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POPULATION DYNAMICS AND EXTINCTION:
AN APPLICATION TO THE FIN WHALE STOCK OFF ICELAND

by:

Halldor Petur Palsson B.B.A, M.A.

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfillment of
the requirements for the degree of

Doctor of Philosophy
Department of Economics

Carleton University
Ottawa, Ontario
September 17, 1991

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ISBN 0-315-70908-1

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The undersigned hereby recommend to
The Faculty of Graduate Studies and Research
acceptance of the thesis,
**"Population Dynamics and Extinction:
An Application to the Fin Whale Stock Off Iceland"**

submitted by
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in partial fulfilment of the requirements
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ABSTRACT

This thesis is an empirical study of the bioeconomics of sole owner exploitation of the fin whale stock off Iceland in the post-1948 period. The purpose is to explain how stock dynamics, economics and stochastic fishing are combined in the sole owner's decision to either mine the stock or harvest it on a sustained yield basis.

To establish stock dynamics the history of whaling around Iceland from 1883 to 1989 is reviewed. The open access period from 1883-1915 saw catches peak in 1902 at 1305 whales and by 1915 the stocks were depleted to low levels. Catches were more stable in the sole owner period from 1948-1989. Species breakdowns of catches prior to 1913 are incomplete but it is evident from data on oil barrels per whale that blue whales were important in the early years. Fin whales dominate in catches in the sole owner period.

The population dynamics used by the International Whaling Commission for baleen whales is applied to both fin and blue whales off Iceland. Population trajectories for 1883-1989 show that stocks were fished down to low levels in the open access period 1883-1915. The fin whale stock recovered and is stable

in the sole owner period while the blue whale stock remained at a fished down level.

Stochastic simulations of the fin whale stock trajectory for the 1883-1989 time period are used to derive distributions of stock levels for 1948 and 1987. Based on the simulations the pristine level for the fin whale stock is determined to be between 6000 and 6750 mature animals in 1883.

The solution to the sole owner's inter-temporal profit maximization problem is derived. The resource base in fin whales is fished down to a stable equilibrium. Numerical simulations of the most rapid approach paths to the optimal stock size demonstrate that at high discount rates the fin whale stock off Iceland would only be fished down slowly because catching capacity of the fleet is low relative to the size of the stock. We therefore conclude that conservation of the fin whale stock is consistent with profit maximization for the sole owner.

The operational characteristics of the catchers and the hunt are reviewed to motivate the use of search theory. The hunt takes place on three distinct whaling grounds and moves north as the season progresses. The stock itself has a wider distribution than the whaling grounds.

Fin whale catch-per-unit effort (CPUE) data is reviewed because it is the most commonly used index of relative abundance for the fin whale stock. CPUE is constant over the season for

the period 1949 to 1979. The CPUE data for the "peak fin whale season" defined as the June 10 to July 20 period shows a small, significant, negative trend over the period 1962-1981. The fraction of the annual fin whale catch taken during the June 10-July 20 period ranges from 38 to 82 per cent and changes in CPUE over the period may be independent of any changes in stock status.

The search for fin whale schools is modeled, and an estimate of the number of schools and whales entering the whaling grounds and the expected catches each year are derived. If a constant population is assumed, the model has a root-mean-square error of 12.34 per cent in predicting the number of schools harvested in a historical simulation. It is estimated that 3-11 per cent of schools entering the grounds were subjected to harvesting. However, only about half of the schools in the stock migrate through the whaling grounds on average.

The annual number of schools on grounds estimate is validated with an in-season micro simulation model of search. The micro model incorporates fleet operations and a markov model of fin whale migration. The in-season micro model replicates actual catching patterns well. The variation in annual catches observed in 1948-81 is consistent with a highly stochastic catching process and a constant fin whale stock. The micro model is then used to determine the marginal product of an additional catcher. A fifth catcher is probably profitable for

the sole owner. Finally, using today's catchers as a benchmark, catches of fin whales in 1915 are consistent with a migration level on the grounds that is 10 per cent of the average migration in the 1948-81 period.

ACKNOWLEDGEMENTS

I would never have developed or finished this thesis without the encouragement and support of my supervisor, Professor Daniel E. Lane. Philippe Crabbé and Jon Conrad launched this thesis with their "do more" comments on a paper I presented at the Natural Resource Modeling Conference in Halifax, September 29-October 1, 1988. I would also like to thank Professors Stephen Ferris and Douglas Smith for all their help on the project.

At various stages, I benefited from discussions and comments from Orlando Manti, Jóhann Sigurjónsson, Thorvaldur Gunnlaugsson, Robert Nowak and R.W. Crowley. I would also like to thank the library staff and my colleges at the Department of Fisheries and Oceans for their support. I would like to thank my fellow students at Carleton University, especially Aslam Anis and Ron Corvari for their encouragement.

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CHAPTER 1: INTRODUCTION

This thesis is an empirical study of the bioeconomics of sole owner exploitation of the whale stocks off Iceland in the post 1948 period. The sole owner was relatively unconstrained by catch regulation from 1948 to 1981. In the 1980s catch quotas from the International Whaling Commission followed by a moratorium on whaling regulated the sole owner out of business after the 1989 season.

The sole owner relied on the fin whale stock off Iceland for his catches. The key to the status of this stock in the post 1948 period is whether the sole owner chose to mine the stock. The interaction of stock dynamics, economics and operational considerations are combined in the sole owner's decision to either harvest on a sustained yield basis or deplete the resource.

The Icelandic Sagas describe whaling by the Viking settlers. This whaling was important enough for the early law book Jonsbok (1281) to detail procedures for determining the ownership of both a beached and a harpooned whale. In later times, the Basques, the French and the Dutch also whaled off Iceland. In 1865 two Americans established a whaling operation in Iceland. Whaling based on their method operated from 1865 to 1872. Modern whaling using the explosive harpoon arrived in Iceland in 1883 when a Norwegian firm established an operation on the northwest coast of Iceland

(Jónsson (1965) p.245). Between 1889 and 1894 four more Norwegian firms started whaling operations in Iceland (Tønnessen and Johnsen (1982) pp.76-77). The success of these firms induced five more firms to start operations between 1896 and 1903. They expanded rapidly and fished the whale stocks off Iceland to near commercial extinction.

From 1896 to 1905 approximately 20 per cent of Iceland's exports came from whale products (Iceland 1984). The actual figures are 21.2 per cent of exports 1896-1900 and 18.2 per cent for 1901-1905. This fell rapidly to 2 per cent in the 1910-15 time period. By that time, the whale stocks had effectively been depleted to levels where commercial exploitation was not attractive. In 1913 the Icelandic parliament passed a 10 year ban on all whaling "...in order to preserve for the Icelanders themselves the whale stocks still remaining" (Tønnessen and Johnsen (1982) p. 82).

In 1925 a new era in whaling began. The introduction of on-board processing on the Norwegian factory ship the *Lancer* was a revolution in whale harvesting technology. A slipway allowed whales to be taken on-board for processing. Prior to that all whale processing was done on land stations or alongside ships in sheltered harbours close to land.

The introduction of whaling from catchers attached to factory ships (pelagic whaling) marked the end of unilateral control of whaling by coastal states like Iceland. Some Norwegian floating factories caught whales off Iceland from

1929-37 but they later departed for better catch rates in the Antarctic. An Icelandic land station operated from 1935-39. There was no whaling in waters off Iceland during World War II.

In 1948 a new Icelandic firm started harvesting the whale stocks off Iceland. This firm has enjoyed exclusive access to the whale stocks off Iceland from 1948 to the present. The effect of this exclusive access on its harvesting behavior is analyzed in this thesis. Icelandic whaling starting in 1948 provides a unique opportunity to study a whale fishery subject to exploitation by only one firm. All other whale fisheries were open access fisheries subject to international management. The pattern of fishing that emerged from that institutional framework made commercial whaling virtually synonymous with over-exploitation and extinction.

This thesis is an empirical study of the bioeconomics of sole owner harvesting of the fin whale stock off Iceland from 1948 to 1981. The purpose is to explain how economic incentives embodied in stock dynamics and a stochastic fishing process are combined in the sole owner's decision to either harvest on a sustained yield basis or deplete the resource. The method used to analyze this question is first to explicitly derive the population dynamics of the fin whale stock from the biology of the stock. Second, the stock status is then indirectly confirmed by solving for the harvesting profiles implied by intertemporal profit maximization. Third,

the search for whale schools is modeled. Fourth, the dynamics of in-season harvesting and optimal investment in catching capacity are analyzed in a micro model incorporating explicitly the search for fin whales.

1.1 PLAN OF THE THESIS

In Chapter 2 a sketch of the economics of whaling prior to World War II is presented. In Section 2.1 the catch and effort data during the open access whaling period from 1883-1915 are briefly reviewed to establish how and what resource base was fished down. Section 2.2 deals with entries into whaling in Icelandic waters after the end of the 10 year ban. In Section 2.3 the harvesting behavior of the company that has sole access to whaling in Icelandic waters since 1948 is examined.

In Chapter 3 the biology and population models are reviewed. The species killed from 1883 to 1915 are derived from aggregate landing data because species killed was not accurately recorded until 1913. In Section 3.2 deterministic population profiles for the fin and blue whale populations off Iceland from 1883 to 1986 are simulated using parameters from biology studies. In Section 3.3 stochastic simulations of fin whale populations are used to estimate the pristine carrying capacity for the fin whale population.

In Chapter 4 the inter-temporal profit maximization problem faced by the sole owner of the fin whale stock is solved.

Numerical simulation of the model is used to infer the discount rate employed by the resource owner.

In Chapter 5 we review descriptive material on the operational characteristics of the catching process. In Section 5.3 available catch per unit effort relationships are critically analyzed and found to be suspect as an index of relative abundance. The analysis of length data in Section 5.4 gives inconclusive evidence on the status of the fin whale stock. In Section 5.5 fin whale school harvesting data is reviewed.

The number of fin whale schools found by catchers is modeled in Chapter 6 to derive the number of fin whale schools migrating into the whaling grounds each year. The annual search model permits the estimation of the number of fin whale schools and thus the number of whales entering the whaling grounds each year. The abundance on the whaling grounds fluctuates widely from year to year with a positive and insignificant trend.

In Chapter 7 a weekly search model is built to take into account the seasonal migration pattern of the fin whales. The in-season interaction of the catchers with the migration is explicitly modeled to validate qualitatively annual estimates of school migrations and abundance on the whaling grounds. The impact of adding an additional catcher vessel is also evaluated as is the degree of depletion of the stock in 1915.

Chapter 8 is a brief summary of the main results of our analysis. The key result of this thesis is that the three modeling approaches used to assess the fin whale stock are all consistent with a stable or a very slowly declining stock in the post 1948 sole owner period. The variation in catches observed can be attributed to a stochastic catching process rather than differences in abundance of the whaling grounds. The conservation of the fin whale stock is consistent with the profit maximization of the sole owner.

Conservation of a whale stock cannot be precisely defined. For the purposes of this thesis it will be defined to mean that the stock would probably be classified as a Sustained Management Stock (SMS) by the International Whaling Commission. A Sustained Management Stock is a stock that is not more than 10 per cent of maximum sustainable yield (MSY) level below MSY stock level, and not more than 20 per cent above that level. A stock can thus range from 0.9 to 1.2 of its MSY level. To cut through the jargon, we will refer to a conserved whale stock as one that is 53-70 per cent of its pristine level.

CHAPTER 2: THE ECONOMICS OF WHALING-THE ECONOMIC HISTORY OF WHALING OFF ICELAND 1883-1981

Prior to World War II, the whaling industry produced predominantly whale oil that competed with other sources of oil and fats. The industry was a price taker in the edible oil market. In the post World War II era, the Japanese market for whale meat has slowly reduced whale oil to a byproduct of meat production. In this Chapter a general description of production processes, marketing channels and revenue cost relationships from 1883 to the 1940s is made. The purpose is to survey the risks and potential profits as they would have looked to someone contemplating entry into whaling following World War II. We then give a brief economic history of Icelandic whaling from 1883 to the present.

The history of whaling is usually divided into the modern period starting in 1867 with Svend Foyn and the old whaling period prior to that. In old whaling rowboats and hand held harpoons were used to catch "whalebone whales". Whalebone whales are the Greenland right, known as the bowhead whale in North America, and the Grey whale. These are slow swimming whale species (maximum speed of about 7 knots) (Tønnessen and Johnsen (1982) p.6) that will float after they have been killed.

The most important product of old whaling was whalebone or baleen. The baleen consists of slabs or plates attached to the side of the upper jaw that carry a fringe of hard bristles

at their inner rim. The baleen forms a grid in between the jaws of the whale that allows water to pass in and out but retain the krill and other prey that the whale lives on. The value of baleen was in its lightness, elasticity and flexibility. The longer baleen was used as springs in mattresses and sofas while the shorter was used for ladies' corsets and frocks. Baleen could also be split into thin fibers and woven into silk fabric that preserved its rigidity. Baleen was so valuable at certain times that the rest of the whalebone whale was discarded (Tønnessen and Johnsen (1982) p.6). As a rule the fat content of these whales was extracted by melting the blubber into whale oil in open pans. Whale oil was used for centuries to light the cities of Europe (Tønnessen and Johnsen (1982) p.53).

The American whale fishery in its "final flurry" in the western Arctic was a modern whalebone fishery. The history of this fishery has been recorded by Bockstoce (1986).

Modern whaling was made possible by the invention of the explosive harpoon by the Norwegian Svend Foyn in the 1860s. Modern whaling is based on catching the fast swimming rorquals (speed of 25-30 knots for short periods) (Tønnessen and Johnsen (1982) p.6) which in order of size are the blue, the fin, the humpback and the sei whale. Unlike the whalebone whales, rorqual whales sink as soon as they have been killed. The line attached to the explosive harpoon is used to haul the dead whale to the surface. The dead whale is then secured and

towed to a shore station for processing. In the early years a significant number of whales killed could not be recovered because the line attached to the harpoon would break or the harpoon would come loose.

Modern whaling in the 1883-1915 period was almost exclusively for oil (Tønnessen and Johnsen (1982) p.10). A detailed account of operations is provided by Jenkins (1921). According to Jenkins (1921) the blubber and the highly oleaginous bone and flesh of the whales were cooked in closed pressure boilers. The whale oil was siphoned off after each boiling. Whale oils are classified as follows:

1. No 1 oil (from blubber).
2. No 2 oil (from second boiling of blubber).
3. No 3 oil (from meat and blubber in closed boiler).
4. No 4 oil (from bones, scraps, and sperm meat).
5. Spermaceti (from the head of the Sperm Whale)
6. Sperm blubber oil

Whale oil is true fat (glyceride of the fatty acids) (Brandt (1940) p.25). It was used to produce margarine, soap etc. "The approximate level of prices obtainable for whale oil is determined by the prices of the numerous competing fats. Hence cost considerations are of no immediate importance for the course of whale-oil prices"(Brandt (1940) p.175). The pressure on whale oil prices from substitutes made whaling unprofitable even on the best grounds in the world in the late 1930s.

Sperm oil is chemically distinct from whale oil. Sperm oil consists mainly of wax alcohol compounds and fatty acids. It is used as an industrial lubricant. Spermaceti is used to manufacture unguents and ointments. A sperm whale can also produce ambergris (secretion from the intestines which is produced as a result of a disease). Ambergris is used in the preparation of perfumes. "Ambergris is comparatively rare, and is worth more than its weight in gold"(Jenkins (1921) p. 42).

The oil yield per whale ranks the species of whales in terms of desirability. "The species of whale yield oil at the following rate: Blue Whale (*Balaenoptera musculus*) fifty to sixty barrels;...; the Finner (*B. physalus*) thirty-five to forty; the Humpback (*Megaptera novaeanglia*) twenty five to thirty-five; and the Sei Whale (*B. borealis*) five to ten barrels" (Jenkins (1921) p.293).

The total value of each species is supplemented by the baleen yield (whalebone yield). The Norwegian whale fishery in Finmark was very similar to the one pursued from Iceland after 1883. "The Finmark fishery, which commenced with four species of Finner Whale; the Blue Whale, which was estimated at this time to be worth one hundred and fifty pounds, of which whalebone furnished sixty pounds; the common Finner (*B. physalus*) worth one hundred and twenty-five pounds (whalebone fifteen pounds); the Humpback worth also one hundred and twenty-five pounds; and the Sei Whale worth forty to

forty-five pounds, to which the whalebone contributed ten pounds"(Jenkins (1921) pp.267-268). The baleen yield by species is roughly proportional to the size differences between the different species of whales. "In about 1880 it was estimated that on average a blue whale could provide 250 kg. of baleens, a fin whale 125, a humpback 100 and a sei whale 80" (Tønnessen and Johnsen (1982) p.53). The information on baleen prices is fragmented.

Prices averaged £120/ton in 1879. For blue whale baleen prices were £45/ton in 1885, £200/ton in 1891, £300 in 1892, £35 in 1898 and £78 in 1900. Fin baleen followed the same pattern but became more expensive than blue baleen 1896-1900. Sei baleen was more expensive than fin baleen (Tønnessen and Johnsen (1982) p.53). The price of whalebone collapsed in 1910-14 to an average of \$0.63/lb. from \$4.38 1905-09 (Best (1987) p.5).

Two important by-products of whale production are guano and cattle-feed. These proved to be important sources of supplemental income to some whaling stations in Iceland. However, many whaling stations only utilized blubber and baleen.

While the rankings by Jenkins of the baleen whales holds for 1883-1915 the value of blue whales should be higher relative to fin whales. The ranking based on oil yield adopted by International Whaling Statistics is: 1 blue whale is equal to a blue whale unit (BWU), equivalent to two fin

whales, two and a half humpbacks and six sei whales (Tønnessen and Johnsen (1982) p.5).

The cost structure of the whaling companies operating out of Iceland from 1883-1915 is not known. However, individual examples of exceptional returns to a catcher in Iceland or Norway and the profitability of the Norwegian whaling industry in general can be used as proxies for the companies in Iceland. In 1887 a catcher in North Norway delivered 35 whales (or 18.5 BWU, 6 blue, 23 fin and 6 sei) after a season of 5 months and 23 days. The catch yielded 2000 barrels of oil and the crew was paid a total of Kr 4,709 (£259). The average catcher took 26.5 whales in 1887 (Tønnessen and Johnsen (1982) p.46).

In 1888 the only company operating in Iceland had a net profit of Kr 77,385 (£4,252) or 34.4 per cent of the share capital. The top catcher in Iceland had 4000 barrels of oil compared to 2700 in North Norway (Tønnessen and Johnsen (1982) p.76).

The profitability of the Norwegian industry from 1910-11 to 1934-35 can be gaged by a biased sample of successful firms from two sources. For 1910-11 to 1914-15 a sample of four firms operating in the Antarctic is provided by Tønnessen and Johnsen ((1982) p.243). Brandt (1940) has a sample from 1919-20 to 1934-35 of 4-12 representative firms. Returns on stock capital range from 6.3 per cent to 167.6 percent (See Table A1 in the Appendix)

An economist writing in 1940 outlined why an oil whale fishery can be particularly destructive of the whale resource base:

"Females show the widest fluctuation of subcutaneous fat deposit. During pregnancy this increases, reaching its peak at parturition. Whale cows during the last months of gestation are therefore the most valuable booty. It is unfortunate that the short-run commercial interest is definitely in favor of killing pregnant whales, for joint destruction of mother and unborn calf accelerates the rate of depletion of the resource" (Brandt (1940) p.26).

2.1 THE OPEN ACCESS PERIOD OFF ICELAND, 1883-1915

In 1883 a Norwegian company established a shore station in a branch of Isafjordur on the extreme northwest coast of Iceland (Tønnessen and Johnsen (1982) p.75). The pioneer Svend Foyn initially subscribed 3/5 of the share capital but sold off the venture to Thomas Amlie when the Icelandic authorities demanded he become a naturalized Icelandic/Dane (Tønnessen and Johnsen (1982) p.76). Amlie's company was the only whaling operation in Iceland from 1883 to 1889. He succeeded after some initial difficulties.

Norwegian whaling in Iceland was largely done by Norwegians who arrived on the catchers in the late spring. All the catching was done exclusively by Norwegians and only a limited number of Icelanders were hired to process the whales. This limited the benefits flowing to Icelanders from the hunt. The value of the hunt to Iceland was limited to some tax

revenue and the sale of local farm products to supply provisions to the whaling operations.

The Icelandic whaling grounds proved to be more lucrative than those off North Norway, primarily because of the higher proportion of blue whales in the catch.

The average oil yield of 36 barrels per whale in Iceland for 1883-1915 is much higher than the 24.5 barrel average obtained in North Norway between 1868-1904 (Tønnessen and Johnsen (1982) p.101).

The whale oil was sold mainly in Glasgow, Scotland with small amounts going to France and Germany. Paris was the most important destination for the baleen. The cost of transporting the whale products by sea to these markets is similar for North Norway and Iceland. The profit differential between North Norway and Iceland would therefore likely be close to proportional to the difference in oil yield. This made Iceland attractive to the whaling firms operating in North Norway.

Between 1889-1894 four Norwegian firms established operations in Iceland. Three more Norwegian firms started between 1896-1903 along with one Icelandic effort and one German effort that both later failed (Tønnessen and Johnsen (1982) p.77). These ten companies established fourteen different land stations, eight on the west coast and six on the east coast (Tønnessen and Johnsen (1982) p.77).

The Norwegian companies that came to Iceland had links to the whaling off Finmark in North Norway. Tønnessen and Johnsen deny that there was "a mass flight of companies from Finmark to Iceland" (Tønnessen and Johnsen (1982) p.77). The evidence seems to support the notion that as the Norwegian whaling grounds were exhausted, operations were transferred to Iceland.

The total number of whales (animals) landed and processed is known with certainty but the species breakdown of the catch prior to 1912 is uncertain. The total whale catch expanded very rapidly from 1889 to 1902 when it peaked. From 1904 to 1910 a slow but steady decline had taken hold. These developments can be seen in Figure 1. In Chapter 3 an estimate of the species breakdown for 1883 to 1915 is derived.

The effort on the whaling grounds off Iceland expanded from one catcher in 1883-85 to 30 in 1902. The number of catchers dropped after 1902 to 25 from 1905-07. However, in 1908 effort increased to 29 catchers and then to 32 in 1910. This led to a collapse in the viability of the whaling industry in Iceland.

FIGURE 1
The Number of Whales Reported Caught Per
Season in Iceland in the Open Access Period 1883-1915.

The increase in the number of catchers had a dramatic effect on the number of whales per catcher as shown in Figure 2. The decline after 1901 is unmistakable. When the total catch peaked in 1902 each of the 30 catchers took 43.5 whales on average. By 1910 there were 32 catchers operating or two more than in 1902. The total catch in 1910 was declining and the average catch was down to 20 whales for each of the 32 catchers.

The production function for the whaling firms in the 1883-1915 period can be specified as $\text{oil barrels} = f(\text{Whales}, \text{Capital}, \text{Labour})$. Whales are for practical purposes a fixed factor in the production of whale oil since there is an upper limit on the amount of oil to be extracted from a whale no matter how good your cutters and boilers are. Factor substitution between K and L is low. Labour operates the catchers, each had a crew of about 10-20, and cuts and loads boilers used to extract the oil. We do not have data to go beyond qualitative analysis of the production function for these firms.

FIGURE 2
The Number of Whales per Catcher.

The cost function for the firms cannot be estimated empirically because of lack of data. However, the cost structure of the industry can be qualitatively specified as: $\text{Total Cost} = \text{Fixed Cost} + rK + (w+b)L$, where r is the rental rate on capital, w is the wage rate and b is bonus. Whaling stations typically paid a wage per day and bonus to crews for each whale and the production staff had day pay plus a small reward for each barrel produced paid at the end of the season. The fixed costs consist of the annual rent for the land used and the cost of enticing and transporting the Norwegian staff from Norway to Iceland each spring. When whaling ended in Iceland the stations were dismantled and moved to sites adjacent to other whaling grounds.

The importance of whales per catcher on the profitability of whaling firms cannot be overstated. The number of whales per catcher bottomed out at 8 in 1912 but only 20 catchers operated that year. The fishery was not viable at those catch rates and an exodus of whaling firms ensued.

The exits of two well known Norwegian whalers from Iceland, Ellefsen and Bull, in response to the decline in catches and profits are typical. Ellefsen who started operations in 1889, "was shrewd enough not to push his luck" and sold out in 1911 with 2,250 barrels after seeing catches drop from 268 whales (10,900 barrels of oil) in 1907 from seven catchers to 170 whales (6,300 barrels) from nine catchers in 1910 (Tønnessen

and Johnsen (1982) p.79) Marcus C. Bull quit in 1913 because production was down to 1,360 barrels which was not profitable compared to his best year in 1909 when he produced 4,100 barrels (Tønnessen and Johnsen (1982) p. 80). After the 1913 season only one firm whaled from Iceland.

The decline in the whale fishery off Iceland was accompanied by a decline in the number of oil barrels per whale from 40 to 32 as shown in Figure 3. Michael Spence (1974) observed that since whale catchers do not specialize in a particular species only the last species (least valuable) in a string of species would be protected by profitability considerations. In the absence of precise species data, the decline in the oil yield per whale is used as a proxy for the falling proportion of blue whales in the catch. It is clear from Figure 3 that less desirable species in terms of oil yield like fin, sei and humpback whales were important when the catch peaked in 1902. However, blue whales were still present in the last season (9 blue and 45 fin whales were caught in 1915).

FIGURE 3

Oil Barrels per Whale Landed in Iceland

The Icelandic parliament passed a 10 year ban on all whaling in 1913 with Law No 68, November 22, 1913. The ban took effect after the 1915 season and expired on January 1, 1925. The law accelerated the departure of the Norwegian whalers. The high prices for whale oil during World War I could have made whaling feasible for a few catchers. However, whaling off Iceland was ending as the ban took effect because the resource was no longer there to be found by the whalers.

2.2 WHALING OFF ICELAND 1929-1939

The Icelandic whaling ban lasted for ten years and no entry occurred for four more years. The stocks were thus protected for fourteen years.

Norwegian floating factories caught whales off Iceland from 1929-37 on some of the same grounds that had been used by catchers from land stations. The total catch for the Norwegian pelagic expeditions from 1929-34 was 243 blue and 2348 fin whales (Jonsson (1964) p.398). The Norwegian floating factories then departed for the richer Antarctic whaling grounds. The Antarctic blue and fin whale populations protected the whales off Iceland with higher yields well into the 1950s.

Floating factories and their catchers are capital intensive relative to land stations. However, pelagic whaling can actively search for whales anywhere in the world. Land

stations are limited to a range around the station of say 200 miles or so.

The Norwegian catches indicate that the stocks had recovered somewhat. Blue whales were not as abundant as prior to 1900 but the fin whale population had recovered to a level where a fishery might be attempted. In 1935 an Icelandic company started operations at Talknafjordur on the west coast of Iceland. It continued through 1939 when operations ceased because of marketing problems arising from the war. Its catches are given in Table 1.

Table 1

SPECIES BREAKDOWN OF THE WHALES CAUGHT OFF ICELAND 1935-39.

Year	Blue	Fin	Sei	Humpback	Sperm	Total Whales
1935	2	25	1	0	0	28
1936	5	72	1	0	7	85
1937	1	56	0	1	21	79
1938	9	113	5	0	20	147
1939	13	109	3	1	4	130

Source: International Whaling Statistics

The species breakdown in Table 1 and the results of the Norwegian pelagic expeditions between 1929-1937 show that any future whale fishery off Iceland would have to be sustained by fin whales.

The available operating performance indicators for the Icelandic land station are given in Table 2.

Table 2

PERFORMANCE INDICATORS FOR THE ICELANDIC WHALING STATION 1935-39

YEAR	Number of Catchers	Whales per Catcher	Oil Barrels per Catcher	Oil Barrels per Whale	No 1 Price PER Ton	
					high	low
1935	2	14	345.6	24.68	20	10
1936	2	42.5	1707.5	40.18	21	17
1937	2	39.5	1431.0	36.23	24	15
1938	3	49	1640.0	33.47	14	11
1939	3	43.33	1254.67	28.95	40	14

Source: International Whaling Statistics and Brandt (1940) is the source for the price data. Prices are in Pounds Sterling. From Table XIX pp.224-225.

The operating results of the Icelandic whaling station were poor compared to those obtained in the Antarctic at the same time. In 1938-39 the 270 catchers in the Antarctic averaged 127 whales and 9,498 oil barrels per catcher. Even so, higher yields could not prevent operating losses by 1938 (Tønnessen and Johnsen (1982) p.333). The Icelandic company ceased operations after the 1939 season in distressed financial condition, not because of resource depletion but because of the depressed state of prices and other marketing problems leading into World War II. According to Einarsson ((1987) p. 144) the company ceased operations primarily because the catchers, which were Norwegian, were drafted into military service in Norway.

World War II made whaling from Iceland impractical. The country was occupied by Britain and its adjacent waters became a battlefield. Iceland became an independent republic in 1944 and after the war interest in whaling returned.

2.3 THE SOLE OWNER PERIOD FROM 1948 TO THE PRESENT

An Icelandic company, Hvalur hf. (Whale Limited!), started operations in Hvalfjordur on the west coast of Iceland in 1948. The operations of this company are the subject of special legislation, Law No 26, May 3, 1949.

The legislation is very brief, consisting of only 12 articles. The legislative intent seems to be to secure whaling for Icelandic interests as well as affording some limited protection to the whales themselves. The enforcement of this legislation against foreign nationals relied on the agreements made by the International Whaling Conference (which later became the International Whaling Commission (IWC)) in Washington in November 1945. At this conference all the principal whaling nations agreed to ban the catching of baleen whales from floating factories in the North-Atlantic. The absence of floating factories in the North-Atlantic combined with a single Icelandic license means that the firm can exercise sole ownership over the whaling grounds off Iceland.

The Icelandic legislation limits whaling permits to Icelandic citizens. No permits will be issued if the

Fisheries Association of Iceland and the Employment Department of the University (fisheries department) advises that additional permits will deplete the whale stocks. In practice, this advisory role is discharged by the Marine Institute of Iceland.

In Article 5 of the law, utilization of the whole whale is mandated. The 6th Article provides for the hiring of inspectors to oversee whaling operations, paid from fees levied on those whaling. Article 9 bases crew remuneration on the value of the catch and not on the number of whales killed. It also bans any payments for illegal whale catches regardless of the degree of illegality of the kill (a 50' fin is a legal kill but a 49' is not). Because these measures try to remove the incentive to waste the resource, these measures could be characterized as conservation oriented. These measures however do not by themselves expressly prevent the stock from being depleted but rely on economic incentives to achieve their effect. No additional companies or whale stations have been allowed after 1948.

The company converted a World War II American naval base at the bottom of Hvalfjord into a whaling station. Four catchers were purchased to do the whaling. Mr. L. H. Skarre of Sandefjord was appointed manager of whaling operations. H. wrote a brief account of operations in 1948. In his account Skarre (1948) emphasized that meat production would be the most important activity. The long tow into the fjord where

the station is situated became a source of complaint by Skarre since Norwegian land stations were usually located at a mouth of a fjord.

The company was lightly regulated by the IWC for most of the period from 1948 to 1981. For example, the six month operating rule per year for land stations set out in the International Convention for the Regulation of Whaling, 1946 was not a real constraint in Iceland. The whaling season in Iceland had never lasted six months since whaling began in 1883. On the other hand the IWC catch treatment rule that specifies a maximum of 30-hours for delivering carcasses is an effective restriction. The most severe restriction by the IWC, however, is the outright ban of catching certain whale species. Humpbacks were completely protected from 1955, blue whales from 1960 and sperm whales from 1983.

The actual catches in Iceland for 1948-1986 are provided in the Appendix in Table A6. In Table 3 the average catches for all the species are provided.

Table 3

The Average Annual Catches of Individual Whale Species 1948-85 by Hvalur Ltd. of Iceland.

Whale Species	Mean catch	S.D.	Period Covered
Fin	234.89	51.98	1948-85
Sei	67.74	51.11	1948-85
Sperm	82.43	45.00	1948-82
Blue	13.58	9.45	1948-59
Humpbacks	0.86	0.90	1948-54

In Figure 4 the actual number of fin whales caught is plotted. Several authors have analyzed the constancy of the numbers and concluded that the fin whale fishery is carried out on a sustained yield basis. That subject and literature related to the population dynamics of fish stocks will be examined in detail in Chapter 3.

The sei whale has been caught as a fin whale substitute on a sustained basis from 1948. The actual catches are plotted in Figure 5a. The sperm whale catch off Iceland is provided in Figure 5b. The sperm whales caught off Iceland are all males because the species is latitudinally segregated by sex. The sperm whale bulls around Iceland are larger than males in the same age group in mixed-sex populations in lower latitudes (Martin (1980) p.229). The uncertainty about the role these larger bulls play in the pregnancy rate in the sperm whale stock led the IWC to protect them after 1982.

The operations of Hvalur Ltd. have been based on four catchers throughout the post war time period. The fleet was renewed completely between 1957 and 1966. The four new catchers had 20-40 per cent more catching power than the old fleet (Rørvik (1980) p.21). The trend in the number of whales per catcher increases somewhat as can be seen in Figure 6 and this increase is sustained. As we shall see, the decline in the number of whales per catcher in the 1980s appears to be due to catch restrictions imposed by the IWC rather than a fall off in available stocks.

FIGURE 4
The Number of Fin Whales Caught off Iceland

FIGURE 5a
The Number of Sei Whales Caught off Iceland

FIGURE 5b
The Number of Sperm Whales Caught off Iceland

FIGURE 6
The Number of Whales per Catcher

THE VALUE OF WHALING AND ITS PROPORTION OF EXPORTS

The economic importance of whaling to Iceland peaked around the turn of the century. From 1896-1900 whale products accounted for 21.2 per cent of exports from Iceland.

The value of the whaling industry to Iceland in more recent times can be approximated from export and production statistics from 1948 to the present. In Table 4 the per cent value of exports derived from whale products since 1880 (column 1) is used to derive a value for total revenue (column 2). A similar calculation, estimating the actual value of exports derived from whale production in U.S. dollars (column 4), should be viewed with greater caution. It does however give an ordering of the relative magnitudes of the actual value of total revenue for the company.

Table 4

The Percentage of Iceland's Total Exports Derived from the Export of Whale Products.

Year(s)	(1) Per cent of value of exports derived from whales	(2) Total exports in KRONA	(3) Krona per U.S. dollar	(4) Estimated value of all whale exports \$US
1881-85	0.1	55,330		
1886-90	0.9	41,010		
1881-95	9.4	60,220		
1896-00	21.2	70,140		
1901-05	18.2	104,240		
1906-10	12.2	137,070		
1911-15	2.1	223,680		
1916-20	0	484,530		
1921-25	0	642,120	0.0584	
1926-30	0	661,040	0.0456	
1931-35	0	466,510	0.0534	
1936-40	0.5	741,610	0.0535	\$69,309
1941-45	0	2,288,550	0.0650	\$0
1946-50	1.3	3,379,510	0.0904	\$485,991
1951-55	1.5	7,536,260	0.1632	\$692,671
1956-60	1.5	13,380,600	0.2068	\$970,546
1961-65	1.1	42,169,520	0.4306	\$1,077,252
1966-70	1.1	74,827,430	0.7289	\$1,129,238
1971-75	1.0	272,427,060	1.1180	\$2,436,736
1975	0.9	474,350,000	1.7080	\$2,499,502
1976	0.8	734,975,000	1.8970	\$3,099,526
1977	1.0	1,018,800,000	2.1310	\$4,780,854
1978	0.7	1,762,858,000	3.1810	\$3,879,285
1979	1.1	2,784,497,000	3.9490	\$7,756,259
1980	1.1	4,459,529,000	6.2390	\$7,862,609
1981	1.3	6,536,214,000	8.1730	\$10,396,523
1982	1.5	8,478,804,000	16.6250	\$7,854,050
1983	1.5	18,632,976,000	28.67	\$9,748,679
1984	1.4	23,760,456,000	40.545	\$8,204,375
1985	1.0	33,749,600,000	42.06	\$8,024,156
1986	0.4	44,967,900,000	40.24	\$4,469,970
1987	0.6	53,053,100,000	35.60	\$8,941,534

Sources: External Trade 1981(Published by the Statistical Bureau of Iceland, Reykjavik, 1982) p.36 Exports by origin of products 1881-1981. Statistical Abstract of Iceland 1984 (Statistical Bureau of Iceland, Reykjavik, 1984) p. 132 Statistical Monthly January issue in various years.

The production activities of Hvalur Ltd. are detailed in Tables 5-7. In Table 5 the total revenues from whaling in U.S. dollars are estimated for 1952-1987. In the 1970s the value of production is in the order of 8-10 million U.S. dollars.

In Table 6 the actual quantities of meat, oil and meal are provided. All three products are important. The increased emphasis on meat production is evident. It must be kept in mind when looking at the relatively large quantities of oil and meal that meat was not produced at all by some operators in the open access period 1883-1915. Meat production became important just before and after World War II.

In Table 7 the revenue by product type is provided. Oil is the most important source of revenue for the company until well into the 1970s. The price of whale meat which is sold mainly in Japan has increased in recent years. The best cuts of a fin whale will fetch as much as \$100 US per kilo. However, the muscle from the tail up the back only yields about a ton or so of meat. Meat production has been increasingly emphasized as can be seen in Table 6.

Table 5

Value of Production from Whaling in Iceland 1952-1987.

Year(s)	Total Revenue	USA Krona Exchange	Revenue from Whaling in \$US
1952-55	138,930	0.1632	\$851,287
1956-59	240,920	0.1632	\$1,476,225
1960	240,920	0.381	\$632,336
1961-65	503,000	0.4306	\$1,168,137
1966	694,000	0.4306	\$1,611,705
1967	460,000	0.5707	\$806,028
1968	600,000	0.881	\$681,044
1969	934,000	0.881	\$1,060,159
1970	1,281,000	0.881	\$1,454,030
1971	1,479,000	0.8742	\$1,691,833
1972	1,388,000	0.979	\$1,417,773
1973	2,480,000	0.84	\$2,952,381
1974-75	2,590,000	1.185	\$2,185,654
1976-78	22,590,000	1.897	\$11,908,276
1979	32,600,000	3.949	\$8,255,254
1980	46,820,000	6.239	\$7,504,408
1981	81,000,000	8.173	\$9,910,682
1982	137,000,000	16.625	\$8,240,602
1983	317,086,000	28.67	\$11,059,854
1984	277,722,000	40.545	\$6,849,723
1985	275,111,000	42.06	\$6,540,918
1986	161,879,000	40.24	\$4,022,838
1987	129,593,000	35.60	\$3,640,253

Sources: Ibid Table 4

Table 6

The Products from Whaling off Iceland 1952-1988

(Metric Tonnes)

Year(s)	Meat	Oil	Meal
1952-55	1532	1952	786
1956-60	2375	3234	1440
1961-65	2328	3122	2038
1966	2711	3129	2138
1967	2213	2774	1792
1968	1740	2103	1537
1970	2353	2808	1995
1971	2575	2490	1809
1972	2362	2866	1940
1973	2134	2473	1819
1974	2684	2498	1875
1975-76	2614	2512	1773
1977-79	4348	2011	1403
1980	4863	2194	1573
1981	4830	2116	1321
1982	4952	2031	1200
1983	5035	1595	943
1984	4629	607	484
1985	3441	725	319
1986	3007	622	507
1987	1646	352	284
1988	988	373	340

Sources: Ibid Table 4

Table 7

Icelandic Export Revenue form Whale Products by Product Form
1952-1987

Year(s)	Meat Revenue	Oil Revenue	Meal Revenue	Total Revenue
	<i>Old Icelandic Krona (1000s)</i>			<i>New Krona</i>
1952-55	4,970	7,350	1,573	138,930
1956-60	7,942	11,820	4,330	240,920
1961-65	16,300	22,500	11,500	503,000
1966	26,900	28,300	14,200	694,000
1967	21,600	13,600	10,800	460,000
1968	26,100	17,100	16,800	600,000
1969	37,600	29,900	25,900	934,000
1970	55,100	42,800	30,200	1,281,000
1971	52,000	68,800	27,100	1,479,000
1972	53,400	49,500	35,900	1,388,000
1973	107,400	74,900	65,700	2,480,000
1974-75	128,000	86,000	45,000	2,590,000
1976-78	1,803,000	307,000	149,000	22,590,000
1979	2,660,000	387,000	213,000	32,600,000
1980	3,864,000	592,000	226,000	46,820,000
	<i>New Icelandic Krona</i>			
1981	68,000	10,000	3,000	81,000,000
1982	125,000	9,000	3,000	137,000,000
1983	309,408	4,173	3,505	317,086,000
1984	266,612	7,540	3,570	277,722,000
1985	263,710	8,171	3,230	275,111,000
1986	153,369	4,848	3,662	161,879,000
1987	119,578	5,595	4,420	129,593,000

Sources: Ibid Table 4

CONCLUSION

Modern whaling on the grounds off Iceland began in earnest with the arrival of the Norwegians in 1883. The hunt from 1883-1915 was an open access fishery. The main product during the open access period was whale oil. Open access competition lead to rapid depletion because of over-harvesting. In addition, in a whale oil fishery, there is an economic incentive to harvest whale cows during the last months of gestation because of their high oil yield. This greatly accelerates the rate of depletion of the resource.

The number of whaling firms and catchers expanded rapidly and the catch peaked in 1902. By 1913 the stocks of whales off Iceland were probably exhausted to a point where profitable harvesting was difficult. The Icelandic parliament banned whaling from Iceland for ten years starting after the 1915 season. The ban was intended to protect the whales and secure a future for a whaling industry owned and operated by Icelanders.

The whale stocks off Iceland were exploited in the 1930s by both Norwegian pelagic expeditions and an Icelandic land station that operated from 1935-39. However, it was only in 1948 that a whaling industry consisting of a single firm became firmly established in Iceland. The main product of the firm was whale oil until the 1960s when whale meat became the most important product from whaling.

CHAPTER 3: THE POPULATION DYNAMICS OF THE FIN WHALE STOCK OFF ICELAND 1883-1989

In this chapter we model the population dynamics of baleen whales. The baleen whale model used by the International Whaling Commission (IWC) is applied to fin whales and used to review the demise of the once commercially important blue whale stock off Iceland. The baleen whale model is used to determine the size and biological productivity of the fin whale stock off Iceland. The stock dynamics of fin whales is an important constraint on the profit maximizing behavior of the sole owner. The task in this chapter is to establish this constraint.

To establish the stock constraint, the population trajectory for fin whales from 1883 to 1987 is simulated to determine the probability of extinction given the catch history. The population trajectories are also used to narrow the range of plausible pristine population levels.

The fin whale stock off Iceland has been exploited for more than a century. Stock size estimates that exist can be used to check the plausibility of the population profile since the beginning of exploitation. A trajectory of the population that passes through a known stock estimate in 1987 would be favored over those that do not. This methodology is widely accepted in fisheries biology and has been applied to other whale stocks. For example, Rørvik (1981) simulates the total stock of Northeast Atlantic minke whales from 1930 to 1980 to get a range

for the initial stock in 1930 of 98,100-110,220. Øien, Jørgensen and Øritsland (1987) apply a population model to the Barents Sea minke whale population and conclude that the present stock is 44-73% of its initial pristine level. Breiwick, Eberhardt and Braham (1984) use historical catch information to get a range of 14,742-23,007 as the size of the pristine stock in 1848 for Western Arctic bowhead whales. Conrad (1989) uses kill estimates from Breiwick, Eberhardt and Braham (1984) to calculate the bowhead population profile from 1848 to 1988.

The best available information on species breakdown of the catch off Iceland is from sample returns obtained from a few companies 1889-1904. This material is summarized in International Whaling Statistics (1931, 1933) in articles written by Risting (1931) and Jahn (1933). The available data are given in the Appendix in Tables A3 and A4.

Jónsson (1965) gives the catch for Ellefsen's station in Önundarfjörður for 1889 to 1900 as 1296 blue, 732 fin, 126 humpbacks and 17 sei whales (Jonsson (1965) p.245). Ellefsen owned the most important whaling concern in Iceland. In 1895, 1902 and 1907 Ellefsen produced over 11,000 barrels of oil or more than one-quarter of all whale oil produced in Iceland (Tønnessen and Johnsen (1982) p.78). What is clear is that blue whales constituted approximately 50-60% of the catch as late as 1900.

Sigurjonsson (1988) estimated that a "... total of 8100 fin, 5800 blue and 2800 humpback whales, together with a few sperm

and sei whales, were caught in the period 1889-1915" (Sigurjonsson (1988) p.327). This estimate is crude and somewhat at odds with Rørvik et al (1976) which indicate that the majority of the catch from 1890 to 1904 consisted of blue whales. Gunnlaugsson, Magnusson and Sigurjonsson (1989) use 7,956 fin whales landed for 1883-1915 in their calculations of fin whale stock trajectories.

In the open access period whale species were depleted to a different degree. The fishery after 1948 is based mainly on fin whales. To be able to accurately model the population dynamics of the fin whale stock an accurate breakdown of catches by species in the 1883-1915 time period is important.

An economic perspective is needed on the question of species breakdown of catches. In International Whaling Statistics in 1931 Risting (1931) shows that from 1868 to 1875 the catch off North Norway consisted of only blue whales (Risting (1931) p.6). Tønnessen and Johnsen (1982) dismiss 'the almost universally accepted legend that "the sea was teeming in whales" and that Foyn "only took the biggest and fattest blue whales" as little more than a fabrication' (Tønnessen and Johnsen (1982) p.36). What truth there is in this Norwegian tale is not known but it is widely accepted that blue whales were much more common off Iceland than off Norway. Therefore, it seems unreasonable given the economic incentive to catch blue whales, which yield approximately twice the revenue of fin whales, to assume that the catch of fins could have been large

in the first few years. It is assumed here that the catch of fin whales was zero for 1883-1885.

The calculation in Table A5 relies on sample returns shown in Table A3. In Table A5 a total of 7,465 fin, 7,139 blue and 2,416 other whales were caught between 1889 and 1915. The estimate in Table A5 uses the available information on catch composition for every year whereas other authors average over more years. No information on the composition of catches is available for 1905 to 1909. The share of fin whales in the catch is assumed constant at 60 per cent for 1905 to 1909. Prior to 1905 the share of fin whales was 35-57 per cent while 1913-1915 it is 57-83 per cent of the whale catch. Population trajectories for 1883 to the 1980s are sensitive to the 60 per cent of catch assumption. If the fraction of fin whales in the catch was lower than 60 per cent the threat of extinction is lower and vice versa.

The derived number of fin whales caught prior to 1913 will be used to calculate a likely profile of the population for 1883 to 1989. It is not possible to obtain the "right" number of fin whales landed prior to 1913. The population dynamics are not sensitive to the differences in the derivation of catches between those stated here and those of Sigurjonsson (1988) or Gunnlaugsson et al (1989).

The number of whales caught is not equal to the number of whales killed. Tønnessen and Johnsen comment at length on this problem for Iceland 1883-1915 and Norway 1868-1904:

"We have numerous accounts of the great loss of whales due to various reasons, the most frequent being the breaking of the whale line. The number of whales that were killed was almost certainly at least 30 per cent greater than the number actually recovered" (Tønnessen and Johnsen (1982) p.83).

Based on this actual catches have been adjusted upwards by 30 per cent for 1883-1915. The adjusted catch history is provided in Table A8 in the Appendix.

3.1 THE BALEEN WHALE MODEL

Allen (1976) introduced the model used by the IWC to analyze baleen whale populations. The description of the mathematical model used by the IWC closely follows May (1980). The population model is in terms of the number of mature animals. The aggregate stock dynamics in the basic baleen whale model used by the IWC is a delay first-order difference equation (1);

$$(1) \quad X_{t+1} = (1-\mu)X_t + R(X_{t-T})$$

where X_t is the population of sexually mature adult whales in year t , μ is the natural mortality rate, T is time needed to reach sexual maturity and R is the recruitment rate into the adult stock for those born T years earlier.

The recruitment function $R(X)$ is modeled as a nonlinear function of the current size of the whale stock. Specifically, the recruitment function is written as:

$$(2) \quad R(X) = 1/2(1-\mu)^T X_{t-T} \left[P + Q \left(1 - \left(X_{t-T}/K \right)^2 \right) \right]$$

where K is the pristine, long-term unharvested whale population level, P the per capita fecundity of females at the pristine equilibrium point when $X=K$, Q the maximum increase in per capita fecundity as the population decreases and the population density falls. Z is the density dependence of fecundity rates. The gestation period for fin whales is approximately 11 months (Lockyer (1984) Table 1).

The nonlinear relation in $R(X)$ reflects the biological assumption that per capita whale fecundity is itself a function of whale population density. Population density is represented by the fraction of the current whale stock, X_t , relative to the equilibrium size of the pristine whale stock, K . More specifically, the per capita fecundity rate is modeled as the sum of two separate parts. First it is assumed that if the whale stock were at its pristine equilibrium level (i.e. $(X_t/K)=1$), the population fecundity rate would be P . Using $X_{t+1}=X_t=X_{t-T}=K$ in (1) and (2) one can solve for a balance equation between natural mortality μ and the recruitment rate:

$$(3) \quad \mu = 1/2(1-\mu)^T P \quad \text{at } X=K.$$

Second, departures of the whale stock below the pristine level are assumed to lead to changes in P by a factor that may not exhibit proportionality. Letting Q represent the maximum possible increase in the fecundity rate from P , the size of the

actual increase from P is assumed to be Q times the fraction $[1-(X_{t-T}/K)^Z]$, where Z measures the degree of departure from proportionality.

The impact of Z on population size is best understood by looking at the per capita growth rate $R(X)/X$ in Figure 7. The density effects are proportional if $Z=1$. For $Z>1$ the density dependent response is more than proportional and most vigorous around the equilibrium point where $X=K$. If $Z<1$ the density dependent effect on recruitment is less than proportional and occurs as the population falls to low levels. The fully adjusted fecundity rate, Fec is then

$$(4a) \quad Fec = P + Q[1 - (X_{t-T}/K)^Z].$$

With the fecundity rate determined, the recruitment rate can be found once the population size is found for which the fecundity rate is relevant. This will be the female whale stock that is sexually mature. Assuming that the number of years from birth to sexual maturity is T and that the natural mortality rate per year is μ , then the probability that any whale born will reach sexual maturity will be $(1-\mu)^T$. This implies that for any steady state whale stock level, X_t , the number of sexually mature female whales, FW , (assuming that the sex ratio is 1:1) will be:

$$(4b) \quad FW = (1/2)(1-\mu)^T X_t$$

FIGURE 7

The Recruitment Function, $R(X)/X$
With Various Z values.

Combining 4a and 4b, the recruitment function is determined as the number of whales entering the population each period. That is,

$$(4c) \quad R(X) = Fec * FW \\ = 1/2(1-\mu)^T X_{t-T} \left[P + Q \left(1 - \left(X_{t-T}/K \right)^Z \right) \right]$$

For some issues it is easier to look at the recruitment rate rather than recruitment level and this can be done by dividing through (4c) by the whale stock, X_{t-T} . The recruitment rate is then

$$(4d) \quad r(X) = R(X)/X_{t-T} = 1/2(1-\mu)^T \left[P + Q \left(1 - \left(X_{t-T}/K \right)^Z \right) \right]$$

The biology behind the model is somewhat simplified. The growth of individuals already recruited into the stock is ignored because sexual maturity in fin whales occurs at roughly 90 per cent of eventual length and weight. Equation (3) is useful as a check on the consistency of mortality and pregnancy rates. In general, for any harvest whereby $X < K$, (3) would not hold since natural mortality would be lower than recruitment into the stock, $\mu < 1/2(1-\mu)^T P + Q[1 - (X_{t-T}/K)^Z]$.

Substituting (2) into (1) the baleen population model can be written as:

$$(5a) \quad X_{t+1} = (1-\mu)X_t + 1/2(1-\mu)^T P X_{t-T} \left[1 + q \left(1 - \left(X_{t-T}/K \right)^Z \right) \right]$$

or alternatively

$$(5b) \quad \Delta X_{t+1} = -\mu X_t + 1/2(1-\mu)^T P X_{t-T} \left[1 + q \left(1 - \left(X_{t-T}/K \right)^Z \right) \right]$$

where $q=Q/P$. In terms of continuous population growth (5b) has an analogous expression as a differential equation:

$$(6) \quad \frac{dX(t)}{dt} = -\mu X(t) + 1/2(1-\mu)^T P X(t-T) \left[1 + q \left(1 - \left(X(t-T)/K \right)^Z \right) \right]$$

The effect of harvesting is to add another term, $-Y(t)$, the number of whales harvested, on the right hand side of (6). Harvesting only occurs on the mature stock in this model. The number of whales harvested is $Y(t)=F \cdot X(t)$, where F is the rate of fishing mortality.

$$(7) \quad \frac{dX(t)}{dt} = -\mu X(t) + 1/2(1-\mu)^T P X(t-T) \left[1 + q \left(1 - \left(X(t-T)/K \right)^Z \right) \right] - Y(t)$$

A new steady state for the whale population in equation (7) must involve a compensating increase in recruitment to offset the deaths caused by harvesting. In the steady state $dX/dt=0$ and $X(t)=X(t-T)=X$. Following May (1980) we simplify the derivation of X_{MSYL} , the maximum sustainable yield level (MSYL)

for the population by assuming that $\mu = 1/2(1-\mu)^T P$, which is only true when $X=K$ and $Y=0$. In terms of (4a), $Fec=P$ and hence we are for the moment ignoring the contribution to Fec from $Q[1-(X_{t-T}/K)^Z]$. This makes the MSYL less than the true level for example $0.6K$ instead of say $0.7K$ and correspondingly overestimates the maximum sustainable yield (MSY). We will return to $X < K$ when survival from births T years earlier would exceed natural mortality or $\mu < 1/2(1-\mu)^T P + Q[1-(X_{t-T}/K)^Z]$. However, when $\mu = 1/2(1-\mu)^T P$ the steady state harvest level can be written as:

$$(8) \quad Y = \mu q X \left[1 - (X/K)^Z \right]$$

and fishing mortality is defined as $F = Y/X = \mu q \left[1 - \left(\frac{X}{K} \right)^Z \right]$. The maximum sustainable yield level (MSYL) of X is the X that maximizes Y in equation (8)

$$(9) \quad X_{MSYL} = \frac{K}{(1+Z)^{1/Z}} \quad \text{and the } Y_{MSY} \text{ at that level is:}$$

$$Y_{MSY} = \mu q K \left[\frac{Z}{(Z+1)(1+1/Z)} \right]$$

If $Z=1$ then we have the logistic case where $X_{MSYL}=K/2$ and $Y_{MSY}=\mu qK/4$. The value of Z , the density dependence of the fecundity is important. "Indeed the rather enigmatic value of $Z=2.39$ is arrived at by the IWC using the general equation (8) in conjunction with the rough guesstimate that the MSYL is around 60% of the pristine stock density for baleen whales; that is $X_{MSYL}/K=0.6$, whence from equation (9) $Z=2.39$ " (May (1980) p.21).

The recruitment rate for a fin whale stock is explored for various Z values in Figure 8. Figure 8 shows $R(X)/K$ plots for (2) as X declines from K . At K , $R(X)/K$ is exactly equal to the mortality rate, $\mu=0.06$. As X is reduced below K , $R(X)/K$ increases for $Z>1$. To derive the growth curves $K=1$, $\mu=0.06$, $T=8$, $P=0.197$ and $Q=0.288$ and Z ranges from .1 to 2.39 where substituted into equation (2). In Figure 9 the surplus production curve for $Z=2.39$ is shown for μ of 5 and 6 per cent respectively. Surplus production is said to be a "backward peaked" logistic curve since it peaks at over half of the pristine stock size K .

FIGURE 8

The Recruitment Function, $R(X)/K$
With Various Z values.

The Number of Fin Whales Recruited as the Population Declines from K.

The dynamics of the fin whale population that we are interested in involve stock levels where $X \neq K$ hence (3) cannot be used to simplify the derivation of Y_{MSY} and X_{MSYL} . Since the simulations in this Chapter are always based on (3) not holding the Y_{MSY} and X_{MSYL} for that case have to be derived. The steady state harvest level must be solved from Equation (7) by noting that $X(t) = X(t-T) = K$.

$$(8') \quad Y = -\mu X + 1/2(1-\mu)^T X \left[P + Q \left(1 - \left(X/K \right)^Z \right) \right]$$

The X_{MSYL} is found by taking the derivative of (8') with respect to X and solving for X . Then X_{MSYL} is substituted into Equation (8') to get Y_{MSY} .

$$\frac{\partial Y}{\partial X} = -\mu + 1/2(1-\mu)^T X \left[P + Q \left(1 - \left(X/K \right)^Z \right) \right] + 1/2(1-\mu)^T X \left[-Z \frac{Q}{K} \left(X/K \right)^{Z-1} \right] = 0$$

solving this for X we obtain:

$$(9') \quad X_{MSYL} = K \left[\frac{\frac{P+Q}{Q} - \frac{\mu}{1/2(1-\mu)^T Q}}{Z+1} \right]^{1/Z}$$

$$Y_{MSY} = K \left[\frac{\frac{P+Q}{Q} - \frac{\mu}{1/2(1-\mu)^T Q}}{Z+1} \right]^{1/Z} \left[\frac{1/2(1-\mu)^T (P+Q) Z}{Z+1} - \mu Z \right]$$

The difference between (9') and (9) is that X_{MSYL} cannot be simply written in terms of K and Z anymore. The connection between X_{MSYL} and the density dependent exponent Z is therefore less intuitive in (9') compared to (9). The Y_{MSY} expression in (9') is similarly much more complicated compared to (9) which makes an intuitive explanation of terms rather difficult.

Outside of the steady state, the exploited whale stock will move through time according to equations (1) and (2) which have been rewritten in equation (10).

$$(10) \quad X_{t+1} = (1-\mu)X_t + 0.5(1-\mu)^T X_{t-T} \left[P+Q \left(1 - \left[\frac{X_{t-T}}{K} \right]^Z \right) \right] - Y_t$$

3.2 POPULATION PARAMETER ESTIMATES

Parameter estimates for μ , T and $P+Q$ are available from biological studies of the fin whales in Icelandic waters. The natural mortality coefficient μ of 0.04, corresponding to the assumption in Lockyer and Brown (1979) and Gambell et al (1973) may be too low. The IWC (1982) uses 0.06 for females and 0.055 for males.

Biologists observe a total pregnancy rate for a whale species. The balance relationship in (3) and the μ value are used to force consistency on the population model by dividing any given observed pregnancy rate into its P and Q components. P , from (3), is the pregnancy rate needed to keep the stock at K given no exploitation while Q measures the extent to which the stock is able to reproduce faster in response to some exploitation. The lower μ the higher is Q . In this thesis we use $\mu=0.06$. The responsiveness of the reproduction of the fin whale stock to exploitation is thereby kept at the lower end of the spectrum by adopting a $\mu=0.06$ as can be seen in Figure 9.

Martin (1982) estimates the pregnancy rate, $P+Q$, at 0.485 with a 95% confidence interval of 0.605 to 0.383 (Martin (1982) p.327). In biology, the pregnancy rates of fin whales are assumed to increase after exploitation starts. This is the justification for Q and for splitting the pregnancy rate into $P+Q$ starting at $X=K$. Some biologists have questioned the

realism of increasing pregnancy rates after harvesting begins.

Assessments of the Icelandic fin whale stock have used these values for the pregnancy rate. Cooke and Beddington ((1981) p. 21) increased $P+Q$ from 0.33 in 1948 to 0.417 by 1970 while lowering the age of maturity from 11.4 years in 1948 to 8 in 1976. Similarly, van Beek ((1983)p.436) uses the time series of pregnancy rates in his simulation study on the effect of size regulation on the dynamics of the fin whale stock off Iceland.

Magnusson (1984) addresses the net increase in juvenile survival and pregnancy rate necessary for an equilibrium fin whale stock in 1948 to move toward a new equilibrium given the level of exploitation. An increase in juvenile survival and pregnancy rate are the two sources of compensating increase in recruitment available to counteract fishing mortality. In (7) q is the term that incorporates this effect and allows the stock to reach a new equilibrium after fishing begins. Magnusson (1984) found:

"The transfer to this new equilibrium will take 20-30 years. If we accept an estimated present total mortality ratio of 0.10 for females and drop in age at sexual maturity from 12.4 years to 8 years, a value of natural mortality rate of 0.06 for females would require the combined pregnancy rate and juvenile survival to have increased by 59% for the present population to be in equilibrium. This would give a present equilibrium population of 6900" (Magnusson (1984) p. 430).

The accepted view was that the pregnancy rates of fin whales increase after exploitation begins. Empirical studies by

Mizroch and York (1984) and Clark (1984) argue against an increase in pregnancy rates after exploitation began in the Antarctic. Holt (1977, 1985) argues on theoretical grounds against such an increase in pregnancy rates. However, Sampson (1989) re-analyzed the data used by Mizroch and York (1985) and found that "females of a given length are more frequently pregnant in the more recent catches" (Sampson (1989) p. 255).

Considering all the arguments a constant value of $P+Q$ of 0.485 from Martin (1982) is adopted for the simulations reported here. To initialize the simulations (3) is assumed to hold at K only. Therefore since $\mu=0.06$ and $T=8$ and $0.06=0.5(1-0.06)^8 P$ or $P=0.197$ and $Q=0.288$ and $P+Q=0.485$. This implies that the pregnancy rates vary from 0.197 in the pristine equilibrium to 0.485 as X goes to zero.

The age of maturity, T , for 50% of female fin whales is given as 55 ft. and an age of between 5 and 6 years by Lockyer and Brown ((1979) p.188). In a later paper Lockyer (1984) reports that the mean age at sexual maturity for North Atlantic fin whales is between 8 and 11 years (Lockyer (1984) p.49). These values are accepted here and $T=8$ is adopted as the age of maturity for Icelandic fin whales.

The values used here for the parameters of (10) imply that the number of recruits will increase initially as the population declines from K , the carrying capacity of the environment for sexually mature adults (see Figure 8). Sidney Holt (1977, 1985) calls this "super compensation" and claims to have difficulty

envisaging biological reasons for such a "vigorous density dependent response" (Holt (1977)p. 488) in a declining whale stock.

An example of this phenomena for equation (10) at $K=6500$ would be as follows. In the pristine equilibrium there are 390 animals recruited into the population 8 years and above. As the population declines recruitment increases and peaks at 505 eight year old animals as the population numbers 4800-5000 sexually mature animals. The gross pregnancy rate needed to achieve this peak recruitment is about 34 per cent or 805 births per year from 2400 females 8 years and above.

The pregnancy rate of 34 per cent that achieves super compensation is below the lower end of the 95% confidence interval range Martin (1982) gives. This does not seem to be an overly "vigorous density dependent response" for a whale stock. Therefore Q is not scaled to ensure that the number of recruits cannot exceed the number of recruits at the pristine equilibrium level.

It would be desirable if the simulated fin whale population trajectories from 1883 to 1986 could be validated by fitting them into the 95 per cent confidence intervals of modern published stock assessments. Historical stock trajectories with end points that "hit" modern assessments are more credible than those that end in say extinction. We now turn to surveying available stock estimates of the fin whale stock off Iceland.

Sigurjonsson and Gunnlaugsson (1985) suggest a local population of 2,000 mixing with a larger population which numbered 7,000 in the late 1960s (Sigurjonsson and Gunnlaugsson (1985) p.361). At the 1989 annual meeting the Scientific Committee of the IWC accepted 6,436 as a population estimate based on sighting data. The assessments of the fin whale stock have a wide range. A brief summary of selected authors is provided in Table 8. These assessments refer to the total stock unless noted by an R, then only the portion recruited into the fishery is assessed which is 75 per cent of three year olds and all age groups above that.

Table 8

Stock Assessments of the East Greenland Iceland Fin Whale Stock by Selected Authors

Author(s)	Mean	95 Confidence Interval
<i>Mark-Recapture-Sighting Methods</i>		
1. Rørvik et al (1976)	6,931	3,281 to 15,269.
2. Rørvik (1981)	9,507	4,501 to 21,905.
3. Sigurjonsson et al (1984)	3,734	1,900 to 7,500
4. IWC (1990)	11,563	CV of 0.261
<i>Population Model-CPUE</i>		
1. Cooke&Beddington (1981)	2,771 ^R	not available
2. Cooke&Beddington (1981)	8,264 ^R	not available
3. van Beek (1983)	6,572	not available
4. Free (1984)	11,963	stock >0.66K
5. Holt (1985)	3,000	stock <0.4K
6. Butterworth (1989)	12,180	5,527 to 17,559

Unfortunately, the width of the 95 per cent confidence intervals and the range of published stock estimates

demonstrates that they can only serve as a rough guide to population simulations.

3.3 DETERMINISTIC SIMULATIONS

In this section the population trajectories for the fin whale stock off Iceland from the beginning of exploitation in 1883 to 1986 are deterministically simulated. The historical stock trajectory should provide a valuable insight into the stock dynamics and the probable size of the fin whale stock.

The simulations of the fin whale population off Iceland were initialized by selecting a value of K and $K = X_{t+1} = X_t = X_{t-T}$ for $t=0$ in 1883 and before. Equation (10) was then simulated forward in time for the given combination of K and $T=8$ values. The adjusted Y_t values used are given in Table A8 in the Appendix. The object of the exercise is to determine a statistically plausible population history given the known levels of annual exploitation, Y_t .

The deterministic simulation reported in Figure 10 is close to the minimum value of K at $T=8$ that does not drive the fin whale population to zero anytime over the period 1883 to 1986. The minimum K which will allow for a positive population in 1986 is greater than 6100. If $K=6100$ the stock goes to zero in 1980. If $K=6200$ there are estimated to be 1,378 sexually mature fin whales in the stock in 1986.

Similarly, if the age of maturity T is increased, higher levels of K have to be selected to prevent the stock from going

to zero. At $K=6,500$ and $T=9$ the stock would be driven to 1,432 in 1986. If K is 6,300 the stock goes to zero in 1975 and a K of 6,400 would leave 336 mature animals in the stock by 1986.

The simulation in Figure 10 conforms closely to a priori expectations based on the reported catch history of the stock. The fin whale stock reaches a minimum of just over 1,300 mature animals in 1911 and 1912 just prior to the 10 year ban on whaling. It is fished down from 1929 to 1934 but reaches just over 4,000 mature animals in 1948. From 1948 to the present the stock stays at about 4,000. Higher values of K at $T=8$ make the fishing down of the stock less dramatic and hence conform less to the history of this fishery.

FIGURE 10
Simulation of the Fin Whale Stock off
Iceland 1883 to 1986

$K = 6,500$, $M = 0.06$, $P = 0.19$, $Q = 0.29$, $Z = 2.39$ and $T = 8$

[—X']

The X_{MSYL} from (9) for the parameters reported in Figure 10 is ≈ 3900 or 60% of K and the corresponding Y_{MSY} is approximately 250. The true X_{MSYL} from (9') is $0.6975K$, or 4,534 mature whales and the maximum sustainable yield from (9') is $Y_{MSY} = 0.0342K$ or 222 mature fin whales per annum.

The population profile from 1948 to 1986 in Figure 10 can be compared to stock trajectories assumed by the IWC and biologists generally. There is a wide range of opinion on what is happening to the fin whale stock off Iceland after exploitation began in 1948.

This issue can be addressed by referring to van Beek (1983). The IWC and biologists generally focus on the exploitable stock as opposed to adult stock which for fin whales means the 75 per cent of three year olds plus all older animals. Adult fin whale stock consists of animals 8 years and over. For the East Greenland-Iceland fin whale stock, van Beek models the age of recruitment into the fishery as 6 in 1948 which declines to 4 years by 1974. Sexual maturity starts as 11.4 years in 1948 and declines to 7.6 years by 1977 (van Beek (1983) Table 1. p. 436)

The IWC assumes that the exploitable fin whale stock in 1948 was 10,718 and that this had been fished down to 54.6% of its size by 1981 or 5,897. In his work, van Beek assumes that the exploitable stock was 8,274 in 1948 which is fished down to 52.9% by 1981 or 4,374 (van Beek (1983) p.437). At the 1989 IWC meetings a revised estimate of the East Greenland-Iceland fin whale stock of 11,563 (coefficient of variation equal to

0.261) with a 95% confidence bounds of 5,527 to 17,599 (IWC, Butterworth (1990)). This work by the IWC and van Beek simply emphasizes that the population profile in Figure 10 represents a minimum size for the fin whale stock off Iceland. The size of K , the unharvested pristine equilibrium for the stock is still an open research question.

The biology of the blue whale stock off Iceland is not as well understood as the one for fin whales. This is because the hunt for blue whales was justifiably terminated in 1959 just as serious research into whales off Iceland began. "With the cessation of whaling, contributions to the biology of blue whales have been small (Bruggeman et al (1985) p. 405). It is only in the late 1980s that biologists are able to gather some useful information about whales without killing them.

Blue and humpback whale sighting records have been kept on the whaling boats operating from Iceland since 1969. The results for the blue whale sightings are provided in Table 9.

Table 9

Sightings of blue whales on the whaling grounds off Iceland by whale boats.

Year	Days worked	Number of Sightings	Number of Blue Whales Sighted
1969	299	95	333
1970	359	69	161
1971	423	102	253
1972	410	164	444
1973	425	165	455
1974	422	140	331
1976	422	134	288
1977	391	174	628
1978	451	230	771
1979	375	267	718
1980	432	201	415
1981	356	267	562
1982	385	245	462
1982	356	267	562
1983	306	135	282
1984	292	336	668
1985	210	238	370
1986	158	158	319

Source: Iceland. Progress Report on Cetacean Research, REP INT. Whal. Commn. Committee, Annex G, Appendix 6, p. 112 for 1969 to 1982 REP. INT. WHAL. COMMN 1985.

Sigurjonsson (1988) reports that sighting surveys of blue whales during the summer of 1987 from research vessels and airplanes indicate that there are less than 1,000 blue whales on the grounds around Iceland (Sigurjonsson (1988) p.521).

In Figure 12 a simulation of the blue whale population off Iceland is reported. A pregnancy rate of 0.46 is used although this value applies more appropriately to the Antarctic blues (Lockyer (1984) p. 33). The age of maturity is assumed to be 9 years, which makes it a slower growing species than fin whales.

The population profile in Figure 11 shows that the little hunting that was done prior to 1960 kept the blue whale population at the fished down level attained in the open access period 1883-1915. The sighting surveys by Sigurjonsson also tend to support the idea that the population must have been fished down to a level where reproduction difficulties may be occurring.

The profile in Figure 11 shows a blue whale stock of under 200 mature animals from 1911 to 1916. If the true blue whale population off Iceland is still below 1000 animals in 1987 very little growth has occurred in the 30 years of total protection. The simulated population profile in Figure 11 may be too optimistic about the recovery of the blue whale population off Iceland.

FIGURE 11
Simulation of the Blue Whale Stock
off Iceland 1883 to 1986

$K=5,350$, $M=0.06$, $P=0.209$, $Q=0.275$, $Z=2.39$ and $T=9$

—X—

3.4 STOCHASTIC SIMULATIONS OF FIN WHALE POPULATION TRAJECTORIES 1883-1989

In this section the model posed by (10) will be expanded. The age structure of the fin whale population will be specified for ages 1 to 7 to allow for pre-adult fishing mortality. Then the uncertainty about the true values of the vital parameters for the fin whale population will be addressed through stochastic simulations where the values of the parameters are drawn from the lognormal probability distribution. The stochastic simulations of the population trajectories from 1883-1989 will be used to derive a prior for K , the environmental carrying capacity for adult fin whales.

The use of stochastic simulations to evaluate the management of whales is well established. Beddington (1978) used the characteristic return time of the population model to measure the relative stability of a harvested population. Horwood, Knight and Overy (1979) used stochastic simulations to quantify the time it would take a theoretical whale population to fall into the protected category (0.9 of $MSYL$) for a constant quota regime and various cutoff schemes. Horwood et al (1979) used variations in recruitment of 25, 50 and 100 per cent of mean recruitment as two standard deviations in their simulations to get a hypothetical range for the 95 per cent confidence interval for recruitment. They concluded that even if recruitment

variability is $\pm 100\%$ of average recruitment it would take hundreds of years for the population to reach the protected level.

Beddington and Grenfell (1979) showed that the results of Horwood et al (1979) depended on "the problematic assumption that natural mortality is invariant with time" (Beddington and Grenfell (1979) p. 171). Beddington and Grenfell simulated equation (10) but allow both μ and $P+Q$ to vary. The inspiration for their study is found in the seminal pieces by Doubleday (1976) and Sissenwine (1977).

Beddington and Grenfell (1979) chose $(1-\mu)$ as $N(0.94, \sigma^2_{(1-\mu)})$. The actual simulations had mean deviation for μ of 2-6% while $P+Q$ fell in the 20-32% range (Beddington and Grenfell (1979) p. 171). Through their simulations they concluded that the mean time to protection was a poor measure of the safety of a management regime. This is because Beddington and Grenfell (1979) found a high probability (22%) of reaching protection in under ten years for stocks with mean time to protection as high as 141 years.

Current use of stochastic population simulations by the IWC is still focused on the safety of different management regimes. The IWC has adopted a set of elaborate simulation trials to evaluate new management procedures. These trials involve both deterministic as well as stochastic simulations (Donavan (1989) pp.23-25).

The simulations here differ from the work surveyed in that a known catch history for a stock is used in conjunction with stochastic parameter values for the stock. The purpose of this work is to assess empirically the pristine stock size for fin whales off Iceland by references to the distribution of stock sizes in 1948 and 1987.

It is not clear what would constitute an acceptable prior on K . There is widespread agreement that the fin whale stock off Iceland is reduced below the pristine level but not to the point of extinction. The number of kills from the stock between 1883-1989 is known if one is willing to guess at the missing years, 1905-1912. It is unacceptable not to use the 1883-1915 period because the fin whale stock probably reached its low point in the open access period. The catch history and stock size distributions in 1987 can be combined to form a judgment on K , the constant expected pristine level.

A low K with a high probability of extinction given the catch levels 1883-1987 is a possibility. The larger K , the lower the probability of extinction given the catch history. When K is high enough the probability of extinction goes to zero. At a high K the hunt is having a negligible effect on the stock and the stock stays near the pristine level. Such K s should perhaps be ruled out on a priori grounds since the stock is affected by the hunt. Alternatively we argue that the stock is not at the pristine level in 1987, whatever the real value of K is.

The model posed by (10) is modified to incorporate a year class structure for incoming year classes. This is necessary to allow fishing to inflict mortality on 3 to 7 year old fin whales.

The age structure of Icelandic fin whale catches 1948 to the present is not known with any precision. Rørvik et al (1976) use length data to classify males 58 feet and above and females 60 feet and above as mature. This procedure showed that 60 per cent of the catch consisted of mature animals (Rørvik et al (1976) p.26). Lockyer and Brown (1979) calculated an average mode of 5 years of age for catches in the 1975-77 seasons but do not explicitly address the fraction mature. Martin ((1982b) p.332) provides a partial maturity key at length for fin females in the Icelandic catch. Applying this key to the length distribution of the female fin catch 1937-39 and 1948-84 one finds that 2,814 out of 4,536 animals landed are mature, or 62 per cent. We assume that maturity from the length key refers to animals 8 years and older.

The available evidence shows that a 60/40 split between mature and immature fin whales is reasonable. The 40 percent of the catch from immature animals is distributed on year classes 3-7. The length limits on catches at 50 feet (local consumption only) and 55 feet (for export) would tend to lead to a push toward 5-7 year olds. They are arbitrarily accorded a 10 per cent share in the annual catch while 3 and 4 year olds account for 5 per cent each.

The year class model shows the progression of fin whales born (K1) until they are recruited into the adult population at age 8. The first time they are subject to capture is as three year olds (K3). The model is specified as follows:

$$(11.1) \quad K1_t = 1/2(1-\mu_t)X_{t-T}(P_{t-T} + Q_{t-T}(1-(X_{t-T}/K)^{2.39}))$$

$$(11.2) \quad K2_t = (1-\mu_t)K1_{t-1}$$

$$(11.3) \quad K3_t = (1-\mu_t)K2_{t-1} - F_{K3}Y_t \quad F_{K3} = 0.05$$

$$(11.4) \quad K4_t = (1-\mu_t)K3_{t-1} - F_{K4}Y_t \quad F_{K4} = 0.05$$

$$(11.5) \quad K5_t = (1-\mu_t)K4_{t-1} - F_{K5}Y_t \quad F_{K5} = 0.10$$

$$(11.6) \quad K6_t = (1-\mu_t)K5_{t-1} - F_{K6}Y_t \quad F_{K6} = 0.10$$

$$(11.7) \quad K7_t = (1-\mu_t)K6_{t-1} - F_{K7}Y_t \quad F_{K7} = 0.10$$

$$(11.8) \quad X_{t+1} = (1-\mu_t)X_t + (1-\mu_t)K7_{t-1} - F_XY_t \quad F_X = 0.60$$

$$(11.9) \quad Rstock = X_t + 0.75 * K3_t + K4_t + K5_t + K6_t + K7_t + K8_t$$

$$(11.10) \quad Stock = X_t + K1_t + K2_t + K3_t + K4_t + K5_t + K6_t + K7_t + K8_t$$

The choice of K, the environmental carrying capacity, is a choice of a population matrix. The pristine level of various age groups K1 to K7 for Ks (Adults) ranging from 5,250 to 7,500 are given in Table 10. Selecting K determines the average level of recruitment into the stock, *ceteris paribus*.

Table 10
The Fin Whale Population Matrix at Various K Levels.
Year Classes 1 to 7

K=8+	K7	K6	K5	K4	K3	K2	K1	Stock	Rstock
7500	479	510	542	577	614	653	694	11,569	10,068
7250	463	493	524	558	593	631	671	11,183	9,733
7000	447	476	506	538	573	609	648	10,798	9,397
6750	431	459	488	519	552	587	625	10,412	9,061
6500	415	442	470	500	532	566	602	10,026	8,726
6250	399	425	452	481	511	544	579	9,641	8,390
6100	390	415	441	469	499	531	565	9,409	8,189
6000	383	408	434	461	491	522	556	9,255	8,055
5750	367	391	416	442	470	500	532	8,869	7,719
5500	351	374	398	423	450	479	509	8,484	7,383
5250	335	357	380	404	430	457	486	8,098	7,048

The recruited stock, Rstock, in Table 10 is 75% of three year olds plus all older age classes. The stock ranges from approximately 8,100 to 11,600 animals at the pristine equilibrium in 1883 prior to exploitation.

It is important to note that this model can yield levels of stock that are higher than at the pristine level. At mean values this does not happen. However a string of low μ_t values combined with high P values will cause the fin whale population to overshoot the pristine equilibrium values.

The stochastic simulations assume that the natural mortality rate, μ_t , and the pregnancy rate $P_t + Q_t$ are independently and identically distributed (IID) random variables having a lognormal distribution with a specified mean and standard deviation. The lognormal distribution applies since the natural mortality and pregnancy rate have a lower bound of zero and

involve many independent multiplicative random components. In addition, the lognormal distribution has the biologically desirable property that it only occasionally produces large natural mortality or pregnancy rate values (Walters (1986) pp. 80-81). The lognormal mean and variance are $M_{LN} = e^{M+\sigma^2/2}$ and $\sigma_{LN}^2 = e^{2M+\sigma^2} (e^{\sigma^2} - 1)$, where M and σ^2 are parameters of the underlying normal distributions.

The review of biological data on fin whales in this Chapter makes it clear that variability in vital rates may be high. The range given by Martin (1982) for pregnancy rates is 0.383 to 0.605 for example while natural mortality is assumed to be of the order 0.04-0.06. The adopted σ_{LN} in Table 11 give a range around mean values for μ and $P+Q$ which reflect the uncertainty about the values of these parameters. The values adopted for the stochastic simulations are provided in Table 11.

Table 11

The Distribution of the Lognormally Distributed Random Parameters.

		M_{LN}	σ_{LN}
Natural mortality	μ	0.06	0.02
Pregnancy rate	P	0.196	0.03
	Q	0.485-P	0.05

Note that P and Q are independently generated. The random variables were generated by converting the $LN(M, \sigma^2)$ to the underlying $N(M, \sigma^2)$. The normal means and variances are

$M_N = \ln[M_{LN}^2 / (\sigma_{LN}^2 + M_{LN}^2)^{0.5}]$ and $\sigma_N^2 = \ln[(\sigma_{LN}^2 + M_{LN}^2) / M_{LN}^2]$. The mean and variances of the underlying normal distributions are provided in Table 12.

Table 12

The Distribution of the Normal Variates Used to Generate the Lognormally Distributed Random Parameters.

		M_N	σ_N
Natural mortality	μ	-2.86	0.32
Pregnancy rate	P	-1.64	0.15
	Q	-0.73-P	0.10

The algorithm used to generate the normal variates is known as the polar method (Law and Kelton (1982) p. 259). In brief, the method works as follows:

1. Generate U_1 and U_2 as IID and $U(0,1)$. Let $V_i = 2U_i - 1$ for $i=1,2$. Let $W = V_1^2 + V_2^2$.
2. If $W > 1$ repeat step 1. Otherwise let $Y = [(-2\ln W)/W]^{0.5}$.
3. Generate the normally distributed random variable $H_i = V_i Y \sigma_N + M_N$.
4. The lognormal variable is $e^{H_i} = \text{LN}(M, \sigma)$.

The simulations are 100 runs of stock trajectories from 1883 to 1987 for every K level. All simulations were initialized by running the model at mean values from 1850 to 1883. When the stochastic simulations start in 1883 all values are at their pristine levels. The status of the stock in 1948 and again in 1987 will be reported.

The level of the stock in 1948 for various K levels is shown in Table 13, 14 and 15. The pristine level for the appropriate component of the stock from Table 10 is provided for comparison purposes. The simulations in Table 13 show the distribution of the stock as a whole in 1948. Table 14 reports on the recruited stock in 1948 for the same trajectories and Table 15 the adult stock.

In Table 13 at K levels above 6250 for the adult stock there are exclusively non-extinction outcomes up to 1948. K values of 6750 and above are associated with mean values of the stock of 93-100 per cent of the pristine equilibrium in 1948. At a K of 6,100 the simulations show a mean value of the stock at 68 per cent of the pristine level but the trajectories are highly dispersed and the stock ranges in value from 10,252 to zero over the 100 trials for this K value. In other words, there are extinction trajectories at K values of 6100 and below as early as 1948.

Table 13

TOTAL STOCK IN 1948 AT VARIOUS K LEVELS.
Number of simulations is 100 at each K level.

Pristine Stock	K	RESULTS OF THE STOCHASTIC SIMULATIONS				ZERO PATHS
		Mean	S.D.	Maximum	Minimum	
11,569	7500	11,642.41	610.74	12,758	9,662	0
11,183	7250	11,104.54	741.30	12,240	8,688	0
10,798	7000	10,467.55	969.12	11,735	7,027	0
10,412	6750	9,678.19	1316.62	11,322	5,003	0
10,026	6500	8,664.96	1789.19	10,946	2,643	0
9,641	6250	7,342.70	2363.42	10,581	125	0
9,409	6100	6,383.53	2685.07	10,252	0	1
9,255	6000	5,684.82	2847.58	9,942	0	2
8,869	5750	3,852.79	2888.81	9,034	0	13
8,484	5500	2,080.95	2459.23	7,914	0	32
8,098	5250	809.88	1582.41	5,792	0	56

The heavy exploitation during the open access period has skewed the age distribution of the stock toward the younger year classes. In Table 14 the recruited stock has not recovered as fully as the total stock. The recruited stock is 90 per cent or better recovered to the pristine level in 1948 at $K \geq 7250$. This pattern is repeated in Table 15. In Table 15 the adult population is only recovered to better than 90 per cent of the pristine level at $K=7500$.

Since these large K values for the stock are unlikely these simulations suggest that the stock was not at the pristine level in 1948. The biological productivity of the stock in 1948 would be underestimated if one assumed that the stock was in equilibrium in 1948.

Table 14

RECRUITED STOCK IN 1948 AT VARIOUS K LEVELS

Number of simulations is 100 at each K level.

Pristine Rstock	K	RESULTS OF THE STOCHASTIC SIMULATIONS				ZERC PATHS
		Mean	S.D.	Maximum	Minimum	
10,068	7500	9,217.48	725.87	10,372	7,261	0
9,733	7250	8,715.80	840.41	10,074	6,420	0
9,397	7000	8,126.92	1017.73	9,778	5,116	0
9,061	6750	7,416.61	1263.21	9,468	3,596	0
8,726	6500	6,542.49	1572.06	9,103	1,879	0
8,390	6250	5,457.79	1924.17	8,596	86	0
8,189	6100	4,700.38	2109.30	8,164	0	1
8,055	6000	4,160.30	2193.47	7,795	0	2
7,719	5750	2,777.13	2148.43	6,901	0	13
7,383	5500	1,478.68	1776.61	5,798	0	32
7,048	5250	567.19	1116.58	4,063	0	56

Table 15

ADULT STOCK IN 1948 AT VARIOUS K LEVELS

Number of simulations is 100 at each K level.

Pristine K=X	RESULTS OF THE STOCHASTIC SIMULATIONS				ZERO PATHS
	Mean	S.D.	Maximum	Minimum	
7500	6,873.20	704.92	8,251	5,112	0
7250	6,445.12	792.53	7,995	4,501	0
7000	5,949.19	915.25	7,739	3,540	0
6750	5,366.34	1070.63	7,422	2,472	0
6500	4,674.76	1251.93	7,001	1,306	0
6250	3,852.24	1446.04	6,419	82	0
6100	3,296.17	1540.99	5,961	0	1
6000	2,905.74	1579.83	5,637	0	2
5750	1,926.81	1506.27	4,972	0	13
5500	1,024.57	1223.57	4,035	0	32
5250	393.10	760.47	2,742	0	56

The real value of these simulations lies in the distributions of stock levels today at different K levels. The size of the stock in 1987 in Table 16 shows that whaling from 1948 to 1987

causes only a small decrease (300-600) in the mean fin whale population at K levels of 6500 and above. However, the dispersion around the mean values has increased substantially over 1948 for Ks from 5750 to 6500. Extinction outcomes are possible for K values of 6,500 and less.

Table 16

TOTAL STOCK IN 1987 AT VARIOUS K LEVELS.

Number of simulations is 100 at each K level.

Pristine Stock	K	RESULTS OF THE STOCHASTIC SIMULATIONS				ZERO PATHS
		Mean	S.D.	Maximum	Minimum	
11,569	7500	11,056.05	610.94	12,082	8,934	0
11,183	7250	10,606.25	615.14	11,653	8,301	0
10,798	7000	10,107.37	630.65	11,214	7,588	0
10,412	6750	9,369.98	1199.08	10,759	1,560	0
10,026	6500	8,114.69	2535.36	10,281	0	5
9,641	6250	6,475.71	3315.68	9,761	0	15
9,409	6100	5,187.74	3654.07	9,410	0	26
9,255	6000	4,289.09	3704.25	9,145	0	36
8,869	5750	2,119.21	3109.98	8,330	0	63
8,484	5500	803.37	1956.58	7,532	0	83
8,098	5250	62.33	365.26	3,199	0	95

The simulations in Table 16 show that at $K \geq 6500$ the stock is on average at 80 per cent or better of the pristine level in 1987. Based on Table 16, surplus production would be high at Ks from 6250 to 6750 given the status of the population relative to the MSY level.

The mean level of the stock has to be used with care if one wants to measure the risk to the stock because the distribution of trajectories tends to be bimodal. The stock either goes to

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high levels or low levels. This is the same point emphasized by Beddington and Grenfell (1979) in the context of the mean time to protection.

The distribution of the stock in 1987 for $K=6250$ is shown in Table 17. In 15 simulations the population had been driven to zero by 1987. The mean total stock size for all 100 simulations is 6,475.71 on the strength of the 62 trajectories with total population levels of 7,500 or better in 1987.

Table 17

FREQUENCY HISTOGRAM FOR THE STOCK IN 1987 FOR $K=6250$.

Number of Simulations is 100 at $K=6250$

Series	Mean	S.D.	Maximum	Minimum
S87	6,475.71	3315.68	9,761	0

INTERVAL	COUNT	HISTOGRAM
0 >= S87 < 750	16	*****
750 >= S87 < 1500	0	
1500 >= S87 < 2250	1	**
2250 >= S87 < 3000	2	***
3000 >= S87 < 3750	4	*****
3750 >= S87 < 4500	1	**
4500 >= S87 < 5250	4	*****
5250 >= S87 < 6000	3	*****
6000 >= S87 < 6750	2	***
6750 >= S87 < 7500	5	*****
7500 >= S87 < 8250	20	*****
8250 >= S87 < 9000	21	*****
9000 >= S87 < 9750	20	*****
9750 >= S87 < 10500	1	**

Table 18

RECRUITED STOCK LEVELS IN 1987 AT VARIOUS K LEVELS.

Number of observations: 100

Pristine Rstock	K	RESULTS OF THE STOCHASTIC SIMULATIONS				ZERO PATHS
		Mean	S.D.	Maximum	Minimum	
10,068	7500	8,412.18	624.92	9,721	6,415	0
9,733	7250	8,040.19	613.78	9,342	5,935	0
9,397	7000	7,623.12	610.27	8,821	5,399	0
9,061	6750	7,018.53	1001.96	8,410	1,124	0
8,726	6500	6,039.43	1945.46	7,978	0	5
8,390	6250	4,783.98	2493.08	7,506	0	15
8,189	6100	3,814.07	2716.52	7,186	0	26
8,055	6000	3,140.53	2734.43	6,944	0	36
7,719	5750	1,541.98	2275.69	6,465	0	63
7,383	5500	576.25	1410.55	5,779	0	83
7,048	5250	45.07	266.23	2,354	0	95

Table 19

MATURE STOCK IN 1987 AT VARIOUS K LEVELS

Number of simulations is 100 at each K level.

Pristine K=X	RESULTS OF THE STOCHASTIC SIMULATIONS				ZERO PATHS
	Mean	S.D.	Maximum	Minimum	
7500	6,019.12	555.87	7,201	4,318	0
7250	5,725.14	536.16	6,831	3,974	0
7000	5,393.38	526.89	6,415	3,593	0
6750	4,926.32	791.94	6,080	673	0
6500	4,204.65	1407.54	5,727	0	5
6250	3,293.75	1760.30	5,342	0	15
6100	2,607.31	1891.38	5,116	0	26
6000	2,136.46	1886.21	4,988	0	36
5750	1,037.65	1546.82	4,639	0	63
5500	381.02	940.62	4,045	0	83
5250	26.86	167.70	1,509	0	95

The fin whale stock is remarkably stable in the face of the hunt from 1948. Comparing total stock and adults from Tables 18 and 19 to Tables 14 and 15 is provided in Table 20. If $K > 6000$

the stock in 1987 is 75-95 per cent of its 1948 value. At $K < 6000$ the drop in stock size seems too large.

Table 20

COMPARISON OF STOCK COMPONENTS IN 1987 AND 1948.

Pristine Stock	K	Stock in 1987 as a % of stock 1948	Adults in 1987 as a % of adults in 1948.
11,569	7500	95	88
11,183	7250	96	89
10,798	7000	97	91
10,412	6750	97	92
10,026	6500	94	90
9,641	6250	88	86
9,409	6100	81	79
9,255	6000	75	74
8,869	5750	55	54
8,484	5500	39	37
8,098	5250	8	7

The work by van Beek (1983) and some stock assessments done by the IWC assumed that the stock had been fished to 53-55 per cent of the 1948 level by about 1981. This would be associated with a K of 5750 in Table 20. However, based on the results of the simulations reported in Tables 16, 18 and 19 a $K=5750$ leads to extinction by 1987 in 63 out of 100 trials. A true K of 5750 therefore seems unlikely given the non-extinction of the fin whale stock and current stock size estimates of approximately 12,000 which are above the pristine level for $K=5750$.

The number of stock trajectories that have extinction as an outcome by 1987 will be referred to here as the probability of extinction. The probability of extinction at various K levels is shown in Figure 12.

$K < 6,000$ has a high probability of extinction. From Table 12, the mean stock sizes for $K < 6000$ are low in comparison to current stock estimates. Similarly, $K > 7,000$ have a zero probability of extinction and stock sizes that seem large in relation to current stock size estimates. K s of 6250 or 6500 are closest to the current IWC stock estimate of 11,563 (Butterworth (1990)).

CONCLUSION

The known catch history for the fin whale stock off Iceland 1883-1989 is combined with a particular view on the variability around mean vital rates. The fin whale is not extinct. This real world result is in principle consistent with all K values from 5,250 to 7,500. To select a particular K one implicitly adopts a view of how steep the decline in the fin whale population was in the post 1948 period. If one accepts a $K > 6,500$ then one necessarily believes that the mature stock declined by about 10 per cent in the post 1948 period based on Table 20.

Based on the stochastic simulations in this chapter, a K of less than 6000 should perhaps be ruled out because of the high probability of extinction. If $K > 6750$ then whaling from 1948 to the present is having a negligible effect on the stock of fin whales off Iceland. While this could be true, it is more likely that the true K is in the 6000 to 6750 range.

The Probability of Extinction at Various K Levels

In the work that follows K will be assumed to be 6500. It follows from Table 13 that the stock was at 86 per cent of its estimated pristine level in 1948, or 8,665/10,026. Similarly, from Table 14, the recruited stock was at 75 per cent of its pristine level in 1948, or 6,542/8,776. Finally, from Table 15 the sexually mature stock adult stock was at 72 per cent or 4,675/6,500. The adult population was probably at close to its maximum sustainable yield level when exploitation began again in 1948.

CHAPTER 4: AN ECONOMIC EXPLANATION OF THE SOLE OWNER PERIOD,
1948-1981.

In Chapter 4 we develop and solve the inter-temporal profit maximization problem for the sole owner of the whale stocks off Iceland. We specifically explore how the dynamics of the whale stock interact with economic factors to prevent depletion of the resource. This will be done within the context of a single species model.

Gordon (1954) suggested that because a sole owner earns the rent from the fishery, the sole owner has an incentive to conserve the resource and maximize the value of the fishery. Scott (1955), using capital theory, concluded that under certain conditions the sole owner's .."most profitable action might be instead to deplete the fishery...to maximize the present value (future net returns discounted to the present) of his enterprise" (Scott (1955) p.122).

If fin whales are not capable of yielding a return similar to other assets in their risk class in the economy they can be said to be an inferior asset. Essentially the resource owner "cashes in" on the slow growing whale stock by driving it to extinction and invests the proceeds somewhere where a higher return can be obtained. This thesis was applied to whales by Clark (1973) and Clark and Lamberson (1982). Clark and Lamberson conclude "...that depletion of certain renewable resources, including the great whale stocks, would be an economic consequence of either

competitive or monopolized exploitation-at least in the absence of regulation designed expressly to prevent such depletion" (Clark and Lamberson (1982) p. 115).

The sole owner was lightly regulated in the 1948-81 period. The laws and regulations in effect had, in practice, only a minor impact on the operations of the company. The regulation of the sole owner, weak as it was, can be characterized as conservation oriented. The provisions that mandate the full utilization of whales killed, size limits of 50 feet, protection of lactating females and that crew wages must be based on the value of the catch and not the number killed prevent a hunt based on indiscriminate harvesting and partial utilization of whales. Fewer whales may have been killed because of these provisions and they therefore act to conserve the stock. However, regulation of the sole owner cannot be credited with expressly preventing depletion of the fin whale stock and the sole owner will therefore be modeled as an unregulated firm.

The economic theory of this problem can be stated quite simply for the case where the population growth function is concave in the domain 0 to K (the environmental carrying capacity) and where it is profitable to harvest at all population levels from 0 to K . For this case extinction is optimal if the discount rate δ exceeds the intrinsic growth rate of the population (Clark (1976)). The resource is said to be submarginal because the present value of extinction is

higher than that of sustained yield harvesting. This is the case that Scott (1955) pointed out above.

For the case where the population growth function exhibits critical depensation and $\underline{X}$ is the minimum viable population level (See Figure 13) the conditions for the optimality of extinction are a little more involved. Berck (1979) analyzed this case for an open access fishery while Lewis and Schmalensee (1977) and Cropper (1988) treated the case of the sole owner.

In the open access case Berck (1979) shows that the relationship between the minimum viable population $\underline{X}$ and the minimum population size at which any exploitation is profitable, X_M , determines whether extinction is feasible. Necessary conditions for extinction need not be characterized by returns to scale or population growth rates. What is required is that $X_M < \underline{X}$, otherwise extinction is impossible. The necessary condition simply says that if fishing is profitable at population levels below the minimum viable population level, $\underline{X}$, extinction is possible.

The usual open access extinction case, as analyzed by Smith (1968) and Clark (1972) and others, assumes that $X_M = \underline{X} = 0$ and that extinction occurs because it is profitable to harvest down to the last members of the species.

Figure 13**The Lewis-Schmalensee Extinction Case**

If harvesting costs increase as the population declines some protection may be afforded to the species under exploitation. However, with some additional restrictive assumptions extinction can still occur. For example, mobile capital, which would see much reduced fishing at low population levels through exit, combined with a negative random environmental shock which would have been absorbed by a large population can drive a stock to extinction. Clark ((1976) p.32-33, (1985), p.54) uses the Peruvian anchovy fishery as an example of this type.

Paterson and Wilen (1977) analyzed the case of the North Pacific fur seal in the 1886-1910 time period. The industry was open access and sealing capital was readily transferred into the halibut fishery. Although the fur seal herd was reduced from 2 million animals to 140,000 the authors conclude that the exit of firms from sealing due to low prices and profits would have saved the herd from extinction.

An industry with fixed immobile capital making losses but covering variable costs may out of inertia harvest to extinction although rational expectations in fishing would suggest that since these firms could not recover their fixed costs they should have remained out of the fishery (Berck (1979) p. 878). Clark and Lamberson ((1982) p. 118) apply the irreversible investment model to Antarctic pelagic whaling and get a "boom-and-bust" path for the industry. In their model, the initial over-capitalization in harvesting capacity reduces the whale stocks below the long run equilibrium level before

capacity reduction through depreciation allows stocks to recover to the long run equilibrium level.

McKelvey (1986) extends the "nonmalleable" investment in harvesting capacity model of Clark, Clarke and Munro (1979) by analyzing open access, oligopolistic and sole owner harvesting. McKelvey (1986) finds that competitive open access results in a final equilibrium state of high capital and low resource-stock compared to the oligopolistic and sole ownership cases. Sole ownership is associated with the lowest level of investment and the highest stock level.

The general conclusion in the economic literature on common property versus sole ownership harvesting of a renewable resource is that the level of depletion will increase with the degree of competition for the resource. This conclusion comes from a variety of models. If a sole ownership is not going to harvest the resource on a sustained basis the resource will be depleted.

In the sole owner case Lewis and Schmalensee (1977) and Cropper (1988) show that extinction is optimal even if the growth rate of the stock exceeds the discount rate under certain circumstances. What is needed for this case is that for a low population level net births become negative as in Figure 13. Extinction is then optimal for small initial stocks. However, large fixed costs have likely saved the whales from extinction since it would not be profitable to incur fixed costs and catching costs at the scale required in

whaling to profitably harvest the low stock levels. The correct proof is in Cropper (1988).

The Lewis-Schmalensee extinction case may not apply to whales. There are no known extinction cases in whale species that were once commercially exploited. However, many stocks were reduced to levels that are so low that a stock as such does not exist for all practical purposes. Individuals of the species are sighted from time to time.

The Scientific Committee of the International Whaling Commission first systematically surveyed the status of various depleted stocks in 1982. Best (1990) updated and expanded this work in his survey of 17 whale stocks that have been protected for at least 20 years. All of the stocks for which estimates of depletion are available were depleted to less than half of one percent of the stock level prior to whaling (Best (1990) p. 129).

The North-Atlantic right whale was believed to be extinct in the early nineteenth century but was caught in small numbers in the early twentieth-century around Iceland, the Faroes, the Shetland Islands, Hebrides and Ireland. The North Atlantic right whale is now extremely rare and only sightings of individual animals are confirmed (Brown (1986)). Many biologists believe these animals to be individual stragglers from a distinct stock off North America.

Butterworth and Best ((1990) p.443) estimate that the South African right whale has recovered from about 0.1 to 3 per cent

of its estimated unexploited size. This stock is estimated to be growing at a rate of 0.068 per cent per year by Butterworth and Best (1990).

Depensation and, more crucially, critical depensation in baleen whale populations are logical possibilities. However, there is no empirical evidence to support either for baleen whale populations. The available empirical work suggests that many baleen whale populations are recovering from near extermination and the few remaining animals are growing at annual rates ranging from 2.5 to 13.8 per cent (Best (1990) p. 129). While this body of empirical work is encouraging one has to acknowledge that many whale populations are still at low levels where they can be assumed to have non-trivial probabilities of extinction.

In what follows the Lewis-Schmalensee extinction case will be assumed away for the East Greenland-Iceland fin whales since the stock recruitment relationship adopted is purely compensatory.

The Gordon-Schaefer model was used in much of the early work on whales. The Gordon-Schaefer model is explored and solved in detail in Clark (1976,1985). We will modify it here by using the delay difference equation with density dependence, equation (7) from Chapter 3, instead of the usual logistic curve. The maximum sustainable yield (MSY) is assumed to be at $0.6K$. The steady state solution is always at positive population levels. The Gordon-Schaefer model framework is useful to explore the

combined effect of restricting effort to four catchers and the discount rate on the operations of Hvalur Ltd.

Instead of the Schaefer differential equation for a fish stock we will use equation (7) from Chapter 3. The delayed differential equation incorporating density dependent recruitment effects is:

$$(1) \quad \dot{X} = -\mu X(t) + 1/2(1-\mu)^T P X(t-T) [1 + q(1 - (X(t-T)/K)^Z)] - Y(t)$$

where $X(t)$ is the number of adult fin whales in the stock at a given instant in time, t , $\dot{X}$ the time derivative at time t , K is the unexploited adult fin whale stock level or environmental carrying capacity (in numbers of fin whales), μ is the natural mortality rate (per cent of whales that die from natural causes), P is the pregnancy rate at K needed to keep the fin whale stock at K given that no fishing occurs (per cent of females pregnant), $q=Q/P$ (dimensionless constant) is the maximum increase in fecundity in the stock at population levels less than K , Z is a constant for the density dependence of fecundity rates, T is the time delay in reaching sexual maturity (years) and $Y(t)$ is the number of adult fin whales caught at time t (number of whales).

$$(2) \quad Y(t) = kX(t)E(t)$$

The catch is assumed to be proportional to the level of effort, $E(t)$ (standard catcher-day), the stock size, $X(t)$ (number of

whales) and a technology constant, k called the catchability coefficient.

At each point in time the firm earns profit, $\Pi(t)$, where

$$(3) \quad \Pi = [pkX - c]E$$

and where p is the selling price per whale and c the cost per day for a catcher. Both p and c are assumed to be constant. Formally, the firm maximizes the present value of the future stream of profits:

$$(4) \quad \text{Max}_{E(t)} = \int_0^{\infty} [pkX - c]E e^{-\delta t} dt$$

Subject to:

$$\dot{X} = -\mu X(t) + G(X(t-T)) - Y(t)$$

$$0 \leq E(t) \leq E_{\text{MAX}}$$

$$X \geq 0 \quad \text{and } X(0) \text{ is given.}$$

where $G(X(t-T)) = \alpha X(t-T) [1 + q(1 - (X(t-T)/K)^2)]$ and $\alpha = 1/2(1 - \mu)^T P$.

Since the catch today affects the stock of whales $t+T$ years in the future, (4) is therefore a deterministic optimal control problem with a delayed response. The problem is linear in the control E .

The current value Hamiltonian used in the solution is:

$$(5) \quad H = [pkX - c]E + \phi(t) \left\{ -\mu X(t) + G(X(t-T)) - kXE \right\}$$

The solution procedure for problems of this type can be found in Kamien and Schwartz ((1981) pp.233-37). In the solution technique E is the control variable, X is the state variable, $\phi(t)$ is the costate variable, $\dot{\phi} = \delta\phi(t) - \frac{\partial H}{\partial X} - \frac{\partial H}{\partial X(t-T)} \Big|_{t+T}$ is the adjoint equation and $\dot{X} = -\mu X + G(X(t-T)) - Y(t)$ is the state equation.

In this problem only contemporaneous values of the state variable and the control variable enter the profit function maximand. The rate of change in the stock of fin whales depends on the current value of the stock (natural mortality), harvest (fishing mortality) and the value of the stock T years past (recruitment). The catch T years ago affects recruitment today. The delay in response of the state to the control is fixed at $T=8$. This simplifies the solution procedure.

The maximum principle requires in part that:

$$(6) \quad \frac{\partial H}{\partial E} = pkX - c - \phi(t)kX = 0$$

Since the Hamiltonian is linear in the control variable, E , it follows from (6), as discussed below, that for E to maximize the function the sole owner should switch E to satisfy $\sigma(t) = p - \frac{c}{kX(t)} - \phi(t)$.

The adjoint equation for this case is:

$$(7) \quad \dot{\phi} = \delta\phi(t) - \frac{\partial H}{\partial X} - \frac{\partial H}{\partial X(t-T)} \bigg|_{t+T}$$

$$= \delta\phi(t) - p k E + \phi(t) \mu + \phi(t) k E - \phi(t+T) \left(\frac{\partial G}{\partial X} \right)$$

In (7) $\dot{\phi}$ should be interpreted as the current-value shadow price of an incremental increase in the stock, X , on the maximand. It follows from the delay in recruitment that one must account for the marginal increase in the size of the stock at time $t-T$ at time t with the term $-\frac{\partial H}{\partial X(t-T)} \bigg|_{t+T}$ since it impacts on the profits available at time t . If there is no time delay in recruitment the adjoint equation is simply $\dot{\phi} = \delta\phi(t) - \frac{\partial H}{\partial X}$.

E must maximize the Hamiltonian which requires, from (6), that:

$$(8) \quad E(t) = 0 \text{ if } p - \frac{c}{kX(t)} - \phi(t) < 0$$

$$E(t) = E_{MAX} \text{ if } p - \frac{c}{kX(t)} - \phi(t) > 0$$

$$E(t) = E^* \text{ if } p - \frac{c}{kX(t)} - \phi(t) = 0$$

where E^* is the effort required to harvest Y^* (surplus production) given that the stock is at its optimum level X^* .

When $p - \frac{c}{kX} = \phi(t) = 0$ the singular solution to the original control problem can be calculated. First, we note that if $p - \frac{c}{kX} = \phi(t)$ then $\phi(t+T) = (p - \frac{c}{kX})e^{-\delta T}$ when evaluated at time t since p , c , k and X are all constant in the steady state. The rate of change in ϕ can be found by taking the time derivative of $\phi(t) = p - \frac{c}{kX}$ from (6), it is:

$$(9) \quad \dot{\phi} = \left[\frac{c}{kX^2} \right] (-\mu X + G - kEX)$$

Equating equations (7) and (9) allows one to solve for the modified golden rule (Clark (1985) p. 77) for this problem:

$$(10) \quad \left[\frac{c}{kX^2} \right] (-\mu X + G - kEX) = \delta \phi(t) - p kE + \phi(t) \mu + \phi(t) kE - \phi(t+T) \left(\frac{\partial G}{\partial X} \right)$$

Simplifying by substituting $(p - \frac{c}{kX}) = \phi(t)$ and $(p - \frac{c}{kX})e^{-\delta T} = \phi(t+T)$ one obtains:

$$(11) \quad \left[\frac{c}{kX^2} \right] (-\mu X + G - kEX) = (p - c/kX) \left(\delta + \mu + kE - \left(\frac{\partial G}{\partial X} \right) e^{-\delta T} \right) - p kE$$

This can be simplified by canceling common terms as follows:

$$(12) \quad -\left[\frac{c}{kX}\right] \left(\mu - \frac{G}{X} + kE\right) = p \left(\delta + \mu + kE - \left(\frac{\partial G}{\partial X}\right) e^{-\delta T}\right) - pkE$$

$$- \left[\frac{c}{kX}\right] \left(\delta + \mu + kE - \left(\frac{\partial G}{\partial X}\right) e^{-\delta T}\right)$$

After canceling common terms and simplifying one obtains:

$$(13) \quad \left[\frac{c}{kX^2}\right] G = \left[p - \frac{c}{kX}\right] \left(\delta - \left(\frac{\partial G}{\partial X}\right) e^{-\delta T}\right) + p\mu$$

which reduces to an expression for the modified golden rule as follows:

$$(14) \quad \delta = \frac{\frac{cG}{kX^2} - p\mu}{(p - c/kX)} + \left(\frac{\partial G}{\partial X}\right) e^{-\delta T}$$

The modified golden rule can be written in a more meaningful way to facilitate interpretation by adding and subtracting c/kX on the right hand side of equation (14). After rearranging terms one obtains:

$$(15) \quad \delta = \frac{\left[\frac{c}{kX} \right] (G - \mu X) + \left[p - \frac{c}{kX} \right] \left(\frac{\partial G}{\partial X} e^{-\delta T} - \mu \right)}{\left(p - c/kX \right)}$$

Following Clark and Munro ((1975) p. 96) and Clark ((1985) p.23), we interpret $\left(\left(\frac{\partial G}{\partial X} \right) e^{-\delta T} - \mu \right)$ as the marginal productivity of the resource stock and $(G(X^*) - \mu X^*)$ as the marginal stock effect. The marginal stock effect specifies the effect of stock thinning on the optimal biomass level. In general, the cost of harvesting will increase as the biomass is fished down. Equation (15) has this property.

The explicit form of the growth function is:

$$(16) \quad G(X(t-T)) = \alpha X(t-T) [1 + q(1 - (X(t-T)/K)^Z)]$$

Taking the derivative of $G(X)$, $\partial G(X)/\partial X$ one obtains:

$$(17) \quad \frac{\partial G}{\partial X} = \alpha + \alpha q - \alpha q(Z+1) \left(\frac{X}{K} \right)^Z$$

Substituting equations (16) and (17) into equation (14) and noting that in the steady state $X(t) = X(t-T) = X^*$ one obtains:

$$(18) \quad \delta = \frac{\left(\frac{c}{kX} \right) \left(\alpha + \alpha q - \alpha q \left(\frac{X}{K} \right)^Z \right) - p\mu}{\left(p - \frac{c}{kX} \right)} + \left(e^{-\delta T} \left(\alpha + \alpha q - \alpha q (Z+1) \left(\frac{X}{K} \right)^Z \right) \right)$$

Equation (18) is complicated. It does not lend itself to an explicit analytical solution for X^* . However, solving (18) for X^* can be done numerically with interval bisection since X^* will always be in the interval from 0 to K .

PARAMETER VALUES

The review of the history and biology of this fishery yielded explicit values for the required parameters. However, there are important qualifiers on these parameters. The period just after World War II saw "the long ton" (6 barrels of whale oil) of whale oil increase from £45 in 1945 to £141 in 1951. It must be emphasized that conditions just after World War II were unusual. The prices paid for all fats were at a record high as can be seen in Figure 14. Brandt (1948) analyzed the market for whale oils just after World War II.

"In line with these first signals of a gradually changing supply situation, the whale-oil market is beginning to reveal the first indications of a price recession. Forward sales for the 1947-48 season have been made at £90 and London reported in September that offers at this price found no buyers" (Brandt (1948) p.41).

A prudent investor in 1948 would not have projected the current market price far into the future since prices were expected to decline. The rationale for parameter values will now be detailed at some length.

Price per whale, p

1. Price per whale, p , is a product of the number of barrels of oil per whale and the market price of oil. Whales off Iceland were shown to have an average yield equal to 36 barrels from 1883-1915. Each long ton is equal to 6 barrels. A long ton of whale oil is valued at £60 to £100 or £360 to £600 per whale in 1948 terms. Byproducts would increase the value of this parameter by about $1/3$. The value of p is assumed to range from £500 to £800 in 1948.

c , the cost per standard catcher day, E

2. The value of c cannot be obtained cleanly. Costs are given for catching and processing a long ton of whale oil. Other sources give the total cost per catcher for the season. In the Antarctic in the mid-1950s the total operating cost for a whale catcher is estimated at £40,000 by Tønnessen and Johnsen ((1982) p.561). This must be translated into cost per catcher day. For a six month season this would amount to £220 to £240 per day. The plausibility of this range can be checked by looking at how this relates to cost per whale. The four Icelandic catchers catch on average 385 fin, sei and sperm whales per season so this would yield approximately £416 per whale. Norwegian

production costs per long ton of whale oil in the Antarctic in 1945-48 are given as £35 by Tønnessen and Johnsen ((1982) p. 513). Applying the £35 to the 6 long tons of oil per whale would yield a production cost of £210 per whale to which one would have to add the cost of processing the byproducts. The Icelandic operation could only hope to achieve those costs by making up for the lower catch rates with used catchers and inexpensive domestic labour relative to the Norwegian crews. The value of c is assumed to range from £150 to £220.

3. The biological parameters are from Figure 10, $q=1.463$, $P+Q=0.485$, $\mu=0.06$ and $T=8$, and $X(0)=4,675$ from Chapter 3.

FIGURE 14

Average Prices of Whale Oil No 1. 1883-1948.

Price Per Long ton=1.016 kg.=6 barrels in Pounds Sterling

4. δ , the discount rate varies from 0-100 per cent. The sole owner's discount rate, δ , would reflect alternative investment opportunities open to him plus the depreciation of whaling capital. Depreciation of whaling capital is slight. The vessels would last for 25-30 years of work in Antarctic conditions but since they are only used for 3-4 months a year they can last upwards of 75 years. At the whaling station much of the oil processing equipment installed for the 1948 season is still in use. The depreciation rate on whaling capital is therefore low, of the order of 2 per cent per annum.

The sole owner puts his interest first and evaluates the fin whale stock by comparing it to his financial alternatives. However, institutional factors in the Icelandic financial market in the 1948-1981 period make this difficult. We cannot determine a risk free rate of interest for Iceland directly by looking at the real rate of interest on government bonds because nominal interest rates were pegged by the Central Bank for much of the period. The real rate of interest on financial assets was kept negative and international capital movements were strictly regulated. Icelandic citizens were not allowed to invest abroad. Depositing money with banks paid a real rate of interest ranging from 4.9 to -27.5 per cent per annum (an average of -8.05 per cent, S.D 7.62) in the 1960-1983 period while borrowing money cost the firm 7.1 to -26.5 per cent per

annum (an average of -7.05 per cent, S.D. of 7.77) (Jonsson (1985) p. 18). Clearly, some proxies from the real economy must be looked at for the sole owner.

Eggertsson (1982, p.2) and Stefansson (1981, p.C5.8) point to returns on real estate and other assets as a measure of the opportunity cost of holding money in Iceland. Using the barter of goods as a proxy, the real growth rate of GNP for the period 1950-1986 was approximately 3.5 per cent (See Table A9 in the Appendix) while national assets (proxy for real estate) grew at an average annual rate of 4.51 per cent 1948-1981 (See Table A10 in the Appendix). The reference real rate of interest for the sole owner in Iceland is the sum of depreciation plus cost of capital which would range from -5 to 6.5 per cent per annum. We assume that δ is approximately 5 per cent for 1948-1981.

5. The season and other operational questions will be dealt with in depth in Chapter 5. However, land stations are allowed to operate for a maximum of six months according to IWC regulations. A theoretical upper limit on effort is therefore 4 catchers for a maximum of 6 months or approximately $(4 \times 6 \times 30) = 720$ catcher days. The actual effort on fin whales is much less. The principal fin whale season is in June and July but fin whales are caught until late September. Unfavourable weather conditions and other operational considerations also limit the number of fin whale catching effort days. Therefore only 30% of the 720 days can be spent hunting fin whales, or $E_{MAX} = 216$ days.

6. Determinants of catchability are discussed more fully in Chapter 5. The catchability coefficient, k was calculated directly from search hours given by Sigurjónsson and Rørvik (1983). The gaps in the data were filled by using average hours for missing years and efficiency corrected average hours for missing vessels to get a gross estimate of effort 1948 to 1981.

Table 21

Regressions to Estimate the Catchability Coefficient per Search Hour, $\hat{k}_H$.

E_t =Weather corrected search hours.

X_t =Stock of fin whales from Figure 10.

Y_t =Catch of fin whales.

$$Y_t = \hat{k}_H * E_t * X_t$$

$\hat{k}_H$ ~ COEFFICIENT	STD. ERROR	T-STAT.	PERIOD
6.040E-05	5.170E-06	11.682996	1948-56
6.641E-05	1.095E-05	6.0624603	1956-61
9.354E-05	1.110E-05	8.4265349	1962-66
7.088E-05	5.366E-06	13.210379	1966-81
6.825E-05	3.699E-06	18.450415	1948-81

Actual Versus Predicted Fin Whale Catches 1948-81.

Series	Mean	S.D.	Maximum	Minimum
Actual Catches	241.82	48.73	348.00	142.00
Predicted Catches	231.70	42.16	328.00	145.64

The k_H is a crude average catchability coefficient per search hour. The vessel factors from Rørvik et. al. (1976) were used

to get standard search hours. The actual versus predicted catches show that the k_H on average is not a bad approximation.

The $\hat{k}_H$ must be converted to k per catcher day. The key is to estimate how much of a typical catcher day, E , is actually spent fishing. Sigurjónsson ((1988) p. 332) provides us with a detailed time budget for vessels number 7, 8 and 9. His table is reproduced here as Table 22.

Table 22

A Summary of Operational Factors Extracted From Log-Books of Catchers Number 7, and 8 June-July 1962-79 and 9, 1966-79, Averages (All times are in hours.).

Vessel	Total Operating Time	Towing	Sailing to Grounds	In Port	Searching Chasing Handling
No 7	1,354	477	464	51	362
Per Trip	45.5	16	15.6	1.7	12.2
% of Op. time	100	35.2	34.3	3.8	26.7
No 8	1,343	505	467	46	325
Per Trip	47.2	17.8	16.4	1.6	11.4
% of Op. time	100	37.3	34.7	3.4	24.2
No 9	1,322	468	477	43	334
Per Trip	46.3	16.4	16.7	1.5	11.7
% of Op. time	100	35.2	36.2	3.3	25.3
Average all	1,339.7	483.3	469.4	46.7	340.3
Per Trip	46.4	16.2	16.2	1.6	11.8
% of OP. time	100	36.1	35.0	3.5	25.4

Source: Sigurjónsson ((1988) p.332) Table 4.

To calculate a range for the catchability coefficient k , we proceed as follows: $Y=kXE$ or $k=Y/EX$. From Table 21, $\hat{k}_H$ ranges

from 0.00006040 to 0.00009354 per hour. By converting the average catcher day into 24 hours the average trip takes $46.4/24=1.93$ catcher days and out of each E only 6.1 hours can be spent fishing. The $\hat{k}_H$ should therefore be multiplied by 6.1 to get k per catcher day, E. This yields k per E ranging from 0.00036 to 0.00057. The largest Y on record is 348 fin whales in 1957 while the smallest Y is 142 in 1961. Effort, E is a maximum of 216. A k which fits the Y limit was chosen by calculating $Y=kX(0)E_{MAX}$. At the lower limit, if $k=0.00036$ then $Y=0.00036*4675*216$ or 363.53 to 575.58 for $k=0.00057$. For the simulations of the most rapid approach path 0.00036 is used.

The comparative statics properties of (18) are explored in Table 23. Equation (18) is solved for p/c ratios ranging from $£500/£220=2.27$ to $£800/£150=5.33$. At each p/c ratio the discount rate is allowed to range from zero to 35 per cent. The results are summarized in Table 23.

Table 23

The Solution for X^* to Equation (18) Using the Assumed Parameter Values of $\mu=0.06$, $q=1.4636$, $k=0.00036$, $\alpha=0.12$, $Z=2.39$ and $K=6,500$.

Discount Optimal Adult Stock Level (8+), X^* , at the Various
Rate $\frac{p}{c/kX}$ Levels.

δ	p/c 2.27	p/c 3.63	p/c 5.33
0%	4,277	4,146	4,059
5	3,144	2,577	2,185
10	2,185	1,433	997
15	1,820	1,155	793
20	1,662	1,048	716
25	1,573	989	676
30	1,518	952	651
35	1,477	926	633

The maximum sustainable yield for the stock should occur at 0.6K or with 3,900 animals in the adult stock. Surplus production peaks at 242 between 3,794 and 4,007. The comparative statics of the model reported in Table 23 show that the model has the usual property that at a zero discount rate the optimal value of the population is always greater than the MSY level. At discount rates less than 5 per cent the sole owner would leave the stock at greater than 0.55 of the MSY level even for high p/c ratios. If the discount rate were as high as 10 per cent then there is only cause for concern about the population at high p/c ratios.

The p adopted for the remainder of the work in this chapter is £650 or a midpoint of the £500 to £800 range. On the cost

side the a cost per catcher day of £220 is accepted. The main reason for adopting high cost per catcher day is the need to employ some Norwegians in key positions for the first seasons. The location of the whale station itself entailed higher operating costs for the vessels which was emphasized by Skarre (1948).

The detailed solution to the optimal control problem in Table 24 and Figure 15 shows that at discount rates, δ , of less than 10 per cent the stock is kept at relatively productive levels. Only at discount rates over 15 per cent would a sole owner drive the stock below 0.2K, which approximately corresponds to the low point for the stock in the open access period in Figure 10.

Table 24

The Solution for the Optimal Stock, X^* to Equation (18), and Yield and Effort Given That $X=0$ and X^* .

Optimal Steady-State Values For:			
Discount Rate	Adult Stock	Harvest	Catcher Days
δ	X^*	Y^*	E^*
0	4,191	239	158
1	3,982	242	168
2	3,738	241	179
3	3,457	237	190
4	3,145	228	201
5	2,816	214	210
7	2,231	181	225
10	1,732	146	233
12	1,564	133	235
15	1,414	121	237
20	1,285	111	238
25	1,215	105	239
30	1,171	101	239
35	1,139	99	240
50	1,083	94	240
100	1,014	88	241

Parameter values are: $p/c=£650/£220=2.95$, $\mu=0.06$, $q=1.4636$, $k=0.00036$, $\alpha=0.12$, $Z=2.39$ and $K=6,500$.

In Chapter 3 on the basis of the stochastic stock simulations the fin whale stock was assumed to be at 4,675 fin whales age 8 and above in 1948. The stock was thus on the most productive part on the stock recruitment curve just above MSY. This information was combined with the solution to the optimal control problem in Table 24 and the most rapid approach path (MRAP) was simulated for different discount rates δ .

FIGURE 15
The Solution to the Optimal Control
Problem Faced by the Sole Owner

In Figure 16 the MRAP to X^* for $\delta=0, 3$ and 10 per cent are shown. The first thing to note is that the most rapid approach paths involve fishing at E_{MAX} until X^* is reached. Once X^* is reached the sole owner fishes at Y^* with effort equal to E^* .

For low discount rates like 0 or 3 per cent the stock would only be fished down for a few years. At high discount rates like $\delta=10\%$ the stock trajectory in Figure 16 is continuously declining because the stock would not be fished down to the low value of X^* in the period 1948-2048 because of the restriction on E_{MAX} . The current harvesting capacity of only four catchers is not consistent with a high discount rate like 10 per cent. Table 25 shows the distribution of stocks for each discount rate.

Table 25

The Average Stock Size for the Most Rapid Approach Paths at Different Discount Rates.

SMPL range: 1948 - 2048

Number of observations: 101

Series	Mean	S.D.	Maximum	Minimum
X0	4198.46	53.35	4675	4191
X3	3528.20	199.57	4675	3455
XT10	3206.35	373.20	4675	2824

FIGURE 16
The MRAP for the Stock to X^* at Different Discount Rates.

FIGURE 17
The Pattern of Catches at Different Discount Rates
on the MRAP.

The average catches are provided in Figure 17 and Table 26. The pattern of catches shows that X^* is reached quite rapidly for low discount rates like 0 or 3%. If the true discount rate is 10 per cent then X^* would not be reached. At high discount rates the stock would decline slowly and the low X^* is not yet reached after 100 years of fishing with the current fleet.

Table 26

The Average Catch Size for MRAPs at Different Discount Rates.

SMPL range: 1948 - 1981

Number of observations: 34

Series	Mean	S.D.	Maximum	Minimum
YT0	246.12	28.20	365	239
YT3	275.12	34.83	365	237
YT10	284.27	25.87	365	256

If the whale stocks around Iceland had been thinned to their sustainable levels by the mid 1960s, then given sole ownership since 1948, only a real discount rate below 5 per cent would be consistent with these values. If the stock declined slowly from 1948 through the end of the hunt in 1989, then only a discount rate that is above 5 per cent would be consistent with the behaviour of the sole owner.

On the one hand, the catching power of the Icelandic whaling fleet seems to be so low that one can rule out an extinction

strategy a priori. On the other, Figure 16 makes it clear that a δ above 10 per cent is of little practical interest because on that path whale stocks around Iceland would still be declining. Because the prevailing view at the IWC is that the whale stocks were by 1989 either stable or growing, a real discount rate at or below 5 per cent seems most likely.

CONCLUSION.

The open access period in Icelandic whaling lasted from 1883 to 1915. It was brought to a close by legislation banning all whaling from Iceland for 10 years. The available evidence indicates that both fin and blue whales were fished down rather severely. The fin whale stock recovered to some extent but the blue whale stock was kept at a fished down level by sporadic exploitation until 1960. The fin whale stock had recovered enough by the 1930s to become a basis for a viable fishery.

A single firm has enjoyed exclusive access to the whaling grounds off Iceland since 1948. The firm's behaviour is in broad conformity with the predictions of the modified Gordon-Schaefer model used in this Chapter. The available biological evidence suggests that a sustained whale fishery based on fin, sperm and sei whales had been established by the mid 1960s. This suggests that the discount rate used by the sole owner must have been below 5 per cent.

The regulation of the resource owner 1948-81 was weak but conservation oriented. However, the regulations seem to lack

the kind of teeth that one would associate with rules that explicitly prevented extinction strategies such as catch quotas. For example capacity regulation was weak. When the company renewed its catchers in the 1956-1966 period it increased the catching power of the fleet by 20-40 per cent. The increased catching power was not enough to threaten the whale stocks off Iceland. In fact, the catching power of the fleet seems so low that one can rule out extinction strategies a priori.

All MRAPs in this Chapter imply some stock decline since 1948. However, if the stock has been relatively stable since the 1960s and the MRAPs are realistic the conduct of the sole owner in the 1948-81 period implies that the catch quotas set by the IWC starting in 1977 are not necessary. The sole owner seems to have self-regulated himself to a harvesting path that is not depleting the stock.

The limited catching power of the fleet is critical to the results obtained from the economic model of sole owner harvesting. The conclusion that the discount rate employed by the firm was in the 5 per cent range depends on it. The proposition that non-extinction is being pursued by the sole owner also depends on the assumed fleet capacity. In Chapter 5 we survey available descriptive material on capacity and then move on to model the search process in harvesting in Chapter 6 to determine the validity of the rather restrictive treatment of catchability and harvesting in the economic model.

CHAPTER 5: THE CHOICE OF HARVESTING CAPACITY FOR A SOLE OWNER OF A FISH RESOURCE SUBJECT TO SEARCH.

Whales, unlike cattle must be found to be caught. In view of this, the efficiency of any particular harvesting by whale catchers can be judged only with reference to a catch function that incorporates search. In this chapter search and stock dynamics will be described and we will look at material on the efficiency of the Icelandic whaling fleet between 1948 and 1982.

The actual whale search process in Iceland involves four independently operating catchers taking trips from the land station in Hvalfjordur. Each round trip lasts a total of about 45-47 hours (Sigurjonsson (1988) p.332). The captain of each catcher boat decides which ground to head for based on personal knowledge gained from earlier trips, radio reports from other vessels, current weather conditions and forecasts (Sigurjonsson(1988) p.332). To reach the grounds takes approximately 10-15 hours. Once on the fishing grounds, the search for fin whales is a search for identifiable schools. Finding schools then means that the entire school is fished out except for those animals less than 50 feet and lactating females. Once killed, a whale must be delivered to the whale station no later than 28-30 hours after it is killed to comply with IWC and company regulations.

Between 1948 and the early 1980s harvesting capacity of the whale fishery was four catchers. In 1983 the number of catchers was reduced to three in response to reduced catch quotas imposed by the IWC. Whether the choice of four catchers used throughout the period 1948 to 1982 can be characterized as optimal is the open question addressed in this chapter and Chapters 6 and 7.

To study the impact of harvesting capacity on stock dynamics a detailed geographic description of the hunt is provided. The starting point is a description of the relatively small area compared to the total area inhabited by the fin whale stock in which the actual hunt occurs. Next a physical description of the whale catchers and their operating characteristics in the hunt is provided. Such a background is necessary to establish the dimensions that will measure the ability of the available harvesting capacity to search for whale stocks.

The results of harvesting are often analyzed by studying evidence on trends in whale lengths and catch per unit effort data. The length distribution of Icelandic fin whale catches in 1937-1939 and 1949-1984 is reviewed in conjunction with catch and effort relationships. Both should yield some insights into stock dynamics. However, the analysis of the length data is inconclusive, and catch-per-unit-effort (CPUE) relationships are not reliable in fisheries where the random components of search are important. (Greater discussion of this latter point may be found in Clark and Mangel (1978) and Mangel (1982)). For these reasons the search process was modeled explicitly in Chapter 6.

The available search data shows that when effort and fin whale availability fluctuate considerably.

5.1 THE GEOGRAPHIC DISTRIBUTION OF THE FIN WHALES AND THE LOCATION OF THE WHALING GROUNDS.

The geographical distribution of fin whales through catch data was first studied by Rørvik et al (1976). Martin(1983), Sigurjónsson (1988) and Sigurjónsson and Gunnlaugsson (1989) each have updated that material. An understanding of the spatial distribution of whale stocks is important in understanding the characteristics of the whale hunt and hence the dynamics of the harvesting activity.

For statistical purposes the company developed a system to code the position of each whale caught. This system is outlined in Figure 18 (Rørvik et al (1976) p. 9). From Figure 19 it can be seen that as a practical matter, only 34 cells constitute the principal whaling grounds. In relation to these areas Rørvik et al (1976) analyzed the location of fin whale catches from 1951-73. Three whaling grounds were identified and appear in the data of Table 27 as South, West and North. Across these regions fin whales migrate north between Iceland and Greenland. Fin whale abundance on the whaling grounds peaks in June and July. For this reason June and July have become the main whale harvesting period. This pattern is evident from Table 27. The east-west distribution of catches is provided in Table 28.

Fig. 18 The statistical areas for the Icelandic fishery and whaling. Catch positions are coded by square number and subsquares (a-d) counted from upper left corner clockwise.

SOURCE: ROXVIK ET AL (1976) p.9

Fig. 19 Western Iceland showing Hvalfjörður (●) and the tin and sei whaling grounds

SOURCE: SKURJÓNSSON (1988)

Table 27

The Average Percentage North-South Distribution of Catches of Fin Whales off the Western Coast of Iceland, 1959-1973.

Areas	May	June	July	August	September	Total
North of 65°N	44.9	13.9	65.4	63.3	67.3	47.1
64°N-65°N	24.7	32.1	27.3	28.3	22.9	28.9
South of 64°N	30.4	53.7	7.3	4.4	9.8	24.0
	<u>100</u>	<u>100</u>	<u>100</u>	<u>100</u>	<u>100</u>	<u>100</u>
Total No. of Whales	69	1,221	1,387	671	214	3,562

Source: Rørvik et al (1976) p.12.

Table 28

The Catches of Fin Whales 64°N and 65°N, 1951-1973, Expressed in Percentages Between the Area West and East of 27°W for Each Month Through the Season.

Areas	May	June	July	August	September	Total
West of 27°W	81	61	42.7	48.7	66.7	53
East of 27°W	19	39	57.3	51.3	33.3	47
	<u>100</u>	<u>100</u>	<u>100</u>	<u>100</u>	<u>100</u>	<u>100</u>
Total No. of Whales	21	754	630	298	81	1,784

Source: Rørvik et al (1976) p.12

The location of the hunt shifted from the Southern and Western grounds to the Northern ground after 1958. Sigurjonsson

(1988) reports that the average distance from the station to the catch position for all species in the 1959-79 period was somewhat above 160 nautical miles. By moving north, the average travel distance increased about 35 per cent from 1951-59 to 1959-78. Sigurjonsson (1988) speculates that better navigational aids and higher sperm oil prices were responsible for the shift to the Northern grounds. Sperm whales are only found on the Northern grounds. The distribution of catches among the three grounds is provided in Table 29.

Table 29

Percentage Distribution of the Fin Whale Catches.

Season	South Below 64°N	West 64°N-65°N	North Above 65°N
1951	51.6	42.9	5.5
1952	43	55.7	1.4
1953	60.9	38.2	0.9
1954	34.5	64.4	1.1
1955	84.3	12.7	3.0
1956	55.1	38.5	6.4
1957	63.0	30.4	6.6
1958	69.2	23.9	6.9
1959	32.2	44.1	23.7
1960	21.9	26.9	51.3
1961	28.2	33.8	38.0
1962	30.7	34.7	34.6
1963	18.4	25.8	55.8
1964	2.3	24.9	72.8
1965	29.8	23.5	46.7
1966	21.0	27.4	51.6
1967	41.8	21.8	36.4
1968	15.6	22.9	61.5
1969	20.3	28.7	51.0
1970	9.9	7.0	83.1
1971	34.6	40.4	25.0
1972	25.6	43.3	31.1
1973	30.0	37.1	33.0

Source: Rørvik et al (1976) p. 17 Table 5.

FIGURE 20

Fig 20 Approximate locations of fin (circles) and sei (boxes) whales sighted during the Ljófari cruise, June/July 1981.

SOURCE: SIGURJÓNSSON (1983)

FIGURE 21

Fig 21 Distribution of fin whale sightings during vessel surveys June-July (Icelandic vessels) and June-August (Faroese vessel) 1987

SOURCE: SIGURJÓNSSON AND GUNNLAUGSSON (1989) p.402

Sigurjónsson (1983, 1987) confirms concentrations of fin whales on the "unexploited E-Greenland grounds" (See Figure 20). The 1987 survey reported in Sigurjónsson (1988) and Sigurjónsson and Gunnlaugsson (1989) found in addition considerable numbers of fin whales south, and north-east of Iceland (See Figure 21, Sigurjónsson and Gunnlaugsson (1989) p. 402). All these fin whales are from the same stock. They are subject to exploitation when they migrate through the whaling grounds between June and the end of September each year.

At the IWC Special Meeting on North Atlantic Fin Whales in February 1991 the issue of stock identity of the East Greenland-Iceland fin whale stock was discussed because a whale from Canada was harvested off Iceland in 1988. One of 27 fin whales marked near Funk Island, Newfoundland (at 49°40'N, 53°10'W) on August 29, 1979 was recovered off Iceland July 7, 1988, 75 nautical miles south of Reykjanes (at 62°30'N, 24°15'W), a distance of 1,590 nautical miles (Sigurjónsson, Mitchell and Gunnlaugsson (1991) p. 4).

This is the only mark recovered from a stock outside the East Greenland-Iceland stock area since fishing began and the recovery position is the eastern most position of a mark return that has been recorded in the Icelandic fishery (Sigurjónsson, Mitchell and Gunnlaugsson (1991) p. 4). At the IWC Special Meeting on North Atlantic Fin Whales in February 1991 the single mark was

considered consistent by some with both a high and a low rate of emigration of fin whales from Canada to waters off Iceland.

Genetic testing has already proven that the Iberian-U.K. fin whale stock is distinct from the East Greenland-Iceland stock and it will resolve the stock identity question in the near future. However, whether there is some in-migration of fin whales from Canada into the East Greenland-Iceland fin whale stock does not matter since it would just enhance the value of the stock to the sole owner operating in Iceland. There is no evidence available on out-migration from the East Greenland-Iceland fin whale stock.

This brief survey of the stock location shows that Icelandic whaling from 1948 to the present does not simultaneously expose all of the East-Greenland-Iceland fin whale stock to exploitation. The hunt can be thought of as a harvest of a fixed patch of the fin whale habitat. This poses some problems if one wants to draw inferences on the stock as a whole from the hunt.

5.2 THE OPERATING CHARACTERISTICS OF INDIVIDUAL VESSELS IN THE FLEET.

Hvalur Ltd, the whaling company, has owned a total of nine different catchers since 1948. At any one time, however, at most four catchers have been used in the harvesting of whales. The horsepower, cruising speed, tonnage and time of operation of these vessels are listed in Table 30. Rørvik et al ((1976) pp. 21-23) noted that in pelagic whaling catcher efficiency is proportional

to tonnage but because of the importance of sailing time between the land station and the whaling grounds in the Icelandic fishery catcher efficiency is not proportional to tonnage.

Table 30

Catchers in the Icelandic whale fishery.

Name	Break Horse Power	Cruising Speed in Knots	Gross Registered Tonnage	Period in Operation
Hvalur 1	800	10.7	248	1948-56, 1961
Hvalur 2	1,288		256	1948-55, 1957-61
Hvalur 3	1,200	10.7	266	1948-61
Hvalur 4	800	10.7	250	1948-61
Hvalur 5	1,400	11.3	387	1956-61
Hvalur 6	2,100	12.6	434	1961-85
Hvalur 7	2,100	12.6	427	1961-82
Hvalur 8	1,800	12.6	481	1962-present
Hvalur 9	1,900	12.6	631	1966-present

Source: Sigurjonsson (1988) Table 2, p.329.

Sigurjonsson and Rørvik (1983) provide an estimate of how long it takes each boat to get to the principal whaling grounds which is reproduced here as Table 31. Rørvik et al (1976) estimate that catchers 6-9 are approximately 12-41 per cent more efficient than catchers 1-5. Most of the efficiency gain comes from higher cruising speeds given the dominance of travel to and from the grounds. The new catchers also slow down less when towing back their catch because of greater tonnage and larger engines than the old catchers. This would magnify the rather small differences in cruising time to the grounds seen in Table 31.

Table 31

Estimated sailing time to the whaling grounds for different vessels in operation in hrs.

Hvalur	Period	Northern North of 65°N	Western 64°N-65°N	Southern South of 64°N
1,3 and 4	1951-58	12.7	10.6	9.7
5	1951-58	12.1	10.1	9.2
3 and 4	1959-60	15.3	12.7	11.5
5	1959-60	14.5	12.0	10.9
6,7 and 8	1962-81	13.0	10.8	9.8
9	1966-81	13.0	10.8	9.8

Source: Sigurjonsson and Rørvik (1983) p. 132.

5.3 CATCH PER UNIT EFFORT IN THE FIN WHALE FISHERY

Catch per unit effort (CPUE) is the most commonly used index of relative stock abundance for whales. A decline in CPUE is used as direct evidence that the stock is declining and conversely if CPUE increases.

The study of CPUE relationships is frequently used in fisheries studies to get a crude index of abundance. CPUE relationships for whales have been shown to be biased in a theoretical context by Beddington (1979), Allen (1980a), Allen (1980b), Zahl (1982), Cooke (1983), Cooke (1985) and others. However, since perfect data are not available, consistent, even if biased, CPUE series are still considered useful to the management of whale stocks.

A survey of 42 whale CPUE series by de la Mare (1984) is an important contribution to our understanding of the reliability of whale CPUE series. The de la Mare study covers both catch per catcher day worked and, what is less common, catch per search hour. The important finding from the de la Mare study is that variability around the mean is high. The survey shows that the coefficient of variation (C.V.) has a mean of 0.35 with a standard deviation of 0.20. The range of C.Vs. is 0.06 to 0.96. The advantage of reporting C.Vs. (Standard Deviation/Mean) is that it standardizes for the scale of the different CPUE series and allows for a convenient comparison of dispersion in series with widely differing range of values. On the basis of the de la Mare study one's prior is that whale CPUE series can be expected to fluctuate widely around their means.

Rørvik (1980) and Rørvik and Sigurjonsson (1981) calculate the catch per unit effort (CPUE) for the Icelandic fin whale fishery. To do so they standardize the fishing season between June 1 to September 20 each year and then adjust catches downward for parts of seasons when three fin whales were allowed per trip and add back in expected catches for seasons missing days in the June 1 to September 20 period since the hunt sometimes starts after June 1 and ends prior to September 20. The resulting CPUE series is shown in Figure 22.

FIGURE 22

Catch Per Unit Effort in the Fin Whale Fishery June 1 to Sept 20

Rørvik and Sigurjonsson (1981) recognize that in 1979 the time from the first kill to delivery of the whales at land was shortened from 30 to 28 hours. Hence they adjust by assuming that 4% more trips will be taken and so multiply the old standard CPUE by 1.04. The distribution of the CPUE is provided in Table 32. The CPUE measure used in their study is the number of fin whales killed per catcher day worked (CDW).

Table 32

The Distribution of CPUE in the Icelandic Fin Whale Fishery Standardized for a June 1 to September 20 Season.

range: 1949 - 1979

Number of observations: 31

Series	Mean	S.D.	Maximum	Minimum
ACPUE	0.9241935	0.1923673	1.4000000	0.5900000

INTERVAL	COUNT	HISTOGRAM
0.45 >= ACPUE < 0.60	1	***
0.60 >= ACPUE < 0.75	5	*****
0.75 >= ACPUE < 0.90	6	*****
0.90 >= ACPUE < 1.05	11	*****
1.05 >= ACPUE < 1.20	6	*****
1.20 >= ACPUE < 1.35	1	***
1.35 >= ACPUE < 1.50	1	***

The distribution of CPUE in Table 32 appears to be normal. The formal χ^2 test for goodness of fit with $df=6$ to the normal distribution from a sample with a mean of 0.9241 and a standard deviation of 0.1924 at the 5% level is the probability that $(9.49 < \chi^2 < \infty)$. The actual $\chi^2(5\%, df=6)=6.71 < 9.49$. Thus the

hypothesis that the distribution of CPUE in the fin whale fishery is drawn from a normal distribution with a mean of 0.924 and a standard deviation of 0.1924 cannot be rejected on statistical grounds.

With this CPUE data we can test the hypothesis that the CPUE has fallen over time. If that were true it would imply that fish stocks have fallen over that period of time since effort levels have remained largely unchanged. When time is regressed against CPUE, the time trend of $CPUE = a_0 + a_1 * Time$, i.e. the a_1 coefficient between the seasonal catch of fin whales per catcher days worked and time (time=1948,1949,,,1979) is insignificant at the 5 per cent level. The actual regression is:

Table 33

Dependent Variable is Actual Annual CPUE

SMPL range: 1949 - 1979

Number of observations: 31

VARIABLE	COEFFICIENT	STD. ERROR	T-STAT.	2-TAIL SIG.
C	14.062403	7.3205228	1.9209561	0.065
Time	-0.0066895	0.0037273	-1.7947278	0.083
R-squared	0.099967	Mean of dependent var	0.924194	
Adjusted R-squared	0.068932	S.D. of dependent var	0.192367	
S.E. of regression	0.185619	Sum of squared resid	0.999176	
Durbin-Watson stat	1.659443	F-statistic	3.221048	
Log likelihood	9.252488			

The F-statistic (3.22) is low enough ($F_{1,29}(.05=4.18)$) to reject the hypothesis that this regression model explains the variation in the CPUE from 1949 to 1979. However, on the basis of the time trend in CPUE in Table 33 the East Greenland-Iceland fin

whale stock could have declined by as much as 20 per cent between 1949 and 1979 (using the slope from Table 33, $e^{-0.0066896 \times 31} = 0.81$). A decline of this magnitude would be consistent with a K well below 6,500 as can be seen in Table 20.

5.3.1 CATCH PER UNIT EFFORT IN THE FIN WHALE FISHERY JUNE 10 TO JULY 10

CPUE data for the whole season lasting from June 1 to the end of September have not been used in recent years. In addition, at the June 1978 IWC meeting the Scientific Committee selected search time as a better effort measure than boat days worked or total hours worked (Zahl (1982) p.809). Whole season CPUE indexes now invariably rely on such search measures for effort. The procedure outlined above must be refined to meet this more exacting standard.

As an alternative to using a whole season, a CPUE measure for the peak of the season (June 10 to July 20) is developed. This allows a more refined CPUE relationship for the fin whale fishery. The rationale for using the June 10 to July 20 time frame is that outside of this "peak" period there are disturbances to the catch effort relationship arising from opportunistic catches of other whale species.

Sigurjonsson and Rørvik (1983) provide these detailed data on the peak catch and search effort in the fin whale fishery between 1951 and 1981. The total time spent searching and handling fin

whales by each catcher boat from June 10 to July 20 is given in Table 34 together with the fin whales caught.

Table 34

The Number of Hours Used for Searching and Handling the First Fin Whale and Searching for the Second From June 10 to July 20 by Boat.

Boat	SEARCH EFFORT		CATCH RESULTS		
	Average Fin Hours	Standard Deviation	Average Total Number of Fin Whales Killed	Standard Deviation	Period
1	354.25	87.03	24.25	6.29	1951-54
2	N/A	N/A	N/A	N/A	
3	315.71	52.3	36.29	9.76	1954-60
4	346.11	69.55	31.11	10.40	1952-60
5	300.20	28.12	36.20	10.50	1956-60
6	286.40	52.11	34.50	8.25	1962-81
7	305.30	54.66	34.00	7.39	1962-81
8	295.50	48.49	33.05	8.33	1962-81
9	317.44	61.73	35.00	8.57	1966-81
Mean	301.16	54.22	34.14	18.14	1962-81

The data in Table 34 show that the operation of a whale catcher from June 10 to July 20 involves searching and handling at approximately 300 hours. Detailed time budgets for trips by vessels 7, 8 and 9 are provided in Table 22 in chapter 4 for this period. Overall, the catchers take a series of trips lasting approximately 45 hours. Each trip involves steaming to the grounds for 15+ hours. Once on the grounds the catcher boats search for whales for 11-12 hours. The harvested whales are then towed for 16-17 hours back to the shore station. During the peak

period the boats stop for less than 2 hours between trips in port. The number of fin whales harvested per catcher from June 10 to July 20 in the 1962-81 period averages between 33-35 whales with a standard deviation of 8-10 whales.

The coverage of catcher boats in the dataset of Table 34 after 1965 is 100% of the fleet. For this reason, the data seem to be comprehensive. However, there are fundamental methodological problems associated with taking a window of 41 days out of a 120 day season and using it to evaluate abundance. The problem is that while the peak of abundance in the season may occur regularly in a 41 day window, that window is not temporally stable from year to year. Hence one is sampling from a different fraction of the abundance distribution in different years. The actual timing of the peak period is a source of noise unrelated to any changes in overall abundance.

In Figure 23 the fraction of the annual fin whale catch taken in the fixed 41 day window is plotted. The fraction of the annual catch of fin whales taken from June 10 to July 20 ranges from a high of 82 percent to a low of 38 per cent. The absolute peak of fin whale abundance can therefore be expected to occur with less regularity within the June 10 to July 20 window than a peak season concept would imply. One virtue of using CPUE for the whole season is that the whole annual abundance distribution is sampled.

FIGURE 25

The Fraction of the Annual Fin Whale Catch Taken June 10 to July 20

To analyze the dataset in Table 34 the CPUE relationship implied by the Gordon-Schaefer model is used to run linear regressions for each catcher. Briefly, catch, Y , is assumed to be directly proportional to the stock, X , the effort level, E and a catchability coefficient k . That is, $Y = kEX$. Biomass is assumed to grow as $F(X) = rX(1-X/K)$, where r is the intrinsic growth rate and K the pristine stock level. Equating Y to $F(X)$, to get a sustained yield equilibrium relationship, and solving gives $Y = kKE(1-kE/r)$. The CPUE relationship is $Y/E = kK - (k^2KE/r)$ which can be written as $Y/E = a - bE$, where $a = kK$ and $b = k^2K/r$.

The equilibrium condition used to derive the regression model above cannot be expected to be true in general. Hence the regression model is not expected to perform well. However, the purpose of the regression work is to look at CPUE by boat and explore how sensitive the CPUE relationship is to outside disturbances.

Two disturbances are considered. First, the change in delivery time from 30 to 28 hours in 1979 is taken as a structural shift in the data that cannot be adequately adjusted for unless one knows the true relationship between CPUE and stock abundance (Cooke (1985)). The reduction in delivery time reduces the search range of the catchers by approximately 20 nautical miles and thus increases the likelihood that fin whales can stay out of range.

To test for this structural shift hypothesis we dummy CPUE regressions with D which is 0 prior to 1978 and 1 after. Secondly, the number of sperm whales caught by each boat in the

June 10-July 20 period is included as an explanatory variable for the CPUE for fin whales. The results are presented in Table 35.

Table 35

The Catch Per Unit Effort Regressions for the First and Second Fin Whale June 10 to July 20.

CPUE Boat	Constant	Effort (Hours)	Sperm Catch (No. of Whales)	$\bar{R}^2$	Period Covered
3	0.327 (4.37)	-0.000859 (2.25)		0.41	1954-60
4	0.310 (4.38)	-0.000556 (2.77)		0.45	1952-60
6	0.5003 (7.08)	-0.00172 (4.47)	0.0459D (1.64)	0.56	1962-81
6	0.507 (8.84)	-0.00152 (4.62)	-0.00651 (3.38)	0.69	1962-81
7	0.368 (8.87)	-0.00093 (4.88)	0.00081D (0.03)	0.54	1962-81
7	0.374 (10.0)	-0.00089 (5.08)	-0.00422 (1.79)	0.61	1962-81
8	0.38015 (7.43)	-0.00106 (4.30)	0.0541D (1.86)	0.58	1962-81
8	0.393 (7.93)	-0.00098 (3.65)	-0.00485 (1.78)	0.58	1962-81
9	0.3968 (7.37)	-0.00108 (4.39)	0.043D (1.58)	0.57	1966-81
9	0.401 (9.83)	-0.000939 (4.86)	-0.01326 (3.69)	0.75	1966-81

The coefficient on D for catchers 6, 8 and 9 is positive but not significant, but the t-statistics are over 1.5. This gives

tentative support to the structural shift after 1978 hypothesis. More important is that the inclusion of sperm whale catches explains a significant amount of the CPUE in the fin whale fishery for catchers 6, 7, 8 and 9. The strongest effect from sperm whales is for catchers 6 and 9.

These regressions show that the fin CPUE data for June 10 to July 20 are subject to structural bias and outside influences like sperm whale abundance. Therefore this CPUE dataset should be used with care to evaluate fin whale abundance.

5.3.2 CATCH PER UNIT EFFORT FOR THE FIRST FIN WHALE CAUGHT IN THE JUNE 10-JULY 20 TIME PERIOD

Discussions of the dataset in Table 34 in the Baleen Whale Committee at the International Whaling Commission focused on the definition of the fin whale season. Specifically, scientists wanted to focus on the prime fin whale season portion from June 10 to July 20. A further refinement on the catch process is that once the first fin whale is found the search is considered over. The justification for this is that fin whales move in schools of several animals and schools tend to be clumped together. Sigurjonsson and Gunnlaugsson (1985) provide this data set for whale catchers 6,7,8 and 9. This data set is summarized in Table 36.

Table 36

Catch and Effort Data for the First Fin Whale From June 10 to July 20.

Boat	Average First Fin Hours	Standard Deviation	Average Number of Fin Whales Killed	Standard Deviation	Period
6	209.75	50.27	19.12	4.11	1962-85
7	213.33	45.72	18.81	3.34	1962-82
8	227.08	48.15	18.44	3.51	1962-86
9	228.81	54.76	19.52	3.62	1966-86

The data in Table 36 makes it clear that operating a catcher from June 10 to July 20 involves harvesting approximately 20 "first" fin whales from June 10 to July 20.

The catch and effort data for the first fin whale from Table 36 was subjected to the same regression analyses as the dataset from Table 34. The structural shift in CPUE caused by the decrease in delivery time from 30 to 28 hours after 1978 and the effect of sperm whale catches are again investigated. The results are shown in Table 37.

Table 37

The CPUE Regressions for the First Fin Whale June 10 to July 20.

CPUE Boat	Constant	Effort (Hours)	Sperm Catch (No of Whales)	$\bar{R}^2$	Period Covered
6	0.2183 (12.44)	-0.000587 (7.52)	0.0010D (1.24)	0.74	1962-85
6	0.2263 (16.65)	-0.000546 (8.29)	-0.0025 (3.85)	0.84	1962-82
7	0.2024 (11.26)	-0.0005123 (6.43)	-0.00096D (0.10)	0.69	1962-82
7	0.198 (13.16)	-0.000472 (6.62)	-0.0014 (1.90)	0.74	1962-82
8	0.2098 (14.37)	-0.0005501 (9.02)	0.00566D (0.91)	0.78	1962-86
8	0.214 (13.8)	-0.00055 (7.43)	-0.00082 (1.14)	0.80	1962-82
9	0.18802 (10.41)	-0.000426 (5.86)	0.00032D (0.04)	0.65	1966-86
9	0.17148 (10.90)	-0.000307 (4.15)	-0.00502 (2.81)	0.76	1966-82

The regressions reported in Table 37 are better fits than those reported in Table 35. The last sperm whale season was 1982. Catchers 6 and 9 show a statistically significant disturbance on fin CPUE from sperm whale catches.

To investigate whether there is a significant negative time trend in CPUE for the first fin whale after one accounts for disturbances from sperm whale catches and shorter delivery times a stepwise regression approach was applied to the dataset in Table

35. In summary, time trend is never significant if effort is included in the regressions. However if effort is excluded and CPUE is regressed on sperm whale catches and the shorter delivery time dummy for seasons after 1979 then adding a time trend improves the fit at the 5 per cent level for vessels 6 and 7. For vessels 8 and 9 the addition of time is significant at the 10 per cent level. The detailed results are provided in Annex B.

The time trend in CPUE for the first fin whale can be used as an index of relative abundance for the fin whale stock. If vessels 6-9 are combined the stock is approximately 96 per cent of its 1966 size in 1982. The decline varies somewhat by vessel. For vessel 6 the stock is 90 per cent of its 1962 size in 1985, vessel 7 shows 93 per cent of 1962 in 1982, 8 is 94 of 1962 in 1986 and 9 is 94 of 1966 in 1986. The first fin whale CPUE data indicates that the stock as a whole may have declined by as much as 5-10 per cent in the last 20-30 years.

The dataset in Table 34 is used to construct an aggregate effort series, of "adjusted hours" used to search and handle the first fin whale and search for the second fin whale from June 10 to July 20, 1948 to 1981. The "adjusted hours" are determined by using the mean of the effort series for each boat for the missing years in operation. The data for the first 5 catchers are incomplete as can be seen from Table 34 since they operated only from 1948 to 1961. For catcher #2 no data are available. The mean of catcher #4 is used as a proxy for vessel #2 since they are closest in efficiency according to Rørvik et al (1976). The

search hours were standardized using boat factors calculated by Rørvik et al (1976). From 1966 to 1981 the coverage of effort is complete.

The catch per unit effort in the constructed June 10 to July 20 series for 1948-1981 shows a significant but small negative trend (Table 38).

Table 38

LS // Dependent Variable is FINCPUE
SMPL range: 1948 - 1981
Number of observations: 34

VARIABLE	COEFFICIENT	STD. ERROR	T-STAT.	2-TAIL SIG.
Constant	0.7031336	0.0577397	12.177639	0.000
E (Hours)	-0.0004736	6.542E-05	-7.2393967	0.000
R-squared	0.620893	Mean of dependent var	0.291768	
Adjusted R-squared	0.609046	S.D. of dependent var	0.095557	
S.E. of regression	0.059748	Sum of squared resid	0.114234	
Durbin-Watson stat	1.752488	F-statistic	52.40886	
Log likelihood	48.58576			

The catch per unit effort (CPUE) in the Icelandic fin whale fishery was studied by Rørvik et al (1976), Rørvik (1980), Rørvik and Sigurjonsson (1981), Cooke and Beddington (1981), Sigurjonsson and Gunnlaugsson (1985) and Harding (1985). There is general consensus in published work that the CPUE in the Icelandic fin whale fishery is either declining or constant over the period 1962-81. The CPUE of the aggregate effort series published by van Beek (1983) are shown in Table 39. The van Beek series is corrected for catcher efficiency differences from 1962 to 1965,

but uncorrected thereafter. The data originate from Sigurjonsson and Rørvik and is for June and July. The CPUE regression again shows a small but significant negative coefficient on the effort series.

Table 39

LS // Dependent Variable is CPUE

SMPL range: 1962 - 1980

Number of observations: 19

VARIABLE	COEFFICIENT	STD. ERROR	T-STAT.	2-TAIL SIG.
Constant	0.3787632	0.0367907	10.295079	0.000
E (Hours)	-0.0001840	3.491E-05	-5.2719504	0.000
R-squared	0.620480	Mean of dependent var	0.190888	
Adjusted R-squared	0.598156	S.D. of dependent var	0.062864	
S.E. of regression	0.039850	Sum of squared resid	0.026997	
Durbin-Watson stat	1.919423	F-statistic	27.79346	
Log likelihood	35.32668			
obs	CATCH	E (Hours)		
1962	160	721		
1963	156	683		
1964	112	984		
1965	180	576		
1966	226	767		
1967	198	1,003		
1968	193	868		
1969	197	1,179		
1970	203	784		
1971	169	1,440		
1972	162	1,172		
1973	192	1,293		
1974	182	1,379		
1975	202	828		
1976	206	1,055		
1977	98	959		
1978	188	1,479		
1979	224	940		
1980	215	1,288		

Rørvik et al (1976) were hesitant to use CPUE to make inferences on stock size trends. They used, among other data, weather corrected data from catcher boat 7 during June and July, 1962 to 1972. They concluded that "the number of fin whales caught in June and July, per estimated hour used for searching and hunting still shows great yearly variations which cannot be caused by variations in the stock size" (Rørvik et al (1976) p. 21).

The CPUE model suggests that the aggregate stock may be declining since increased effort leads to marginally lower catches, i.e., $\partial \text{CPUE} / \partial E$ is negative. The negative $\partial \text{CPUE} / \partial E$ was insignificant in the CPUE series for June 1 to September 20 but became significant in the two CPUE series in the June 10 to July 20 window. The analysis of the two June 10 to July 20 CPUE series showed that the abundance in that time frame seemed to fluctuate somewhat independently of the annual abundance level. This would seem to counsel caution in interpreting a significant negative coefficient on $\partial \text{CPUE} / \partial E$ in the window as evidence of a general decline in the stock.

The CPUE in a fixed area on a migration run of fish such as salmon or tuna is expected to decline a priori away from the peak of the run. The CPUE for fin whales will have this same property. Thus if the June 10 to July 20 period is not peak in some seasons then the CPUE will be lower than otherwise expected.

However, there may be other reasons for this decline in CPUE, including capital depreciation, changes in decision making,

exogenous effects due to poor weather at peak catching times and so forth.

In summary, the CPUE model is not a reliable method in itself for predicting stock abundance changes in whales. The analysis of the fin CPUE data showed that for the whole season CPUE is stable. The two June 10-July 20 fin CPUE datasets were shown to have significant disturbances from catches of other species and the shifting temporal peak of the fin whale season.

5.4 THE ANNUAL FIN WHALE CATCH AND LENGTH OF CATCH DISTRIBUTIONS

In this section the physical properties of caught fin whales are studied. The physical properties of the catch can be expected to yield some insights into the exploitable population. For example, declining catches with increasing length at age would indicate that the stock was declining. We expect that as the fin whale stock approaches carrying capacity food scarcity will decrease length at age.

ANNUAL FIN WHALE CATCHES

The frequency distribution of fin whale catches by all catchers from 1948 to 1981 is given in Table 40. The mean catch per year is 241.82 fin whales and the standard deviation is 48.73.

Table 40

Number of Fin Whales Killed Per Year in the Icelandic Fin Whale Fishery.

range: 1948 - 1981

Number of observations: 34

Series	Mean	S.D.	Maximum	Minimum
Fin whales	241.82	48.73	348	142
INTERVAL	COUNT	HISTOGRAM		
120 >= FIN < 150	2	*****		
150 >= FIN < 180	3	*****		
180 >= FIN < 210	4	*****		
210 >= FIN < 240	8	*****		
240 >= FIN < 270	7	*****		
270 >= FIN < 300	6	*****		
300 >= FIN < 330	3	*****		
330 >= FIN < 360	1	*****		

The distribution of catches is approximately normal. The χ^2 test for goodness of fit for the normal distribution at the 1% level is the probability that $(15.1 < \chi^2 < \infty) = 0.01$. The calculated χ^2 statistic is only 2.25, hence one cannot reject the hypothesis that the distribution of yearly catches in Table 40 is normal at the 99% level of significance.

THE LENGTH DISTRIBUTION OF FIN WHALE CATCHES

The study of length distributions of fin whale catches is potentially useful as an indicator of over-exploitation of the stock. If the average length of fin whales caught is becoming shorter over a long period of time, then the stock is being fished down, other things being equal.

However, complications sometimes arise since whale populations are often segregated by length. Rørvik et al (1976), for example, have observed that the fin whale stock off Iceland is segregated by length:

"Fin whales caught east of 27°W had a clear tendency to be shorter than those caught west of 27°W . This is particularly pronounced for the Western ground where large catches have been taken on both sides of 27°W " (Rørvik et al (1976) p.13).

"The mean length in catches east of 27°W do not show any significant north south segregation. When comparing the mean lengths in the catches west of 27°W , it is clear that the mean lengths from the Northern ground are larger than those from the Western ground during the whole season, especially for females in July and August. Although there are few catches, it appears that the mean lengths on the southern ground west of 27°W are more like the corresponding mean lengths from the Northern ground than the Western ground" (Rørvik et al (1976) p.15).

Martin (1983) confirmed the length segregation findings of Rørvik et al. Martin concluded that:

"In males, and in females as a whole, the proportion of larger animals is higher at the beginning and end of the season than in July and August. This may be due to large animals passing in a north or northwesterly direction to feeding grounds probably out of range of the Icelandic catcher boats then returning, many weeks later through the Denmark Strait on their way southward" (Martin (1983) p.334).

The length distribution of the female and male fin whale catches by sex from 1937-39 and 1949-84 are provided in Figure 24 and Figure 25.

The average length of catches of both sexes of fin whales for 1937-39 and 1949-84 are provided in Figure 26. The average length of the fin whale catches has a spike in 1968. The average length for both sexes fluctuates randomly from 1949-84 with no apparent

trend over this period. From 1949-53, steep declines are registered for both sexes. However, from 1953 to 1968 the average length increases. The periods from 1949-53 and 1968-84 are arguably consistent with a heavy fishing hypothesis. However, the 1953-68 length increase could point to environmental factors as being important. Martin(1983) concludes that:

"There can be little doubt that year-to-year fluctuations in both the corrected and uncorrected mean catch length of this species are not solely due to the influence of the Icelandic catching operations. Sea temperature and the abundance of food, either in the Denmark Strait itself or to the south of Iceland, are likely to be important factors in determining the abundance and size distribution of fin whales on the grounds" (Martin(1983) p.334).

FIGURE 24

**Length Distribution of Fin Females
Harvested 1937-39 and 1949-84**

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FIGURE 25

**Size Distribution of Male Fin Whales
Harvested 1937-39 and 1949-84**

FIGURE 26

Length of Fin Whales Killed by Sex 1937-39 and 1949-84

Cooke (1984) explicitly studies the effects of depletion on the length distribution of baleen whale catches in a theoretical simulation model. His analysis suggests that depletion alone will not change the mean length of catches significantly unless the stock is close to extinction. This is especially true for the case where biological parameters are invariant to the state of the stock. In this case, the age of sexual maturity, natural mortality and the pregnancy rate are not allowed to change as the stock is reduced to a low level. However, if the pregnancy rate alone is allowed to increase from 0.35 to 0.50 with a decrease in the stock size, Cooke (1984) finds a 3 per cent decline in the mean length of the catch. This decline in length was significant at the 95 per cent level for an annual harvest of 200 whales that reduced the stock to one quarter of its pristine level in 20 years. Even more importantly, if age of maturity, pregnancy rate and natural mortality all change simultaneously as the stock departs from its pristine value, then, according to Cooke (1984), one should expect to receive a significant warning of depletion from the length distribution data.

Cooke (1984) cautions that if the catch is concentrated to a restricted range of ages or size classes, one should not expect to pick up the effects of exploitation on the length distribution of the catch. Indeed, the length distribution data from the Icelandic fin whale catch is from a restricted range (fin whales over 50 feet). For all these reasons, then, the length data is

noisy and do not give a clear signal of the health of the stock. Portions of the data are consistent with an hypothesis of either a growing or a declining whale stock. Other methods are needed to pronounce on the health of the stock. We turn to the analysis of data on the search for fin whales.

5.5 WHALE SCHOOL HARVESTING DATA

The number of fin whale schools from which fin whales were harvested between early June and late September is known in detail for years 1951 to 1983 (Sigurjónsson and Gunnlaugsson (1985) p.109). These data are shown in Table 41. The distribution of the number of schools in Figure 27 shows considerable variation.

The raw data are shown in columns 2 and 3 in Table 41. The number of fin schools and the mean size of schools show that the actual number of schools harvested has ranged from a low of 40 in 1962 to a high of 270 in 1974. The trend in the number of schools harvested has increased through time because the coverage of catchers was incomplete prior to 1967. For this reason the data have to be adjusted.

The derived number of schools is shown in column 7, Table 41. The schools in column 7 are determined using the average number killed per school in 1967-83 to derive the number of schools that would have had to be encountered to produce the observed harvest levels. To get a reference level on the number of schools available in the fin whale stock, the population simulation in Figure 10 from Chapter 3 and average school size were used to

predict the number of schools in existence. This was done by dividing the average number of animals per school into the total population. The result of this calculation was that the number of schools in the fin stock was found to range between 3,372 and 4,874. These values are shown in the last column of Table 41.

The distribution of the average number of fin whales per school harvested from in Figure 28 ranges from 1.8 to 2.7. It seems clear that the average number of fin whales per school is 2+.

The distribution of the adjusted school data from Table 41 column 7 is as follows:

FIGURE 27

The Number of Fin Whale Schools Harvested
From 1951 to 1983

Table 41

Calibrating the Fin School Data to get the Total Number of Schools

Year	RAW SCHOOL DATA							Number of Fin Schools
	Search of Fin Hours	Number of Fin Schools	Mean School Size	Fin Whales Landed	Fins Killed @School	Schools Killed From	Total Number of Fins	
1948	895	0	0	195		173	8980	4257
1949	895	0	0	249		221	9020	4276
1950	938	0	0	226		200	9002	4267
1951	882	110	2	312	2.836	276	9009	4505
1952	955	194	2.289	224	1.154	198	8920	3897
1953	956	131	2.084	207	1.580	183	8922	4281
1954	1239	79	1.835	177	2.241	157	8944	4874
1955	898	61	1.131	236	3.869	209	9004	4268
1956	908	0	0	265		235	9002	4267
1957	793	81	2.222	348	4.296	308	8981	4042
1958	861	76	2.513	289	3.803	256	8869	3529
1959	984	43	2.615	178	4.140	158	8817	3372
1960	801	43	1.93	160	3.721	142	8891	4607
1961	917	40	2.125	142	3.550	126	8980	4226
1962	776	77	2.455	303	3.935	268	9088	3702
1963	795	83	2.193	283	3.410	251	9021	4114
1964	859	52	1.942	217	4.173	192	8977	4623
1965	641	145	2.172	289	1.993	256	9005	4146
1966	595	0	0	310		275	8960	4247
1967	614	237	2.456	239	1.008	237	8886	3618
1968	716	202	2.386	202	1.000	202	8880	3722
1969	929	249	2.337	251	1.008	249	8915	3815
1970	551	270	2.552	272	1.007	270	8899	3487
1971	1213	208	2.188	208	1.000	208	8869	4053
1972	987	230	2.513	238	1.035	230	8908	3545
1973	968	236	2.267	267	1.131	236	8911	3931
1974	1072	270	2.193	285	1.056	270	8887	4052
1975	748	232	2.267	245	1.056	232	8844	3901
1976	953	202	2.188	275	1.361	202	8839	4040
1977	847	105	2.4	144	1.371	105	8798	3666
1978	1093	173	2.399	236	1.364	173	8903	3711
1979	826	189	2.593	260	1.376	189	8912	3437
1980	778	171	2.064	236	1.380	171	8891	4308
1981	651	251	2.45	254	1.012	251	8897	3631
1982	0	193	2.606	194	1.005	193	8885	3409
1983	0	142	2.254	144	1.014	142	8940	3966

Table 42

range:	1948	-	1981
Number of observations: 34			
=====			
Series	Mean	S.D.	Maximum Minimum
=====			
SCHOOLS	214.97059	47.484278	308.00000 105.00000
=====			
INTERVAL	COUNT	HISTOGRAM	
=====			
90 >= SCHOOLS < 120	1	****	
120 >= SCHOOLS < 150	2	*****	
150 >= SCHOOLS < 180	5	*****	
180 >= SCHOOLS < 210	9	*****	
210 >= SCHOOLS < 240	6	*****	
240 >= SCHOOLS < 270	6	*****	
270 >= SCHOOLS < 300	4	*****	
300 >= SCHOOLS < 330	1	****	
=====			

The school data indicates that killing two fin whales from the same pod/school would not be common. Of the 2+ animals per school only one would represent a legal kill. The other whales in the school would typically be lactating females or young animals under the 55' size limit (50'-55' animals can be taken for local consumption only).

FIGURE 28

The Average Number of Fin Whales Per
School Harvested From 1951 to 1983

CONCLUSION

The description of geographic distribution of the fin whales and the location of the whaling grounds is a necessary background for theoretical modeling of the searching process. The description of the operating characteristics of the catchers is also needed for that purpose.

CPUE is the most commonly used index of relative abundance in whale stock assessments. The CPUE index for the fin whale fishery is highly variable especially if it is only measured for the June 10 to July 20 period. Disturbances from sperm whale catches impact significantly on fin whale CPUE in that period. The time trend in the CPUE index for the first fin whale 1962-1986 indicates that the stock may have declined by 5-10 per cent in 24 years.

The annual catches of fin whales are consistent with a sample drawn from a normal distribution which is supportive of a stable stock. The time trend in the annual CPUE data, although not very statistically significant, indicates that the fin whale stock declined by as much as 20 per cent between 1949 and 1979. The analysis of length data provides inconclusive evidence on stock status.

The number of schools harvested from and the mean school size is available from 1951 to 1983. Enough search data exists to make empirical modeling of the search process feasible. This is our task in Chapter 6.

CHAPTER 6: MODELING THE SEARCH PROCESS: THEORY

Our task is to model the harvesting of fin whales as described in Chapter 5. We will proceed by reviewing the theoretical aspects of search theory and tailoring a model to the search data reviewed in Chapter 5.

Whaling off the west coast of Iceland involves intercepting fin whale schools on their migration north to summer feeding grounds. In the jargon of search theory, the whale problem involves independent searchers looking for many moving targets.

Modern mathematical search theory was developed during World War II to fight German "Wolf pack" submarines in the North-Atlantic (Koopman (1980)). Non-military applications of search theory are a more recent development (Haley and Stone (1979)). The literature on the application of search theory in fisheries has been developed by Mangel (1982), Mangel and Clark (1983), and Mangel and Beder (1985). An embellished version of the model developed by Mangel and Beder (1985) will be applied directly to the harvesting of fin whales off the west coast of Iceland. The binomial model in Mangel and Beder (1985) is well known in the context of census plots of animal populations (Seber (1982) p. 22).

In modeling the search for whales we make the following standard assumptions:

1. The search process involves the search for discrete schools.
2. Catchers search randomly, or alternatively, the times between detections are independent, exponentially distributed random variables. The distribution of times between detections changes due to search.
3. The entire school of harvestable whales is fished out when it is found by a whale catcher.

These assumptions hold approximately in the fin whale fishery. The fishery involves a search for pods/schools of whales. All whales above 55 feet in a detected pod are taken provided it is legal to kill them. The time between detecting pods/schools is random and can be assumed to be an independent drawing from a given population distribution.

Following Mangel and Beder (1985), the search model is a Poisson process, where the whale stock is randomly distributed over the available fishing ground. λ is assumed to be the number of whale schools found per basic time unit when none of the whale stock have been caught. As the number of whales caught increases, the thinning of the whale stock decreases the probability of finding a whale. The rate at which the number of whales caught declines per unit of time is assumed to be c so that after whales have been caught λ declines by a factor of nc , where n is the number of whales harvested thus far. The search for a fin whale school is therefore modeled as:

$$(1) \text{ Prob}\{\text{find another school in the next } \Delta t | n \text{ were found thus far}\} = (\lambda - n\epsilon)\Delta t$$

$$\text{Prob}\{\text{do not find another school in the next } \Delta t | n \text{ were found thus far}\} = 1 - (\lambda - n\epsilon)\Delta t$$

The two parameters λ and ϵ now have to be estimated. In the poisson search process λ becomes the mean rate of detection of schools and ϵ is a search effectiveness parameter. One can solve for the λ by assuming that N schools are present initially and using the independence assumption. In particular N/A is the probability of finding a school in any unit space, Wv is the number of spaces searched in a unit of time. Hence the mean rate of detection λ is given by:

$$(2) \quad \lambda = N \frac{Wv}{A}$$

where: W =search width of the catcher boat
 v =the speed of the catcher
 A =the area of water where the schools may be located at the time of the search effort.

Since λ is the mean rate of detection, (2) says that the schools are distributed with one school in every A/N square nautical miles on average. When the first school has been detected there are $(N-1)$ schools left and therefore the new rate of detection per unit of time will be $\lambda = [(N-1)Wv/A] - \epsilon$ and solving for ϵ yields:

$$(3) \quad \epsilon = \frac{Wv}{A}$$

where ϵ is a measure of searchability which gives the fraction of the area searched per basic time unit. Mangel and Beder (1985) thus have a searchability parameter that is independent of either the stock or the catch data being analyzed.

ϵ is an interesting generalization of the "law of random search", $p = 1 - e^{-WL/A}$ (Koopman (1980) pp. 71-79), where A is area to be searched, W effective search width and L the total length of search path in A ($L = vt$). If there are k searchers present that search independently, (1) is modified by replacing $(\lambda - n\epsilon)\Delta t$ by $k(\lambda - n\epsilon)\Delta t$.

Consider a population of $N = \lambda/\epsilon$ schools in which n schools have already been detected (and removed without replacement). Then the $P(\text{detection of a school in the next } \Delta t | \text{no new school has been detected in } t)$ is $k(\lambda - n\epsilon)\Delta t$. Thus, $P(\text{no detection in } \Delta t | n \text{ detected so far})$ is $1 - k(\lambda - n\epsilon)\Delta t$. Since the probability of successive detections is independent, then

$$\begin{aligned} (4) \quad & P(\text{no detection in } t + \Delta t | n \text{ so far}) \\ &= P(\text{no detections in } t | n \text{ so far}) * P(\text{no detection in } \Delta t | n \text{ so far}) \\ &= P(\text{no detections in } t | n \text{ so far}) * [1 - k(\lambda - n\epsilon)\Delta t] \end{aligned}$$

Equivalently,

$$P(\text{ND in } t+\Delta t|n) = P(\text{ND in } t|n) * [1 - k(\lambda - n\epsilon)\Delta t]$$

$$P(\text{ND in } t+\Delta t|n) - P(\text{ND in } t|n) = -k(\lambda - n\epsilon)\Delta t * P(\text{ND in } t|n)$$

$$\frac{P(\text{ND in } t+\Delta t|n) - P(\text{ND in } t|n)}{\Delta t} = -k(\lambda - n\epsilon) * P(\text{ND in } t|n)$$

$$P'(\text{ND in } t|n) = -k(\lambda - n\epsilon) * P(\text{ND in } t|n)$$

$$\frac{P'(\text{ND in } t|n)}{P(\text{ND in } t|n)} = -k(\lambda - n\epsilon)$$

Integrating both sides with respect to t yields:

$$(5) \quad \int \frac{P'}{P} dt = \int -k(\lambda - n\epsilon) dt$$

$$\log P = -k(\lambda - n\epsilon)t + c$$

$$P(\text{ND in } t|n) = Ae^{-k(\lambda - n\epsilon)t}, \quad A = e^c$$

Now we can use the fact that $P(\text{ND in } 0|n) = 1$ so $A = 1$, therefore:

$$(6) \quad P(\text{ND in } t|n) = e^{-k(\lambda - n\epsilon)t}$$

For a population of size $(N-n)$ where each member (pod/school) is assumed to be equally likely to be detected we have:

$$(7) \quad P(\text{ND in } t|n) = P(\text{schools } 1, 2, \dots, N-n \text{ are not detected in } t|n) \\ = P(\text{school } 1 \text{ ND in } t|n) * P(2 \text{ ND in } t|n) * \dots * P(N-n \text{ ND in } t|n)$$

$$N-n$$

$$P(\text{ND in } t|n) = \prod_{i=1}^{N-n} (P \text{ school } i \text{ ND in } t|n)$$

Now by the independence assumption on the probability of detecting (or not detecting) individual schools we have:

$$(8) \quad P(\text{school } i \text{ ND in } t|n) = P(\text{school } j \text{ ND in } t|n), \text{ for } i \neq j = 1, \dots, N-n$$

It follows that the probability of detecting any individual school is:

$$(9) \quad P(\text{any individual school ND in } t|n) = \left[P(\text{ND in } t|n) \right]^{\frac{1}{N-n}}$$

Noting that $\frac{1}{N-n} = \frac{1}{(\lambda/\epsilon)-n} = \frac{\epsilon}{\lambda-n\epsilon}$ we have:

$$(10) \quad P(\text{any individual school ND in } t|n) = \left[e^{-k(\lambda-n\epsilon)t} \right]^{\frac{\epsilon}{\lambda-n\epsilon}}$$

$$P(\text{any individual school ND in } t|n) = e^{-k\epsilon t}$$

It is important to note that (10)' is independent of n .

Considering a search for any school out of all schools (N in total) as a "trial" in the sense that each is equally likely to be subject to discovery leads to a binomial distribution with parameters $N = \lambda/\epsilon$, $q = e^{-k\epsilon t}$ and $p = 1 - e^{-k\epsilon t}$. The probability of k searchers discovering n schools in t can be written as:

$$(11) \quad \text{Prob}(k \text{ searchers discover } n \text{ schools in } t) = p(k, n, t, \epsilon)$$

$$= \binom{\lambda/\epsilon}{n} (1 - e^{-k\epsilon t})^n (e^{-k\epsilon t})^{((\lambda/\epsilon) - n)}, \quad n = 1, \dots, \lambda/\epsilon$$

$$= 0$$

otherwise

This result is based on the argument of random, independent times between detections that leads to the exponential distribution. The logical extension of counts to the Poisson is approximate since N is assumed to be finite. However, with N large relative to $1-e^{-k\epsilon t}$ this approximation is justifiable.

The expected number of schools discovered $E_t(n)$, and the variance in the number of schools discovered, $V_t(n)$, in the interval $(0,t)$ are given by:

$$(12) \quad E_t(n) = \frac{\lambda}{\epsilon} (1-e^{-k\epsilon t})$$

$$V_t(n) = \frac{\lambda}{\epsilon} (1-e^{-k\epsilon t}) e^{-k\epsilon t}$$

The ratio λ/ϵ can be interpreted as the initial number of schools and t refers to search time hours only.

The properties of this model can be explored by solving (12) for parameter values based on the dataset in Table 41 and the range of actual search times. The expected number of schools discovered, $E_t(n)$, for $\lambda=0.16$ and 0.18 with $\epsilon=0.000735$ (the derivation of the values for λ and ϵ is discussed below) and t ranging from 500 to 1450 are plotted in Figure 29. The value of $E_t(n)$ is flat over this range of t with a range of 165-215 school harvested from for $\lambda=0.16$ and 190-240 for $\lambda=0.18$. The number of schools killed from in Table 41, column 7 ranges from 126 to 308.

The value of λ can be increased for a given c to show the effect on $E_t(n)$ from a larger population. This is done in Figure 30 for $t=650$ and $t=1000$.

For a Poisson process $c=0$ and $\lambda=n/T$, the number of encounters per period of time. Mangel and Beder (1985) give two maximum likelihood estimators of λ given that $c \neq 0$. The estimator best suited to the data in Table 41 fixes the number of schools discovered in variable time.

Suppose that n schools were discovered previously and that T_i is the additional time needed to discover the i -th school once the i -1st school is found. The total search time used to discover n schools is $T = \sum_{i=1}^n T_i$. The search model in equation (1) assumes that the time between encounters $\tilde{T}_i$ is a random variable that is exponentially distributed. The time between the $(i-1)$ st and i -th encounter would have the parameter $\lambda - (i-1)c$. The $\tilde{T}_i$, $i=1, \dots, n$ are independent but not identically distributed random variables. The likelihood function, $\mathcal{L}$, of the set $\{T_1, \dots, T_n\}$ is

$$(13) \quad \mathcal{L} = \prod_{i=1}^n (\lambda - (i-1)c) e^{-(\lambda - (i-1)c)T_i}$$

The maximum likelihood estimator for λ is found by taking the derivative of the logarithm of $\mathcal{L}$.

FIGURE 29

The Expected Number of Schools at Lambda Values (Epsilon=0.000735)

FIGURE 30

The Expected Number of Schools Harvested From

$$(14) \quad \frac{\partial}{\partial \lambda} \log \mathcal{L} = \sum_{i=1}^n \left\{ \frac{1}{\lambda - (i-1)\epsilon} - T_i \right\}$$

Solving (14) by setting the right hand side equal to zero gives a n-th order equation:

$$(15) \quad \sum_{i=1}^n \frac{1}{\lambda - (i-1)\epsilon} = T$$

When ϵ is small equation (15) can be solved for λ as a power series in ϵ . This yields the following estimator for λ (Mangel and Beder (1985) p. 152):

$$(16) \quad \lambda = \frac{n}{T} + \left(\frac{n-1}{2} \right) \epsilon - \frac{(n^2-1)T\epsilon^2}{12n} + \epsilon^3(0)$$

where λ is the number of schools encountered per period of time, n the number of schools killed from in a season, T the total search time and ϵ the fraction of the area searched.

The estimator of λ in (16) uses the actual n and T to set the mean encounter rate λ such that $E(n)=n$. The purpose of using (16) to derive λ is to obtain a conditional distribution for $p(n)$.

The importance of an independent estimate of λ in this study is that it can be used validate the population trends obtained from the biological model in Chapter 3. Historical values for λ lead directly to estimates of n and N in future periods.

6.1 MODELING THE SEARCH PROCESS: EMPIRICAL APPLICATION

The annual data in Table 41 can be used to fit the analytical model. First, the c has to be calculated. The sweep width of the searcher is approximately 1.75 nautical miles (depending on weather, etc.). The vessel cruising speed v ranges from 10.7 to 12.6 knots (Table 30). For the purposes of calculating c , 12.6 knots is used.

The total area A is calculated as 25,358 nautical square miles based on Sigurjónsson ((1988) p.332). This is rounded to 30,000 nautical square miles based on Rørvik et al ((1976) p.10) because they showed fin whale catches distributed over a wider area than Sigurjónsson. The area, A refers here to the size of the area where the harvesting occurs. The stock itself is distributed over a much larger area.

$$c = \frac{12.6 * 1.75}{30,000} = 0.000735$$

The maximum likelihood estimator for λ was calculated using (16) one year at a time. The value of λ fluctuates considerably from year to year in the period 1948 to 1981 as can be seen in Figure 31.

FIGURE 31

Lambda with Epsilon=0.000735

The expected number of schools encountered in area A is calculated using (12) and setting $k=1$ because the effort is in aggregate search hours by all vessels. The expected number of schools encountered is equal to the actual number of schools with a slight negative bias because of the approximation procedure used in deriving (16). More importantly, the variance of the expected number of schools is smaller than the mean (i.e. $e^{-k\lambda t} < 1$).

Mangel and Clark (1986) observe that in a wide variety of resource problems using search theory the variance greatly exceeds the mean (Mangel and Clark (1986) *ibid* p. 7). This is known as the over dispersion problem which limits the usefulness of predictions based on the means of search models. Allen and Punsly (1984) claim that a poor fit is due to too many intervals that are either too short or too long suggesting that vessels hit fishing holes rather than searching randomly in an area (Allen and Punsly (1984) p.306).

The use of actual n and T after the fact to center a distribution on n is not much of a test on the robustness of the search model. However, if the search model performs well for a fixed λ and variable T (which may occur due to weather conditions across seasons for example) it indirectly confirms a non-decreasing population.

To estimate the best λ the period 1966 to 1981 is used since the dataset was not adjusted for missing values in that period. The best λ is selected as the value of λ that minimizes the root mean square error (RMSE) for the period 1966-81. Values between

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0.15 and 0.40 were tried iteratively as constant λ and the RMSE calculated. A λ value of 0.3363 minimized the RMSE for 1966-81.

The $\lambda=0.3363$ is then used to forecast the number of schools harvested. The root mean square percentage error is 12.34 per cent as shown in Figure 32. The constant λ of 0.3363 also performs better than using last years λ and other such naive autoregressive schemes.

INFERENCES ON THE POPULATION

The annual school data are the number of schools harvested from each year. The assumption that the probability of finding any particular fin school at any point in the search area in a given period is the same for all schools led to the binomial distribution for the number of schools harvested. The natural estimate for N , the total number of schools in a closed area, $\hat{N}$ is (Seber (1973) p.22):

$$(17) \quad \hat{N} = \frac{n}{p} = \frac{n}{(1-e^{-\epsilon t})}$$

FIGURE 32

Actual vs. Expected Number of Fin Whale Schools Harvested, $\Lambda=0.3363$

This estimate of N must be adjusted for migration out of the area to provide an estimate of the number of schools in the 30,000 square nautical mile area within the range of the whale catchers. Whether there is a reliable relationship between the number of fin whales in the population and the number in and out of range of catcher operations is not known. However, since the catchers search in blocks of approximately 15 hours in trips of 45 hours, the actual n has to be grossed up for the time absent from the grounds for the schools that would have been harvested (observed) on their migration.

The migration is a continuous flow of whale schools through an area and one has to account for the time not sampling from the flow. This factor was estimated at 0.25 based on the fraction of operating time spent searching, chasing and handling in Table 22, or the catchers are not searching 75 percent of the time that the migration takes place. The 0.25 value is high since it ignores downtime for the vessels during the season. A more complete treatment of these issues can be found in Seber (1973), Nisbet and Gurney (1982) and Zeh et al (1986).

In Table 43 the calculated $\hat{N}$ from 1948 to 1981 using (17) with $n/0.25$ is shown. Column two uses the average number of whales per schools from Table 41 to arrive at an estimate for the number of whales on the grounds each year. The per cent of N subject to harvest is the number of fin whales landed from Table 41 divided by the number of whales estimated to be in the N schools that passed through the grounds each year.

Table 43

Year	Number of Schools N	Number of Whales in N Schools	Percent of N Subject to Harvest
1948	1,356	2,780	5.88%
1949	1,732	3,551	5.88%
1950	1,515	3,105	6.07%
1951	2,196	4,393	5.96%
1952	1,479	3,386	5.51%
1953	1,366	2,847	6.05%
1954	953	1,749	8.14%
1955	1,638	1,853	10.68%
1956	1,822	3,735	5.94%
1957	2,671	5,934	4.97%
1958	2,076	5,216	4.66%
1959	1,148	3,001	4.92%
1960	1,217	2,350	5.76%
1961	968	2,057	5.77%
1962	2,366	5,808	4.43%
1963	2,168	4,755	5.04%
1964	1,561	3,031	6.02%
1965	2,644	5,744	4.32%
1966	3,018	6,187	4.32%
1967	2,536	6,228	3.70%
1968	1,903	4,541	4.29%
1969	1,898	4,434	5.29%
1970	3,169	8,088	3.26%
1971	1,286	2,813	6.74%
1972	1,671	4,198	5.13%
1973	1,742	3,948	5.61%
1974	1,838	4,032	6.21%
1975	2,108	4,779	4.66%
1976	1,509	3,301	5.75%
1977	861	2,067	4.83%
1978	1,159	2,780	5.76%
1979	1,583	4,104	4.39%
1980	1,504	3,105	5.27%
1981	2,559	6,269	3.88%
<hr/>			
Average	1,801	4,005	5.44%
S.D.	579	1,488	1.31%

The first thing to note about the search model results in Table 43 is that the abundance of schools on the grounds

fluctuates between 850 and 3100. The number of whales ranges from a low of 1749 to just over 8000. Secondly, the fraction of $\hat{N}$ harvested averages 5.44 per cent with a S.D. of 1.31.

The search model replicates the observed hunt and predictions of catches based on the model have a RMSE of 12.34 per cent. However to judge the plausibility of the search model it is important to link the results of the search model with those obtained with the biological model in Chapter 3. The prior on the fin whale population from Chapter 3 is reported in the last two columns of Table 41. In short, the fin whale population is relatively constant from 1948-81 at just under 9,000 animals that school to 3,400-4,900 pods.

In Figure 33 the number of schools in Table 43 is compared to the number of schools in the total population from Chapter 3 reported in Table 41. The search model result is that on average about 46 per cent of fin whale schools migrate through the whaling grounds. In a year of high fin whale abundance the search model results suggest that 70 per cent of all schools in the population pass through the whaling grounds. In a bad year less than 20 per cent of all schools go through the grounds.

FIGURE 33

The Number of Fin Whale Schools in the Population and Those Entering the Whaling Grounds 1948-1981

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The central message from the search model is that the number of animals entering the whaling grounds fluctuates considerably from year to year. There is a positive but statistically insignificant trend in the number of schools and whales entering the grounds according to the search model results reported in Table 43. Therefore one must conclude that the fluctuations in the number of animals entering the grounds may be due to irregular migration patterns as much as population fluctuations.

A constant λ of 0.3363 implies a constant N of 1830 entering the grounds out of about 4000 schools in the population from Chapter 3 and the last column of Table 41. The number of whales on the grounds would have averaged 4038 with a S.D. of 506 out of approximately 9000 from Table 41. The number of whales entering the grounds fluctuates because the average school size is variable from year to year.

CONCLUSION

The annual search model adds to our understanding of the investment decision faced by the sole owner of the fin whale stock. The harvesting capacity is used in a season that lasts from June 1 to the end of September. During the season abundance peaks in late June and early July after which fin whales become scarce. The sole owner's decision is to balance the extra revenues and costs associated with taking full advantage of the peak of the migration. The harvest capacity decision is a peak load abundance problem but the peak abundance fluctuates. The

sole owner must invest in discrete units of capacity that cannot be used for other types of fishing but can be used in other than peak periods of whale abundance. A full understanding of this problem requires a model of in-season harvesting dynamics.

CHAPTER 7: THE DYNAMICS OF THE IN-SEASON HUNT

In this chapter we model in season harvesting dynamics for the fin whale stock. In-season dynamics are important because the sole owner catches whales that migrate with a sharp peak period of 6-8 weeks between June and July every year. The monthly pattern of catches was reported in Tables 27-29. Broadly speaking, the hunt begins on the Southern ground and then moves north to the Western and Northern grounds. In this chapter we will use the available data on catcher operations to model how the fleet interacts with a hypothetical annual fin whale migration on a weekly basis.

The three available datasets on individual catcher operations have been discussed in terms of CPUE. The sources for the data are Rørvik and Sigurjónsson (1981) presented in Table 22, Sigurjónsson and Rørvik (1983) summarized in Table 34 and Sigurjónsson and Gunnlaugsson (1985) shown in Table 36. The Rørvik and Sigurjónsson (1981) dataset is a detailed per trip account of operations in June and July. Sigurjónsson and Rørvik (1983) restrict the data to June 10 to July 20 and compile searching, chasing and handling times for the first and second fin whale in each trip. Sigurjónsson and Gunnlaugsson (1985) look at the search time for the first fin whale only. We will draw on per trip information in these datasets to validate the search model.

The physical characteristics of the whaling grounds is dealt

with briefly before discussing the catch results for the fleet within a given season.

The physical location of the three grounds clearly ranks them in terms of distance and the estimated sailing time in Table 31. The southern ground is reached in 9.8 hours, the western in 10.8 and the northern in 13. Since whales are towed back at lower speed a switch to a more distant ground has some cost in terms of operating time. We can assume that catchers will only leave the southern ground for the other grounds when higher expected catch on the other grounds is high enough to compensate for the longer travelling time. Alternatively, there comes a time each year during the whale migration when abundance on the southern ground declines to the point that catchers cannot deliver 2 fin whales to the whaling station within 28-30 hours of killing the first whale. Accordingly the catchers tend to follow the whales on their south-north migration to maintain high catch opportunities.

The size of the three whaling grounds must be taken into account. Our measure of searchability, c , from (3) in Chapter 6 is therefore different for each of the three grounds.

$$\epsilon_S = \frac{Wv}{A} = \frac{1.75 \cdot 12.6}{14,000} = 0.001575$$

$$\epsilon_W = \frac{Wv}{A} = \frac{1.75 \cdot 12.6}{10,000} = 0.002205$$

$$\epsilon_N = \frac{Wv}{A} = \frac{1.75 \cdot 12.6}{6,000} = 0.003675$$

The value of ϵ is the fraction of the area searched in one hour. The value of ϵ is dependent on the size of each ground (A). Vessel speed (v), and sweep width (W) are assumed to be the same on all grounds.

The search hours, t , can be determined by using the data from Rørvik and Sigrjónsson (1981) in Table 22. Total operating time per trip ranges from 45.5 to 47.2 hours in June and July with somewhat longer trips in August and September. We assume that each trip takes 48 hours and that search time per trip is 12 hours. Physically it would therefore be possible for each of the four vessels to produce a maximum of $3.5 \text{ trips} \cdot 12 \text{ hours} = 42$ search hours per week. However, actual operating performance for vessels number 7, 8 and 9 is given by Rørvik and Sigrjónsson (1981) for June and July 1962-79 falls short of this physical limit. The number of trips in June and July is given in Table 44.

Table 44

The Number of Trips in June and July for Selected Catchers.

Catcher	Mean # of Trips	S.D.	Min	Max	Years
7	29.67	5.33	17	38	1962-79
8	28.39	4.52	16	36	1962-79
9	28.57	4.91	18	37	1966-79

Catchers seem to average 3.15-3.3 trips per week when conditions are best in June and July. The range in the number of trips per season shows that in some years trip length falls well short of the 45-48 hour average. We will assume that catchers average 3 trips a week and that it is therefore 36 hours of search per week per catcher.

The 36 search hours must be adjusted for bad weather. Reduced visibility due to rain or fog allows fin whales to evade capture. Bad weather lengthens trips and one could reduce the number of trips that can be taken in a given week rather than adjust search hours. The fraction of total operating time classified as bad weather is provided in Table 45.

Table 45

The Fraction of Total Operating Time in June and July With Bad Weather Conditions.

Catcher	Mean Fraction	S.D.	Min	Max	Years
7	0.124	0.042	0.062	0.205	1962-79
8	0.138	0.057	0.031	0.245	1962-79
9	0.145	0.047	0.075	0.202	1966-79

The average of seasonal averages shows that bad weather prevents operations for 12.4-14.5 per cent of the time depending on the vessel. Based on this the average search time per week was reduced to 30 hours per week.

Catchers are usually limited to two but are sometimes allowed to take three fin whales per trip for a short period of time. Sigrjónsson ((1988) p.330) notes that "up to the 1979 season only 10 per cent of the fin whale catch was taken on trips where more than 2 fin whales were taken". The most common combinations of species according to Sigurjónsson (1988) were 2 fin whales, 2-5 sei whales or 2 sperm whales per trip. The average number of fin whales per trip data in Table 46 reflects this.

Table 46

The Average Number of Fin Whales Per Trip in a Season for Selected Catchers 1962-79.

Catcher	Fins Per Trip	S.D.	Min	Max	Years
7	1.69	0.34	1.10	2.62	1962-79
8	1.59	0.33	1.10	2.50	1962-79
9	1.73	0.29	1.28	2.43	1966-79

Based on Table 46 encountering more than 3 schools never yields any extra catch but it may reassure the catchers that returning to the ground is "worthwhile". The Rørvik and Sigrjónsson (1981) data show that on average catchers brought back 1.59 to 1.73 fin whales per trip during June and July 1962-79. The average maximum weekly catch is therefore assumed to be 3.0

trips*2 fin whales*4 catchers or 24 fin whales per week.

The season has short periods of time when fin whales are not subject to capture because the catchers are not operating or they target for other species. Sigrjónsson and Gunnlaugsson ((1985) data for catchers 6, 7, 8 and 9 for June 10 to July 20 1962-83 can be used to quantify this explicitly. The data for days not operating is summarized in Table 47.

Table 47

The Number of Days in the June 10-July 20 Period When Catchers Were Not Operating for the 1962-81 Seasons.

Catcher	# of Days		S.D.	Min	Max	Years
	Mean					
6	1.75	3.93	0	13	1962-81	
7	2.15	4.34	0	13	1962-81	
8	1.67	4.02	0	13	1962-81	
9	2.09	4.32	0	13	1966-81	

The data show that days not operating average from 1.67 to 2.15 days in the June 10 to July 20 period depending on the vessel or 4-5.2 per cent of the total operating time. Sigurjónsson ((1988) p.330) attributes stops of up to several days to processing capacity limitations and problems associated with processing baleen and sperm whales together. Strikes in 1970 and 1977 which lasted for 12-13 days also meant that fin whales were not subject to capture.

The number of trips without fin whale catches can be addressed with data from Sigurjónsson and Gunnlaugsson (1985). The data on trips without fin whale catches is provided in Table 48.

Table 48

The Number of Trips Without Fin Whale Catches in the June 10-July 20 Period for the 1962-1981 Seasons.

Catcher	# of Trips Mean	S.D.	Min	Max	Years
6	2.05	2.06	0	7	1962-81
7	1.30	1.75	0	7	1962-81
8	1.85	1.93	0	6	1962-81
9	0.87	1.02	0	4	1966-81

Trips without fin whale catches average from 0.87-2.05 trips from June 10-July 20 1962-81 depending on catcher. Hence zero fin catches are registered in 4.2-9.75 per cent of all trips.

The capacity of the fleet to harvest fin whales must be adjusted downward for days not operating and also trips taken without fin whales. One can speculate that trips without fin whales only occur when fin whales are scarce. However large sperm whales are close enough in value to fin whales to make opportunistic catches tempting in circumstances where fin whales are available after further search. Rather than adjust catchability factors downward for these factors the total catch for a given size migration will be adjusted downward by a maximum of 15 per cent.

The subjective estimate of λ for each ground is given by (2) from Chapter 6 and is equal to $\hat{N}_i c_i = \lambda_i$, where i =south, west and north ground respectively. We know c_i does not change but that $\hat{N}_i$ does. The expected number of encounters with fin whale schools is then, given t , $E_{ti}(n)$ from (12) in Chapter 6, or

$E_{ti}(n) = \lambda_i / c_i (1 - e^{-k c_i t})$. From Table 41 we know that the average number of fin whales killed per school ranges from 1 to 1.38 for 1967-1983, the period for which we have complete data. We will assume for simplicity that one whale is killed per school.

The in-season migration of the fin whale population is not well understood. Sigrjónsson (1983) and Sigrjónsson and Gunnlaugsson (1985) summarize what is known about in-season migration based on 13 in-season mark-recaptures of fin whales. Sigrjónsson and Gunnlaugsson ((1985) p.360) observe that 10 of 13 in-season recoveries show a net northward movement of 2.6 nautical miles per day. An examination of the data shows that the 6 fin whales caught less than 10 days after being marked show a per day movement ranging from less than 2 nautical miles to just under 35 with an average of 17.7 nautical miles per day. The distance straight north through the three whaling grounds is of the order 160-180 nautical miles. The two average speeds of migration, the 2.6 or 17.7 nautical miles per day would have the fin whales pass through the grounds in either 60 or 9 days. It is clear from the limited data that fin whale migration patterns are variable and that generalizing them will tend to be somewhat arbitrary.

The fin whale migration north must be modeled in order to revise our weekly estimate of λ to know which of the three grounds to target the fleet on in any given week. We will assume that the in-season migration is a Markov process with an absorbing state. The absorbing state is simply that all schools eventually exit the three whaling grounds. The abundance of schools on each ground is

assumed to be revised each week according to the following transition matrix (P):

END					
START	South	West	North	OUT	
South	0.55	0.25	0.20	0	=P
West	0	0.55	0.25	0.20	
North	0	0	0.55	0.45	
OUT	0	0	0	1.00	

The transition matrix P formalizes a view of migration via the mean first passage times implied by it. All schools are expected to start on the Southern ground and migrate out in 5.13 weeks. The speed of the migration is then of the order of 4-6 nautical miles north each day. In Figure 34 the state probabilities for the location of a school at time t starting on the Southern ground at time $t=0$ are plotted.

The flow pattern of the migration north is not known with any certainty. A peak in abundance sometime around late June mid July is a regular feature. For the purposes of modeling the flow will be assumed to last seven weeks and to have a peak with equal number of whales on each side.

FIGURE 34

The Expected Location of a Fin Whale School Seen on the Southern Ground

The actual migration into the grounds was assumed to be a series of seven vectors $I_{ti} = (N, 0, 0, 0)$, where i = south, west, north and out, reflecting in-migration into the Southern ground. The in-migration vectors are updated by applying the transition matrix to them to obtain a school state vector $\hat{N}_{ti}$ at the beginning of the next week period. The state vector is updated with the P matrix in every transition and is used to keep track of the location of each wave of migrants.

In practice the problem for the whale catchers is to decide which ground to fish given some general pattern of fin whale migration from south to north. Each catcher would therefore trade off travel time, which increases the further north one fishes, with his perception of abundance on a whaling ground before deciding to fish there. Then, presumably, if perceptions of abundance differ, catchers would be switching between grounds at different times. However, to simplify the model all four catchers will be assumed to go to the most accessible ground with the expected abundance each week that can meet catcher capacity.

The theory behind the simulation model is discussed in Chapter 6. Only the week-by-week migration accounting through the markov process in the simulation model is new. The simulation model can be summarized as follows:

Step 1: Establish the number of schools on each ground.

$$(18.1) \quad \hat{N}_{ti} = (I_{ti} + V_{ti}) * P \quad i = \text{South, West, North and Out}$$

where V_{ti} is the state matrix for all schools in the system that have not been harvested at the beginning of period t .

Step 2: Calculate the λ for each ground.

$$(18.2) \quad \lambda_{ti} = \hat{N}_{ti} \epsilon_i \quad i = \text{South, West and North}$$

Step 3: Calculate the expected number of schools encountered on each ground for a given total search hours.

$$(18.3) \quad E_{ti}(n) = \frac{\lambda_i}{\epsilon_i} (1 - e^{-k \epsilon_i t}) \quad i = \text{South, West and North}$$

Step 4: Select which whaling ground the fleet operates on by sequentially evaluating (a), (b) and (c) for a given week.

(a) Fish the Southern ground if $E_S(n) \geq \text{MAX}$ or $E_S(n) > E_W(n)$ and $E_S(n) > E_N(n)$ and MAX is the catching capacity of the fleet which is assumed to be 24 fin whales per week.

(b) Fish the Western ground if $E_W(n) \geq \text{MAX}$ or $E_W(n) > E_N(n)$ and $E_W(n) > E_S(n)$.

(c) Fish the Northern ground if $E_N(n) \geq \text{MAX}$ or $E_N(n) > E_W(n)$ and $E_N(n) > E_S(n)$.

Step 5: Catch is MAX if $E(n)$ exceeds the catching capacity of 24 fin whales per week, otherwise catch is $E(n)$.

$$(18.4) \quad Y_{ti} = \begin{cases} \text{MAX} & \text{if } E_{ti}(n) \geq \text{MAX} \\ E_{ti}(n) & \text{if } E_{ti}(n) \leq \text{MAX} \end{cases} \quad i = \text{South, West and North}$$

where MAX is the weekly catch capacity of 24 for the fleet.

Step 6: Subtract the catch from the fin school state vector and initialize V for the next transition, go back to Step 1.

$$(18.5) \quad V_{t+1,i} = N_{t+1,i} - Y_{ti}$$

The average migration was estimated to be about 1,800 fin whale schools in Table 43. To test the in-season simulation model the 1,800 schools were broken into a symmetrical seven week north migration of 100, 200, 350, 500, 350, 200 and 100 schools entering in the south. The expected number of schools encountered and the actual catch are presented in Table 49. The total catch of 294 fin whales should be adjusted downwards by an average of about 15 per cent for trips without fin whales and days not operating. This would yield an adjusted catch of 250 fin whales which is in line with the average actual fin whale catch of about 240+.

Table 49

The Expected Number of Fin Schools Found on Each Whaling Ground.

Week	South E(n)	West E(n)	North E(n)	Actual Catch	Catch Location
1	9	6	7	9	South
2	23	17	24	24	South
3	46	38	50	24	South
4	70	64	95	24	South
5	70	78	129	24	South
6	55	77	142	24	South
7	37	65	136	24	South
8	18	47	113	24	West
9	10	29	86	24	West
10	6	16	60	24	North
11	3	11	37	24	North
12	2	7	21	21	North
13	1	4	11	11	North
14	1	3	6	6	North
15	0	2	3	3	North
16	0	1	2	2	North
17	0	1	1	1	North
18	0	0	1	1	North
19	0	0	0	0	
20	0	0	0	0	
TOTAL CATCH				294	

The total number of fin whale sightings in a season by the catchers was not recorded until 1979. Sigurjónsson and Gunnlaugsson ((1990) p.541) publish data on total sightings 1979-1988. The 1981 and 1982 the catchers saw 722 and 736 schools respectively. If the catchers had always searched the ground with the highest expected catches in Table 49 they would have seen 926 fin whale schools or 787 after the 15 per cent adjustment for not operating and bycatches. The number of sightings in the model are

therefore in line with the little we know about the expected number of total fin whale school sightings in a season.

The real value of applying the in-season simulation model is not in validating it arbitrarily close to the actual catch history but rather in qualitatively replicating the seasonal pattern in the hunt. This is achieved to some degree in the simulation results reported in Table 49 and plotted in Figure 35.

In Figure 35 the season starts and then with a delay of two to three weeks the catchers essentially operate at catching capacity for some weeks unconstrained by abundance of fin whales. This pattern in catches continues until the fin whales migrate out of range. Rørvik et al ((1976) p.13) show a per day catch of 2+ fin whales a day for much of June and July in the 1948-1973 period with a 3+ catch of about 30 days. By comparison the peak in the simulation in Table 49 is perhaps a bit too long compared to the average for 1948-73. This result can be found by making the migration sharper over say 5 or 6 weeks or by lowering the level of persistence in the transition matrix P (increasing the speed of the migration).

The number of schools after harvesting on each whaling ground at the end of the week is provided in Table 50. In the deterministic simulation of the model 1800 schools pass through the grounds and we assume accurate knowledge of the number of schools on each ground on the basis of sampling from previous trips.

FIGURE 35

The Expected Number of Fin Whale School Sightings by the Fleet Per Week

Table 50
The Number of Fin Schools on Each Whaling Ground West of Iceland.

	South	West	North	Outside
Week	$\hat{N}$	$\hat{N}$	$\hat{N}$	$\hat{N}$
1	46	25	20	0
2	135	75	43	14
3	243	163	139	48
4	385	275	266	143
5	380	335	362	318
6	295	329	399	548
7	193	280	381	793
8	106	178	318	1020
9	58	101	241	1199
10	32	70	145	1328
11	18	47	80	1407
12	10	30	38	1452
13	5	19	20	1475
14	3	12	11	1488
15	2	7	6	1495
16	1	4	4	1499
17	0	3	2	1502
18	0	2	1	1503
19	0	1	1	1504
20	0	1	0	1505

The deterministic in-season catcher-migration model qualitatively confirms the results of the empirical application of the search model to the annual data in section 6.1. Catchers operating in the modeled spatial environment at mean conditions would need an annual migration averaging about 1300 schools to achieve an annual average catch of 240+ fin whales. However, the model has to be modified if one wants to use it to explore the effect of uncertainty in both catcher operations and migrations.

We know empirically that migrations are somewhat irregular and of an uncertain size each year. The modeling strategy here is

to make the dynamic path of the migration regular but the size and speed can vary. Our prior from Table 43 is that an average migration is 1800 schools. To explore the effect of changes in abundance on catcher operations the seasons in Table 43 can be divided into high, medium and low seasons in terms of the size of migrations. The division of seasons is as follows:

Range	Number of Schools Used	Actual Number of Seasons
3200 > High > 2100	2400	9
1400 < Medium < 2100	1800	15
1400 > Low	1200	8

The in-migrations into the Southern ground are assumed to be in discrete groups over seven weeks equally distributed around a peak in week four as follows:

Week	1	2	3	4	5	6	7
High	150	300	450	600	450	300	150
Medium	100	200	350	500	350	200	100
Low	50	150	200	300	200	150	50

The uncertainty in catcher operations associated with the number of days not operating and disturbances from catches of other species will all be incorporated into the fin catch function as 15 per cent zero fin catch. Based on Tables 46-48 the following cumulative normal catch function was adopted:

Fin Catch	Range
0	0-0.15
1	0.15-0.30
2	0.30-0.90
3	0.90-1.00

The average fin whale catch per trip is 1.65.

The effect of bad weather from Table 45 were assumed to reduce average weekly search time randomly by 14.5 per cent with a standard deviation of 5.7 per cent.

These modifications to the deterministic in-season simulation model allow us to study the effect of the uncertainty in catcher operations on the catch from a migration of a given size. In effect we can look at how the catcher fleet performs if it can exploit a migration of 1200, 1800 and 2400 fin whale schools having only to face the uncertainty associated with weather and its own operations. The result of 100 seasons at each migration level are presented in Table 51. The search hours are the same at each migration level, the size of the migration just determines the CPUE.

Table 51

The Results of 100 Dynamic Simulations at Each Migration Level With Whale Migrations Obeying P.

Series	Mean	S.D.	Maximum	Minimum
CATCH2400	254.31	32.85	329	175
CATCH1800	237.17	31.49	300	161
CATCH1200	209.05	29.14	265	134
HOURS	615.63	9.82	641	593
PER CATCHER				

The simulations in Table 51 demonstrate that at constant migration levels seasonal catches vary over a wide range. Historical catches in the 1948-81 period ranged from a low of 142 in 1961 to a high of 348 in 1957. This would suggest that catches of 142 in 1961 and 144 in 1977 are the product of both low migration and unfavorable operating conditions. Catches of well over 300 fin whales in 1951, 1957, 1962 and 1966 would conversely be the product of favorable operating conditions and a large migration. The 24 years in the 1948-81 period with catches ranging from 202-289 are consistent with a medium migration and varying operating conditions.

The results of the simulations in Table 51 illustrate well the degree of uncertainty associated with CPUE as an index of population abundance in this fishery. This is not surprising since the fishery only occupies a limited range in the habitat of the fin whale.

The transition matrix P limits the generality of the results in Table 51. A second transition matrix, P^F , which implicitly incorporates a faster migration through the whaling grounds can be used to explore the limitations imposed by P . The fast transition matrix P^F is defined as follows:

END

	South	West	North	OUT	
START	+-----				
South	0.45	0.30	0.25	0	= P^F
West	0	0.45	0.30	0.25	
North	0	0	0.45	0.55	
OUT	0	0	0	1.00	

The main difference between P and P^F is that the mean first passage time for a fin whale school to go from the Southern ground to Out goes from 5.13 weeks to 4.17. The speed of the migration north is increased by about a nautical mile each day (from 4.5 to 5.5). The results of the simulations using P^F are shown in Table 52.

Table 52

The Results of 100 Dynamic Simulations at Each Migration Level With Whale Migrations Obeying P^F .

Series	Mean	S.D.	Maximum	Minimum
CATCH2400	215.57	30.57	285	116
CATCH1800	199.86	28.58	263	113
CATCH1200	179.51	26.94	237	105
HOURS PER CATCHER	615.79	9.07	636	589

The impact on catches from increasing the speed of the migration is negative at all abundance levels. The difference between mean catches in Table 51 and 52 is 38 or 39 for a migration of 1800 and 2400 schools respectively and 30 at 1200 schools. The decline in catches is 14-16 per cent from Table 51. The catch results are therefore fairly sensitive to the speed as well as the size of the migration. If migration speed is variable from year to year this would add to the already considerable uncertainty in interpreting CPUE data.

THE MARGINAL INVESTMENT DECISION

The sole owner has employed four vessels throughout 1948-81. The impact of adding the fifth vessel to the fleet can be addressed by setting $k=5$ in (18.3). The additional vessel is assumed to have the same operational characteristics as the other vessels in the fleet. The results of the simulations are presented in Table 53.

Table 53

The Result of 100 Simulations at Different Migration Levels With Five Whale Catchers, Migrations Obeying P.

Series	Mean	S.D.	Maximum	Minimum
CATCH2400	308.32	40.37	395	212
CATCH1800	286.09	37.97	355	194
CATCH1200	251.66	35.35	321	160

The fifth vessel would catch 54, 49 or 42 fin whales at respectively 2400, 1800 and 1200 fin school migration levels. The real world average fin catch per vessel 1948-81 is about 60 per season. This average is achieved in Table 51 at a migration level of 1800 fin whale schools, hence the marginal catch is expected to be of the order of 49 fin whales per season. Three catchers would average 185.43 (S.D of 25) fin whales per season at a migration

level of 1800. The marginal product from the third to the fourth catcher is therefore about 52 fin whales.

The marginal catcher is subject to diminishing returns. The marginal product of the fifth vessel is less than the average product of the four catchers already in use. However, the marginal product of the fifth vessel is probably high enough to be profitable today. The reason the sole owner did not add a fifth catcher is not known. The sole owner was not overtly constrained but he may have been subject to indirect threats of regulation if he intended to increase the average catch in terms of the model from 237 to 286.

The optimality of four catchers cannot be ascertained with any certainty. The production function for catching whales is not a fixed-proportions production function but adding crew is not an effective way to increase output. The marginal crew member scanning the horizon for whales may not help the 6 or so already engaged in that activity in search mode find any more whales. Output is the number of fin whales fished and steaming and searching for whales dominates in the production process. Total product is maximized when the average and marginal product for catchers are equal. The marginal and average product of four catchers are close, hence a necessary condition for optimality is met. However, given the lumpy nature of capital in this industry this is perhaps all that can be achieved.

The investment in whale catchers and other associated land based capital is specialized to the point of being sunk. Whale

catchers cannot be used for other types of fishing and moving to other whaling grounds is not feasible. This makes mining the resource more difficult in practice since all assets have to be cashed out with the resource.

The fifth catcher would have run into diminishing returns to scale. Investing in the fifth catcher would probably be profitable. The fact that the sole owner stopped at four catchers is consistent with a cautious strategy. The uncertainty with respect to the size of the resource was probably large well into the 1960s and indirect regulatory pressure may have been brought to bear on the firm not to expand. However, the history of the industry in Iceland is filled with financial disasters for firms. One would therefore expect to see a fairly conservative approach to investing.

SEARCH THEORY AND THE DEPLETION OF THE FIN WHALE STOCK 1883-1915

The theory of search can be used to examine to what degree the open access hunt depleted the fin whale stock off Iceland. Our prior from Chapter 3, Figure 10 is that the fin whale stock was reduced from 6500 adults to 1300 or to about 20 per cent of its pristine level. Fin catches 1913 to 1915 were 84, 20 and 45 respectively (Table A5). The number of catchers was 13 in 1913, 3 in 1914 and 4 in 1915 so the fin whale catch per catcher was 6.46, 6.67 and 11.25. We also know that the number of schools

encountered was probably less because there was no protection for females with a sucklings or fin whales under 50 feet.

In terms of the search characteristics technology has not changed much. The first whale catcher that started operations in Iceland in 1883, the Isafold, was 84 gross tons with a 180 horse power engine "ensuring the respectable speed of 11 knots" (Tønnessen and Johnsen (1982) p. 76). The catchers that followed were larger and somewhat faster. Towing boats were also introduced as catchers had to move further offshore to find whales (Gunnlaugsson, Magnusson and Sigurjónsson (1989) p. 271). The use of towing boats allowed catchers to search more intensively than is now possible since towing boats are banned.

The season for fin and blue whales would last up to six months. The season is described by Tønnessen and Johnsen ((1982) p.78):

"At the end of March and beginning of April these [fin and blue whales] would arrive at great speed along the west coast, continuing on their way towards the Greenland ice in the Denmark Straits. It was possible to commence catching operations as early as April off the Vestmanna Islands, and then follow the migrating whales north. In June and July whales caught had to be towed all the way down to Isafjörður; at the end of August and in September there followed the hectic pursuit of the whales moving south."

While modern science cannot confirm the south migration conjecture in the statement the season was longer than is the practice in the 1948-81 period. We conclude that search efforts per catcher in a season in the 1883-1915 period were at least on par with what is achieved in the 1948-81 period.

In 1914 and 1915 a single landstation operated in Isafjördur with 3 and 4 catchers respectively. The catchers probably only fished the Western and the Northern grounds. The catchers likely fished further north than is currently the practice. Rather than dwell on these differences between location of catches, catcher efficiency and search time between 1915 and a typical season in the 1948-81 period, we will investigate how many schools would have to migrate through the three grounds to yield only 45 fin whales in a season with current operational characteristics.

The number of schools in existence at the start of the 1915 is unknown. We expected it to be, from our prior on the population, 1,300 or so adults plus immature animals divided by average school size of approximately two from Table 41. An upper limit of 1000 schools can be postulated and a range of 20-70 per cent of those would come within catcher range.

The simulations are 100 seasons of migrations of 300, 170 and 120 fin whale schools respectively. The migration pattern is:

Week	1	2	3	4	5	6	7
Total							
300	20	40	50	80	50	40	20
170	10	20	30	50	30	20	10
120	5	15	20	40	20	15	5

The results of the simulations are presented in Table 54.

Table 54

The Result of 100 Simulations at Depleted Migration Levels With Four Whale Catchers, Migrations Obeying P.

Series	Mean	S.D.	Maximum	Minimum
CATCH300	103.50	11.35	120	64
CATCH170	60.44	6.39	69	39
CATCH120	43.42	4.58	49	28
HOURS	615.63	9.82	641	593
PER CATCHER				

The key result from Table 54 is the scale of migrations that are needed to get a low catch like 45 fin whales in a season. Migrations are expected to be about 1/10 of the current average migration level of 1800 schools. Four catchers, searching at current levels of efficiency for a whole season and finding only 45 fin whales cannot be consistent with anything but a fin whale stock depleted to less than 25 per cent of its current size.

Modern catchers are more efficient than the catchers that operated in the open access period. The peak catch per catcher in the 1883-1915 period was 48 whales of all species in 1895. Catchers in 1915, twenty years later, may have been somewhat more efficient. Even if catchers in the 1948-81 period are two to three times as efficient at producing search tracks 1.75 nautical miles wide as the catchers operating in 1915, presence of fin

whales on the whaling grounds in 1915 is only a fraction of what it is on average in the 1948-81 period.

CONCLUSION

The in-season catcher migration model qualitatively confirms the results obtained with the annual search model in Chapter 6. Catchers will only intercept a fraction of schools migrating through the whaling grounds.

The stochastic catcher operations model using a deterministic annual migration of 1800 schools is capable of generating catches that cover nearly the range of catches observed in the 1948-81 time period. Historical catches ranged from a low of 142 to a high of 348 whereas the model simulations show annual catches of 161 to 300 over 100 trials. The simulations show that the catch process itself is stochastic enough to generate the observed variation in annual catches given constant abundance.

The marginal catcher is evaluated using the in-season model. Both the fourth and the fifth catchers are subject to diminishing returns but the marginal and average products are close together. The fifth catcher would probably have been profitable.

Finally, the in-season model can be used to infer the degree of depletion of the fin whale stock at the end of the open access period in 1915. The simulation results show that a catch of 45 fin whales in a season by four catchers is consistent with a migration of under 200 schools which is 10-15 per cent of the average migration in the 1948-81 period.

CHAPTER 8: SUMMARY AND CONCLUSION

This thesis is an empirical study of the bioeconomics of sole owner exploitation of the fin whale stock off Iceland from 1948 to 1981. The aim is to explain how the interaction of stock dynamics, economics and operational considerations are combined in the sole owner's decision to either harvest on a sustained yield basis or deplete the resource. Commercial whaling has a history of depleting virtually every whale stock ever exploited to the point of extinction. The stocks of blue, fin, humpback and other whales off Iceland were seriously depleted in an open access hunt from 1883 to 1915. Our analysis confirms that the blue whale stock off Iceland remains depleted.

In Chapter 2 the economics of whaling from 1883 to pre-World War II is briefly sketched. It is noted that whaling was primarily for oil and that the hunt was destructive of the whale stocks because pregnant females were favoured as targets due to their high oil yield.

In section 2.1 the open access period off Iceland from 1883-1915 is shown to be a typical boom bust fishery. The number of whale catchers went from one in 1883-85 to 30 in 1902, when catches peaked, and then to 32 in 1910. In the 1912-1915 seasons the number of whales per catcher fell to 8.8-13.5 animals from an average of 40.65 in 1895-1905 and similarly oil

barrels per catcher fell to about a third of the 1895-1905 average. These are all indications of a severe stock decline. In response, the Norwegian whalers moved to new grounds in the southern hemisphere and elsewhere.

In 1913 the Icelandic parliament legislated an end to the hunt after the 1915 season to be followed by a ten year ban, which expired January 1, 1925. All but one firm left the fishery after the law passed.

After the ban whaling from Norwegian floating factories began in 1929 and continued to 1937. An Icelandic land station operated from 1935-39. The catches resulting from these fishing efforts are important because they can be used to infer to what degree the whale stocks off Iceland had recovered from the open access period. It is clear from these catches that fin whales would have to be the mainstay of any whale fishery.

The sole owner hunt from 1948 to 1981 was mainly for fin whales (240 average per year). Blue and humpback whales were taken in small numbers early in the period. There is a small positive time trend in sperm whale catches (82 average per year over 1948-1982) and sei whale catches (average 68). Both whale species are important as by-catch throughout the whole period. Wide fluctuations around mean catches for fin whales but there is no time trend in fin whale catches.

The varied pattern of exploitation of the whale stocks off Iceland is interesting in terms of the implied stock dynamics.

In 1912 the 20 catchers in the hunt found 8.8 whales each searching for over five months all around Iceland. In the 1914 season only 3 catchers participated in the hunt with 4 catchers participating in 1915 with equally bad catch results. The degree of stock depletion must have been severe but the fin whale stock recovered enough to sustain the hunt in the 1930s and again from 1948 onwards. However, the degree of stock depletion cannot be determined without modeling explicitly the stock dynamics of the fin whales off Iceland.

The methods used to assess the status of the fin whale stock in this thesis are population modeling, optimal control theory and search theory. These methods are all subservient to the primary aim of this thesis which is to determine how economic incentives impact on the fin whale stock. While these methods are all known in bioeconomics it is rare to find a fishery with enough data to warrant their use. All these methods are applied to draw inferences about stock trajectories through time. Moreover, the results from the different modeling approaches can be used to validate the results obtained by the other methods and provide a fresh perspective on the fin whale stock. In addition a micro model of catching is developed to study the optimal investment decision in harvesting capacity when the fishing process is stochastic.

The biological modeling in Chapter 3 is needed to establish the size and growth range for the fin whale stock. The dynamics

of the fin whale stock are a constraint in the optimization problem for the sole owner in Chapter 4 and serve as a check on the stock dynamics implied by the search model in Chapter 6.

The stock dynamics from the basic baleen whale model is deterministically fitted to both fin and blue whales to get a reference level for their population profiles 1883-1986. The fin whale model is then expanded to include age classes 1 to 7 individually with a pool for adult stock. Dynamic simulations which allow for variability in natural mortality, μ , and fertility are then performed to get extinction probabilities for the stock given pristine adult stock levels, K , ranging from 5,250 to 7,500.

The results of the stochastic simulations show that if $K \geq 6,500$ the stock is at about 90 per cent of its 1948 value in 1987. Furthermore, the probability of extinction given the pattern of catches is 5 per cent at $K=6,500$ and 95 per cent at $K=5,250$. If $K > 6,500$ the probability of extinction drops to negligible levels given the catch history of the fin whale stock. Based on the dynamic simulations an adult stock of $X=K=6,500$ in 1883 and $X=4,675$ in 1948 is postulated as the most likely level of the pristine stock and is used in the economic model.

In Chapter 4 the economics of fisheries is briefly surveyed for material pertaining to the decision problem faced by the sole owner of a fish resource like whales. Depensation which

favours extinction is rejected as a relevant characteristic of the reproduction of whales. The inter-temporal profit maximization problem for the sole owner subject to the fin whale stock dynamics from Chapter 3 is then solved.

The solution has the usual modified golden rule property that the marginal productivity of the resource must equal the discount rate in equilibrium (Clark and Munro (1975)). The comparative statics of the problem reveal that at discount rates below 5 per cent (the real discount rate for the sole owner was about 5 per cent over the period) the sole owner would leave a stock corresponding to greater than 0.55 of the MSY level for price cost ratios ranging from 2.27 to 5.33. The stock would be left at 34-48 per cent of its pristine level. The sole owner requires both a high discount rate and a high price cost ratio before he would mine the stock down to 20 per cent of its pristine level, K . Based on Figure 10, the low point in the open access period was about $0.2K$. We therefore conclude that the conservation of the fin whale stock (stock greater than $0.53K$) is a likely outcome from the profit maximizing behavior of the sole owner.

The fin whale stock was assumed to be 4,675 adult whales in 1948 in Chapter 3. This is used as X_0 in the simulation of the most rapid approach paths for the model at various discount rates. At low discount rates like 0 or 3 per cent, the target stock X^* is reached quite rapidly, however, if the true discount

rate is 10 per cent (2-3 times the growth rate of the Icelandic economy) then X^* is not reached in 100 years of fishing with the current fleet. The catching capacity of the current fleet seems insufficient to mine the stock over the short term. These results of course depend critically on the limited catching capacity of the fleet which is the subject matter in Chapter 6.

In Chapter 6 the catching process is explicitly modeled. The capacity of the catchers is critically analyzed to determine whether the restrictive definition of catching power used in the economic model in Chapter 4 is a realistic representation of catching capacity. In Chapter 5 the operational characteristics of the hunt are detailed with respect to the physical location and the catching process.

The available catch per unit effort (CPUE) data is re-analyzed in Chapter 5. The definition of a peak season lasting from June 10 to July 20 is revealed to be empirically suspect. The fraction of annual fin whales in this peak period range from 38-82 per cent. Bycatches of sperm whales are statistically significant in the fin CPUE regressions for this period.

Annual CPUE data for the whole season 1949-79 has a small negative time trend, which is significant at the 10 per cent level. If annual CPUE is a reliable index of relative abundance the fin whale stock has declined by about 20 per cent between 1949 and 1979. Similarly, the time trend in CPUE for the first

fin whale in the June 10 to July 20 time period 1962-86 is consistent with a decline of 5-10 per cent in 24 years. CPUE data is thus generally supportive of a small gradual decline in the post war period.

The diminishing returns to effort, the statistical significance of a small negative coefficient on $\partial \text{CPUE} / \partial E$ in the June 10-July 20 period can be interpreted as supportive of a general decline in the fin whale stock. However, explanations based on the depreciation of capital and aging crews may be equally plausible.

Dissatisfaction with CPUE and knowledge of the number of schools harvested from and the mean size of schools from 1951 to 1983 leads us to the theory of search. CPUE is known to be unreliable as an index of relative abundance in fisheries where search is important. However, a relationship between search effort and stock size may be a more reliable indicator of abundance. In addition search theory has the advantage of explicitly modeling fishing as a stochastic process whereas CPUE models are usually based on simple deterministic models.

The theoretical developments in search theory relevant to search fisheries like tuna and whaling are surveyed in Chapter 6. The fin whale fishery as a search problem involves single, independent searchers looking for many moving targets. The model adopted is a generalization of the "law of random search" due to Koopman (1980).

A search for any school is viewed as a "trial" in the sense that each school is equally likely to be subject to discovery. The discovery of n schools in t search hours is a binomial distribution.

In section 6.1 the theoretical search model is fitted to the annual data on schools harvested from and to total search time during the period June 10 to July 20. The abundance level of schools is fixed and actual search time is used to forecast the number of schools harvested from. The fixed abundance level and actual search time predict actual schools harvested from with a root mean square per cent error of 12.34 per cent.

The annual school search model is then used to draw inferences on the population. The estimate for total number of schools in a closed area must be adjusted for time not sampling from the migration since catchers do not observe all the whales passing through the fishing grounds. The annual average number of fin schools passing through the whaling grounds during the period 1948-81 is estimated at 1800 schools or about 4000 animals. School abundance on the grounds fluctuates between 800 and 3100.

The plausibility of the school population estimate is validated by comparing the number of schools predicted in the search model with those obtained by converting the population into schools using the biological model in Chapter 3 (Figure 33). The best estimate is that on average only 16 per cent of

the schools enter the grounds. In a year of high fin whale abundance on the fishing grounds the search model suggests that 70 per cent of all schools in the population pass through the whaling grounds but in a bad year only about 20 per cent would be exposed to capture. While there is a slightly positive trend in the total number of schools in the whale population and whales entering the grounds it is statistically insignificant. The central conclusion from the annual search model is that the fluctuation in the number of schools and fin whales entering the grounds may be due to irregular migration patterns as much as to population fluctuations.

In Chapter 7 the dynamics of the in-season hunt is modeled. The operations of the four catcher fleet on a weekly basis is used to calibrate a deterministic simulation model which explicitly incorporates a hypothetical migration of the fin whales and the search of the catchers to qualitatively mimic the seasonal pattern of catches observed in the 1948-81 period. Stochastic factors such as bad weather, bycatches from other species and days not operating are used to demonstrate the uncertainty associated with harvesting operations. The catch results in the modeled stochastic environment are in line with actual catch results 1948-81.

The in-season catcher search model is used to explore the marginal catcher investment decision by the sole owner. In the modeled environment both the fourth and the fifth catcher are

subject to diminishing returns. The fifth catcher would probably be profitable. The marginal catch of the fifth catcher is 42-54 fin whales per season. The reason the sole owner did not invest in a fifth catcher is likely due to a cautious business approach or to the threat of regulation.

The in-season migration catcher search model is finally used to check the implied depletion of the fin whale stock given the low fin whale catch at the end of the open access period in 1915. In 1915 four catchers searched all season and landed 45 fin whales. The efficiency of catchers in 1915 is lower than those operating in the 1948-81 period. However, in terms of producing search tracks 1.75 nautical miles wide the difference in efficiency is not large. Less regulation and better landstation location in 1915 make it possible that catchers operating in 1915 had a search output on par with what is achievable today.

If today's catchers had only found 45 fin whales in a season, the total migration through the whaling grounds would have been less than 200 schools. This confirms the conjecture from Chapter 3 that the fin whale stock only had 1300 or so mature animals left at the end of the open access period in 1915. The micro search model suggests that presence of fin whales on the whaling ground in 1915 was only 10 per cent or so of levels seen in the 1948-81 period. Based on Chapter 3 the fin whale

population in 1948-81 has increased by a factor of 3-5 since 1915.

By modeling the behaviour of the sole owner firm we validate the results of the standard baleen whale model from Chapter 3. At the end of the open access period the fin population was depleted and only a small fraction of that depleted population was within catcher range. In 1915 catchers operated in an area that to a significant extent overlaps with the 1948-81 whaling grounds which was found without fin whales. Norwegian and Icelandic catches in the 1930s prove that the area was again populated with fin whales. The implication is that either the fin whale stock grew fast and re-populated the area or in-migration neutralizes the mining of the stock on the whaling grounds west off Iceland. There is a documented case of one fin whale marked off Newfoundland which was harvested off Iceland in 1988. However, it would seem that the unit stock concept should still be used for the East Greenland-Iceland fin whale stock and that conservative catch quotas based on in-migration from adjacent depleted stocks can not be justified in this case.

The sole owner was essentially unregulated up to 1981. The results of Chapter 4 suggest that the sole owner had an economic incentive to conserve the resource during the 1948-81 period. Chapter 5 confirmed that the catching capacity of the installed catching capital is too low to mine the resource in the short term. The loss of resource tenure suffered in the 1980s will

lead the sole owner to increase his discount rate. However, as long as the sole owner cannot increase catching capacity he is in no position to mine the fin whale stock.

The sole owner of the fin whale stock off Iceland adopted stock conservation 1948-1981 based essentially on self-regulation. However, we recognize that the IWC or some other body will regulate the harvesting of whales off Iceland whether there is any demonstrated need or not due to pressure from environmental groups.

The natural regulatory strategy seems to be to limit catching capacity strictly and keep the sole owner locked into his 1948-81 strategy of catching an average of about 240 fin whales a year. Based on Hannesson and Steinshamn (1991, p.77) we conclude that constant effort regulation is optimal in the sense of yielding more profit to the sole owner than a constant catch regime. We know that the fin whale catch depends on the size of the stock as well as fishing effort. The effort cost function must be convex with respect to effort and it therefore follows that constant effort will cost less than variable effort that maintains a catch equal to the expected catch of the constant effort. Alternatively the IWC should restrict catches to what they were in the 1948-81 period.

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Appendix A

Table A1

Profits of Norwegian Whaling Companies as a Percentage of Stock Capital 1910-11 to 1934-35

Year	Profits/Stock Capital	Ton of #1 Whale Oil ³
1910-11	96.6 ¹	£21.15
1911-12	26.1 ¹	20.15
1912-13	50.9 ¹	20
1913-14	40.6 ¹	22.3
1914-15	76.8 ¹	21.15
1919-20	167.6 ²	£67.15
1920-21	6.8 ²	86
1922-23	35.6 ²	32.5
1924-25	53.1 ²	36.10
1926-27	9.3 ²	32
1928-29	39.0 ²	29.15
1930-31	29.2 ²	21.10
1932-33	32.1 ²	13
1933-34	6.3 ²	12
1934-35	17.4 ²	10.15

Source:1. 4 whaling companies in the Antarctic, Tønnessen and Johnsen p.243. 2. Lynges sample of 4-12 representative Norwegian firms, Brandt Ibid p.127. 3. Mean of high and low for No 1, Ibid Brandt p.227

Table A2

Norwegian North Atlantic and Arctic Pelagic Whaling 1929-1937

Year	Blue	Fin	Humpb	Sei	Sp.	Oth.	Total	Factory Ships	Whale Catchers	Oil
1929	29	192	3	0	1		225	2	4	11,375
1930	60	580	53	1	1		695	4	11	27,485
1931	52	456	39	8	0		555	2	7	21,869
1932	38	443	9	24	0	4	518	2	7	20,159
1933	43	549	7	0	41		640	3	10	25,005
1934	21	128	3	0	0		152	1	4	6,720
1935										
1936										
1937	28	461	7	100	218		814	2	11	32,375
Total	271	2,809					3599			

Source: International Whaling Statistics, XXVII, Oslo
1951, p.22

Table A3

Catch Composition By Species Based on Sample Returns

Year	Blue	Fin	Sei or	Humpback	Total
1889 ¹	24	38	1		63
1890 ¹	50	23	1		74
1891 ¹	39	43	1		83
1892 ¹	80	47	1		128
1893 ¹	77	113	5		195
1894 ¹	127	79	10		216
1895 ¹	219	112	12		343
1896 ¹	219	45	7		271
1897 ²	137	96	12		245
1898 ³	190	127	78		395
1899 ³	217	140	54		411
1900 ³	186	172	36		394
1901 ²	72	99	22		193
1902 ¹	21	18	17		56
1903 ¹	16	21	13		50
1904 ¹	19	40	11		70

1) 1 whaling company 2) 2 whaling companies 3) 3 whaling companies.

Source: *International Whaling Statistics IV* (1933), Gunnar Jahn, "Review of the Results of International Whaling Statistics" p.15. The original source for these returns is Sigurd Risting *Av Hvalfangstens Historie*.

Table A4

Whaling off Iceland from 1890 to 1909

Year	Blue	Fin	Hump.	Sperm	Others ¹	Total
1890	79	23	1	-	57	160
1891	67	43	1	-	95	206
1892	122	47	1	-	146	316
1893	116	113	2	3	271	505
1894	196	79	8	2	238	523
1895	309	112	8	4	335	768
1896	327	45	6	1	413	792
1897	190	36	6	2	ca. 416	ca. 650
1898	216	57	66	6	451	796
1899	247	82	40	6	493	868
1900	234	95	26	1	467	823
1901	38	13	12	6	1123	1192
1902	21	18	14	3	1249	1305
1903	16	21	7	6	1207	1257
1904	19	40	7	4	913	983
1905	n/a	n/a	n/a	n/a	1041	1041
1906	n/a	n/a	n/a	n/a	650	650
1907	n/a	n/a	n/a	n/a	843	843
1908	n/a	n/a	n/a	n/a	761	761
1909	n/a	n/a	n/a	n/a	947	947

1) No specifications. The animals recorded here are chiefly blue- and fin-whales. Humpbacks were only caught in considerable numbers in the period 1898 to 1902. Only a few sei-whales. Sperm whales and nordcapers were only present in very scanty numbers.

Source: *International Whaling Statistics II* (1931) Sigurd Risting, "The Development of Modern Whaling" p.7

Table A5
Estimated Total Catch of Blue and Fin Whales from
1883 to 1909 Based on Sample Returns in Table A3 and A4 Above

Year	Blue share	Fin share	Other share	Total landed	Blue	Fin	Other
1883	1.0	0	0	8	8	0	0
1884	1.0	0	0	20	20	0	0
1885	1.0	0	0	21	21	0	0
1886	0.92	0.08	0	25	23	2	0
1887	0.875	0.125	0	40	35	5	0
1888	0.8536	0.1463	0	82	7	12	0
1889	0.3809	0.6031	0.016	65	25	39	1
1890	0.7212	0.267	0.0118	160	115	43	2
1891	0.5367	0.4526	0.0107	206	111	93	2
1892	0.6713	0.3217	0.007	316	212	102	2
1893	0.4452	0.5311	0.0237	505	225	268	12
1894	0.5848	0.3214	0.0938	523	306	168	49
1895	0.6760	0.2925	0.0315	768	519	225	24
1896	0.8354	0.1423	0.0223	792	662	113	18
1897	0.6855	0.2728	0.0417	650	446	177	27
1898	0.5535	0.2433	0.2032	796	441	194	162
1899	0.5932	0.2796	0.1272	868	515	243	110
1900	0.5646	0.3516	0.0838	823	465	289	69
1901	0.4618	0.3506	0.1875	1192	551	418	224
1902	0.3750	0.3214	0.3036	1305	489	419	396
1903	0.3200	0.4200	0.2600	1257	402	528	327
1904	0.2714	0.5714	0.1572	983	267	562	155
1905	0.25	0.6	0.15	1041	260	625	156
1906	0.25	0.6	0.15	650	163	390	98
1907	0.25	0.6	0.15	843	211	506	126
1908	0.25	0.6	0.15	761	190	457	114
1909	0.25	0.6	0.15	947	237	568	142
1910	0.184	0.672	0.144	649	119	436	93
1911	0.184	0.672	0.144	428	79	288	62
1912	0.184	0.672	0.144	176	32	118	25
1913	0.184	0.672	0.144	125	23	84	18
1914	0.4285	0.5714	0	35	15	20	0
1915	0.1666	0.8333	0	54	9	45	0
Total 1883 to 1915				17,216	7,316	7,484	2,416
Total 1889 to 1915				17,020	7,139	7,465	2,416

Sources:

1. The species breakdown for 1883 is known from IWS and Tønnessen and Johnsen. 2. The actual species caught 1913-1915 are known. Use 1913 for 1910 to 1912. The 1905 to 1909 shares are a guess.
3. Calculations by author.

Table A6
Whaling off Iceland 1948 to 1985

Year	Blue	Fin	Sei	Sperm	Humpback
1948	24	195	5	15	0
1949	33	249	12	28	2
1950	28	226	0	11	0
1951	11	312	2	13	1
1952	14	224	25	2	0
1953	5	207	70	48	2
1954	9	177	93	54	1
1955	10	236	134	20	0
1956	8	265	72	95	0
1957	10	348	78	81	0
1958	5	289	91	123	0
1959	6	178	67	120	0
1960	0	160	42	177	0
1961	0	142	58	150	0
1962	0	303	44	136	0
1963	0	283	20	136	0
1964	0	217	89	138	0
1965	0	289	74	69	0
1966	0	310	41	86	0
1967	0	239	48	119	0
1968	0	202	3	75	0
1969	0	251	69	103	0
1970	0	272	44	61	0
1971	0	208	240	106	0
1972	0	238	132	76	0
1973	0	267	138	47	0
1974	0	285	9	71	0
1975	0	245	138	37	0
1976	0	275	3	111	0
1977	0	144	131	110	0
1978	0	236	14	140	0
1979	0	260	84	96	0
1980	0	236	100	101	0
1981	0	254	100	43	0
1982	0	194	71	87	0
1983	0	144	100	0	0
1984	0	167	95	0	0
1985	0	161	38	0	0
1986	0	76	40	0	0

Source: *International Whaling Statistics* Various Years

Table A7

The Amount of Capital and Labour Employed in Whale Harvesting off Iceland 1948-1985.

Year	GRT	BHP	Manyr
1948	1020	4000	
1949	1020	4000	
1950	1020	4000	12
1951	1020	4000	
1952	1020	4000	
1953	1020	4000	
1954	1020	4000	
1955	1020	4000	
1956	1151	4200	
1957	1159	4600	
1958	1159	4600	
1959	1159	4600	
1960	1159	4600	20
1961	1240	4969	
1962	1729	7400	
1963	1729	7400	21.7
1964	1729	7400	22.1
1965	1729	7400	23.7
1966	1973	7900	25.9
1967	1973	7900	23.3
1968	1973	7900	22.9
1969	1973	7900	27.1
1970	1973	7900	34
1971	1973	7900	33.8
1972	1973	7900	30.9
1973	1973	7900	28.8
1974	1973	7900	29.2
1975	1973	7900	
1976	1973	7900	
1977	1973	7900	32
1978	1973	7900	38
1979	1973	7900	35
1980	1973	7900	32
1981	1973	7900	26
1982	1973	7900	26
1983	1546	7900	25
1984	1546	7900	27
1985	1546	7900	15

Notes:

GRT= Gross Registered Tonnage

BHP=Break Horse Power

Manyr=Manyyears

Table A8

Fin Whale Catches off Iceland 1883 to 1989

Year	Actual Catches	Actual Adjusted for Hits Lost at Sea
1883	0	0
1884	0	0
1885	0	0
1886	2	3
1887	5	7
1888	12	16
1889	39	51
1890	43	56
1891	93	121
1892	102	133
1893	268	348
1894	168	218
1895	225	293
1896	113	147
1897	177	230
1898	194	252
1899	243	316
1900	289	376
1901	418	543
1902	419	545
1903	528	686
1904	562	731
1905	625	813
1906	390	507
1907	506	658
1908	457	594
1909	568	738
1910	436	567
1911	288	374
1912	118	153
1913	84	109
1914	20	26
1915	45	59

1916 to 1928 there was no hunt.

Year	Actual Catches	Adjusted for Hits Lost at Sea
1929	192	192
1930	580	580
1931	456	456
1932	443	443
1933	549	549
1934	128	128
1935	25	25
1936	72	72
1937	517	517
1938	113	113
1939	109	109
1940 to 1947	there was no hunt	
1948	195	195
1949	249	249
1950	226	226
1951	312	312
1952	224	224
1953	207	207
1954	177	177
1955	236	236
1956	265	265
1957	348	348
1958	289	289
1959	178	178
1960	160	160
1961	142	142
1962	303	303
1963	283	283
1964	217	217
1965	289	289
1966	310	310
1967	239	239
1968	202	202
1969	251	251
1970	272	272
1971	208	208
1972	238	238
1973	267	267
1974	285	285
1975	245	245
1976	275	275
1977	144	144
1978	236	236
1979	260	260
1980	236	236
1981	254	254
1982	194	194
1983	144	144
1984	167	167
1985	161	161
1986	76	76

1987	80	80
1988	68	68
1989	68	68

Table A9

Gross National Product in Iceland at
1980 Prices

Year	IFS 99a.p GNP	Growth Rate	
1950	3,930		
1959	5,799	3.22	Average 1950-59
1960	6,013	3.56	
1961	6,048	0.58	
1962	6,575	8.02	
1963	7,229	9.05	
1964	7,935	8.90	
1965	8,499	6.64	
1966	9,219	7.81	
1967	9,042	-1.96	
1968	8,490	-6.50	
1969	8,759	3.07	3.915 Average 1960-69
1970	9,487	7.67	
1971	10,701	11.34	
1972	11,315	5.43	
1973	12,183	7.12	
1974	12,614	3.42	
1975	12,339	-2.23	
1976	12,690	2.77	
1977	14,161	10.39	
1978	15,000	5.59	
1979	15,754	4.79	5.629 Average 1970-79
1980	15,094	-4.37	
1981	15,338	1.59	
1982	15,104	-1.55	
1983	14,274	-5.81	
1984	14,666	2.67	
1985	15,292	4.09	
1986	16,249	5.89	2.328 Average 1977-86

3.63 Average 1960-1986

Source: International Monetary Fund, International Financial
Statistics, Yearbook, 1987

Table A10

NATIONAL ASSETS IN ICELAND AT THE
END OF YEAR 1945-82
Depreciated Repurchase Value

Year	Total at 1969 Prices	Volume Index National Assets	Growth Rate (index)
1945	39,269	100.0	
1946	43,630	111.1	9.99
1947	48,067	122.4	9.23
1948	50,783	129.3	5.34
1949	52,385	133.4	3.07
1950	53,225	135.5	1.55
1951	54,224	138.1	1.88
1952	55,256	140.7	1.85
1953	57,036	145.2	3.10
1954	59,170	150.7	3.65
1955	63,071	160.6	6.16
1956	66,419	169.1	5.03
1957	69,677	177.4	4.68
1958	72,880	185.6	4.42
1959	76,556	195.0	4.82
1960	80,210	204.3	4.55
1961	82,038	208.9	2.20
1962	85,600	218.0	4.17
1963	90,995	231.7	5.91
1964	97,180	247.4	6.35
1965	102,526	261.1	5.25
1966	110,139	280.5	6.92
1967	119,532	304.4	7.85
1968	123,693	315.0	3.37
1969	127,106	323.7	2.69
1970	131,572	335.1	3.40
1971	140,470	357.7	6.32
1972	148,085	377.1	5.14
1973	157,781	401.8	6.15
1974	170,100	433.0	7.21
1975	178,300	454.0	4.63
1976	185,800	473.0	4.02
1977	196,100	499.0	5.21
1978	203,700	519.0	3.85
1979	212,000	540.0	3.89
1980	221,400	564.0	4.26
1981	231,600	590.0	4.41
1982		613.0	3.75

Average 1948-1981

4.51

Source: Statistical Abstract of Iceland 1984

Appendix B

CATCH PER UNIT EFFORT REGRESSIONS FOR THE FIRST FIN WHALE JUNE 10 TO JULY 20 BY VESSEL.

1. VESSEL NUMBER 6.

The definition of variables is as follows:

FCPUE6=Fin whales caught per unit effort (hours) searched in the
June 10 July 20 time period.

TS6=Total search hours in the June 10 July 20 time period.

SPT6=Total number of sperm whales caught in the June 10-July 20
time period.

DUM79=Dummy variable that takes on a value of 1 after 1978 to
account for the cut in delivery times from 30 to 28 hours.

Time=Time trend variable.

The variables for vessels 7, 8 and 9 have the appropriate
subscripts.

SMPL range: 1962 - 1985

Number of observations: 24

Variable	Mean	S.D.	Maximum	Minimum
FCPUE6	0.0977500	0.0356349	0.1700000	0.0280000
TS6	209.75000	50.272518	314.00000	115.00000
SPT6	4.8333333	5.3215449	17.000000	0.0000000
DUM79	0.2916667	0.4643056	1.0000000	0.0000000
TIME	1973.5000	7.0710678	1985.0000	1962.0000

	Covariance	Correlation
FCPUE6, FCPUE6	0.0012169	1.0000000
FCPUE6, TS6	-1.4773125	-0.8604969
FCPUE6, SPT6	-0.0940417	-0.5174759
FCPUE6, DUM79	0.0053229	0.3357015
FCPUE6, TIME	-0.0142500	-0.0590116
TS6, TS6	2422.0208	1.0000000
TS6, SPT6	59.416667	0.2317519
TS6, DUM79	-5.4687500	-0.2444764
TS6, TIME	45.000000	0.1320931
SPT6, SPT6	27.138889	1.0000000
SPT6, DUM79	-1.2430556	-0.5249673
SPT6, TIME	-16.250000	-0.4506237
DUM79, DUM79	0.2065972	1.0000000
DUM79, TIME	2.4791667	0.7879528
TIME, TIME	47.916667	1.0000000

There is high correlation among SPT6, Time and Dum79. The regression of these variables together will inevitably involve some multicollinearity. This is a problem with all vessel specific CPUE data.

LS // Dependent Variable is FCPUE6
 SMPL range: 1962 - 1985
 Number of observations: 24

VARIABLE	COEFFICIENT	STD. ERROR	T-STAT.	2-TAIL SIG.
C	0.2256871	0.0165874	13.605907	0.0000
TS6	-0.0006100	7.699E-05	-7.9223534	0.0000
R-squared	0.740455	Mean of dependent var		0.097750
Adjusted R-squared	0.728657	S.D. of dependent var		0.035635
S.E. of regression	0.018562	Sum of squared resid		0.007580
Log likelihood	62.66839	F-statistic		62.76368
Durbin-Watson stat	2.156088	Prob(F-statistic)		0.000000

Residuals from this regression=RES61

Add: SPT6

```
=====
F-statistic      14.7066      Probability    0.0010
Likelihood ratio 12.7395      Probability    0.0004
=====
```

Add: TIME

```
=====
F-statistic      0.24889      Probability    0.6230
Likelihood ratio 0.28278      Probability    0.5949
=====
```

Add: DUM79

```
=====
F-statistic      1.44470      Probability    0.2428
Likelihood ratio 1.59678      Probability    0.2064
=====
```

SMPL range: 1962 - 1985

Number of observations: 24

```
=====
Variable          Mean          S.D.          Maximum      Minimum
=====
FCPUE6            0.0977500      0.0356349      0.1700000      0.0280000
RES61             6.791E-11      0.0181544      0.0339756     -0.0482940
SPT6              4.8333333      5.3215449      17.0000000      0.0000000
DUM79             0.2916667      0.4643056      1.0000000      0.0000000
TIME              1973.5000      7.0710678      1985.0000      1962.0000
=====
```

The high correlation of FCPUE6 and the residuals RES61 is a cause for concern, the model appears to be mis-specified.

	Covariance	Correlation
FCPUE6,FCPUE6	0.0012169	1.0000000
FCPUE6,RES61	0.0003159	0.5094557
FCPUE6,SPT6	-0.0940417	-0.5174759
FCPUE6,DUM79	0.0053229	0.3357015
FCPUE6,TIME	-0.0142500	-0.0590116
RES61,RES61	0.0003159	1.0000000
RES61,SPT6	-0.0578004	-0.6243018
RES61,DUM79	0.0019873	0.2460084
RES61,TIME	0.0131978	0.1072795
SPT6,SPT6	27.138889	1.0000000
SPT6,DUM79	-1.2430556	-0.5249673
SPT6,TIME	-16.250000	-0.4506237
DUM79,DUM79	0.2065972	1.0000000
DUM79,TIME	2.4791667	0.7879528
TIME,TIME	47.916667	1.0000000

LS // Dependent Variable is FCPUE6

SMPL range: 1962 - 1985

Number of observations: 24

VARIABLE	COEFFICIENT	STD. ERROR	T-STAT.	2-TAIL SIG.
C	0.1083267	0.0097124	11.153395	0.0000
RES61	0.5995439	0.4505831	1.3305955	0.1976
SPT6	-0.0021883	0.0015372	-1.4235916	0.1693
R-squared	0.324714	Mean of dependent var		0.097750
Adjusted R-squared	0.260401	S.D. of dependent var		0.035635
S.E. of regression	0.030646	Sum of squared resid		0.019723
Log likelihood	51.19391	F-statistic		5.048964
Durbin-Watson stat	2.130058	Prob(F-statistic)		0.016204

Add: DUM79

F-statistic	0.33437	Probability	0.5696
Likelihood ratio	0.39792	Probability	0.5282

Add: TIME

F-statistic	2.55369	Probability	0.1257
Likelihood ratio	2.88399	Probability	0.0895

LS // Dependent Variable is FCPUE6

SMPL range: 1962 - 1985

Number of observations: 24

VARIABLE	COEFFICIENT	STD. ERROR	T-STAT.	2-TAIL SIG.
C	0.1110173	0.0123449	8.9929577	0.0000
SPT6	-0.0031544	0.0014634	-2.1554967	0.0429
DUM79	0.0067852	0.0167728	0.4045372	0.6899
R-squared	0.273443	Mean of dependent var	0.097750	
Adjusted R-squared	0.204247	S.D. of dependent var	0.035635	
S.E. of regression	0.031788	Sum of squared resid	0.021220	
Log likelihood	50.31575	F-statistic	3.951728	
Durbin-Watson stat	1.912770	Prob(F-statistic)	0.034941	

Add: TIME

F-statistic	14.7289	Probability	0.0010
Likelihood ratio	13.2442	Probability	0.0003

The time trend coefficient in the following regression is the basis for the decline in relative abundance in the fin whale stock from vessel 6 in Chapter 5.

LS // Dependent Variable is FCPUE6

SMPL range: 1962 - 1985

Number of observations: 24

Add: TIME

VARIABLE	COEFFICIENT	STD. ERROR	T-STAT.	2-TAIL SIG.
C	9.0857067	2.3385011	3.8852694	0.0009
SPT6	-0.0034633	0.0011408	-3.0357985	0.0065
DUM79	0.0595824	0.0189570	3.1430212	0.0051
TIME	-0.0045546	0.0011868	-3.8378281	0.0010
R-squared	0.581584	Mean of dependent var		0.097750
Adjusted R-squared	0.518822	S.D. of dependent var		0.035635
S.E. of regression	0.024719	Sum of squared resid		0.012220
Log likelihood	56.93784	F-statistic		9.266443
Durbin-Watson stat	2.787279	Prob(F-statistic)		0.000479

2. VESSEL NUMBER 7.

The correlation among the independent variables is lower for vessel 7 than vessel 6.

SMPL range: 1962 - 1982

Number of observations: 21

Variable	Mean	S.D.	Maximum	Minimum
FCPUE7	0.0929241	0.0274756	0.1415090	0.0506320
TS7	213.33333	45.722350	288.00000	106.00000
SPT7	3.1428571	4.4077853	20.000000	0.0000000
DUM79	0.1904762	0.4023739	1.0000000	0.0000000
TIME	1972.0000	6.2048368	1982.0000	1962.0000
		Covariance	Correlation	
FCPUE7, FCPUE7		0.0007190	1.0000000	
FCPUE7, TS7		-1.0143795	-0.8478412	
FCPUE7, SPT7		-0.0509546	-0.4417793	
FCPUE7, DUM79		0.0028607	0.2717013	
FCPUE7, TIME		-0.0149607	-0.0921432	
TS7, TS7		1990.9841	1.0000000	
TS7, SPT7		52.857143	0.2753874	
TS7, DUM79		-5.8730159	-0.3351908	
TS7, TIME		-5.1428571	-0.0190342	
SPT7, SPT7		18.503401	1.0000000	
SPT7, DUM79		-0.3605442	-0.2134507	
SPT7, TIME		-9.8571429	-0.3784335	
DUM79, DUM79		0.1541950	1.0000000	
DUM79, TIME		1.6190476	0.6809085	
TIME, TIME		36.666667	1.0000000	

LS // Dependent Variable is FCPUE7

SMPL range: 1962 - 1982

Number of observations: 21

VARIABLE	COEFFICIENT	STD. ERROR	T-STAT.	2-TAIL SIG.
C	0.2016145	0.0159323	12.654448	0.0000
TS7	-0.0005095	7.310E-05	-6.9696409	0.0000
R-squared	0.718835	Mean of dependent var		0.092924
Adjusted R-squared	0.704036	S.D. of dependent var		0.027476
S.E. of regression	0.014947	Sum of squared resid		0.004245
Log likelihood	59.52074	F-statistic		48.57589
Durbin-Watson stat	1.743619	Prob(F-statistic)		0.000001

Add: SPT7

F-statistic	3.60794	Probability	0.0736
Likelihood ratio	3.83647	Probability	0.0501

Add: TIME

F-statistic	0.78357	Probability	0.3877
Likelihood ratio	0.89483	Probability	0.3442

Add: DUM79

F-statistic	0.01125	Probability	0.9167
Likelihood ratio	0.01312	Probability	0.9088

LS // Dependent Variable is FCPUE7

Date: 9-14-1991 / Time: 13:58

SMPL range: 1962 - 1982

Number of observations: 21

VARIABLE	COEFFICIENT	STD. ERROR	T-STAT.	2-TAIL SIG.
C	0.0983841	0.0077820	12.642444	0.0000
SPT7	-0.0025065	0.0013212	-1.8970609	0.0740
DUM79	0.0126920	0.0144735	0.8769104	0.3921
R-squared	0.228143	Mean of dependent var		0.092924
Adjusted R-squared	0.142381	S.D. of dependent var		0.027476
S.E. of regression	0.025444	Sum of squared resid		0.011654
Log likelihood	48.91725	F-statistic		2.660194
Durbin-Watson stat	1.976691	Prob(F-statistic)		0.097237

Add: TIME

F-statistic	10.0569	Probability	0.0056
Likelihood ratio	9.75929	Probability	0.0018

The time trend coefficient in the following regression is the basis for the decline in relative abundance in the fin whale stock from vessel 7 in Chapter 5.

LS // Dependent Variable is FCPUE7

SMPL range: 1962 - 1982

Number of observations: 21

Add: TIME

VARIABLE	COEFFICIENT	STD. ERROR	T-STAT.	2-TAIL SIG.
C	6.8506508	2.1292164	3.2174516	0.0051
SPT7	-0.0036841	0.0011398	-3.2321109	0.0049
DUM79	0.0459052	0.0157813	2.9088326	0.0098
TIME	-0.0034254	0.0010801	-3.1712590	0.0056
R-squared	0.515038	Mean of dependent var		0.092924
Adjusted R-squared	0.429456	S.D. of dependent var		0.027476
S.E. of regression	0.020753	Sum of squared resid		0.007322
Log likelihood	53.79689	F-statistic		6.018093
Durbin-Watson stat	2.625255	Prob(F-statistic)		0.005498

3. VESSEL NUMBER 8

SMPL range: 1962 - 1986

Number of observations: 25

Variable	Mean	S.D.	Maximum	Minimum
FCPUE8	0.0866932	0.0302995	0.1558440	0.0428010
TS8	227.08000	48.158523	316.00000	115.00000
SPT8	3.9200000	4.8641546	16.000000	0.0000000
DUM79	0.3200000	0.4760952	1.0000000	0.0000000
TIME	1974.0000	7.3598007	1986.0000	1962.0000
		Covariance	Correlation	
FCPUE8, FCPUE8		0.0008813	1.0000000	
FCPUE8, TS8		-1.2464113	-0.8897781	
FCPUE8, SPT8		-0.0585177	-0.4135929	
FCPUE8, DUM79		0.0033156	0.2394210	
FCPUE8, TIME		0.0007988	0.0037311	
TS8, TS8		2226.4736	1.0000000	
TS8, SPT8		69.406400	0.3086368	
TS8, DUM79		-3.7856000	-0.1719873	
TS8, TIME		-4.0400000	-0.0118733	
SPT8, SPT8		22.713600	1.0000000	
SPT8, DUM79		-1.0144000	-0.4562856	
SPT8, TIME		-13.960000	-0.4062008	
DUM79, DUM79		0.2176000	1.0000000	
DUM79, TIME		2.7200000	0.8086075	
TIME, TIME		52.000000	1.0000000	

LS // Dependent Variable is FCPUE8
 SMPL range: 1962 - 1986
 Number of observations: 25

VARIABLE	COEFFICIENT	STD. ERROR	T-STAT.	2-TAIL SIG.
C	0.2138158	0.0138866	15.397288	0.0000
TS8	-0.0005598	5.987E-05	-9.3498849	0.0000
R-squared	0.791705	Mean of dependent var		0.086693
Adjusted R-squared	0.782649	S.D. of dependent var		0.039299
S.E. of regression	0.014126	Sum of squared resid		0.004589
Log likelihood	72.06243	F-statistic		87.42035
Durbin-Watson stat	2.262332	Prob(F-statistic)		0.000000

Add: SPT8

F-statistic	2.51217	Probability	0.1272
Likelihood ratio	2.70318	Probability	0.1001

Add: DUM79

F-statistic	0.84344	Probability	0.3684
Likelihood ratio	0.94054	Probability	0.3321

Add: TIME

F-statistic	0.00493	Probability	0.9446
Likelihood ratio	0.00561	Probability	0.9403

LS // Dependent Variable is FCPUE8

Date: 9-14-1991 / Time: 13:58

SMPL range: 1962 - 1986

Number of observations: 25

VARIABLE	COEFFICIENT	STD. ERROR	T-STAT.	2-TAIL SIG.
C	0.0947748	0.0101247	9.3607460	0.0000
SPT8	-0.0023943	0.0013562	-1.7654862	0.0914
DUM79	0.0040754	0.0138558	0.2941300	0.7714
R-squared	0.174306	Mean of dependent var		0.086693
Adjusted R-squared	0.099243	S.D. of dependent var		0.030299
S.E. of regression	0.028757	Sum of squared resid		0.018193
Log likelihood	54.84656	F-statistic		2.322127
Durbin-Watson stat	1.758077	Prob(F-statistic)		0.121621

Add: TIME

F-statistic	3.60763	Probability	0.0713
Likelihood ratio	3.96335	Probability	0.0465

The time trend coefficient in the following regression is the basis for the decline in relative abundance in the fin whale stock from vessel 8 in Chapter 5.

LS // Dependent Variable is FCPUE8

SMPL range: 1962 - 1986

Number of observations: 25

Add: TIME

VARIABLE	COEFFICIENT	STD. ERROR	T-STAT.	2-TAIL SIG.
C	4.9039770	2.5320097	1.9367923	0.0663
SPT8	-0.0025680	0.0012856	-1.9975803	0.0589
DUM79	0.0337749	0.0203994	1.6556770	0.1127
TIME	-0.0024407	0.0012850	-1.8993752	0.0713
R-squared	0.295358	Mean of dependent var		0.086693
Adjusted R-squared	0.194695	S.D. of dependent var		0.030299
S.E. of regression	0.027190	Sum of squared resid		0.015526
Log likelihood	56.82824	F-statistic		2.934119
Durbin-Watson stat	2.016864	Prob(F-statistic)		0.057100

4. VESSEL NUMBER 9.

SMPL range: 1966 - 1986
 Number of observations: 21

Variable	Mean	S.D.	Maximum	Minimum
FCPUE9	0.0906540	0.0284997	0.1474350	0.0370370
TS9	228.80952	54.757300	338.00000	129.00000
SPT9	1.6190476	2.3764720	9.0000000	0.0000000
DUM79	0.3809524	0.4976134	1.0000000	0.0000000
TIME	1976.0000	6.2048368	1986.0000	1966.0000
		Covariance	Correlation	
FCPUE9, FCPUE9		0.0007736	1.0000000	
FCPUE9, TS9		-1.2187887	-0.8200413	
FCPUE9, SPT9		-0.0421692	-0.6537501	
FCPUE9, DUM79		0.0029454	0.2180701	
FCPUE9, TIME		-0.0234296	-0.1391180	
TS9, TS9		2855.5828	1.0000000	
TS9, SPT9		61.832200	0.4989181	
TS9, DUM79		-6.7369615	-0.2596087	
TS9, TIME		-3.8095238	-0.0117730	
SPT9, SPT9		5.3786848	1.0000000	
SPT9, DUM79		-0.6167800	-0.5476397	
SPT9, TIME		-2.9523810	-0.2102319	
DUM79, DUM79		0.2358277	1.0000000	
DUM79, TIME		2.4761905	0.8420754	
TIME, TIME		36.666667	1.0000000	

LS // Dependent Variable is FCPUE9

SMPL range: 1966 - 1986

Number of observations: 21

VARIABLE	COEFFICIENT	STD. ERROR	T-STAT.	2-TAIL SIG.
C	0.1812426	0.0211374	8.5744793	0.0000
TS8	-0.0004044	9.220E-05	-4.3861375	0.0003
R-squared	0.503115	Mean of dependent var		0.090654
Adjusted R-squared	0.476963	S.D. of dependent var		0.028500
S.E. of regression	0.020611	Sum of squared resid		0.008072
Log likelihood	52.77336	F-statistic		19.23820
Durbin-Watson stat	1.875244	Prob(F-statistic)		0.000318

Add: SPT9

F-statistic	13.1959	Probability	0.0019
Likelihood ratio	11.5482	Probability	0.0007

Add: TIME

F-statistic	0.11400	Probability	0.7395
Likelihood ratio	0.13257	Probability	0.7158

Add: DUM79

F-statistic	0.53217	Probability	0.4751
Likelihood ratio	0.61187	Probability	0.4341

LS // Dependent Variable is FCPUE9

Date: 9-14-1991 / Time: 13:59

SMPL range: 1966 - 1986

Number of observations: 21

VARIABLE	COEFFICIENT	STD. ERROR	T-STAT.	2-TAIL SIG.
C	0.1098345	0.0089625	12.254892	0.0000
SPT9	-0.0091529	0.0024931	-3.6712408	0.0017
DUM79	-0.0114489	0.0119066	-0.9615618	0.3490
R-squared	0.455365	Mean of dependent var		0.090654
Adjusted R-squared	0.394850	S.D. of dependent var		0.028500
S.E. of regression	0.022170	Sum of squared resid		0.008847
Log likelihood	51.80992	F-statistic		7.524836
Durbin-Watson stat	1.586485	Prob(F-statistic)		0.004216

Add: TIME

F-statistic	3.17459	Probability	0.0927
Likelihood ratio	3.59542	Probability	0.0579

The time trend coefficient in the following regression is the basis for the decline in relative abundance in the fin whale stock from vessel 9 in Chapter 5.

LS // Dependent Variable is FCPUE9

SMPL range: 1966 - 1986

Number of observations: 21

Add: TIME

VARIABLE	COEFFICIENT	STD. ERROR	T-STAT.	2-TAIL SIG.
C	6.0172827	3.3155650	1.8148589	0.0872
SPT9	-0.0063461	0.0028333	-2.2398497	0.0388
DUM79	0.0273855	0.0245264	1.1165742	0.2797
TIME	-0.0029994	0.0016834	-1.7817378	0.0927
R-squared	0.541067	Mean of dependent var		0.090654
Adjusted R-squared	0.460078	S.D. of dependent var		0.028500
S.E. of regression	0.020941	Sum of squared resid		0.007455
Log likelihood	57.60763	F-statistic		6.680807
Durbin-Watson stat	1.002525	Prob(F-statistic)		0.003511

5. THE SUM OF CATCH AND EFFORT FOR VESSELS 6-9 FOR JUNE 10 JULY 20.

SMPL range: 1966 - 1982
Number of observations: 17

Variable	Mean	S.D.	Maximum	Minimum
AGCPUE69	0.0903298	0.0272643	0.1314199	0.0413307
AGTS69	878.88235	191.98661	1127.0000	490.00000
AGSPERM	12.882353	10.307051	37.000000	0.0000000
DUM79	0.2352941	0.4372373	1.0000000	0.0000000
TIME	1974.0000	5.0497525	1982.0000	1966.0000
		Covariance	Correlation	
AGCPUE69, AGCPUE69		0.0006996	1.0000000	
AGCPUE69, AGTS69		-4.2127723	-0.8551279	
AGCPUE69, AGSPERM		-0.1984864	-0.7504650	
AGCPUE69, DUM79		0.0056555	0.5040628	
AGCPUE69, TIME		0.0030799	0.0237684	
AGTS69, AGTS69		34690.692	1.0000000	
AGTS69, AGSPERM		1262.4567	0.6778601	
AGTS69, DUM79		-36.384083	-0.4605239	
AGTS69, TIME		-98.470588	-0.1079181	
AGSPERM, AGSPERM		99.986159	1.0000000	
AGSPERM, DUM79		-2.1487889	-0.5066069	
AGSPERM, TIME		-6.9411765	-0.1416960	
DUM79, DUM79		0.1799308	1.0000000	
DUM79, TIME		1.5294118	0.7359801	
TIME, TIME		24.000000	1.0000000	

LS // Dependent Variable is AGCPUE69
 SMPL range: 1966 - 1982
 Number of observations: 17

VARIABLE	COEFFICIENT	STD. ERROR	T-STAT.	2-TAIL SIG.
C	0.1970596	0.0170776	11.539038	0.0000
AGTS69	-0.0001214	1.901E-05	-6.3884784	0.0000
R-squared	0.731244	Mean of dependent var		0.090330
Adjusted R-squared	0.713327	S.D. of dependent var		0.027264
S.E. of regression	0.014598	Sum of squared resid		0.003196
Log likelihood	48.79892	F-statistic		40.81266
Durbin-Watson stat	1.969164	Prob(F-statistic)		0.000012

The residuals from this regression=AGRES1.

Add: AGSPERM

F-statistic	3.51846	Probability	0.0817
Likelihood ratio	3.81137	Probability	0.0509

Add: TIME

F-statistic	0.25187	Probability	0.6236
Likelihood ratio	0.30312	Probability	0.5819

Add: DUM79

F-statistic	0.85264	Probability	0.3714
Likelihood ratio	1.00505	Probability	0.3161

SMPL range: 1966 - 1982
 Number of observations: 17

Variable	Mean	S.D.	Maximum	Minimum
AGCPUE69	0.0903298	0.0272643	0.1314199	0.0413307
AGRES1	1.712E-10	0.0141343	0.0168929	-0.0352623
AGSPERM	12.882353	10.307051	37.000000	0.0000000
DUM79	0.2352941	0.4372373	1.0000000	0.0000000
TIME	1974.0000	5.0497525	1982.0000	1966.0000
		Covariance	Correlation	
AGCPUE69, AGCPUE69		0.0006996	1.0000000	
AGCPUE69, AGRES1		0.0001880	0.5184171	
AGCPUE69, AGSPERM		-0.1984864	-0.7504650	
AGCPUE69, DUM79		0.0056555	0.5040628	
AGCPUE69, TIME		0.0030799	0.0237684	
AGRES1, AGRES1		0.0001880	1.0000000	
AGRES1, AGSPERM		-0.0451761	-0.3294798	
AGRES1, DUM79		0.0012370	0.2126780	
AGRES1, TIME		-0.0088782	-0.1321626	
AGSPERM, AGSPERM		99.986159	1.0000000	
AGSPERM, DUM79		-2.1487889	-0.5066069	
AGSPERM, TIME		-6.9411765	-0.1416960	
DUM79, DUM79		0.1799308	1.0000000	
DUM79, TIME		1.5294118	0.7359801	
TIME, TIME		24.000000	1.0000000	

LS // Dependent Variable is AGCPUE69

SMPL range: 1966 - 1982

Number of observations: 17

VARIABLE	COEFFICIENT	STD. ERROR	T-STAT.	2-TAIL SIG.
C	0.1124879	0.0071186	15.801985	0.0000
AGRES1	0.5867366	0.3250201	1.8052314	0.0926
AGSPERM	-0.0017200	0.0004457	-3.8591173	0.0017
R-squared	0.645676	Mean of dependent var		0.090330
Adjusted R-squared	0.595058	S.D. of dependent var		0.027264
S.E. of regression	0.017350	Sum of squared resid		0.004214
Log likelihood	46.44946	F-statistic		12.75592
Durbin-Watson stat	2.453025	Prob(F-statistic)		0.000701

Add: DUM79

F-statistic	0.62749	Probability	0.4425
Likelihood ratio	0.80138	Probability	0.3707

Add: TIME

F-statistic	0.03091	Probability	0.8631
Likelihood ratio	0.04038	Probability	0.8407

LS // Dependent Variable is AGCPUE69

SMPL range: 1966 - 1982

Number of observations: 17

VARIABLE	COEFFICIENT	STD. ERROR	T-STAT.	2-TAIL SIG.
C	0.1105813	0.0098030	11.280404	0.0000
AGSPERM	-0.0017618	0.0005290	-3.3306818	0.0050
DUM79	0.0103910	0.0124695	0.8333174	0.4187
R-squared	0.583840	Mean of dependent var		0.090330
Adjusted R-squared	0.524388	S.D. of dependent var		0.027264
S.E. of regression	0.018803	Sum of squared resid		0.004950
Log likelihood	45.08217	F-statistic		9.820447
Durbin-Watson stat	2.183531	Prob(F-statistic)		0.002162

Add: TIME

F-statistic	3.93181	Probability	0.0689
Likelihood ratio	4.49216	Probability	0.0341

The time trend coefficient in the following regression is the basis for the decline in relative abundance in the fin whale stock from vessels 6-9 in Chapter 5.

LS // Dependent Variable is AGCPUE69

SMPL range: 1966 - 1982

Number of observations: 17

Add: TIME

VARIABLE	COEFFICIENT	STD. ERROR	T-STAT.	2-TAIL SIG.
C	5.4283851	2.6818738	2.0241016	0.0640
AGSPERM	-0.0013505	0.0005238	-2.5781294	0.0229
DUM79	0.0382528	0.0180554	2.1186279	0.0540
TIME	-0.0026999	0.0013616	-1.9828797	0.0689
R-squared	0.680478	Mean of dependent var		0.090330
Adjusted R-squared	0.606742	S.D. of dependent var		0.027264
S.E. of regression	0.017098	Sum of squared resid		0.003800
Log likelihood	47.32825	F-statistic		9.228603
Durbin-Watson stat	2.875344	Prob(F-statistic)		0.001554

END

28·0|5·92

FIN