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Economics and the Resumption of Commercial Whaling

by

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ABSTRACT

There is now strong scientific evidence that several species of baleen whale and possibly the sperm whale, have recovered to levels that would support commercial harvest. The stock of fin whales (*Balaenoptera physalus*) off the eastern coast of Iceland and the minke whale (*Balaenoptera acutorostrata*) in the Northeast Atlantic, off the coast of Japan and in the Southern Ocean are prime candidates for commercial harvest. Should commercial whaling be resumed? If so, what role should economics play in determining the level of harvest and management policies?

A bioeconomic model for baleen whales is developed and applied to the stock of minke whales in the Northeast Atlantic. A delay-difference equation is used to model the population dynamics and an exponential production function is estimated relating harvest, to population size and the number of catcher vessels. If whaling is resumed, the optimal stock size and harvest may critically depend on the price-cost ratio and catcher productivity. We identify plausible combinations of price, cost and productivity where whaling is not optimal and the minke whale population in the Northeast Atlantic equilibrates at about 82,000 adult animals. Under a high price-cost ratio and high catcher productivity, the optimal stock ranges from 51,000 to 59,000 whales supporting a harvest of 1,600 to 1,750 whales by 90 to 115 catchers.

The paper examines two economic arguments that might be advanced for prohibition of commercial whaling. The first is utilitarian in nature and the second is based on the extension of rights traditionally reserved for *homo sapiens*. The paper advocates a tolerant position, where individuals of different countries democratically choose whether they wish to allow or ban whaling and the import of whale products, with the proviso that no stock be threatened with extinction.

Key Words: economics, whaling, minke whale

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I. Introduction and Overview

In 1986 the International Whaling Commission (IWC) declared a five-year moratorium on commercial whaling. The moratorium had been adopted for at least three reasons. First, there was scientific evidence that many of the stocks of baleen whales were dangerously depleted and making only slow recovery from the intensive whaling that had taken place between the two World Wars and in the thirty-year period following World War II.[1] Second, there was a conspicuous lack of information on the status of many stocks, and therefore little basis for making informed decisions on allowable harvest.[2] Third, and perhaps most important, the whale had become a powerful symbol within the environmental movement. For many, the depleted stocks of baleen whales, in particular the blue whale (*Balaenoptera musculus*), typified the "tragic" result of man's exploitation of the environment and common property resources.

During the moratorium several countries, including Iceland, Japan and Norway, continued to harvest a limited number of whales for scientific purposes. Eskimos in Alaska and Greenland and the

Inuit of the Canadian Arctic were also allowed to harvest the bowhead whale (*Balaena mysticetus*), the beluga whale (*Delphinapterus leucas*) and the narwhal (*Monodon monoceros*) under the IWC's aboriginal exemption; provided that such harvests did not threaten a stock with extinction.

It was agreed that during the moratorium scientific surveys would be conducted to estimate current stock size and to provide a basis for estimating life-history parameters, important in modeling the dynamics of whale populations. Updated stock estimates were to be presented at the IWC meetings in Reykjavik, Iceland in May of 1991 and the IWC would then determine whether the moratorium should be extended or whether commercial whaling might resume. If commercial whaling were allowed, harvest would presumably come from stocks which the IWC classified as "sustained management" or "initial management." A sustained management stock is one estimated to lie within 10% below to 20% above the stock level supporting maximum sustainable yield (X_{MSY}), while an initial management stock would have recovered to more than 20% above X_{MSY}. Stocks lying more than 10% below X_{MSY} would remain protected under the current IWC classification system (Breiwick 1983).

There is, of course, a more fundamental question. Should whales be harvested at all? Different cultures have answered this question differently at different times. The answer may hinge on the degree to which a society has vested rights traditionally reserved for *homo sapiens* to other animal species. We will return to this question and some of the economic dimensions of the animal-rights movement in Section IV.

If commercial whaling is resumed, how should economic factors, like the cost of harvest, the prices for whale products and the rate of discount affect the optimal stock and rate of harvest? Spence (1974) was one of the first economists to develop a bioeconomic model and apply it to the stock of blue whales in the Southern Ocean.[3] While innovative, Spence's model of population dynamics was unrealistic, and led to implausible rates of recovery.[4]

Clark (1976) employs a more realistic delay-difference equation to describe the population dynamics of the fin whale (*Balaenoptera physalus*), also in the Southern Ocean. His cost function, however, is derived from a Cobb-Douglas production function which is an unrealistic form when harvesting from a stock resource.[5]

Clark and Lamberson (1982) provide an economic history of modern whaling in the Southern Ocean and develop an aggregate model of optimal harvest which draws from the theoretical work of Clark, Clarke and Munro (1979). A simple continuous-time model, employing a symmetric logistic function and a Cobb-Douglas production function, is used to estimate the optimal stock of baleen whales (in blue whale units) and the sustainable harvest it would support.

Conrad (1989) develops a model to examine the hunt for the bowhead whale as conducted by the the Alaskan Eskimo. The hunt contributes to the continuity of cultural traditions and the subsistence economy within Eskimo villages. No formal production function was specified; rather the optimal stock and harvest were determined as a function of the discount rate and a relative weight assigned to the stock of bowhead whales.

The purpose of this paper is to develop a more realistic model of commercial whaling; one that is based on a delay-difference equation for growth and an exponential production function. The model is applied to the stock of minke whales (*Balaenoptera acutorostrata*) in the Northeast Atlantic. This stock was never regarded as endangered and is a candidate for commercial harvest.[6]

We identify economic conditions where the resumption of commercial whaling is optimal and where it is not.

In the next section we present a model of population dynamics for baleen whales. This is followed by a section which develops a bioeconomic model. In both of these sections we will identify plausible functional forms and estimate or assign parameter values thought to be appropriate for the minke whale in the Northeast Atlantic. We then derive rules for optimal escapement, stock, harvest and effort, provide numerical solutions for a range of economic parameters and identify conditions when commercial harvest might be economically justified. The fourth section examines the economic basis of certain animal-rights arguments to prevent the resumption of commercial whaling. The fifth section summarizes our major conclusions.

II. Population Dynamics

The dynamics of whale populations are frequently modeled using a delay-difference equation (Clark 1976). If the species is not subject to harvest this equation might take the general form

$$X_{t+1} = (1 - M)X_t + F(X_{t-\tau}) \qquad (1)$$

where X_t is the stock of adult (sexually mature) whales in year t, M is annual rate of mortality in adults and $F(X_{t-\tau})$ is a recruitment function defining the recruits to the adult population in year t+1 as a function of the adult population in year t-τ. The recruitment function is assumed to incorporate certain environmental constraints including the overall availability of food and its effect on the relative rate of population growth.

If the adult population is unchanging over some interval of time, then natural mortality is precisely offset by recruitment and $MX_0 = F(X_0)$. The equilibrium or fixed point, X_0, will be stable if $|F'(X_0)| < M$, where $F'(\cdot)$ is the first derivative of $F(\cdot)$. The equilibrium stock is sometimes used as an estimate of the "pristine population," that is, the population in existence prior to the start of commercial exploitation. With a particular functional form for $F(X_{t-\tau})$ it may be possible to solve explicitly for X_0.

With a commercial harvest of $Y_t < X_t$ adult whales per year it is useful to define escapement as $Z_t = X_t - Y_t > 0$. Equation (1) is then modified to become

$$X_{t+1} = (1 - M)Z_t + F(Z_{t-\tau}) \tag{2}$$

Thus, the adult stock in year t+1 is determined by the unharvested adults which survive from year t, plus recruitment, which is a function of escapement in year $t-\tau$.

The generalized logistic function is often used in modeling whale populations. In this case the recruitment function takes the form

$$F(X_{t-\tau}) = rX_{t-\tau}[1 - (X_{t-\tau}/K)^{\alpha}] \tag{3}$$

where r is the intrinsic growth rate, K is a carrying capacity parameter, and α is a parameter that causes the recruitment function to become skewed. If $\alpha > 1$, then the generalized logistic is skewed to the left and the maximum recruitment level, X_{MR}, lies above 0.5K. The IWC regards maximum recruitment as occurring at about 0.6K, which is the case when $\alpha = 2.39$. For the generalized logistic the pristine population is given by $X_0 = K[(r-M)/r]^{1/\alpha}$.

In addition to α, there are four other parameters, M, r, K and τ which must be estimated if one wishes to simulate population dynamics using the generalized logistic. While specific estimates of all of these parameters for the minke whale population in the Northeast Atlantic are lacking, values are available from studies of other minke whale stocks or from models of other species of baleen whale.

Walløe et al. (1987) use an annual mortality rate of 0.10 in their study of the minke whale stock in the northeast Atlantic. The age at sexual maturity appears to vary by sex, with females reaching maturity at about 7 years, and males at about six years of age (Christensen 1981). We set $\tau = 7$, a value that is also used by Walløe et al. (1987).

Estimates for r and K are particularly troublesome. We ran several simulations with $M = 0.10$, $\tau = 7$ and various combinations of r and K. The results when $r = 0.15$ and $K = 130{,}000$ are shown in Table 1. These values imply a pristine population level of $X_0 = 82{,}093$ whales. This seems to be a conservative result, given that over 100,000 whales were harvested by Norwegian whalers between 1938 and 1987 and that recent estimates by Ugland (1986) place the current stock between 50,000 and 80,000 whales.

In Table 1, the data on harvest comes from Øien et al. (1987) and Statistisk Sentralbyrå (1989). Data on vessel numbers prior to 1946 were not available. For the period 1946 to 1987 the data on vessel numbers comes from Statistisk Sentralbyrå (1978 and 1989).

In simulating the minke whale population it was assumed that the stock was in equilibrium at the pristine population for the years 1931 -1938 and that whaling effectively commenced in 1938. According to this simulation the stock of minke whales declines from the pristine population to a low of slightly less than 52,000 whales in 1973, after which it slowly climbs to 58,742 in 1990. Our estimates of stock size are plotted in Figure 2, while harvest and vessel numbers are plotted in Figures 1 and 3, respectively.

Variations in the underlying parameters will result in different stock estimates. By reducing r or increasing M it is possible to reduce the population to significantly lower levels.[7] The resulting 1990 population, however, is then below the lower bound estimates of recent studies using mark-recapture, transect or other stock assessment methods.

While there is considerable uncertainty over these biological parameters, they are individually plausible and they collectively lead to estimates of the pristine population, X_0, and stock in 1990 which are conservative. This will lead to estimates of biologically sustainable harvest that we also regard as conservative.

III. Bioeconomics

If commercial harvest is resumed it will probably be necessary to regulate the hunt in order to avoid the inefficiencies of open access. An optimal quota and fleet size can be calculated for the minke whale stock in the Northeast Atlantic. It will depend, in part, on the efficiency, prices and cost facing the remnants of a fleet which has been idle or regeared for other fisheries.

Suppose that the price per harvested whale is constant, denoted by p, and that the cost of harvesting Y_t whales from a population of size X_t is given by the cost function $C(X_t, Y_t)$. Net revenue in year t may then be written as

$$\pi(X_t, Y_t) = pY_t - C(X_t, Y_t) \tag{4}$$

Maximization of the present value of net revenue subject to the dynamics of the whale population may be stated as

$$\begin{aligned} &\text{Maximize} \quad \sum_{t=0}^{\infty} \rho^t \, \pi(X_t, Y_t) \\ &\text{Subject to} \quad X_{t+1} = (1 - M)Z_t + F(Z_{t-\tau}) \\ &\qquad\qquad\quad\;\; Z_t = X_t - Y_t \end{aligned}$$

where $\rho = 1/(1 + \delta)$ is a discount factor and δ is the rate of discount.

Conrad (1989) derives the first-order necessary conditions for this problem. When they are evaluated in steady state, optimal escapement will be defined by the equation

$$\left[\frac{\pi_X + \pi_Y}{\pi_Y}\right][1 - M + \rho^{\tau} F'(Z)] = 1 + \delta \tag{5}$$

where π_X and π_Y are the partial derivatives of $\pi(X,Y)$ and $F'(Z)$ is the first derivative of the recruitment function.

Suppose the production function, relating harvest to stock size and effort takes the exponential form $Y = X(1 - e^{-qE})$, where E is the level of effort and the parameter $q > 0$ might be referred to as the "catchability coefficient."

If the unit cost of effort is constant, denoted by c, then total cost in any year is given by the cost equation $C = cE$. Solving the production function for E as a function of X and Y and substituting into the cost equation one obtains a cost function which takes the form $C = (c/q)\ln[X/(X - Y)]$, where $\ln[\cdot]$ denotes the natural log operator. Substituting this function into the expression for net revenue leads to the partial derivatives $\pi_X = cY/[qX(X - Y)]$ and $\pi_Y = [pq(X - Y) - c]/[q(X - Y)]$. If these partial derivatives are substituted into equation (5), defining optimal escapement, and using the definition $Z = X - Y$, it is possible (after quite a bit of algebra) to obtain an expression defining X as a function of Z. This takes the form

$$X = \frac{Z[1-M+\rho^{\tau}r(1-(\alpha+1)(Z/K)^{\alpha})]}{(p/c)qZ[\rho^{\tau}r(1-(\alpha+1)(Z/K)^{\alpha})-(\delta+M)]+(1+\delta)} \tag{6}$$

Evaluating the delay-difference equation in steady state, it is possible to obtain an expression defining Y as a function of Z. This is less tedious algebraically, and takes the form

$$Y = [r - M - r(Z/K)^{\alpha}]Z \tag{7}$$

By substituting the last two expressions into the definition of escapement we can obtain a single expression in Z. Unfortunately, it is not possible to obtain an explicit expression for optimal escapement, but we can write the implicit form as

$$G(Z) = \theta(Z)\{(p/c)qZ[\phi(Z)-(\delta+M)]+(1+\delta)\}-[1-M+\phi(Z)] \tag{8}$$

where $\phi(Z)=\rho^{\tau}r(1-(\alpha+1)(Z/K)^{\alpha})$ and $\theta(Z)=1+r-M-r(Z/K)^{\alpha}$. Optimal escapement is a root or zero of G(Z). If a root exists, the optimal values of X and Y can be obtained from equations (6) and (7).

The optimal level of escapement depends on the five biological parameters α, M, r, K and τ and on three economic parameters; q, (p/c) and δ. With our simulated values for the minke whale stock we are in a position to directly estimate a production function. While this stock was harvested commercially until 1988, the fleet of Norwegian vessels came under quota restrictions as early as 1973 (Walløe et al. 1987). We opted for a sample period from 1952 through 1972 and estimated the exponential production function $Y = X(1 - e^{-qE})$ by regressing $\ln[(X - Y)/X]$ on effort, E, measured as the vessel numbers. One would anticipate a negative coefficient on effort and an insignificant constant.

The results are shown in Table 2 for OLS regressions with and without correction for first-order autocorrelation. The estimate for q is 2.7045E-4 without correction and 2.4465E-4 with correction and both are significant at the 1% level. The constant is not significant at the 5% level in either regression. In the numerical analysis that follows q will be set at 2.0E-4, 2.5E-4 and 3.0E-4.

The relative price-cost ratio (p/c) was calculated for the years 1980-1987. Table 3 contains data on the total number of whales taken by vessels in the small-whale fleet and the total revenue (in nominal Norwegian Kroner) obtained from meat and blubber. Dividing total revenue by the number of whales we obtain a price per whale. Table 3 also contains estimates of the operating cost of a small-whale vessel for an entire season of approximately 36 weeks. During each season vessels would typically participate in other fisheries. It was estimated that during this period approximately 35 to 41 percent of operating time was spent whaling. The p/c ratios in the right-most column of Table 3 are calculated by dividing price per whale by cost per vessel. If it were appropriate to prorate costs to different fisheries by their percentage of time during a full season, then the (p/c) ratios might increase by a factor of 1/(0.38) = 2.63. We set (p/c) at 0.05, 0.07 and 0.09, which, as it turns out, covers a critical range of operating behavior and resource management.

The final economic parameter needed to calculate optimal escapement is δ, the discount rate. In our sensitivity analysis, we set δ at 0.02, 0.04 and 0.06. A simple interactive algorithm was developed to find the zero of G(Z) in equation (8) which proved to be unique and stable. The results are displayed in Table 4.

There are three blocks to Table 4 corresponding to the base-case q = 2.5E-4 and then a less productive fleet (q = 2.0E-4) and a more productive fleet (q = 3.0E-4). Within each block the price-cost ratio is varied vertically and the discount rate horizontally. For the base-case q and the median values of (p/c) and δ, the optimal stock is 68,142 adult whales supporting a harvest of 1,297 adults taken by 77 catcher boats. Within the base-case q block, the optimal stock ranges from a high level 81,052 whales [at (p/c) = 0.05 and δ = 0.02] to a low of 57,770 whales [at (p/c) = 0.09 and δ = 0.06]. The high stock was associated with a harvest of 137 whales taken by 7 catcher boats, while the low stock was associated with a harvest 1,675 whales taken by 118 vessels.

When the catchability coefficient is reduced to q = 2.0E-4, we observe that whaling becomes unprofitable at the low price-cost ratio. In the long run the stock returns to X_0 = 82,093 whales. In general, the reduction in q causes an increase in the optimal stock and a decrease in harvest and fleet size, *ceteris paribus*.

The case where whaling becomes unprofitable due to a low price-cost ratio may be of relevance if commercial whaling is resumed. In 1981, when a total of 1,890 whales were harvested from

Northeast and Central stocks (see Table 3), the adjusted price-cost ratio would have been (2.63)•(0.02) = 0.0526. At this ratio whaling would have been unprofitable for vessels with a catchability coefficient of q = 2.0E-4. It is not known what the price elasticity for whale meat will be in the primary fish markets of Japan. It is also not known if Japan will commence whaling from stocks in their coastal waters, nor the number of whales they might harvest. If markets are slow to expand and demand is inelastic, the resumption of commercial whaling may be short-lived for purely economic reasons.

The final block in Table 4 corresponds to the high productivity case. Here the optimal stock may fall as low as 51,538 whales; below the minimum of our simulation in Table 1. This stock would be optimal under a high price-cost ratio and a high discount rate. In this case 1,736 whales are harvested by 114 vessels. At the other extreme, a $(p/c) = 0.05$ and $\delta = 0.02$, the optimal stock is 74,353, supporting a harvest of 853 whales by 38 vessels.

These results seem plausible in light of the historical landings listed in Table 1. Annual harvests that exceeded 2,000 whales during the 1950s and 1960s caused the stock to decline to about 52,000 whales by the mid-1960s. Harvests around 1,500 during the 1970s appear, in our simulation, to have been sustainable.

IV. Externalities and Animal-Rights

The analysis of the previous section would imply that a sustainable harvest of minke whales from the stock in the Northeast Atlantic is feasible and, under certain bioeconomic conditions, profitable.[8] Should it be allowed?

There are two economic arguments which might be advanced for making the current moratorium permanent. The first relates to the neoclassical notion of externality, while the second is based on the notion of property, specifically the evolution of common property to private property and, in the case of animals, to the extension of rights traditionally reserved for the species *homo sapiens*.

From the perspective of neoclassical economics, the killing of wildlife or the slaughter of domestically-raised animals may negatively affect the utility of individuals who place a value on animal life as opposed to a value based on the products which might be derived from that animal. The animal's welfare, defined from a human perspective, enters positively into the individual's utility function. Such individuals would oppose the killing of animals unless they could be convinced that some more valuable purpose was being served. If meat and blubber are not sufficiently important to warrant the killing of a whale, perhaps medical research or some other purpose might be of high enough value to offset the negative utility from taking an animal's life.[9]

This utilitarian philosophy, while allowing animal life to have value beyond the products they might provide, is conceptually distinct from a strict animal-rights perspective. Under this perspective all animals are seen as having the same rights to life as *homo sapiens.* Here there is no human-derived value to animal life, rather other species are equal in their right to a full and "natural" life. Stone (1974) discusses the historical evolution and ultimately the extension of basic human rights to all races of mankind and asks whether such rights should be extended to natural objects. Humans can no longer be regarded as private property, although this was not the case as recently as one hundred and fifty years ago in the United States.

In the great American novel *Moby Dick*, Chapter 89, is entitled *Fast-fish and Loose-fish*, and Melville (1851) puts forth perhaps the earliest discussion on the distinction between common property and private property. In the heyday of American whaling "a fast-fish belongs to the party fast to it," while "a loose-fish is fair game for anybody who can soonest catch it." Such rules were important in regulating the conduct on crowded whaling grounds when boats from different ships might have the opportunity to strike the same whale. Melville saw the notion as applicable to human behavior, specifically the economic relationships, at that time, between landlord and renter and creditor and debtor. ("And what are you, reader, but a Loose-Fish and a Fast-Fish, too?")

Have whales evolved from being regarded as common property to having full and equal rights to man? Do the products currently derived from baleen whales justify their death?

The answers to these questions will vary within and across cultures. We advocate a tolerant position, where individuals of different countries are allowed to democratically choose whether they wish to allow or ban whaling and the import of whale products. The answers by a majority of citizens in the United States or Sweden may be different than the majority opinion in Iceland or Japan. If commercial whaling is resumed a more acceptable proviso may be that whaling should never again be allowed to threaten the existence of a particular stock.

V. Conclusions

The core of this paper is a bioeconomic model that might be used to evaluate the long run net economic value from the resumption of commercial whaling. This is a contentious issue, one which the IWC seems ill-equipped to handle. The limited number of bioeconomic models that have been developed to examine the optimal management of baleen whales have not been presented at the IWC meetings, nor have they appeared in its published reports. These studies, while well-founded in the economics of dynamic optimization, have often suffered from unrealistic assumptions about growth and production. The delay-difference equation and exponential production function have strong intuitive appeal and seem to fit the historical data for the minke whale in the Northeast Atlantic. These functional forms lead to an optimal escapement rule which depends on eight bioeconomic parameters and which is readily solved by basic numerical methods. The minke whale is abundant in both the Pacific and Southern Oceans and is a prime candidate for harvest in these areas as well. As better estimates of the bioeconomic parameters become available our model can be updated and resolved.

Analysis of the minke whale in the Northeast Atlantic is based on what we regard as a conservative set of biological parameters. The stock declines from about 82,000 whales in 1938 to just under 52,000 whales in 1973. Under a strict quota beginning in 1984 and the limited scientific harvest in 1988 and 1989, the stock slowly recovers to just under 59,000 whales in 1990.

Our analysis identified a critical combination for the price-cost ratio and catchability coefficient. Commercial harvest will not be optimal for low productivity vessels (q = 2.0E-4) facing a low price-cost ratio (p/c = 0.05). This is true for $0.02 \leq \delta \leq 0.06$. At the other extreme, a highly productive fleet (q = 3.0E-4) facing a high price-cost ratio (p/c = 0.09) will harvest 1,736 whales from an optimal stock of 51,538 whales using 114 vessels. Given the moratorium, there is little current information on the likely productivity of vessels or the price elasticity for meat and blubber. Large volumes of meat being supplied to limited markets may make whaling unprofitable on purely economic grounds.

Should commercial whaling be resumed? The answer will vary within and across cultures. It is perhaps appropriate for each country to choose whether to allow or prohibit whaling subject to the proviso that no whaling nation be allowed to threaten a stock with extinction.

Endnotes

[1]Baleen whales, of the suborder *mysticeti*, are equipped with baleen plates that hang from the upper jaw and are used like a sieve or strainer as the whale swims through swarms of plankton or schools of small fish. The other living suborder is *odontoceti*, or toothed whales. Members of this suborder, such as the sperm whale, *Physeter catodon*, feed on squid, larger fish and, in the case of the killer whale, *Orcinus orca*, seals and sea birds.

[2]In a special issue of the *Marine Fisheries Review*, devoted to the status of whales, Braham (1984) lists eight endangered species. Seven are baleen whales and the other is the sperm whale. Each species had two or more "unit stocks," thought to be relatively independent groups that might be managed as a separate unit. At that time, eight stocks were thought to be less than 10% of their pre-exploitation level, 13 stocks were listed as having no reliable population estimate, and only two stocks were thought to have recovered; those being the gray whale, *Eschrichtius robustus*, in the Eastern North Pacific, and the humpback, *Megaptera novaengliae*, in the Western North Atlantic.

[3]The Southern Ocean refers to the southern portions of the Atlantic, Pacific and Indian Oceans surrounding Antarctica.

[4]In Spence's model the dynamics of the blue whale stock was characterized by the first-order difference equation $X_{t+1} = aX_t^b - Y_t$, where X_t is the stock of blue whales, and Y_t is annual harvest. For his estimates of a = 8.356 and b = 0.8204, an initial stock of X_0 = 1,639 whales would grow to a population of 120,000 whales in 17 years with zero harvest (Y_t = 0). Harvest of the blue whale was banned by the IWC in 1967 and the most recent estimates of the blue whale population in all oceans is about 10,000 (Darling 1988).

[5]Clark's analysis of the fin whale assumes a production function of the form $Y_t = qX_tE_t$, where E_t is a measure of effort, say the number of factory vessels or catcher boats. For a given estimate of the catchability coefficient, $q > 0$, and a finite stock level X_t, there are finite levels of effort for which $Y_t > X_t$. A more plausible form for the production function, one used by Spence and one which will be used in the application in this paper, is $Y_t = X_t(1 - e^{-qE_t})$.

[6]The minke whale is the smallest of the rorquals; a group that includes the blue, fin and sei (*Balaenoptera borealis*) whale. Being the smallest, it was the last whale to be intensively harvested by whalers working the Southern Ocean in the early and mid-twentieth century (Clark and Lamberson 1982). The population in the northern hemisphere is generally thought to be separate from the population in the southern hemisphere. The delineation of separate (noninteracting) stocks in the north Atlantic is subject to debate, but the International Whaling Commission (IWC) recognizes four stocks defined by area as (1) the Canadian East Coast Stock, (2) the West Greenland Stock, (3) the Central North Atlantic Stock and (4) the Northeast Atlantic Stock. This latter stock migrates along the Norwegian coast into the Barents Sea.

[7]A key relationship is $(r - M)$, sometimes referred to as the maximum rate of net recruitment. When $r = 0.13$, and all other parameters are the same, $X_0 = 70{,}386$ and the population declines to a low of 24,226 in 1984 before rising to 26,687 in 1990. When $r = 0.14$, $X_0 = 76{,}966$ and the population declines to 39,309, also in 1984, increasing to 43,794 by 1990. In each case, the simulated stock level for 1990 falls below the lower limit of 50,000 estimated by Ugland (1986).

[8]If the price per whale is 50,000 NK and the prorated cost of whaling is 714,286 NK, so that $(p/c) = 0.07$, and if $q = 2.5E\text{-}4$ and $\delta = 0.04$, then, given the other biological parameters, the optimal (base-case) stock is $X = 68,142$ with a harvest of $Y = 1,297$ adult whales. The annual net revenue is $\pi(X,Y) = pY - (c/q)\ln(X/(X - Y)) = 9,943,386$ NK with a present value of $\pi = \pi(X,Y)(1 + \delta)/\delta = 258,528,043$ NK. At an exchange rate of 6.5 NK = 1 USD these values translate to $1,529,751 and $39,773,545, respectively.

[9]Rabbits have been used in testing the level of irritation and the health risk from using certain chemicals in making eyeliner and mascara. The animals undoubtedly suffered, and many were euthanized. Individuals concerned with animal welfare may not view the production of eye make-up as a sufficiently compelling reason for the suffering and premature death of any animal. For some, however, there might be medical research, say cancer research, where the suffering and premature death of an animal might be justified on an expected-utility basis.

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Figure 1. Harvest of Minke Whales from the Northeast Atlantic Stock

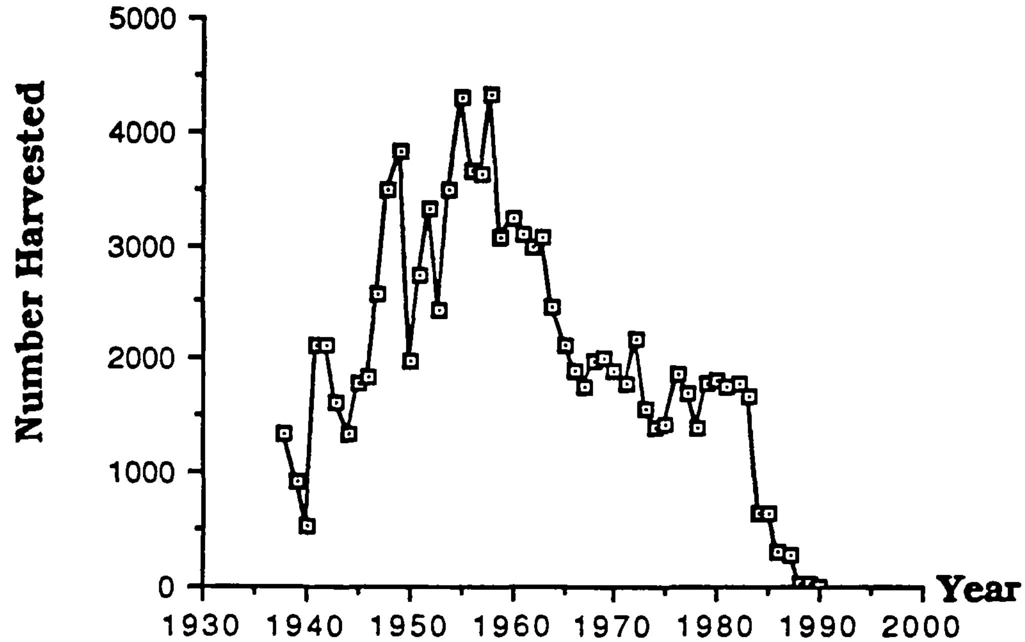

Figure 2. Estimated Population of Minke Whales in the Northeast Atlantic Stock

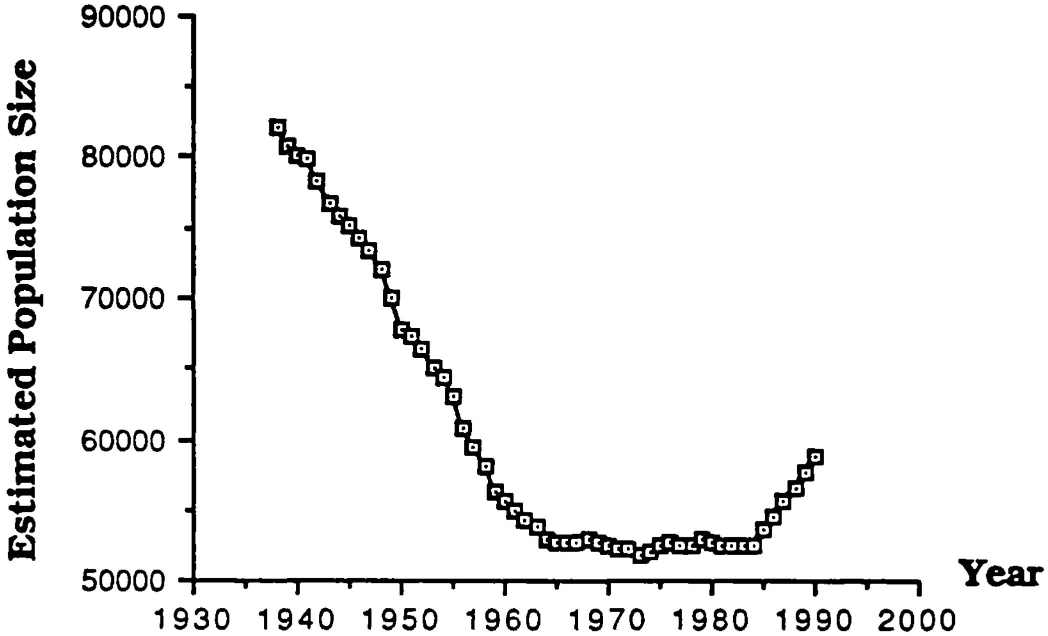

Figure 3. Number of Norwegian Vessels Harvesting Minke Whales

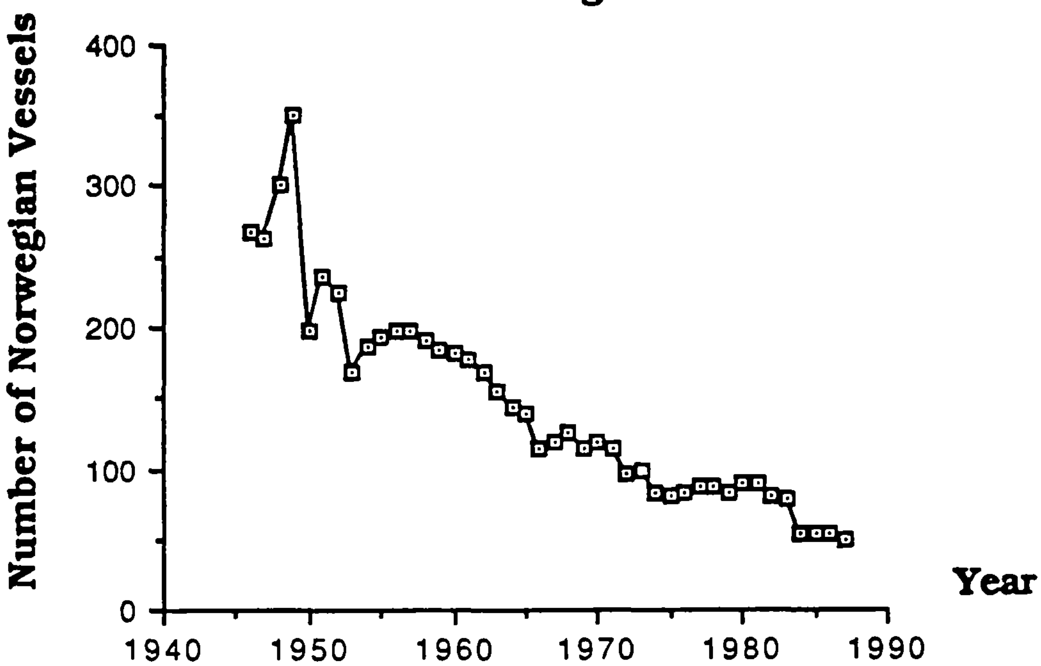

Table 1. Harvest, Number of Norwegian Vessels and the Estimated Stock of Minke Whales in the Northeast Atlantic

Year	Harvest	Vessels	Stock
1938	1345	na	82093
1939	915	na	80882
1940	539	na	80180
1941	2109	na	79886
1942	2133	na	78209
1943	1612	na	76667
1944	1348	na	75768
1945	1782	na	75188
1946	1833	268	74296
1947	2556	264	73412
1948	3487	300	72013
1949	3840	350	69922
1950	1990	198	67714
1951	2751	236	67381
1952	3324	225	66387
1953	2433	169	64958
1954	3499	186	64452
1955	4309	193	62994
1956	3654	198	60870
1957	3624	197	59440
1958	4338	192	58162
1959	3062	185	56311
1960	3233	183	55705
1961	3092	178	54973
1962	2975	168	54340
1963	3059	156	53715
1964	2463	144	52966
1965	2114	139	52715
1966	1902	115	52633
1967	1758	119	52700
1968	1986	126	52818
1969	2014	115	52665
1970	1890	118	52453
1971	1799	114	52306
1972	2172	96	52241
1973	1558	99	51857
1974	1410	84	52076
1975	1426	80	52426
1976	1884	83	52717
1977	1698	87	52548
1978	1383	87	52556
1979	1786	84	52841
1980	1807	89	52692
1981	1770	89	52561
1982	1782	80	52512
1983	1688	79	52490
1984	630	55	52538
1985	634	53	53536
1986	298	53	54461
1987	279	50	55584
1988	29	scientific	56596
1989	17	scientific	57723
1990	na	scientific	58742

Table 2. Estimation of the Catchability Coefficient for the Exponential Production Function $Y = X(1 - e^{-qE})$ for the period 1952 - 1972, where Y is Harvest, X is the Estimated Stock and E is the number of Vessels

A. OLS: No Correction for Autocorrelation,
Dependent Variable: $\ln((X - Y)/X)$

Variable	Coefficient	Standard Error	t - ratio
E	-2.7045E-4	0.49360E-4	-5.4790
constant	-7.6683E-3	7.99220E-3	-0.9595

R-Square = 0.6124 R-Square Adjusted = 0.5920 F = 30.02
Durbin-Watson = 1.1562

B. OLS: Correction for First-Order Autocorrelation
Dependent Variable: $\ln((X - Y)/X)$

Variable	Coefficient	Standard Error	t - ratio
E	-2.4465E-4	0.61141E-4	-4.0014
constant	-1.1557E-2	9.96360E-3	-1.1599
rho	0.33145	0.20588	1.6099

R-Square = 0.6559 R-Square Adjusted = 0.6378
Durbin-Watson = 1.6454

Table 3. The Relative Price-Cost Ratio for the Period 1980 - 1987

Year	Number of Whales[1]	Value of all Products[2]	Price per Whale (p)[3]	Cost per Vessel (c)[4]	p/c
1980	2,054	39,660,000	19,308	756,805	0.0255
1981	1,890	35,719,000	18,899	945,557	0.0200
1982	1,963	39,837,000	20,293	952,142	0.0213
1983	1,869	45,617,000	24,407	940,714	0.0259
1984	804	32,681,000	40,648	802,423	0.0510
1985	771	34,626,000	44,910	1,007,118	0.0450
1986	383	20,489,000	53,496	846,068	0.0632
1987	375	21,294,000	56,784	944,670	0.0601

[1]The number of whales listed in this table is larger than the number listed in Table 1 because it includes the harvest of minke whales from the Central Atlantic stock. Source: *Fiskeristatistikk 1987.*

[2]The primary products from the minke whale are meat and blubber which are consumed by Norwegians or exported to Japan for human consumption. A very small fraction (less than one percent by weight) is processed into animal feed. This value is given in nominal Norwegian Kroner. Source: *Fiskeristatistikk 1987.*

[3]The price per whale, p, is calculated by dividing the value of whale products by the number of whales harvested.

[4]During the period 1980 - 1987 vessels in the Norwegian coastal fleet operated approximately 36 weeks per year. The cost estimates listed here are operating costs for the entire 36-week season. During such a season a vessel would typically spend 35 to 41 percent of its time whaling. The rest of the time was spent harvesting cod, haddock, herring and other species. The distribution of costs between these fishing activities is problematic. If it were appropriate to calculate whaling cost as season cost times the proportion of time spent whaling, it would more than double the p/c ratios listed in the right-most column. Source: *Lønnsomhetsundersøkelser* for the years 1980 - 1987.

Table 4. The Optimal Stock, X, Harvest, Y, and Effort, E, in the Norwegian Minke Whale Industry for the Bioeconomic Model with α = 2.39, r = 0.15, K = 130,000, M = 0.10, τ = 7 and alternative values of q, δ and p/c

With q = 2.5E-4

	$\delta = 0.02$	$\delta = 0.04$	$\delta = 0.06$
p/c=0.05	X = 81,052 Y = 137 E = 7	X = 80,995 Y = 145 E = 7	X = 80,941 Y = 151 E = 8
p/c=0.07	X = 69,472 Y = 1,217 E = 71	X = 68,142 Y = 1,297 E = 77	X = 67,041 Y = 1,356 E = 82
p/c=0.09	X = 62,735 Y = 1,543 E = 100	X = 59,977 Y = 1,627 E = 110	X = 57,770 Y = 1,675 E = 118

With q = 2.0E-4

	$\delta = 0.02$	$\delta = 0.04$	$\delta = 0.06$
p/c=0.05	X = 82,093 Y = 0 E = 0	X = 82,093 Y = 0 E = 0	X = 82,093 Y = 0 E = 0
p/c=0.07	X = 76,760 Y = 627 E = 41	X = 76,376 Y = 666 E = 44	X = 76,043 Y = 698 E = 46
p/c=0.09	X = 68,648 Y = 1,268 E = 93	X = 67,175 Y = 1,350 E = 101	X = 65,960 Y = 1,410 E = 108

With q = 3.0E-4

	$\delta = 0.02$	$\delta = 0.04$	$\delta = 0.06$
p/c=0.05	X = 74,353 Y = 853 E = 38	X = 73,713 Y = 908 E = 41	X = 73,172 Y = 952 E = 44
p/c=0.07	X = 64,453 Y = 1,478 E = 77	X = 62,120 Y = 1,565 E = 85	X = 60,236 Y = 1,621 E = 91
p/c=0.09	X = 58,614 Y = 1,659 E = 96	X = 54,637 Y = 1,719 E = 107	X = 51,538 Y = 1,736 E = 114