CATCH STRATEGIES FOR THE PACIFIC SARDINE (*SARDINOPS SAGAX*)

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ABSTRACT

In this paper we develop a model of the long-term prospects for the Pacific sardine (*Sardinops sagax*) in which the surplus growth of the stock is influenced by random fluctuations. This can have an enduring effect partly through a serial correlation in the environmental disturbances, but also, and more importantly, because the effect of these random disturbances is related to the size of the stock itself. We use the model to generate fluctuations in the sardine stock to compare alternative fishing strategies: (i) constant escapement; (ii) constant exploitation rate; and (iii) a hybrid of the two. We find that strategy (i) results in greater catches per year and greater variability than (ii). The hybrid, (iii), results in greater catches and greater variability than (i). We conclude that the model supports the existing management of the U. S. Pacific sardine fishery.

INTRODUCTION

In the 1930s and 1940s the Pacific sardine (*Sardinops sagax*) supported one of the largest fisheries not just in the United States but the whole world (fig. 1). In the 1940s and 1950s the landings declined steeply despite a short recovery around 1950, and in the early 1960s the fishery stopped. Parallel to the decline in landings the stock also declined, which initially was blamed on overfishing. Later research has, however, indicated that in the past, and long before any fishing began, the sardine stock has been subject to similar crashes (Baumgartner et al. 1992). Overfishing thus may not have been the sole cause of the decline of the sardine stock in the 1930s and 1940s, and it might have declined in any case due to natural reasons.

This suggests that a model of the long-term prospects of the Pacific sardine must be capable of generating a collapse of the sardine stock in the absence of any fishing. Such a model must rely on either explicit environmental variables that can generate such fluctuations or other mechanisms, possibly related to the sardine stock itself. This paper examines a model of this kind in which the surplus growth of the stock is influenced by a random variable that generates fluctuations in stock size. These fluctuations can have an enduring effect partly through a serial correlation in the environmental disturbances but also, and more importantly, because the effect of these fluctuations is related to the size of the stock itself. The random disturbances will be calibrated based on the history of the stock.

The main purpose of the model is to generate fluctuations that resemble those that may be expected to occur in reality, in order to compare the effect of alternative fishing strategies. The model does not attempt to explain the fluctuations in the sardine stock, as it does not incorporate any physical processes that would generate such fluctuations. From the history of the sardine fishery and the sardine stock it is clear that fluctuations in the environment strongly influence stock development whatever the underlying physical factor is. To the extent the model generates realistic fluctuations in the stock, it suggests that just a few unlucky draws of nature are all that's needed to produce long periods of low stock abundance, such as have occurred in the past. It takes a long time for the stock to recover from such declines, simply because a small stock generates little growth. Hence, long waves of climate fluctuations, referred to as regime shifts, may not be necessary to produce prolonged periods of low stock abundance. As an illustration, suppose the stock has been knocked down to 5,000 metric tons (mt), which is believed to be its low point during the 1960s and 1970s. With a growth rate of 40% per year it would take the stock 16 years to recover above 1 million mt. In its heyday in the 1930s and 1940s it was well above that level. Such a high growth rate was observed in the 1980s and 1990s, a period of favorable environmental conditions (PFMC 1998, Appendix B).

How, then, should a stock subject to such dramatic random fluctuations be managed? We shall compare two alternative fishing strategies, one that attempts to always leave behind a certain minimum stock for growth and reproduction (target escapement), and one that catches a certain share of the stock available each year (constant fishing mortality). In addition we will look at a hybrid of these, one in which a certain share of the stock beyond a certain minimum is caught each year. This is to approximate the strategy currently employed in the management of the Pacific sardine under the U. S. Pacific

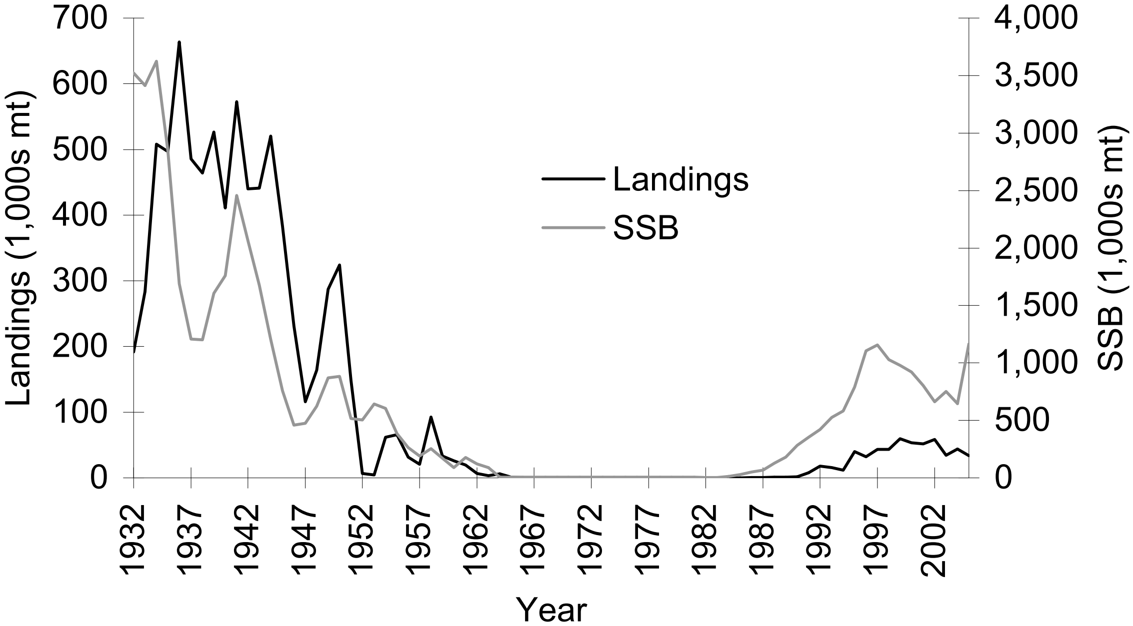

Figure 1: Spawning stock biomass (SSB) and landings (in California) of Pacific sardines (*Sardinops sagax*).

Fishery Management Council's (PFMC) Coastal Pelagic Species Fishery Management Plan (PFMC 1998, Appendix B), where the share of the stock that the industry is allowed to catch every year depends on environmental conditions, measured as the average sea surface temperature for the three most recent years. To mimic that strategy, we let the share being taken depend on the realized random environmental variable for the two most recent years.

The alternative strategies will be compared based on the average fish catches they would generate over a long time period and on the variability in the catches, measured as standard deviation and maximum and minimum annual catches. The variability of catches is also reflected in the number of years without fishing, either because there is virtually no fish to be caught or because the stock is below the escapement target.

Using stochastic models to analyze alternative fishing strategies for the sardine stock is not novel. In the management plan for sardine (PFMC 1998, Appendix B), a stochastic model, different from the one used here, was employed to simulate the development of the stock under different exploitation rates: target escapement and maximum catches. Since there is considerable uncertainty about what kind of model would be most appropriate for the sardine stock, it is of interest whether both models produce similar results with respect to the relevant management criteria.

The present model is a simple one, being a surplus growth model without any age structure. Nevertheless, such models can be useful to study the implications of alternative management strategies and related issues. An approach similar to the one taken here could be useful not only for other pelagic stocks that are highly variable; for example, it has been applied to study the implications of overfishing of the northeast Arctic cod (Hannesson 2007).

THE MODEL

Data on catches and the (spawning) stock of the Pacific sardine go back to 1932[1]. From these it is possible to calculate the surplus growth in year t as the difference in stock size between year $t+1$ and t plus the catches of fish in year t. According to Jacobson et al. (2005) only 83% of landings in any year represent surplus growth (some fish that were caught would have died for natural reasons). We shall follow that procedure here.

Figure 2 shows the surplus growth and the spawning stock of the Pacific sardine 1932–2004. Clearly the surplus growth is largely independent of the stock size, but it also appears that the variability in surplus growth increases with the stock, up to a point. A logistic surplus growth function was estimated by minimizing the sum of squared differences between the curve and the cal-

[1]California sardine landings for the period 1932–80 are from the PFMC's Coastal Pelagic Species Fishery Management Plan (PFMC 1998, Appendix A); sardine landings for 1981–2005 are from the PacFIN management database. Pacific sardine spawning stock biomass estimates for the period 1932–2000 are from Amendment 10 to the PFMC's Coastal Pelagic Species Fishery Management Plan (PFMC 2002, Appendix C); sardine biomass estimates for 2001–05 are from the PFMC's annual stock assessment and fishery evaluation document for coastal pelagic species (PFMC 2007).

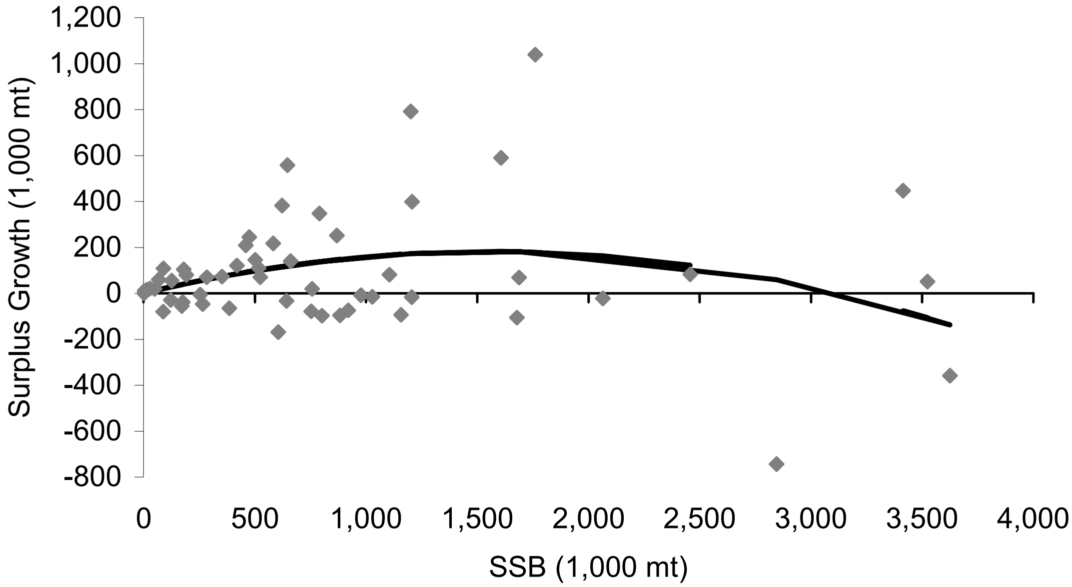

Figure 2: Surplus growth and spawning stock of Pacific sardine (*Sardinops sagax*) 1932–2004, and the estimated surplus growth curve.

culated surplus growth. This curve is also shown in Figure 2 and has the parameters $r = 0.2337$ and $K = 3121$.[2]

The next step is to define fluctuations in surplus growth as deviations (D) from the surplus growth curve, giving:

$$D_t = G_t - rS_t\,(1 - S_t/K), \tag{1}$$

where G is the calculated surplus growth, shown by the points in Figure 2, and S is the stock. Behind this deviation is the realization of a random environmental variable. However, the environmental variable is not what we observe but how it translates into surplus growth. Figure 2 suggests, as the curve indicates, that good or bad environmental conditions have a larger impact on surplus growth as the stock increases up to a certain point, but a diminishing impact after that. To elicit the environmental variable, we estimate the absolute value of D as, respectively, a quadratic versus a logarithmic function of S:

$$|D| = aS - bS^2; \tag{2}$$

$$ln|D| = \alpha + \beta lnS. \tag{3}$$

Table 1 shows the results of estimating these parameters by ordinary least squares. All parameters except α are highly significant, indicating that the deviations in surplus growth increase with the stock but either decline beyond a certain stock level (Equation 2) or increase with the stock at a diminishing rate (Equation 3). In the following we will use both equations and refer to them as the quadratic (Equation 2) versus logarithmic (Equation 3) model.

TABLE 1
Estimated parameters of how variations in surplus growth depend on stock size.

Parameter	Estimate	t-value
a	0.295	7.3
b	5.6733E-05	3.8
α	0.1633	0.2
β	0.6914	5.5

By dividing D by the right-hand side of Equation 2 versus Equation 3, we can calculate the environmental disturbance (U) which caused the deviation in the surplus growth:

$$U_t = \frac{D_t}{aS_t - bS_t^2}\,; \tag{4}$$

$$U_t = \frac{D_t}{S_t^{\beta} e^{\alpha}}\,. \tag{5}$$

The pattern in the data indicates that the disturbances are serially correlated. Regression analysis supports this for both models, although for the quadratic model, the support is weak (critical p-value 0.054). Using the estimates in Table 2, we can calculate the pure random disturbance each year (V_t):

$$V_t = U_t - k - mU_{t-1}\,, \tag{6}$$

[2]A linear regression of surplus growth on the spawning stock and spawning stock squared gives virtually identical results, and both parameters (r and r/K) are statistically significant.

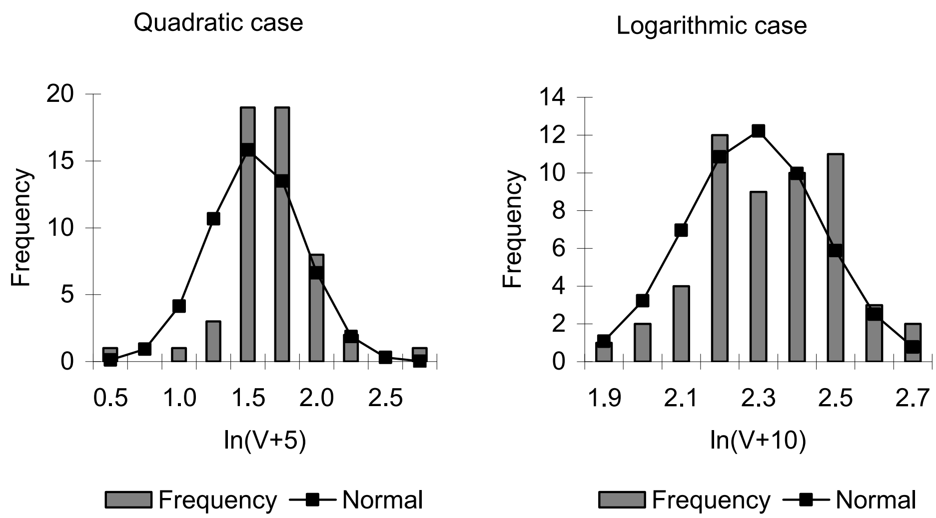

Figure 3: Histogram of *lnV* transformed and a normally distributed variable with the same mean and variance.

TABLE 2
Estimates of serial correlation in environmental disturbances ($U_t = k + mU_{t-1}$), *p*-values in parentheses.

Model	*k*	*m*
Quadratic (Eq. 2)	0.1709 (0.507)	0.2677 (0.054)
Logarithmic (Eq. 3)	0.0658 (0.791)	0.3334 (0.019)

with U_t being determined from Equation 4 or Equation 5, depending on whether we are using the quadratic or the logarithmic model (Equation 1 or 2). After a suitable linear transformation, the logarithms of the *V*s are close to normally distributed, as shown in Figure 3.

Using normally distributed random numbers to generate *lnV* and the serial correlation to generate *U*, we are able to generate quite varied development patterns for the sardine stock in the absence of fishing[3]. Three different runs for each of the above models are shown in Figures 4 and 5. What is worthy of note is the possibility of generating crashes of the stock, after which it persists at a very low level until recovery slowly succeeds. Such patterns seem to have occurred in the past (Smith 1978; Baumgartner et al. 1992) and certainly describe the development of the stock after the moratorium in the 1960s and until recovery set in around 1990. Some runs produce cycles, and in some the stock varies around a level close to the average carrying capacity ($K = 3121$) without much of a trend. If anything, the quadratic model seems better able to produce crashes that persist for decades, like the one from the 1960s to about 1990[4]. One difference between the two models is that the stock

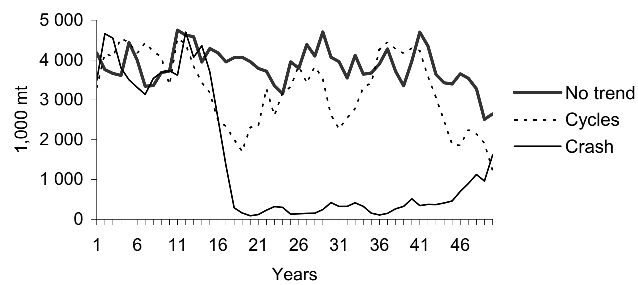

Figure 4: Alternative patterns for the stock produced by three runs of the quadratic model without fishing over a 50 year period.

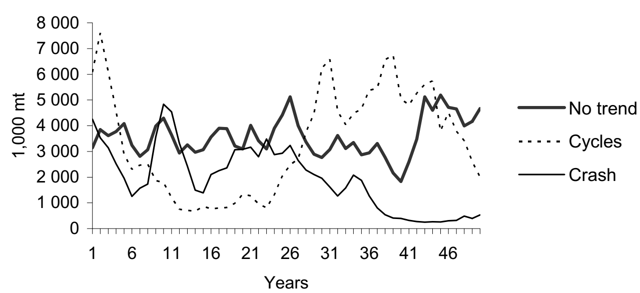

Figure 5: Alternative patterns for the stock produced by three runs of the logarithmic model without fishing over a 50 year period.

can become considerably greater in the logarithmic model than in the quadratic model. The reason is that a random draw of an advantageous environmental variable always increases surplus growth in the logarithmic model, but less and less the larger the stock is. In the quadratic

[3]There is in principle no upper or lower bound to the normally distributed random variable. We have precluded extinction of the stock due to an extremely unfavorable environment by imposing the restriction that the stock can never fall below 5,000 mt, the assumed minimum in the 1960s and 70s. Extremely favorable environmental conditions can occur, but with a low probability.

[4]A referee pointed out that the occasionally very high stock levels produced by the logarithmic model agree with the evidence from scale sediments that the sardine stock has in earlier times reached higher peaks than in the 1930s (Smith 1978; Baumgartner et al. 1992), and that the occasional peaks of the Japanese and the Humboldt sardine stocks lend credence to the logarithmic model.

model, a large stock is directly counterproductive, leading to a smaller surplus growth for any draw of the environmental variable.

TARGET ESCAPEMENT VERSUS CONSTANT FISHING MORTALITY

What are the implications of the above model for the management of the stock? We shall look at this in two simplified settings. In one, a constant escapement strategy is followed. This aims at always leaving behind some target level of the stock after fishing every year. In years when the stock is below the target level there is no fishing. Formally, the target escapement rule is:

$$Q = \max(0, S - \overline{S}), \tag{7}$$

where Q is the permitted catch (total catch quota) and $\overline{S}$ is the target escapement. Under this rule, the catches of fish will vary because the stock varies and all the stock beyond the target level will be taken. The catch per year in a long-term perspective depends on the target level set, and so do the variations in the catch. There might be some trade-off, however, between the catch per year and the variability, measured as standard deviation, maximum versus minimum catch, or the number of years in some given time period without any fishing at all. The high variability of catches under the target escapement strategy is likely to be undesirable, because of the large, but only occasionally utilized, fishing and processing capacity necessary to cope with the occasional peaks in catches.

In the other case, a certain share of the stock is fished every year (constant fishing mortality), except that when the stock is below a critically low level it is left unfished. This critical level is set at 5,000 mt, the level the stock is believed to have been close to during the catch moratorium 1968–86. In this case:

$$Q = \max(0, sS \textit{ if } S > 5000), \tag{8}$$

where s is the rate of exploitation. Under this strategy the catches will vary proportionately with the stock, but they will presumably be less variable than under the target escapement strategy. On the other hand, catching a given proportion of the stock will not spare the stock when it happens to be at a low level (except if it is below the critical level), which might impede a recovery of the stock when it has fallen to a low level. This could lead to a lower average catch than the target escapement strategy and possibly even to a greater variability by impeding stock recovery at low stock levels.

The two strategies are investigated by simulating the stock over a 100-year period, making 100 simulations for each target stock level or fixed exploitation rate. The simulations start with a plentiful stock of 4.0 million mt, close to the level in the early 1930s. Then a value of the random environmental variable is drawn for each year with a random number generator and the stock is updated according to the catch strategy followed. Both the quadratic and the logarithmic model discussed above are examined.

Target Escapement

Under this strategy, the initial stock level is reduced during the first year to the target escapement level, which in most cases produces an unrealistically large initial catch. This initial catch is ignored in calculating the average, maximum, and standard deviation of catches. The catch is set equal to the beginning stock level each year plus the surplus growth less the target stock, or zero otherwise, so ignoring that some fish that are caught would have died within the year for natural reasons.

The results are summarized in Figures 6 and 7. The former shows the average catch per year, the standard deviation of the catch over the 100-year period averaged over the 100 simulations, and the maximum and minimum catch per year obtained in any simulation. Both models produce similar results. The catch per year rises as the escapement level increases up to a level of 1.4 (logarithmic model) or 1.6 (quadratic model) million mt and then the catch stays relatively constant at about 160,000 (logarithmic model) or 200,000 (quadratic model) mt per year. Thereafter it falls off as the

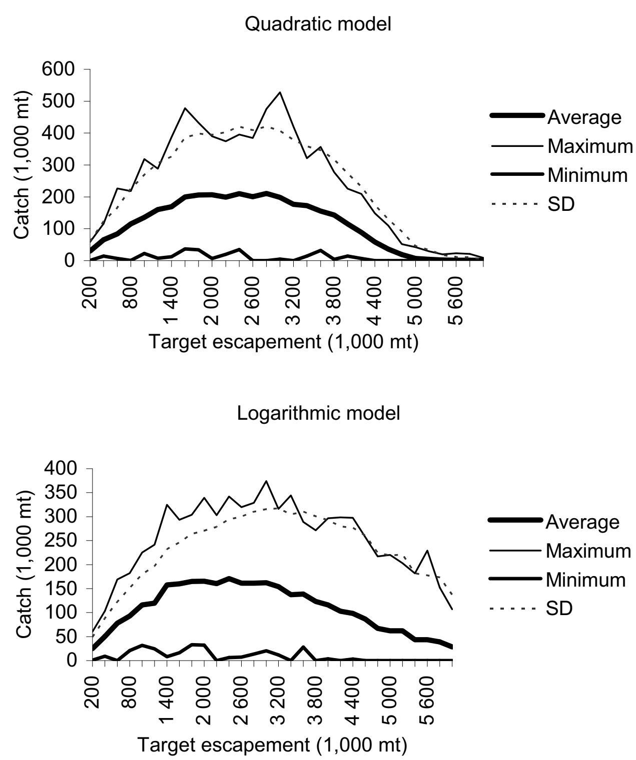

Figure 6: Average, maximum, and minimum catch per year, and standard deviation (SD) of catches as functions of target escapement.

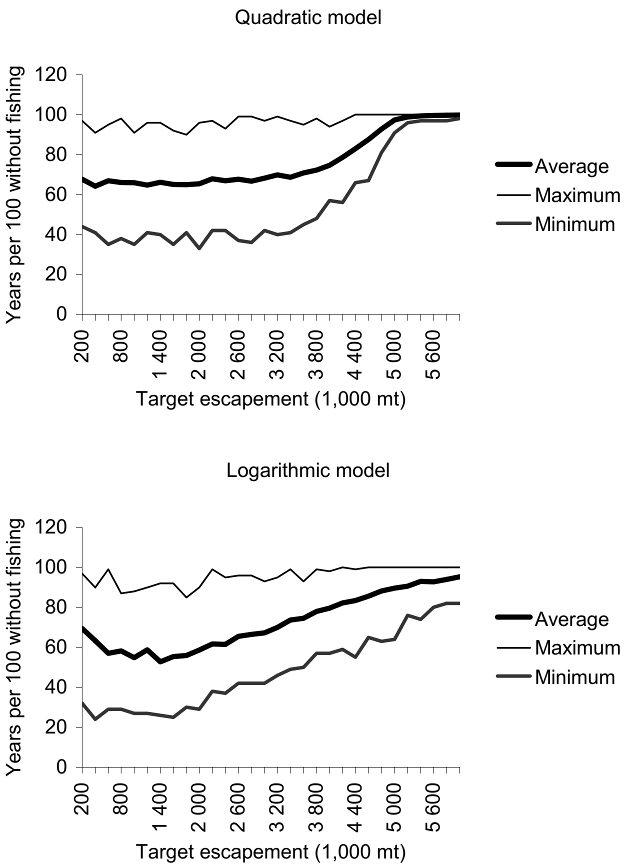

Figure 7: Average, maximum, and minimum number of years (T) without fishing as functions of target escapement.

escapement level exceeds 3.0 (quadratic model) or 3.4 (logarithmic model) million mt per year. At an escapement level of 5.0 million mt there is virtually no catch in the quadratic model, but still some in the logarithmic model because of its ability to sustain a large stock with a positive surplus growth where the quadratic model would produce a negative growth. Note that some catches are possible even if the target escapement is set well above the average carrying capacity parameter (K = 3.1 million mt) because of the variability of surplus growth.

The catches are highly variable. The standard deviation, averaged over the 100 simulations, is about as large as the maximum annual catch, especially in the quadratic model. The maximum catch is greater and more variable in the quadratic model, but both models produce a minimum catch quite close to zero for all target escapement levels. This variability is reflected in the number of years without any fishing. The average number of years without any fishing in a 100-year period is fairly constant in the quadratic model, slightly above 60, up to a target escapement level of about 3.0 million mt. After that, it rises gradually until there is hardly ever any fishing as the target escapement level exceeds 5.0 million mt. The minimum number of years without fishing in any 100-year period hovers around 40 years with an escapement level up to 3.4 million mt.

In the logarithmic model, the average number of years without fishing is slightly more variable. Initially it falls as the target escapement level rises and dips below 60 years, and then rises gradually as the target escapement exceeds 2.0 million mt. It takes a higher escapement level than in the quadratic model to reduce the years with fishing to zero. The minimum number of years without fishing in any 100-year period is lower than in the quadratic model, staying between 25 and 30 years until the target escapement exceeds 2.0 million mt. The maximum number of years without fishing in any 100-year period is similar to the quadratic model but somewhat more variable; it can be close to 100 even with target escapement as low as a few hundred thousand metric tons.

There is not really much of a trade-off between catch per year and the variability of catches. In the quadratic model, the catch per year is fairly constant over a range of escapement levels from 1.6 to 3.0 million mt. Both the standard deviation of catches and the average number of years without fishing are also fairly constant over that range. In the logarithmic model, both the standard deviation of catches and the average number of years without fishing continue increasing after the average catch has flattened out. On the basis of this model there would be no point in raising the escapement level beyond 1.4 million mt, when the average catch begins to flatten out.

Constant Exploitation Rate

Let us then turn to the case where a constant share of the stock is caught every year. Figure 8 shows how the average catch per year, the maximum and minimum catch per year, and the standard deviation of catch per year vary with the share of the stock being fished. The average catch peaks for quite a low exploitation rate, approximately 10%, both in the quadratic and the logarithmic model. There is not much difference between the peaks produced by the two models; the quadratic model produces a slightly higher peak, 140,000 mt, while the logarithmic model gives about 130,000 mt. For higher exploitation rates, the average catch per year tapers off rather quickly. It is noteworthy that the maximum catch per year in any simulation peaks at a higher exploitation rate than the average catch per year; it increases steeply to 350,000–400,000 mt for an exploitation rate of 0.15 and then falls quickly[5]. The standard deviation of catches increases with the exploitation rate until the latter reaches 20% and then stays high, tapering off as the exploitation rate exceeds 50%.

[5]In the simulations reported, the exploitation rate was varied in intervals of 0.05.

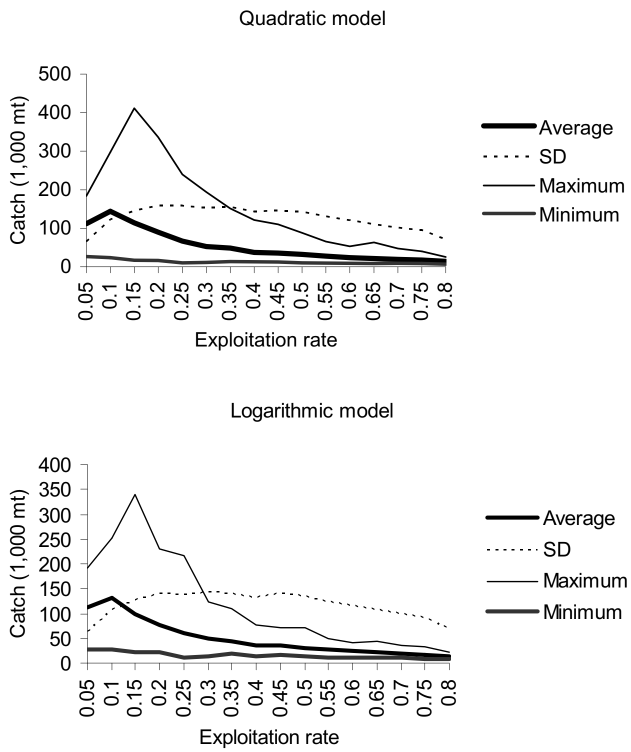

Figure 8: Average, maximum, and minimum catch per year and standard deviation (SD) of catches as functions of the share of the stock caught.

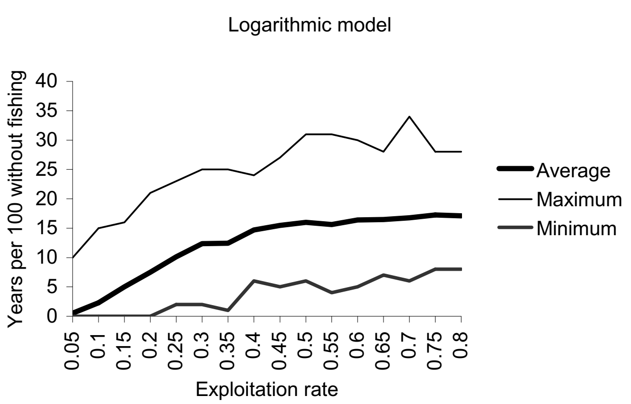

Figure 9: Average, maximum, and minimum number of years (*T*) without fishing as functions of the share of the stock caught.

In the quadratic model, the fishery is hardly ever shut down (recall that this was assumed to happen if the stock fell below 5,000 mt, which is an almost trivially low level). In the logarithmic model, this occurs more frequently (fig. 9). For an exploitation rate of 10%, which produces the maximum average catch per year, this hardly ever happens on the average, or in less than one year out of 100, but the maximum number of years that the fishery could be shut down because of this is 10. The number of shut-down years increases quickly with the exploitation rate, but even with an exploitation rate of 80% the fishery would only be shut down about 17 years on average, while the maximum number of years of shutdown could be around 30.

Comparing the Strategies

The target escapement strategy results in a greater catch per year. This is especially so in the quadratic model, where it produces about 200,000 mt per year on the average, while the constant exploitation rate produces 140,000 mt. In the logarithmic model, target escapement produces 160,000 mt per year on the average, while a constant exploitation rate produces 130,000 mt. But the variability of catches is much greater with the target escapement strategy. The maximum standard deviation is more than twice what it is under the constant exploitation rate: 420,000 mt versus 160,000 mt in the quadratic model, and 310,000 mt versus 140,000 mt in the logarithmic model. The much higher variability of catches under the target escapement strategy is also reflected in more frequent shut-downs; on average the fishery would be closed more than half the time (50–60 years out of 100) under a target escapement strategy that aimed at maximizing the average catch, while this would seldom happen with a constant exploitation rate. Higher yields on average would thus be attained at the expense of more frequent closures.

So, even if the target escapement strategy would yield higher catches per year it is not obviously better than the constant exploitation rate, as it produces a much greater variability in catches and much more frequent fishery closures. It is noteworthy that the exploitation rate that maximizes the average catch is quite low, only 10%, and the target escapement level that maximizes the average annual catch is rather high, 1.4 and 1.6 million mt, depending on which model we use.

These results are rather similar to those reported in the fishery management plan for the coastal pelagic species (PFMC 1998, Appendix B). There it was found that with a constant fishing mortality, the maximum average catch per year would be obtained when $F = 0.12$, resulting in an average annual catch of about 180,000 mt, a standard deviation of 180,000 mt, and no year without any catch. The instantaneous natural mortality of sardines has been estimated at 0.4, so $F = 0.12$ corresponds to an exploitation rate of 9% per year. With our model, we find that an exploitation rate of 10% per year would give a maximum annual catch of 130,000 mt or 140,000 mt, a standard deviation of a little over 100,000 mt, and very few or no years without any fishing at all. In the management plan it was found that a pulse fishery with a target escapement of 1.0 million mt would maximize the average annual catch, providing an average of about 200,000 mt, and result in no fishing about half the time and a standard deviation of catches of about 300,000 mt. In our model, we find that a target escape-

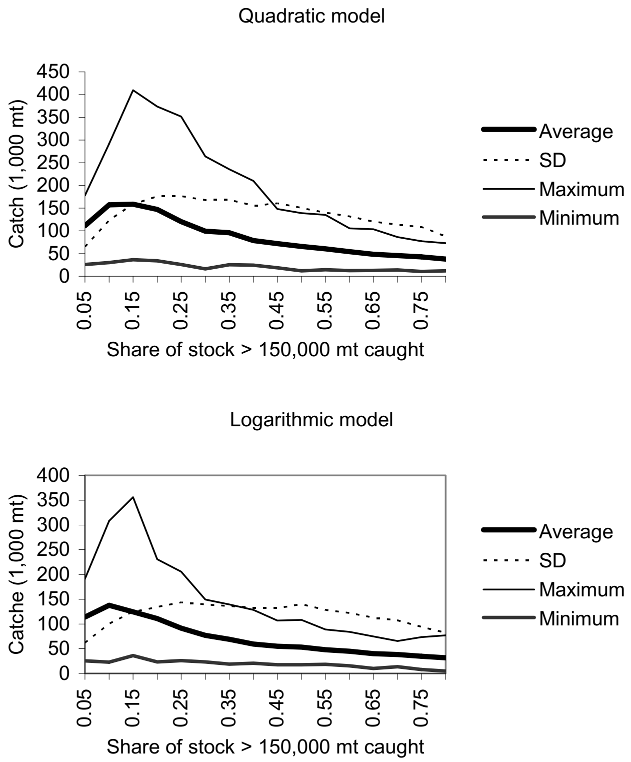

Figure 10: Average, maximum, and minimum catch per year and standard deviation (SD) of catches as functions of the stock share in excess of 150,000 mt caught.

ment of 1.4 or 1.6 million mt would maximize the average annual catch at 160,000 mt or 200,000 mt, but probably result in a closure of the fishery more than half the time and a standard deviation of catches of 230,000 mt or 390,000 mt. Thus, there is clearly a tradeoff between average annual catch and the variability of catches; greater stability and fewer closures of the fishery must be bought for lower catches on the average.

A HYBRID STRATEGY

The current PFMC management strategy employed for the Pacific sardine is a hybrid of the two considered above (PFMC 1998). The total catch quota is set equal to a certain fraction of the stock beyond a target escapement of 150,000 mt, the fraction depending on environmental conditions measured by the average sea surface temperature at the Scripps pier over the last three years. Under the current strategy, the total catch quota is also subject to a maximum allowable catch constraint.

Here we initially consider the hybrid strategy with a constant exploitation rate and then allow the share of the stock beyond 150,000 mt to vary according to the random environmental variable. For comparison with the earlier strategies we do not impose the maximum allowable catch constraint. The catch quota (Q) is:

$$Q = \max\,[0, s\,(S - \overline{S})]\,, \qquad (9)$$

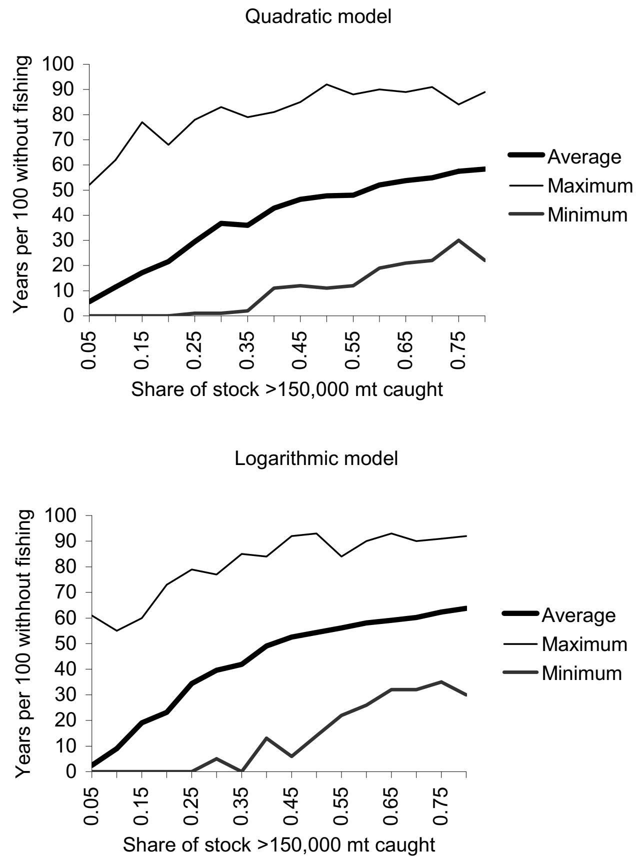

Figure 11: Average, maximum, and minimum number of years (*T*) without fishing as functions of the share of the stock beyond 150,000 mt caught.

where *s* is the exploitation rate and $\overline{S}$ the target escapement (150,000 mt).

The results (figs. 10 and 11) are not very different from those obtained for the constant exploitation rate above (figs. 8 and 9). The average annual catch is still maximized with an exploitation rate of 10%, although a rate of 15% gives virtually the same average annual catch in the quadratic model. For the quadratic model, the average annual catch is a bit higher in the hybrid strategy, about 160,000 mt compared with just over 140,000 mt in the simple constant exploitation rate strategy. For the logarithmic model, the average annual catch in the hybrid strategy is 137,000 mt, versus 132,000 mt in the simple constant exploitation rate strategy. But the variability is considerably greater. This is reflected primarily through longer period the fishery is shut down and less so through a higher standard deviation of catches. In the quadratic model, the standard deviation of the annual catch is virtually the same in the hybrid strategy as it is for the simple constant exploitation rate strategy at the 10% rate of exploitation, while in the logarithmic model it is slightly higher (107,000 mt versus 100,000 mt). But while in the quadratic model the fishery was

TABLE 3
Results from adjusting the exploitation rate according to environmental conditions. Catches in thousands of metric tons, shut-down time (T) in years out of 100.

	Hybrid, adjustable exploitation rate strategy						Constant exploitation rate strategy	
	k	Average catch	Average T	Average s	Maximum s	Minimum s	Average catch with s = 0.1	Average T with s = 0.1
Quadratic	0.06	185.1	16.8	0.114	0.759	0	143.7	0
Logarithmic	0.04	162.6	9.9	0.105	0.405	0	131.9	2.3

almost never shut down under the simple constant exploitation rate strategy, it is shut down for about 11 years on the average under the hybrid strategy, with the maximum and minimum number of shut-down years being 62 and 0, respectively. In the logarithmic model, the average number of shut-down years is 9.05 for the hybrid strategy compared with 2.29 in the simple constant exploitation rate strategy. The hybrid strategy, thus, is not unambiguously better than the constant exploitation rate strategy; it buys a higher average catch for greater variability in catches and more frequent shut-downs.

As already mentioned, the management strategy currently employed for the sardine stock lets the exploitation rate vary according to environmental conditions. Here we shall mimic this by letting the rate of exploitation deviate from the optimal constant one (s^o) according to the realized value of the environmental variable (U) in two adjacent periods. The catch quota (Q) in Equation 9 above is modified to:

$$Q = \max\left[0, \left(s^o + k\left(\frac{U_{t-1} + U_t}{2}\right)\right)(S_t - \overline{S})\right], \qquad (9')$$

where s^o = 0.1, k is an adjustment factor to be determined so as to maximize the average catch per year, and U is determined by Equation 6 and the random draw of V. The resulting exploitation rate, s^o+ k, is bound between 0 and 1.

The results are shown in Table 3. The adjustment factor k is sufficiently high for both models to produce quite high maximum exploitation rates (0.759 and 0.405, higher for the quadratic model) and minimum exploitation rates of 0. This is not entirely surprising; the target escapement strategy is the one that maximizes the average annual catch, which implies a quite variable exploitation rate. The average annual catch is raised by 20%–30%, but this comes at the cost of greater variability and having to shut down the fishery 10%–20% of the time on the average. Whereas, with a constant exploitation rate of 0.1, the fishery is hardly ever shut down. So, by adjusting the exploitation according to environmental conditions it would be possible to increase the average annual catch, but at the expense of more variable catches and having to shut down the fishery more often.

CONCLUSION

In this paper, we have used a surplus growth model to analyze the California Pacific sardine fishery. The model is capable of producing crashes in the stock even in the absence of fishing, which has apparently occurred several times in the past. All it takes to produce such crashes is a few unfortunate draws of a random variable reflecting unfavorable conditions in the environment. Once the stock has been knocked down to a very low level it will take a long time to recover because small stocks produce little surplus growth despite favorable environmental conditions. Long recovery periods after crashes could thus be due to this small-stock-little-growth effect rather than prolonged unfavorable environmental regimes.

Maximizing the average annual yield from the stock would entail a fishing strategy which aims at leaving behind a certain target stock (escapement). That this kind of strategy maximizes the returns from a fishery, given a constant price of fish, is long since well established (Reed 1979). But for fluctuating stocks this comes at the cost of highly variable catches; in the sardine case the fishery would be shut down more than half of the time if the policy aims to maximize the average annual catch. This is indeed likely to cause inconvenience for the industry.

Alternatively, one could use a constant rate of exploitation. This would mean less variability of catches, but they would still vary as long as the stock varies. The exploitation rate that would maximize the average annual catch is in fact quite low, only about 10%. The results from our model are in broad agreement with simulations undertaken to determine the optimal harvest policy for sardine in the Pacific Fishery Management Council's Fishery Management Plan for Coastal Pelagic Species (PFMC 1998), which were conducted using a different model; there it was found that the optimal fishing mortality was 0.12, implying an exploitation rate of about 9%. Our model produces an average annual catch that is somewhat lower, 130,000–140,000 mt compared to 180,000 mt. The simulations in the fishery management plan also found that a target escapement policy would maximize the average annual catch, but would shut down the fishery almost half the time. In our model, the fishery is shut down even more frequently, and the

TABLE 4
Comparison of results for four exploitation strategies.
Catches in thousands of metric tons, shut-down time in years out of 100.

	Average catch		Shut-down years	
Strategy	Q-model	Log-model	Q-model	Log-model
Target escapement	210	170	67	61
Constant exploitation rate	144	132	0	2
Hybrid, constant exploitation rate	158	137	11	9
Hybrid, adjustable exploitation rate	185	163	17	10

target escapement that maximizes the average catch per year is greater.

The currently employed harvest control strategy in the sardine fishery is a hybrid strategy, with a low (150,000 mt) target escapement, an exploitation rate that adjusts according to the ocean temperature at the Scripps pier for the last three years, and a maximum allowable catch constraint. Our model shows that such a hybrid strategy can indeed increase the average annual catch (without exceeding the current maximum allowable catch: 200,000 mt), but at the cost of greater variability, again manifested in more frequent shut-downs. Varying the exploitation rate according to environmental conditions increases the average annual yield still further, but also increases the variability in catches and results in more frequent fishery closures. Table 4 compares the results of the four strategies considered.

The target escapement harvesting strategy, the constant exploitation rate strategy, and the hybrid strategy could all be implemented through individual fishing quotas, which could be transferable or not. Whichever of these strategies is applied, the total catch quota would be set on the basis of stock assessment. With the target escapement strategy the total allowable catch would be set as the difference between the assessed stock level and the escapement level, while with the constant exploitation rate strategy it would be set as a prescribed share of the assessed stock. Since stock assessment is often inaccurate and can be improved as more is learned about the stock during the fishing season, it could be advisable to allow for revisions of the total allowable catch as the fishing season progresses. In some other fisheries the management authorities have been compelled to revise their quota prescriptions during the fishing period, usually downwards.

Individual quotas could be determined as fixed shares of the total allowable catch. Under this arrangement, which is the one usually applied in countries where fisheries are regulated with individual transferable quotas, the industry bears all the risk associated with the variability of the fish stock. As the variability in the total allowable catch, as well as the frequency of fishery closures, depends critically on the choice of harvest policy (exemplified here by the target escapement, constant exploitation rate, and the hybrid harvesting strategies), it is only reasonable that the industry has a say, perhaps a decisive say, in what rule is applied. That said, there are clearly aspects of the management of the sardine stock that lie beyond the purview of the industry, especially such as have to do with the importance of the sardine as a source of food for other species.

ACKNOWLEDGEMENTS

We extend thanks to Larry Jacobson and two anonymous reviewers for extremely helpful comments on an earlier version of the manuscript, and to John Heine for the invitation to participate in the CalCOFI symposium.

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