RECENT INCREASED ABUNDANCE AND POTENTIAL PRODUCTIVITY OF PACIFIC MACKEREL (*SCOMBER JAPONICUS*)

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ABSTRACT

Cohort analysis (VPA) of recent Pacific mackerel catches off southern California and northern Baja California shows that total biomass (age 1+) increased sharply beginning in 1977. The increase followed a period of extreme depletion, and continued for several years, reaching a peak of 300,000 to 500,000 MT in 1982. Abundance decreased substantially in 1983 and 1984 because of very weak recruitment. The 1978 year class was considerably stronger than the previous largest year class. The recent pattern of reproductive success has been more variable than was seen historically, although the underlying cycle seems to continue.

We investigate potential productivity of the Pacific mackerel resource by simulating the fishery from 1929 to 1968. The model assumes a Ricker stock-recruitment relationship, and retains the historical pattern in anomalies in reproductive successes, logarithm of recruits per spawner. We examine sensitivity of the simulation results to several alternative models of stock-recruitment compensation; the results are most robust to these assumptions if exploitation rates (annual catch divided by total biomass) are near 0.2. A yield isopleth diagram summarizes average annual yields for linear harvest formulas of the type: harvest equals a *fraction* of the total biomass in excess of a *cutoff* level. The present California Pacific mackerel fishery regulations (*fraction* = 0.2, *cutoff* = 18,144 MT total biomass) should produce an average yield of 27,000 MT/yr with an annual standard deviation of about 15,000 MT. Average yield could be increased to about 29,000 MT/yr if the *fraction* is increased to 0.28, but the annual standard deviation would increase to about 19,000 MT, and the average total biomass would decrease by about 25 percent. Because present California fishery regulations do not include all catches of Pacific mackerel in the harvest formula, the present effective value of the *fraction* exceeds its nominal value of 0.2.

RESUMEN

Análisis de las cohortes en capturas recientes de la caballa del Pacífico a la altura del sur de California y norte de Baja California indican que la biomasa total (edad 1+) aumentó abruptamente desde 1977. El incremento sucedió a un período de gran pauperización y continuó durante varios años, alcanzando, en 1982, un máximo de 300,000 a 500,000 toneladas métricas (TM). En 1983 y 1984 la abundancia disminuyó considerablemente debido al escaso reclutamiento. La clase anual de 1978 fué considerablemente más robusta que la clase anual anterior de mayor magnitud. El reciente patrón de éxito reproductivo fué más variable de lo registrado históricamente, pero el ciclo subyacente parece continuar. Investigamos el potencial reproductivo del recurso de la caballa del Pacífico mediante la simulación de la pesquería desde 1929 hasta 1968. El modelo presupone una relación Ricker de stock-reclutamiento, y conserva el patrón histórico de anomalías en el éxito reproductivo, i.e., logaritmo de reclutas por desovante. Examinamos la sensibilidad de los resultados de la simulación con respecto a varios modelos alternativos de compensación stock-reclutamiento; los resultados mas coherentes frente a estos supuestos se obtienen si los ritmos de explotación (captura anual sobre biomasa total) se mantienen en alrededor de 0.2. Un diagrama de isolíneas de rendimiento resume los rendimientos anuales medios para fórmulas de cosechas lineales del siguiente tipo: la cosecha es igual a una fracción de la biomasa total la cual excede un valor límite dado. Las reglamentaciones californianas actuales sobre la pesca de la caballa del Pacífico (fracción = 0.2, valor límite = 18,144 TM de biomasa total) deberían producir un rendimiento promedio de 27,000 TM por año, con una desviación estándar anual de aproximadamente 15,000 TM. La captura promedio podría ser aumentada a alrededor de 29,000 TM por año si la fracción fuera incrementada a 0.28, pero esto llevaría a un aumento de la desviación estándar anual a unas 19,000 TM, y la biomasa media total disminuiría en un aproximadamente 25%. Dado que las actuales reglamenta-

ciones pesqueras de California no incluyen todas las capturas de caballa del Pacífico en la fórmula del rendimiento, el valor actual efectivo de la fracción excede su valor nominal de 0.2.

INTRODUCTION

The Pacific mackerel (*Scomber japonicus*) resource off California is one of the most thoroughly studied in world fisheries. Its population dynamics, nonetheless, remain enigmatic in many respects. Fishery data have allowed cohort analyses to extend from the beginning of the fishery in 1929 to its collapse in the late 1960s, a period of about 40 years (Parrish and MacCall 1978). The California fishery was closed by legislation in 1970 and reopened in 1977, when abundance increased (Klingbeil 1983). Lack of fishery data during this closed period prevents detailed analysis of the collapsed population. However, the relatively large fishery since 1977 once again has supplied data sufficient for population estimates, the results of which are reported here.

In 1972 the California legislature enacted an innovative management law that established Pacific mackerel catch quotas according to a formula based on estimated resource abundance. The formula was changed in 1978 to its present wording, whereby seasonal harvest is to be no more than 20 percent of the excess over 20,000 short tons (18,144 MT). Klingbeil (1983) gives a detailed history of the fishery's management, including provisions for incidental catch allowances and size limits. Recent biological and economic conditions have caused both the southern and central California purse seine fleets to increase reliance on Pacific mackerel. The result has been that during recent seasons (1983-84 and 1984-85), quotas have been met much earlier than they otherwise would have been. Fishermen were then faced with several months of interseason restrictions on the catch of Pacific mackerel with virtually no alternative species available for redirected effort. Fishery managers have been faced with imposing short-term economic hardships on fishermen or else increasing quotas above the quantity dictated by the harvest formula and current abundance estimate.

Accordingly, some parts of industry and management have expressed interest in either modifying the harvest formula or replacing it with other management measures (e.g., constant quotas) in order to allow higher catch rates and/or lessen the need for in-season quota adjustments. Because the formula adopted in 1978 was not based on extensive fishery analysis, we have undertaken an evaluation of that formula in comparison with a range of alternative management measures. This analysis provides a guide for revising the

management regime as well as an assessment of reasonable expectations for future catch levels and patterns.

ABUNDANCE ESTIMATES

Method

Because many segments of the Pacific mackerel fishery are highly seasonal, we have compiled catches on a quarterly basis beginning with the fourth quarter of 1976, when incidental catches rose to a level allowing monitoring (Table 1). Accuracy of abundance estimates by cohort analysis requires that all catches be accounted for, so we have included estimates of the northern Baja California commercial catch (provided by Biol. Walterio Garcia, Instituto Nacional de Pesca, Ensenada, B.C.N., Mexico), and the recreational catch on the Pacific coast of the United States. Some of these source data were aggregated by year, and others are not yet available; reasonable assumptions (documented in Table 1) were employed where necessary to complete the catch information base. Errors in cohort analysis that arise from converting annual

TABLE 1
Season (July-June) Catches (MT) for Commercial and Recreational Segments of the Pacific Mackerel Fishery

Season	California Comm.	California Recr.[b]	Mexico[a] Comm.	Total	Fraction sampled (California comm./total)
1976-77	2603	190	1271	4064	0.64
1977-78	7787	872	5168	13827	0.56
1978-79	18249	1678	7376	27303	0.67
1979-80	27753	1648	5153	34554	0.80
1980-81	27910	1910	3368	33179	0.84
1981-82	37950	(1366)[c]	3045	42361	0.90
1982-83	30045	(1412)	(4518)	35975	0.84
1983-84	35908	(1412)	(4518)	41838	0.86

All fish for which ages were determined were sampled from the California commercial landings.

[a] Annual Mexican commercial catches and estimates of recent catches were supplied by Walterio Garcia (personal communication, Instituto Nacional de Pesca, Ensenada, Mexico). We calculated seasonal values by assuming 40% of the annual catch is taken in January-June.

[b] California partyboat catch is converted to total recreational catch based on the Marine Recreational Surveys of 1979 and 1980 (Holliday et al. 1984).

[c] Monthly partyboat catches are known through August 1981. Annual catch is known for 1981 and 1982. Annual catches for 1983 and 1984 are assumed to be the same as in 1982.

catches to nominal seasonal catches are not likely to be large (Sims 1982). Because age composition estimates are lacking for the Mexican and recreational fishery segments, their age compositions were assumed to be the same as that of the commercial fishery monitored at San Pedro, California. Although there are errors associated with these assumptions, much larger errors would necessarily result from omitting catch estimates for these incompletely reported segments.

The cohort analyses were conducted similarly to earlier estimates, except that the solution uses an accounting season beginning July 1 rather than May 1, as was used by Parrish and MacCall (1978). As before, fish 4 years old or older (age 4+) are assumed to be fully and equally available to the fishery; fishing mortality rates of age 4+ and age 5+ fish are equated in each season in order to "link" the solutions for adjacent cohorts. The instantaneous natural mortality rate (M) was assumed to be 0.5/yr (Parrish and MacCall 1978).

Current values of fishing mortality rates (F) need to be assumed in order to obtain F estimates for earlier time periods. The current values are imprecise, not being based on direct evidence; fortunately, estimates of fishing mortality rates for earlier periods become less arbitrary because of converging properties of cohort analysis (Parrish and MacCall 1978, 38-39). Lacking independent indices of mackerel abundance, we must base the estimate of current F (and hence the current biomass) on internal consistency and experience with fishery analysis; it would be misrepresen-

TABLE 2
Fishing Mortality Rate Estimates for Age 4+ Fish, for Various Initial Assumed Values

Season	Annual F estimate for age 4+		
1978-79	0.264	0.279	0.289
1979-80	0.417	0.450	0.473
1980-81	0.295	0.330	0.355
1981-82	0.292	0.341	0.378
1982-83	0.282	0.348	0.403
1983-84 (assumed)	0.3	0.4	0.5

tation to claim this to be more than an elaborate educated guess.

Our rationale for postulating initial values of F is as follows:

Fully available ages (4+). Trial solutions using a variety of current (1983-84 season) F estimates (Table 2) showed that a value of 0.3/yr produced consistently similar values for the preceding three seasons, and would correspond to roughly constant fishing mortality rates generated by the fishery. However, since mid-1983 jack mackerel (*Trachurus symmetricus*, the main alternative species in the fishery) have been much less available than usual, suggesting that fishing has been directed more specifically toward Pacific mackerel than in previous periods. Also, the abundance of Pacific mackerel has declined in the 1982-83 and 1983-84 seasons for all trial solutions (Figure 1),
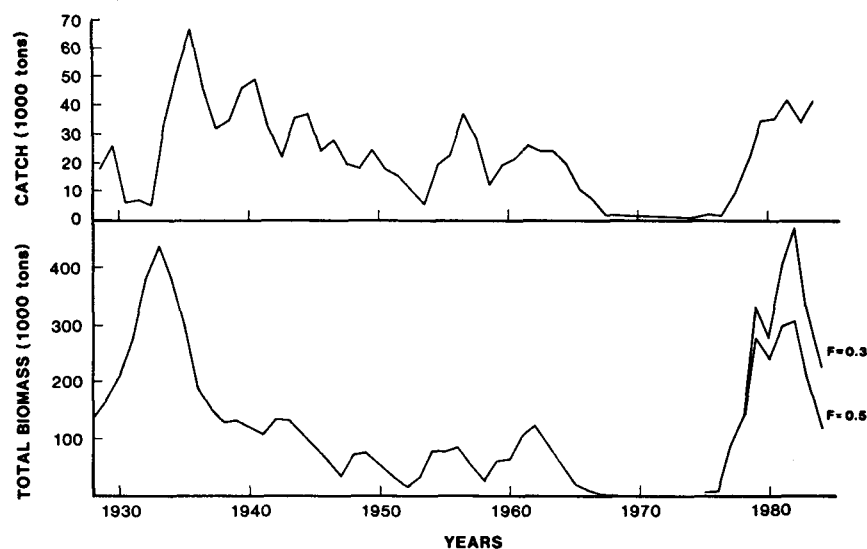

Figure 1. History of total harvest and total abundance (age 1+) of Pacific mackerel. Recent abundances reflect the range of assumed current fishing mortality rates (F) used in the analysis.

and F may have increased because of an abundance-dependent increase in the catchability coefficient, as is typical for coastal pelagic fisheries (cf MacCall 1976). Associated with this decline is a much older age composition, which in itself should result in higher average availability and consequently higher fishing mortality rates given similar levels of nominal fishing effort. Moreover, total catches during 1984 reached nearly 41,000 MT, one of the highest levels since the recovery began (Figure 1). On the other hand, the Pacific mackerel population extended northward much farther than normal in 1983 and 1984, probably in association with warm oceanic conditions. This would have reduced the available fraction of the stock, and would have reduced F accordingly. An F approaching 0.5/yr was generated on fully available fish in the 1979-80 season (Table 2), indicating that a value this high is clearly possible. We concluded that a range of current F from 0.3/yr to 0.5/yr is roughly consistent with these observations. These values provide nominal upper and lower abundance estimates, respectively (Figure 1). We feel that true abundance probably lies somewhere between these levels, but only future catch patterns can confirm these estimates.

Partially available ages (0,1,2,3). We obtained estimates of historical abundance of the 1980 and earlier year classes by assuming values of current F for fully available fish. We then evaluated availability of younger ages relative to age 4+ for the 1979-80 through 1982-83 seasons. Mean availabilities differed very little for the three solutions, and were 0.026, 0.153, 0.380, and 0.717 for ages 0 through 3 in the current F = 0.4/yr solution. Current F values for the partially available ages were obtained by multiplying estimated F for fully available ages by mean availability at age. These estimates become very imprecise for the younger age groups, but the effect on the 1984 abundance estimate is relatively small because the contribution from the 1982 and 1983 year classes is unusually small. Nominal estimates for age 0 fish are inaccurate because the fish appear in the catch only toward the end of the season.

Annual biomasses are calculated for July 1 of each year, using estimated abundances (Table 3) and observed mean weights at age for the third quarter of that year. We calculated spawning biomasses according to the spawning fractions at age given by Parrish and MacCall (1978, 26-27). Where comparisons with the historical fishery were desired, we projected numerical abundances back to May 1 by multiplying by EXP $[(F+M)/6]$, and calculated biomasses based on mean weights at age from the second quarter of the year.

Results

Pacific mackerel abundance from 1977 to 1984 was of a magnitude that has not been experienced for nearly 50 years in California (Figure 1). The high biomasses estimated by Parrish and MacCall for the 1930s were based on length-composition information that they considered unreliable. Thus the reality of those extremely high abundance estimates seemed questionable. However, the similar abundances estimated for the recent period confirm that the resource can attain such high levels. The contrast between recent abundances and those of the previous decade (1967-76) is even more remarkable. In view of this apparently unusual behavior of the resource, it is reasonable to inquire whether the recent patterns of Pacific mackerel population dynamics are similar to, or different from those of the preceding period.

The historical relationship between recruitment and spawning biomass has been nebulous, even when viewed on a log-log scale (Figure 2). Yet the recent estimates are variable even by historical standards: many of the new observations fall on the periphery or outside the "cloud" of points established during the previous 40 years of fishery analysis. The 1976 year class that initiated the fishery recovery was moderately strong, but was produced by a spawning biomass much smaller than any parental abundance previously
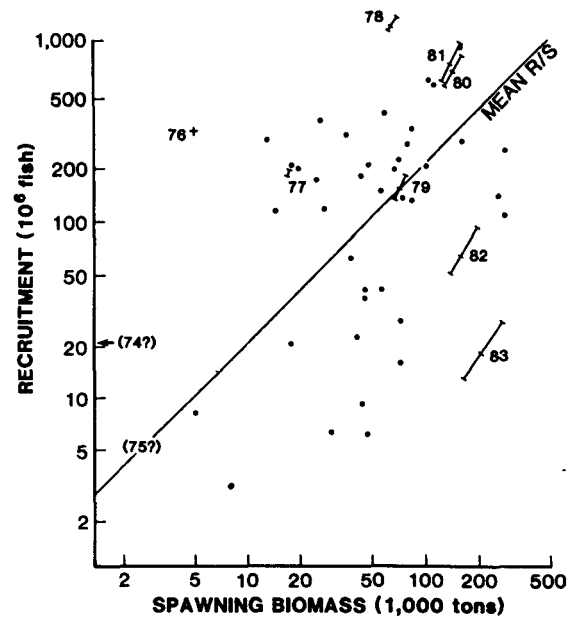

Figure 2. Relationship between Pacific mackerel recruitment and spawning biomass (log-log scale). Ranges of recent estimates reflect the range of assumed current fishing mortality rates (F) used in the analysis. Historical values (dots) are included for comparison.

TABLE 3
Annual Catches at Age (C, 10⁶ Fish), Estimated Fishing Mortality Rates (F, Year ⁻¹), and
Initial Abundances at Age (N, 10⁶ Fish on July 1) for the Current F = 0.4/yr Solution

	Age						
Season	0	1	2	3	4	4+	5+
1976-77							
C	15.5	0.05	1.3				
F	0.041	0.015	0.156				
N	—	5.0	11.7				
1977-78							
C	7.9	38.3	0.08	0.21			
F	0.034	0.172	0.036	0.045			
N	—	304.8	3.0	6.1			
1978-79							
C	64.2	20.9	30.8	0.85	0.68	0.68	
F	0.041	0.165	0.286	0.894	0.279	0.279	
N	—	173.7	155.6	1.8	3.5	3.5	
1979-80							
C	0.1	105.3	14.2	13.5	0.13	0.60	0.47
F	0.001	0.120	0.224	0.273	0.451	0.451	0.451
N	—	1181.8	89.4	70.9	0.4	2.1	1.6
1980-81							
C	16.2	1.4	77.7	7.6	7.3	7.5	0.18
F	0.019	0.012	0.167	0.249	0.330	0.330	0.330
N	—	141.6	636.1	43.3	32.7	33.5	0.8
1981-82							
C	6.1	33.8	5.8	66.6	4.7	8.1	3.4
F	0.007	0.069	0.090	0.296	0.341	0.341	0.341
N	—	641.7	84.8	326.3	20.5	35.1	14.6
1982-83							
C	0.6	19.9	23.7	7.4	34.5	38.1	3.6
F	0.008	0.037	0.086	0.221	0.348	0.348	0.348
N	—	693.9	363.2	47.0	147.2	162.4	15.2
1983-84							
C	0.2	2.8	45.3	40.2	6.0	—	18.4
F	0.010	0.061	0.152	0.287	0.400	—	0.400
N	—	59.9	405.6	202.1	22.9	—	69.6
July 1, 1984							
N	—	16.5	34.2	211.3	92.0	—	37.6

The 1974 year class (upper right diagonal) includes all older ages.

seen to have produced such a level of recruitment. The recruitment strength of the 1978 year class (1.21 to 1.44 billion fish on May 1) was 27% to 52% larger than the previous record 1932 year class (0.95 billion fish). Indeed, three of the four largest year classes on record (1978, 1980, and 1981) may have occurred since the recovery. In contrast, the 1982 and 1983 year classes appear to be unusually weak with respect to the large spawning biomasses that produced them. This belies the previous impression (Parrish and MacCall

1978, 42) that recruitment strength is much less variable when spawning biomass exceeds 100,000 MT, and that this abundance provides insurance against recruitment failure.

The temporal pattern of reproductive success, measured as the logarithm of recruits per spawning biomass, historically followed a roughly cyclic pattern (Figure 3). As expected from Figure 2, the amplitude of recent fluctuations is larger than was seen in the historical pattern. The decline in reproductive success
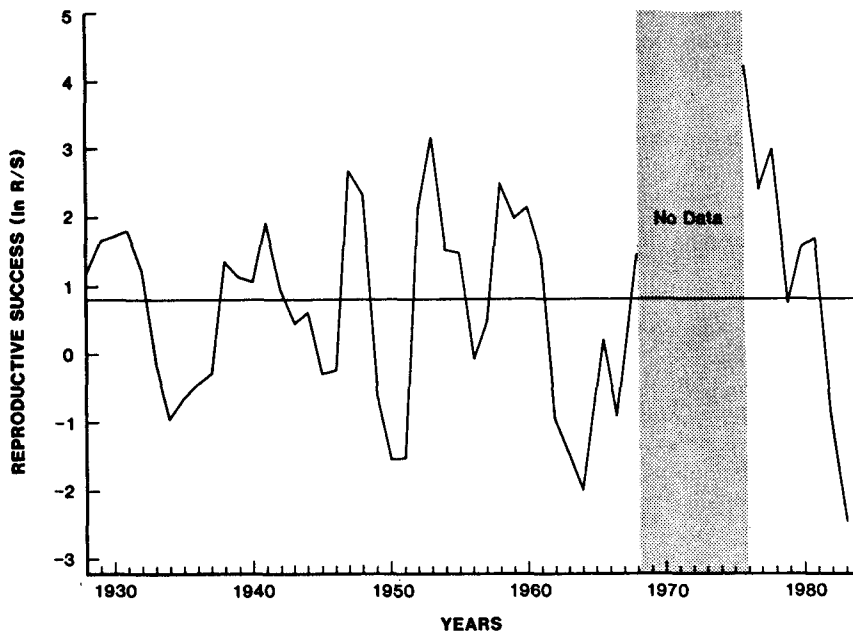
Figure 3. Time series of Pacific mackerel reproductive successes, based on an assumed current F of 0.4/yr. R is recruitment in numbers of fish; S is spawning biomass in kg.

from 1976 to 1983 shows a multiyear decline similar to previous declines, but with short-term reversals that have not been common previously. The presumptive cycle is not yet complete; early catches of the 1984 year class indicate that it is stronger than the two preceding year classes. Of course, a prolonged series of poor reproductive success is possible, especially in view of the historical pattern of poor recruitments from 1933 to 1938, immediately following the very high abundances of the early 1930s. The recent decline from the top (1976) to the bottom (1983?) of the present cycle in reproductive success has taken at least eight years, which is one year longer than the previous longest decline (from 1957 to 1964). The reproductive success at the top of the recent cycle was approximately 750 times that at the presumptive bottom of the cycle, making Pacific mackerel off California one of the more variable cases known to fishery science. The temporal pattern of reproductive success since the recovery is roughly congruent with the previous historical pattern, but the scale appears to be different. The unreliability of the values estimated by Parrish and MacCall for the 1930s limits our ability to draw definitive comparisons.

POTENTIAL PRODUCTIVITY

Method

The Pacific mackerel resource is by nature highly variable. Standard fishery models, most of which are based on equilibrium assumptions, are inappropriate for addressing this variability and its consequences. Here we assess potential productivity by means of computer simulations. We re-create the fishery from 1929 to 1968 under various harvesting policies, basing the simulated resource response on the observed history of reproductive successes, and thus preserving the important temporal pattern of the fluctuations (cf Figure 3). The calculations use Pope's (1972) approximation to the catch equation, whereby annual catches are removed from the simulated stock instantaneously at midseason. Weights at age are taken from Parrish and MacCall (1978, Table 7), and availabilities at age are based on the average F relative to that of age 4+ for the 1945-46 to 1964-65 seasons, during which period the resource was fully exploited. The natural mortality rate (M) was assumed to be 0.5, and ages 4 and older are combined into a single age group. Table 4 gives age-specific parameter values used in the simulations.

Treatment of the stock-recruitment relationship (SRR) has a strong influence on estimates of productivity, and deserves extensive discussion. Because the simulated spawning biomass is usually different from the historical spawning biomass for a particular year, the simulated recruitment should be correspondingly different from the historical recruitment. The nature and extent of that difference is given by the SRR. Unfortunately, the historical reproductive successes do not show a clear functional SRR (Figures 2,4).
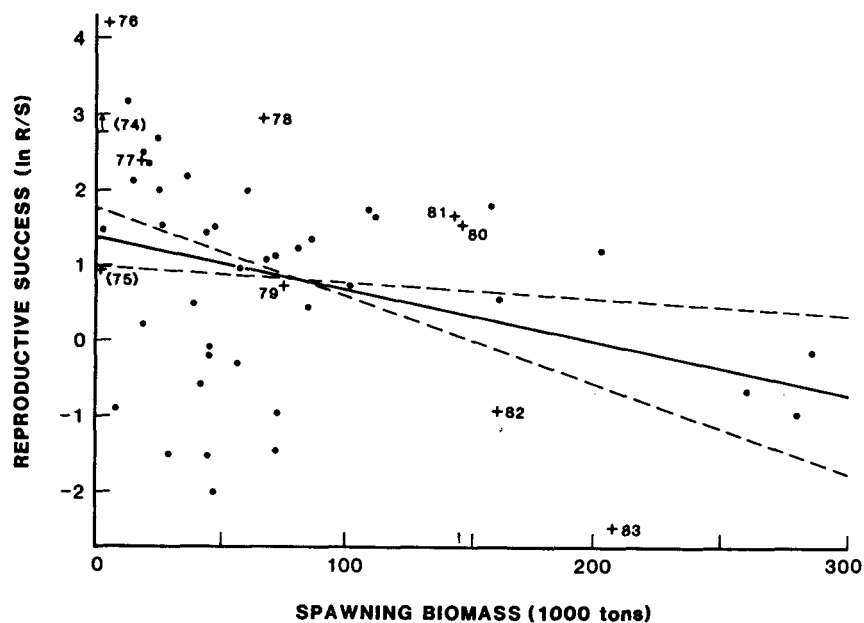
Figure 4. Relationship between Pacific mackerel reproductive success and spawning biomass, showing the linear regression estimates. Dashed lines show a nominal 90 percent confidence interval for the slope, b.

Therefore we consider two null models: first, that of "constant reproductive success" (CR/S), where historical reproductive successes are used without compensatory modification, and at the other extreme, "constant recruitment" (CR), where the historical recruitments themselves are used without modification, i.e., complete compensation. The true response must lie between the two extremes given by these null models, so they provide reasonable bounds on the estimated productivity of the resource. An intermediate level of compensation is represented by the Ricker SRR, which can be defined by a linear regression of $\ln(R/S)$ on spawning biomass (S). Some degree of compensation seems necessary because the abundance

trajectory of the 40-year simulation reaches unreasonably high levels in the absence of harvest, whereas use of the Ricker SRR produces an abundance trajectory with upper bounds similar to the abundance levels observed in the 1930s and 1980s (Figure 5). It is important that we have no objective evidence that a Ricker SRR is appropriate. However, the model agrees with the trend in the data (Figure 4), and is mathematically convenient.

The Ricker SRR used in the simulations retains the observed time series of anomalies in historical reproductive success,

$$\ln(R/S)_i = a - bS_i + e_i$$

where R_i is recruitment (in numbers) from the spawning in year i,

S_i is spawning biomass (kg),

a and b are parameters estimated from the historical data from 1929 to 1983,

and e_i is the anomaly in year i.

Although this regression estimate of parameters may be assumed to provide the best estimates of resource productivity from the simulations, the extreme variability of reproductive success (Figure 4) makes sensitivity analysis appropriate. In addition to the best-fitting Ricker SRR ($a = 1.352$, $b = 6.788/10^6$MT, $SE_b = 2.818/10^6$MT, $46df$), we examined cases corresponding to the upper and lower 90% con-

TABLE 4
Age-Specific Parameters Used in the Pacific Mackerel Fishery Simulations

	Age				
	1	2	3	4	5+
Availability	0.366	0.494	0.711	1.000	1.000
Weight (kg)	0.192	0.317	0.448	0.574	0.725
Fraction spawning	*	0.77	0.88	1.00	1.00
Initial abundance (10^{6}fish)	229.6	207.0	33.2	24.4	0.0

*Fraction age 1 is 0.54/EXP(15.8B), where B is total biomass (age 1+) in 10^{6}MT (Parrish and MacCall 1978).
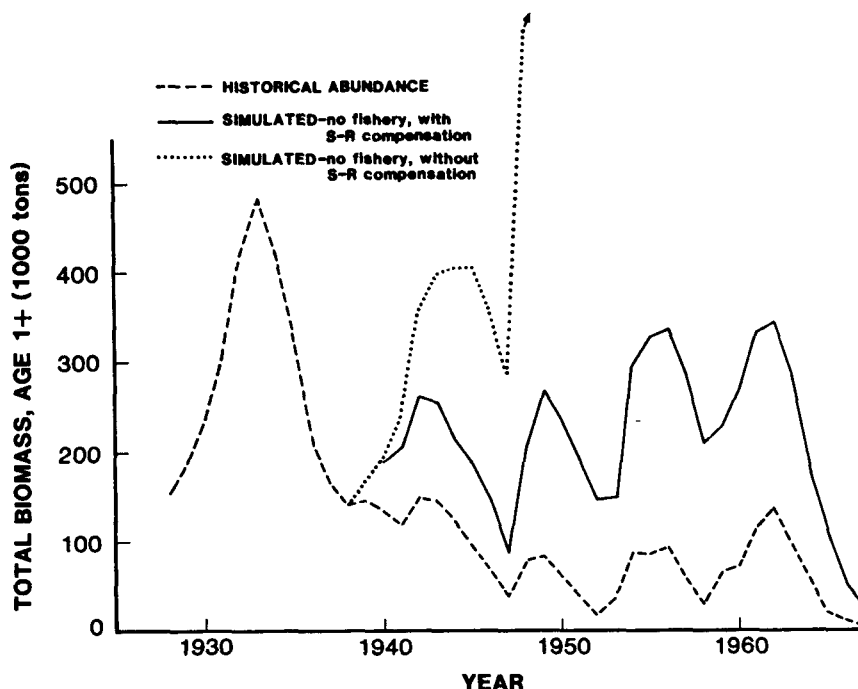
Figure 5. Time trajectories of simulated total biomass of Pacific mackerel. Solid line is based on the best-fitting Ricker SRR; dashed line is based on the CR/S model.

fidence limits of the slope parameter from the regression ($b_{upper} = 11.521/10^6$MT, $b_{lower} = 2.055/10^6$MT). Besides imprecision arising from natural variability, estimates of b are also influenced by systematic biases resulting from violations of simplifying assumptions. For example, Ludwig and Walters (1981) showed that random error in measurement of spawner abundance (S_i) tends to produce underestimates of b. In contrast, Walters (1985) showed that the time-series dynamics of propagation of environmental perturbations (e_i) tend to lead to overestimation of b. The extent of, and interaction among, these systematic biases is unknown.

Results

Although a wide variety of management policies could be evaluated by our simulation procedure, we present results for only one type of policy—that corresponding to the linear harvest formula of the present California management law. This type of policy can be written as

$$H = p(B-B_{min}) \quad \text{if } B > B_{min}$$
$$H = O \text{ otherwise.}$$

Thus, the harvest (H) is specified by two parameters, and is given by the fraction (p, the *fraction*) of the

excess of the total biomass (B) over a minimum total biomass (B_{min}, the *cutoff*). Note that if the formula implies a negative harvest, no harvest is allowed. A *cutoff* of zero abundance is analogous to a constant effort policy. *Cutoff* values greater than zero approach a constant escapement policy, whereas *cutoff* values less than zero approach a constant harvest policy.

For the purpose of sensitivity analysis, we compare yields averaged over the 40-year simulation, given the five different stock-recruitment compensation models discussed above (Figure 6). This comparison examines the set of harvest formulas consisting of various *fractions*, given a *cutoff* of 18,144 MT (20,000 short tons) total biomass. The average annual yields are very consistent for *fractions* from 0.2 to 0.25; simulated spawning biomasses are most near their historical values (average is 80,573 MT); spawning successes are most near their historical values; and the influence of different assumed models of compensation is minimal. Accordingly, we should be able to place our greatest confidence in this region of the yield curves. Unlike the other models, the CR model produces an asymptotic yield curve because the model lacks feedback of harvests on subsequent recruitments. The CR/S model behaves badly at low fishing intensities, because it allows the simulated abundance to become unreasonably large, as was mentioned previously. As might be expected, the yield curve corre-
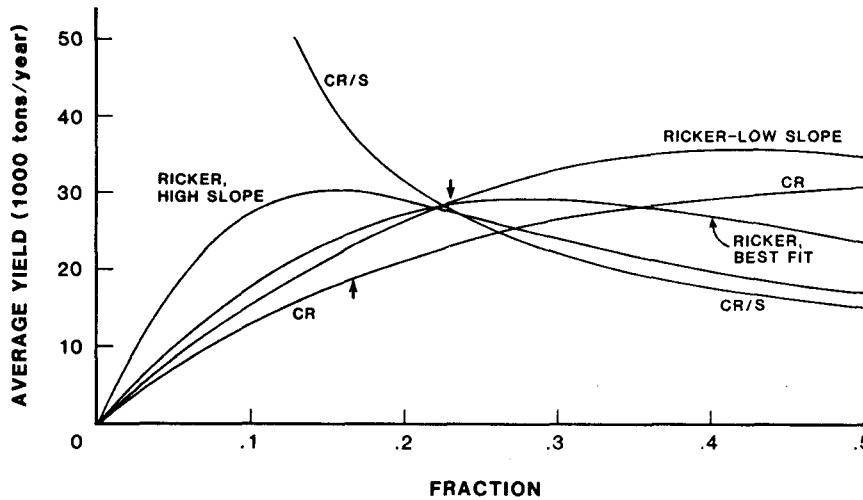
Figure 6. Comparison of average Pacific mackerel yields from linear harvest policies with a *cutoff* of 18,414 MT (20,000 short tons), and five assumed models of stock-recruitment compensation. The arrow denotes the simulations with greatest robustness, where simulated average spawning biomass is equal to the historical average.

sponding to the upper confidence limit for parameter *b* (i.e., the most compensation) tends to resemble the CR yield curve, and the lower confidence limit (i.e., least compensation) produces a yield curve closely resembling the CR/S curve at higher fishing intensities. Although the fishing intensity needed to produce the maximum average yield is sensitive to the assumed compensation model, the maximum average yield itself is much less sensitive, ranging from 29,000 to 36,000 MT (within the 90% confidence limits of the Ricker SRR).

Our simulation results are summarized by a yield isopleth diagram showing the average yields for various combinations of the *cutoff* and *fraction* parameters of the linear harvest formula (Figure 7). The region of greatest confidence in the simulation results, where average simulated spawning biomass is equal to the historical average, extends across the center of the diagram, rising slightly toward the right. Maximum average yield for a given *cutoff* appears as a ridge also rising toward the right. Maximum average yield for a zero-*cutoff* (constant effort) policy is 28,500 MT/year, whereas it exceeds 30,000 MT/year at large *cutoff* values.

In general, the standard deviation of annual harvest increases with larger *fractions*, but is nearly independent of *cutoffs* in the range of values examined here. The standard deviation of annual harvest rises in proportion to the *fraction* to about 15,000 MT at a *fraction* of 0.2, and then becomes roughly asymptotic at about 20,000 MT for *fractions* above 0.3. Because higher *cutoffs* require higher fractions to maximize yield, variability also increases with maximum average yield.

Formulas with negative *cutoffs* do not curtail harvest at low abundances, and therefore run a high risk of depleting the resource. The region of Figure 7 marked "collapse" shows those parameter values that result in total loss of the resource within the 40-year period of the simulation; the actual region of potential collapse extends to much lower *fractions*, but does not extend to positive values of *cutoff*, which serve to protect against total loss of the resource. Also, the isopleths of average yield for negative *cutoffs* do not recognize the long period of no yield following a collapse, so actual isopleths must bend downward much more sharply than is shown by the upper left section of Figure 7.
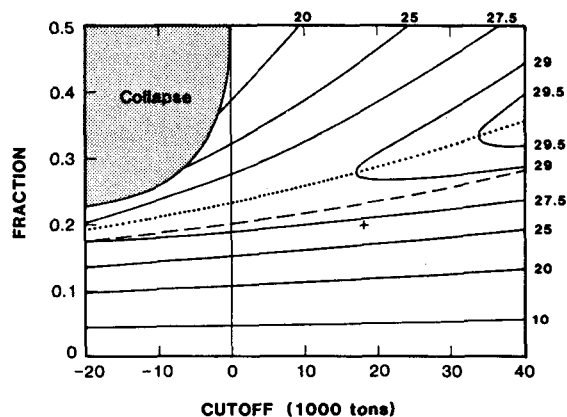

Figure 7. Average yield isopleths for linear harvest policies and the best-fitting Ricker SRR. Dotted line is maximum average yield, given the *cutoff*. Dashed line is the locus of greatest robustness, where simulated average spawning biomass is equal to the historical average. The cross denotes present management policy.

DISCUSSION

The high abundances of the 1930s and 1980s are remarkable events in the history of the fishery (Figure 1). We are now able to attempt to estimate how often these events occur. The paleosedimentary record of Pacific mackerel scales in the Santa Barbara Basin (Soutar and Isaacs 1974) shows two peak periods of deposition since 1800. One is in 1925-35, corresponding to the known abundance peak at that time. The other event occurred about 1830. Albeit imprecise, the simulated trajectory of Pacific mackerel abundances in the absence of a fishery (Figure 5) suggests that none of the post-1930 peaks would have been as large. Thus we can tentatively identify three major eruptions of the resource in the last 185 years, and conclude that the recent level of abundance is a rare event.

The ecological effects of increased Pacific mackerel abundance are confounded with other recent changes in the environment and fisheries. Mackerel extended their range far to the north during the 1980s, but the migratory effects of population pressure are difficult to separate from the influence of the strong 1982-84 oceanic warming. During 1983 and 1984 Pacific mackerel schools were reported in Puget Sound and Queen Charlotte Sound (Canada), and frequently were caught off Oregon in "blind" purse seine sets sampling nekton (W. Pearcy, Oregon State Univ., pers. comm.). Mackerel were abundant in Monterey Bay and the Gulf of the Farallons, off San Francisco. James Messersmith (CDF&G, Sacramento, California, pers. comm.) identified a very small juvenile Pacific makerel caught in 1984 in Humboldt Bay, near Eureka. This is clear evidence for at least marginally successful spawning over 400 nmi north of Point Conception, the usual northern boundary of spawning (Kramer and Smith 1970).

Mais (1981) reported a sudden change toward a much younger age composition of northern anchovies (*Engraulis mordax*) in southern California beginning about 1977. He suspected increased predation by Pacific mackerel and increased fishing pressure from the expanding Mexican anchovy fishery to be the major causes of this shift. Also, anchovy abundance has declined severely from the levels of the mid-1970s (ca. 2 million MT spawning biomass) to 1984 (ca. 0.3 million MT). In view of the Pacific mackerel abundances estimated in this paper, which are much larger than the previous estimates available to Mais, an increased mortality rate of anchovies due to mackerel predation is a very likely cause of these changes in the anchovy stock. Anchovy age composition analysis by Methot (1983) indicated large changes in the natural mortality rate of anchovies, but a conclusive statistical demonstration of this phenomenon is difficult.

The northerly extension of Pacific mackerel has been popular with commercial fishermen at Monterey, where landings have reached record levels. On the other hand, recreational fishermen seeking salmon in the Gulf of the Farallons have complained about interference and gear losses caused by mackerel. Salmon biologists in Canada have been concerned about potential increased predation on salmon smolts in Queen Charlotte Sound. To the south, recreational fishermen often spurn Pacific mackerel in the pursuit of more esteemed sportfish. Indeed, some recreational fishermen blame increased abundance of Pacific mackerel for the increased harassment of recreational fishermen by California sea lions (*Zalophus californianus*). The importance of Pacific mackerel as forage aside, these perceptions combine with the harvesting desires of southern and central California commercial fishermen to form an unusually unified public opinion that allowable catches should be increased. This opinion is strengthened by the prevailing industry opinion—confirmed by the estimates in this paper—that Pacific mackerel abundance, and hence allowable harvest, have been underestimated for several years.

Evaluation of the present management policy requires consideration of both interacting components of this policy: the harvest formula, and the abundance estimates used to implement it. Within the framework of the present linear harvest formula there is little reason to change the present *cutoff* level of 18,144 MT (20,000 short tons). This level provides sufficient protection from severe depletion while allowing a fishery in nearly all years. The latter consideration is additionally important because the present method of estimating abundance depends entirely on fishery information.

The present *fraction* of 0.2 is more amenable to change. The simulations, which assume all catches are accounted for in the harvest formula, indicate that a higher *fraction* is likely to increase average yield up to a maximum of about 29,000 MT/yr at a *fraction* of 0.28 (Figure 7). The sensitivity analysis showed that the optimal *fraction* is strongly influenced by the assumed model of compensation. However, for simplicity the following discussion will consider only the results of the best-fitting Ricker SRR, the case that best corresponds to available information.

Strict maximization of yield is often undesirable because the last increments in yield are achieved at the cost of relatively large decreases in abundance and correspondingly large increases in fishing effort. Of course, if Pacific mackerel are perceived as pests, this reduction in abundance may be desirable in its own right. Assuming we wish to conserve the resource, a popular rule of thumb is the "$F_{0.1}$" policy suggested

TABLE 5
Yield and Biomass Statistics for Various *Fractions*, Given a *Cutoff* of 18,144 MT (20,000 Short Tons), Based on Simulations Using the Best-Fitting Ricker Stock-Recruitment Model

| Fraction | Yield | | Biomass | |
	Average	Standard deviation	Average total	Average spawning
0.00	0.0	0.0	236	160
0.01	2.14	1.02	232	157
0.20	27.1	15.4	153	90
0.24	28.6	17.3	137	78
0.28	29.0	18.7	122	67
0.30	29.0	19.2	115	63
0.40	26.7	20.4	85	44

(Values in 1000 MT).

by Gulland and Boerema (1973), whereby fishing effort should not be greater than the intensity at which the marginal yield from an additional unit of effort is ten percent of the marginal yield at very low levels of fishing. For the present case of Pacific mackerel, *fraction* may be substituted for "effort", giving a *fraction*$_{0.1}$ of 0.24. Table 5 gives some values of *fraction* together with comparative statistics from the simulation results. It is important that these yield estimates assume that all catches are accounted for by the harvest formula, whereas present management policy ignores recreational catches, incidental catches during the closed commercial season, and foreign fishery catches—all of which add up to many thousand tons. Thus the effective *fraction* must be considered to be somewhat larger than the nominal *fraction* in the wording of the official management policy. Finally, the 40,000 MT harvests that have been taken from

1979 to 1984 must not be expected to continue for long under the present, or any, management policy.

ACKNOWLEDGMENTS

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