CONSISTENT HARVESTING STRATEGY IN SALMON AQUACULTURE

by

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Abstract

The goal of this study was to design a consistent harvest strategy using various types of salmon smolts differentiated by species, weight and timing of introduction into seawater. Consistent harvesting is a production strategy leading to the continuous harvest of fresh salmon at a predictable size 52 weeks of the year. The economic and production characteristics of six chinook salmon (*Oncorhynchus tschawytscha*) and six Atlantic salmon (*Salmo salar*) cohorts were first analyzed to establish the economic and production factors leading to their respective optimal harvest time and to compare the performance of each cohort. The study was developed with reference to the British Columbia salmon farming industry.

To achieve these objectives, a discrete and deterministic bioeconomic model was developed following the theoretical framework proposed by Bjorndal (1988, 1990). A series of sub-models were incorporated to simulate three major components of the biological system. First, fish growth was simulated using a modified Iwama-Tautz growth model to which was added a dampening factor to embody a size/growth relationship. Second, feed requirements was computed using a bioenergetic feeding model based on a formulation empirically derived by Cho (1992) and the work published by Maroni *et al* (1994) on differential feed conversion efficiencies. Finally, two mortality rate scenarios were specified on the basis of the underlying causes of mortality and the effect of sexual maturation on fish quality and survival. In scenario 1, a fixed mortality rate was relaxed by the convergence of two conditions beyond which the mortality rate began to increase. These conditions were specified as a lower fish weight threshold and a spring to fall timeframe during the year. In scenario 2, the mortality rate was assumed fixed through the production cycle.

The results showed that most fish cohort had a comparative advantage in terms of maximizing returns over a specific market window during the year. The major factors determining the comparative advantage of each cohort were life expectancy and growth performance in relation to water temperature. As a result, the optimal harvest timeframe for a cohort selected within a production portfolio could differ from its own optimal harvest time as a single production unit.

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1. Introduction and problem statement

1.1 Problem statement

For most agricultural livestock production, the delivery of live animals to market on a year-round basis is not only an accepted reality, it is expected by the market. As a result, producers and processors routinely engage in contractual agreements to ensure continuous supply and to minimize price uncertainties. At the production level, it is economically efficient to rear livestock to meet these year-round market expectations because producers benefit from well established species that have a long history of domestication, as well as, from the support of evolving new technologies and husbandry practices. However, most species of finfish bred for intensive food production have only been recently domesticated. Producers in salmon aquaculture have been confined to a traditional cycle of production as dictated by the biology of salmon, which is similar to that of their wild cousins. Recent advancements in rearing practices make it possible to obtain a marketable size salmon outside the traditional harvest period. Still, the delivery of fresh fish to the market place at certain times of the year is complicated by biological factors, which have significant economic implications. The demand for a consistent supply of fresh salmon is increasing and this poses a bio-economic challenge for salmon aquaculture.

Consistent harvesting is defined as a production strategy leading to the continuous harvest of a uniform sized product throughout the year (Hatch and Hanson 1995). In salmon aquaculture, this strategy reflects a desire to supply the market with fresh fish of a predictable size continuously throughout the year. This approach can be viewed as a marketing effort to differentiate cultured salmon from wild caught salmon by removing supply uncertainties.

At the production level, consistent harvesting involves the continual availability of live salmon of a targeted size. The production objective is to rear a cohort of fish to the desired harvest weight just as the harvest of another cohort of fish is completed. One way of achieving sequential harvest of uniform size fish is to control the weight and the time at which salmon smolts are introduced into seawater.

In the course of production, however, an important factor affecting fish growth is water temperature (Stauffer 1973; Brett 1979). Typically, the growth rate is lowest in the cold water of winter and highest in the warmer water of summer. Salmon smolts of the same species and of equal size but introduced to seawater at different times of the year are likely to reach a harvestable weight at different ages. In general, the economic and biological optimal harvest times can be expected to vary as a function of seawater entry weight and time.

The main purpose of this study is, first, to determine the relative economic merits of standard smolt entry types in the production of chinook salmon and Atlantic salmon in British Columbia, Canada. Based on the optimal harvesting principles presented in Bjorndal (1988, 1990), the economic characteristics of each smolt entry type at optimal harvest time can be compared in terms of their economic benefits and in terms their respective position in time. Second, the results derived from this analysis will be used to establish a set of qualitative principles for designing a consistent harvest strategy. The focus of the analysis is on the seawater production activities.

1.2 Salmon smolt characteristics and production strategies

Recent innovations in salmon aquaculture make it possible to introduce larger smolts throughout the year and to raise stocks to market size in a shorter period of time. This technological shift enables producers to design a more flexible production strategy to meet their marketing objectives. In particular, there are benefits for producers positioned to supply the market with a fresh and consistent product on a year-round basis. The intense competition prevailing in the world market for salmon means that marketing objectives must be balanced against the cost of producing salmon in an intensive system of production. Consequently, the relative economic merit of each smolt introduction strategy is an essential element of the decision making process associated with production planning. The economic characteristics of a given smolt type compare to an alternative may yield lower rents in absolute terms, regardless of the time at which optimal rent is achieved. If time is considered, the same smolt type may yield superior rents during part of the year, thus providing a relative advantage over the alternative. Based on the principles of optimal harvesting theory, the present study proposes a discrete economic model to analyze production resulting from variations in the characteristics of salmon smolts at seawater entry. Results derived from the analysis can then be incorporated into a consistent harvest strategy so as to establish a market presence throughout the year. The analysis is developed with reference to the salmon farming industry in British Columbia, Canada.

Both chinook salmon (*Oncorhynchus tschawytscha*) and Atlantic salmon (*Salmo salar*) are farmed in British Columbia. Salmon are an anadromous species spending part of their life in fresh water and part in saltwater. In aquaculture, the fresh water phase is replicated in hatcheries where salmon eggs are incubated until hatching and the newly hatched fry are raised until they reach the smoltification stage. This stage is marked by a physiological transformation that enables the juvenile salmon to survive the transition into salt water. At first, Atlantic salmon typically had a longer fresh water phase than farmed Pacific strains. With improved rearing practices, the fresh water phase for chinook salmon is now usually extended and is comparable to the Atlantic salmon fresh water phase.

For both species, a better understanding of the smolting process allows for the production of bigger smolts almost year-round. The introduction of larger smolts although more costly, reduces the time required for the fish to reach market size and reduces the risk associated with mortality. Moreover, the ability to manipulate the seawater entry time provides the producer with better control over the time at which a salmon stock reaches a harvestable size. Flexible availability of smolts opens the doorway for strategically planning production as a function of market requirements and marketing objectives.

In contrast to the benefits associated with the introduction of older and bigger smolts, the first chinook smolts used in intensive aquaculture were known as S0 ("S Zeros") and were typically very small when they were delivered to seawater sites each spring. A significantly longer production cycle was required for such fish stocks to reach market weight. Further, because of the homogeneous characteristics in the delivered smolts, all the fish stocks reached market size at a similar time. It was also common for producers to encounter periodic cash flow problems forcing them to harvest stocks sub-optimally. At the industry level, the supply of farmed salmon from British Columbia was often characterized by seasonal gluts of similar sized fish, thereby exacerbating price instability in an already very competitive market. The growth characteristics and constraints of relying on chinook S0 made it difficult to adopt means of production that spread the risks associated with uncertain market prices.

One attractive feature associated with continuous harvesting is the capacity of the fish farmer to remove the uncertainty in supply that typifies commercial salmon fisheries and at first characterized salmon aquaculture. By altering management routines to favour year-round availability of fish, producers have been more successful in generating interest in their product from retailers and restauranteurs (Shepherd and Bromage 1988). At first, harvesting was seasonal and mainly occurred during the winter and early spring months. Customers relied on wild fisheries in season to meet their needs. Recently, the improved availability and predictability of supply has resulted in many buyers becoming year-round customers of farmed salmon. Farmed salmon is also favoured in the market place because of its consistent high quality and freshness (ARA Consulting Group Inc 1994). Together, these elements are required if producers are to enter contractual agreements and plan future sales.

British Columbia producers are at a comparative advantage relative to other producing regions such as Chile and New Zealand because of their close proximity to major markets in the United States. Fresh salmon can be delivered to most markets within 48 hours of harvest. Chilean producers, however, realize substantial savings in labour and feed costs relative to Canadian producers (Anon. 1992; Ridler 1992). While lower transportation costs in British Columbia act as a buffer against higher production costs, this advantage is diminished when competitors market value-added[1] or frozen farmed salmon. To remain

[1] Value-added products include additional processing such as filleting and other consumer ready portions.

competitive, local producers must seek the most economically efficient production strategy within the framework of their marketing objectives.

1.3 Thesis structure

Optimal and consistent harvesting analysis relies on the development of a deterministic bioeconomic model for salmon aquaculture. Developed in a discrete time frame, the model draws from the general bioeconomic principals derived and presented by Bjorndal (1988, 1990). The bioeconomic system itself is composed of sub-models to describe fish growth, water temperature, feed requirements and population dynamics. The model is then applied to twelve smolt stocking strategies to estimate their economic characteristics.

The study begins with a description of the activities integrated in the bioeconomic function and is followed with the model formalization. The production activities related to the grow-out of salmon aquaculture are reviewed in Chapter 2. This includes a description of inputs from hatcheries as well as processing and selling activities. This section also discusses the market price structure for farmed salmon. The bioeconomic model is presented in Chapter 3. This section begins with a review of bioeconomic literature. The bioeconomic model is then developed in a continuous time frame and specified in a discrete time frame using a series of sub-models. Chapter 4 focuses on the calibration and specification of model parameters. This section outlines data sources and discusses the assumptions underlying the analysis. Optimal harvesting and consistent harvesting results are presented and discussed in Chapter 5. Chapter 6 concludes the study with a discussion of the implications of the results.

2 Production phases in salmon farming

This section provides a brief overview of the activities integrated to salmon aquaculture. First, the discussion introduces the concept of aquaculture in terms of intervention and control that is possible over a system of production. Next, the various phases during the production process for intensive salmon aquaculture are presented and individually reviewed. In the section dealing with the fresh water rearing of smolts in hatcheries, the nomenclature and characteristics attributed to the production of different smolt type are presented. In the saltwater grow-out section, the production cycle strategies derived from the use of specific smolt types are presented in the context of consistent harvesting. Chapter 2 closes with a brief discussion of market prices.

2.1 Definition of salmon aquaculture

Aquaculture is defined as the cultivation of aquatic organisms. It is differentiated from other aquatic production by the level of human intervention and control that is possible. Aquacultural systems can be classified according to the level of intensification adopted (Shepherd and Bromage 1988; Pillay 1997). These systems are generally classified as extensive, semi-intensive and intensive depending upon factors such as stocking density, yield per surface area, feeding regimes and input costs.

Extensive systems of aquaculture yield lower rates of production (Pillay 1997). The release from hatcheries of fry fingerling into the wild for salmon enhancement programs (also referred as aquaculture-based fisheries) or for salmon ranching are examples of low intensity or very extensive systems of production. In both cases, fingerlings are released into a river and left to feed on natural food in the ocean. The key issue differentiating these two systems is fish ownership. Stock enhancement programs are a public good whose purpose is to restore declining stocks or to introduce a valuable species. This description includes salmon enhancement in British Columbia by federally sponsored fish hatcheries.

Enhancement efforts in British Columbia are an important resource management activity contributing to commercial and recreational fisheries. Ocean ranchers, as practiced in Alaska, have property rights specifically protected during the inland water migration phase of anadromous species (Pillay 1997). Upon returning to the river to spawn, most fish are recaptured and harvested, while some are let through for reproduction. Apart from increasing smolt survival rate, ocean ranching and stock enhancement programs are indistinguishable from the natural level of fish productivity in the wild (Shepherd and Bromage 1988) since control over growth and survival is not possible.

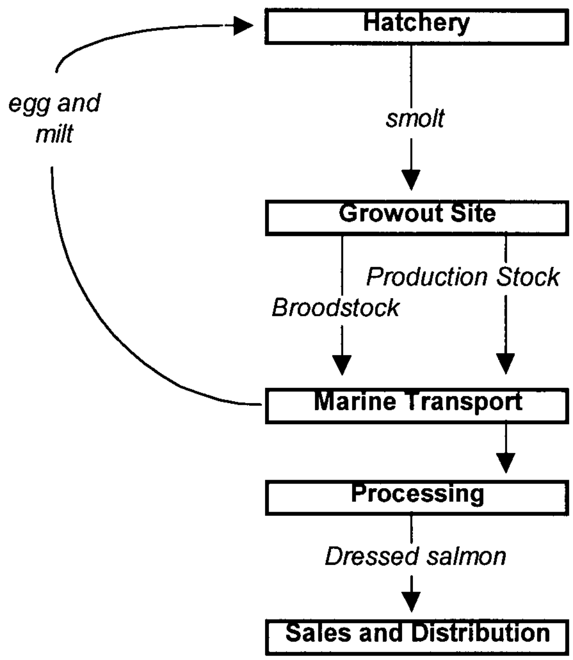
In Japan, a marginally more intensive production system is practiced in corded off coastal lagoons. Fry are released and left to grow to market size by feeding on the natural supply of food present in the lagoon. The lagoon is controlled as a fishing zone and managed by removing predators, thereby improving survival rates during the grow-out period.

Salmon farming as practiced in British Columbia is a very intensive system of production. In this case, fish are reared in net pens and cared for during their entire life at sea. During that time, the producer has control over daily feed intake and harvesting. Intervention is necessary to control health related problems, to minimize predation and to maintain stocking density within an optimal range.

The production cycle in intensive salmon farming is closed. It involves raising fish from the egg stage to a marketable size ranging from one to seven kilograms. Salmon farming operations usually retain ownership of the fish until they are sold to food service operations. The production cycle is composed of several distinct and integrated phases. Figure 1 shows the regular flow of activities.

The focus of this study centers on the grow-out activities. The other phases of production can be viewed as inputs to the grow-out process. These activities and their relationships are described next.

Figure 1 Phases in the salmon farming production process.



2.2 Fresh water rearing of smolts in hatcheries

Salmon are an anadromous species. After spending most of their life at sea, these fish migrate back to fresh water to spawn. Their offspring will hatch and spend the early part of their life in fresh water before migrating to the sea as salmon smolts. After hatching the alevin feeds from the yolk-sac protruding from its belly. Once the yolk-sac is completely absorbed (the alevin is said to 'button up' at that stage), the alevin becomes a fry and must than seek its nourishment to survive. In the wild, chinook fry remain in fresh water from 3 months to 1 year (Childerhose and Trim 1983) while most Atlantic fry spend 1 to 3 years in fresh water (Sedgwick 1982). In the later stage of fresh water development the fry becomes known as a parr when distinctive vertical markings appear on its flanks (Shepherd and Bromage 1988). The parr salmon eventually transforms into a smolt when it is physiologically ready to move from fresh water to saltwater. Commercial hatcheries specialize in replicating the fresh water phase of the salmon life cycle. For intensive salmon aquaculture, the fresh water phase typically lasts anywhere from six months to two years.

Broodstock fish are raised at grow-out sites and selected for reproduction on the basis of their genetic traits. Eggs are stripped from healthy females and mixed with male milt. The fertilized eggs are placed in trays and incubated in a carefully controlled environment. Water temperature is the main element regulating embryo development. At approximately 460 ATUs[2] after fertilization, the alevins emerge and remain in the trays for first feeding and until their yolk sac is absorbed (buttons up). The salmon fry actively feed on commercial diet and are then moved into tanks, pools or raceways to grow.

The transformation of the parr into smolts marks the time at which the juvenile salmon is physiologically ready to be transferred to saltwater. It involves marked changes in the behaviour, body shape, colour and the development of tolerance to seawater. The smoltification process[3] is the metamorphosis of osmotic regulators that enable fish to retain water and excrete salt so as to maintain their hypertonic[4] balance in a saltwater environment. The most visible change is the appearance of a silvery coating of guanin that is laid down in the skin. This crystalline deposit acts as a barrier to osmotic exchange and prevents the loss of water through the skin.

The onset of the smoltification process is a function of changes in photoperiod and temperature regimes. This process can be delayed through photoperiod manipulation by covering the fish tank with a black tarp and providing adjusted artificial light using an electronic timer.

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[2] ATUs are accumulated thermal units and equal the sum of daily temperature in degrees Celsius.

[3] Smoltification process reverses the osmotic regulation in anadromous or catadromous bony fishes. Freshwater fish maintains osmotic and ionic balance in its dilate environment by actively absorbing sodium chloride across the gills (some salt enter s with food). To flush out excess water that constantly enters the body, glomerular kidney produces a dilute urine by reabsorbing sodium chloride. Marine fish must drink seawater to replace water lost osmotically to its salty environment. Sodium chloride and wter are absorbed from the stomach. Excess sodium chloride is secreted outward by the gills. Divalent sea salts, mostly magnesium sulfate, are eliminated with feces and secreted by tubular kidneys (Hickman, Cleveland P *et al.* 1984).

[4] Hypertonic: Solution of higher osmotic pressure than another solution with which it is compared (Webster's)

There are three levels of control used in the hatchery to produce particular smolt types. These controls are water temperature, photoperiod and time. Water temperature is the most important input regulating growth rate. Hatcheries with various sources of fresh water have access to different temperature profiles. These sources of water include wells, rivers and lakes in which water can be extracted from various depths. Fingerlings grown under 'normal' temperature regimes are defined as 'regular track' or traditional smolts. 'Fast track'[5] smolts are fish raised to a bigger size within the same time frame by imposing a higher temperature regime. Conversely, 'slow track' smolts are the result of maintaining a lower than normal temperature regime to obtain smaller fish.

Photoperiod manipulation is used at the hatchery to prevent salmon parr from undergoing the smoltification process. The objective in this procedure is the production of larger smolts and/or the production of smolts at a specific time of the year. Photoperiod manipulation essentially tricks the fish into believing that it is to early to migrate to seawater.

The time required to produce a salmon smolt after hatching determines the smolt type as a function of time. The nomenclature describing smolt types is based on the rounded age of the fingerling. Smolts produced six months and a year after hatching are known as 'S0' (S-Zero) and S1 (S-One) smolts, respectively. For intermediate strategies, smolts raised seven and ten months post-hatching are referred as S1/4 (S-Quarter) and S1/2 (S-Half) respectively. Production of S1 1/2 (S- one and a half, eighteen months in fresh water) and S2 (S-Two, two years in fresh water) are also possible but not common in British Columbia because of the costs involved.

With improving rearing practices in the hatchery, smolt characteristics can be increasingly tailored to meet grow-out needs. Given some level of control over water temperature and photoperiod, hatchery operators have some flexibility for producing smolts of a desired size at a specific time of the year. Table 1 summarizes fresh water development time in the hatchery associated with the common types of smolt

5 At the grow-out level of production, the term fast-track as a different meaning as it refers the pre-grilse harvesting of early maturing Atlantic salmon.

production.

Table 1 Length of fresh water phase in hatchery for selected smolt types

Smolt Type	Fresh water Phase *Months*
S0	6
S1/4	7-8
S1/2	9-11
S1	12
S11/2	18
S2	24

Table 2 summarizes the characteristics of some standard smolt types available for establishing a grow-out production strategy using multiple smolt entries. Several other combinations of smolt size and entry date that exist. In particular, it is possible to obtain larger smolts for both species. Producers commonly use the smolt types selected for this study.

There is often a non-linearity between the time required to produce a smolt and the size of that smolt. The relationship between the production time in fresh water and smolt size is a function of species, strain, genetics, production conditions and grading. For instance, the best performing individuals within a population may be graded and slated through a fast-track program for early delivery to the grow-out site as a S1/2 smolt. A traditional program may be applied in turn to the smaller individuals of that same population for the production of S1 smolts. These late delivery fish will sometimes transform into smolts of a similar size or even smaller than their S1/2 counterparts. Such an occurrence is presented in Table 2 with the Atlantic salmon cohorts 4 and 6.

Table 2 Smolt type commonly produced in British Columbia hatcheries

Cohort	Species	Smolt	Entry Date	Entry Weight *grams*
1	Atlantic salmon	S1/2	01-Oct-94	50
2		S1/2	15-Dec-94	90
3		S1	20-Jan-95	90
4		S1	01-Feb-95	50
5		S1	15-Feb-95	100
6		S1	15-Mar-95	45
7	Chinook salmon	S0	01-Jun-94	7
8		S1/4	01-Aug-94	40
9		S1/2	15-Sep-94	35
10		S1/2	01-Nov-94	50
11		S1	15-Jan-95	55
12		S1	01-Mar-95	55

Sources: Cooperative Assessment of Salmonid Health
Personal Communication

Smolts are delivered to grow-out sites using helicopters or terrestrial and marine vehicles. Grow-out producers typically pay per unit of smolt surviving transport and saltwater introduction. The unit cost of smolts depends mostly on the species and the time required for producing the fingerling.

2.3 Saltwater grow-out

Smolts are introduced to sea water and reared in net pens. The grow-out phase is analyzed with smolts considered as an input to the production process. The grow-out production system can be viewed in terms of the interaction between the cultural environment and technological and biological factors.

The cultural environment refers to the physical and environmental characteristics of the site location. The location attributes with greatest influence on production are seabed topography, flushing action, water temperature, photoperiod, salinity, organic material and protection from waves and wind. These attributes are exogenous to the production process, as only limited control can be exercised over them.

The technological factors of production include the cage systems, the equipment used to perform various tasks and the feed delivery systems. The cage system consists of galvanized steel floaters to which the net pens are attached. These floaters are sometimes individually anchored (circles) or organized into an anchored platform complete with walkways between pens. The physical characteristics of these systems permit their easy transport to a different location. Float houses and storage facilities are usually attached to a cage system. Platform systems are in general better suited for the use of labour-saving equipment for sampling, feeding, net cleaning and harvesting.

Feed delivery systems refer to the method by which feed is provided. The methods range from hand feeding to automatic feeders and data-controlled feeders operated from self-contained floating tanks.

The biological factors in the grow-out phase start with the choice of species and smolt type. Both chinook salmon and Atlantic salmon are farmed in British Columbia. Atlantic salmon is the predominant species produced. Several strains of Atlantic salmon have been imported through various routes from Norway, Scotland, Ireland, Eastern Canada and the United States. This species is more docile than Pacific salmon and can be reared at higher stocking densities, thereby reducing capital costs for net pens and equipment. It is also reputed for its relatively superior growth rate in colder temperatures and its resilience to disease and injuries in saltwater, which lead to higher survival rates. However, they are more difficult to rear in the hatchery and more vulnerable to algae blooms. Atlantic smolts introduced to seawater in British Columbia are typically of the S1/2 and S1 varieties. They are better suited to colder waters.

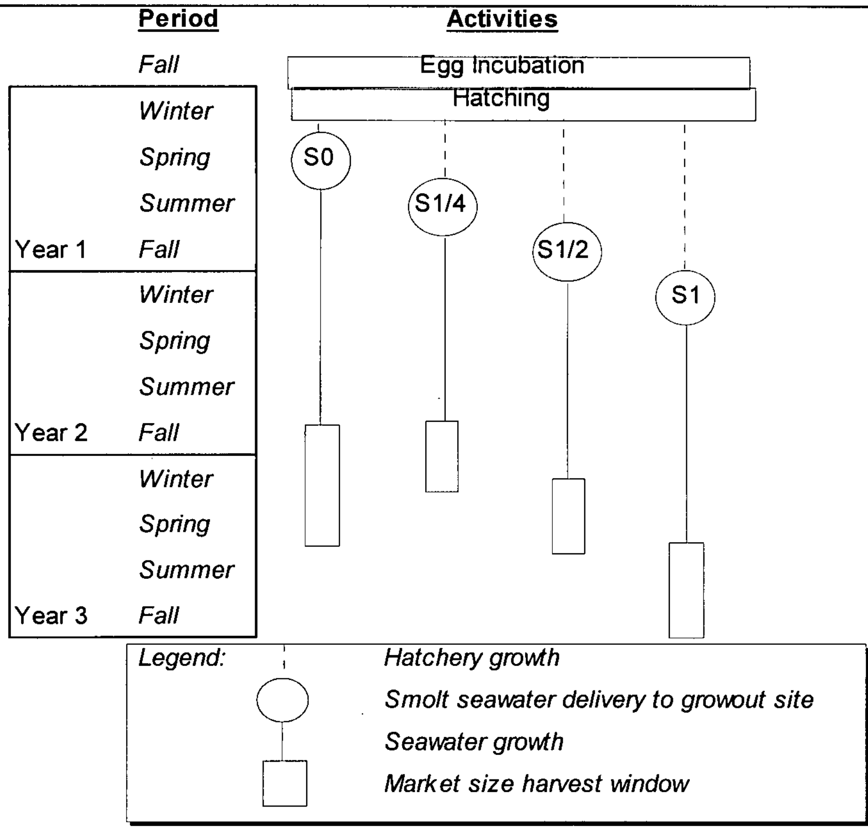
The predominant experience with chinook salmon has been using the S0 variety. S0 smolts are typically introduced to seawater as seven grams fingerlings, five to seven months after hatching. These smolts are much cheaper to produce than S1/2 and S1 smolts but take longer to reach market size. Further, considerable losses are usually incurred during the first months at sea and they often remain vulnerable to disease throughout the production period. S1/2 and S1 chinook salmon, also known as yearling chinook, are more comparable to their Atlantic salmon counterparts. Their growth rates are comparatively higher than chinook salmon S0 and higher than Atlantic salmon in warmer water, but lower in colder water. Atlantic salmon still tend to have higher survival rates, particularly in the later stages of production.

There are two important benefits to the introduction of yearling chinook salmon and Atlantic salmon. First, a harvestable size fish can be raised in twelve to eighteen months in seawater. Second, by varying smolt entry times, it is becoming possible to carry out a year-round harvest of a consistent size fish. Figure 2 shows graphically how the timing of smolt entry enables continuous harvesting. Regardless of the species, this figure demonstrates that the choice of appropriate smolt types in production planning enables continuous harvesting. The question of whether such strategies are economically efficient will be addressed later.

In the course of production, the total value of a fish stock will increase with its population biomass. Starting from the input of smolts, the population yield increases as a result of growth and decreases as a result of mortality. Growth is achieved by providing commercial feed formulated to meet the dietary requirements of the fish. Considerable investments are accrued over the time necessary to reach a harvestable size. It follows that the optimal harvesting time is important.

Salmon stocks need to be continuously monitored throughout production as a means of disease control. There are two particularly critical periods. The first is when the smolts are placed in saltwater and the second is prior to sexual maturation. At maturation, the Pacific salmon dies, while the quality of Atlantic salmon is reduced so drastically that it is unfit for consumption. It is therefore critical to plan harvesting prior to maturation.

Figure 2 Grow-out production cycle strategies available within a generation class in British Columbia.



Salmon farming is labour intensive. Throughout production, the fish demand constant care. The average farm in British Columbia produces between 200 to 300 tonnes of dressed salmon per year and employs five or six full-year equivalent persons (ARA Consulting Group Inc. 1994). Fish stocks are fed at least once per day, using hand feeding or automated feeding methods. To reduce feed waste, feed recovery systems (feedback) are installed in the pens to signal when the fish have stop feeding. Other activities performed by farm labour or contractors include collecting dead fish (morts), making net check dives, changing nets, sampling, grading, harvesting, collecting data and maintenance. Specialized suppliers are often contracted to provide services related to fish health and diagnostics, net washing and marine transport.

2.4 Harvest and marine transport

The main tasks performed by marine transport operations are feed delivery and transport of the harvested fish from the farm site to the processing plant. Fish are harvested using a seine net or a pump. They are stunned and bled on site and placed in iced totes, or transported live to the processing plant in a specially designed haul boat. Harvest usually occurs at night and the fish is brought to the plant for processing by morning. This system enables the fish to be trucked to market the same day.

2.5 Processing

The processing phase includes the gutting, grading and boxing of salmon. It may also be extended to include items such as steaks, fillets and other forms of "value-added" products. The various types of processed products are classified in Table 3. Farmed salmon in British Columbia is predominantly sold fresh as a primary product in the dressed head-on form (ARA Consulting Group 1994). Although most value-added activities occur at wholesale centres, processors are increasingly getting involved with custom processing in the secondary and tertiary product sectors.

Table 3 Value-added processing matrix for finfish.

Raw Material	Primary Products	Secondary Products	Tertiary Products	Finished Products
Round Fish	Dressed head-on	Skin-on sides	Portion fillets	Fillet entrees
	Dressed head-off	Skin-off sides	Skinless fish blocks	Marinated fillets
	Roe	Steaks	Minced fish	Breaded fillets
	Sperm	Canned	Fish Flakes	Breaded nuggets
	Viscera	Fish meal	Smoked fish	Chowder, soup, stew
	Heads	Fish oil		Spreads
		Fish fertilizer		

Source: Fish Food for Thought, Vol.4-1 (1996)

The raw material for processors is the whole non-gutted fish or round fish. The weight of the live salmon is known as the round weight and is usually expressed in grams or kilograms. The dressed head-on primary product is the whole gutted salmon. The weight of the whole gutted salmon is commonly referred to as the dressed weight and, in North America, is expressed in terms of pounds.

Farmed salmon is sold on the market as a fresh product and shipped to buyers in Styrofoam boxes of sixty pounds (27 kg) each. There are two levels of grading, quality and weight class. First, the fish are quality graded according to a set of criteria that includes flesh colour, texture and firmness as well as body shape and condition. The common quality grades are premium, standard and utility. Second, the fish is graded on the basis of its weight. In North America, the standard weight classes are set in increments of two pounds, although broader or odd based weight classes are sometimes agreed upon between producers and buyers. Standard weights for other international sales are usually set in increments of one kilogram.

2.6 Sales and distribution

As products are chiefly exported in fresh forms, efficient systems of distribution are required both in the producing and consuming countries (Bjorndal 1990). This is an issue of particular importance to Canadian producers if they are to benefit from their comparative advantage relating to their close proximity to the United States.

Producers of farmed salmon in British Columbia are geared toward export markets. In 1995, farmed salmon was British Columbia's largest agricultural export totaling $165 millions. Production figures for that year are summarized in Table 4. Exports to the United States and Japan accounted for 85% of the province's total production. The remaining 15% were sold on the domestic market, mostly in British Columbia. In 1992, the Pacific Northwest of the United States (Washington and Oregon) and the state of California were together the most important destinations for farm salmon from British Columbia accounting for 58% of exports to that country (Kenney 1993).

Table 4 British Columbia farmed salmon in 1995: Production and markets.

Market	Tonnes	Share	Value *(Million)*
United States	16,916	76.0%	$ 124
Japan	2,003	9.0%	$ 15
Rest of Canada	1,781	8.0%	$ 14
British Columbia	1,559	7.0%	$ 12
Total Production	22,259		$ 165

Source: BCSFA, 1996

With a market that crosses boundaries, oceans and cultures, farmed salmon is sold through a variety of distribution channels. Selling activities are undertaken using in-house resources, fish brokerage services and merchant exporters. Some of the largest producers have their own sales team with North American coverage (ARA 1994). For producers with a large enough output, this level of vertical integration enables them to capture fees paid to middlemen and transpose these resources toward developing their own marketing strategies. Some operations conduct their own wholesale. Their customer base includes processors, fish brokers, wholesalers, retailers and restauranteurs (Kenny and Thorpe 1991). In addition to marketing their own products, some firms will also in market fish from other producers.

The majority of producers in British Columbia market their fish using third parties and fish clearing houses, most of which are located in Vancouver and Seattle. Many brokerage services also market wild salmon and other seafood products. Fish brokers also resell to processors, wholesalers, retailers and food services. Most oversea exports occur through merchant exporters who then resell to merchant importers or to retailers in the country of destination (Kenny and Thorpe 1991).

The major ports of entries into the United States are Seattle, Los Angeles, Boston and Miami. Most farmed salmon are distributed through out the country from these centres. International sales of farmed salmon from British Columbia are often quoted FOB Seattle. With many Asian fish brokers located in the Seattle area, most exports to Japan are also shipped from that city (ARA 1994).

2.7 Market prices

Market price for farm-raised salmon is a function of size, grade (colour, freshness and condition) and species. The standard size and quality grades were discussed in section 2.5. Most prices are set on the spot market and negotiated daily between sellers and buyers. On occasion, some producers and brokers enter contractual arrangement and plan forward sales. In this type of transaction the seller offers the buyer to remove uncertainty in supply in exchange for stable price levels and an assured outlet for his products over the life of the contract. Such agreements presupposes that the fish product meets the buyer's specification in terms of quality and size characteristics over the life of the agreement

Price monitoring provides market agents with guidelines to evaluate their own performance. It can also be used as a tool for price arbitration between geographical market regions. Urner Barry Publications Inc. provides one of the most reliable and accurate price monitoring services (Kenny and Thorpe 1991). This organization reports prices on a variety of food commodities. They publish a price sheet called "Seafood Price Current" twice a week in which prices are quoted for over 100 species of seafood products sold in the United States. Prices are reported for various regions as sales by first receivers. These are, in effect, the selling prices obtained by brokers or distributors. Quoted prices for farmed salmon from British Columbia are based on the Seattle selling price. This price is quoted in US dollars and incorporates both transport costs from Vancouver to Seattle (Cdn$0.05/lb) and the seller's sales commission (5%-8% of value).

There is a positive relationship between the price and the size of salmon, which implies a significant differentiation of the product (Hochman *et al.* 1990). Certain types of buyers have well defined preferences for a certain size fish. For instance, restaurant chefs may prefer 8-10 pound Atlantic salmon because a single cut of steak is an ideal size for preparing an order. It is also less work to prepare than dealing with an equivalent portion made up of two smaller steaks. Retail stores may prefer smaller sized fish, as these are ideal barbecuing item for an average family of four. Product differentiation is a condition in which similar products are perceived by the consumer to be unique in at least one dimension of the product attribute (Kinnucan and Wessells 1997). Price differential is one basis for distinguishing similar products. The distinction between actual and perceived product attributes emanates from promotions and image-building efforts by the industry. It is ambiguous whether the positive relationship between price and size is a result of promotional efforts by suppliers or is the consequence of practical or cultural preferences demanded by consumers.

A priori, distinctive preferences on the basis of fish size can also be indicative of market segmentation. Market segmentation is a state of demand heterogeneity such that the total market demand can be disaggregated into segments with distinctive demand functions (Kinnucan and Wessells 1997). Some authors have argued that salmon is a heterogeneous product and that demand is a function of attributes such as species, country-of-origin, production method, quality, fresh or frozen, and product availability (Bjorndal 1990). Market segmentation has been clearly diagnosed in comparing two distinctive cultural markets, such as the Japanese and US markets (Wessells and Wilen 1992). In the literature, however, there is no reference to market segmentation resulting from fish size. Because of the traditional seasonality of production, market segmentation is likely blurred by a high degree of substitution between weight classes.

Prices are set on the spot market as negotiated between sellers and buyers. Short-run prices are thus subject to fluctuation, especially arising from seasonal variation in supply. In North America, the peak landing months for wild Pacific salmon is during the summer (June to September). Over that period of time, fresh commercially caught salmon is in abundant supply in the United States. This availability of fresh products typically results in slack market prices. Farmed chinook salmon is particularly vulnerable at this time of the year since it competes undifferentiated with its cheaper and more exotic wild cousin. Farmed salmon traditionally dominates the fresh market from October to May.

3 Model development

This section presents the theoretical framework for the bioeconomic model required for estimating optimal harvest time and planning a consistent harvest strategy. This chapter opens with review of relevant bioeconomic literature dealing with optimal harvest time and consistent harvesting in intensive finfish aquaculture. The bioeconomic model is then presented beginning with the production function and completed with the development of the variable profit function. The development of the production function initially focuses on the theory underlying biomass growth, which is a function of fish growth and population dynamics. Sub-models are then specified for various components of the biological model, including a modified Iwama-Tautz fish growth model, a bioenergetic feeding system and a sine wave temperature model. The rule for optimal harvesting time is derived theoretically using a variable profit function. Finally, the conceptual approach to designing a consistent harvest strategy is presented in the last section of this chapter.

The economic analysis will initially focus on the technical aspect of production. The production function describes the technical relationship between input factors and product output. Its most fundamental element is the biological model describing the dynamic process by which the yield or biomass of a population changes over time as a result of mortality and growth. Two basic economic input factors in yield dynamic are the number of salmon smolt, which establishes the initial population level, and feed, which is the fundamental driving force of the growth process (Stauffer 1973). The production function is then expanded with a feeding system to model the main input factor required for achieving growth. Throughout this section, water temperature is an exogenous input factor regulating growth and feed rate. The bioeconomic model follows with the addition of factor costs and market prices.

Some preliminary definitions are necessary;

1. Each smolt entry group of fish is referred to as a cohort.
2. A group of cohorts of the same post-hatching age and harvested sequentially in a manner so as

to provide continuous harvest coverage for a period of twelve months is referred as a cohort portfolio or a portfolio yearclass.

3.1 Literature review

This section presents a review of the bioeconomic literature dealing with optimal harvest time and consistent harvest strategy in aquaculture. In general, bioeconomic models designed for estimating optimal harvest time seek to maximize profit or minimize cost subject a set biological conditions and production constraints. The objective of consistent harvesting is to maximize profits for each of the 52 weeks of the year or for specific target dates spread out throughout the year. While there is a growing body of literature focusing on optimal harvest time, few references exist on the concept of sustained or consistent harvest strategy. The emphasis of this review is on salmon production. It also includes models designed for other species that have similar attributes to salmon production.

Bioeconomic applications provide tremendous flexibility in simulating a variety of situations and in highlighting potential area of research. In this type of models, technical relationships are clearly defined so that the effect of model parameters on different variables can be isolated (Cacho 1993). Generally speaking, a bioeconomic model is composed of a biological model describing a production system, and an economic model relating the production system to market prices and resource constraints (Cacho 1997). The biological model is usually composed of two essential building blocks, a fish growth expression and a population dynamic model. The economic model includes a revenue function and a cost function.

Bjorndal (1988, 1990) presents a complete treatment of optimal harvest time based on the comparative static analysis of a theoretical bioeconomic model. A simple biological expression is developed using a Beverton-Holt recruitment model to simulate population dynamic, and a generic growth function to define individual fish growth. Next, the economic model is introduced starting with a revenue function in which market price is positively correlated with individual fish weight. The variable cost function includes a discount rate as well as harvest, feed and insurance costs. Using comparative static analysis, Bjorndal than analyzes the effect of each variable cost elements on the optimal harvesting rule. He provides optimal harvesting examples for salmon and turbot, using an empirically fitted third degree polynomial fish growth function. In his examples, feed rate is an exogenous function of growth rate and is estimated using a feed conversion ratio assumption.

Hean (1994) uses Bjorndal's theoretical model to analyze the effect of discount rate, harvest costs, feed costs and stocking density on the optimal number of smolts to stock and on the optimal harvest time. The analysis utilizes an empirically fitted third degree polynomial fish growth function and a feed conversion ratio assumption to estimate feed requirements. She concludes that the discount has little impact on the optimal harvest time and confirmes Bjorndal conclusions concerning the important of feed costs on the results.

Arnason (1992) examines the interdependence of the feeding schedule and harvest time in aquaculture. He extends Bjorndal's analysis to a general dynamic model by endogenizing feed rates and presenting a comparative dynamic analysis. He concludes that given a positive discount rate and that feeding does occur, marginal revenue of feeding must exceed marginal cost except at harvest time. This result is consistent with the fact that feed intake is a necessary condition for growth (Stauffer 1973) and that growth a directly responsible for increasing revenue under fixed market price assumptions. Heaps (1993) extends Arnason's model by including feed rate as a decision variable. In his model, harvest time and harvest weights are independent choices.

Springborn *et al.* (1992) compares organic to inorganic fertilization treatment on the optimum harvest time of cultured Nile tilapia, *Oreochromis niloticus*. The bioeconomic approach in this study is similar to Bjorndal's model. In this study, population dynamic is modeled using a Beverton-Holt recruitment model and growth is model using a Von Bertalanffy equation, in which fish weight increases toward an asymptotic value. One interesting result of this study is that both fish yield and profit are maximized at the same time due low input requirements and minimal fish production cost on a daily basis.

Cacho *et al.* (1990) incorporate a bioenergetic model to a bioeconomic structure to determine the nature of interactions between ration size and dietary protein in the production of channel catfish (*Ictalurus punctatus*). Their analysis shows that both factors exhibit decreasing marginal product, as expected from the law of diminishing return. They use isoquant analysis to estimate the effect of diet quality and quantity given a predetermined harvest weight and crop length.

Cacho *et al.* (1991) further present an optimal control model of fish growth for determining cost-effective feeding regimes and quantifying the interplay between feed allowance, protein intake and harvesting date. The model is developed with reference to pond reared channel catfish and incorporates the effect of water temperature on fish appetite. An economically optimum fish growth trajectory is obtained by controlling feed-intake. Specifically the objective of this study is to determine the trajectory of ration size minimizing the cost of producing a fish to predetermined weight and at specific time.

The objective in the Cacho *et al.* (1991) bioeconomic model for catfish production is to minimize the cost of producing a specific size fish at a specific time. In contrast, the objective in the Bjorndal bioeconomic model is to let the profit maximization solution determine harvest time and harvest size. Models developed for cultured salmon usually assume that the fish is allowed to grow at a maximal rate for given its size and the water temperature, so as to minimize time-to-harvest (McDonald *et al.* 1996). Under such assumption, feed rate is a function of growth requirements. In Bjorndal, a fixed feed to weight gained ratio is assumed for calculating feed rate requirements given a specific growth path. Alternatively, a bioenergetic approach to model growth endogenizes feed rate (Cacho *et al.* 1990, 1991; Hatch and Hanson 1995; McDonald *et al.* 1996). In bioenergetic models, feed rates are more responsive to the effect to temperature and fish size.

Hatch and Hanson (1995) explicitly discuss the concept of consistent harvest strategy. In their study, they built upon the Cacho *et al.* (1990, 1991) simulation model for catfish to illustrate the effect of feeding restrictions on optimal management strategies. They specifically address the question of how restricting maximum feeding allowance to maintain higher water quality impacts net returns and increases feed requirements to reach a fish target size at three distinct harvest dates (June, August and October). Hochman *et al.* (1990) also derive a consistent harvest model for shrimp culture using a stochastic dynamic programming model. Their model provides an optimal stocking and harvesting schedule for 52 weeks of the year using a set of intra- and interseasonal decision rules expressed in terms of cutoff revenues and probabilities of harvest postponement.

Growth in salmon is continuous throughout the year. Assuming that the growth rate of fish is maximized during the production process, the equality between marginal cost and marginal revenue determines the economic optimal time of harvest as well as the weight at which the fish is harvested. The Bjorndal approach was selected as a base model because of its simplicity and its flexibility in modeling the time rate of change in revenue and cost parameters. Sub-model components are easily incorporated to the base model.

3.2 Production function

3.2.1. Theory

The yield or biomass of a population will change over time as a result two fundamental processes, mortality and growth. While mortality represents a loss of value to the producer, growth is a gain in value. The change in yield over time incorporates the product of population dynamics and fish growth.

3.2.1.1 Population dynamics

A population is a group of organisms of the same species sharing a particular space (Hickman *et al.* 1984). Typically, it shares a common gene pool and certain density path, age ratio, mortality rate and reproductive rate characterize its behaviour. Mathematical representations of population dynamic fundamentally describes the process by which the number of individual within a population increases as a function of reproductive (birth) rate and decreases as a function of mortality (death) rate. In salmon aquaculture, the reproductive rate of a population can be equated with a one-time introduction of salmon smolts into seawater. Together, these smolts form a cohort. A Beverton-Holt model can represent the rate of change in the fish numbers of a population;

$$N_0 = \mathrm{R} \tag{1}$$

$$\frac{dN}{dt} = N_t^{'} = -M_t N_t \quad , \; 0 \le t \le \overline{T} \tag{2}$$

$$N_t = \mathrm{Re}^{-\int_0^t M(u)du} \tag{3}$$

In this model the variable t measure the time elapsed since the release of smolts in saltwater. The changes in population levels will occur between seawater entry time (t_0) and sexual maturation[6] at time $\overline{T}$. In equation 1, the initial population at time 0, N_0, equals the initial number of smolts released (R) in salt water. The rate of change in population (N) as described in equation 2 is a function of the mortality rate (M) over time. N_t in equation 3 represents the population remaining a time t. In equations 2 and 3, the mortality rate varies over time. If the mortality rate is assumed constant, then

$$M = M_t = \text{constant}$$

and equation 3 is simplified as follow:

$$N_t = \mathrm{Re}^{-Mt}. \tag{4}$$

Equations 1 to 4 describe the dynamics of a declining population resulting from mortality. In a discrete setting, equations 3 and 4 can also be expressed as

$$N_t = N_{t-1}\left(1 - M_t\right). \tag{5}$$

Together, these equations only refer to the change in fish numbers over time.

3.2.1.2 Fish growth

Growth represents a gain in stock value and results from the incremental weight (w) of individual members of a population. The growth rate describes the rate of change in weight of representative member of a population as a function of time (t), population density (D) and feed (F);

$$w_t' = \frac{dw}{dt} = f\left(t; D, F\right). \tag{6}$$

In salmon aquaculture, producers aim at obtaining the highest possible growth rate so as to reduce the time required for the fish to reach market size. The partial derivatives of weight with respect to each the explanatory variable in equation 6 describes the influence of these variables on growth.

The relationship between growth and stocking density varies between species. In general it must be kept within some optimal range (Jobling *et al.* 1993). Excessive density leads to reduced growth and is often associated with increasing mortality rates. Low density in turn, often results in large differences in size between individuals. Density is essentially a husbandry issue. The growth model in this study will assume that density is maintained within an optimal range. This in turns implies that the availability of sea rearing space is not a constraint.

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[6] Salmon must be harvested before the onset of sexual maturation.

The relationship between growth and feed is the subject of considerable research effort in the industry because feed bears the largest share of input costs and is the main driving force behind growth. Feed is positively correlated with growth. Cultured salmon are fed to near-satiation at least once daily. The amount of feed provided during a feeding session is dictated by the feeding behaviour of the fish population. One of the particular problems characterizing finfish aquaculture in general is that water acts as the feeding medium. Feed not consumed immediately cannot be recovered and is likely to settle on the ocean floor where it decomposes. If not managed properly, the deposition and accumulation of nutrient rich organic matter below net-pens systems to adversely impact production performances (McDonald *et al.* 1996). Still, producers have a strong incentive to feed all that is required by the population to optimize growth. There is a disincentive to under-feed the fish because of the opportunity costs associated with lost growth. Alternatively, over-feeding the fish leads to inefficiencies (externalities such as pollution) and increased costs of production. Feed is the sole driving force of growth, with water temperature regulating feed rate levels over time and fish weight acting as a scaling factor in adjusting feed rates to the size of the fish (Stauffer 1973). If the objective is to maximize growth and if one assumes that there is a maximum growth biologically inherited for an individual fish, than this individual should only be fed with the amount that enables it to reach its maximum growth rate. Given the above objective, feed rate is endogenously determined by growth.

The relationship between growth and time presupposes a certain density and feeding path. Growth can only be optimized if feed is provided in sufficient quantity in a timely fashion and if density is maintained below a certain threshold. In general, the weight of a fish over time is described with the following identity;

$$w_t = w_{t-1} + \int_{t-1}^{t} w_u \, du$$

The weight of a fish at time t (w_t,) is equal to its weight at the last period (w_{t-1}) plus the weight gained over the time elapsed between the last period and the current one. Over time, the weight of the individual fish increases at a decreasing rate toward a maximum, typically coinciding with sexual maturation. In the process, water temperature plays an important role as it regulates the growth rates. The concept of accumulated thermal units (ATU) translates the effect of time on growth in term of the daily summation of water temperature over a growth period. The function describing fish growth can be rewritten as follows;

$$w_t^{'} = \frac{dw}{dt} = f(T(t); D, F) \tag{6.1}$$

In this equation, growth is expressed as a function of cumulative thermal unit over time, assuming that density and feeding have been optimized.

3.2.1.3 Biomass yield

Population biomass (B) is defined as

$$B_t = w_t N_t \tag{7}$$

The rate of change in the population biomass is

$$\begin{aligned} B_t^{'} &= w_t^{'} N_t + w_t N_t^{'} \\ &= \left(\frac{w_t^{'}}{w_t} \mathrm{Re}^{-Mt} - M_t \, \mathrm{Re}^{-Mt} \right) w_t \\ &= \left(\frac{w_t^{'}}{w_t} - M_t \right) B_t \end{aligned} \tag{8}$$

In this expression, $\frac{w_t^{'}}{w_t}$ is the relative growth rate and is presumed to be decreasing over time as the size of the average fish increases. The mortality rate is represented by M_t and is assumed constant over time. Changes in biomass occur according to the following relationship:

1. If $\frac{w_t^{'}}{w_t} > (<) M_t$ the population biomass increases (decreases);
2. If $\frac{w_t^{'}}{w_t} = M_t$ the biomass gained from growth equals the biomass lost from mortality and the population biomass has reached its maximum.

In this identity, the relative growth rate is assumed positive. Therefore, the individual fish is still growing regardless of changes in biomass. As long as the relative growth rate is greater than the mortality rate, than the population biomass increases. As the relative growth rate equals the mortality rate, the gain in biomass from growth is offset by the lost of biomass resulting from mortality. The implication of this result is that in the case of a positive mortality rate, the maximum population biomass is reached earlier than maximum individual fish weight. The only case where individual fish and population biomass is reached at the same time is when the mortality rate equals 0.

3.2.1.4 Relationship between yield per smolt and population biomass

Yield per smolt is a common measure of performance in aquaculture incorporating growth and survival rate to harvest. Yield per smolt (*Y*) is expressed as follow;

$$Y_t = \frac{B_t}{N_0} = \frac{N_0 e^{-Mt} w_t}{N_0} = e^{-Mt} w_t$$

If one assumes the existence of a indefinitely divisible virtual fish, then setting N_0=1 in the above equation and using Equation 7 results in the following equality;

$$B_t = N_t w_t = N_0 e^{-Mt} w_t = e^{-Mt} w_t = Y_t$$

In this expression, yields per smolt equals the product of the survival rate to the fish weight at time t. This relationship normalizes population with respect to one smolt input and holds as long as the surviving members are reared and harvested as a block.

3.2.2 Discrete production model specification

In this section, three sub-models to the bioeconomic model are presented. First, a fish growth model is specified using the Iwama-Tautz mathematical expression that is modified with a dampening factor to model the size-growth relationship expected as an individual fish increases in size. A bioenergetic model is then presented to model feed intake. Finally, this section closes with the description of a water temperature model.

3.2.2.1 Fish growth model

The problem of predicting fish growth in the course of production is of particular economic importance because fish size and growth are both essential prerequisites for estimating feed input requirements as well as for establishing the potential value of stocks over time. Consequently, a model describing the pattern of growth over time is necessary to properly monitor and evaluate expected feed requirements and to estimate the marginal value of stocks in the course of production.

There are several approaches and concepts that have been developed to describe fish growth. It is common to find growth expressed as the rate of change in terms of body weight, or sometimes length, with respect to time without reference to environmental or technical factors involved in the production process. For example, one of the most commonly used formulations is the specific growth rate (SGR) which is based on the natural logarithm of body weight over a specific lapsed of time. The specific growth rate is calculated as follows;

$$SGR = \frac{\ln W_f - \ln W_i}{t_f - t_i} \tag{9}$$

where W_f and W_i are, respectively, fish weights at time f and time i. The denominator represents the number of days elapsed between time f and i. This expression is also known as the instantaneous growth rate and is usually expressed in percentage terms. Its popularity comes from its simplicity and from its value in providing a standard by which to compare the relative growth rate of two fish stocks with similar initial weights, reared over a similar period of time and under comparable environmental conditions. As a mechanism to predict fish weight, however, the natural logarithm of weight underestimates predicted body weight between the initial and the final fish weights used in the calculation and increasingly over-estimates the predicted weight thereafter. The specific growth rate decreases at a decreasing rate as the fish increases in weight and in age. Therefore its application should be restricted to estimating fish weight at a specific time in the future. A different or adjusted value should be used to estimate fish weight outside that time frame. Despite these limitations and the lack of reference to factors such temperature, the specific growth rate remains a popular method for estimating and comparing growth among fish culturists and scientists alike.

The fish growth function involves a fundamental relationship between weight gain, feeding standards (feeding ration and frequency), environmental conditions (temperature and photoperiod), husbandry practices (rearing density) and the biological characteristics of a specific fish stock (species and genetics). In reviewing the factors having the greatest influence on fish growth, Stauffer (1973) concluded that for a given species and diet, a minimum variables that should be included in a growth ration (feed), size (fish weight) and temperature.

The growth model presented by Iwama and Tautz (1981) is based on the cubic root of weight and the concept of accumulated thermal units[7] as a substitute for time. One important characteristic of this model is that at maximum food ration[8], the cubic root of weight is a monotonic increasing function of time over a stanza of undisturbed growth. Further, temperature is considered a major regulating force controlling the

[7] In the context of aquaculture, accumulated thermal units (ATU) is the summation of daily water temperatures.
[8] Maximum food ration is defined as the feeding regime required for optimizing the growth rate.

rate of growth and feed intakes. This model provides a method for comparing the growth rates of fish of different sizes and reared at various temperatures. A complete mathematical derivation of the model is presented in Appendix 1. The basic form of the Iwama and Tautz model is expressed as follow;

$$w_t^{1/3} = w_i^{1/3} + \frac{T}{1000}t \qquad (10)$$

where w_i is the initial weight (grams), w_t is the weight at time t (grams), T is the average temperature (Celsius) and t is the time in days. The expression $T/1000$ is termed the growth slope (Gs) and represents the slope of the line. For salmonids grown in a hatchery environment at constant temperature and maximum ration, the attributes of this model are that the cubic root of weight increases in a linear fashion over time and the effect of temperature on growth is near linear below 15 degree Celsius. This is deemed a desirable attribute since it allows the use of accumulated thermal units (ATU) in growth prediction (Iwama and Tautz 1981). This relationship was first empirically estimated by Haskell (1959) and reviewed by Stauffer (1973) and Iwama and Tautz (1981).

Farmed salmon reared in salt water, however, grow at about twice the rate predicted by the model. To take into account this factor, a growth index termed the growth coefficient (Gc) is introduced in the model. An alternate formulation of this coefficient was proposed by Cho and Woodward (1989) and termed the thermal growth coefficient (TGC). This index is computed by solving the basic equation for T and is expressed as follows:

$$TGC = \frac{w_t^{1/3} - w_i^{1/3}}{\sum_{i=0}^{t} T_i} \qquad (11)$$

The thermal growth coefficient is then substituted in the place of the growth slope factor in the Iwama-Tautz model:

$$w_t = \left(w_i^{1/3} + \sum_{j=i}^{t} TGC \cdot T_j \right)^3 \tag{12}$$

There are several benefits associated with this particular formulation. First, growth is explicitly expressed as a function of temperature. As a result, the growth curve shows a slower rate of increase during colder temperatures and is faster during warmer temperatures. Second, the growth coefficient provides a more accurate means by which to compare the growth performance of two or more fish stocks over a similar time period and growth stanza[9] during the course of production.

The downsides of this model is that it suffers from some of the same problems characterizing the specific growth rate when a fixed growth index is used in computing weight over time. The actual growth index calculated from seawater entry to a series subsequent sample weights are highly correlated to their respective specific growth rate (Dubreuil and Sams 1992). Overtime, the growth coefficient decreases at a decreasing rate for constant water temperature. This observation is consistent with the size effect on growth reported for many fish species (Cuenco *et al.* 1985). Specifically, under constant levels of environmental factors and excess food, the weight increase in fish reduces the relative growth rate at a decreasing rate. Iwama and Tautz (1981) demonstrated the relationship between the specific growth rate and equation 10. Consequently, in estimating growth over the entire life of production stanza, the fixed growth coefficient leads to the weight being underestimated in the earlier part of the lifecycle and grossly overestimated beyond the point at which the coefficient was computed.

The growth coefficient computed over time also fluctuates in a manner that is positively correlated with water temperature. This relationship between temperature and growth is consistent with reported observation for many fish species (Cuenco *et al.* 1985). The relative growth rate in fish rapidly increases as temperature rises, passing through a peak at optimal temperature and quickly falling as higher temperature become adverse. One of the conditions that must be satisfied in using the Iwama-Tautz model is that water temperature must be within normal operating range[10] and not rise above an optimal temperature level.

While the temperature effect on growth is capture by the model (especially if the model is applied over discrete intervals), the size effect on growth is nullified with the use of a fixed growth coefficient. Nevertheless, the model has been used with success as a short term prediction tool during grow-out to forecast harvest weight several months prior to harvest (Holmefjord *et al.* 1995, 1997). It is particularly accurate in cases where temperature and size are increasing together, so that the size effect is balanced out by the temperature effect.

Within any growth stanza of plants or animal, the increase in size may follow an S-shaped curve referred as a Sachs cycle (Ricker 1979). Typically, the lower part of the S curve may be approximated by an exponential curve, while the upper part tends toward an asymptotic value, which may reflect preparations for the next stanza. The S-shaped curve describes growth in several fish species including salmon. The Iwama-Tautz growth model approximates the lower part of the S-curve, but it has no mechanism to approximate the upper part of the S-curve. To compensate for this problem in modeling the production cycle, the Iwama-Tautz growth model is modified as follows;

$$w_t = \left(w_{t-d}^{1/3} + Gi \cdot T_t \frac{d}{1000} \right)^3 \left[\frac{Df - w_{t-d}}{Df} \right] \qquad (13)$$

in which w is the weight, t is the current time, d is the time elapsed between periods, T is the water temperature and Df is the incremental weight dampening factor. In this model, the growth index (Gi) performs the same function as the original growth coefficient (Gc) but is not equivalent relative to the Iwama-Tautz model because of the impact the dampening factor exerts on the modeled growth rate. The

[9] Growth during the life of a fish can be divided in a series of stages or stanza. The change from one stanza to the next is characterized by a major crisis or a discontinuity in development (Ricker 1979). Changes in growth stanza occurs at hatching, smoltification and sexual maturation.

[10] Iwama and Tautz (1981) calibrated their model salmonid hatchery data from various sources. Normal operating range in salmonid hatchery is 4°C to 18°C.

dampening factor ratio, in the set of square brackets, reduces actual growth below potential growth as calculated in the Iwama model. This is achieved by decreasing the actual size of the fish by a factor depending on the current weight itself. The rate of decrease is compounded over time and is a function of the time intervals between growth computations.

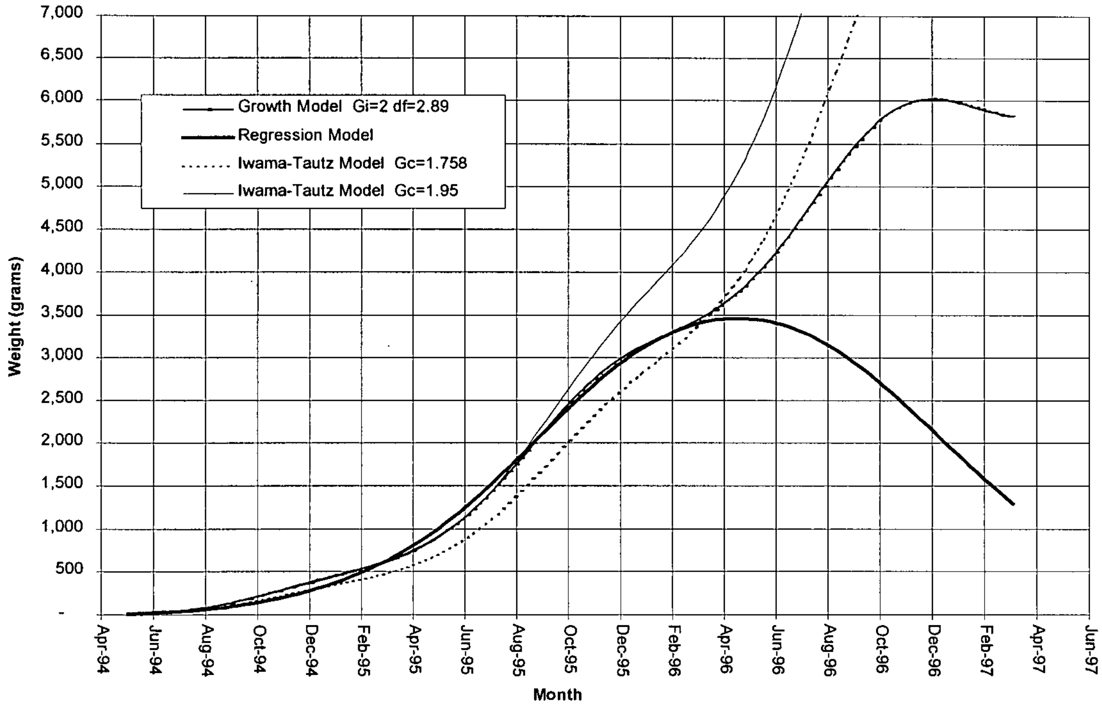
The objective of the dampening factor is to force the expected size/growth relationship in the original Iwama-Tautz model. This particular relationship should cause the curve to increase at a decreasing rate at some point of the growth curve. Some forms of dampening factors have been introduced in other growth model for similar purposes. In Hatch and Hanson (1995), water quality and stocking density were specified as dampening factors reducing actual growth below potential growth as calculated in a bioenergetic growth model developed in Cacho *et al* (1990). Asymptotic growth curves, such as the model proposed in Pauly (1986), imply that size will tend toward some fixed limit regardless of age (Ricker 1979). The weight limit in such model can also be considered a type of dampening factor.

Figure 3 shows the impact of the dampening factor applied to the Iwama-Tautz model. In this graph, the growth model presented in equation 13 was fitted to a set of sample and harvest growth observations. The second curve is a third degree polynomial model that was estimated following a procedure proposed in Bjorndal (1988, 1990). Both, the proposed growth model and the regression models had identical adjusted $\overline{R}^2$ of 0.986 with significant parameters and goodness of fit values. The Iwama-Tautz model was applied in deriving the third and fourth curves using growth coefficients of 1.758 and 1.95 respectively.

The major difference between the proposed growth model and the Bjorndal model is the direction of the curve beyond the growth observations. In the Bjorndal model the top of the growth curve is dictated by the data set and coincides with the last observations. The Bjorndal curve is very valuable in its ability to model the absolute growth path over an actual production cycle. However, it does suffer two serious limitations: First, the optimal fish weight and population biomass derived from the model does not indicate the potential of a fish cohort since it is unable to provide a possible outcome beyond the observed values.

Second, the estimated parameters are only applicable for forecasting purposes to cohorts with similar characteristics and reared under similar environmental conditions.

Figure 3 Comparative growth curves for chinook S0 salmon comparing three growth models: Third degree polynomial regression model and the regular and dampened Iwama-Tautz mathematical growth models.



The difference between the two Iwama-Tautz models resides in the influence of the growth coefficients (Gc). The value used for the lower Gc predicts the average harvest weight at the end of the production cycle but consistently underestimates the actual growth path during production. The value used for the higher Gc appears to provide a good fit for half of the actual growth path and then continues to increase at an increasing rate, pulling away from the actual growth path. It results in a gross over-estimation of fish weight at harvest. The lack of growth/size relationship limits the usefulness of the model for optimal harvesting analysis to short periods of growth. For long run projections, the use of a fixed growth coefficient would result in a weight approaching infinity. The introduction of the dampening factor introduces a growth/size relationship that then extends the usefulness of this model over the entire production cycle. It also allows for speculative growth beyond data set limitations and in cases where fish characteristics and/or environmental conditions differs from past experiences.

3.2.2.2 Feeding system model

The most important input factor in intensive finfish culture is feed. The specification of a particular feeding system is an integral part of the production function. Feeding systems are defined as all feeding standards and practices employed to deliver nutritionally adequate and balanced diets to animals so as to maintain normal growth, health and reproduction together with performance of work (Cho 1992). Elements of feeding systems include energy and nutrient requirements, daily feed allowance of a specific diet, method as well as frequency of delivery and physical characteristics of feed pellets. The planning process is concerned with obtaining an accurate estimate of the feed needed to achieve optimal growth over time.

Feeding of terrestrial animals is determined by voluntary intake of a given diet. Feed provided can be consumed immediately or at a later time. In aquaculture, feed is delivered through a water medium. As a result, feedstuff requires particular physical properties along with special feeding techniques to obtain maximal feed intake. Feed not immediately consumed by the fish cannot be recovered for later used.

During a feeding period, it is a population that is fed rather than an individual fish. Therefore, it is not possible to feed fish *ad libitum* in the course of single feeding period (Cho 1992; Cowey 1992). The most satisfactory way to maximize feed intake and growth rate is to feed a population to satiation several times per day. Daily feed rations must meet the energy and nutrient requirements essential for maintenance and growth functions. The determination of feed rates is an integral component in planning the economics of production and is a useful guideline to follow in the course of operation to minimize instances of under or over feeding.

Several methods for estimating daily feed allowance have been proposed by feed companies and researchers alike (Iwama 1989; Furnell 1989; Cho 1992). A popular approach is based on incremental fish weight, dry weight of feed and expected feed conversion ratio. Examples of this type of method are feed rate tables supply by feed companies. Another class of method is based on bio-available energy, the nutrient contents in feeds and the protein and energy retention by the body (Cho 1992). This approach is more appropriate for calculating the requirements of highly enriched feed.

Producers have traditionally use feed tables, often supplied by feed companies to estimate future feed requirements. These feed tables provide the user with expected feed rates as a function of fish weight and water temperature. The daily feed rate at time t is expressed as:

$$\phi_t = \frac{F_t}{w_t} \text{ per day,} \tag{14}$$

where ϕ_t is feed rate, F_t the amount of feed required in kilograms at time t and w_t the average weight of fish in kilograms at time t. Such tables are useful guidelines but may require adjustments for use on particular stocks as a result of two fundamental assumptions underlying the proposed feed rates. First, it assumes a fixed biological feed conversion ratio (BFCR). The BFCR measures the degree to which the feed consumed by a single fish is assimilated and converted into incremental biomass over a discrete period of time[11]. This identity thus represents the relationship between feed quantity and growth. Although it is common practice in salmon farming to use a constant BFCR factor as a simplifying assumption (Bjorndal 1990), conversion efficiency can vary from one stock to the next and is seldom static in practice. To the contrary, it is subject to constant fluctuations depending on factors such as the water temperature and other environmental factors (Iwama 1989), the size and health of the fish, husbandry practices and feed quality. Ideally, the BFCR should be a by-product of the feeding model rather than the driving force behind it.

Second, the feed rates lifted from feed rate tables assume some underlying growth rates since the lookup

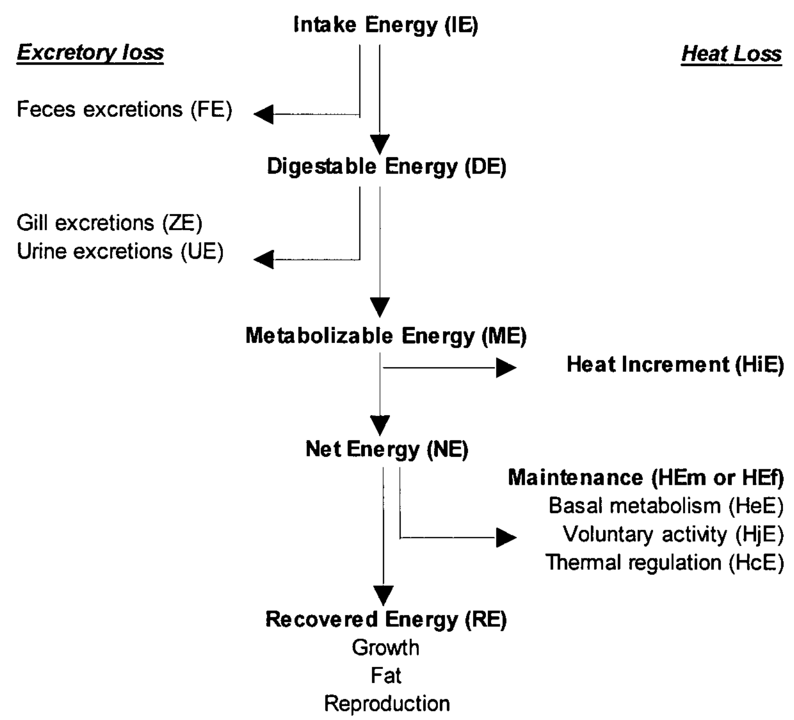
[11] The BFCR refers to the capacity of a single fish to convert feed into biomass. The economic feed conversion ratio (EFCR) refers to the capacity of a fish population to convert feed into biomass. The EFCR computation includes the feed consumed by fish that died during the production process.

values are calculated using a fixed BFCR and are determined as a function of fish size and water temperature. However, the growth rate of fish stocks of similar weight and reared in equivalent water temperature varies according to the species, the strain and the smolt type. Unless feed tables are utilized on the stock type with which the table was designed initially, their interpretation often becomes an art rather than a scientific exercise.

As a proxy to feed tables, the weight gain per day estimated from a growth model can be multiplied by an assumed BFCR to obtain the feed rate (Iwama and Fidler 1989). Alternatively producers also project their historical data forward to estimate feed requirements. Although this method is adequate is cases where production parameters are similar, it can led to erroneous estimates in planning for different strains and smolt types (cohort) and in cases where a feed of different composition is utilized.

The method proposed by Cho (1992) involves first calculating the weight gain and deriving the energetic requirement for achieving the incremental weight. In this system, the dietary allowance is estimated by equating animal performance with the available energy accountable in feed stuff. The energy flow of ingested feed into the animal's body is illustrated in Figure 4 along with accepted abbreviations of energy metabolism terms.

Figure 4 Schematic presentation of energy flow in fish.



Sources: Adapted from National Research Council (1981) and Cho (1992)

The energy requirement defines the dietary intake necessary to maintain life processes. As shown in Figure 4, there are several places where energy is lost between feed intake and recovered energy. Maintenance requirements in fish are equivalent to heat production plus excretory losses of a fasting animal. This amount of dietary energy is the absolute minimum needed before growth. If this amount is not met, tissues catabolize as energy expenditure exceeds intake of dietary fuel (Cho 1992).

The feeding standard proposed by Cho (1992) is computed on the basis of the energy requirements of fish and an optimum protein: energy ratio. Although this feeding standard was developed using rainbow trout production data, it is also applicable to other salmonid species. The feeding standard relies on a growth model to derive the incremental weight expected over a discrete time period and for which energy requirements are computed. The steps are as follows;

i. Compute expected weight gain and retained energy based on dry matter (*DM*) and energy contents of carcass ($EC = \frac{kJ}{gDM}$):

$$RE = (w_t - w_{t-1}) \cdot \%DM \cdot EC$$

ii. Allocate approximate maintenance (fasting) energy requirement:

$$HEf = \left[\left(-1.04 + 3.26T - 0.05T^2\right)kg \cdot w_t^{0.824}\right] \text{kJ/day}$$

iii. Allocate approximate heat increment of feeding for maintenance and growth ration:

$$HiE_{MG} = HEf \cdot 0.6$$

iv. Allocate approximate non-fecal energy loss:

$$ZE + UE = (RE + HEf + HiE) \cdot 0.06$$

v. Calculate the digestible energy (*DE*) provided in the diet. This is achieved, either, by direct measurement or by the sum of the apparent digestibility coefficient (ADC) of ingredient. The feed manufacturer normally provides this figure.

vi. The minimum digestible energy requirement ($DE_{\min}$) that should be fed to the fish is the sum of retained energy and energy lost,

$$DE_{\min} = RE + HEf + HiE + ZE + UE.$$

Using the above entity, the feed rate can be computed for any growth period on a daily, weekly or monthly basis. The feed required for an average animal is expressed as follow;

$$F_t = \frac{DE_{\min}}{DE} \tag{15}$$

The feed rate is obtained by inserting Equation 15 into Equation 14.

This feeding standard model was calibrated using rainbow trout (*Oncorhynchus mykiss*) reared in laboratory conditions. The computed feed rates should thus be regarded as a minimum requirement since they represent the technical feed rate per fish reared in under ideal conditions. The model is also applicable to other salmonid species.

Using this feeding standard model, the feed conversion ratio is easily computed by dividing the feed quantity required per fish by the incremental weight per fish over a discrete period of time. This is an important result since the conversion ratio is no longer the driving force behind the feeding standard. Now, the conversion ratio is an endogenous factor derived from the feeding standard itself.

The feed to weight gain ratio calculated using the Cho feeding standard is theoretical in nature. This ratio is termed the technical feed conversion ratio (TFCR). Analyzing feed conversion ratios for Norwegian cultured salmon, Maroni (1994) analysed the biological and the technical feed conversion ratios and estimated an average deviation of 40% between the two values. The deviation of the BFCR from the TFCR is a measure of feeding inefficiencies caused by a variety of factors external to the relationship between the metabolic processes in the fish and the feed composition. In the present study, this deviation is termed the extrinsic factor (ε) and is calculated as follow;

$$\varepsilon = \frac{BFCR - TFRC}{TFCR}$$

There are several elements explaining the extrinsic factor. These are summarized in Table 5. The deviation between the TFCR and the BFCR were found to be related to feeding issues, disease, lice and site characteristics. The deviation between the BFCR and the economic feed conversion ratio (EFCR) showed the impact of lost biomass due to mortality on feeding efficiency. These problems are, to various degrees, common the most producing areas of the world. Although the study was carried out in a Norwegian context, for the purpose of this study its results are assumed applicable to any other producing region, including British Columbia.

Table 5 Analysis of Feed Conversion Ratio Norwegian salmonid farms in 1993

Conversion Type	Feeding Externalities			Conversion rate	Deviation from TFCR
	Causes	Units	Deviation		
TFCR (base)				0.85	
	Feeding	0.15	18%		
	Disease	0.06	7%		
	Site	0.04	5%		
	Lice	0.04	5%		
	Other	0.04	5%		
	Dust	0.01	1%		
BFCR (base and extrinsic factor)				1.19	40.0%
	Mortality	0.09	10.6%		
EFCR (base, extrinsic and mortality)				1.28	50.6%

Source: Adapted from Maroni (1994)

Feeding inefficiencies are caused by feeding practices, such as over and under feeding, health and stress factors, site location and feed quality. Using his model, Cho (1992) recomputed a feeding standard for rainbow trout. The resulting table showed optimal feed rates for fish of various sizes to be 20-40% less than the rates recommended by many of the feed tables provided by several manufacturers. This observation is similar to that reported in Norway.

To account for systemic feeding inefficiencies, the extrinsic factor is incorporated into Equation 15 as follows:

$$F_t = \frac{DE_{\min}(1+\varepsilon)}{DE} \tag{16}$$

Incorporating Equation 16 into Equation 14 and expanding $DE_{\min}$ into its components yields the following bio-energetic feed rate:

$$\phi_t = \frac{\left\{\left\{\left[\frac{dw_t}{dt} \cdot DM \cdot EC + \left[\left(-1.04 + 3.26T_t - 0.05T_t^2\right) \cdot w_t^{0.824} \cdot 1.6\right]\right] \cdot 1.06\right\} \cdot (1+\varepsilon)\right\}}{DE \cdot w_t}$$

where ϕ_t = feed rate as percent body weight per day

w = weight (kg)

T = temperature (°C)

ε = extrinsic factor.

3.2.2.3 Water temperature model

Water temperature has considerable effects on growth and feed utilization (Stauffer, 1973; Cacho *et al.*, 1988). It is an explanatory variable in both standard growth and feed models. The daily average temperature follows an annual cycle that can be approximated by the following function;

$$T_t = T_A + T_R Sin\left(\frac{2\pi(t_C - t_A}{365}\right) \tag{17}$$

where T_A is the mean annual water temperature, T_R is the range of temperature about T_A, t_A the time of the year at which $T=T_A$, and t_C is the current time of the year defined as

$$t_c = t_0 + t,\ 1 \le t_0 \le 365.$$

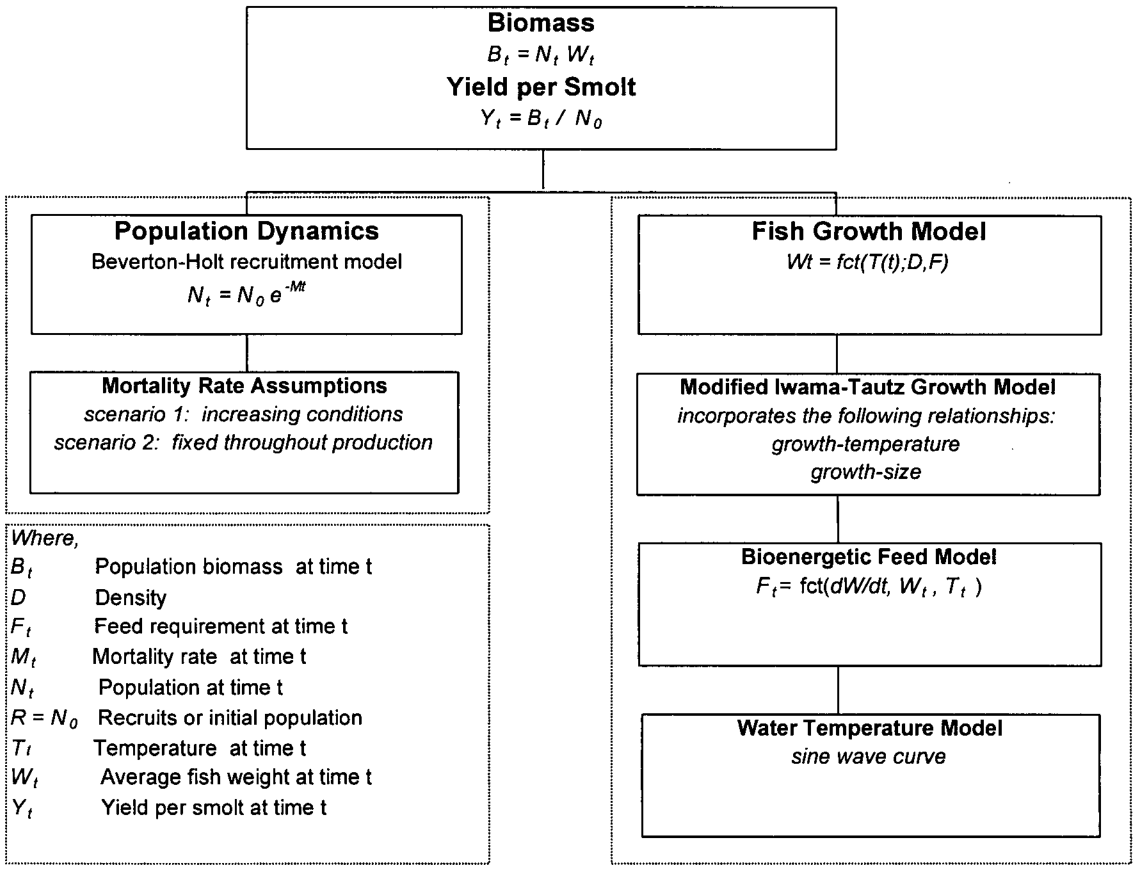
t_0 is the stocking date and equals 1 on January 1, and t is the number of days from stocking to the current day.

3.2.3 Summary of the biological model

The structure of the biological system is summarized in Figure 5. The biological model illustrates the changes in biomass over time that results from population dynamic and growth. Over time, the number of fish within a population decreases as a result of mortality. The lost of biomass resulting from mortalities represents an economic cost in terms of reduced revenues and lost of the capital invested in the fish. Two mortality rate scenarios are presented to simulate the underlying causes of mortality and the effect of sexual maturation on fish quality and survival. These mortality rate assumptions are specified in Chapter 4. In the scenario 1, the mortality rate is held at a constant level until the convergence of two conditions beyond which the mortality rate begins to increase. In scenario 2, the mortality rate is fixed throughout production.

Biomass growth represents an economic gain. Over time, biomass increases as a result growth. In this study fish growth is simulated using a modified Iwama-Tautz growth model, which incorporates size-growth and temperature-growth relationships. In this model, the growth rate is maximized over an undisturbed period of growth assuming an optimal feeding path. The required feed requirement is estimated using a bioenergetic feeding model. Water temperature is simulated through a sine wave curve.

Figure 5 Schematic summary of the sub-models underlying the biological system.



3.3 Economic model

The objective of consistent harvesting is the continuous, year-round harvesting of a relatively uniform fish product in terms of size and quality. This objective must be achieved with the goal of optimizing profits for a given year class of fish. Because of the growth characteristics inherent to a single fish cohort, the above stated objective can only be attained with a "portfolio" of fish cohorts. Each individual cohort is introduced as smolt into sea water at a size and time resulting in each one reaching the desired market size at a unique period of time. Cohorts in the portfolio are then harvested sequentially, in a domino fashion.

The portfolio composition of smolt cohorts forms a production strategy for a year class of fish. The producer's problem is to determine the composition of his portfolio. The economic merit of each smolt cohort needs to be analyzed in the context of optimal harvesting theory. In a consistent harvesting framework, the analyst is interested in both the time and size at which harvest is economically optimized. Analyzing optimal harvesting with respect to time should indicate the degree of harvest continuity possible from the portfolio. The optimal harvesting model from Bjorndal (1989, 1990) provides the backbone of the bioeconomic model required for this type of analysis.

The biological model illustrates the dynamic of growth in production as characterized by the biological processes of growth and mortality. In economic terms, growth represents a gain, while mortality a loss. The purpose of the analysis is to determine the time and the weight at which the present value of each cohort is optimized, given its biological constraints. To simplify the analysis the following assumptions are adopted:

i. Individual fish members of a cohort have weights normally distributed around the mean.

ii. The mortality rate for each cohort is constant over time except at sexual maturation.

iii. The discount rate and all prices for inputs as well as for each market weight class are constant over time.

iv. The farm operations are fully developed.

v. Credit is not a limiting constraint and taxes are disregarded.

vi. Carcass quality at harvest is homogeneous.

vii. The entire cohort is harvested together. This implies that the harvested population at time t equal N_t

The economic model is developed following the Bjorndal model with some modifications. The model development begins with a mathematical definition for the gross market price. The gross and net values of harvested stocks are then defined and analyzed. This is followed with a definition for the profit function and the rule for optimal harvesting time.

3.3.1 Gross and net revenue functions

The gross market price is calculated as the mean distributed market price. P_w is defined as the mean distributed market price for a cohort at time t with an average weight at harvest of w_t. P_W is described by the following vectorial factor;

$$P_w = P_{it}\beta_{ti}, \qquad (18)$$

$$\sum_{i=1}^{n}\beta_{ti} = 1, \; n \geq 1$$

where P_{it} is the price per biomass unit at time t for fish of weight within the i unit weight category; n is the number of market unit weight categories; β_{it} is the proportion of biomass harvested for fish of weight within the i unit weight category; and v_{it} is the fraction of fish whose average weight falls within the i unit weight category;

$$\beta_{ti} = \frac{v_{it}w_{ti}}{\sum_{i=1}^{n} v_{it}w_{ti}}, \qquad (19)$$

$$\sum_{i=1}^{n} v_{it} = 1$$

Notice that P_W is a function of w_t which is itself a function of time. In general, salmon prices increases with weight so that $P_w^{'} > 0$.

Using equation 7 and 18, the present value of harvest is given by

$$V_t = B_t P_w e^{-rt} \tag{20}$$

where r is the discount rate and V_t is the gross value of the cohort. The changes in V_t over time are given by:

$$V_t^{'} = B_t^{'} P_w e^{-rt} + P_w^{'} w_t^{'} e^{-rt} - r B_t P_w e^{-rt} \qquad 0 \leq t \leq T, \tag{21}$$

Substituting equation 8 in the above identity yields:

$$\frac{V_t^{'}}{V_t} = \frac{w_t^{'}}{w_t} - M + \frac{P_w^{'}}{P_w} w_t^{'} - r \tag{22}$$

The first order condition for optimizing the gross value with respect to time implies that $V_t^{'} = 0$. Rearranging equation 22 yields the optimal harvesting rule for the gross valuation of a fish cohort with respect to time;

$$\frac{w_t^{'}}{w_t} + \frac{P_w^{'}}{P_w} w_t^{'} = r + M. \tag{23}$$

The left-hand side represents the gross marginal value with respect to time and is assumed to be declining over time. It is composed of the relative growth rate plus the price appreciation for the increased weight. The right-hand side depicts the gross marginal cost incurred from not harvesting. The gross marginal cost is equal to the discount rate (r) plus the mortality rate (M). Assuming that both r and M are fixed, the gross marginal cost is constant over time.

The economic optimal harvesting rule described by equation 23 is equated to the biological optimal harvesting rule extracted from equation 8 when the price appreciation due to growth equals the discount rate. Under this condition, the present value of investment and the population biomass for a cohort are maximized at the same point in time. In addition, if the mortality rate equals 0, the economic and biological harvest time for a cohort population will also coincide with the time at which individual fish weight is maximized.

In the case where the discount rate is greater than the price appreciation due to growth at optimal harvest time, the optimal present value of investment is reached before the time at which biomass is maximized. Further, a mortality rate greater than 0 implies the economic and biological harvest time for a cohort population occurs before the time of optimal fish weight.

The net value of the cohort is found by introducing the harvest cost per biomass unit defined as C_h;

$$V_t = B_t P_w e^{-rt} - B_t C_h e^{-rt} . \tag{24}$$

The change in the net value with respect to time is;

$$V_t^{'} = \left(P_w^{'} w_t^{'} B_t + B_t^{'} P_w - rB_t P_w - B_t^{'} C_h + rB_t C_h \right) e^{-rt} . \tag{25}$$

Substituting equation 8 into 25 and rearranging yields:

$$V_t^{'} = \left[\frac{P_w^{'}}{P_w} w_t^{'} + \left(\frac{P_w - C_h}{P_w} \right) \left(\frac{w_t^{'}}{w_t} - M - r \right) \right] V_t \tag{26}$$

The first order condition for optimizing the net value with respect to time is $V_t^{'} = 0$. Rearranging equation

26 yields the optimal harvesting rule for the net valuation of a fish cohort with respect to time;

$$\frac{w_t^{'}}{w_t}+\frac{P_w^{'}}{P_w-C_h}w_t^{'}=r+M\,. \tag{27}$$

In this identity the price appreciation term is increased with the introduction of the net market price, $P_w - C_h$.

3.3.2 Profit function

The profit function is the difference between the net value of the cohort at harvest time minus the cost of rearing the cohort to that time. The cost function can be divided into the following four components;

1. Start-up costs: These costs are incurred at the start of production and primarily include costs related to purchasing and delivering smolts to grow-out farms.
2. Fixed costs: These costs include financial resources allocated toward overhead expenditures, repair and maintenance, veterinarian and diagnostic services, management salaries and depreciation. In some operations, farm labour is also considered a fixed cost. Fixed costs do not vary with changes in fish inventory or biomass levels.
3. Variable costs: These costs include the purchases of feed, insurance, and farm labour during the production process. Variable costs do vary with changes in fish inventory or biomass levels.
4. Harvest cost: This is a fixed cost that depends on the amount of biomass harvested.

In this framework, variable costs and fixed costs are financial resources cumulating over time, whereas start-up costs are financial resources strictly required to embark into production. Harvest cost is incurred at harvest time only.

In their analysis of optimal harvest time in the production of Nile tilapia, Springborn *et al.* (1992) identified two levels of fixed costs. The first sets of fixed costs are incurred at the time at which production begins and at which it ends. These are start-up costs, which includes fingerling and pond preparation expenditures, and harvest costs, which is a function of the number of hectare under production. These types of fixed cost do not affect the optimal harvest time, but act instead as a scaler in determining the net present value at harvest. The second set of fixed costs is incurred on a daily basis and includes factors such as depreciation and interest on investment capital. Such cost do affect optimal harvest time since they are cumulated as a function of time. Depreciation, for instance, is an expense in the same way as rent is an expense (Pyle *et al.* 1985). Once production reaches a certain stage or is completed, equipment and infrastructure can be reallocated to more profitable activities.

The incorporation of fixed costs in the analysis is a departure from the structure proposed in Bjorndal (1988, 1990). The objective in his study is to maximize the present value of investment into the fish to determine the optimal harvest time for a single cohort. This approach is based on the assumption that in the short run, only costs associated with holding the fish and influencing the cash flow generated from the investment are relevant to the analysis (Bjorndal and Uhler 1990). A similar argument is also made in Hean (1994) and Cacho *et al* (1991). However, some cost factors that are generally considered fixed cost do affect cash flow. Farm labour is an example of a cost that may remained fixed through out the production process, but that is necessarily incurred at each pay period. Other cost factors such as depreciation do not affect cash flow directly and are often considered sunken costs. However, the seawater age at which two cohorts reach their respective optimal harvest time can be expected to vary as a function smolt size and time of entry into seawater. In comparing such cohorts it is appropriate to account through depreciation for the use of equipment and infrastructures.

The following costs are considered;

1. C_s is the cost per smolt purchased and introduced into seawater.
2. C_f is the cost per unit of feed (Ft) required per fish at time t (see equation 14).
3. C_l is the cost per unit of time required for the cohort. The amount of labour required for rearing a cohort is assumed fixed.
4. k is the insurance premium as function of V_t over the production cycle.
5. C_x are all other fixed costs.
6. C_h is the cost of harvest per unit of biomass harvested

The profit function is estimated by computing the net present value of the investment at time t:

$$\pi_t = (P_w - C_h)B_t e^{-rt} - C_s N_0 - \int_0^t C_f F_u N_0 e^{-(M+r)u} du - \int_0^t k V_u e^{-ru} du - \int_0^t C_l e^{-ru} du - \int_0^t C_x e^{-ru} \quad (28)$$

The optimal profit is found by solving the following maximization problem:

$$\text{Max } \pi_t = (P_w - C_h)B_t e^{-rt} - \int_0^t C_f F_u N_0 e^{-(M+r)u} du - \int_0^t kV_u e^{-ru} du - \int_0^t C_l e^{-ru} du - \int_0^t C_x e^{-ru}$$

$$0 < t \leq T$$

In the above identity, smolt costs are not included because they are incurred at the start of production. They are considered sunken costs irrelevant to the optimization problem. From the first order condition, the following rule for optimal harvesting time is:

$$\frac{w_t^{'}}{w_t} + \frac{P_w^{'}}{P_w - C_h} w_t^{'} = r + M + \frac{C_f F_t}{w_t (P_w - C_h)} + \frac{P_w k}{P_w - C_h} + \frac{C_l}{B_t (P_w - C_h)} + \frac{C_x}{B_t (P_w - C_h)} \tag{29}$$

Introducing the feed rate identity (Equation 14) and rearranging the above equation yields:

$$\frac{w_t^{'}}{w_t} + \frac{P_w^{'}}{P_w - C_h} w_t^{'} = r + M + \frac{1}{P_w - C_h}\left[C_f \phi_t + kP_w + \frac{C_l + C_x}{B_t} \right] \tag{30}$$

The left hand set of Equation 30 represents the net marginal revenue with respect to time. It is equal to the relative growth rate plus the net price appreciation due to growth. The relative growth rate [12] is expected to decrease at a decreasing rate over time as fish weight increases. It will, however, be subjected to an increase with rising water temperature and to a decrease with declining water temperature. The relative price appreciation depends on the price function. For $P_w^{'} = 0$, market price is unrelated to fish size and the marginal revenue with respect to time is solely determined with the relative growth rate component. For $P_w^{'} > 0$, fish price is positively related to fish size. In the case of a linear price function, the marginal revenue with respect to time is greater for larger fish than smaller one since a greater weight increase in absolute terms for larger fish implies a correspondingly greater price appreciation vis-à-vis smaller

[12] The relative growth rate is also termed the instantaneous growth rate or the specific growth rate (SGR). It is equivalent to Equation 9.

individual. For $P_w^{'} < 0$, fish price is negatively related to fish size so that larger fish are worth less per until of weight then smaller fish. This situation often occurs for higher weight classes where the demand for larger fish is limited to few segmented markets relative to smaller fish.

The right-hand side of this equation represents the marginal cost with respect to time. It is influenced by the discount rate, the mortality rate and the opportunity cost associated with feed rate, insurance, labour and other fixed factors of production. The effect of including all costs of the system implies that it is optimal to harvest the cohort earlier than in a situation with no input costs. In comparing equation 8 with equation 30, the economic optimal harvest time occurs at a time and a yield less than at the time of maximum yield. At some time before maximum yield, costs start increasing at a faster pace than marginal revenue so that harvest must take place before that time.

3.3.3 Specification of the bioeconomic model in a discrete time frame

The continuous bioeconomic model described above is transformed into a discrete model. This is easily achieved by converting the integration of cost factors to the summation of cost factors and using a discrete discounting formula. The following relationship exits between the continuous and the discrete discounting formulas:

$$e^{-rt} = (1+i)^{-t},$$

where r is the continuous discount rate and i the discrete discount rate. Time units are defined on a weekly basis. The schematic representation of the economic system in a discrete time frame is summarized in Table 6

3.3.3.1 Methodology for computing optimal harvest time

For the optimal harvesting analysis, the net present value of the investment is estimated with respect to the time at which the investment is undertaken. Under this condition, the smolt stocking date is the point of reference. The economic characteristics of each cohort can then be estimated with reference to the length of its production cycle. The optimal harvest time for each cohort is determined in a discrete framework though equation 30. The net present value for the corresponding optimal harvest time is provided by equation 28. The optimal harvest time rule is summarized in the bottom section of Figure 6.

3.3.3.2 Methodology for selecting a consistent harvest strategy

For consistent harvesting purposes, the economic and production characteristics of each cohort must be analyzed in the context of a global production and output. Each cohort must be compared to one another in terms of their capacity to maximize rent and to provide the desired output. The analysis needs to be performed with respect to a common point of reference. A logical point of reference is the time at which egg fertilization takes place. At this time, a decision must be taken as to the type of smolt to obtain from a hatchery.

The primary objective of consistent harvesting strategy is to harvest the cohort providing the highest return for each week of the year, regardless of the age or the size of the average fish. The method for deriving an optimal sequential harvesting strategy first consist in computing the net present value for each cohort from seawater entry to maturation or the time at which the cohort is no longer economically viable[13]. Second, the highest net present value obtained over the lifetime of each cohort from week 1 to week 52 is extracted. Third, the cohort providing the highest positive net present value for any given week is selected into the cohort portfolio.

The consistent harvesting rule is described as follow;

$$\pi_s = \max_{t,j}\left[\pi_{s(t),j}\right],$$

where s denotes the week number (s=1 to 52), t represents the age of the fish in weeks (t=0 to time of death or maturation) and j is the cohort number (j=1 to 12). The consistent harvesting rule is summarized in the upper section of Figure 6.

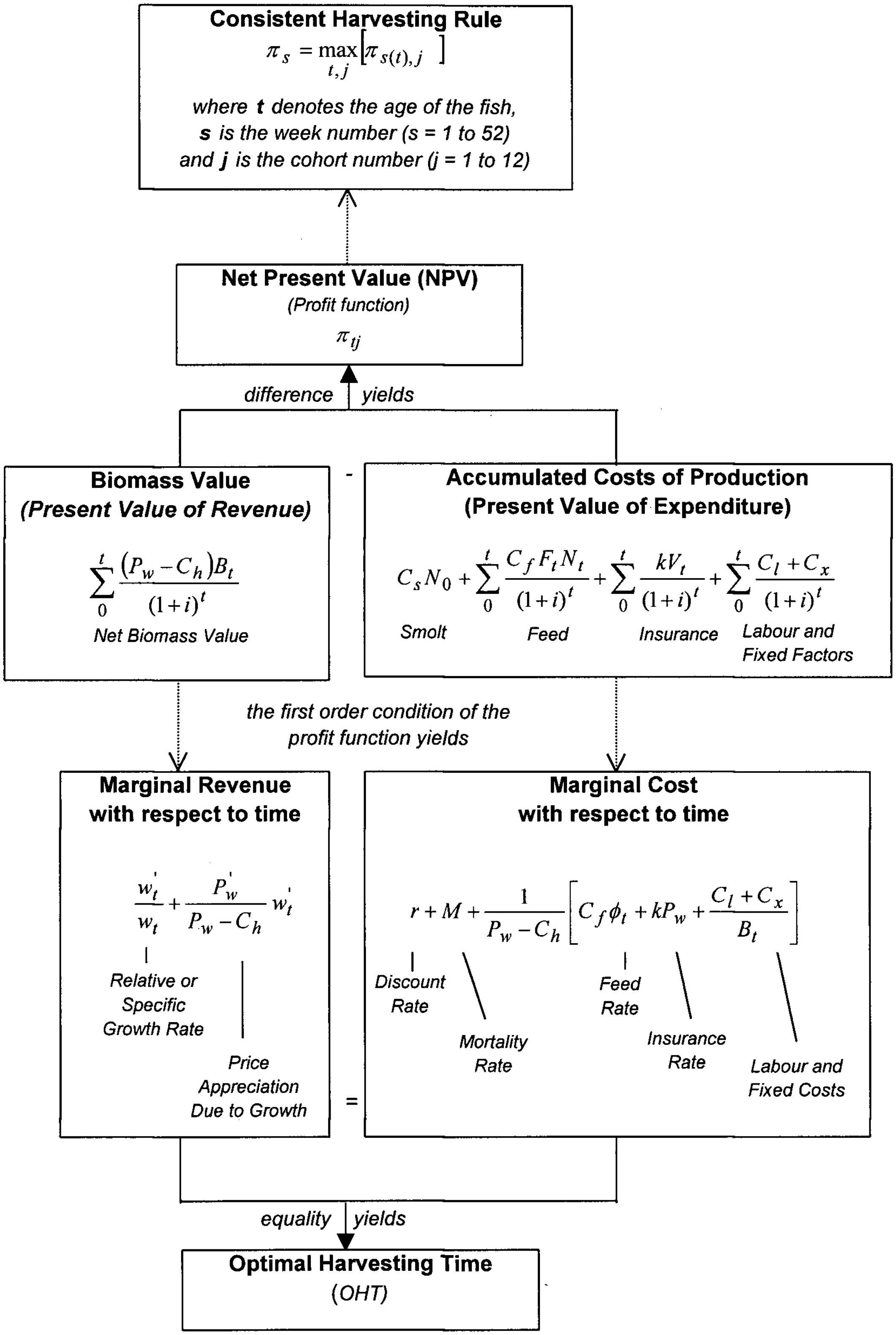
3.3.4 Summary of the economic model

The structure of the economic model is summarized in Figure 6. For each individual week of the year, a consistent harvesting strategy is achieved by selecting the cohort providing the highest net present value (NPV). The NPV is a result of the profit function and is the difference between the discounted value of biomass at harvest and the discounted value of the accumulated costs of producing the biomass from the purchase of smolts to harvest.

The first order condition of the profit function with respect to time yields the optimal harvesting rule. The optimal harvest time (OHT) is reached when the incremental (marginal) revenue gained from keeping a cohort for one more unit of time is offset by the incremental (marginal) cost incurred in the process.

[13] The cohort is no longer economically viable if its net present value is decreasing and falls below 0.

Figure 6 Schematic representation of the economic system in its discrete form.



4 Specification of model parameters

This study focuses on the two most important salmon species under culture in British Columbia, Chinook salmon and Atlantic salmon. For each species, six smolt entry strategies are considered. Strategies are differentiated by the timing of delivery and weight of the smolt to sea water. The characteristics of each strategy were presented in Table 2.

The bioeconomic model is composed of a biological model and an economic model. Both of these components rely on a series of sub-models. This chapter explains the assumptions underlying each sub-model. It also provides the source of the data used for modeling and calibration. Some of the data used for calibration was provided under strict confidentiality and therefore cannot be released.

4.1 Biological parameters

4.1.1 Growth curves

The growth model presented in equation 13 is a modified version of the Iwama-Tautz growth expression (1981). The original Iwama-Tautz expression captures the relationship between temperature and growth when weight gain is calculated over discrete intervals, but does not incorporate the relationship between size and growth. This latter relationship was introduced in Chapter 3 as a dampening factor (Df) reducing fish weight as calculated with the Iwama-Tautz expression. The modified growth expression models the expected relative growth path of a fish over its entire grow-out cycle. The absolute growth path for a representative member of a cohort requires calibrating the growth index (Gi) and the dampening factor.

The relationship between the Iwama-Tautz growth coefficient (Gc) and the Thermal Growth Coefficient (TGC) represented by Equation 11 is presented in Appendix 1. This relationship is summarized by the following equality;

$$Gc = TGC * 1000 .$$

With a specified Gc, fish weights forecasted by the growth model closely approximate actual weights over a short period of time. For predicting weight over the entire grow-out cycle, Df is required to introduce a size-growth relationship in the model.

Conceptually, the calibration procedure involves laying the growth curve predicted by the growth model over the actual growth curve, which is composed of actual fish weight data points. The growth curve calibration is a three-step procedure. The first step requires the calculation of a pair of growth coefficients (Gc). Over an undisturbed stanza of growth, the growth curve is expected to follow an S-shaped pattern called a Sachs cycle (Ricker 1979). Two inflexion points characterize this type of curve, the first one located near the bottom of the S-shaped curve and the second one located near top of the S-shaped curve. Each Gc should be calculated as close as possible to the time at which these two inflexion points occur. Using actual data, the first Gc (labeled Gc1) was computed for the interval covering seawater entry to approximately six months of grow-out age. The second Gc (labeled Gc2) was calculated for the interval of seawater entry to anytime between three months prior to harvest and harvest time. The second step involves the calibration of a preliminary growth curve. Using the first value calculated in the first step, the growth curve is specified by setting Gi equal to Gc1 and by setting Df to infinity in order to make this parameter an insignificant contributing factor. The first calibration step is then repeated on the data generated by the growth model and over the same time intervals used to generate Gc1 and Gc2. The resulting growth coefficients estimated using growth model data are labeled Gcm1 and Gcm2 respectively. The third and final step involves simultaneously adjusting the growth model parameters (Gi and Df) until Gc1 equals Gcm1 and Gc2 equals Gcm2.

The growth model was calibrated for five distinct groups of fish. The calibration results are presented in Table 6. In this table, the calibrated curve for each cohort was regressed against actual data using a standard OLS procedure. The statistical results for each cohort are shown below the estimated model parameters for each cohort. The actual growth data used in the calibration were aggregated composites of sample and harvest mean weight for various yearclass. The data are proprietary and cannot be disclosed.

Table 6 Growth curve calibration statistics for selected salmon cohorts

Production Cohorts					
Cohort	2	3	7	9	12
Species	Atlantic	Atlantic	Chinook	Chinook	Chinook
Smolt	S1/2	S1	S0	S1/2	S1
Growth model parameters estimates					
Gi	2.17	2.55	2.00	2.61	2.19
Df	3.75	2.75	2.90	1.60	4.27
Regression Results of Predicted to Actual data					
Coefficient	1.0330	1.0682	0.9666	1.0079	0.9708
Standard Error	0.0219	0.0244	0.0061	0.0096	0.0189
t Stat	47.2	43.8	158.8	104.8	51.5
Adj.R^2	93.0%	92.5%	93.8%	96.1%	92.4%
F Test	813	698	7,032	3,540	855
n	34	34	452	34	52

The model parameters for chinook salmon cohorts not part of the above table were estimated by interpolating values from calibrated results. For the Atlantic salmon cohorts not part of the above table, the model parameters were estimated using harvest data from the latter part of the growth cycle. The growth path derived for the non-calibrated cohorts are based on limited information and involve an 'educated guess'. The parameters for all cohorts are shown in Table 9. The non-linearity between the Atlantic salmon parameters is reflective of the variety of growth behaviours that exist between various strains and brood years of the same strain.

4.1.2 Feeding system

The feeding model parameters and their specified values are presented in Table 7. The digestible energy (DE) figure is a value commonly found in commercial diets. The energy content (EC) and dry matter (DM) figures are values that were estimated in wild adult chinook salmon. One would expect these values to differ for farmed stocks and between species (Dr. J.S. Anderson, pers. comm.), but the lack of references or data dealing with this issue prevented any discrimination between these factors. In this study, the parameter values are assumed to apply to both species.

All feed variables listed in Table 7 are assumed fixed within the model and over the entire production cycle. The extrinsic factor (EF) is set at 50% instead of 40% because the feed rate is computed using the starting weight. Fish mortalities incurred within the time frame for which the computations are done, are assumed to have consumed feed. Therefore, the appropriate EF is derived from the difference between the economic feed conversion ratio (EFCR) and the technical feed conversion ratio (TFCR).

Table 7 Feeding system parameters specification

Variable	Definition	Values
DM	Dry Matter	31.6
EC	Energy Content of Carcass	0.256
DE	Digestible Energy	20.5
EF	Extrinsic Factor	0.50

Sources: Higgs et al. (1995)
Northern Aquaculture, Feed Supplement (1996)

The feed model was tested on actual chinook salmon and Atlantic salmon data. Modeled feed rates for both groups were estimated using weekly weights periodically adjusted with sample and harvest data. For the same data sets, feed rates were extracted from a commercial feeding table adjusted to a feed conversion ratio (FCR) of 1.35. This FCR value resulted in the best fit, both, for the Atlantic salmon and chinook salmon data sets. For both species, actual feed rates were regressed against model feed rates and commercial table feed rates using the ordinary least square method. The coefficients of determination for each regression are presented in Table 8. For both species, higher coefficients of variation were obtained with the feeding model. The model performed better statistically on the chinook salmon data then it did on the Atlantic salmon data. Discrepancies between actual and model data for Atlantic salmon feed rates were likely related to data quality and husbandry practices. Overall, it is felt that the feeding model performed well for both species and that, pending more information and research on the source of discrepancies, the feeding model is considered the best available feed rate guideline for forecasting feed requirements.

Table 8 Coefficient of determination results from regressing actual feed rates against model and commercial table feed rates.

Species	Feeding Standard Model	Commercial Feed Table
Chinook salmon	86.4%	79.2%
Atlantic salmon	64.9%	40.1%

4.1.3 Mortality rates

During the course of production, the fish inventory of a given cohort is expected to decline over time as a result of continuously low level of mortality. In their respective studies, Bjorndal (1988, 1990) and Hean (1994) estimated a fixed mortality rate (M) parameter using the average natural mortality rate for a yearclass of Atlantic salmon. They further assumed that the fixed mortality rate held throughout the lifetime of the cohort. In British Columbia, there are indications that the mortality rate may have a propensity to increase as fish of a particular strain reaches sexual maturity. Each strain has it own characteristics with respect to the timing of maturation and the conditions that triggers this process. Given a set of assumptions, the mortality rate expected from particular strains may indeed be approximated with a fixed coefficient, while other strains may exhibit a significant increase in their death rate in the late stages of grow-out.

Actual mortality data was not available for this study. In lieu of actual data, two mortality rate scenarios are presented. The background information serving as the basis for the assumption underlying these two scenarios is first outlined. Mortality is a function of complex interaction between the environment, husbandry practices and the age/size/type of the fish. It varies over time and between generations. The discussion underlying the mortality scenarios presented below provides a simplistic, yet realistic reflection of a complex reality.

4.1.3.1 Causes of mortality

An essential element of fish husbandry is concerned with disease and health management. Mortality in cultured fish results from disease, predation and stress. Disease is one of the most limiting factors to viable fish farming (Anon. 1992). The prevalence of disease within a population is classified as follow (Stephen and Iwama 1997):

1. Epidemic: Disease occurs at a rate greater than expected in a population.
2. Endemic: Disease expected to occur at a specific regularity in a population.
3. Sporadic: Disease expected to occur in a population, but at low rates and at irregular intervals.

The term natural mortality as employed in Bjorndal (1988, 1990) and Hean (1994) presumably excludes disease outbreak of epidemic proportion. Such an event sustained over a short period of time would cause a sudden drop in live biomass. The fixed mortality rate assumption is more consistent with the endemic manifestation of a disease within a population.

Stress as a mortality factor is well established within the aquaculture community. Disease outbreaks are often linked to stress. A diseases is caused by a pathogen (bacterial, viral, fungal or parasitic organisms) altering the structure or function of a body which then presents a particular set of signs and symptoms that are distinctively different from what is considered a normal state (Stephen and Iwama 1997). Exposure to a pathogen is not enough to cause a disease. An exposed population must be susceptible to the strain of pathogen presented in sufficient quantity and long enough to cause disease. In addition, the dynamics of the population and the pathogen must be such that the disease can be perpetuated to cause adverse effects in the population (Stephen and Iwama 1997). Stress factors (stressors) can act to compromise the immune system so that the growth and proliferation of pathogen(s) is favoured (Wedemeyer 1997).

There are many sources of environmental, physical and biological stressors. Unfavourable water temperature and low dissolved oxygen levels in the water column are example of environmental stressors. The main sources of stress under normal cultural conditions and present toward the later stages of grow-out are physical and biological in nature. Physical stressors include disturbances such as fish handling, crowding and confinement. Typically, as fish within a cohort become larger, biomass density per cage also increases. Beyond certain density thresholds, the risk of incurring higher mortalities is significant (Wedemeyer 1997). At that point, pen density is reduced through harvesting, grading or by splitting the population.

Biological stressors do occur naturally during the salmon life cycle at critical stages of development such as parr-smolt transformation, sexual maturation and spawning. In particular, maturing fish show lower disease resistance than adult stage fish prior to sexual maturation (Stephen and Iwama 1997). Maturation is energetically expensive and is believe to significantly reduce the effectiveness of the immune system (Dr. G.A. Karreman, pers. comm.). Sexually maturing fish become increasingly susceptible to a variety of infections (Balm 1997). This in turns increases the number of fish susceptible to disease and other sources of stress.

4.1.3.2 Sexual maturation

Sexual maturation in salmonids is often accompanied by a slowing of the growth rate, increased mortality and a reduction in flesh quality (Jobling *et al.* 1993). In the aquacultural jargon the maturation process is referred to as jacking in chinook salmon and grilsing in Atlantic salmon. The maturation process may be under the influence of environmental signals and particularly dependent of photoperiod. Given its genetic predisposition, this process may be more prevalent as the fish reach certain age or weight thresholds (K. Onclin, pers. comm.). Prior to maturation, some aquaculturists have suggested that salmon may undergo a growth spur. This idea is controversial since there appears to be little empirical evidence supporting that claim (Dr. G. A. Karreman, pers. comm.). Still, assuming a positive correlation between growth and maturation, this hypothesis would suggest an early maturing cohort might have a relatively higher growth performance within a certain age bracket prior to maturation than a late maturing cohort within the same age bracket of its life.

Depending on their characteristics (species, strain and genetic condition), stocks will show marked changes in their appearance from early summer to late fall. As fish mature, flesh colour and quality deteriorates, and the skin changes from a silvery to a brownish colour. Both mortality and flesh quality deterioration result in an economic loss to the producer. While in some stocks the mortality effect predominates over the flesh quality problems, the reverse may also apply in other stocks. Regardless, flesh quality deterioration is equivalent in economic terms to an increase in the mortality rate. In his analysis, Bjorndal (1990) also equates sexual maturation with the end of the natural life cycle for a cohort of fish. This is despite the fact that Atlantic salmon has the capacity to recondition themselves to a relatively healthy silver condition. However, the economic viability of reconditioned stocks is compromised because of lost growth incurred during the maturation process and also because they are prone to a different set of post-harvesting problems.

4.1.3.3 Specification of two mortality rate scenarios

To analyze the economic impact of mortality during grow-out, two mortality scenarios are presented. The fixed mortality rate structure proposed in Bjorndal (1988, 1990) and Hean (1994) is retained as a basis in both cases. The fixed mortality rate assumes that fluctuations associated with sporadic or endemic disease manifestations are averaged out over time and it also assumes that no epidemic disease outbreak occurs over the life cycle of the fish.

4.1.3.3.1 Scenario 1: Fixed mortality relaxed by conditions for sexual maturation.

In this scenario, the mortality rate is held fixed until the cohort meets two initial conditions in the course of production. These conditions are specified as a weight threshold and a time threshold. When both conditions are meet, the mortality rate begins to increase in a proportion related to the growth rate. This procedure results in the mortality rate climbing at a faster rate for faster growing fish. Conversely, once the conditions are meet, this procedure results in a relatively lower mortality rate for slower growing fish. The weight threshold (LBMat) is set at 3000 grams and 3500 grams for chinook salmon and Atlantic salmon, respectively. A weekly mortality ceiling is set at 2.25% per week. The time threshold is set as any time between April 1st to September 30th of any year.

The mortality rate increases until either an upper weight threshold of 6500 grams (UBMat) is obtained or until the date of September 30th is reached. Once one of these two conditions is obtained, the mortality rate decreases at a rate of 10% per week and until the initial fixed mortality rate is re-established.

Once the two initial conditions are meet, the mortality rate increases in the following fashion;

$$M_t = M_{t-1}\left(1 + \frac{w_t - LBMat}{LBMat}\right),$$

given the following constraints;

1. $Month(4) \le Month(Date(t)) \le Month(9)$,
2. $LBMat \le w_t \le UBMat$,
3. $\mathrm{Max}(M_t)$=2.25%,

and where

Mt = Mortality rate at time t (percent).

Wt = average fish weight at time t (grams).

LBMat = Lower bound weight or initial weight condition (grams) above which the increasing mortality mechanism is initiated.

UBMat= Upper bound weight at which the increasing mortality mechanism is cancelled.

This formulation was derived based on personal observation and discussion. It reflects a simplified representation of reality. For some groups, the weight threshold may require a lower or higher value. The time threshold may also vary according to the strain and the water temperature. For simplicity, all values used in this study are kept the same for each cohort of each species. These values can be varied within the scope of a sensitivity analysis.

4.1.3.3.2 Scenario 2: Fixed mortality for the entire life cycle

In this scenario, the mortality rate is held fixed throughout the entire life cycle of the cohort. This type of scenario may be regarded as very optimistic in the British Columbia context. But it may be more consistent for strains that have been selected for their late-maturing characteristics.

4.1.3.3.3 Specification of weekly mortality rate parameters

In a submission to the Salmon Aquaculture Review Committee, the Cooperative Assessment of Salmonid Health (CASH) program indicated that Atlantic salmon sites reported in 1994 an average cumulative mortality rate of 15% after 23 months at sea. Chinook salmon sites reported in 1993 an average cumulative mortality rate slightly less than 20% after 24 months at sea (Stephen and Iwama 1997). For the purpose of this study, the weekly mortality rate for Atlantic salmon is set at 0.15% of inventory at the start of each week (13.8% cumulative mortality after 23 months). The weekly mortality rate for chinook salmon is set at 0.18% of inventory at the start of each week (17.1% cumulative mortality after 24 months). The parameter values presented above result in slightly better performance than those reported by the CASH program. This reflect the fact that higher mortality rates are typically incurred at smolt delivery for both species and that the actual chinook figures are likely influenced by S0 smolt performances which tends to sustain a greater proportion of loss within the first 6 months of production (Dr. G. Karreman, pers. comm.)

4.1.4 Summary specification of biological parameters

The values specified for the biological parameters required in the bioeconomic model are summarized in Table 9. For each cohort, the growth parameters and mortality rate assumptions are presented. The lower and upper weight thresholds for scenario 1 rate of mortality are labeled LBMat and UBMat respectively. Finally, the carcass recovery for chinook salmon and Atlantic salmon are 86% and 90% respectively. These values are required for converting fish round weights (whole fish) to fish head-on dressed weights (gutted weight).

Table 9 Specification of growth and mortality rate parameters for 12 salmon cohorts

Cohort	Smolt Type	Smolt Delivery Date	Smolt Entry Weight *g*	Gi	Df 10^5	Mortality Rate to Maturation *% per week*	LBMat *g*	UBMat *g*
Atlantic								
1	S1/2	1-Oct-94	50	2.05	3.50	0.15%	3,500	6,500
2	S1/2	15-Dec-94	90	2.10	3.50	0.15%	3,500	6,500
3	S1	20-Jan-95	90	2.20	2.75	0.15%	3,500	6,500
4	S1	1-Feb-95	50	2.20	2.75	0.15%	3,500	6,500
5	S1	15-Feb-95	100	2.35	4.50	0.15%	3,500	6,500
6	S1	15-Mar-95	45	2.20	2.75	0.15%	3,500	6,500
Chinook								
7	S0	1-Jun-94	7	2.00	2.90	0.18%	3,000	6,500
8	S1/4	1-Aug-94	40	2.11	3.10	0.18%	3,000	6,500
9	S1/2	15-Sep-94	35	2.21	3.25	0.18%	3,000	6,500
10	S1/2	1-Nov-94	50	2.28	2.75	0.18%	3,000	6,500
11	S1	15-Jan-95	55	2.31	2.25	0.18%	3,000	6,500
12	S1	1-Mar-95	55	2.67	1.70	0.18%	3,000	6,500

4.2 Economic Parameters

The economic model was outlined in Chapter 3. In keeping with the deterministic characteristics of this study, fluctuations and seasonal variations commonly found in some parameters were removed by averaging values over time. This is an issue particularly relevant with market prices and exchange rates. The major variable costs included in the model were also assumed fixed throughout the production cycle.

4.2.1 Market prices and exchange rates

Market prices for a selection of seafood products are collected and reported by Urner-Barry Publications in their bi-weekly Seafood Price-Current. Farmed salmon prices are quoted by weight class for each producing region supplying the US market and according to their port of entry or centre of distribution in the US. Farmed salmon originating from British Columbia are predominantly marketed through Seattle and are classified under the heading of West Coast Atlantic and Canadian King (alias spring or chinook). FOB Seattle market prices were extracted for West Coast Atlantic and Canadian King between November 2, 1995 and November 7, 1996. From this set of data, annual averages were computed for each weight class. The average exchange rate (US$/Cdn$) over that period of time was $0.7389. The resulting values for both species are presented in Table 10.

Table 10 FOB Seattle farmed salmon prices: Averages between November 2, 1995 and November 7, 1996

	Atlantic		**Chinook**	
Weight Classes	$US/ Dr Lb.	$Cnd/Dr kg	$US/ Dr Lb.	$Cnd/Dr kg
0-1 lb	$ -	$ -	$ -	$ -
1-2 lbs	$ 1.34	$ 3.99	$ 1.98	$ 5.90
2-4 lbs	$ 1.79	$ 5.34	$ 2.21	$ 6.61
4-6 lbs	$ 2.14	$ 6.37	$ 2.30	$ 6.86
6-8 lbs	$ 2.31	$ 6.89	$ 2.30	$ 6.86
8-10 lbs	$ 2.39	$ 7.14	$ 2.33	$ 6.94
10-12 lbs	$ 2.42	$ 7.22	$ 2.33	$ 6.94
12 lbs up	$ 2.39	$ 7.14	$ 2.33	$ 6.95

Source: Urner Barry Publications Inc., Toms River, NJ (various issues of Seafood Price Current)

4.2.2 Factor costs

The major inputs used during production are smolts, feed, insurance services, labour, fixed and harvest costs. The factor costs related to the latter five elements are presented in Table 11. Each cost factor is assumed fixed over the entire production cycle. Labour and fixed costs are assumed to be a direct function of the species and the number of smolt recruited for production. Lower values are assigned to Atlantic salmon to reflect the higher density characterizing the rearing of that species. The labour cost structure also implicitly assumes the utilization of autofeeders to minimize hand feeding activities, thus enabling the producer to regulate labour requirements over time. Harvest costs include the cost factors incurred between on-site harvesting and delivery of the dressed head-on product to Seattle. This definition of harvest cost incorporates harvest and marine transport of the fish to the processing plant, gutting and boxing activities (including boxing material) at the processing/boxing plant and, finally, the freight expenses to deliver the boxed product to Seattle. It excludes fees paid to brokers.

Table 11 Specification of selected cost parameters

Factor costs		**Cost *(Cdn$)***
Feed cost per kg		$ 1.25
Annual insurance rate		3.50%
Daily labour cost per smolt – Chinook salmon		$0.00260
Daily labour cost per smolt – Atlantic salmon		$0.00240
Daily fixed cost per smolt – Chinook salmon		$0.00325
Daily fixed cost per smolt – Atlantic salmon		$0.00300
Harvest Cost per kg:		
Marine transport	$ 0.20	
Gutting	$ 0.45	
Boxing	$ 0.35	
Land Transport to Seattle	$ 0.22	
Total harvest cost		$ 1.02

Sources: ARA Consulting Group Ltd (1994)
Personal Communication

Smolt expenses vary depending on the species and the age of the smolt. Atlantic smolt costs are typically higher than Chinook smolt costs because of greater rearing time required in fresh water and because of supply restrictions in importing Atlantic eggs. The Atlantic fry is more labour intensive than its chinook counterpart since it requires additional care to survive the fry growth stanza. The smolt costs used in this study are listed in Table 12. Smolt costs do fluctuate as a function of supply and demand. The figures presented in Table 12 are mean expected market prices.

Table 12 Average smolt costs for selected types of production

Species	Smolt type	Cdn$/Smolt
Atlantic salmon	S1	$ 2.50
	S1/2	$ 2.50
Chinook salmon	S0[14]	$ 0.70
	S1/4	$ 2.00
	S1/2	$ 2.25
	S1	$ 2.25

Sources: Personal Communication
ARA Consulting Group Ltd (1994)

4.2.3 Discount rates

In the context of investment theory, the optimal harvesting problem is solved by maximizing the present discounted value of the investment (Bjorndal 1990). The capital required for rearing salmon in an enclosed area is the value invested in the fish, which accumulates as they grow. These capital resources are committed into the fish rather then in another investment earning an available rate of return. The foregone interest or rental rate of capital is an opportunity cost that is captured with the selection of a discount rate.

The selection of the discount rate depends upon available sources of credit and the level of risk involved in a project. The appropriate discount rate to introduce to an analysis can be inferred from available market

[14] S0 chinook salmon are introduced as 5 to 7 grams smolts into sea water after six months of fresh water rearing (post-hatching). This type of smolt is much cheaper to produce since it is far less labour intensive to rear than older and bigger smolts, which require grading and a higher degree of attention. Because of their size, S0 salmon smolts need very little rearing space relative to an equivalent number of bigger smolts.

opportunities. The interest rate offered by banks, for instance, may be appropriate for debt financing relatively low risk ventures. However, uncertainties in a project appraisal may require the incorporation of a risk premium to the discount rate. Uncertainty can be expressed in terms of the probability of failure of the project or in terms of risk aversion (Sugden *et al.* 1986). In either case, the addition of risk premium to the discount rate depends of the perception the capital lender has of the firm and the industry.

In aquaculture, sensitivity analysis is a popular means of estimating the impact of various discount rates on the optimal harvest time. Risk management being an intrinsic reality in salmon farming, several authors have used discount rates of 0%, 5%, 10% and 20 % (Bjorndal 1988, 1990; Hean 1993; Arnason 1992). However, the real rate of return on all debt and equity capital in Canada is estimated at 4% to 7%. In the aftermath of a massive restructuration in the early 1990's, the salmon farming industry in Canada as emerged as a more stable and globally competitive aquacultural sector. Given the level of maturity attained by the industry, discount rates of 5% for average operations and 7% for riskier operations are more in line with the real rate of return on capital with other spheres of economic activities in Canada. In their studies, Bjorndal (1988, 1990) and Hean (1994) concluded that the timing of optimal harvest in salmon aquaculture was relatively insensitive to changes in the interest rate. Given these conclusions and the risk associated with production and market prices for the industry today, a discount rate of 7 percent seems an appropriate figure.

5 Results and discussion

Salmon cohorts of a same species are differentiated by their genetic origins, their smolt size and stocking date into sea water. The elaboration of a consistent harvest strategy involves the selection of cohorts that together will provide a sustained availability of harvest size fish year-round in an economically efficient manner. Using the theory of optimal harvest time developed in Chapter 3, the analysis initially focuses on the biological and economic aspects characterizing each cohort. The results of this analysis are presented in section 5.1. Results extracted from the bioeconomic model are then collated together to derive a consistent harvesting strategy. The objective in this type of analysis is to select the cohort providing the highest present value from investment. The results of the consistent harvesting analysis are presented and discussed in section 5.2.

5.1 Optimal harvest time results

The optimal harvest times (OHT) for the twelve cohorts presented in Table 9 were computed using the bioeconomic model developed in Chapter 3 and the optimal harvesting rule presented in Equation 30. The OHT for each cohort were calculated for the two mortality rate scenarios described in section 4.1.3. In scenario 1 the mortality rate is held fixed until two conditions are met, after which it begins to increase in a proportion related to the growth rate. This assumption is regarded as more realistic or middle of the road scenario since it encompasses the economic effects of maturation and pathogenic factors on the mortality rate and/or the flesh quality deterioration. In scenario 2, the mortality rate is held fixed throughout the life of the cohort. This scenario is generally considered optimistic. Together, these two scenarios provide a risk perspective with scenario 1 representing a lower bound or a less risky option, while scenario 2 represents an upper bound or more risky option.

The OHT for a given cohort occurs when the marginal revenue with respect to time equals the marginal cost of holding the fish for an additional unit of time. As described mathematically in Equation 30, the OHT is reached when the relative growth rate plus the net price appreciation due to growth is offset by the summation of the discount rate, the mortality rate and the relative costs of feed, insurance, labour and fixed components. The relative growth rate is expected to vary over time as a function of water temperature (growth/temperature relationship) and to decrease at a decreasing rate as fish increases in size (growth/size relationship). The price appreciation component is expected to be positive as along as price is positively correlated with fish weight. On the cost side, feed, insurance, labour and fixed cost components are all a partial function of fish weight. In general, these costs are expected to decrease at a decreasing rate as the fish increases in size. A decline in biomass, however, would result in a relative increase in labour and fixed costs. The temperature effect on growth is important as it could result in local OHT. The search for the global OHT is achieved by calculating the present value of a cohort for discrete time periods up to the time at which maximum fish weight is achieved.

The OHT results for the twelve cohorts are presented in Tables 13 and 14. In Table 13, the optimal harvest conditions were computed assuming the increasing mortality rate case (scenario1). In Table 14, the optimal condition reflects the fixed mortality rate case (scenario 2). In both tables, the optimal harvest times are provided for the number of weeks required to reach the economic optimum (present value), maximum population biomass (yield) and maximum fish weight (weight). The relative contribution of the marginal revenue and marginal cost parameters are also presented for the week at which the economic OHT is reached. Relative contribution figures provide a standardize mean by which to compare and rank the importance of a specific parameters vis-à-vis other parameters.

There are several observations to draw from these results. For all cohorts in both mortality rate scenarios, the economic OHT precedes the time at which maximum biomass is reached, which itself occurs before maximum fish weight. This result is consistent with the theoretical observations discussed in comparing Equation 23 to Equation 8 in section 3.3.1. The time of maximum fish weight represents the economic OHT in the hypothetical case where there is no correlation between fish weight and market prices, and

Table 13 Relative change in marginal revenue and marginal cost parameters at optimal harvest time (OHT) as a proportion of biomass value assuming scenario 1 mortality rates. Also shown with the economic OHT are the times at which biomass and individual fish weight are maximized.

Optimal Harvest Times				Marginal Revenue		Marginal Cost					
Cohort	Present Value *Week*	Yield *Week*	Weight *Week*	Relative Growth Rate *%*	Relative Price Apprec. *%*	Discount Rate *%*	Mort. Rate *%*	Feed Rate *%*	Insu-rance *%*	Labour *%*	Fix *%*
1	98	100	123	0.333	0.031	0.019	0.154	0.135	0.012	0.011	0.014
2	87	89	112	0.370	0.031	0.019	0.151	0.140	0.012	0.011	0.014
3	78	80	100	0.379	0.031	0.019	0.171	0.140	0.012	0.011	0.014
4	91	102	145	0.208	0.017	0.019	0.063	0.103	0.012	0.011	0.014
5	77	82	144	0.427	0.027	0.019	0.194	0.148	0.012	0.010	0.013
6	89	113	140	0.152	0.013	0.019	0.020	0.087	0.012	0.011	0.014
7	84	107	133	0.191	0.006	0.019	0.026	0.095	0.012	0.021	0.026
8	75	96	124	0.194	0.006	0.019	0.026	0.094	0.012	0.019	0.023
9	88	91	124	0.319	0.009	0.019	0.132	0.131	0.012	0.015	0.019
10	84	88	112	0.340	0.011	0.019	0.126	0.142	0.012	0.016	0.021
11	82	84	101	0.364	0.011	0.019	0.154	0.155	0.012	0.016	0.020
12	75	78	92	0.354	0.011	0.019	0.124	0.154	0.012	0.016	0.020

Table 14 Relative change in marginal revenue and marginal cost parameters as a proportion of biomass value at optimal harvest time (OHT) assuming scenario 2 mortality rates. Also shown with the economic OHT are the times at which biomass and individual fish weight are maximized.

Optimal Harvest Times				Marginal Revenue		Marginal Cost					
Cohort	Present Value *Week*	Yield *Week*	Weight *Week*	Relative Growth Rate *%*	Relative Price Apprec. *%*	Discount Rate *%*	Mort. Rate *%*	Feed Rate *%*	Insu-rance *%*	Labour *%*	Fix *%*
1	109	119	123	0.169	0.004	0.019	0.021	0.094	0.012	0.009	0.011
2	99	109	112	0.174	0.002	0.019	0.021	0.092	0.012	0.009	0.011
3	92	99	100	0.164	0.001	0.019	0.021	0.094	0.012	0.008	0.010
4	93	102	145	0.166	0.011	0.019	0.021	0.092	0.012	0.010	0.013
5	93	143	144	0.149	0.000	0.019	0.021	0.081	0.012	0.007	0.009
6	89	137	140	0.152	0.013	0.019	0.021	0.087	0.012	0.011	0.014
7	121	131	133	0.198	0.003	0.019	0.026	0.117	0.012	0.012	0.016
8	112	122	124	0.198	0.002	0.019	0.026	0.116	0.012	0.011	0.014
9	110	120	124	0.192	0.001	0.019	0.026	0.106	0.012	0.009	0.012
10	101	110	112	0.201	0.003	0.019	0.026	0.114	0.012	0.011	0.014
11	91	100	101	0.202	0.004	0.019	0.026	0.115	0.012	0.013	0.016
12	83	90	92	0.203	0.005	0.019	0.026	0.119	0.012	0.013	0.017

where the cost of production and the mortality rate are both set equal to 0. For a given cohort, maximum fish weight is the same in both tables since it is assumed to be independent of mortality.

The time of optimal yield represents the economic OHT in the hypothetical case where the mortality rate equal the relative growth rate and where the sum of the discount rate, feed rate, insurance, labour and fixed cost components is equal to the net price appreciation due to growth.

The major difference between results derived from the scenario 1 and scenario 2 mortality rate assumptions reside in the difference between the OHT and the time at which yield is maximized. In Table 14, a continually low and fixed mortality rate represents on average 13% of incremental costs at OHT, whereas feed cost accounts for 53% to 58% of incremental costs. The relatively low impact of mortality rate on the cost structure implies that the time of optimal yield is closer to the time of optimal fish weight than it is to the OHT. The gap between the OHT and time of optimal yield is a result of feed costs and worsening biological feed conversion ratio (BFCR) as the fish increases in weight. In the case of fixed mortality rate (scenario 2), the dominating effect of feed cost on the OHT is consistent with the conclusions reached by Bjorndal (1988, 1990) and Hean (1993).

In Table 13, the increase in mortality rate has a predominant impact on the economic and the time of optimal yield. At the OHT, the mortality rate and the feed rate represent respectively 34% and 43 % of average incremental costs. In many cases, the contribution from the mortality factor on the marginal cost at OHT surpasses the contribution from the feed factor. The relatively higher impact of mortality rate on the cost structure implies that the time of optimal yield is closer to the OHT than it is to the time of optimal fish weight. The OHT is reached earlier in scenario 1 since the cost of a higher mortality rate is incurred at the expense of a higher relative growth rate. A higher mortality rate implies an opportunity cost from lost biomass as well as from lost revenue due to growth and to the net price appreciation resulting from growth.

The impact of increasing mortality in adult fish is evident in comparing optimal harvest times and maximum yields times from both mortality rate scenarios. With one exception, economic and biomass optima consistently occur at earlier times under the case where mortality increases (scenario 1 in Table 13). The reason behind this result is found in analyzing the contribution of marginal cost components to the OHT presented in, both, Table 13 and Table 14. For instance, the OHT for the Atlantic salmon Cohort 3 occurs at 78 weeks under the increasing mortality rate scenario and at 92 weeks under the fixed mortality rate scenario. In both scenarios, fish growth is identical regardless of mortality. At their respective OHT, the contributions of the mortality rate to marginal costs are 0.171% and 0.021% of biomass value for the increasing mortality case and the fixed mortality case, respectively. In the latter case, it is profitable to growth the fish population for an additional 14 weeks because extra profits are captured until week 92 of production into sea water. Since the relative growth rate of the fish is a decreasing function of fish weight, the relative growth rate of the fish during these 14 weeks decreases as fish increases in size. As shown in equation 30, the relative growth rate is an important component of the marginal revenue structure, as is the mortality rate for the marginal cost structure. At OHT, the contributions of the relative growth rate to marginal revenues are 0.379% and 0.164% of biomass value in the increasing mortality case and fixed mortality case, respectively. Because biomass losses are much lower in the fixed mortality scenario, production is pursuit until the incremental value of growth is primarily offset by mortality and feed related costs. Maximum yield occurs ten weeks after OHT when the gain in biomass due to a decreasing growth is offset by the loss in biomass due to a constant mortality rate. As shown in equation 8, maximum yield is not a function of feed cost. In the increasing mortality case, maximum yield occurs only two weeks after OHT as biomass loss due to mortality quickly offset biomass gain due to growth.

The effect of increasing mortality onto the marginal cost in relation to the marginal revenue for cohort 3 is graphically represented in Figure 12 (page 89). In this figure, the thick full line shows the change in the marginal cost with respect to time for scenario 1. At the time where the mortality rate begins to increase above the fixed mortality rate level, the thick full line increases upward and departs from the path it would have followed had the mortality rate remained fixed. The path for marginal cost with respect to time under the fixed mortality rate scenario (scenario 2) is represented by the dotted line that emerges from the thick full line at the point where the two conditions triggering scenario 1 are meet. Coming from above, the thin full line depicts the change in the marginal revenue with respect to time. The intersection between the thin full line and the thick full line represents the OHT for the increasing mortality case (scenario 1). This point also corresponds in Figure 11 with the time at which the NPV per smolts is maximized. In this particular figure the OHT occurs before the time at which the optimal biomass (yield per smolt) is reached, itself preceding the time at which individual fish weight is achieved. The time at which the thin full line and the dotted line intersect in Figure 12 is the OHT corresponding to scenario 2.

Over time, the incremental fish weight decreases in relation to the actual fish weight because of the fish size/fish growth relationship discussed in Section 3.2.2.1. With a constant temperature regime, this characteristic of fish growth means that the marginal revenue decreases over time. This reflects the law of diminishing returns. The upward fluctuations in the marginal revenue curve are caused by the positive correlation between water temperature and growth[15]. Alternatively, slow growth in the fall and winter months causes the marginal revenue curve to decrease at an increasing rate over a certain period of time. In adult fish and under the fixed mortality rate scenario case, the rate of decrease in the marginal revenue is greater than the rate of decrease in the marginal cost curve. Consequently, an increase in the mortality rate occurring in the later stage of growth implies that cost attributed to lost biomass causes the marginal cost curve to increases beyond the diminishing gains attributed to growth. This situation is well represented in Figure 8 (Atlantic salmon cohort 1), Figure 10 (Atlantic salmon cohort 2), Figure 12 (Atlantic salmon cohort 3), Figure 16 (Atlantic salmon cohort 5), Figure 24 (chinook salmon cohort 9), Figure 26 (chinook salmon cohort 10), Figure 28 (chinook salmon cohort 11) and Figure 30 (chinook salmon cohort 12). In each of these cases, the two conditions required to trigger an increase in mortality occur early in the spring or summer. These cohorts could be assumed to have a high maturation rate. However, in the case where those two harmful conditions occur in late summer (July and August), the contribution of the mortality factor to the marginal cost is less dramatic than in the former case. This situation is represented in Figure

[15] The positive correlation between growth and temperature is valid over a certain range of water temperature. Above a certain threshold, water temperature can be negatively correlated with growth (Kreiberg 1990b; McDonald *et al.* 1996). In this study, the water temperature is assumed not to increase above that particular threshold.

14 (Atlantic cohort 4) and Figure 18 (Atlantic cohort 6). For both cohorts, the OHT under mortality rate scenarios 1 and 2 are close or identical. This type of cohort could be assumed to have a low maturation rate and a high resilience to pathogenic agents.

A peculiar situation occurs with the chinook salmon S0 (cohort 7) and S1/4 (cohort 8). This story is represented in Figure 18 and Figure 20 respectively. These cohorts are characterized by low growth indices relative to other chinook salmon cohorts. In both cases, the cost of holding the fish over the winter months is greater than the benefits gained from growing them. With increasing water temperature, the benefits of holding these stocks becomes greater than the additional costs of rearing them if mortality is controlled. If mortality is allowed to increase in the spring as the trigger conditions are meet, the OHT would take place at the start of the winter, 84 weeks into production in the case of cohort 7. The calendar dates corresponding to each OHT is provided Table 15 and Table 16. However, if mortality remains constant, the OHT occurs at the end of the following summer, 121 weeks into production for cohort 7. For both cohorts, the discounted gains cumulated during the second summer offset the losses sustained over the winter.

Economic and production performances at OHT

The economic and production performances at optimal harvest time for the twelve cohorts are presented Table 15 and Table 16 for mortality rate scenarios 1 and 2 respectively. In the first section of these Tables, three economic thresholds are presented. The first threshold is the time at which the investment into the cohort breaks even (where average revenue (AR) equal average cost (AVC)). The second threshold is the time at which the variable cost is minimized (AVC equal marginal cost (MC)). The third threshold is the optimal harvest time, which represents the time at which profit is maximized (MC equal marginal revenue (MR)). These economic thresholds are essential consideration in planning the harvest of a cohort. The earliest time when a cohort may be harvested is at the break-even point. If a cohort is harvested over a period of time, harvest may be postponed until the production cost reaches its minimum. This may be a particularly appropriate strategy in a situation where market prices are stochastic.

The production and economic performances at optimal harvest time are presented, respectively, in the second and third sections of Table 15 and Table 16. These results assume that the entire cohort biomass is harvested at its economic optimum. Under this condition, the population biomass resulting from one smolt equal the yield per smolt, which is itself the product of fish weight and the survival rate at harvest. These parameters along with the economic feed conversion ratio are presented in the production performance section. In comparing the results from both tables, cohorts are harvested at a smaller weight under the higher mortality rate scenario (Table 15). In the economic performance section, the present value (PV) per smolt at harvest for the increasing mortality scenario is also characterized by lower returns relative to the fixed mortality case scenario.

The direct cost of mortality and the opportunity cost related to foregone growth for a particular cohort is represented by the difference between the present value per smolt in the two tables, which is equivalent to the net profit at OHT. For instance, the opportunity cost attributable to a surge in mortality for cohort 7 (Chinook S0 group) is estimated at $2.77 per smolt and result in the optimal harvest time occurring 37 weeks earlier than a situation where the mortality rate is fixed. The small difference in the survival rates between the two mortality rate scenarios implies that by harvesting the cohort at its economic optimum, the financial loss directly attributable to dead fish biomass is minimized. The difference in the yield per smolt between the tables is the biomass foregone because of the surge in the mortality rate. For cohort 7, this difference in the yield per smolt is 1.75 kg or 48.3% of the yield in scenario 2. The minimum opportunity cost resulting from this lost of yield is difference between the two present values, which amounts to $0.85 per smolt. For large operations, the opportunity cost resulting from increasing mortality is an important source of economic lost.

Under the assumptions underlying the bioeconomic model and parameters, the figures presented in Table 15 and Table 16 suggest that the production of Atlantic salmon results in production and economic performances that are superior to those obtained with chinook salmon. This conclusion is consistent with the increasing predominance of farmed Atlantic salmon in the British Columbia industry since 1992. There are several factors that would explain the economic advantage of Atlantic salmon. First, carcass yield recovered after processing (dressed weight) is higher with Atlantic salmon (assumed 90% for Atlantic salmon and 86% for Chinook salmon). This characteristic implies that a greater proportion of invested capital is recovered per weight of fish harvested. Second, the mortality rate for Atlantic salmon is typically lower, particularly during the second year of production. Over that same period of time, chinook salmon health is less resilient, resulting in a higher mortality rate of harvest size fish. These characteristics were included as assumptions in the analysis and specified in terms of a lower mortality rate for Atlantic salmon and a higher weight threshold at which the mortality rate began to increase. The impact of these assumptions is reflected in the results. A lower mortality rate for Atlantic salmon resulted in a comparatively better EFCR[16] and lower feed costs. It also resulted in a lower marginal cost, which enabled a longer period of growth to be capitalized in terms of additional profit. The later benefit is reflected in higher yields per smolt and both benefits together contributed for higher variable profits and present values per smolt.

The timing of OHT under a fixed mortality rate scenario (Table 16) draws attention to the influence of water temperature on growth. In this scenario, all OHTs occur in the fall between the months of September and November. The marginal revenue is offset by the marginal cost as the water temperature decreases at an increasing rate. As the water temperature falls, feeding becomes less efficient and other costs remain fixed. Under an increasing mortality rate scenario, mortality becomes the most limiting factor. With the special exception of cohort 7 and 8, the influence of water temperature on OHT is dampened by the mortality factor. For cohorts 9 to 12, the OHT takes place throughout the summer. Overall, warm water temperatures have a significant influence in determining the OHT.

The timing of smolt introduction into seawater influences the length of the production cycle in the fixed mortality case. A fall seawater introduction implies that a cohort is reared over two sea winter, time at

[16] Economic feed conversion ratio, which is the amount of feed units required to gain one additional unit of population biomass.

which growth is the slowest. A late winter or spring entry involves less rearing time in cold water conditions. In Table 16, fall entry cohorts have the longest rearing time and spring entry cohorts have the shortest rearing time. In the increasing mortality scenario, the effect of the timing of smolt introduction on OHT is ambiguous since it also influences with smolt size and growth potential (determined by the *Gi* and *Df* coefficients) the conditions triggering an increase in the mortality rate.

The effect of smolt size on OHT or profitability is largely a function of the fish growth potential. However, if two cohorts are introduced as smolt into seawater at a similar time and are believed to have the same growth potential, the larger smolt would be harvested earlier and would reap larger profits in a deterministic scenario. The results for Atlantic cohort 3 and cohort 4 provide an example of this situation. These cohorts were introduced to seawater as 90 gram and 50 gram smolts respectively. In the fixed mortality rate scenario, cohort 3 reaches its OHT one week earlier than cohort 4 since its specific growth rate, which is a function of fish weight, is lower (6.61 kg versus 5.11 kg at OHT for cohorts 3 and 4 respectively). In the increasing mortality scenario, cohort 3 reaches its OHT 13 weeks earlier than cohort 4 as a result of triggering at an early time the conditions activating the increasing mortality rate mechanism. Despite the substantial gap in the timing of their respective optimal harvest time, harvest weights for both cohorts is similar. This time gap results in lower costs for cohort 3 and a higher profit per smolt, despite the fact that both cohorts earned similar nominal revenues at harvest. Given the similar time of smolt entry and equal growth potentials, bigger smolt sizes result in shorter rearing time and lower cost of production during grow-out.

Table 15 Economic thresholds and performances at optimal harvest time (OHT) assuming an increasing mortality rate (scenario 1). The economic thresholds section shows the seawater age and the time at which the break-even point (AR=AC), the cost minimizing time (AC=MC) and the OHT (MC=MR) are reached for each cohort. The second and third sections present the state of key production and economic parameters at OHT. Production figures include weight, maximum yield per smolt, survival rate and economic feed conversion ratio. Economic figures include the nominal and real market prices, the average revenue and average cost, the profit per kilogram and the net present value per smolt. All biomass and currency figures are in round (whole) fish weight (rnd kg) and in Canadian dollar ($Cdn) respectively.

	Economic Thresholds						**Production performance at OHT**				**Economic performance at OHT**					
Cohort	AR = AC	AC = MC	MC = MR	AR = AC	AC = MC	MC = MR	Weight	Max. Yield	Surv.	EFCR	Market Price (nom.)	Market Price (real)	AR	AC	profit per kg	NPV per smolt
	Number of Weeks				*Week*		*rnd kg*	*rnd kg/ smolt*	*%*		*$Cdn/ rnd kg*	*$Cdn/ rnd kg*	*$Cdn/ rnd kg*	*$Cdn/ rnd kg*	*$Cdn/ rnd kg*	*$Cdn/ smolt*
Atlantic salmon (*Salmo salar*)																
1	59	97	98	12-Nov-95	04-Aug-96	11-Aug-96	4.87	4.06	83.3	1.50	6.37	5.58	4.51	3.30	1.21	4.90
2	48	86	87	12-Nov-95	04-Aug-96	11-Aug-96	4.96	4.21	84.8	1.43	6.37	5.67	4.58	3.07	1.51	6.38
3	39	77	78	15-Oct-95	07-Jul-96	14-Jul-96	4.98	4.26	85.4	1.38	6.37	5.74	4.64	3.00	1.64	6.96
4	62	87	91	07-Apr-96	29-Sep-96	27-Oct-96	4.99	4.21	84.3	1.47	6.38	5.64	4.56	3.22	1.34	5.64
5	40	76	77	19-Nov-95	28-Jul-96	04-Aug-96	5.23	4.46	85.3	1.35	6.39	5.76	4.66	2.89	1.77	7.90
6	61	85	89	12-May-96	27-Oct-96	24-Nov-96	4.88	4.22	86.5	1.44	6.37	5.65	4.56	3.16	1.40	5.91
Chinook salmon (*Oncorhynchus tschawytscha*)																
7	58	80	84	09-Jul-95	10-Dec-95	07-Jan-96	3.11	2.67	85.8	1.34	5.89	5.25	4.16	3.13	1.04	2.77
8	52	73	75	30-Jul-95	24-Dec-95	07-Jan-96	3.43	2.99	87.2	1.32	5.90	5.33	4.23	3.27	0.96	2.87
9	52	87	88	10-Sep-95	12-May-96	19-May-96	4.35	3.62	83.4	1.39	5.93	5.27	4.19	3.27	0.91	3.31
10	47	84	84	24-Sep-95	09-Jun-96	09-Jun-96	4.02	3.36	83.7	1.41	5.92	5.29	4.20	3.38	0.82	2.76
11	44	82	82	19-Nov-95	11-Aug-96	11-Aug-96	4.19	3.49	83.4	1.42	5.93	5.30	4.21	3.37	0.84	2.94
12	35	75	75	29-Oct-95	04-Aug-96	04-Aug-96	4.07	3.46	85.1	1.39	5.93	5.35	4.25	3.29	0.96	3.31

Where AR = average revenue; AC = average cost; MC = marginal cost; MR = marginal revenue; NPV = net present value.

Table 16 Economic thresholds and performances at optimal harvest time (OHT) assuming a fixed mortality rate (scenario 2). The economic thresholds section shows the seawater age and the time at which the break-even point (AR=AC), the cost minimizing time (AC=MC) and the OHT (MC=MR) are reached for each cohort. The second and third sections present the state of key production and economic parameters at OHT. Production figures include weight, maximum yield per smolt, survival rate and economic feed conversion ratio. Economic figures include the nominal and real market prices, the average revenue and average cost, the profit per kilogram and the net present value per smolt. All biomass and currency figures are in round (whole) fish weight (rnd kg) and in Canadian dollar ($Cdn) respectively.

	Economic Thresholds						Production performance at OHT				Economic performance at OHT					
Cohort	AR = AVC	AVC = MC	MC = MR	AR = AVC	AVC = MC	MC = MR	Weight	Max. Yield	Surv.	EFCR	Market Price (nom.)	Market Price (real)	AR	AVC	profit per kg	PV per smolt
	Number of Weeks				*Week*		*kg*	*kg/smolt*	*%*		*$Cdn/ rnd kg*	*$Cdn/ rnd kg*	*$Cdn/ rnd kg*	*$Cdn/ rnd kg*	*$Cdn/ rnd kg*	*$Cdn/ smolt*
Atlantic salmon (*Salmo salar*)																
1	59	107	109	12-Nov-95	13-Oct-96	27-Oct-96	5.93	5.03	84.8	1.55	6.42	5.54	4.49	3.14	1.34	6.75
2	48	96	99	12-Nov-95	13-Oct-96	03-Nov-96	6.26	5.39	86.1	1.49	6.42	5.62	4.55	2.92	1.63	8.79
3	39	88	92	15-Oct-95	22-Sep-96	20-Oct-96	6.61	5.75	87.0	1.46	6.42	5.68	4.60	2.84	1.76	10.10
4	62	90	93	07-Apr-96	20-Oct-96	10-Nov-96	5.11	4.44	86.8	1.45	6.38	5.63	4.55	3.13	1.42	6.31
5	40	88	93	19-Nov-95	20-Oct-96	24-Nov-96	7.29	6.33	86.8	1.42	6.43	5.67	4.59	2.70	1.89	11.96
6	61	86	89	12-May-96	03-Nov-96	24-Nov-96	4.88	4.27	87.4	1.43	6.37	5.65	4.56	3.13	1.43	6.10
Chinook salmon (*Oncorhynchus tschawytscha*)																
7	58	119	121	09-Jul-95	08-Sep-96	22-Sep-96	5.51	4.42	80.3	1.66	5.96	5.06	4.02	3.21	0.82	3.62
8	52	111	112	30-Jul-95	15-Sep-96	22-Sep-96	6.10	4.98	81.6	1.64	5.96	5.13	4.08	3.25	0.82	4.09
9	52	108	110	10-Sep-95	06-Oct-96	20-Oct-96	7.06	5.78	81.9	1.52	5.97	5.15	4.10	2.96	1.14	6.59
10	47	99	101	24-Sep-95	22-Sep-96	06-Oct-96	5.81	4.83	83.2	1.52	5.96	5.20	4.14	3.12	1.02	4.92
11	44	90	91	19-Nov-95	06-Oct-96	13-Oct-96	5.01	4.25	84.7	1.47	5.95	5.26	4.18	3.21	0.97	4.10
12	35	81	83	29-Oct-95	15-Sep-96	29-Sep-96	4.76	4.09	86.0	1.45	5.94	5.31	4.22	3.19	1.03	4.21

Where AR = average revenue; AC = average cost; MC = marginal cost; MR = marginal revenue; NPV = net present value.

Figure 7 Dynamics of fish growth, population yield and present value from investment for cohort 1 and assuming mortality rate scenario1

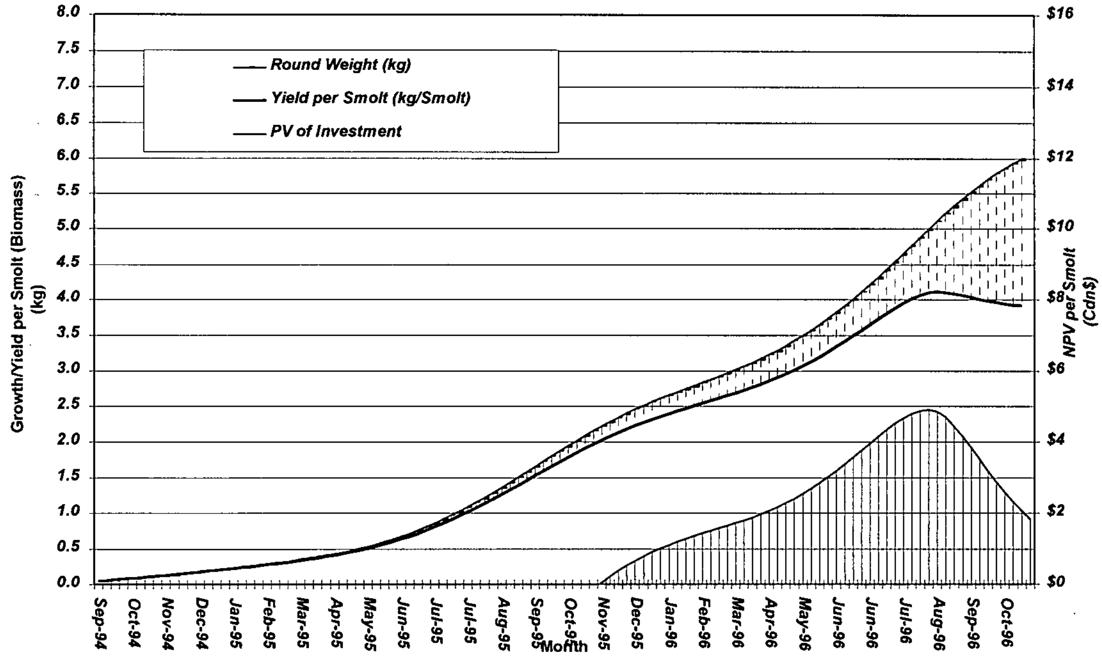


Figure 8 Marginal time rate of change in the revenue and variable cost functions for cohort 1

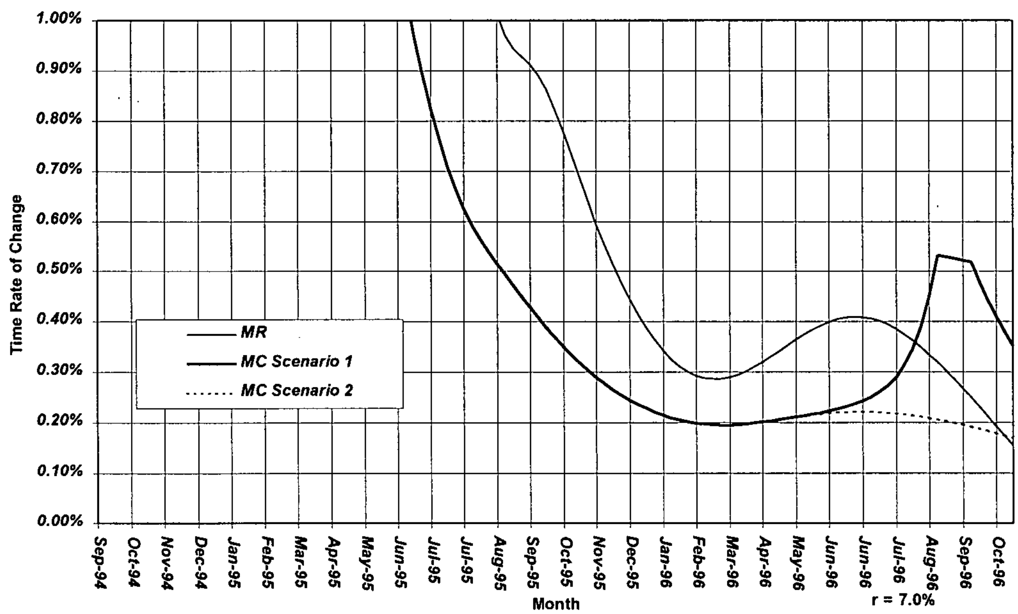


Figure 9 Dynamics of fish growth, population yield and present value from investment for cohort 2 and assuming mortality rate scenario1

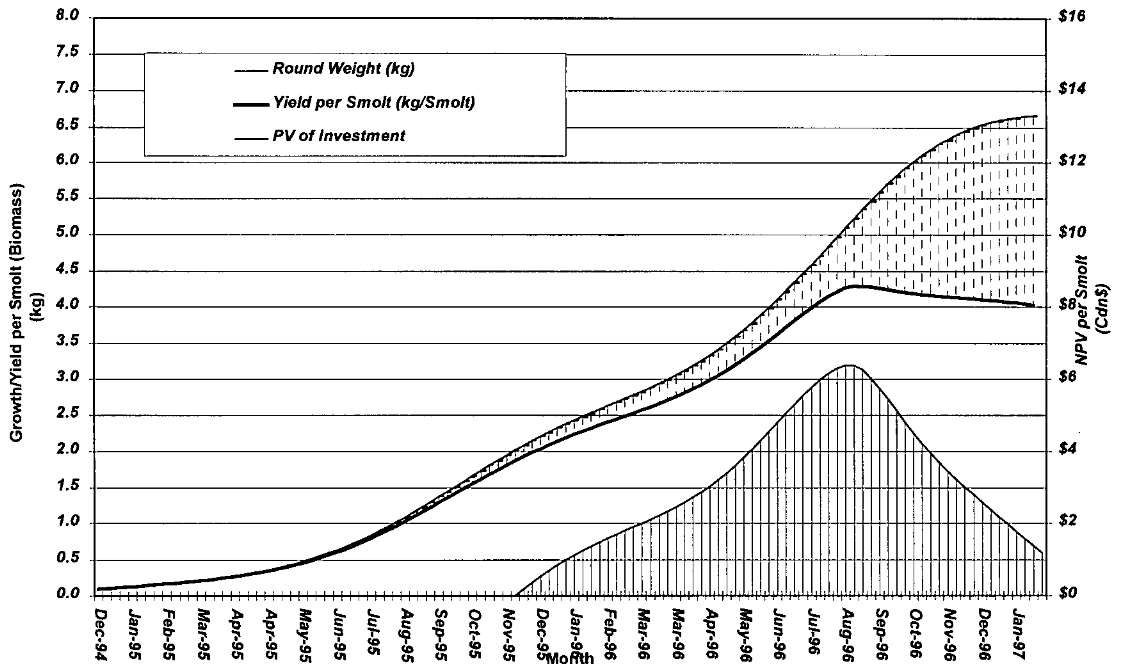


Figure 10 Marginal time rate of change in the revenue and variable cost functions for cohort 2

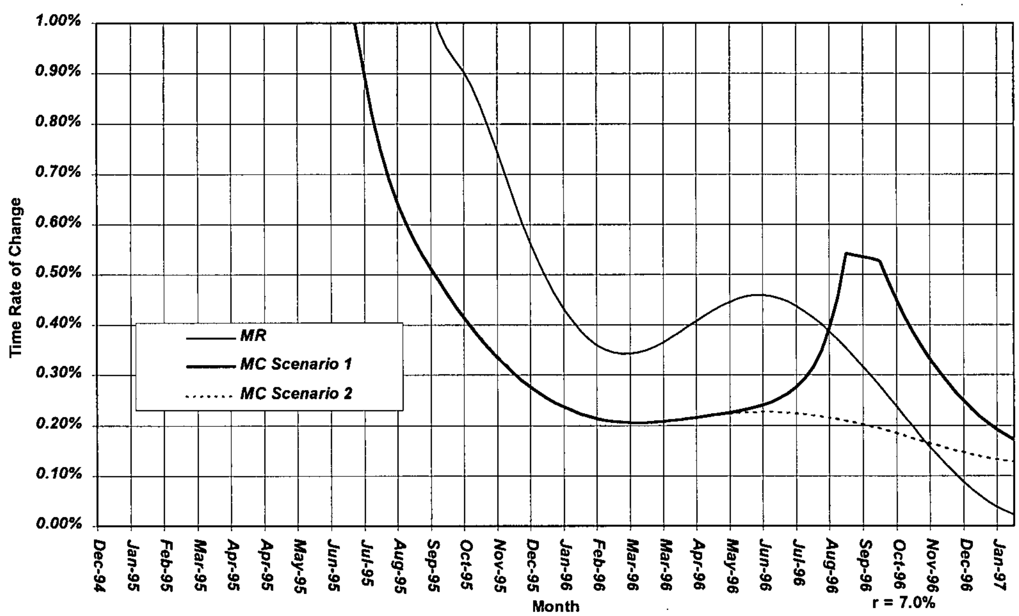


Figure 11 Dynamics of fish growth, population yield and present value from investment for cohort 3 and assuming mortality rate scenario1

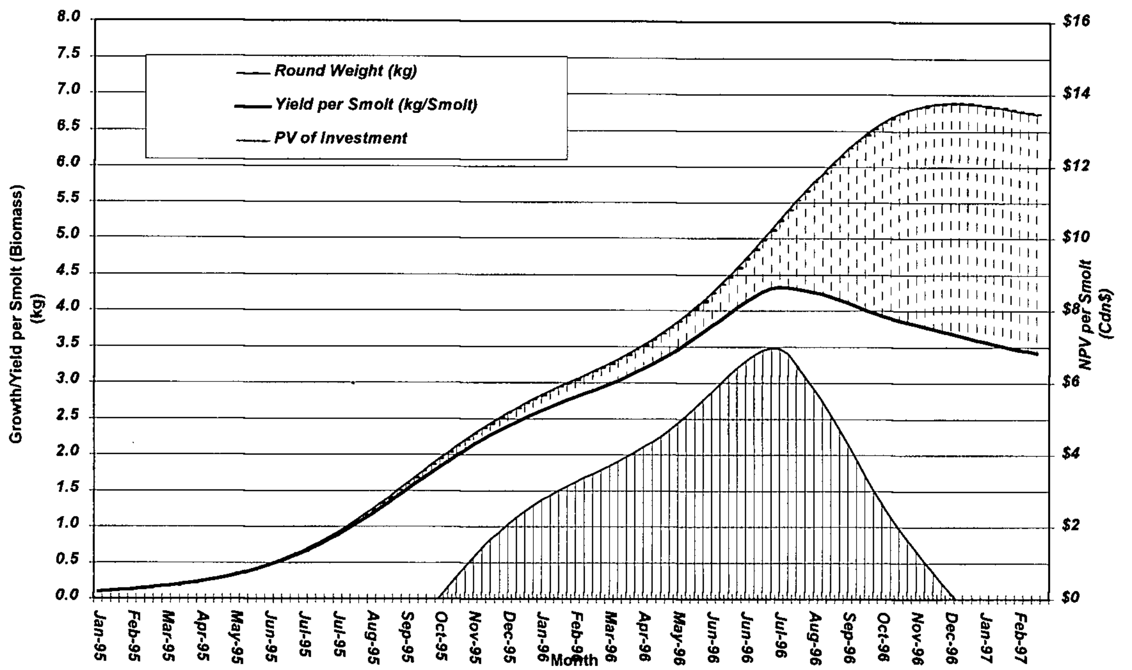


Figure 122 Marginal time rate of change in the revenue and variable cost functions for cohort 3

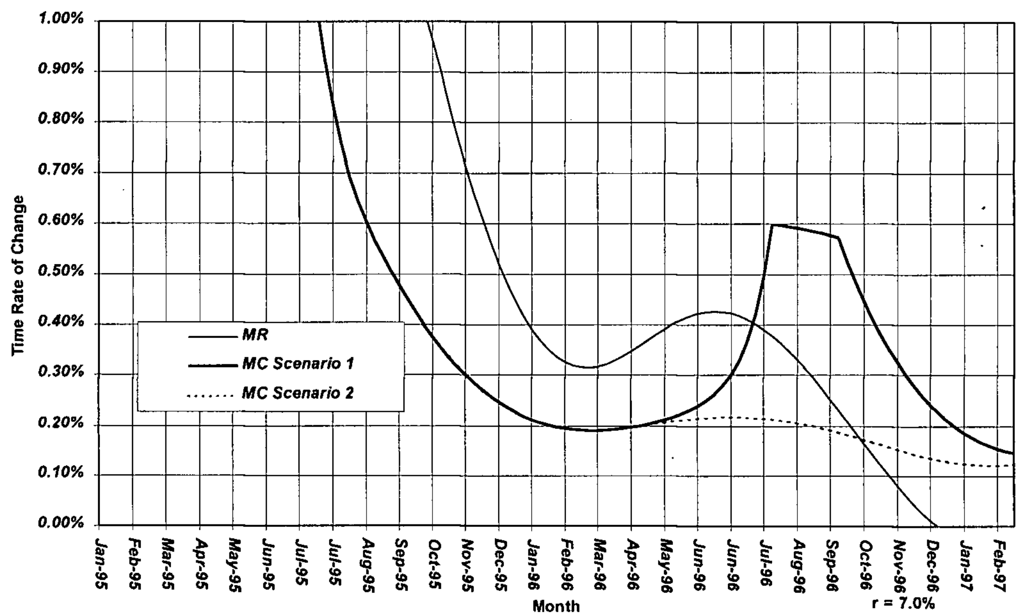


Figure 13 Dynamics of fish growth, population yield and present value from investment for cohort 4 and assuming mortality rate scenario1

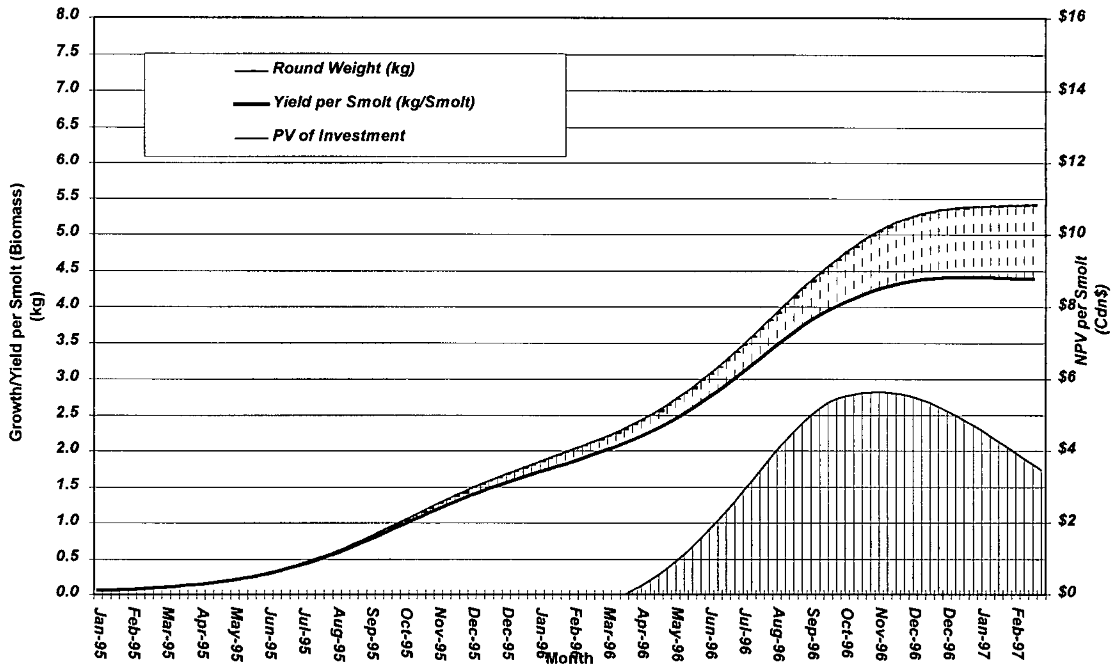


Figure 14 Marginal time rate of change in the revenue and variable cost functions for cohort 4

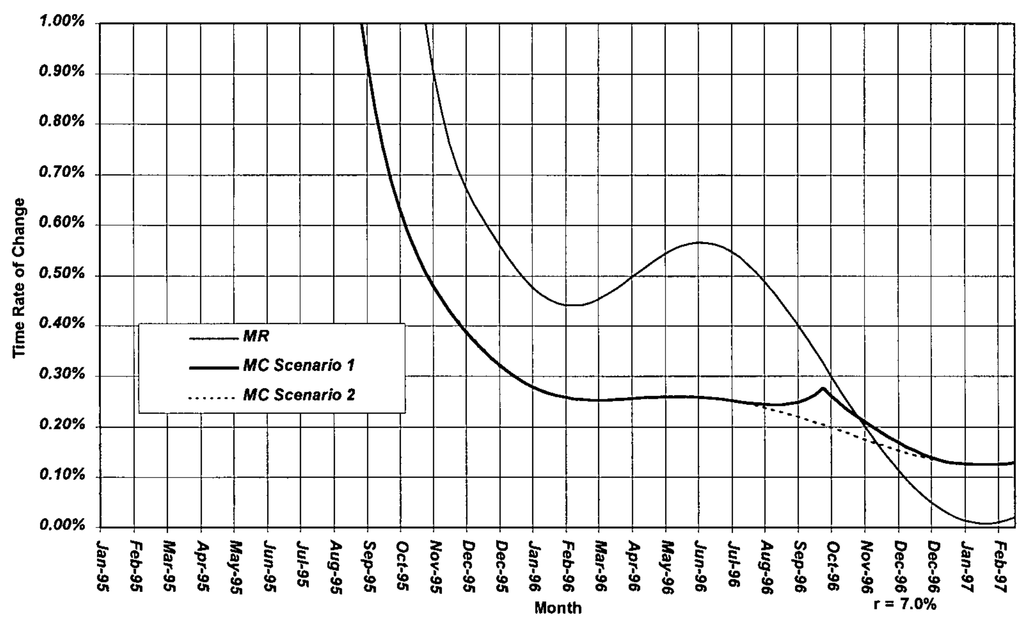


Figure 15 Dynamics of fish growth, population yield and present value from investment for cohort 5 and assuming mortality rate scenario1

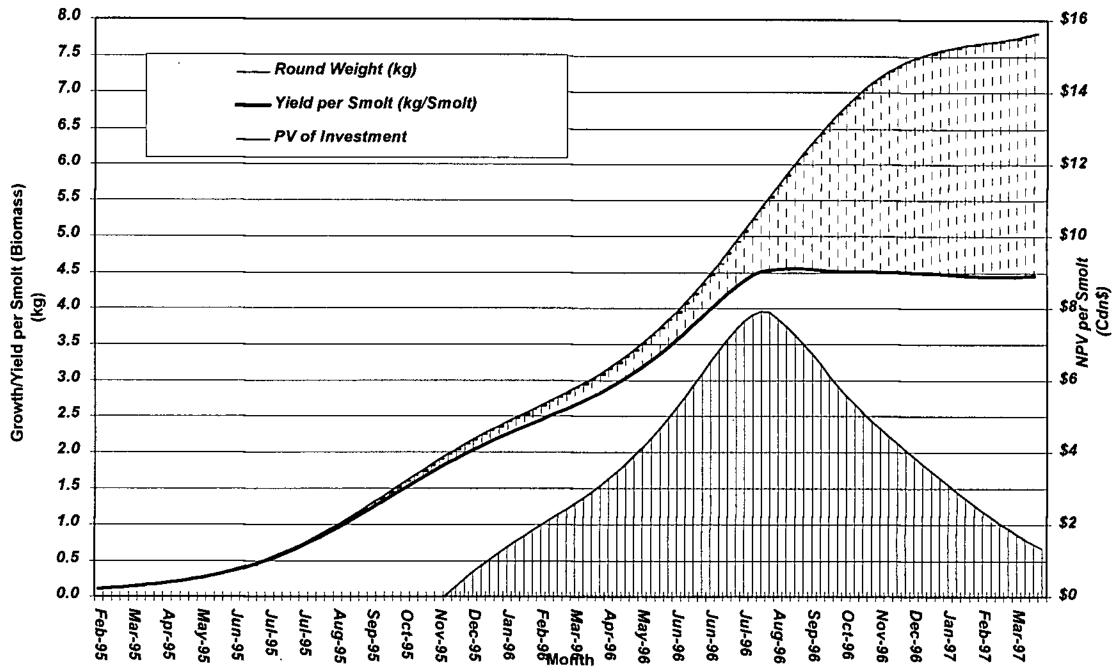


Figure 16 Marginal time rate of change in the revenue and variable cost functions for cohort 5

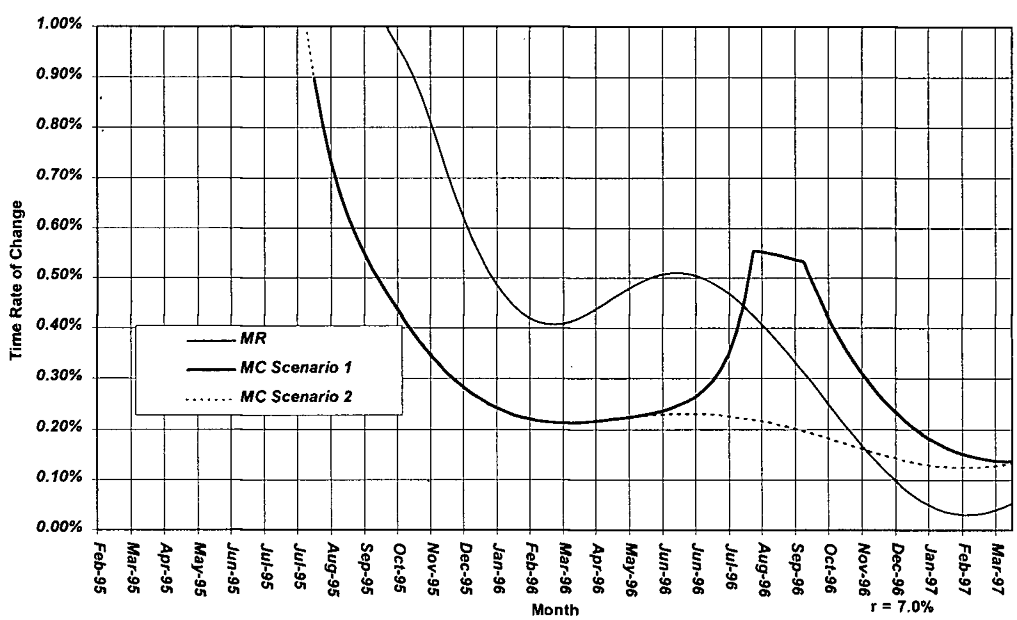


Figure 17 Dynamics of fish growth, population yield and present value from investment for cohort 6 and assuming mortality rate scenario1

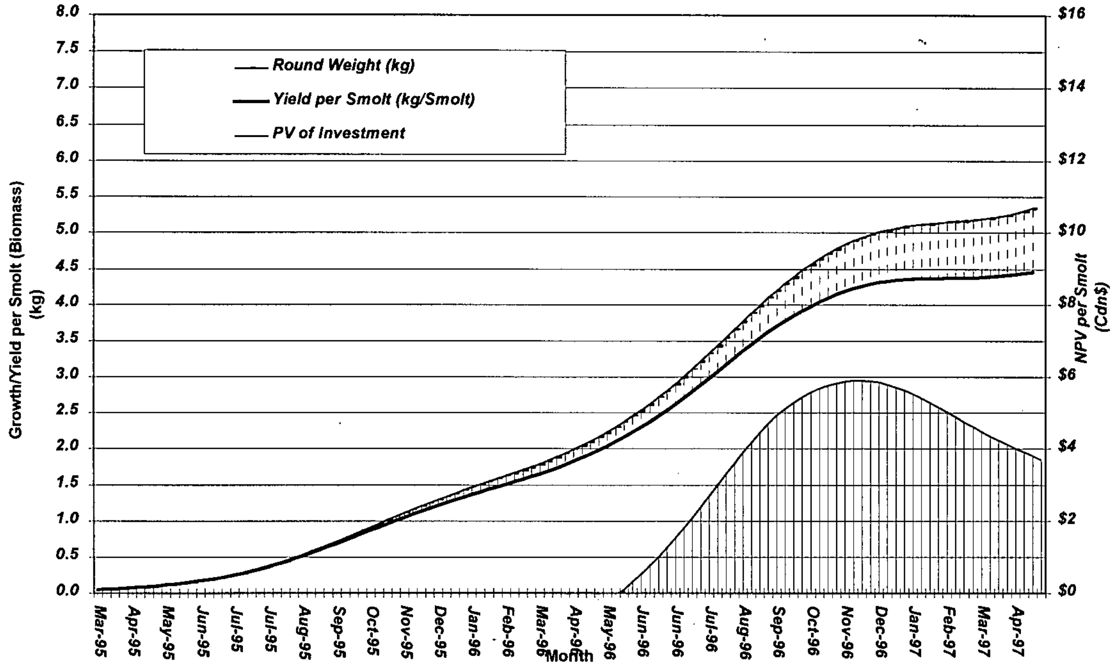


Figure 18 Marginal time rate of change in the revenue and variable cost functions for cohort 6

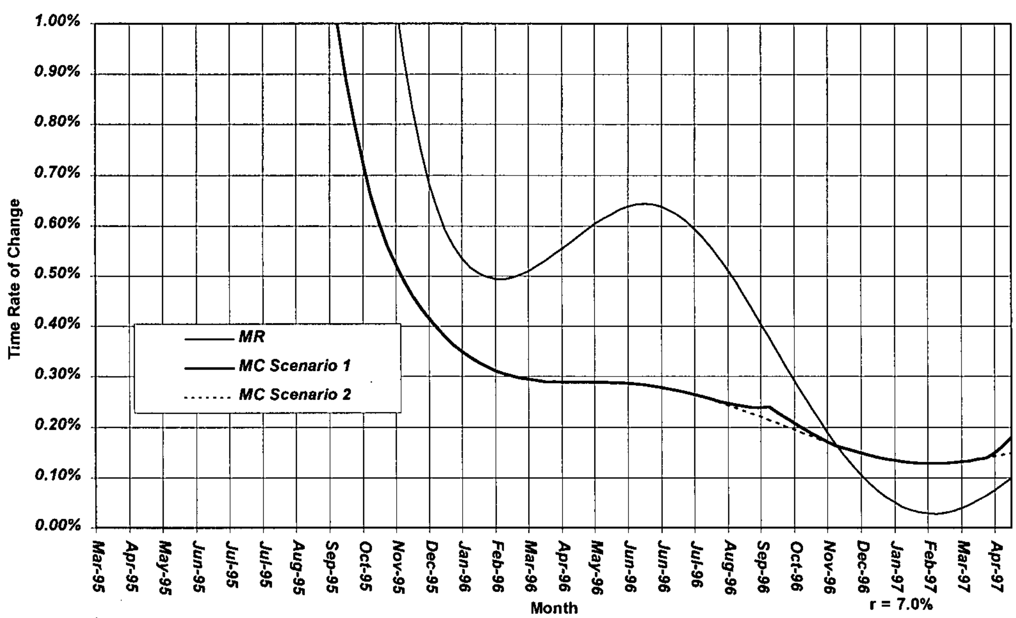


Figure 19 Dynamics of fish growth, population yield and present value from investment for cohort 7 and assuming mortality rate scenario 1

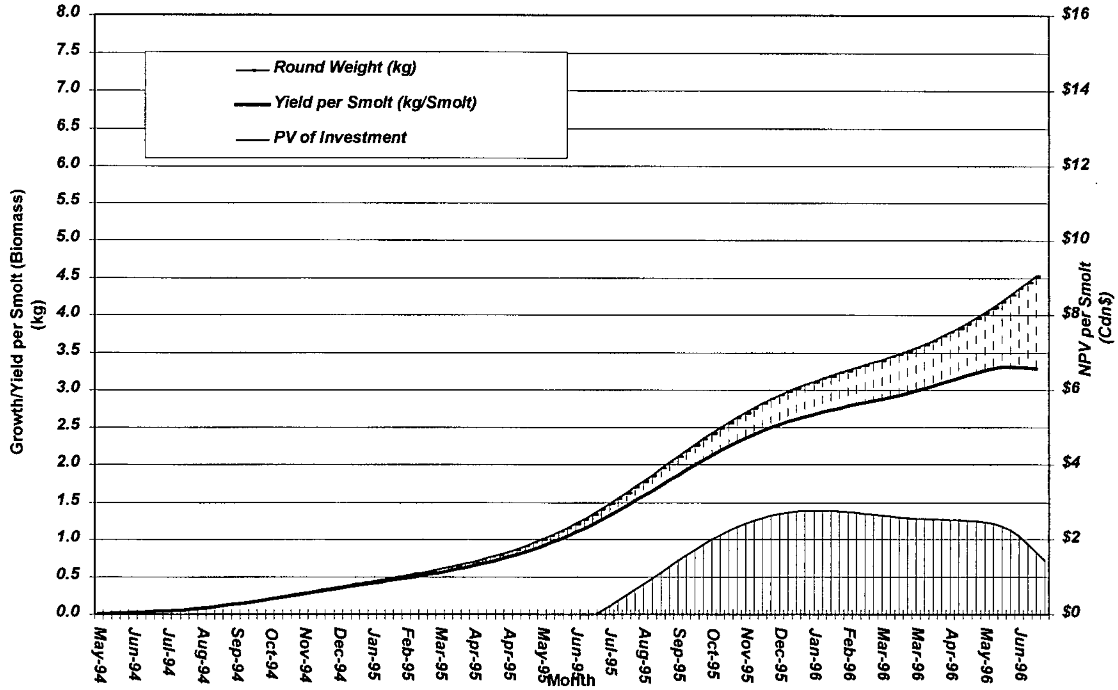


Figure 20 Marginal time rate of change in the revenue and variable cost functions for cohort 7

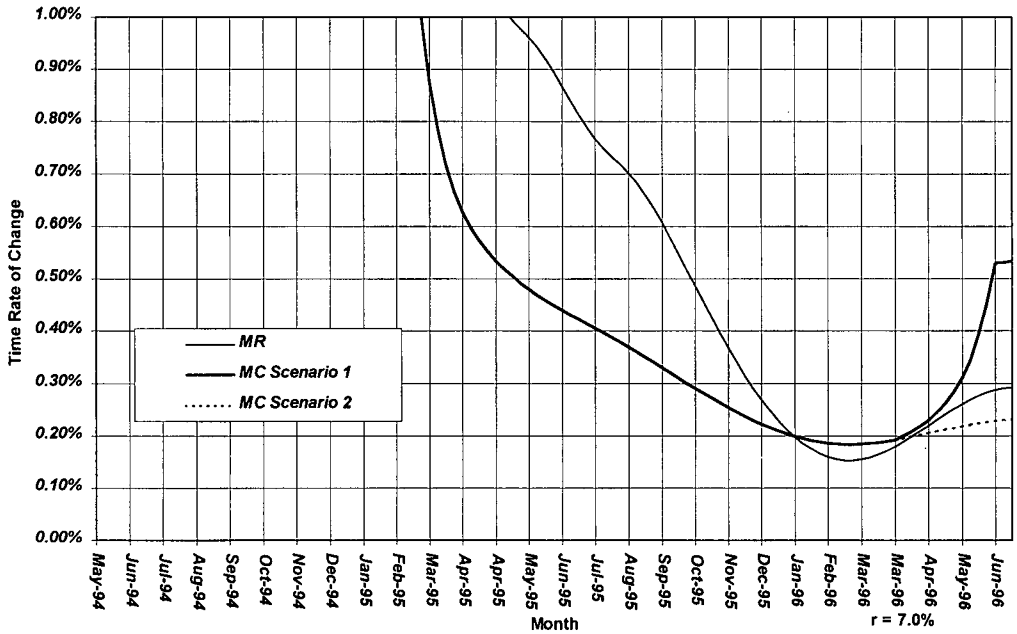


Figure 21 Dynamics of fish growth, population yield and present value from investment for cohort 8 and assuming mortality rate scenario 1

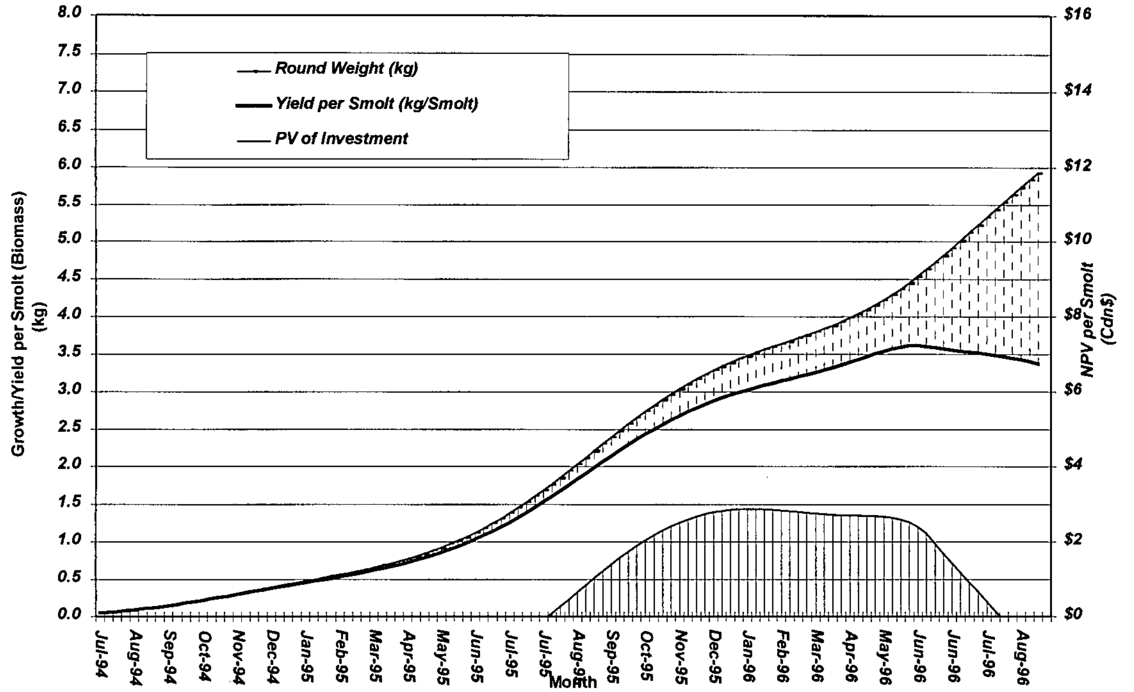


Figure 22 Marginal time rate of change in the revenue and variable cost functions for cohort 8

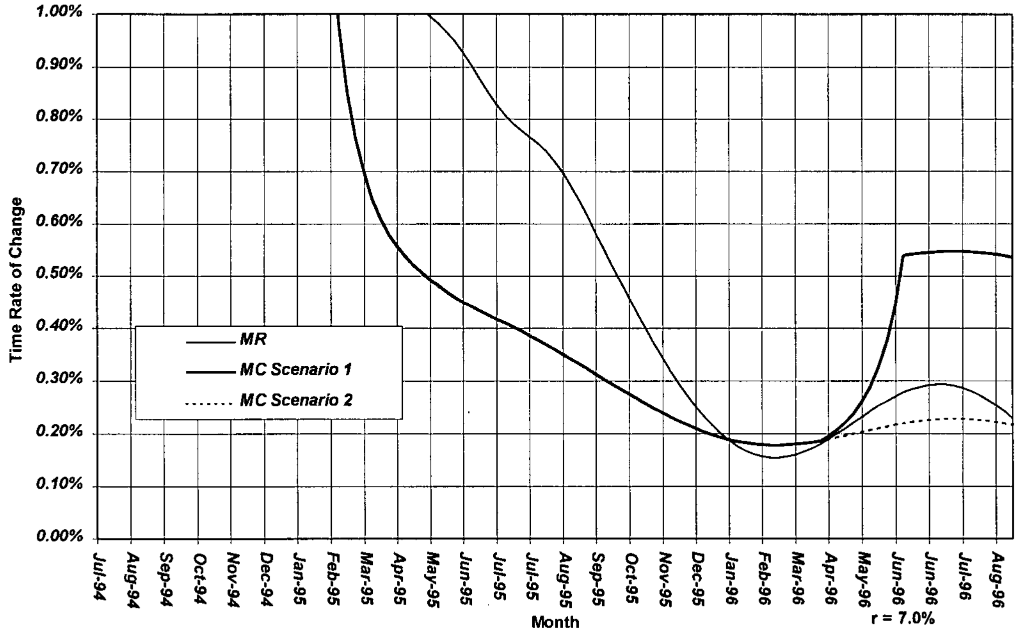


Figure 23 Dynamics of fish growth, population yield and present value from investment for cohort 9 and assuming mortality rate scenario1

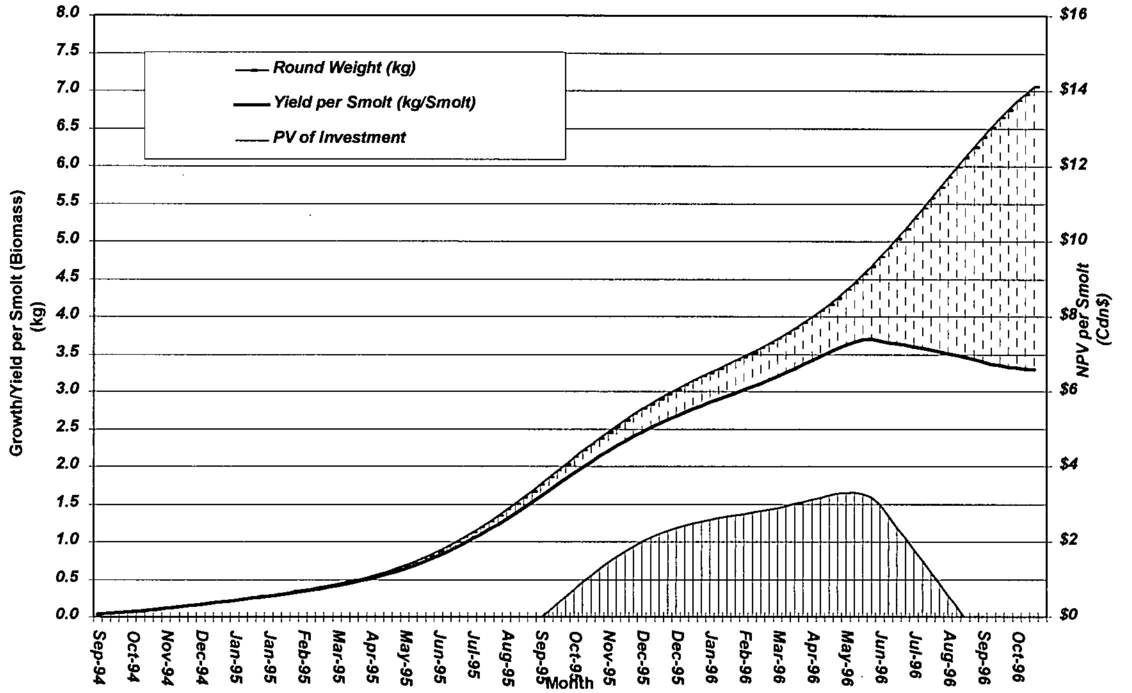


Figure 24 Marginal time rate of change in the revenue and variable cost functions for cohort 9

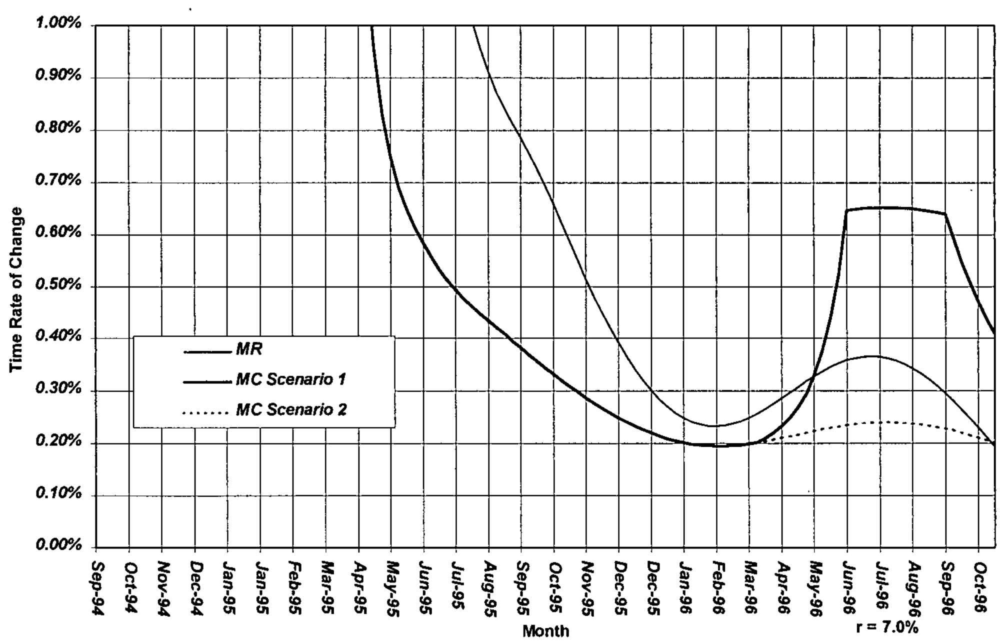


Figure 25 Dynamics of fish growth, population yield and present value from investment for cohort 10 and assuming mortality rate scenario1

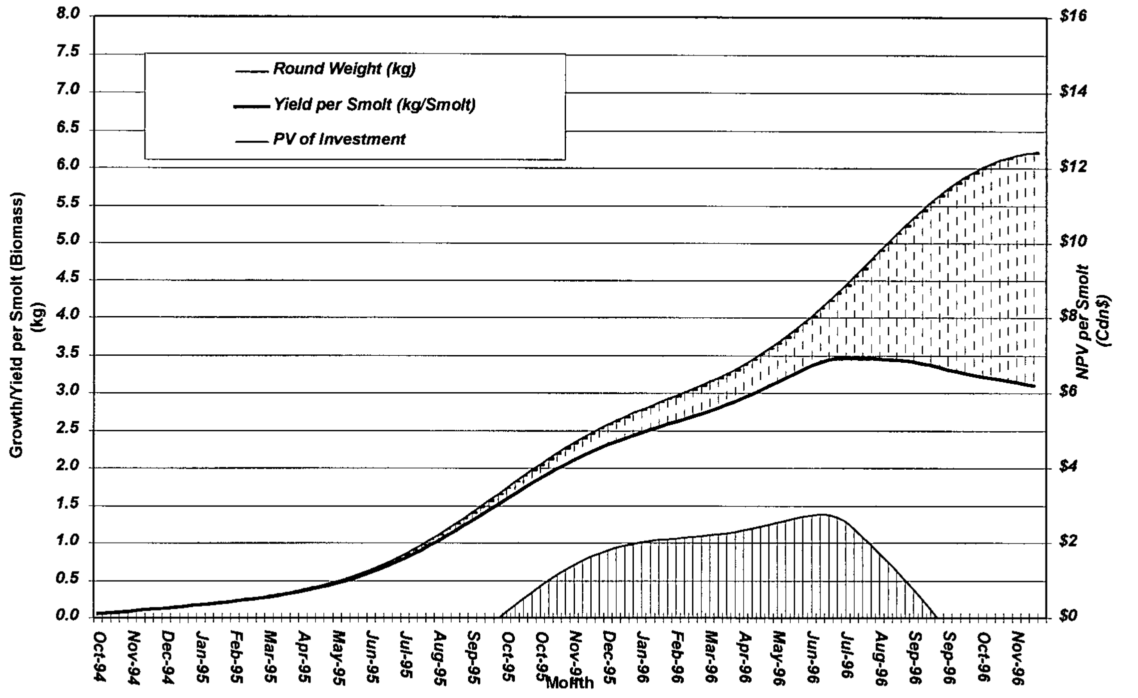


Figure 26 Marginal time rate of change in the revenue and variable cost functions for cohort 10

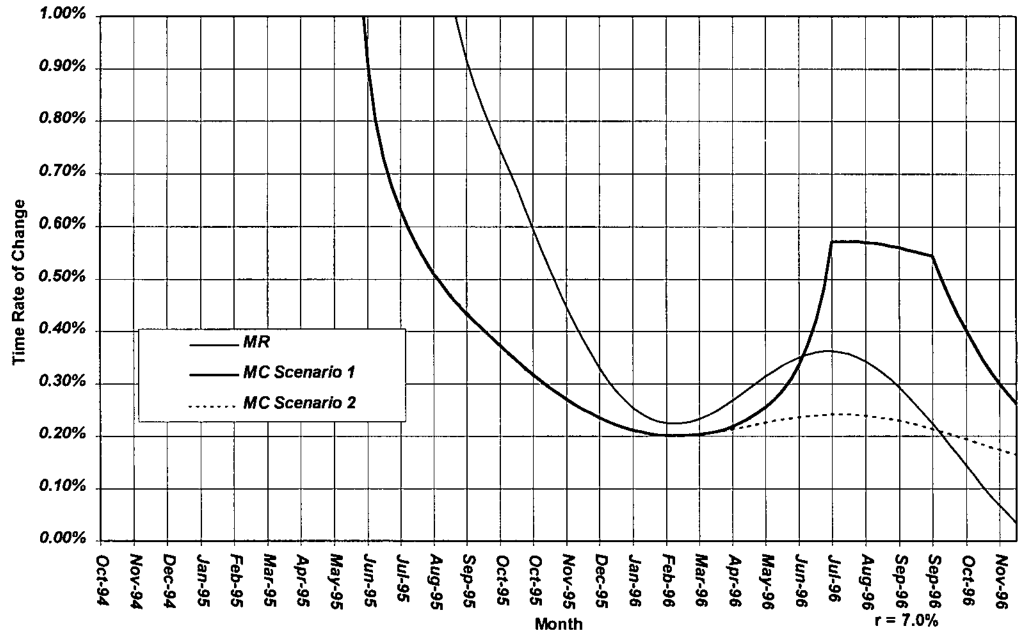


Figure 27 Dynamics of fish growth, population yield and present value from investment for cohort 11 and assuming mortality rate scenario1

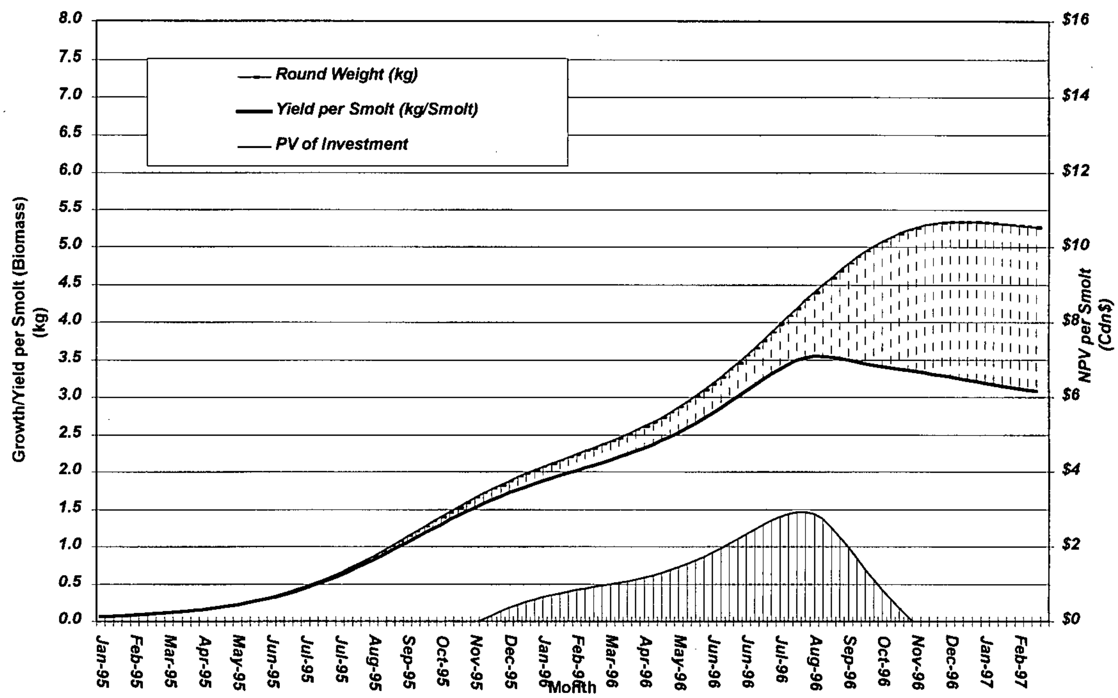


Figure 28 Marginal time rate of change in the revenue and variable cost functions for cohort 11

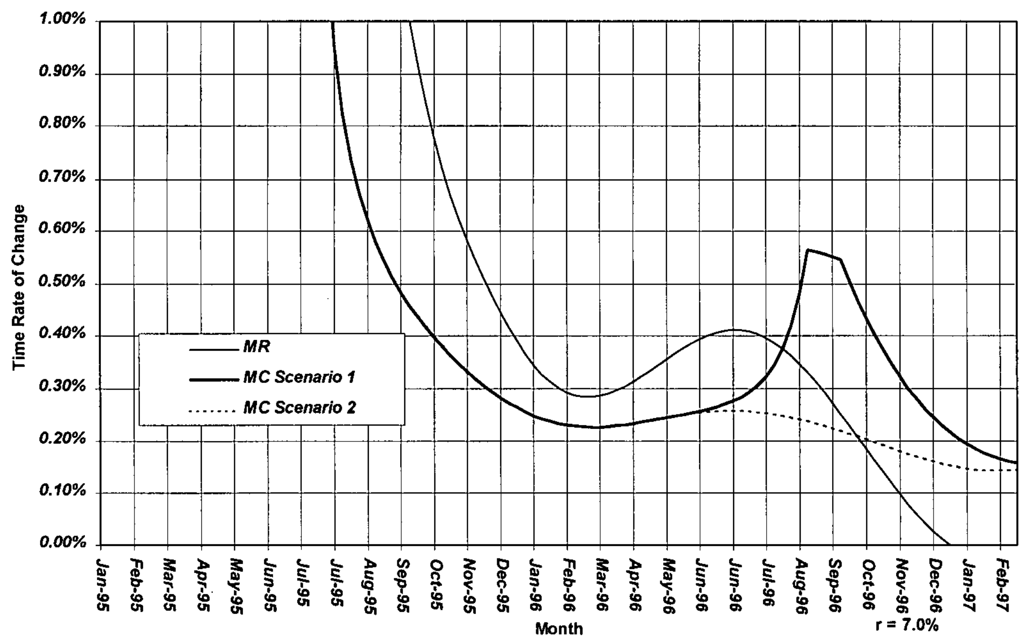


Figure 29 Dynamics of fish growth, population yield and present value from investment for cohort 12 and assuming mortality rate scenario1

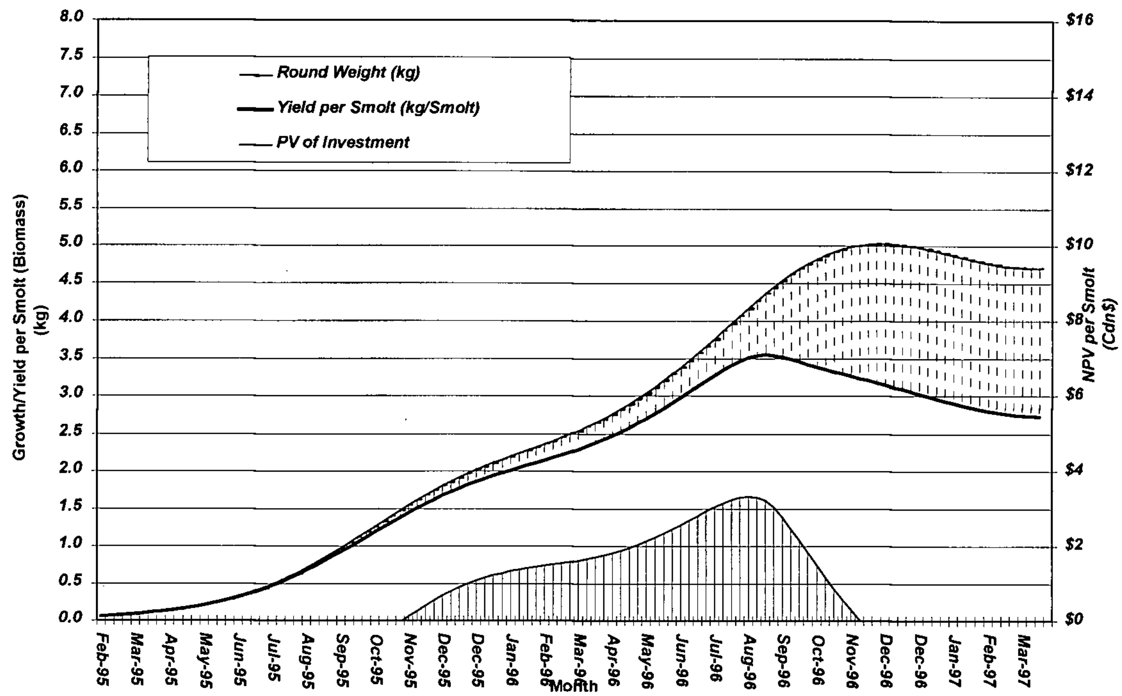
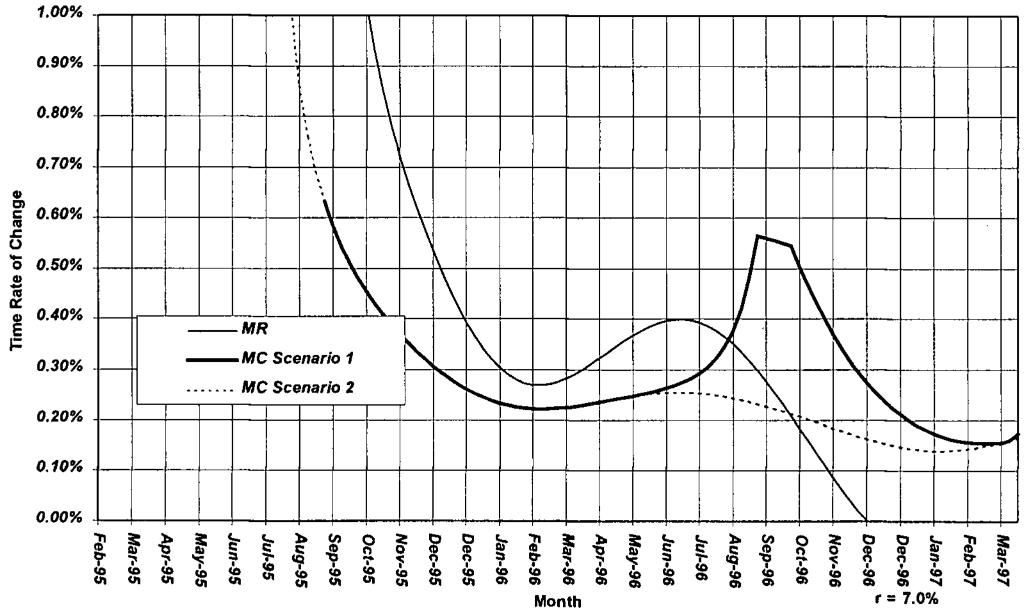


Figure 30 Marginal time rate of change in the revenue and variable cost functions for cohort 12



5.2 Consistent harvest analysis

Consistent harvesting presupposes a production strategy leading to the sustained output of a product with known or expected characteristics. In this study, the primary goal of this strategy is to harvest salmon continuously for the 52 weeks of the year. In the optimal harvesting analysis, the objective was to harvest a selected cohort at a time that would maximize profits. Given a selected cohort, the choice variable in this type of analysis was time. With consistent harvesting, these roles are reversed: Given a selected time, such as a particular week during the year, the choice variable is the cohort maximizing profits. With this strategy, the rule is to select a cohort for harvest at a particular time as long as the present value obtained from its harvest surpasses the present value that would be obtained from harvesting any other cohort. This rule implies that the harvest of a cohort may start before its optimal harvest time is reached and may continue beyond its optimal harvest time for as long as its present value is positive and is greater than harvesting any alternative cohort. Therefore, the comparative advantage of a particular cohort resides in its present value at any point in time surpassing the present value obtained from any other cohort.

To construct a consistent harvesting strategy, the economic performances of individual cohorts are ranked on a weekly basis. A cohort portfolio consists of the top ranked cohorts for each of the 52 weeks of the year. In this type of analysis however, future values for each cohort must be discounted to a common time. This point of reference in the discounting process was chosen as the time at which eggs are fertilized and incubated. The present values of each cohort over a production period of 147 weeks were extracted into a matrix table with the calendar week as a common link between the cohorts. From this table, the optimal present values for each week number (1 to 52) and for each cohort were extracted into a second matrix table. For each week number, the cohort with the highest present value was admitted into the portfolio. The analysis was performed using the scenario 1 mortality rate assumptions only. The present value results are presented in Table 17. Weekly optimal values are italicized and demarcated with a full line border for Atlantic salmon cohorts and with a dotted line border for the chinook salmon cohorts. The bolded values highlight the weekly global present values. The live weights corresponding to each value in Table 17 are shown in Table 18 along with the portfolio harvest dates and weights for both the selected Atlantic salmon and chinook salmon cohorts.

Given the assumptions underlying the analysis, the results in Table 17 suggest that profits are optimized with a production strategy involving Atlantic cohorts only. Atlantic cohorts consistently yielded a higher present value in all 52 weeks. A production portfolio comprising Atlantic salmon only would include all S1 cohorts and exclude all S1/2 cohorts (cohorts 1 and 2). Harvest through the optimal harvest time would occur for cohorts 5 and 6 only. For both cohorts, the harvest period would straddle the optimal harvest time. For cohorts 3 and 4, harvest would take place before their respective optimal harvest times. The comparative advantage of each of these cohorts lies in their capacity to provide a more valuable alternative to other cohorts over a distinct period of time.

A portfolio composed of chinook salmon would include all cohorts, except 11. The inclusion of cohort 7, which is chinook salmon S0, and the important role it plays in the portfolio mix is a surprising result given the fact this smolt strategy is no longer actively pursued in British Columbia. In Table 15, the survival rate for cohort 7 at optimal harvest time was 85.8%. This smolt strategy often resulted in much lower survival rates in actual production setting, varying anywhere from 50% to 75%. Within the chinook salmon portfolio, harvests through the OHT would occur for cohorts 8, 9 and 12. Harvests would take place before OHT for cohort 7 and after OHT for cohort 10.

Chinook salmon cohorts consistently yielded lower profits than Atlantic salmon. The reasons for this result are related to the lower carcass recovery at processing for chinook salmon and the lower weight threshold assumed in the mortality rate scenario 1. Based on personal experience, the timing of harvest and the average weight at harvest appear consistent with harvest behaviour of the industry in British Columbia. Traditionally, chinook salmon S0 were first harvested beginning in early October after 16 to 17 months in seawater. Production would than continue with the chinook salmon S1/2 and the chinook salmon S1 into the following summer. In Table 17, the harvest sequence follows this pattern. Late into their second summer, chinook S1 often begin to mature, at which point mortality begins to increase along with the incidence of harvest down grading. This situation is reflected in cohort 12 where its present value begins to decrease after week 33 (11-Aug-96).

The first Atlantic salmon harvest from a new generation usually occurs later than the first chinook salmon harvest. In Table 17, the first Atlantic salmon harvest occurs in March 1996 at approximately 7 pounds dressed (3500 grams in round weight). The early maturing stocks are first harvested followed by the late maturing stocks, which can be reared through two summers in seawater, and into the following winter. It is now common in the months of January and February to see Atlantic salmon from Canada marketed at an average of 10 to 14 dressed lbs (Urner Barry Publications, various issues).

The consistent harvesting table is a powerful tool to design a sequential harvesting strategy that is economically viable. The comparative advantage of a particular cohort revolves in its ability to provide, relative to other cohorts, the highest return on investment over a certain period of time during the year. Comparative advantage is independent of OHT timing or ranking among cohorts. Instead, it is based on the capacity of a cohort to supply a market window more efficiently than any alternative cohort. A high growth potential cohort with low resilience to mortality (or a high early maturation rate) may be as valuable as a cohort with a relatively lower growth potential, but having a higher resilience to mortality (or a low early maturation rate). Cohort 3 is an example of the former case and cohort 6 an example of the latter case.

Consistent harvesting analysis in the context of planning for production

Based on a profit maximizing criteria, the consistent harvesting algorithm developed in this study leads to the selection of a cohort portfolio that provides sequential harvests for an uninterrupted period of 52 weeks. The model assumes that resources required to produce the profits maximizing solution are not limiting factors. Further, it also assumes that market prices are fixed in each weight category. However, production is limited by infrastructure constraints, by the supply of input factors and by demand. Also, market prices typically fluctuate as a result of seasonal fluctuation in supply levels and demand. Each of these constraints imposes some degree of limitation on the size and the scope of production. The problem for the producer to determine the number of smolts to purchase from each salmon cohort given his production constraints and his market price expectations.

Lets assume that that production is limited by the harvesting and processing capacity of the firm, but that there is an unlimited supply of the smolts required for producing an optimal consistent harvesting strategy and no constraints on rearing space. In this case, the number of smolts to introduce in sea water is a function of the biomass that can be harvested, processed and marketed over a specific period of time. For instance, let suppose that the biomass target for marketing in week 1 is 75,000 kg (round weight). As indicated in Table 18, Cohort 6 provides the profit maximizing solution for that week with a yield of 5,06 kilogram per smolt. The number of smolts required at stocking time for harvest in week 1 is obtained by dividing the biomass target by the yield per smolt. In the above example, the biomass target for week 1 would require the introduction of 14,822 smolts. This exercise is repeated for every week of the year to determine the number of smolts to purchase of a particular strain and to establish a stocking strategy leading to continuous sequential harvesting

In practice, the availability of limited resources may lead to the adoption of a second best solution. For instance, the available supply of smolts needed of a particular cohort may be short of the number required. In this case, the limited supply of smolts purchased would be allocated over the period of time where it is most profitable. Where it is least profitable for that particular cohort, the next most profitable cohort should be used to fill the void as long as its net present value is positive. For instance, suppose that the number of smolts available of cohort 6 were enough to pursuit the consistent harvesting strategy portrayed in Table 17 until to week 9. The period encompassing week 10 to week 13 would then be covered with cohort 3, which is the second most profitable group of fish in Table 17.

Other limiting resources include the carrying capacity of a grow-out site and the number of sites available for production. The long term objective of consistent harvesting is to harvest 52 weeks of the year, year after year, and to maximize assets utilization so as to minimize their related operational and fixed costs. The number of farms and their respective carrying capacity may limit the producer's ability to design a consistent harvesting strategy. It is common practice to raise smolt to market size without any new addition of fish to the site (MacKinnon 1997). Ideally, the practice of raising single year class fish is interspersed with a fallow period in order to provide time necessary for the benthic area underneath the farm site to restore itself. It is also an effective method to control the important economic pest that is sea lice (*Lepeophtheirus salmonis* and *Caligus clemensi* in the Pacific waters). Therefore, smaller entreprises with limited rearing space may not have the capacity to harvest a year-round, unless they enter cooperative arrangements with other industry players.

Stochastic considerations

The results derived from the application of the deterministic model presented in this study reveals that growth and mortality are the most important economic factors delimiting the comparative advantage of each cohort for supplying a specific market window. A deterministic approach is useful in the context of production planning or in analyzing the production behaviour characterizing an industry. A consistent harvesting table is also a useful tool to better understand the mechanism of market supply. The reality of production, however, is not of a deterministic nature. Production and market risk considerations are inherent parts of salmon aquaculture during the production process. Managers must adapt to new information or events affecting the profitability of the enterprise. For instance, fish growth will be affected adversely during the course of production by husbandry events, such sampling or grading, by predation or by disease outbreaks. Further, prices in the open market typically vary according to seasonal factors, to supply from other producers and commercial fisheries, and to demand on the world market. Stochastic factors can be accommodated by adjusting model parameters or by introducing actual data in a discrete model framework.

In the course of production, there are events and physiological constraints that are likely to lower actual productivity below the growth rate predicted by the growth model. With a fixed *Gi* and a constant *Df*, the model provides the growth path for a given cohort over an undisturbed period of growth stanza. Any event causing a disruption in the growth stanza results in a lost of growth as predicted by the model. Disruptions resulting from husbandry practices such as fish sampling or feeding below satiation during an algae bloom, is accounted for by assuming that growth is stunted over the period of disruption and by reducing accordingly the number of days used in calculating growth. In these types of disruption the parameter values (Gi and Df) do not need to be adjusted or recalculated since the growth potential of the fish is not affected. However, the growth potential of the fish is affected by physiological disruption caused by exogenous factors such as diseases. In this case, both Gi and Df need to be adjusted or recalculated.

The consistent harvesting analysis result presented in Table 17 assumes that market prices are fixed in each of the weight categories through which salmon is typically marketed. In this study, these prices were specified as the average price for each weight class over a one-year period. Prices were converted to Canadian dollars from US dollars using the average exchange rate in effect over that one-year period. This assumption is realistic in the case were market agents enter into long term sales agreements. This type of arrangement presupposes that output is consistent and predictable in terms of its qualitative characteristics (flesh colour, fish size, flesh quality, etc). However, most production usually sold in the open market where prices fluctuate according to supply and demand factors. In this case, the introduction of an actual market price matrix into the model is more appropriate to account for the impact of seasonality and other market factors on profitability.

Table 17 Consistent harvest strategy based on the selection of cohorts maximizing the weekly present value of profits under the increasing mortality assumption (Scenario 1). Harvest windows for cohorts selected into the production portfolio are italicized, with bolded values highlighting global economic optimal harvest windows. Optimal harvest windows for Atlantic salmon cohorts are delineated with a full line, while optimal harvest windows for chinook salmon cohorts are delineated with a dotted line.

Week Number	Maximum PV		Atlantic (*Salmo salar*) Cohorts						Chinook (*Oncorhynchus tshawytscha*) Cohorts					
	Atlantic	Chinook	1	2	3	4	5	6	7	8	9	10	11	12
1	*$5.11*	*$2.72*	$0.95	$1.63	$2.37	$4.58	$2.99	***$5.11***	$2.66	*$2.72*	$2.29	$1.79	$0.54	$0.98
2	*$5.02*	*$2.72*	$1.04	$1.45	$2.51	$4.46	$2.82	***$5.02***	**$2.66**	***$2.72***	$2.35	$1.84	$0.60	$1.05
3	*$4.91*	*$2.72*	$1.12	$1.27	$2.63	$4.33	$2.65	***$4.91***	$2.66	*$2.72*	$2.40	$1.88	$0.65	$1.11
4	*$4.80*	*$2.72*	$1.20	$1.37	$2.76	$4.19	$2.48	***$4.80***	$2.64	*$2.72*	$2.44	$1.91	$0.70	$1.16
5	*$4.68*	*$2.70*	$1.28	$1.47	$2.87	$4.05	$2.31	***$4.68***	$2.63	*$2.70*	$2.48	$1.93	$0.74	$1.20
6	*$4.56*	*$2.69*	$1.35	$1.56	$2.98	$3.90	$2.15	***$4.56***	$2.61	*$2.69*	$2.51	$1.96	$0.78	$1.24
7	*$4.43*	*$2.67*	$1.41	$1.65	$3.08	$3.75	$2.00	***$4.43***	$2.59	*$2.67*	$2.55	$1.98	$0.81	$1.28
8	*$4.31*	*$2.65*	$1.48	$1.75	$3.18	$3.61	$2.07	***$4.31***	$2.56	*$2.65*	$2.58	$2.00	$0.85	$1.31
9	*$4.18*	*$2.63*	$1.55	$1.84	$3.28	$3.46	$2.20	***$4.18***	$2.54	*$2.63*	$2.61	$2.01	$0.88	$1.34
10	*$4.06*	*$2.65*	$1.61	$1.94	$3.39	$3.32	$2.34	***$4.06***	$2.52	$2.61	*$2.65*	$2.03	$0.92	$1.37
11	*$3.95*	*$2.69*	$1.69	$2.04	$3.49	$3.19	$2.49	***$3.95***	$2.49	$2.59	*$2.69*	$2.05	$0.95	$1.40
12	*$3.84*	*$2.73*	$1.76	$2.15	$3.61	$3.06	$2.64	***$3.84***	$2.48	$2.58	*$2.73*	$2.08	$0.99	$1.43
13	*$3.73*	*$2.77*	$1.85	$2.26	***$3.73***	$2.94	$2.79	***$3.73***	$2.46	$2.57	*$2.77*	$2.11	$1.04	$1.46
14	*$3.86*	*$2.82*	$1.94	$2.38	***$3.86***	$2.83	$2.96	$3.64	$2.45	$2.57	*$2.82*	$2.14	$1.08	$1.50
15	*$4.00*	*$2.88*	$2.03	$2.51	***$4.00***	$2.71	$3.14	$3.55	$2.44	$2.56	*$2.88*	$2.18	$1.14	$1.54
16	*$4.15*	*$2.93*	$2.14	$2.65	***$4.15***	$2.60	$3.33	$3.45	$2.44	$2.56	*$2.93*	$2.22	$1.19	$1.59
17	*$4.31*	*$2.99*	$2.26	$2.80	***$4.31***	$2.48	$3.54	$3.35	$2.43	$2.55	*$2.99*	$2.27	$1.26	$1.65
18	*$4.48*	*$3.04*	$2.38	$2.97	***$4.48***	$2.34	$3.76	$3.24	$2.42	$2.53	*$3.04*	$2.32	$1.33	$1.71
19	*$4.66*	*$3.08*	$2.52	$3.14	***$4.66***	$2.18	$3.99	$3.11	$2.41	$2.51	*$3.08*	$2.37	$1.41	$1.77
20	*$4.86*	*$3.11*	$2.67	$3.33	***$4.86***	$1.98	$4.24	$2.94	$2.40	$2.46	***$3.11***	$2.42	$1.50	$1.85
21	*$5.06*	*$3.11*	$2.82	$3.53	***$5.06***	$1.72	$4.50	$2.73	$2.37	$2.39	*$3.11*	$2.48	$1.59	$1.93
22	*$5.26*	*$3.08*	$2.99	$3.74	***$5.26***	$1.38	$4.78	$2.44	$2.33	$2.28	*$3.08*	$2.52	$1.69	$2.02
23	*$5.47*	*$2.99*	$3.16	$3.96	***$5.47***	$1.44	$5.06	$2.05	$2.26	$2.11	*$2.99*	$2.56	$1.80	$2.12
24	*$5.68*	*$2.82*	$3.34	$4.19	***$5.68***	$1.66	$5.35	$1.67	$2.16	$1.85	*$2.82*	**$2.57**	$1.91	$2.23
25	*$5.88*	*$2.56*	$3.53	$4.42	***$5.88***	$1.89	$5.65	$1.31	$2.01	$1.60	$2.53	*$2.56*	$2.03	$2.33

Table 17 *(Continued)*

Week Number	Maximum Present Value		Atlantic (*Salmo salar*) Cohorts						Chinook (*Oncorhynchus tshawytscha*) Cohorts					
	Atlantic	Chinook	1	2	3	4	5	6	7	8	9	10	11	12
26	*$6.06*	*$2.51*	$3.71	$4.66	*$6.06*	$2.13	$5.94	$1.38	$1.80	$1.36	$2.25	*$2.51*	$2.15	$2.45
27	*$6.23*	*$2.56*	$3.89	$4.89	$6.22	$2.38	***$6.23***	$1.63	$1.58	$1.11	$1.97	$2.40	$2.27	*$2.56*
28	*$6.51*	*$2.67*	$4.07	$5.12	$6.33	$2.63	***$6.51***	$1.90	$1.37	$0.87	$1.69	$2.21	$2.38	*$2.67*
29	*$6.76*	*$2.77*	$4.23	$5.33	**$6.40**	$2.89	***$6.76***	$2.17	$1.15	$0.62	$1.41	$2.01	$2.49	*$2.77*
30	*$6.97*	*$2.86*	$4.37	$5.53	$6.38	$3.16	***$6.97***	$2.44	$0.94	$0.38	$1.13	$1.81	$2.58	*$2.86*
31	*$7.14*	*$2.94*	$4.49	$5.70	$6.25	$3.42	***$7.14***	$2.72	$0.72	$0.13	$0.85	$1.60	$2.65	*$2.94*
32	*$7.22*	*$3.00*	$4.57	$5.82	$5.97	$3.67	***$7.22***	$2.99	$0.62	$0.25	$0.56	$1.39	$2.69	*$3.00*
33	*$7.20*	*$3.02*	**$4.59**	**$5.90**	$5.68	$3.92	***$7.20***	$3.26	$0.76	$0.43	$0.27	$1.17	**$2.70**	***$3.02***
34	*$7.03*	*$3.00*	$4.55	$5.90	$5.37	$4.16	***$7.03***	$3.53	$0.91	$0.61	$0.00	$0.95	$2.65	*$3.00*
35	*$6.85*	*$2.92*	$4.42	$5.80	$5.04	$4.37	***$6.85***	$3.79	$1.06	$0.79	$0.00	$0.71	$2.52	*$2.92*
36	*$6.64*	*$2.77*	$4.16	$5.56	$4.70	$4.57	***$6.64***	$4.03	$1.21	$0.97	$0.00	$0.47	$2.30	*$2.77*
37	*$6.41*	*$2.52*	$3.89	$5.31	$4.34	$4.75	***$6.41***	$4.26	$1.36	$1.15	$0.15	$0.21	$2.07	*$2.52*
38	*$6.16*	*$2.25*	$3.61	$5.04	$3.96	$4.89	***$6.16***	$4.46	$1.51	$1.32	$0.33	$0.00	$1.82	*$2.25*
39	*$5.89*	*$1.97*	$3.30	$4.75	$3.57	$4.99	***$5.89***	$4.65	$1.65	$1.49	$0.51	$0.14	$1.56	*$1.97*
40	*$5.60*	*$1.79*	$2.99	$4.44	$3.16	$5.06	***$5.60***	$4.80	*$1.79*	$1.64	$0.70	$0.31	$1.28	$1.67
41	*$5.33*	*$1.92*	$2.70	$4.16	$2.78	$5.10	***$5.33***	$4.94	*$1.92*	$1.79	$0.87	$0.47	$1.02	$1.36
42	*$5.14*	*$2.04*	$2.43	$3.90	$2.43	***$5.14***	$5.09	$5.06	*$2.04*	$1.93	$1.05	$0.63	$0.78	$1.07
43	*$5.16*	*$2.15*	$2.17	$3.65	$2.11	***$5.16***	$4.86	$5.16	*$2.15*	$2.06	$1.21	$0.79	$0.55	$0.79
44	*$5.24*	*$2.24*	$1.93	$3.42	$1.80	**$5.17**	$4.65	***$5.24***	*$2.24*	$2.18	$1.36	$0.93	$0.33	$0.53
45	*$5.30*	*$2.33*	$1.71	$3.20	$1.50	$5.16	$4.45	***$5.30***	*$2.33*	$2.29	$1.51	$1.07	$0.12	$0.27
46	*$5.34*	*$2.41*	$1.49	$2.99	$1.22	$5.13	$4.26	***$5.34***	*$2.41*	$2.38	$1.64	$1.20	$0.00	$0.24
47	*$5.37*	*$2.48*	$1.27	$2.78	$1.26	$5.10	$4.07	***$5.37***	*$2.48*	$2.46	$1.77	$1.32	$0.06	$0.37
48	*$5.37*	*$2.53*	$1.07	$2.58	$1.48	$5.04	$3.88	***$5.37***	*$2.53*	*$2.53*	$1.88	$1.42	$0.15	$0.49
49	*$5.35*	*$2.59*	$0.87	$2.39	$1.68	$4.97	$3.70	***$5.35***	$2.58	*$2.59*	$1.98	$1.52	$0.25	$0.61
50	*$5.32*	*$2.64*	$0.67	$2.19	$1.87	$4.89	$3.52	***$5.32***	$2.61	*$2.64*	$2.07	$1.60	$0.33	$0.71
51	*$5.27*	*$2.67*	$0.74	$2.00	$2.05	$4.80	$3.34	***$5.27***	$2.64	*$2.67*	$2.15	$1.68	$0.41	$0.81
52	*$5.20*	*$2.70*	$0.85	$1.82	$2.21	$4.69	$3.17	***$5.20***	$2.65	*$2.70*	$2.23	$1.74	$0.48	$0.90

Table 18 Harvest weights and summary of harvest dates leading to a consistent harvest strategy (Scenario 1). Harvest windows for cohorts selected into the production portfolio are italicized with global economic optimal harvest windows bolded. Atlantic salmon (*Salmo salar*) economic optimal harvest windows are delineated with a full line, while corresponding optimal harvest windows for chinook salmon (***Oncorhynchus tshawytscha***)are delineated with a dotted line.

	Harvest Dates and Weights						Weights (Round or whole kilogram per fish) corresponding to maximizing Present Value for each week per cohort.											
	Atlantic			Chinook			Atlantic Cohorts						Chinook Cohorts					
Week Number	Harvest Week	nd g	Dr. lb.	Harvest Week	Rnd kg	Dr. lb.	1	2	3	4	5	6	7	8	9	10	11	12
1	29-Dec-96	5.06	10.03	31-Dec-95	3.39	6.42	6.26	6.61	2.70	5.35	2.29	***5.06***	3.07	*3.39*	3.03	2.63	5.34	4.97
2	5-Jan-97	5.08	10.07	7-Jan-96	3.43	6.50	2.61	6.63	2.77	5.37	2.35	***5.08***	3.11	*3.43*	3.09	2.68	5.34	4.95
3	12-Jan-97	5.09	10.11	14-Jan-96	3.48	6.59	2.65	6.64	2.82	5.38	2.41	***5.09***	3.15	*3.48*	3.14	2.73	5.33	4.92
4	19-Jan-97	5.11	10.13	21-Jan-96	3.52	6.67	2.70	2.53	2.88	5.38	2.47	***5.11***	3.19	*3.52*	3.20	2.78	5.32	2.15
5	26-Jan-97	5.12	10.16	28-Jan-96	3.56	6.74	2.74	2.58	2.94	5.39	2.53	***5.12***	3.23	*3.56*	3.25	2.83	5.31	2.20
6	2-Feb-97	5.13	10.18	4-Feb-96	3.60	6.82	2.79	2.63	2.99	5.39	2.59	***5.13***	3.26	*3.60*	3.31	2.87	5.30	2.24
7	9-Feb-97	5.14	10.20	11-Feb-96	3.64	6.89	2.83	2.68	3.04	5.39	2.64	***5.14***	3.30	*3.64*	3.36	2.92	5.28	2.28
8	16-Feb-97	5.15	10.22	18-Feb-96	3.67	6.96	2.88	2.73	3.10	5.40	2.70	***5.15***	3.33	*3.67*	3.41	2.96	5.27	2.32
9	23-Feb-97	5.16	10.24	25-Feb-96	3.71	7.04	2.92	2.78	3.15	5.40	2.76	***5.16***	3.37	*3.71*	3.47	3.01	2.32	2.36
10	2-Mar-97	5.17	10.26	3-Mar-96	3.52	6.68	2.97	2.83	3.21	5.41	2.82	***5.17***	3.40	3.75	*3.52*	3.05	2.37	2.40
11	9-Mar-97	5.18	10.28	10-Mar-96	3.58	6.79	3.01	2.88	3.26	5.41	2.88	***5.18***	3.44	3.79	*3.58*	3.10	2.41	2.45
12	16-Mar-97	5.20	10.32	17-Mar-96	3.64	6.90	3.06	2.94	3.32	5.42	2.95	***5.20***	3.48	3.84	*3.64*	3.15	2.46	2.49
13	23-Mar-97	5.22	10.35	24-Mar-96	3.70	7.02	3.11	2.99	***3.38***	5.44	3.02	***5.22***	*3.52*	3.88	*3.70*	3.20	2.51	2.54
14	31-Mar-96	3.45	6.84	31-Mar-96	3.77	7.15	3.17	3.05	***3.45***	5.45	3.09	5.24	3.56	3.93	*3.77*	3.26	2.56	2.59
15	7-Apr-96	3.52	6.98	7-Apr-96	3.84	7.28	3.22	3.12	***3.52***	5.48	3.16	5.27	3.61	3.98	*3.84*	3.32	2.61	2.64
16	14-Apr-96	3.59	7.12	14-Apr-96	3.91	7.42	3.28	3.18	***3.59***	5.50	3.24	5.30	3.66	4.04	*3.91*	3.38	2.67	2.70
17	21-Apr-96	3.67	7.28	21-Apr-96	3.99	7.56	3.35	3.25	***3.67***	5.53	3.33	5.33	3.71	4.09	*3.99*	3.44	2.73	2.76
18	28-Apr-96	3.75	7.44	28-Apr-96	4.07	7.72	3.41	3.33	***3.75***	5.57	3.42	5.37	3.77	4.16	*4.07*	3.51	2.80	2.82
19	5-May-96	3.84	7.61	5-May-96	4.16	7.88	3.49	3.41	***3.84***	5.61	3.51	5.42	3.83	4.22	*4.16*	3.58	2.86	2.89
20	12-May-96	3.93	7.80	12-May-96	4.25	8.06	3.56	3.49	***3.93***	5.65	3.61	5.47	3.89	4.29	*4.25*	3.66	2.94	2.96
21	19-May-96	4.03	7.99	19-May-96	4.35	8.24	3.64	3.58	***4.03***	5.70	3.72	5.52	3.96	4.37	*4.35*	3.75	3.01	3.03
22	26-May-96	4.13	8.20	26-May-96	4.45	8.44	3.72	3.68	***4.13***	5.76	3.83	5.58	4.03	4.45	*4.45*	3.83	3.09	3.11
23	2-Jun-96	4.24	8.41	2-Jun-96	4.56	8.64	3.81	3.77	***4.24***	5.82	3.95	5.65	4.10	4.53	*4.56*	3.92	3.18	3.20
24	9-Jun-96	4.35	8.63	9-Jun-96	4.67	8.85	3.91	3.88	***4.35***	5.88	4.07	5.71	4.18	4.62	*4.67*	4.02	3.27	3.28
25	16-Jun-96	4.47	8.87	16-Jun-96	4.12	7.81	4.00	3.99	***4.47***	3.07	4.20	5.79	4.26	4.71	4.79	*4.12*	3.36	3.37

Table 18 *(Continued)*

Week Number	Harvest Dates and Weights						Weights (Round or whole kilogram per fish) corresponding to maximizing Present Value for each week per cohort.											
	Atlantic			Chinook			Atlantic Cohorts						Chinook Cohorts					
	Harvest Week	nd g	Dr. lb.	Harvest Week	Rnd kg	Dr. lb.	1	2	3	4	5	6	7	8	9	10	11	12
26	23-Jun-96	4.59	9.11	23-Jun-96	4.22	8.00	4.10	4.10	***4.59***	3.16	4.33	5.86	4.35	4.81	4.91	4.22	3.46	3.47
27	30-Jun-96	4.72	9.36	30-Jun-96	3.56	6.76	4.21	4.21	4.72	3.26	***4.47***	2.90	4.44	4.91	5.04	4.33	3.55	*3.56*
28	7-Jul-96	4.85	9.62	7-Jul-96	3.66	6.94	4.31	4.33	4.85	3.37	***4.62***	3.00	4.53	5.01	5.17	4.44	3.66	*3.66*
29	14-Jul-96	4.77	9.45	14-Jul-96	3.76	7.13	4.42	4.45	4.98	3.48	***4.77***	3.11	4.62	5.11	5.30	4.55	3.76	*3.76*
30	21-Jul-96	4.92	9.75	21-Jul-96	3.86	7.33	4.53	4.58	5.11	3.58	***4.92***	3.21	4.71	5.21	5.43	4.66	3.87	*3.86*
31	28-Jul-96	5.07	10.06	28-Jul-96	3.97	7.52	4.65	4.71	5.25	3.70	***5.07***	3.32	4.81	5.32	5.57	4.78	3.97	*3.97*
32	4-Aug-96	5.23	10.37	4-Aug-96	4.07	7.71	4.76	4.83	5.38	3.81	***5.23***	3.43	4.90	5.42	5.71	4.89	4.08	*4.07*
33	11-Aug-96	5.38	10.68	11-Aug-96	4.17	7.90	4.87	4.96	5.52	3.92	***5.38***	3.55	5.00	1.85	5.85	5.01	4.19	*4.17*
34	18-Aug-96	5.54	10.99	18-Aug-96	4.26	8.08	4.99	5.09	5.65	4.03	***5.54***	3.66	5.09	1.94	1.50	5.12	4.29	*4.26*
35	25-Aug-96	5.70	11.31	25-Aug-96	4.36	8.26	5.10	5.22	5.78	4.14	***5.70***	3.77	5.18	2.03	1.59	5.23	4.40	*4.36*
36	1-Sep-96	5.86	11.61	1-Sep-96	4.45	8.43	5.21	5.34	5.91	4.25	***5.86***	3.88	1.94	2.12	1.67	5.34	4.50	*4.45*
37	8-Sep-96	6.01	11.92	8-Sep-96	4.53	8.59	5.31	5.47	6.03	4.36	***6.01***	3.99	2.02	2.21	1.76	5.44	4.60	*4.53*
38	15-Sep-96	6.16	12.21	15-Sep-96	4.61	8.74	5.42	5.59	6.14	4.46	***6.16***	4.09	2.10	2.30	1.85	5.54	4.69	*4.61*
39	22-Sep-96	5.70	11.31	22-Sep-96	4.69	8.89	5.52	5.70	6.25	4.56	***6.30***	4.20	2.18	2.39	1.94	1.65	4.78	*4.69*
40	29-Sep-96	5.81	11.52	1-Oct-95	2.26	4.29	5.61	5.81	6.36	4.66	***6.44***	4.29	*2.26*	2.48	2.03	1.73	4.86	4.76
41	6-Oct-96	4.75	9.42	8-Oct-95	2.34	4.44	5.70	5.91	1.76	4.75	***6.57***	4.39	*2.34*	2.56	2.12	1.81	4.94	4.82
42	13-Oct-96	4.84	9.59	15-Oct-95	2.42	4.58	5.78	6.01	1.85	***4.84***	6.70	4.48	*2.42*	2.65	2.20	1.89	5.01	4.87
43	20-Oct-96	4.91	9.75	22-Oct-95	2.49	4.72	5.86	6.10	1.94	***4.91***	6.82	4.56	*2.49*	2.73	2.29	1.97	5.07	4.91
44	27-Oct-96	4.99	9.89	29-Oct-95	2.56	4.86	5.93	6.19	2.03	4.99	6.93	***4.64***	*2.56*	2.81	2.38	2.05	5.13	4.95
45	3-Nov-96	5.05	10.02	5-Nov-95	2.63	4.99	5.99	6.26	2.12	5.05	7.03	***4.71***	*2.63*	2.89	2.46	2.12	5.18	4.98
46	10-Nov-96	5.11	10.14	12-Nov-95	2.70	5.12	6.05	6.33	2.20	5.11	7.13	***4.77***	*2.70*	2.97	2.54	2.20	5.22	5.00
47	17-Nov-96	5.17	10.25	19-Nov-95	2.76	5.24	6.10	6.39	2.28	5.17	1.89	***4.83***	*2.76*	3.04	2.62	2.27	5.26	5.02
48	24-Nov-96	5.21	10.34	26-Nov-95	3.10	5.88	6.14	6.45	2.36	5.21	1.96	***4.88***	*2.82*	*3.10*	2.69	2.34	5.29	5.02
49	1-Dec-96	5.25	10.42	3-Dec-95	3.17	6.00	6.18	6.49	2.43	5.25	2.03	***4.93***	2.88	*3.17*	2.76	2.40	5.31	5.03
50	8-Dec-96	5.28	10.48	10-Dec-95	3.23	6.12	6.21	6.53	2.51	5.28	2.10	***4.97***	2.93	*3.23*	2.83	2.46	5.32	5.02
51	15-Dec-96	5.31	10.54	17-Dec-95	3.28	6.22	6.23	6.57	2.58	5.31	2.17	***5.00***	2.98	*3.28*	2.90	2.52	5.33	5.01
52	22-Dec-96	5.03	9.98	24-Dec-95	3.34	6.32	6.25	6.59	2.64	5.33	2.23	***5.03***	3.03	*3.34*	2.97	2.58	5.34	4.99

6 Conclusion

This study demonstrated that each fish group or cohort has a comparative advantage for supplying a particular market window during the year. In other words, the optimal harvest time for a cohort as part of a portfolio may differ from its own optimal harvest time as a single production unit. The growth characteristics and life expectancy were major contributing factors determining the comparative advantage of each cohort. Optimal harvesting times for each fish group must be considered in the context of overall production. Assuming that mortality increases in adult salmon under certain conditions, the optimal portfolio of salmon cohorts was found to include relatively fast growing/early maturing fish and slow growing/late maturing fish. While the harvest window for some cohorts straddled their own optimal harvest time, the harvest window for others occurred strictly before or after their respective optimal harvest time.

Several studies have examined optimal harvest time in aquaculture (Bjorndal 1988, 1990; Arnason 1992; Springborn *et al.* 1992; Heaps 1993; Hean 1994). This type of analysis is useful to explore the economic characteristics involved in the production of a particular group of fish and to rank groups of fish on the basis of their respective economic benefits. In the context of salmon aquaculture, a production strategy based on optimal harvesting time is unlikely to yield continuous harvest output. As demonstrated in this study the regulating action of water temperature on growth and feed conversion efficiency means that the optimal harvest times for different groups of fish are likely to occur within a similar time frame. Notwithstanding risks associated with price volatility and biomass losses, this result also implies that harvest may not occur for a substantial period of time during the rest of the year because it would not be optimal to do so.

Relatively few studies have investigated the idea of consistent harvesting in aquaculture. Yet, there is an undeniable trend from food processors and retailers alike to seek a greater security of supply as market matures (Bromage *et al.* 1988). Given the extend of global competition in the market for fresh salmon, consistent harvesting analysis is an essential planning and managerial exercise to undertake if suppliers are to maintain a competitive position and provide the quality of products and service expected by market agents. In such an environment, it is no longer sufficient to be market driven or to be production driven. Faced with declining prices and expanding markets, producers must instead become economically driven to balance market interests with production constraints.

The results for both Atlantic salmon and chinook salmon showed that consistent harvesting analysis can assist to better understand and analyze the mechanisms regulating market supply. In the simulation results, early maturing Atlantic cohorts were harvested first, beginning in the month of March. Late maturing cohorts were harvested last and into the next year. For chinook salmon, the first harvest of a new generation occurred early in the fall and continued until the late summer of the next year. The underlying supply by weight class expected from these production patterns were found to be consistent with data and observations reported in Seafood Price-Current publications (Urner-Barry Publications, various issues). It is unclear whether producers are planning a consistent harvesting strategy on the basis of economic criteria. As demonstrated in the optimal harvest time analysis under an increasing mortality rate assumption, there is little difference between the economic optimal harvest time and the time at which yield per smolt (biomass) is optimized for most cohorts.

The bioeconomic application developed in this study was instrumental in simulating the behaviour of the key production parameters required in the optimal harvesting analysis and for designing a consistent harvest strategy. The deterministic bioeconomic model was developed following the theoretical framework published by Bjorndal (1988, 1990). Three innovative sub-models were specified and incorporated into a discrete bioeconomic framework to simulate fish growth, feed requirements and mortality. First, the Iwama-Tautz growth model was modified through the addition of a dampening factor to embody the size/growth relationship expected in fish growth. Second, a bioenergetic feeding model was developed based on a formulation empirically derived by Cho (1992) and the work published by Maroni *et al.* (1994) on differential feed conversion efficiencies. Finally, two mortality rate scenarios were specified based on the underlying causes of disease manifestation and the effect of sexual maturation on fish quality and survival. In many respects, dynamic optimization of agricultural production is as much an art as a science (Cacho 1993). Several aspects of these sub-models were assumed to provide a rational extension beyond the limits imposed by available data. While much of the arguments rationalizing these extensions were supported by general principles extracted from the literature, the art aspect of modeling raises opportunities for new areas of investigation.

The first of the three sub-models is the generalized salmonid growth model, which combines a temperature-growth relationship and a fish size-growth relationship. Through the calibration of the growth index and the addition of a dampening factor, the model provided a growth path for the entire production cycle over a period of an undisturbed growth stanza. This attribute of the growth model has important economic implications since it provides a more accurate description of the rate of change in the cost and revenue functions over time. One of the main consequences of the environmental and physiological relationships regulating growth is that marginal and average costs almost level off in adult salmon as they enter a second winter in the sea. This characteristic of the growth model is an important factor for establishing the comparative advantage of some cohorts in providing the highest economic returns over seasonal market windows.

The second sub-model is the feeding standard. The growth rate variable required in the bioenergetic feeding model was computed using the growth model. The major benefit of this feeding standard is its generality in computing feed rates as a function of species, feed quality, water temperature, fish size and growth rate. In the model, feed rates are endogenously estimated on the basis of physiological requirements to achieve a certain growth. As a result, the biological feed conversion ratio is a figure derived from feeding model instead of factor determining feed rates. The feeding model thus eliminates the guess work often in selecting a biological feed conversion ratio to calculate feed requirements. This type of model is also a valuable tool for estimating the sources of variation in feeding efficiency over time. As a component of a bioeconomic model, the bioenergetic feeding standard simulates the impact of water temperature and fish size on the efficiency of the fish in converting feed into growth.

In the third sub-model, the assumptions regulating the mortality rate are based on a simple generalization of the underlying causes of mortality. These assumptions were instrumental in demonstrating the economic impact of fish mortality on the optimal harvest time for all cohorts. The contributions of the relative growth rate and price appreciation to the marginal revenue structure at optimal harvest time were found to be higher in the increasing mortality case than they were in the fixed mortality case. The difference in the relative growth rates between the two mortality rate scenarios at their respective optimal harvest time is indicative of the opportunity cost of foregone growth due to mortality. Growth is the driving economic force in generating value for a fish cohort. With a fixed (low) mortality rate, growth was predominantly limited by feed cost considerations. This result is consistent with conclusions reached by Bjorndal (1988, 1990) and Hean (1994).

Future research agenda items

In the increasing (high) mortality rate scenario, growth was predominantly limited by the contributions of the feed rate and mortality rate. A sustained increase in the mortality rate resulted in substantial economic losses in terms of foregone revenue and invested capital in lost biomass. This explains the efforts of the salmon farming industry directed to acquire a better understanding of causal mortality factors and developing solutions to control them. Toward this end, the BC Salmon Farmer Association established the Cooperative Assessment of Salmonid Health (CASH) in 1990 to develop a record of production program for producing members with a particular emphasis on health issues and reducing costs of production. An industry assessment of salmon aquaculture in British Columbia identified research and development targeted toward specific pathogenic agents as a priority (Anon. 1992). This focus on salmon health is common to all producing areas of the world and demonstrates a general consensus on the economic benefits to be gained from reducing mortality. From a bioeconomic perspective, there is a great need to formalize a mortality model that would explicitly account for stress factors, presence of pathogens, fish characteristics, environmental factors and effects of therapeutic interventions.

In designing a consistent harvesting strategy, the increasing mortality scenario was a primary factor in determining the comparative advantage of cohorts selected into the production portfolio. Under a fixed mortality rate assumption, the comparative advantage of selected cohorts would be determined predominantly by their growth rate performance, with minimal impact from the mortality rate. This case would lead to the selection of one or two cohorts into the production portfolio. A cohort could supply a harvest window for up to twelve months. This situation would result in a substantial difference in the average weights between the first harvest and the last harvest for stocks not graded on the basis of weight classes. Without a grading program to separate the fish on the basis of its market weight category, the distribution of harvest weights would show a greater variance over time than would likely be desirable within a consistent harvest strategy. If the marketing objective is to supply the market with a specific range of weight classes year-round, the fastest stocks would be harvested first before they become to big and the smallest member of the population would be allowed to growth to a target weight. The economic implications from a cohort production portfolio composed of one or two cohorts needs to be investigated in the context of the optimal grading strategy to adopt.

The potential benefits related to smolt size is an issues that remains to be addressed as the value of rearing larger smolts is still an issue under debate among some scientists (Morgan 1996). In this study, larger smolts reached market weight at an earlier time. Given equal growth potential, these cohorts also yielded a higher return at optimal harvest time relative to smaller smolts. Smolt size and growth potential were contributing factors to determine the benefits related to the timing of smolt introduction to seawater. The growth attributes related to different smolt sizes is a biological question that remains to be evaluated.

Bioeconomic modeling is a powerful instrument to gain insight into the nature of interactions between economic and production variables, to assist in production planning at the firm level or to anticipate market supply behaviour. The deterministic bioeconomic model presented in this study serve as a basis upon which stochastic variations can be introduced for analyzing market or production risks. There is a considerable time lag between the planning process of production and the marketing of harvested stocks. To remain competitive in an internationally active industry, producers must design strategies that are economically motivated and they must anticipate the impact of various risk factors on their operation. A stochastic extension of the model would prove very useful in the intensive production of cultured salmon

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Appendix 1: Mathematical derivation of the Iwama-Tautz growth model

The easiest method to monitor the growth of an organism is achieved by measuring its body weight. A more complex but accurate method to measure growth involves calculating the incremental energy content of the body acquired from feeding (Stauffer, 1973; Corey *et al.* 1983) which is than converted into a biomass gain. An alternate method is to assume an optimal growth path and compute the energy required to achieve it. In this study, growth is measured in terms of discrete changes in the biomass over time. The energy requirement to achieve this incremental growth is than calculated using a bioenergetic model as proposed by Cho (1992).

The growth function utilized in this study follows the formulation published by Iwama and Tautz (1981). Based on an extensive review of fish growth literature, Iwama and Tautz presented a simple mathematical model in which growth is based on an exponent of weight (b) and the concept of accumulated thermal units (ATU). For most fish species, including Chinook salmon and Atlantic salmon, an exponent of weight equal to 1/3 has been applied with adequate results in several studies.

To compare fish of different sizes reared under different temperature regime, Iwama-Tautz introduces a growth index, which they termed the growth coefficient. Other authors within the context of the original Iwama-Tautz growth model (Cho 1992; Holmefjord *et al.* 1995) have redefined this index. Despite their acronyms and their particular formulations, these indexes are all equivalent and are mathematically derived below along with the Iwama-Tautz model.

Over an undisturbed period of growth, the growth rate can be described as a power of weight (Parker and Larkin 1959);

$$\frac{dw}{dt} = kw^x \qquad (1)$$

where w is the weight, x the power of weight and k a constant. Rearranging and integrating equation 1 yields,

$$w^{-x}dw = kdt \qquad (2)$$

$$\int_{w_0}^{w_t} w^{-x}dw = k\int_0^t dt \qquad (3)$$

$$\frac{w_t^{(1-x)} - w_0^{(1-x)}}{(1-x)} = kt \qquad (4)$$

Letting (1-x) = b and rearranging the terms provides a basic identity for the expected weight;

$$w_t^b = w_0^b + bkt \qquad (5)$$

Define $kb = Gs$. Gs is termed the growth slope and assumes a linear relationship between W^b and time. Iwama-Tautz determined the growth slope to be approximately equal the average temperature ($T°$) over 1000;

$$Gs = \frac{T°}{1000} \qquad (6)$$

With the introduction of identity 6 into 5, the basic growth model then is formulated as follow,

$$w_t^b = w_0^b + \frac{T°}{1000}t \qquad (7)$$

Iwama and Tautz found that the cubic root of weight (b=1/3) provided the best linear fit between the growth slope and normal operating water temperature and between w^b and time. In addition, $w^{1/3}$ and length are convertible using the following relationship (Springborn *et al.* 1992);

$$w_t = \left(a^{1/3}L_t\right)^3.$$

In this identity, L is fish length and a is the condition factor.

A growth index is introduced in equation 7 to accounts for factors such as species, strain, size differences, environmental factors and husbandry practices. This growth index is termed the growth coefficient (*Gc*) in Iwama and Tautz (1981), the thermal-unit growth coefficient (*TGC*) in Cho *et al.* (1989, 1990, 1992) and the growth factor 3 (*GF3*) in Holmefjord *et al.* (1995).

The basic formulation of the model (equation 7) provides the relative growth path for a homogeneous group of fish over an uninterrupted growth stanza. The growth index acts as scaling factor by increasing the growth rate if the index is greater than one and decreasing the growth rate if the index is smaller than one. The growth index is usually assumed fixed over the production cycle, although Iwama recommends it be recalculated for distinctive growth stanza. Iwama and Tautz defined the growth coefficient (*Gc*) as the ratio of the theoretical growth slope over the actual growth slope. The theoretical growth slope is computed by solving the basic model (equation 7) for the average temperature (T^*) required to obtain a specific weight w at time t;

$$T^* = \frac{(w_t^b - w_0^b)1000}{t} \tag{8}$$

Define the expected average temperature as follows;

$$\bar{\bar{T}} = \frac{\sum_{i=0}^{t} T_i}{t} \tag{9}$$

The actual growth slope is calculated using the expected average temperature (T^*) required to obtain a

specific weight w at time t;

$$T^* = \frac{(w_t^b - w_0^b)1000}{t} \tag{8}$$

Define the expected average temperature as follows;

$$\bar{\bar{T}} = \frac{\sum_{i=0}^{t} T_i}{t} \tag{9}$$

The actual growth slope is calculated using the expected average temperature ($\bar{\bar{T}}$) over the production cycle. The growth coefficient is the following ratio;

$$Gc = \frac{Theoretical[Gs]}{Actual[Gs]} \tag{10}$$

$$Gc = \frac{T^*/1000}{\bar{\bar{T}}/1000} \tag{10.1}$$

$$Gc = \frac{\frac{(w_t^b - w_0^b)1000}{t}}{\frac{\sum_{i=0}^{t} T_i}{t}} \qquad (10.2)$$

$$Gc = \frac{(w_t^b - w_0^b)1000}{\sum_{i=0}^{t} T_i} \qquad (10.3)$$

With b=1/3, the above expression is the growth index as defined in Holmefjord *et al.* (1995);

$$GF3 = \frac{(w_t^{1/3} - w_0^{1/3})1000}{\sum_{i=0}^{t} T_i}. \qquad (11)$$

Equation 11 implies that $Gc = GF3$.

Inserting the growth coefficient into the basic model yields the growth model as formulated in Iwama and Tautz (1981);

$$w_t^b = w_0^b + Gc\frac{\text{T}°}{1000}t\cdot \qquad (12)$$

Cho's growth model formulation is found by first expanding the above expression using identity 10.3;

$$w_t^b = w_0^b + \left[\frac{(w_t^b - w_0^b)1000}{\sum_{i=0}^{t} T_i}\right]\frac{\text{T}°}{1000}t \qquad (13)$$

$$w_t^b = w_0^b + \left[\frac{(w_t^b - w_0^b)}{\sum_{i=0}^{t} T_i}\right]\text{T}°t\cdot \qquad (13.1)$$

In identity 13.1, the expression in the square brackets is the thermal growth coefficient (*TGC*) as defined in Cho;

$$TGC = \frac{(w_t^{1/3} - w_0^{1/3})}{\sum_{i=0}^{t} T_i}. \tag{14}$$

The above expression implies that $Gc = TGC \cdot 1000$. Using identity 14, identity 13.1 is rewritten as follow;

$$w_t^{1/3} = w_0^{1/3} + TGC \cdot \mathrm{T}°t. \tag{15}$$

Substituting the temperature $T°$ with equation 9 yields;

$$w_t^{1/3} = w_0^{1/3} + TGC \cdot \frac{\sum_{i=0}^{t} T_i}{t} t \tag{16}$$

$$w_t^{1/3} = w_0^{1/3} + TGC \cdot \sum_{i=0}^{t} T_i \tag{16.1}$$

Identity 16.1 is the fish growth model as formulated in Cho. It explicitly expresses growth as a function of accumulated thermal units (ATU).

The growth model as formulated in Holmefjord *et al.* (1995) is obtained by first substituting identities 9 and 11 into 12;

$$w_t^b = w_0^b + \frac{GF3}{1000} \cdot \frac{\sum_{i=0}^{t} T_i}{t} t \tag{17}$$

Setting b=1/3,

$$w_t^{1/3} = w_0^{1/3} + \frac{GF3}{1000} \cdot \sum_{i=0}^{t} T_i. \tag{17.1}$$

As with identity 16, the above expression is an explicit function of ATUs.