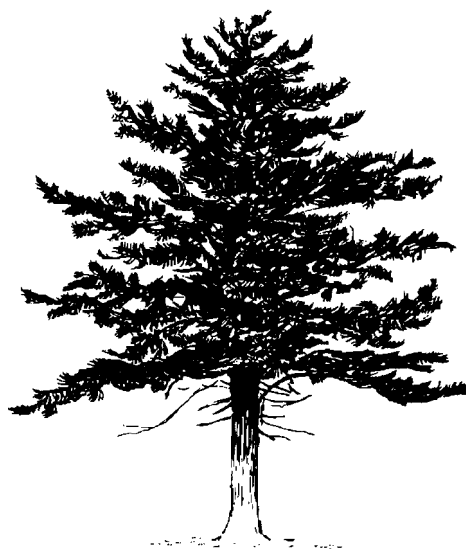


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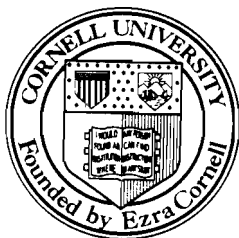
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**Fishery Management:  
The Consequences of Honest Mistakes  
in a Stochastic Environment**

**Jon M. Conrad, Andres Lopez, and Trond Bjørndal**

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**The Consequences of Honest Mistakes in a Stochastic Environment**

*by*

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*ABSTRACT*

A recent article by Lauck et al. (1998) questions our ability to manage marine fisheries in the face of "persistent and irreducible scientific uncertainty." This paper examines the role that a safe minimum biomass level (SMBL) might play when stochastic recruitment is compounded by unbiased (honest) observation error. Specifically, a bioeconomic optimum is combined with a SMBL to formulate a linear, total allowable catch (TAC) policy. In a deterministic world such a policy may asymptotically guide an overfished stock to the optimum. In a stochastic model, the TAC policy will result in a distribution of stock and harvest about the bioeconomic optimum. The approach is applied to the Norwegian spring-spawning herring, a once abundant and highly migratory species in the northeast Atlantic. The effectiveness of the proposed SMBL for spring-spawning herring is examined with stochastic recruitment, and observation error. Observation error greatly increases the coefficient of variation for harvest, and may allow the stock to (unknowingly) fall below the SMBL.

**Keywords:** fishery management, bioeconomics, stochastic recruitment, observation error, linear TAC policies, Norwegian spring-spawning herring.

# **Fishery Management: The Consequences of Honest Mistakes in a Stochastic Environment**

## **I. Introduction and Overview**

The sorry state of the world's fisheries has lead to a questioning of our ability to manage commercially valuable species in a complex and stochastic marine environment. Lauck *et al.* (1998) go so far as to suggest that there is a "persistent and irreducible scientific uncertainty" in such systems. This uncertainty, combined with the rent-seeking behavior of fishers [Gordon (1954) and Homans and Wilen (1997)] and the political influence of the fishing industry, is viewed as a recipe for overfishing. The unforeseen collapse of the cod fishery in the Canadian Maritimes and off the east coast of the United States would seem to indicate that even developed countries, with the best fishery scientists, can be completely wrong in their assessment of a fish stock. As a "hedge" against such ignorance, Lauck *et al.* propose the creation of marine reserves, where fishing would be prohibited. In a stochastic model, Conrad (1997) has shown that a reserve, adjacent to a fishing grounds managed under a regime of regulated open access, can increase the average harvest from the grounds while reducing its variation. The increased yield in this model was the result of migration of fish from the reserve to the grounds, while the reduced variation occurred if the fluctuations in the fish population in the reserve were uncorrelated and could partially offset, fluctuations on the grounds. There was an opportunity cost to the marine reserve, in the form of foregone harvest. While harvest on the grounds might increase, the overall harvest was likely to be lower than under regulated open access of both areas.

The policy twist in this paper is the combination of a safe minimum biomass level (SMBL), as might be identified by fisheries biologists, with the optimum from a bioeconomic model, to formulate a linear total allowable catch (TAC) policy. In a deterministic model this linear TAC policy could asymptotically guide an overfished stock to the bioeconomic optimum. In a stochastic model, this linear TAC policy will result in a distribution of biomass and harvest about the deterministic optimum. Two frequently mentioned sources of uncertainty are stochastic recruitment and observation (or measurement) error. How would the linear TAC policy perform with one or both sources of uncertainty present? This question is not easily answered analytically; in the sense that it does not appear possible to derive closed-form distributions for biomass and harvest. Instead we conduct numerical analysis of the Norwegian spring-spawning herring, a once abundant and highly migratory species found in the northeast Atlantic. This population is recovering from overfishing and biologists have proposed a safe minimum for spawning biomass to avoid overfishing in the future.

The remainder of the paper is organized as follows. In the next section we construct a biomass model with delayed recruitment and pose and solve a problem to maximize the present value of net benefits. The linear TAC policy is derived. The model is then modified to introduce stochastic recruitment and observation error when adaptively setting the TAC.

In the third section the model is applied to the Norwegian spring-spawning herring. The linear TAC policy is shown to be stable. The effects of stochastic recruitment and observation error are analyzed via simulation. The fourth and final section summarizes the major conclusions and makes a suggestion when setting the TAC for Norwegian spring-spawning herring.

## II. The Models

In this section we (a) construct a bioeconomic model with delayed recruitment, (b) define the concept of a safe minimum biomass level, (c) derive a linear TAC policy that might guide an overfished stock to the bioeconomic optimum and (d) introduce two important sources of uncertainty present in most marine fisheries.

Let  $X_t$  denote the "fishable biomass," measured in metric tons, in period  $t$ . We will assume that the fishable biomass corresponds to the adult or spawning biomass, and that there is a lag of  $\tau+1$  periods from spawning until recruitment to the adult, fishable population. These assumptions are more or less consistent with the biology and harvest of the Norwegian spring-spawning herring. It is relatively easy to construct a model where both juveniles and adults are subject to harvest [see Conrad and Bjørndal (1991)].

With no random components in recruitment or harvest the fishable biomass in period  $t+1$  would be

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

where  $M$  is the rate of natural mortality, and  $(1 - M)(X_t - Y_t)$  is the adult stock which escapes harvest and survives to period  $t+1$ . The fishable biomass surviving to period  $t+1$  is augmented by new recruits spawned  $\tau+1$  periods earlier.

Suppose that the net benefit from harvest in period  $t$  is given by the concave function  $U(Y_t)$  and that the objective of fishery management is to maximize the present value of net benefits. This problem may be stated

mathematically as

$$\begin{aligned}
& \text{Maximize} && \sum_{t=0}^{\infty} \rho^t U(Y_t) \\
& \text{Subject to} && X_{t+1} = (1 - M)(X_t - Y_t) + F(X_{t-\tau}) \\
& && X_0 \text{ given}
\end{aligned} \tag{2}$$

where  $\rho = 1/(1 + \delta)$  is the discount factor and  $\delta$  is the per period rate of discount. The Lagrangian for this problem may be written

$$L = \sum_{t=0}^{\infty} \rho^t \{U(Y_t) + \rho \lambda_{t+1} [(1 - M)(X_t - Y_t) + F(X_{t-\tau}) - X_{t+1}]\} \tag{3}$$

where  $\lambda_{t+1}$  is the multiplier or shadow price on a marginal unit of biomass (in the water) in period  $t+1$ . The first-order conditions, when  $Y_t$ ,  $X_t$ , and  $\lambda_{t+1}$  are positive, require

$$\partial L / \partial Y_t = \rho^t \{U'(Y_t) - (1 - M)\rho \lambda_{t+1}\} = 0 \tag{4}$$

$$\partial L / \partial X_t = \rho^t \{(1 - M)\rho \lambda_{t+1}\} - \rho^t \lambda_t + \rho^{t+\tau+1} \lambda_{t+\tau+1} F'(X_t) = 0 \tag{5}$$

$$\partial L / \partial [\rho \lambda_{t+1}] = \rho^t \{(1 - M)(X_t - Y_t) + F(X_{t-\tau}) - X_{t+1}\} = 0 \tag{6}$$

Evaluating these conditions in steady state results in the following three equations which can be solved for the bioeconomic optimum,  $(X^*, Y^*, \lambda^*)$

$$\lambda = \left[ \frac{(1 + \delta)}{(1 - M)} \right] U'(Y) \tag{7}$$

$$F'(X) = (\delta + M)(1 + \delta)^\tau \quad (8)$$

$$Y = \frac{[F(X) - MX]}{(1 - M)} \quad (9)$$

For example, if the delayed recruitment function takes the form  $F(X_{t-\tau}) = rX_{t-\tau}(1 - X_{t-\tau}/K)$ , then

$$X^* = \frac{K[r - (\delta + M)(1 + \delta)^\tau]}{2r} \quad (10)$$

$$Y^* = \frac{[r - M - rX^*/K]X^*}{(1 - M)} \quad (11)$$

The safe minimum biomass level is a lower bound which results in a zero harvest rate. Specifically, if  $X_s$  is designated as the safe minimum biomass level, and if  $X_t \leq X_s$ , then  $Y_t = 0$ . For  $X_t > X_s$  we assume that management authorities set a total allowable catch (TAC) according to  $Y_t = \alpha + \beta X_t$  where  $0 = \alpha + \beta X_s$ , and  $Y^* = \alpha + \beta X^*$  imply that  $\beta = Y^*/(X^* - X_s)$  and  $\alpha = -\beta X_s$ , and it is also assumed that  $X^* > X_s$ . Figure 1 shows a plot of  $Y = [F(X) - MX]/(1 - M) = [r - M - rX/K]X/(1 - M)$  when  $r=0.4$ ,  $M = 0.15$ , and  $K=18,500$ , and  $Y = \alpha + \beta X$  for  $\alpha = -835$  and  $\beta = 0.334$ . The values of  $\alpha$  and  $\beta$  are implied by  $X_s = 2,500$ ,  $X^* = 5,000$ , and  $Y^* = 835$ , and are the values that emerge from one specification of the model of the Norwegian spring-spawning herring (with  $\delta = 0.02$  and  $\tau = 3$ ). Note that for  $X_t < X^*$ , mortality adjusted net growth exceeds harvest as determined by the TAC policy and fishable biomass will increase with a lag of  $\tau+1$  periods. For  $X_t > X^*$ , harvest from the TAC policy will exceed mortality adjusted net growth and fishable



biomass will decrease. Based on this observation we would expect that a linear TAC policy defined by the points  $(X_s, 0)$  and  $(X^*, Y^*)$  should result in an asymptotically stable approach from  $X_0 > 0$  to  $X^*$ .<sup>1</sup>

Up to this point the model has been completely deterministic. Suppose now that equation (1) is modified to become

$$X_{t+1} = (1 - M)(X_t - Y_t) + z_t F(X_{t-\tau}) \quad (12)$$

where the  $z_t$  are independently and identically distributed random variables with expectation  $E\{z_t\}=1$  and finite variance  $\sigma_z^2$ . This is a delayed-recruitment version of a model considered by Reed (1979), and will give rise to a distribution for  $X_t$  when harvest is set according to a linear TAC policy like  $Y_t = \alpha + \beta X_t$ . In equation (12) recruitment is said to be stochastic.

It is usually the case that fishable biomass can only be imperfectly observed and that the TAC in any period is based on an estimate of  $X_t$  given by

$$\tilde{X}_t = u_t X_t \quad (13)$$

where  $u_t$  is another independently and identically distributed random variable. The TAC in period  $t$  is then determined by  $Y_t = \alpha + \beta u_t X_t$ . If  $E\{u_t\} = 1$ , we say that the management authority is making "honest mistakes" in its stock assessment. If the random variable  $u_t$  has a finite variance it will likely increase the variation of  $X_t$  about  $X^*$  and may actually result in the management authority unknowingly setting a positive TAC when fishable biomass is actually below  $X_s$ .

The fishable biomass, with both stochastic recruitment and observation error, would evolve according to

$$X_{t+1} = (1 - M)[X_t - (\alpha + \beta u_t X_t)] + z_t F(X_{t-\tau}) \quad (14)$$

when  $u_t X_t > X_s$ , and according to

$$X_{t+1} = (1 - M)X_t + z_t F(X_{t-\tau}) \quad (15)$$

when  $u_t X_t \leq X_s$ . The combined effect of these sources of uncertainty, when harvest is set according to our linear TAC policy, will be examined within the context of the Norwegian spring-spawning herring fishery, only now recovering from significant overfishing in the 1950s and 1960s.

### III. The Norwegian Spring-Spawning Herring

In the 1950s and 1960s, the Norwegian spring-spawning herring (*Clupea harengus*) was a major commercial species, harvested by vessels from Norway, Iceland, the Faroe Islands, the former Soviet Union and other European nations. Before depletion from overfishing, the species was highly migratory. The migratory pattern and number of components to the stock changed between 1950 and 1970. In the 1950s and early 1960s, adults would spawn off the south-central coast of western Norway (near Møre) from February through March. The adults would migrate west and southwest through international waters toward Iceland (April and May), spending the summer (June through August) in an area north of Iceland. In September the adults would migrate south to a wintering area east of Iceland before

returning to western Norway for spawning. Juveniles, including the recently spawned "zero cohort," would migrate north, but remain in Norwegian waters until sexually mature, around age four or five, when they would join the adult migratory pattern.

In the mid-1960s a second, more northerly, stock component appeared. This component would spawn south of the Lofoten Islands (which are north of Møre) with the adults migrating northwest into the north Norwegian Sea, then northeast into the Barents Sea, and finally south where they would winter west of the Lofoten Islands before moving south to spawn. By 1966 the northern component was the largest of the two. Because of overfishing and poor recruitment, the spawning biomass of both components fell precipitously in 1968 and 1969, leading to near extinction by 1972 (see Figure 2). In its depleted state the adult population ceased migration and both adults and juveniles remained in Norwegian waters year round.

Recruitment remained weak throughout the 1970s, and it was not until the strong year class of 1983 joined the adult population in 1986 that the stock began to recover. The main component of the stock has reestablished itself on the spawning grounds off Møre. After spawning the adults now migrate west through international waters (called the "Ocean Loop"), but because of extended jurisdiction in the mid- and late-1970s, the migrating adults will also pass through the Exclusive Economic Zones of the Faroe Islands and Iceland on their way to the summer feeding area near Jan Mayen Island. In the 1990s the herring have followed the southern edge of the cold East Iceland stream, north and northeasterly, crossing into the Barents Sea before turning south and southeast to winter in the fjords of northern Norway.

The migratory pattern of the Norwegian spring-spawning herring takes on importance since, as a "straddling stock," the herring are exposed to territorial and distant water fleets with strong incentives to harvest the population before it moves elsewhere (Bjørndal et al. 1998). If a cooperative management policy (with an equitable distribution of harvest) cannot be agreed upon, Norway, Iceland, the Faroe Islands, Russia, and distant water vessels fishing in the Ocean Loop, may resort to strategic overfishing which could jeopardize continued recovery.

In the remainder of this section we seek to define an adaptive, SMBL-based, harvest policy which might be used to determine the annual total allowable catch. Total allowable catch must then be distributed, in a cooperation-inducing manner, among the countries with territorial or historical claims to harvest. Fishery scientists have already specified a SMBL of 2,500 ( $\times 10^3$ ) metric tons for the adult spawning biomass (Bjørndal *et al*, 1997). Given the presence of both stochastic recruitment and observation error, will the linear TAC discussed in the previous section keep the actual spawning biomass from dropping below the SMBL? To answer this question we must estimate a form for the delayed recruitment function,  $F(X_{t-\tau})$ , derive the SMBL-based linear TAC, and specify the stochastic processes generating  $z_t$  and  $u_t$ .

Table 1 contains estimates of total biomass, spawning biomass, and harvest from 1950 through 1996 as reported in Patterson (1998). All data are measured in thousands of metric tons. The data on spawning biomass was plotted in Figure 2. In estimating delayed recruitment, it will be assumed that  $\tau = 3$  implying that herring reach sexual maturity at age four. This can be determined through examination and aging of herring harvested on the spawning grounds. Age at sexual maturity is known to vary with

overall biomass density. In the 1950's, when total biomass was nearer its carrying capacity, herring were thought to spawn for the first time at age five. The greater competition for food and slower weight gain resulted in a longer time to age at first spawning. With overfishing and more abundant food for herring that escaped harvest, age at first spawning was lowered to about four.

There are many possible forms for the recruitment function,  $F(X_{t-\tau})$ . Three forms were estimated using constrained nonlinear maximum likelihood. The forms were (a) logistic, where  $F(X_{t-\tau}) = rX_{t-\tau}(1 - X_{t-\tau}/K)$ , (b) Gompertz, where  $F(X_{t-\tau}) = rX_{t-\tau} \ln(K/X_{t-\tau})$ , and (c) exponential, where  $F(X_{t-\tau}) = \gamma X_{t-\tau}^\eta$ . Annual adult mortality was fixed at 0.15, to be consistent with the value reported in Patterson (1998). With  $\tau = 3$  and  $M = 0.15$ , it is possible to make predictions for  $[X_{1954}, \dots, X_{1996}]$  based on each functional form and to search for the values of  $r$  and  $K$  (for the logistic and Gompertz forms) or  $\gamma$  and  $\eta$  (for the exponential form) which minimize the sum of the squared residuals. Goodness of fit might be roughly gauged by calculating  $R^2 = 1 - SS_R/SS_T$ , where  $SS_R$  is the sum of the squared residuals and  $SS_T$  is the sum of the squared variations about mean spawning biomass from 1954 through 1996. The constrained maximum likelihood estimates and the implied values for  $X^*$  and  $Y^*$  when  $\delta = 0.02$  are reported in Table 2.

For the logistic form the intrinsic growth rate is estimated to be  $r = 0.293$  while the carrying capacity is estimated at  $K = 25,165$  ( $\times 10^3$  mt). The  $R^2$  for this form is 0.92 and the implied optimal biomass and harvest, at  $\delta = 0.02$ , are 4,835 ( $\times 10^3$  mt) and 493 ( $\times 10^3$  mt), respectively.

The Gompertz function gives the same fit ( $R^2 = 0.92$ ) but with  $r = 0.112$  and  $K = 45,413$ , implying  $X^* = 3,337$  and  $Y^* = 559$  when  $\delta = 0.02$ . The exponential has an  $R^2 = 0.93$  with estimates of  $\gamma = 29.6$  and  $\eta = 0.44$ ,

implying an optimal spawning biomass of  $X^* = 2083$  and harvest of  $Y^* = 637$ .

The implication of the high  $R^2$  for all functional forms is that the data in Table 1 are having difficulty discriminating between possible concave recruitment functions and, as it turns out, for the logistic form when  $r$  is increased and  $K$  is lowered. If  $r$  is increased to 0.40 and  $K$  is reduced to 18,500 with  $\tau$  and  $M$  fixed at 3 and 0.15, respectively, the fit declines slightly in the third decimal, but still rounds to  $R^2 = 0.92$ . These are perhaps "more plausible" parameter estimates, as discussed below. The predicted values of  $X_t$  for these parameter values lie on the dashed line in Figure 3.<sup>2</sup>

A  $K$  value of 18,500 seems plausible, given that spawning biomass in 1950 (at  $12,066 \times 10^3$  mt) is regarded as being in excess of  $K/2$  by most fishery biologists. At the same time an  $r$ -value of 0.293 seems low, given that the intrinsic growth rate for the North Sea herring (*Clupea harengus* L), as described by Bjørndal and Conrad (1987), had an estimated  $r$ -value of 0.8. This causes us to regard the values  $r = 0.4$  and  $K = 18,500$  as a more plausible (MP) parameter combination for the logistic form. These values imply  $X^* = 5,078$  and  $Y^* = 838$  when  $\delta = 0.02$ . If we round  $X^*$  to 5,000 and  $Y^*$  to 835, and combine them with the SMBL of 2,500, we obtain  $\alpha = -835$  and  $\beta = 0.334$ , and the (deterministic) sustainable harvest function and linear TAC policy appear as they were drawn in Figure 1. The MP Logistic parameter set becomes  $r = 0.4$ ,  $K = 18,500$ ,  $\tau = 3$ ,  $M = 0.15$ ,  $\alpha = -835$  and  $\beta = 0.334$ . We will use this parameter set to explore the consequences of observation error and stochastic recruitment.

Table 3 lists the MATLAB (Version 5) program used to simulate the linear TAC policy when both observation error and stochastic recruitment are present. It is possible to "disable" the stochastic elements to

numerically assess the stability of the TAC policy in a deterministic environment. This was done as follows. In lines 13 and 14 of the code, change  $OBX(t,i)$  to  $X(t,i)$ . This causes the TAC to be set based on the actual (realized) values of spawning biomass, instead of on the observed values  $[OBX(t,i)]$  which are displaced by a uniform random variate,  $2 > u_t > 0$ , with an expected value of one and a variance of one-third. To disable the stochastic recruitment simply delete  $z$  in the equation for  $X(t+1,i)$  in line 26. When this is done, and the program is executed, spawning biomass approaches  $X^* = 5,000$  and harvest approaches  $Y^* = 835$  as shown by the bar charts in Figure 4.

The effect of stochastic recruitment can be assessed by reintroducing  $z$  back into the equation for  $X(t+1,i)$  in line 26. The value of  $z$  in a particular period is determined by the outcome of another uniform variate, now ranging between zero and one. If the variate exceeds 0.9 (which will happen with a probability of 0.1),  $z = 2$ . If the variate is less than 0.1 (again with a probability of 0.1),  $z = 0$ . If the variate is less than or equal to 0.9 but greater than or equal 0.1 (with a probability of 0.8),  $z = 1$ . The expected value of  $z$  is one and its variance is 0.2. The effect of this stochastic process on spawning biomass and harvest is shown in Figure 5 for the first realization performed by MATLAB. Spawning biomass ranges between 6,886 and 2,649 (thousand mt) while harvest ranges between 1,464 and 49 (thousand mt). The sample mean, standard deviation, and the coefficient of variation for spawning biomass and harvest are given in Table 4 under the column  $z_t$ .

Removing  $z$  once more from line 26 and substituting  $OBX(t,i)$  for  $X(t,i)$  in lines 13 and 14 will permit us to run the model with observation error but deterministic recruitment. The first MATLAB realization is shown in Figure 6. In comparison to Figure 5, the mean and standard deviation for

spawning biomass both decrease and the coefficient of variation increases slightly from 19.02 to 19.51. The SML of 2,500 is "mildly" violated since the minimum spawning biomass level is 2,351. The major change, however occurs in the distribution of harvest under the linear TAC policy. Harvest now ranges from 2,401 to zero. The average harvest increases from 697 to 736 but the standard deviation increases to 730, more than doubling the coefficient of variation to 99.18. As shown in Figure 6, fishers would alternate between a bonanza and a moratorium where observation error might cause management authorities to set a TAC higher or lower than it should, based on the "true" spawning biomass. For example, in Figure 6, in  $t=47$ , the actual spawning biomass is  $X_{47} = 3,945$  while the observed biomass was  $1,365 < \text{SML}$ . The TAC set by the management authorities would have been  $Y_{47} = 0$  when they could have allowed  $Y_{47} = -835 + 0.334(3,945) = 483$ .

In Figure 7 we show the first realization with both stochastic recruitment and observation error. Spawning biomass ranges from a high of 6,939 to a low of  $1,821 < \text{SML}$ , with a mean of 4,011, a standard deviation of 1,034 for a coefficient of variation of 25.78. The distribution for harvest exhibits a smaller mean and standard deviation than with observation error alone, although the coefficient of variation increases when both stochastic processes present.

Figures 4-7 and Table 4 show the results for the first realization. When the number of realizations,  $N$ , is increased to 1,000, we observe the following frequencies. With stochastic recruitment and no observation error (just  $z_t$ ), 335 out of the 1,000 realizations would result in  $X_t$  falling below the SML at some time during the 99 year horizon,  $t=6, \dots, 104$ . When there is observation error and deterministic recruitment (just  $u_t$ ), 283 out of the



1,000 realizations result in  $X_t$  falling below the SML, and when stochastic recruitment and observation error are both present ( $z_t$  and  $u_t$ ), 949 out of 1,000 realizations will result in  $X_t$  falling below the SML. Stochastic recruitment and observation error resulted in a high probability (greater than 0.9 in our model) that actual spawning biomass would fall below the SML during a 99 period simulation of the linear TAC.

#### IV. Conclusions

This paper has accomplished two things. First, it has shown how to construct a linear TAC policy for a delayed-recruitment fishery when biologists have identified a safe minimum biomass level. The bioeconomic optimum for such a model is easily computed (in our example there was a closed-form solution for  $X^*$ ). The bioeconomic optimum ( $X^*, Y^*$ ) can then be combined with the safe minimum biomass level ( $X_S, 0$ ) to form a linear, adaptive TAC policy  $Y_t = \alpha + \beta X_t$ , where  $\beta = Y^* / (X^* - X_S)$  and  $\alpha = -\beta X_S$ . Baring cyclical or chaotic dynamics (often associated with intrinsic growth rates in excess of two), our linear TAC policy can smoothly guide an overfished stock to the optimum.

Second, if we admit the presence of stochastic recruitment and/or observation error, the linear TAC policy will result in a distribution for  $(X_t, Y_t)$  about the bioeconomic optimum. Observation error by itself has the potential to drastically alter the distribution of allowable catch. Fishers might alternate between a bonanza or a moratorium. With observation error, management authorities can make two types of mistakes, setting the TAC too high or too low compared to the level which would be set if the stock could be accurately assessed. Stochastic recruitment and observation error can jointly result in a high probability that  $X_t$  will fall below the SML during

a simulation horizon of 99 periods. Thus, announcing and incorporating a SML into a TAC policy is no guarantee that a fish stock can be maintained above the SML. This result might reinforce Lauck et al (1998) recommendation that marine reserves be used as a hedge against the uncertainty inherent in a marine ecosystems.

The application of this approach to the Norwegian Spring Spawning herring may be of some interest in assessing current management practices and in setting a TAC which would then be distributed among the countries harvesting this straddling stock. In comparing the actual 1996 TAC of 1,197 (thousand metric tons) from a stock estimated at 5,483 (thousand metric tons), as reported in the last entry of Table 3 in this paper, we would have advocated a TAC of  $Y_{1996} = -835 + 0.334(5,483) = 996$ , or about 200 (thousand metric tons) less than what was harvested. Such harvest rates might impede the recovery of the herring stock and could cause it to decline back toward  $X_S$ . We suggest that the actual management of the Norwegian spring-spawning herring would benefit from an explicit discussion of the alternative adaptive rules that might be used to set total allowable catch.

### Endnotes

<sup>1</sup>No optimality claims can be made for a linear TAC policy based on  $X_S$  and  $X^*$ . It is the offspring of a minimum safe standard, based on the expert opinion of biologists, and a desirable steady-state stock from a simple bioeconomic model. If such a linear TAC policy is employed from an initial condition,  $X_0$ , which is significantly in excess of  $X^*$ , there is a potential for the TAC to allow an initial harvest,  $Y_0$ , so large as to drive  $X_1$  below  $X_S$ . Since most commercial fisheries are operating below the likely value for  $X^*$ , this property of the linear TAC policy is not likely to be of practical importance.

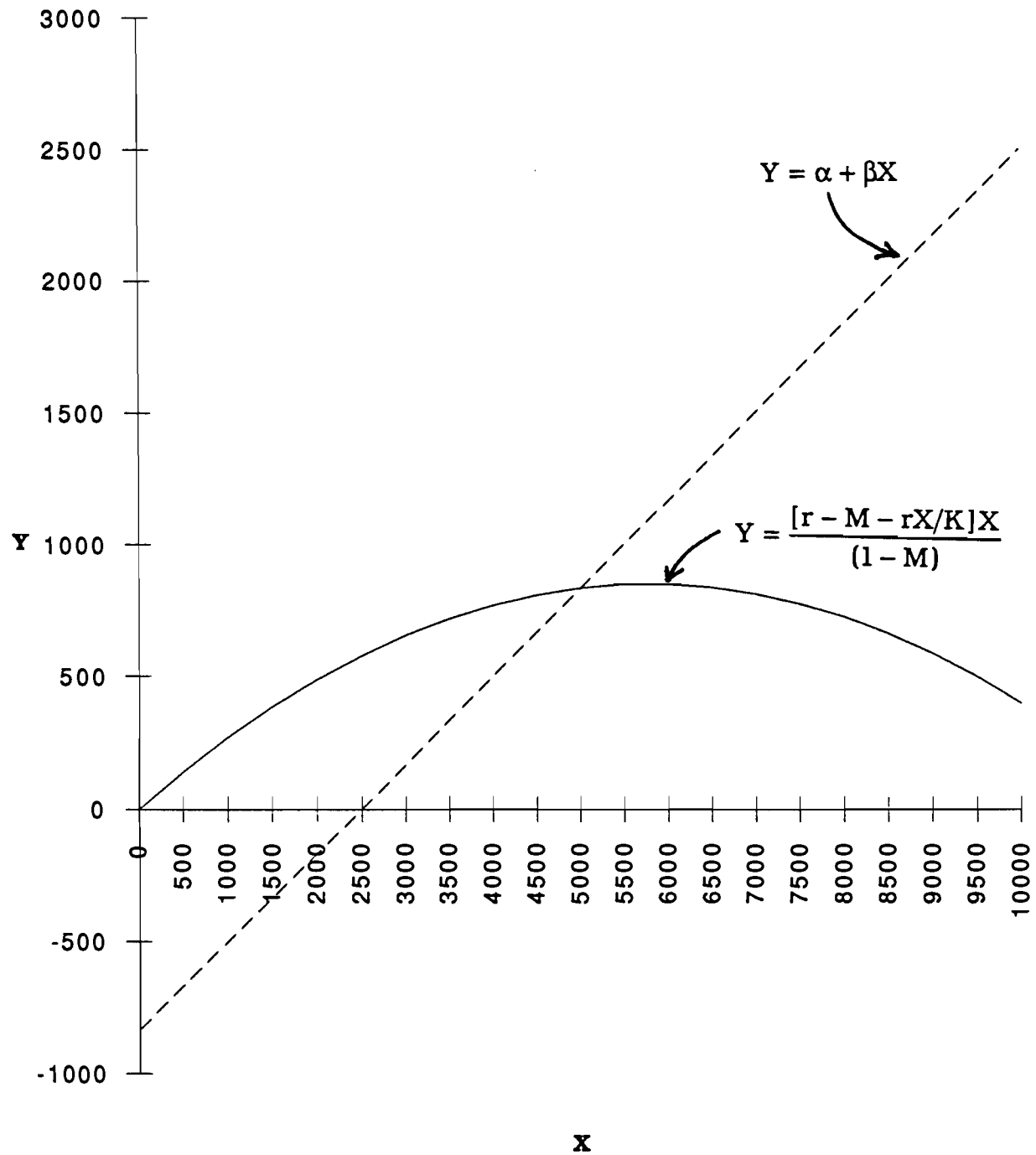
<sup>2</sup>For the logistic form, the escapement-survival term,  $(1 - M)(X_t - Y_t)$  dominates the one-period forecast "explaining" 70 percent of the biomass in period  $t+1$ . As can be seen from Figure 3, the complete model, with logistic delayed recruitment, predicts best when biomass levels are low ( $X_t < 2,000 \times 10^3 \text{mt}$ ).

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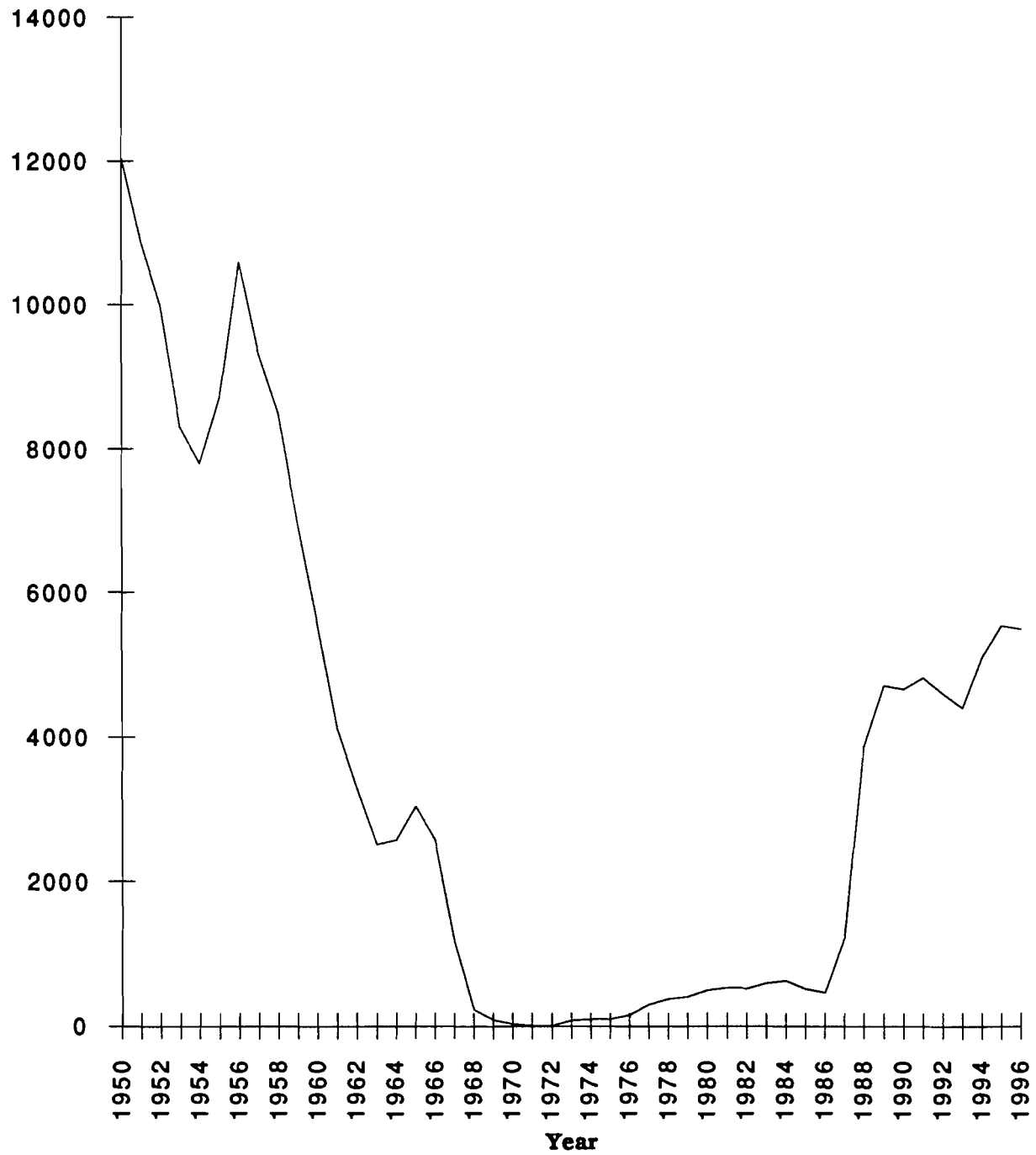
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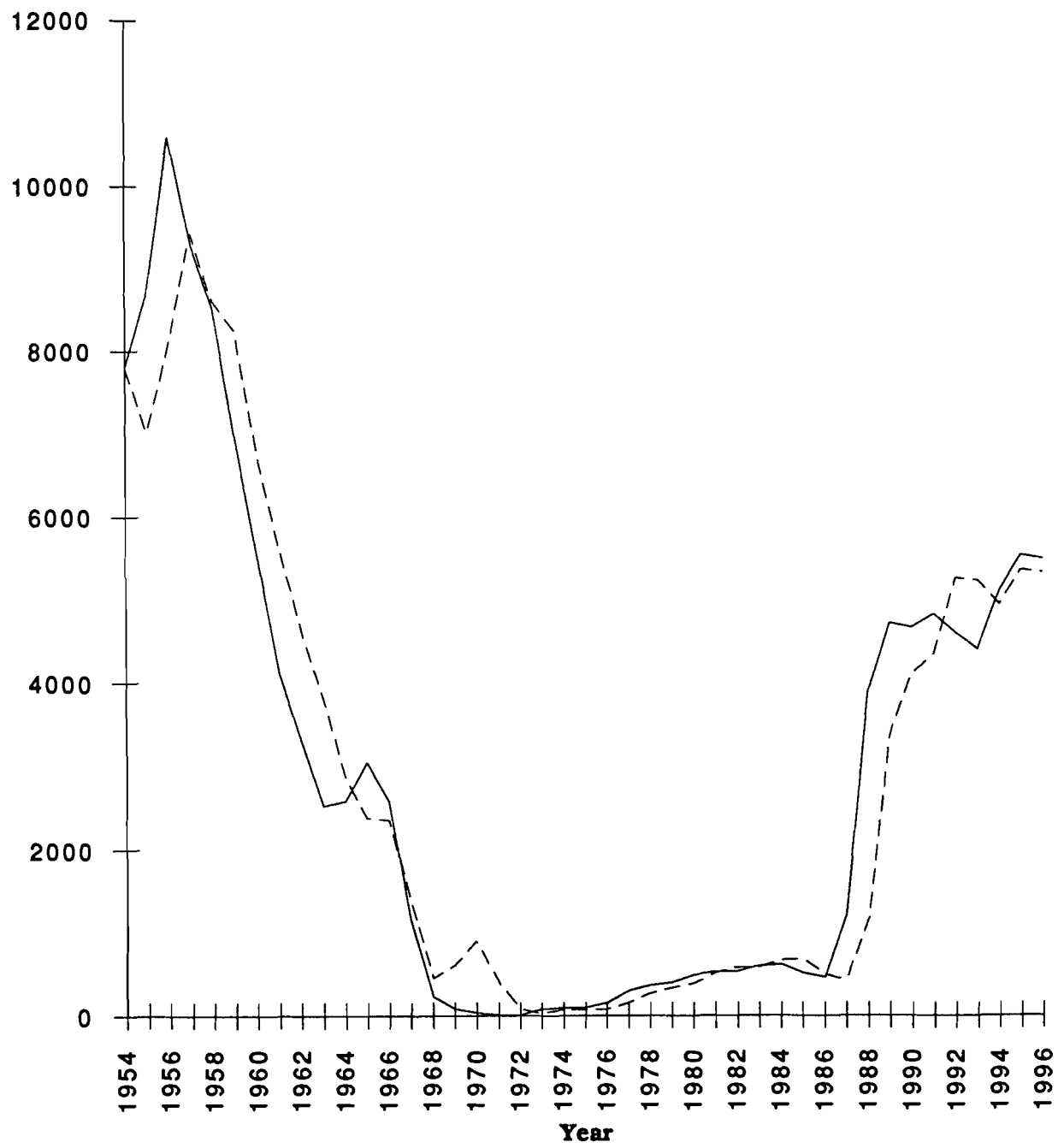
**Figure 1. Using A SMBL-Based TAC to Reach The Bioeconomic Optimum**



**Figure 2. Estimated Spawning Biomass ( $\times 10^3$  mt), 1950-1996.**

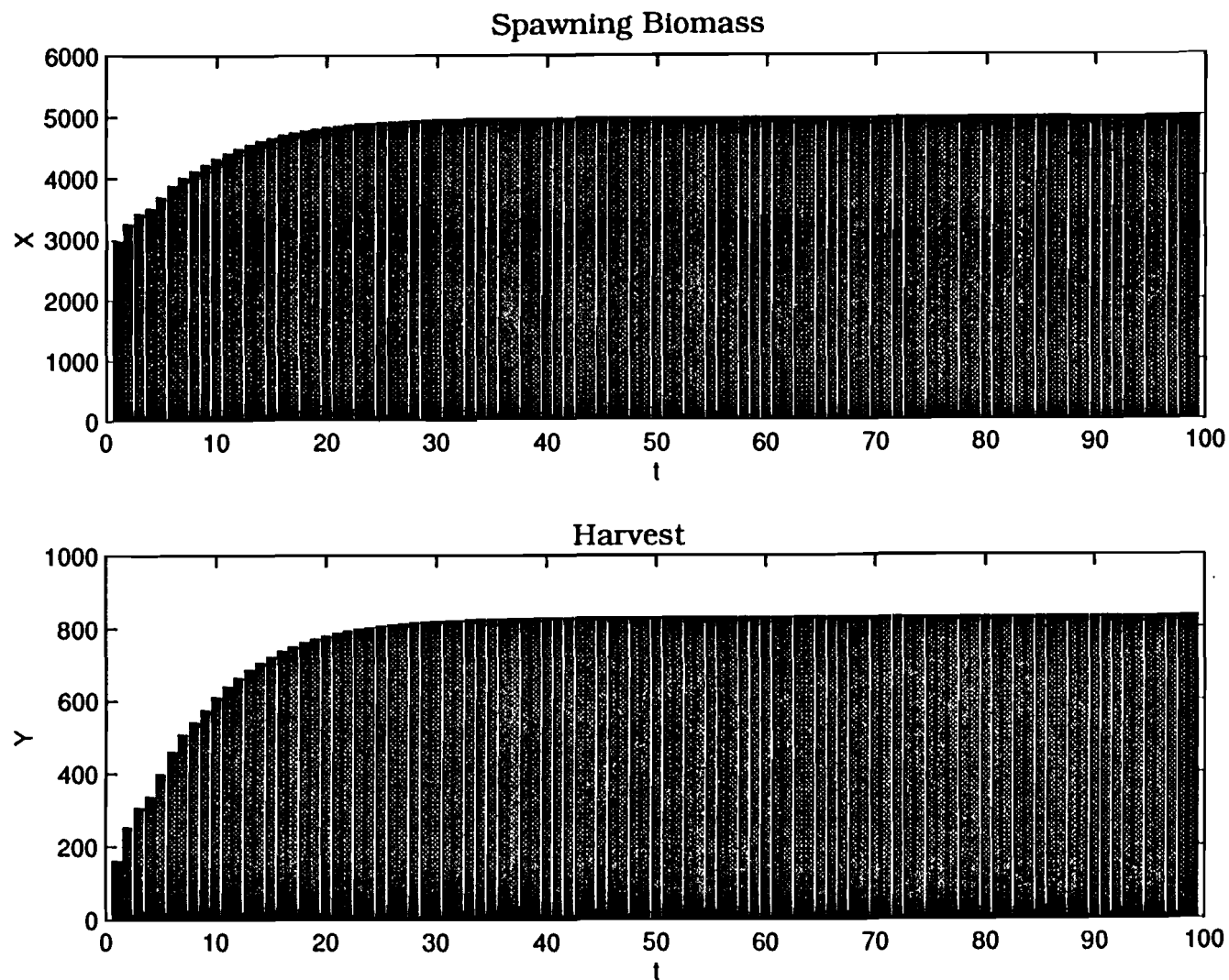


**Figure 3. Spawning Biomass from Table 1 and the Fit with Delayed Logistic Recruitment ( $\tau=3$ ,  $r=0.4$ ,  $K=18,500$ , and  $M=0.15$ )**

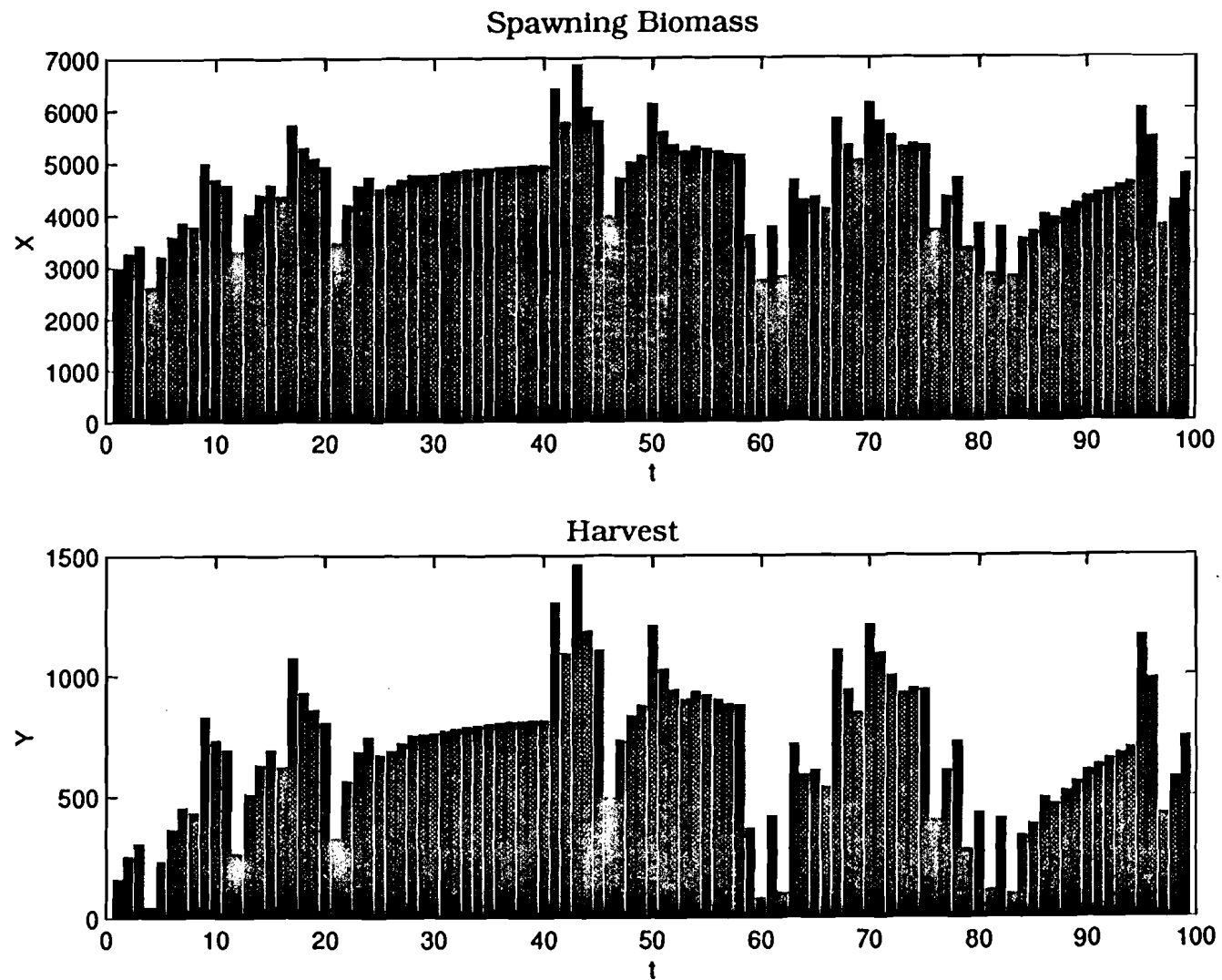




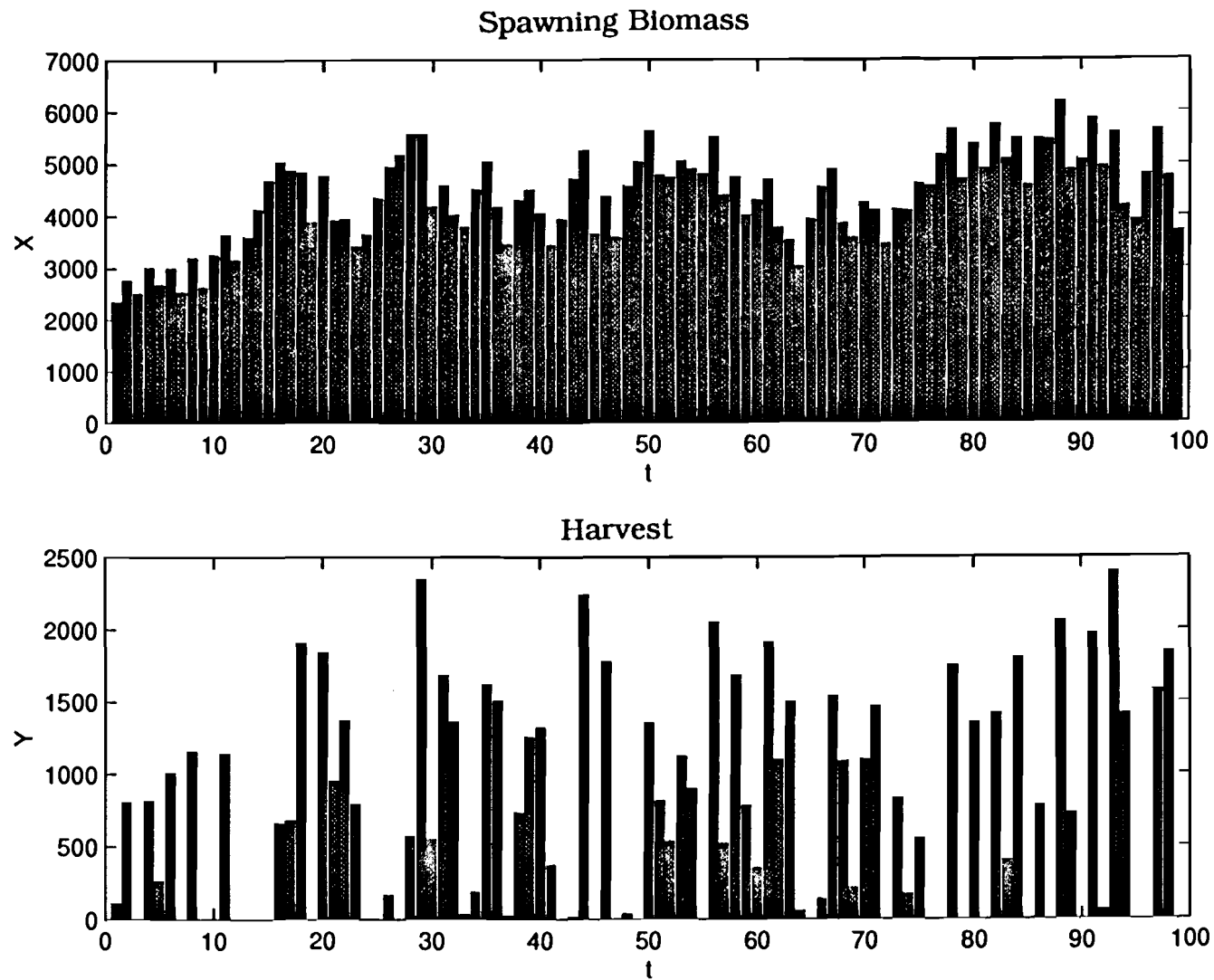
**Figure 4. The Asymptotic Approach to  $X^* = 5,000$  and  $Y^* = 835$  from  $X_0 = 2,500$  Under a Linear TAC Policy with SML in a Deterministic Environment**



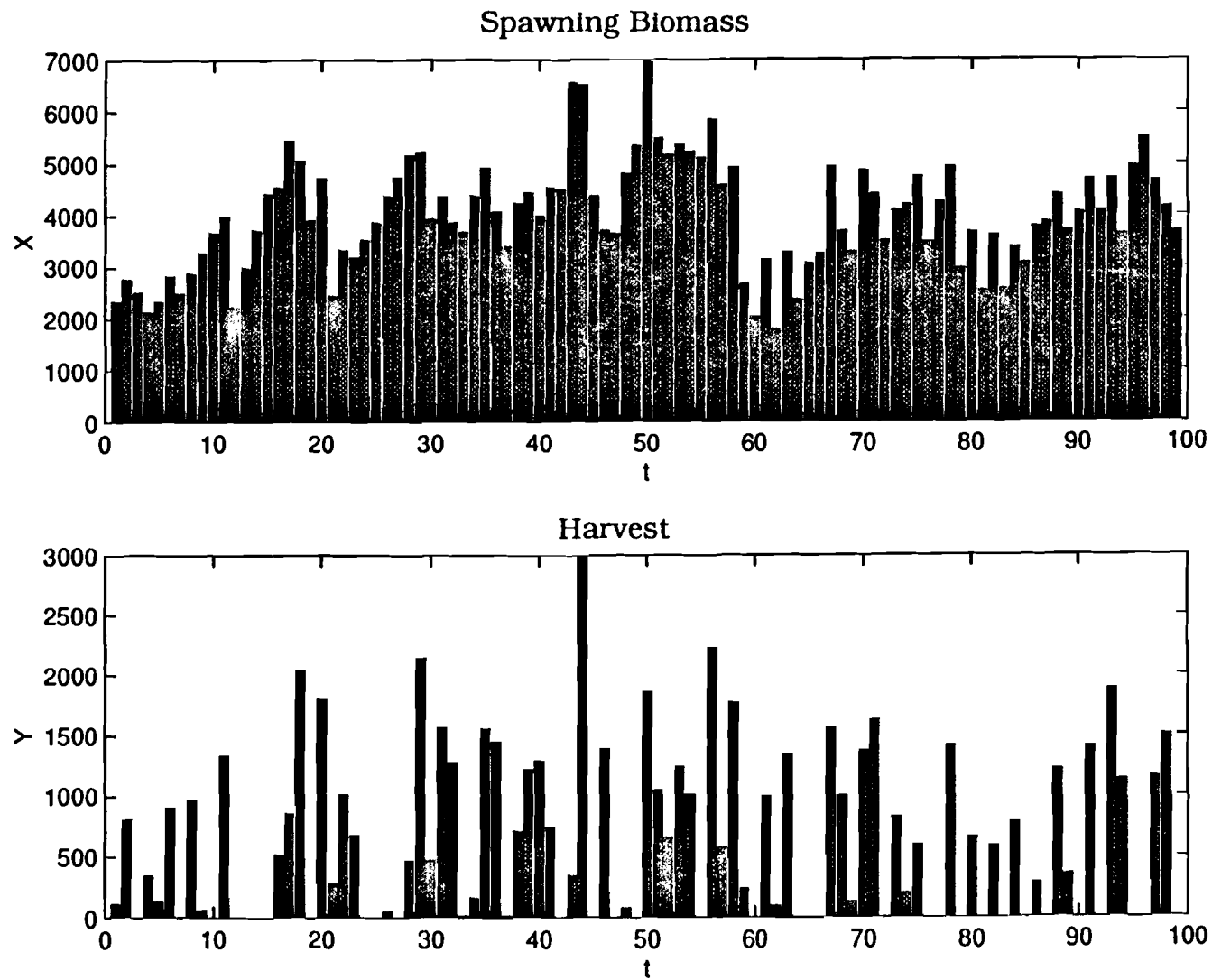
**Figure 5. Spawning Biomass and Harvest with Stochastic Recruitment But No Observation Error**



**Figure 6. Spawning Biomass and Harvest with Observation Error and Deterministic Recruitment**



**Figure 7. Spawning Biomass and Harvest with Observation Error and Stochastic Recruitment**



**Table 1. Total Biomass, Spawning Biomass, and Harvest of Norwegian Spring-Spawning Herring ( $\times 10^3$  mt), 1950-1996**

Year	Total Biomass	Spawning Biomass	Harvest
1950	17,677	12,066	933
1951	17,484	10,881	1,278
1952	19,092	9,979	1,255
1953	16,636	8,302	1,091
1954	17,363	7,800	1,645
1955	15,083	8,705	1,360
1956	13,434	10,585	1,659
1957	10,726	9,311	1,320
1958	9,322	8,506	987
1959	7,825	6,933	1,111
1960	7,321	5,547	1,102
1961	7,508	4,120	830
1962	6,615	3,297	849
1963	6,786	2,517	985
1964	6,540	2,575	1,282
1965	5,982	3,042	1,548
1966	4,328	2,580	1,955
1967	2,872	1,158	1,677
1968	885	221	712
1969	125	78	68
1970	78	31	62
1971	107	8	21
1972	71	2	13
1973	101	75	7
1974	155	87	8
1975	299	93	14
1976	361	149	10
1977	432	288	23
1978	588	361	20
1979	644	393	13
1980	761	481	19
1981	812	518	14
1982	742	517	17
1983	1,230	590	23
1984	2,553	615	54
1985	2,364	509	170
1986	2,280	456	225
1987	4,101	1,202	127
1988	4,660	3,874	135
1989	5,324	4,711	104
1990	5,994	4,654	86
1991	6,793	4,814	85
1992	7,494	4,591	104
1993	7,835	4,396	232
1994	8,471	5,098	479
1995	8,952	5,531	902
1996	8,096	5,483	1,197

**Source:** Patterson (1998)

**Table 2. Constrained Maximum Likelihood Estimates of  $r$  and  $K$  or  $\gamma$  and  $\eta$  when  $\tau = 3$  and  $M = 0.15$  are given and the Implied Values of  $X^*$  and  $Y^*$  When  $\delta = 0.02$**

	<u>Logistic</u>	<u>Gompertz</u>	<u>Exponential</u>	<u>MP Logistic</u>
$r$	0.293	0.112	----	0.4
$K$	25,165	45,413	----	18,500
$\gamma$	----	----	29.6	----
$\eta$	----	----	0.44	----
$R^2$	0.92	0.92	0.93	0.92
$X^*$	4,835	3,337	2,083	5,078
$Y^*$	493	559	637	838

**Table 3. A Listing of the MATLAB Program for Simulation of Observation Error with Stochastic Recruitment**

```
% Stochastic Simulation of the Norwegian Spring-Spawning Herring Stock under a Linear TAC Policy with a SMBL
T=105;N=1; % (T-1)=terminal period in realization when t=0 is initial period, N=the number of realizations.
r=0.4;K=18500;M=0.15;tau=3;SMBL=2500;alpha=-835.5;beta=0.334;
X=[T:N];OBX=[T:N];Y=[T:N];
for i=1:N % Initial Conditions for the tau+1 values of spawning biomass
for t=1:5
X(t,i)=2500;
end
end
for i=1:N
for t=5:T-1
OBX(t,i)=2*rand*X(t,i); % Possible Observation Error
if OBX(t,i)>SMBL
Y(t,i)=alpha+beta*OBX(t,i);
else
Y(t,i)=0;
end
u=rand; % Possible Stochastic Recruitment
if u>0.9 % This will occur with probability 0.1
z=2;
elseif u<0.1 % This will occur about with probability 0.1
z=0;
else % This will occur with probability 0.8
z=1;
end
X(t+1,i)=(1-M)*(X(t,i)-Y(t,i))+z*r*X(t-tau,i)*(1-X(t-tau,i)/K);
end
end
t=(6:1:T-1); % Time Interval for Bar Graphs
i=1; % Realization You Wish to Graph, N≥i≥1
figure
subplot(2,1,1);
bar(X(t,i)),xlabel('t'),ylabel('X'),title('Spawning Biomass under the Linear TAC Policy with SMBL')
subplot(2,1,2);
bar(Y(t,i)),xlabel('t'),ylabel('Y'),title('Harvest under the Linear TAC Policy with SMBL')
disp('Maximum Spawning Biomass ='),disp(max(X(t,i))),
disp('Minimum Spawning Biomass ='),disp(min(X(t,i))),
disp('Median Spawning Biomass ='),disp(median(X(t,i))),
disp('Mean Spawning Biomass ='),disp(mean(X(t,i))),
disp('Standard Deviation of Spawning Biomass ='),disp(std(X(t,i))),
disp('Maximum Harvest Rate ='),disp(max(Y(t,i))),
disp('Minimum Harvest Rate ='),disp(min(Y(t,i))),
disp('Median Harvest Rate ='),disp(median(Y(t,i))),
disp('Mean Harvest Rate ='),disp(mean(Y(t,i))),
disp('Standard Deviation of Harvest Rate ='),disp(std(Y(t,i))),
```

**Table 4. Descriptive Statistics for the Distributions of Spawning Biomass and Harvest with Stochastic Recruitment ( $z_t$ ), Observation Error ( $u_t$ ) or Both ( $z_t, u_t$ )**

	$z_t$	$u_t$	$z_t, u_t$
$X_{MAX}$	6,886	6,197	6,939
$X_{MIN}$	2,649	2,351	1,821
$\bar{X}$	4,589	4,368	4,011
$s_X$	873	852	1,034
$CV_X$	19.02	19.51	25.78
$Y_{MAX}$	1,464	2,401	2,981
$Y_{MIN}$	49	0	0
$\bar{Y}$	697	736	634
$s_Y$	291	730	694
$CV_Y$	41.75	99.18	109.46



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