributions

This dissertation began with a brief description of the variable and sometimes troubled state of the Fraser River sockeye salmon fishery, and then raised a set of broad biological, policy, and methodological questions about the mechanisms underlying this state, and how it has been and might potentially be approached by management. These general questions were then refined into a set of more specific research questions (in section 1.4.2) that were addressed in Chapters 3 through 5, using the general simulation model outlined in Chapter 2. A fourth question regarding methodology was also examined in the context of each chapter. This section synthesizes the findings of the dissertation with respect to these questions, and links them to the broader context of fisheries policy and management.

The first research question asked had several parts: How would different management approaches have affected the economic benefits obtained historically from a fishery, if other aspects of that fishery had remained the same? To what extent would the benefits of these approaches have depended on the mechanisms that generated fish stock dynamics, and how would the outcomes have differed if erroneous assumptions had been made about the underlying dynamics? The analysis in Chapter 3 addressed these questions, and found in general that significantly more economic benefits could have been obtained from the fishery during 1948-1998 if it had been managed using either a fixed exploitation rate or target escapement policy. This analysis also found that the actual outcomes of management depended heavily on assumptions about the underlying stock dynamics, but also on which of the two policies was employed. The target escapement policy yielded greater average economic benefits, but these benefits were more variable from year to year. The findings in this chapter aligned well with those of Martell et al. (2008), who came to similar conclusions but did not include an economic component in their analysis. This chapter, which was published (Marsden et al., 2009) in a form quite similar to that presented here, is the first published empirical bioeconomic analysis of the Fraser sockeye fishery, and thus provides a contribution to knowledge with respect to this fishery in particular, as well as to the bioeconomic literature in general.

The second research question was: What is the trade-off between economic benefits and conservation risk in the fishery from this point forward? In other words, how much economic benefit must be forgone to reduce conservation risk?; or conversely, how much must conservation risk be increased in order to pursue greater economic benefits? Chapter 4 used a prospective simulation analysis to quantify the trade-offs between vessel profit and conservation risk to 19 stocks of Fraser sockeye, including the endangered Cultus Lake stock that drives much current management. This analysis found a relatively broad set of harvest rules that could provide outcomes that are substantially better in terms of both objectives, and explored the implications of a selection of these rules relative to the baseline policy currently employed in managing the fishery. The harvest rule suggested by this analysis as a suitable alternative to the current policy was found to be reasonably robust to uncertainty about whether the Ricker or Larkin model was the most appropriate way to model stock dynamics. The trade-offs between objectives were visualized by plotting outcomes in terms of both objectives under consideration, first when varying a single management parameter (e.g., ER floor in Figure 4.5) and then when varying all three parameters at once (e.g., Figure 4.12). This approach has been taken by others (Sylvia and Enriquez, 1994; Cheung and Sumaila, 2008), and provides a clear illustration of what outcomes are possible. Ultimately, and perhaps surprisingly, the trade-off between the objectives examined was not a particularly difficult one, at least under the baseline productivity regime examined in this chapter. The trade-off is for the most part convex, meaning that desirable outcomes in terms of both objectives are relatively attainable. A general lesson from this chapter is that presenting trade-offs in this way can provide information that allows stakeholders, managers and policy-makers to have an informed discussion about the implications of alternative policies and make a decision on this basis.

The third question was closely related to the second: How is this trade-off between economic benefits and conservation affected by different assumptions about future trends in stock productivity? Chapter 5 examined this question in a similar framework to that used in the preceding chapter, while making a change in key parameters to simulate recent observations that the productivity of many sockeye salmon stocks has changed, in most cases toward lower productivity. The analysis demonstrated that outcomes under this modified productivity regime will tend to be significantly worse with respect to both objectives. Furthermore, while there is some convexity in the trade-off relationship under this modified regime, the trade-off becomes more difficult because increases in economic benefits can only be obtained through much more drastic increases in conservation risk than under the baseline regime.

Finally, the fourth research question concerned methodology: What are the advantages and disadvantages of retrospective and prospective analysis for examining fisheries policy issues? Chapter 3 used a retrospective analysis to examine the research questions, while Chapters 4 and 5 used a prospective analysis. As discussed in the introductory chapter, each of these approaches has strengths and weaknesses. A retrospective analysis allows for the incorporation of more observational data than a prospective analysis, as the latter by definition takes place in the future, where outcomes are unknown. However, this incorporation of historical outcomes may produce bias in the results obtained in the retrospective analysis. This may be a problem with the retrospective analysis conducted in this dissertation: as noted in section 4.4.1, the particularly high profits in the 1980s and early 1990s may be a consequence of abnormally high recruitment during these years. If such high recruitment is truly out of the ordinary, it is unlikely to be repeated, and so policies developed and expectations generated based on these unusually prosperous years are likely to be biased. Likewise, if recent observations suggesting *decreased* overall productivity in the system are abnormal and transient, then policies may erroneously be designed to allow for this decreased productivity, and it may take many years before it becomes clear that this change was in fact temporary. Finally, policy development tends to lag scientific findings and developments by many years, so there is a risk that such biased approaches will remain 'locked in' for a significant period of time even after their lack of suitability becomes clear from a scientific perspective.

Chapter 5 demonstrated perhaps the most important advantage of prospective analysis, which is that it allows the parameters of the model to be altered to test alternative assumptions about future changes in the fishery or the underlying fish stocks. In the case of this dissertation, this key change was in the productivity of the stocks, but many other changes could also be examined in this way. While such an analysis could theoretically be conducted in a retrospective setting, its outcomes would have little intuitive meaning. For example, I could have asked what would have happened if productivity had declined permanently in Fraser sockeye stocks in 1980 and remained low. However, this change did *not* occur, so there is little point in asking this question. Ultimately, the choice of whether to use a retrospective or prospective analysis will largely be determined by the questions being asked. Questions about historical management can be well-grounded by known observations of the outcomes of stochastic processes, but questions about current and future management will usually be best examined in a prospective context.

An important point regarding the results in the prospective analysis is that the objective of this work was not to find an 'optimal' policy or harvest rule, and I have intentionally avoided using this or similar words to describe any of the findings in this dissertation. Rather, the objective has been to reveal trade-offs between objectives and present these trade-offs in an understandable form. Any discussion of an 'optimal' policy or rule requires value judgements – explicitly or otherwise – about how much of one objective one is willing to forgo in order to improve performance with respect to another objective. Rather than impose my own values on the analysis (other than the unavoidable subjectivity implicit in the selection of objectives, indicators, and other aspects of the analytical framework itself), I have presented the implications of different choices in order to allow readers to explore possible futures themselves.

One question that might arise with respect to the results in the prospective analysis is, if the currently applied harvest rule is dominated by so many alternative rules, why is this rule still applied? Walters and Martell (2004) suggest three possibilities when we find that a current policy is clearly dominated: (1) the trade-off analysis is being conducted incorrectly, e.g., there is an error in the model that leads to misrepresentation of possible outcomes; (2) an important objective has been omitted from the analysis, and the current policy is in fact on the Pareto frontier; or (3) the system is indeed not being managed as well as it could be.

The next section addresses some weaknesses of the analyses described in this dissertation, some of which might have introduced bias into the trade-off analysis. The harvest rule currently applied in the fishery is chosen based in part on consultations with stakeholders centred around the FRSSI model, which incorporates many complexities that are not dealt with in my model (see below). Some of the complexities that I have omitted from my model may contribute to bias in the analysis here.

Regarding other objectives that might be considered when setting escapement goals, there are several possibilities. In the WSP context as noted in the first chapter, First Nations food, social and ceremonial fisheries are given the highest priority once conservation goals have been met. This suggests that the current harvest rule may be chosen to minimize risk to these fisheries. However, the structure of the routine in the model that allocates allowable harvest should prevent this as, in keeping with current practice, the first one million fish are allocated to First Nations harvesters. This can be seen clearly when examining time series of the First Nations harvest over the 24 simulated years when the alternative harvest rule is applied either under the baseline or the modified productivity regime (Figure 6.1). Harvests by First Nations fluctuate in early years as stocks rebuild from current levels, but by the end of the 24 years they consistently obtain their full allocation, or nearly so.

Perhaps another objective that is being accounted for in the selection of harvest rules is conservation of small, relatively unproductive sub-stocks. While the model here and in other contexts (Grant et al., 2011; Pestal et al., 2011; MacDonald and Grant, 2012) deals with these 19 primary stocks, there is in fact sub-structure within many of these stocks. It may be that conservative harvest rates are being applied, for example, through the application of a TAM cap of 0.6, in order to limit the risk to some of these sub-populations, which are likely to have differing productivities and thus different vulnerabilities to higher harvest rates. Indeed, Pestal et al. (2008) stated that a TAM cap of 0.6 was implemented to protect "stocks that are less abundant, less productive, or both," and this TAM cap also allows for uncertainty about the stocks that may not be recognized in these models (A-M. Huang, DFO, pers. comm.). In other words, this particular level of TAM cap is intended to apply a precautionary approach to the fishery.

Another more subtle concern is that a harvest rate applied to a management unit will not be exactly applied to all stocks in that unit. Because of the random spatial distribution of the fish throughout the migration, it is likely that some stocks will be over-represented (relative to their proportion in the

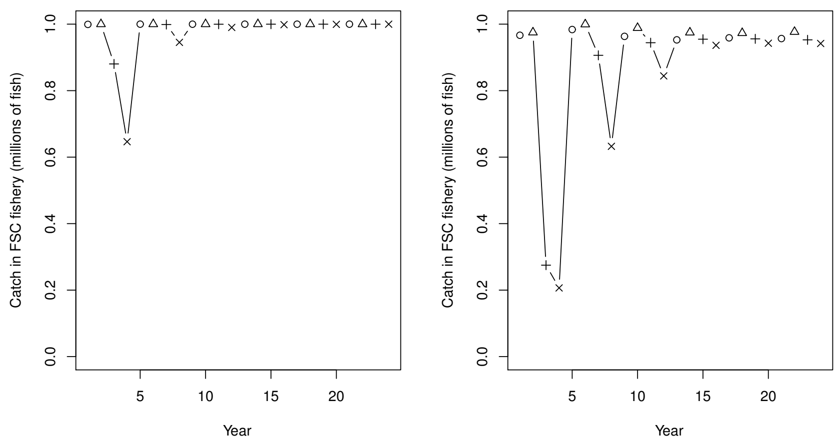

Figure 6.1: Time series of First Nations food, social and ceremonial harvests under: (1) the baseline productivity regime when the alternative harvest rule (ER floor = 0.4, TAM cap = 0.95, target escapement = twice the current level) is applied; and (2) the modified productivity regime when the alternative harvest rule (ER floor = 0.1, TAM cap = 0.95, target escapement = 1.5 times the current level) is applied.

overall management unit in that year) in a particular area, while others will be under-represented. If the run in question consists of a few large stocks then this will not pose a serious concern, but if, for example, the very small Cultus stock is migrating with a very large run of Late Shuswap sockeye, a very high harvest rate may not negatively affect the Late Shuswap stock but may inadvertently capture the majority of the Cultus fish if they happen to be clustered in an area where the fishery is opened. This risk is partly mitigated through the details of the PSC's in-season management system, but also through placing a cap on TAM.

A conclusion here is that management has been imposing a harvest rule that appears to be dominated in the context of my analysis, but which is in fact chosen to satisfy other objectives not considered here, specifically precaution with respect to what we may not know about the fish stocks. As well, this particular rule may have other benefits in terms of avoiding serious implementation errors, but these errors are not modelled in either my work or in the FRSSI model. It could be argued, however, that changes in the harvest rule, whether along the lines described above or more conservatively, could still allow a high degree of precaution while also allowing greater economic benefits to be obtained.

6.2 Strengths and weaknesses

The strengths of the analysis conducted in this dissertation are outlined in the preceding chapters. The empirical bioeconomic framework used here provides a flexible approach that allows incorporation of a great number of issues and considerations as appropriate for the research questions being addressed. The retrospective analysis provided answers to historical questions, while the prospective analysis allowed examination of questions about future management.

There are, however, weaknesses in the analysis as it was conducted, some of which could be mitigated in future research. All of the analyses conducted here relied on frequentist estimates of stock-recruitment parameters, and then used the mean estimates of these parameters to drive simulations. This approach was used here because of its relative tractability and simplicity, but it does not allow the analysis to take into account the uncertainty about these parameters. A more suitable approach would be to conduct Bayesian estimations of relevant parameters (McAllister and Kirkwood, 1998a; Michielsens and McAllister, 2004) and include this uncertainty in a decision-analytic framework that described outcomes in probabilistic terms (McAllister and Kirkwood, 1998b; Robb and Peterman, 1998; Schnute et al., 2000; Pestes et al., 2008). This Bayesian approach is used in the current FRSSI model (Pestal et al., 2011).

The retrospective analysis was limited in the sense that it explicitly quantified economic benefits but did not address conservation risk. This was partly a consequence of the retrospective framework and the assumption that recruitment anomalies would have been constant regardless of the management approach used – such an assumption would make simulations of the type used in the prospective analysis meaningless, as the outcome would always be the same. However, conservation risk – or more specifically, avoiding conservation risk – was implicitly included in the analysis. The first two harvest rules applied, fixed exploitation rate and target escapement, were defined with respect to MSY, which by definition will avoid depleting the stocks, while the hypothetical 'omniscient manager' avoided overexploitation to the extent that it would decrease profits, and indeed none of the scenarios tested involved stock depletion. Rather, all simulations run with alternative policies led to greater stock size than was historically observed.

With respect to the economic components of the analyses, there were two weaknesses. The first was the linear structure of the catch and cost models employed. In the retrospective analysis, both CPUE and the cost per unit effort were assumed to be independent of the amount of effort applied and the run size, and CPUE was assumed to increase by a constant percentage per year. These assumptions were necessary to make the analysis tractable given the data available, but are not ideal assumptions. In particular, alternative management regimes like the ones tested, if they had in fact been applied over a long time period might have induced changes in fishing behaviour that would have changed cost structures and/or CPUE. A more detailed analysis of one or both of these models with better data may yield somewhat different results than those obtained here. Likewise, in the prospective analysis, while the catch model allowed for changes in CPUE with different run sizes and amounts of effort, the data available still required a relatively crude estimate of these effects. A particular challenge in estimating these effects is the relative lack of commercial fisheries in recent years (M. Lapointe, Pacific Salmon Commission, pers. comm.): given low abundance through the early 2000s, commercial fisheries have been rare, and thus detailed data on catch rates are limited. As in the retrospective analysis, the cost model in the prospective analysis is, by necessity given available data, relatively crude. Thus, while the models and estimates used here are sufficient for the broad policy-oriented analysis conducted here, they would not be appropriate to use for more detailed analysis of finer scale issues such as in-season management.

A second weakness in the economic components of the model is the omission of consideration of fixed costs, in particular the potential overcapacity of the fishing fleet. This consideration was omitted for simplicity, and justified based on the relatively low contribution of Fraser sockeye to overall decisions about investment in fleet capacity. Approaches to this issue used by other authors are: allocating an arbitrary portion of the total fixed cost of the fleet to the sockeye fishery (e.g., Gislason, 2011); or conducting an integrated analysis of performance of the fleet in all fisheries in which it participates (e.g., Nelson, 2009). In any case, while questions related to fleet capacity in this and other fisheries are important, they were not the focus of this dissertation, and were thus left aside. However, in future analyses it may be advisable to include such issues as they may modify the outcomes somewhat.

The simulation approach and the harvest rule used in the prospective analyses provided a reasonable approximation of the actual management system currently in place. One limitation in the analysis conducted here is that essentially a single harvest rule was applied to all four management units.

The only allowance that was made for difference between the units was that target escapement was set in relative terms; so, for example, a target escapement of '2' in the harvest rules discussed above actually meant that the target escapement of each management unit was set to twice the value currently being applied in the fishery. For the other harvest rule parameters – ER floor and TAM cap – the same value was applied to all four units and the results examined. This imposes a degree of rigidity in the analysis, in the sense that the suitability of a particular rule is assessed with respect to its performance when applied in the whole fishery. A more flexible set of trials would examine how each rule performs on each management unit, and choose suitable rules on a unit-by-unit basis. This approach was not taken here as it would have added another dimension to an already complex analysis and presentation, but this would provide a more complete assessment of the suitability of different harvest rules.

Finally, it could be argued that the indicators chosen to represent the two objectives under consideration – mean annual vessel profit over all 1000 simulations, and the proportion of four-year cycles during which the mean fish stock size falls below a standard benchmark – are not the most appropriate. Some might argue that a wider range of economic benefits should be included, such as wages to crew members, profits in the processing industry, or other values. Likewise, there may be other conservation-related variables that would be more appropriate, and indeed there is much ongoing work within the WSP framework to develop benchmarks for conservation units (Holt et al., 2009; Holt, 2009; Grant et al., 2011). Nevertheless, the indicators chosen seem appropriate for the broad-scale analysis undertaken here. Future work could examine results in terms of other objectives if those were deemed to better reflect the government's and society's aims for this fishery and ecosystem.

6.3 Policy implications

There are several policy implications of the findings in this dissertation. The general implication is that incorporation of economic analysis and objectives into analysis of fisheries can yield important information about the outcomes of different policy choices that would not otherwise be clear. Particularly in the Canadian context where "economic prosperity" is being incorporated as a fundamental objective of fisheries policy, explicit integration of economics will help in developing policies that help balance trade-offs between all objectives that are considered in decision-making with respect to Canadian fisheries. Approaches like the one taken here can help to reveal outcomes and trade-offs with respect to objectives that have not always been incorporated to this point.

The other finding that is likely to be applicable in other systems is the strong implications of changes in the underlying biology of the ecosystem. As seen here, a change in the biology of a sub-set of the stocks being fished leads to a dramatic change in the nature of the trade-off between objectives, from a relatively 'easy' trade-off where desirable outcomes are obtainable in terms of both objectives, to a much more difficult trade-off where the cost of improving with respect to one objective is quite high. This suggests that policy and management systems should both be designed to the extent possible to be robust to such changes, for example, through harvest rules that are sensitive to stock size, but also through consultation processes and other engagement with stakeholders that allows discussion of these trade-offs.

With respect to the Fraser sockeye fishery more specifically, my analysis suggests that the current harvest rule being applied may not be the most suitable, whether the baseline or modified productivity regimes applied here are more appropriate. This suggests that modifications in the harvest rule may be called for. As noted, there are some drawbacks in the current analysis that may call into question the precise quantitative predictions made here. However, the findings make a case for reassessing the current harvest rule and considering whether something closer to the alternative harvest rules described in the prospective analyses may be suitable. More generally, my findings suggest that further economic analysis would be justified in examining the trade-offs among objectives, and may help to find strategies that might improve outcomes in terms of both economic benefits and conservation.

The report of the Cohen Commission was released to the public on October 31, 2012. It found no definitive cause behind declines of Fraser sockeye productivity, but made a number of recommendations, including some concerning a research program to examine the cumulative effects of multiple stressors on the stocks (Cohen, 2012). Of more direct interest in the context of this dissertation, the Commission recommended that DFO complete a "...socio-economic framework for decision making in the integrated strategic planning process...," and "...integrate meaningful socio-economic input into fisheries management decision making, beginning with planning for the 2014 fishing season." As the Canadian government and DFO consider how to address and implement these and other recommendations, they would do well to consider how economic considerations can be incorporated more fully into the analytical approaches to the Fraser sockeye fishery. There are many similarities between the work described in this dissertation and the FRSSI process undertaken by DFO over the last decade (Cass et al., 2004; Pestal et al., 2008, 2011). The FRSSI model addresses many of the issues addressed here – uncertainty about stock dynamics, trade-offs between objectives, etc. – but takes a much more comprehensive approach to many other issues. These issues include: a Bayesian estimation of stock recruitment parameters and incorporation of the resulting estimates of uncertainty into a decision analysis framework; and an ability to simulate depensatory mortality of stocks, where productivity declines at low abundance; and many others. However, as noted previously, the FRSSI model does not incorporate economic considerations, other than attempting to avoid years with low commercial harvest. More explicit incorporation of economic analysis and objectives into the FRSSI model, whether using a model similar to the one developed here or a more sophisticated approach, would undoubtedly yield additional insights from an already well-established process and model for addressing the issues raised in this dissertation.

Fraser River sockeye salmon and the fisheries that harvest them will always remain highly variable and complex systems about which we will never know as much as we would like. Quantitative, probabilistic modelling can and has helped in designing management strategies that are as robust as possible to this variability, complexity and uncertainty. This dissertation has shown that economic analysis has an important contribution to make as this process continues to develop and unfold.

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Appendix A: Methodological Details

Derivation of variable cost of fishing in Chapter 3

Labour Cost

I took the wage rate that a fisherman could reasonably expect to make if s/he were not fishing for sockeye salmon as the social opportunity cost of labour for that fisherman. Since the sockeye fishery is a small portion of the total fishery, I assumed that people fishing sockeye would be able to fish other species and/or work in other resource industries if they were not fishing sockeye, i.e., the other industries would be able to absorb the labour from the sockeye fishery with little change on wages. I obtained wage data from two sources:

- 1950-1984: The Government of Canada (1986) published annual data from income tax returns showing the total number of fishermen in British Columbia, and their total income. Dividing the latter number by the former gives the average annual income of fishermen in BC.
- 1986-2002: Statistics Canada's CANSIM II database (2006) includes a table (number 202-0107; obtained from the Survey of Labour and Income Dynamics) of earnings of individuals, with a series (number V25718758) for "British Columbia; forestry; fishing, mining; oil and

gas; average earnings." While these data were not specifically for fisheries, they (1) gave a reasonable indication of earnings in resource industries in general, and (2) matched quite closely with the trend seen in the fisheries data from before 1985.

- To obtain a value for the single missing year (1985) I took the average of the three preceding and three following years.

From these overall average earnings I also needed to estimate the greater earnings of skippers as compared to deckhands. Canada's census data from 1980, 1985 and 1990 give average annual earnings for each of these two groups. I took the average earnings (in real dollars) for each group over the three census years ($45,249 for captains, $27,497 for deckhands), and calculated the ratio between this value and the average from the above data sets of overall average earnings over the period 1976-1994 (overall average $40,029). The ratio is therefore 1.13 for captains and 0.687 for deckhands. For each year during 1950-2002, I then multiplied the overall average wage by the appropriate ratio to estimate annual earnings for captains and deckhands. I divided these annual average wages by 260 to obtain a rough daily wage.

The crew size (captain plus deckhands) on salmon boats during different periods was obtained from a variety of economic studies of the BC fishing fleet (Buchanan and Campbell, 1957; Gislason, 1997; Campbell and Young, 1962, 1966; Campbell, 1969b; Hsu, 1974). In years for which I lacked data, I (1) interpolated along a straight line between the nearest data points, (2) extrapolated along a flat line for 1950-51, and (3) extrapolated along a linear regression conducted on 1976-1995 data to obtain estimates for 1996-2002. The resulting estimated crew size for each fleet was then multiplied by the appropriate wage rates to estimate the labour cost per vessel-day.

Other variable costs

The other variable cost data required were those associated with operating the vessel for sockeye fishing, not those that would be incurred for fishing other species. I had three sources of raw data for this purpose.

- 1953, 1954: Buchanan and Campbell (1957) estimated, based on surveys of four types of fishermen (gillnetters, trollers, seine captains and seine assistants), an accounting of **average operating expenses**. Of the items that they listed as operating expenses, I included the following in my estimate of variable cost of fishing: fuel and oil; bait and ice; and rentals. Items not included, i.e., those that I considered fixed with respect to the amount of fishing effort directed at sockeye, were: gear material and repairs; gillnet purchases; hull painting and repairs; engine and equipment repairs; fish clothes; wages paid; taxes, license fees, etc; insurance; interest; and other. These data are provided along with the **average number of days afloat** for fishermen of that type, allowing me to calculate the **variable cost per fisherman-day**. Data on gillnetters and trollers describe costs for the vessel as a whole (since during this period these fishermen did not typically hire an assistant), but seiner costs are distributed between captains and assistants. I took the average number of seine assistants per vessel to be five, as given in several subsequent reports (Buchanan and Campbell, 1957; Campbell and Young, 1962, 1966; Campbell, 1969b). I multiplied these average crew sizes by the cost per crew member, and added the result to the captain's costs, giving the (non-labour) variable cost per vessel-day for seiners for 1953 and 1954.

- 1968: Campbell (1969a) provided data on costs for each fleet. I included the following in my calculation of variable cost: fuel and lubrication; and ice and bait. I excluded: hull and engine maintenance; other maintenance; insurance; wharfage and slip charges; food; hull, engine and electronic equipment; gear; marine insurance; and wages. For each fleet Campbell (1969a) estimated these **costs for typical vessels of three different sizes**, with different levels of gross income; I used the cost values given for the size/income level closest to the average observed in that fleet, as given by Campbell (1969a). From the same report I had the **total number of days fishing** or number of deliveries of fish to processors (the latter being a reasonably close proxy for days fishing), and the **number of vessels in each fleet**, which allowed me to calculate the average number of days fishing for each vessel. This then allows calculation of variable cost per vessel-day.

- 1976-1995: Gislason (1997) estimated variable costs over a 20-year period based on several economic surveys conducted on the BC salmon fleet. His variable cost data include estimates of fuel and "food and other" costs, of which I used only fuel. Gislason's effort data are in weeks fished, so I obtained days fishing or deliveries of fish from government fisheries statistics for the same period DFO (1995b). Gislason included the total number of vessels in the fleet in his report. This combination of data allowed me to calculate variable costs per vessel-day.

The data as described above were then compiled and converted to real 2000 dollar values. The real variable cost per day for each fleet showed a reasonably smooth trend over the 53-year time period, tending toward an exponential relationship. This is consistent with the trend in the fishery toward larger, more powerful vessels, which cost more to run.

I ran regressions of these variable cost values versus the year, and used the value predicted by the regression as the non-labour variable cost per vessel-day for the simulations, even in years for which I had raw data from the sources listed above. I took this approach because I considered the scatter around the exponential relationship to be more attributable to data quality than to true variation in operating costs.

The total of labour cost and other variable cost per vessel-day was then taken to be the total variable cost per vessel-day of fishing, $c_{f,t}$.

Appendix B: Detailed Results

The tables in this Appendix give numerical details on the results obtained in some of the simulations in Chapters 4 and 5.

Table A.1: Economic and conservation outcomes from simulations of selected harvest rules in Chapter 4. The baseline rule and alternative rules are as discussed in sections 4.4 and 4.5, and defined in the legend of Figure 4.16; alternative rule 1 has ER floor = 0.4, while alternative rule 2 has ER floor = 0.6. In Figure 5.21, alternative rule 1 is referred to as "rule B."

Outcome	**Baseline rule**	**Alt. rule 1**	**Alt. rule 2**
Mean profit (million CAD)	9.24	17.09	19.81
SD of profit	11.07	9.15	10.37
Aggregate cons. risk	1.108	1.115	1.352
Mean conservation risk by stock			
Early Stuart	0.023	0.072	0.173
Bowron	0.211	0.230	0.358
Fennell	0.039	0.043	0.063
Gates	0.072	0.117	0.127
Nadina	0.010	0.019	0.096
Pitt	0.008	0.017	0.062
Raft	0	0	0.007
Scotch	0.060	0.085	0.122
Seymour	0.118	0.095	0.183
Chilko	0.007	0.005	0.008
Late Stuart	0.273	0.256	0.303
Quesnel	0.047	0.024	0.024
Stellako	0.003	0.018	0.015
Cultus	0.964	0.966	0.984
Harrison	0.082	0.126	0.174
Late Shuswap	0.159	0.086	0.126
Portage	0.020	0.025	0.028
Weaver	0.017	0.035	0.040
Birkenhead	0.021	0.032	0.065

Table A.2: Economic and conservation outcomes from simulations of selected harvest rules in Chapter 5. The baseline rule and alternative rules are as discussed in sections 5.3 and 5.4, and defined in the legend of Figure 5.17; alternative rule 3 has ER floor = 0.1, while alternative rule 4 has ER floor = 0.3. In Figure 5.21, alternative rule 3 is referred to as "rule C."

Outcome	**Baseline rule**	**Alt. rule 3**	**Alt. rule 4**
Mean profit (million CAD)	6.37	10.31	11.53
SD of profit	4.95	6.22	6.75
Aggregate cons. risk	2.557	2.223	2.582
Mean conservation risk by stock			
Early Stuart	0.047	0.041	0.077
Bowron	0.965	0.824	0.899
Fennell	0.102	0.135	0.126
Gates	0.072	0.085	0.090
Nadina	0.675	0.489	0.596
Pitt	0.005	0.005	0.008
Raft	0	0	0
Scotch	0.055	0.034	0.033
Seymour	0.118	0.076	0.089
Chilko	0.052	0.176	0.184
Late Stuart	0.455	0.548	0.557
Quesnel	0.043	0.019	0.020
Stellako	0.005	0.014	0.013
Cultus	0.923	0.926	0.950
Harrison	0.072	0.079	0.102
Late Shuswap	0.151	0.100	0.143
Portage	0.018	0.029	0.025
Weaver	0.087	0.125	0.158
Birkenhead	0.192	0.226	0.277