Proc. Res. Inv. NWHI
UNIHI-SEAGRANT-MR-84-01

BIOLOGICAL CONSTRAINTS ON PRODUCTION AND RELATED MANAGEMENT ISSUES IN THE HAWAIIAN DEEPSEA HANDLINE FISHERY

Stephen Ralston

Southwest Fisheries Center Honolulu Laboratory, National Marine
Fisheries Service, NOAA, P.O. Box 3830, Honolulu, Hawaii 96812

ABSTRACT

Specifically designed to gather data and information to meet the management needs of the Hawaiian deepsea handline fishery for demersal bottomfishes, a Sea Grant project (NI/R-7) was undertaken from 1976 to 1981. The resource in the main Hawaiian islands was assessed by surplus-production and yield-per-recruit methods to identify the extent of recruitment and/or growth-overfishing. The former analysis revealed that around the Maui-Lanai-Kahoolawe-Molokai (MLKM) bank, the main producer in the state, fishing activity is excessive relative to obtaining a maximum in sustained yield (MSY). The latter treatment demonstrated that at Penguin Bank an optimal level of fishing mortality is in effect for maximizing the growth potential of opakapaka, *Pristipomoides filamentosus*. These two assessments are consistent with the literature where it has been shown that MSY fishing mortality is generally restricted to values less than that which maximizes yield per recruit. In contrast with the main islands, the bottomfish resource of the Northwestern Hawaiian Islands is underutilized at present, where it is estimated that an annual harvest of at least 330 metric tons (MT) with an ex-vessel value of $2 million may be taken.

bottomfish
mortality
opakapaka
yield per recruit
surplus-production
maximum sustained yield

INTRODUCTION

The Hawaiian Archipelago stretches 1,500 nautical miles (nmi) from Cape Kumukahi on the island of Hawaii to Hancock

Seamounts, far to the northwest (Figure 1). The main high islands are basaltic formations and support all population centers in the state of Hawaii, but many small islands, pinnacles, and atolls extend for miles to the northwest, including Nihoa, Necker Island, French Frigate Shoals, Gardner Pinnacles, Laysan and Lisianski Islands, Pearl and Hermes Atoll, Midway Islands, and Kure Atoll. In addition to these largely uninhabited islands there are extensive shoal areas in the Northwestern Hawaiian Islands (NWHI) (e.g., Neva Shoal, Brooks Banks, St. Rogatien, Raita Bank, Maro Reef, and Hancock Seamounts).

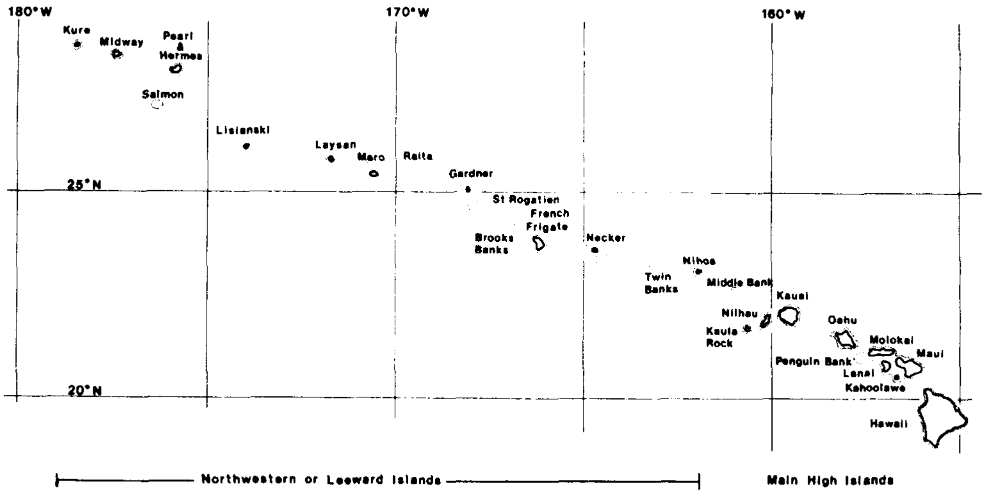

Figure 1. The Hawaiian Archipelago showing the approximate positions (dotted lines) of 100-fathom isobaths

Throughout the islands the myriad systems of submerged reefs, banks, and pinnacles harbor stocks or populations of commercially important bottomfishes. In particular, the snappers (Lutjanidae), groupers (Serranidae), and jacks (Carangidae) comprise some of the most valuable fishes harvested by the Hawaiian fishing industry, with some species at times commanding ex-vessel prices in excess of $15/kg. These are for the most part benthic fishes, in contrast with the pelagic tunas, living on or near the bottom in water depths of 20 to 200 fathoms. Most are found in regions of high physical relief which are thus unsuitable for trawling. They are caught almost exclusively with baited hook-and-line gear from fishing vessels which generally range in length from 7 to 30 m (Ralston, 1979). The mixed catch is marketed primarily in the round as fresh fish through several fish auctions and fishermen's cooperatives in the state.

In the past most fishing has been conducted around the main islands of the archipelago, especially at Penguin Bank off the island of Molokai (Figure 1) (Ralston and Polovina, 1982). However, as catch rates around the high Hawaiian islands declined and larger vessels entered the fishery, exploitation in the NWHI began to increase. Since 1976, when the extended 200-mile U.S. fishery conservation zone under the authority of the Magnuson Fishery Conservation and Management Act was implemented, interest in the bottomfish resources of the NWHI increased greatly. Recognizing these developments the Western Pacific Regional Fishery Management Council authorized the development of a fishery management plan for these stocks and emphasized the need to acquire biological information to manage the resource. At the time there had been no studies of these fishes in Hawaii and virtually nothing was known of their population dynamics (Ralston, 1979).

Accompanying this increased interest in the NWHI, the Southwest Fisheries Center Honolulu Laboratory, National Marine Fisheries Service, joined in a cooperative tripartite agreement in 1977 with the U.S. Fish and Wildlife Service (FWS) and the Hawaii Division of Aquatic Resources (DAR) to investigate the biotic resources of the area. Shortly thereafter the University of Hawaii Sea Grant College Program became a fourth active participant in the resource investigations of the NWHI. This Sea Grant project was initiated at that time with the intent of developing a basis for managing the deepsea handline fishery.

Since its inception, this project sought to gather data and information to meet the needs of fisheries management. This research project, "Development of a biological basis for managing the handline fishery for snapper and grouper population in the Hawaiian Archipelago", is now concluded and the proceedings of this second symposium on resource investigations in the NWHI offer an ideal forum for summarizing some of the project's more important findings. In this paper an overview is presented which specifically relates to management questions in the deepsea handline fishery. Almost all of the information presented here is a product of Sea Grant project NI/R-7, although relevant literature and outside data have been included where appropriate. However, most of the information resulting from this program has already been reported in a series of publications and manuscripts (Ralston, 1979, 1980a, 1980b, 1981a, 1981b, 1982; Ralston and Miyamoto, 1982, in press; Ralston and Polovina, 1982). Much of that which is presented here is summarized from this literature.

OBJECTIVES

From a management perspective the objective of the Sea Grant project was to assess the condition of bottomfish stocks in Hawaii relative to historical and present levels of exploitation. This fundamental problem was approached using two classical methods. In the first of these the entire bottomfish community was treated as a multispecies fishery and was analyzed by total biomass surplus-production methods. Twenty years of DAR catch statistics were summarized and Schaefer analyses performed at different levels of species aggregation (Ralston and Polovina, 1982). Results from this type of study are used to identity the latent capability of fish stocks to respond to exploitation in a compensatory fashion, and thus this first approach deals in a general sense with the question of recruitment/stock-overfishing. The second approach to stock assessment involved studying growth-overfishing in opakapaka, Pristipomoides filamentosus, the single most important species in the Hawaiian handline fishery. This problem was evaluated at steady state using of the Beverton and Holt (1957) yield-per-recruit year-class model in which opakapaka growth dynamics were determined by analyzing the width of daily otolith increments (Ralston and Miyamoto, 1982, in press) and mortality rates were estimated from catch curves after a regression model was formulated to permit development of an age-length key (Ralston, 1981b). In addition to the stock-production and dynamic-pool analyses (Beverton and Holt, 1957), ancillary studies of gear selection (Ralston, 1982), bottomfish depth distributions, and opakapaka reproductive biology provided other types of information which were useful not only from a biological/ statistical perspective but from management's viewpoint as well.

SURPLUS-PRODUCTION ANALYSIS OF BOTTOMFISH

The basic premise of most stock-production models is that the per capita (i.e., weight specific) net productivity of a stock ($dB/B \cdot dt$) is a monotonic decreasing function of standing crop biomass (B). However, because total net production also depends in a positive way upon B, the greatest net production usually occurs at an intermediate level of standing crop. A maximum in sustained yield can then be obtained from a stock by cropping it annually to this specific level while harvesting the "latent" or "surplus" production. The fundamental problem then is to estimate this intermediate level and also the annual fishing effort needed to reach it.

The usual procedure is to assume that the catch rate or catch per unit of fishing effort (C/f) is in simple proportion to the biomass of standing crop and that fishing effort (f) is in simple proportion to fishing mortality. The empirically observed functional relationship between C/f and f can then be used to predict the response of the stock to exploitation. The well-known Graham-Schaefer model asserts that these two variables demonstrate an inverse linear relationship, from which it follows that the growth of the stock follows the logistic equation.

This seems to make good sense but there are serious deficiencies in this kind of approach. The most obvious is the inability of these models to adequately describe variation in stock age structure (but see Deriso, 1980). A ton of larvae, for example, responds differently to attempts at exploitation than does a ton of adults. Thus, to model a stock using biomass as the only stated variable is clearly an extreme simplification.

Another deficiency which is somewhat more subtle arises when determining the statistical relationship between C/f and f. An inverse association between these variables is expected even in the situation where catch and effort are completely independent-orthogonal random variables (Schnute, 1977; Mohn, 1980). Nevertheless, when these are the only statistics available, the use of surplus-production models can provide a crude but useful means of assessing the condition of a stock.

Accordingly, the status of the deepsea handline fishery in Hawaii was evaluated by application of the Graham-Schaefer model to 20 years of DAR catch statistics (Ralston and Polovina, 1982). Several problems unique to this specific fishery complicated this analysis. The first is the question of stock definition. At the present time there is insufficient information available to determine the extent of bottomfish larval dispersal between discrete islands of the archipelago. A recent starch-gel electrophoretic analysis of opakapaka enzyme systems failed to detect genetic differences from populations as widely separated as Molokai and Maro Reef, a distance of 750 nmi (Shaklee and Samollow unpublished manuscript). Negative biochemical evidence such as this is difficult to interpret, but does not disprove isolation although it does suggest intermixing of the stocks. Another problem, however, is that the total biomass model which was used in the analysis (Pope, 1979) pools catch statistics across different species, a procedure which contradicts all conventional notions of the unit stock.

A third problem was that an extensive history of fishing and corresponding catch statistics were available for high island areas only and were completely lacking for the NWHI. Consequently, this approach could only be used for the former region. Problems also arose in formulating a suitable measure of fishing effort and there were difficulties in dealing with the unreported recreational catch of bottomfish as well. Needless to say, a variety of assumptions were made but the analysis did provide internally consistent results which gave a reasonably clear indication of the status of bottomfish resources in the high Hawaiian islands.

The study demonstrated that the fishery could be effectively described by aggregating the catch statistics of the 13 major bottomfishes into 3 species groups identified by cluster analysis. No interactive effects were detected among these multispecies groups, as they seemed to behave as independent entities. Although there were strong correlations in fishing mortality among the groups, this was apparently due to fishing activity rather than having a biological basis.

Acceptable statistical results were only obtained from the Maui-Lanai-Kahoolawe-Molokai stock which alone accounted for over 50 percent of the total state landings of bottomfish. The maximum in sustained yield for this stock was estimated to be 106 metric tons per year, equivalent to 272 kg/nmi of 100-fathom isobath per year when standardized for habitat area. It was also determined that an annual fishing effort of about 900 fishermen (vessel)-days would result in a harvest equal to the projected MSY.

A plot of total annual landings of all bottomfish species reveals past trends as well as the current status of the MLKM fishery (Figure 2). It is apparent that from 1961 to 1963 an abrupt jump occurred in total landings (56 percent increase), leading to harvests moderately in excess of the estimate of MSY (18 percent above). In the 6 years after the peak harvests of 1963 and 1964 catches stabilized briefly around MSY but then a definite decline in bottomfish landings occurred which reached a nadir in 1970 at a level of 38 percent below MSY. Since that time catches of bottomfish increased for a while and as of 1980 the harvest hovered at a level somewhat less than MSY (10 percent below). At present there are no estimates available for the annual landings of 1981 or 1982.

This pattern of catches appears to be adequately explained by changing trends in fishing effort within the fishery (Figure 2). Rapid increases in effort during 1963 and 1964 were associated with the peak harvests of those years. These catches in excess of MSY may have been the results of disequilibrium and the "fishing up" effect (Ricker, 1975). The yield from the fishery then stabilized near MSY (1965-68) as fishing effort approached an optimal level. The reason for the abrupt decline in landings which occurred in 1970 is difficult to determine. The causality between the effects of catch on effort and, conversely, the effects of effort on catch are confounded in this instance. Although it is not certain whether the decline was due specifically to some kind of stock failure, there are at least two factors which support this possibility. The first is that fishing effort had been steadily increasing and was at a level in excess of optimal effort during 1968 and 1969, just prior to when landings fell. The second is that throughout the time period in question the ex-vessel price per pound of bottomfish was increasing. Figure 2 also shows that the average ex-vessel value of the catch rose from $0.58/lb in 1963 to $0.81/lb in 1970. These figures have been adjusted by consumer price indices for Honolulu and represent the actual deflated value of the catch measured in 1967 dollars. Thus, it is unlikely that the decline in landings could have been due to unfavorable market conditions for the product. Immediately following the decline of 1970, and perhaps as a result of it, fishing effort decreased to suboptimal levels in 1971 and 1972 and landings began to increase again. However, the level of fishing effort increased abruptly in 1973 and 1974 to levels substantially in excess of an optimal amount, and since that time yields have consistently been less than the Ralston and Polovina (1982) estimate of MSY. The obvious conclusion is that the fishery for bottomfish at the MLKM bank is now on the descending limb of the catch curve, with further increases in fishing effort likely to result in further decreases in catch. From the perspective of MSY the fishery appears to be overexploited.

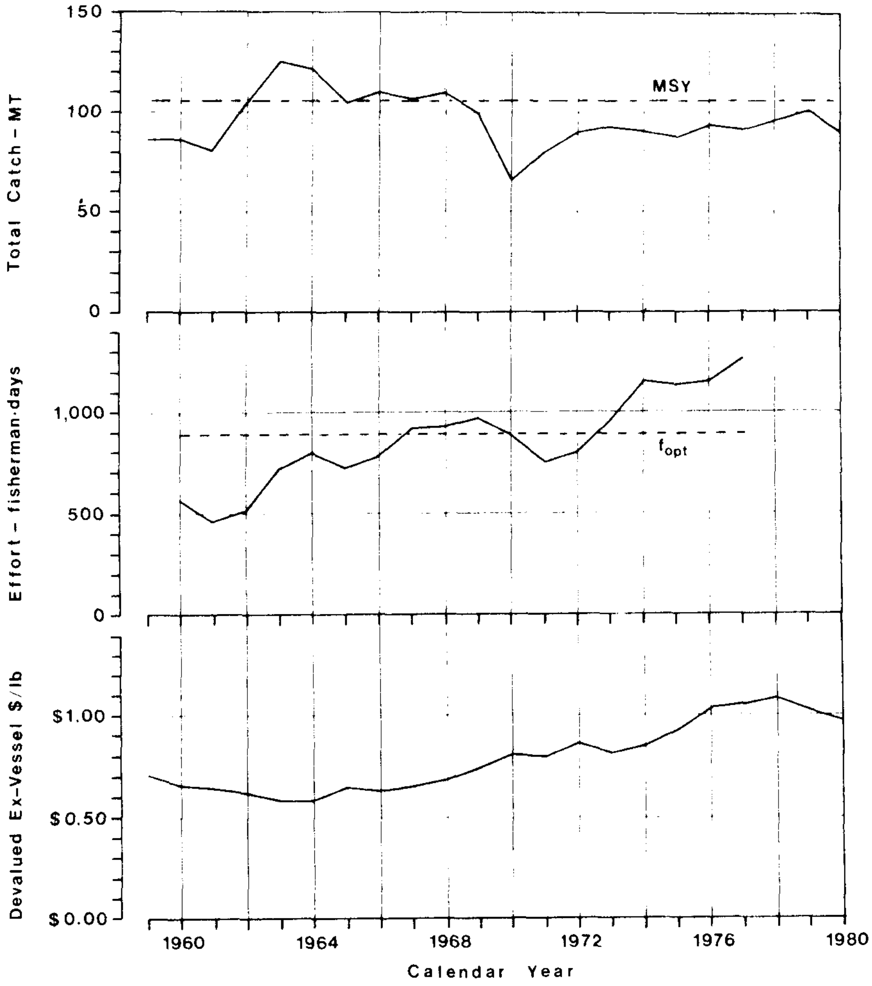

Figure 2. Trends (1959-80) within the fishery for bottomfish at the Maui-Lanai-Kahoolawe-Molokai bank. The top panel shows total catch relative to the estimate of maximum in sustanined yield, the middle panel shows annual fishing effort relative to the estimate of f_{opt}, and the bottom panel shows deflated ex-vessel price per pound in 1967 dollars.

Other aspects of the surplus-production study provide managers with food for thought if not concrete information on which to base policies. Two of these deserve mention here. The first relates to the estimate of MSY from the MLKM stock. Pope (1979) argued that if in a multispecies fishery exploitation is exerted in such a way that the fishing mortalities of the various species remain in constant ratio to one another, then use of the total biomass Schaefer model may have real meaning. However, he also showed that it cannot be concluded that an MSY estimated from the model need be the global maximum. These are relevant considerations because, as alluded to previously, there are high correlations of fishing effort among the three species groups. Thus, it is theoretically possible that a yield larger than 106 MT per year could be sustained if one could alter the ratios of fishing mortality among the species groups. This may not be an unrealistic proposition because the three groups are for the most part spatially separated. In principle, appropriate management action could thus reduce fishing on one group while simultaneously increasing that on another, but with the present state of our knowledge it would be futile to speculate about the possible extent of any increase in MSY resulting from such action.

A second outcome of the study worthy of consideration by managers involves the notion of species succession in multispecies fisheries. The production analysis of the three species groups comprising the MLKM stock suggested that each of the groups is characterized by its own unique combination of Malthusian parameter and carrying capacity. The trajectory of the system's biomass approaching a new equilibrium point would therefore be likely to undergo shifts in composition of one group relative to the others. In particular, the species group composed of ulua species (*Caranx* and *Carangoides* spp.); taape (*Lutjanus kasmira*); uku (*Aprion virescens*); and aawa (*Bodianus bilunulatus*) has a Malthusian parameter estimated to be almost twice that of the remaining two groups. If fishing were relaxed abruptly one would thus expect a transitory increase in the relative contribution of these species to the total harvest of bottomfish from the MLKM stock. Given that the economic value of the different species of bottomfish varies greatly, this may or may not be a desirable result of managing the resource.

YIELD PER RECRUIT ANALYSIS OF OPAKAPAKA

Consider the progression of a single year-class or cohort of fish through time. Early in its lifespan there are many very small recruits. Later on, due to the inevitable force of natural mortality, there are fewer fish alive but these are larger through growth. Only very few individuals ultimately survive to reach old age and large size. It is also true that at any point in time the cohort biomass is equal to the product of the number of individuals alive at the time and their average weight. Because within a year-class these two quantities are inversely related, that is to say, either many small fish are present or a few big ones, the biomass of a fish cohort usually reaches a maximum value at some intermediate stage in its lifespan. An optimum combination of size at harvest and probability of capture therefore exists which will maximize expected yield.

Beverton and Holt (1957) formalized these ideas and showed that the yield of a cohort over its fishable lifespan $(t_c - t_\lambda)$

equal to the integral of the product of instantaneous fishing mortality (F) and cohort biomass at time t. Yet, as noted previously, biomass is simply the product of the number of individuals alive times their average weight. Hence:

$$Y = \int_{t_c}^{t_\lambda} F \cdot B(t) \cdot dt = \int_{t_c}^{t_\lambda} F \cdot N(t) \cdot W(t) \cdot dt$$

They also showed that under equilibrium conditions the yield of a cohort over its fishable lifespan is in effect equal to the annual yield from a fishery composed of mixed cohorts. Equilibrium conditions imply a relatively constant supply of recruits, constant fishing mortality over a time period equal to $t_\lambda - t_c$, and similar constancy in all the parameters which characterize the mortality N(t) and growth W(t) functions.

The solution to this equation provides a means of selecting optimal fishing mortality and age at entry to the fishery (t_c) so as to maintain high yields. If too much fishing mortality is inflicted early in life, a year-class will not have had sufficient opportunity for growth. Conversely, if harvesting is delayed too long, many individuals will be lost to natural mortality and with it their potential contribution to total yield.

This type of calculation addresses the question of growth-overfishing or harvesting fish before their optimal size is attained. The basic problem is to characterize the growth and mortality functions, W(t) and N(t), and this was attempted for opakapaka.

The growth of opakapaka was studied by examining daily growth increments which are known to be deposited in the otoliths of many fishes (Ralston and Miyamoto, 1982, in press). Because these growth marks are frequently difficult to resolve throughout an otolith, a method was devised to estimate the age of individual opakapaka, based upon the pattern of otolith growth rate as indicated by increment width. Integration of regression equations of otolith growth rate on otolith size provided estimates of specimen ages in days. The method proved to be reasonably accurate (the median coefficient of variation of age estimates was 6 percent) and was also successful in accounting for most of the variation in otolith growth rate (the median r^2 for all regressions was 77 percent) (Ralston and Miyamoto, 1982). One major finding was that growth in mature opakapaka seemed to be discontinuous, requiring restrictive assumptions about growth in this size range. Nevertheless, increment periodicity was validated by tetracycline injection of experimental fish and shifts in size-frequency modes of samples from French Frigate Shoals closely matched estimates of growth rate derived from the study of otoliths. Both estimates compared favorably with the available literature and a growth curve for opakapaka was ultimately obtained (Ralston and Miyamoto, in press).

Mortality rates were estimated from catch curves or age-frequency distributions. A regression approach to generating an age-length key for opakapaka was developed as a means of transforming length-frequency data into age-frequency distributions (Ralston, 1981b). In this procedure a nonlinear regression of age on length provided an equation for estimating mean age as a function of fish length. The squared deviations in age (i.e., residuals^2) from this fit were subsequently regressed on length as well, resulting in an equation for estimating the mean squared deviation in age (variance in age) as a function of length. These two equations provided estimates of mean age and variance in age as functions of length. An age-length probability matrix was then calculated using the normal distribution function which, when post-multiplied by a length-frequency column vector, resulted in another vector of estimated age frequencies (Ralston, 1981b).

This age-length probability matrix was applied to length-frequency samples of opakapaka from Penguin Bank, Necker Island, French Frigate Shoals, and Maro Reef (Figure 1). The resulting estimated age-frequency distributions were then analyzed by traditional catch curve methods and the total rate of instantaneous mortality (Z) and age at entry to the fishery were determined. Several estimates of Z were obtained from each locality, but ultimately a pooled mean estimate of total mortality rate ($\bar{Z}$), weighted by sample size, was calculated for each site under the assumption that populations were age-stationary. Figure 3 shows that $\bar{Z}$ is inversely related to distance to Honolulu. This is likely due to variation in fishing pressure along this gradient. At the time of the study, the stock at Maro Reef in the NWHI was for all practical purposes unfished. During the period 1959-78, only 31 catch records from this site were filed with DAR. For purposes of comparison, nearly 58,000 catch records were filed from Penguin Bank during the same period. Similarly, over 2,600 records were filed from Necker Island. If we assume that during the study fishing mortality (F) at Maro Reef was negligible, then the estimate of total mortality (0.22 per year) provides an estimate of natural mortality (M) because $Z = M + F$. This assumption seems to be reasonable because the calculated value of $\bar{Z}$ from Maro Reef is the lowest of all fishing banks examined. Natural mortality rate was predicted by the method suggested by Pauly (1980) as an independent check on this estimate, resulting in a predicted value of 0.32 per year. The agreement between the two estimates seems reasonable, and, as a representative figure for opakapaka natural mortality, a value of 0.25 per year was used in all subsequent analyses. Characterizing the rate of opakapaka natural mortality allowed separation of $\bar{Z}$ into its component parts. Thus, at Penguin Bank fishing mortality rate (F) was estimated to be 0.48 per year (0.73 minus 0.25).

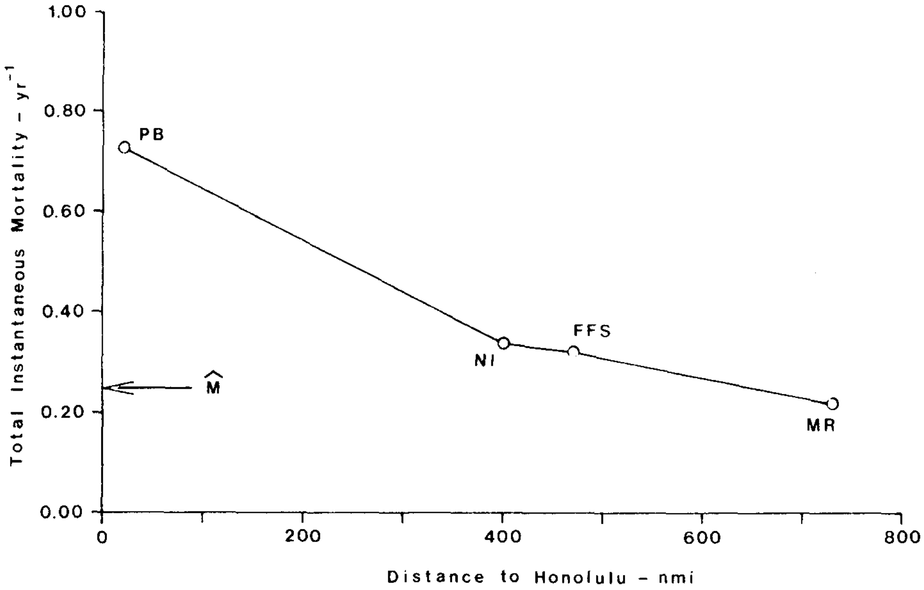

Figure 3. The relationship between the pooled mean total mortality rate ($\bar{Z}$) of opakapaka and distance to Honolulu. PB = Penguin Bank, NI = Necker Island, FFS = French Frigate Shoals, and MR = Maro Reef. The estimate of natural mortality is indicated by an arrow on the ordinate.

The foregoing results completed the determination of the opakapaka mortality function, N(t), which was then combined with the growth function, W(t), permitting numerical solution of the Beverton-Holt yield equation. The results are displayed graphically in Figure 4. In this figure constant values of yield per recruit (isopleths) are mapped onto a two-dimensional surface of management control (fishing mortality rate and age at entry to the fishery). Note that the eumetric fishing line is the locus of points which gives the maximum yield per recruit at fixed levels of fishing mortality. The single point on the isopleth surface represents Penguin Bank where $\hat{F}$ = 0.48 per year and $\hat{t}_c$ = 4.0 years.

From these results it is possible to conclude that there is little that could be done in the sense of growth-overfishing to improve the fishery for opakapaka at Penguin Bank. The specific combination of F and t_c at this site places it very close to the eumetric line. Estimated yield per recruit is about 0.36 kg per recruit and only very large increases in fishing mortality could increase this figure substantially. Such a policy would certainly risk recruitment-overfishing, violating a critical assumption of the model. From these considerations it is clear that the fishery for opakapaka at Penguin Bank is fortuitously close to an optimum level of exploitation inasmuch as the fishery has never been seriously regulated.

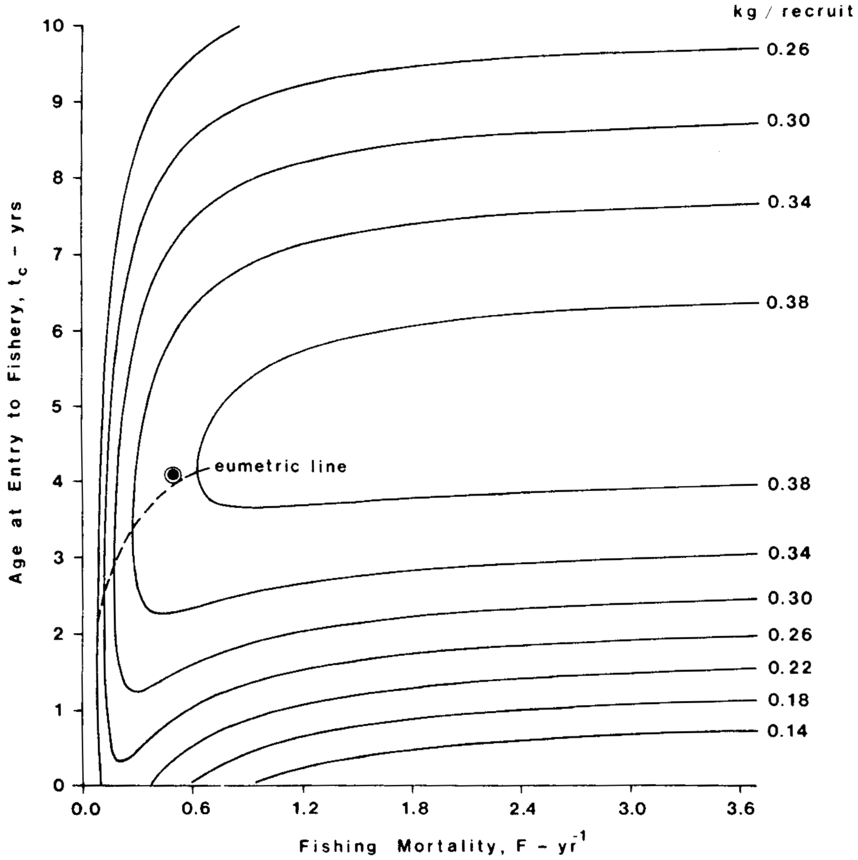

Figure 4. Beverton-Holt yield-per-recruit surface for opakapaka. The point represents the estimated position of Penguin Bank in 1980.

DISCUSSION

The results of both the surplus-production analysis of bottomfish from the MLKM stock and the yield-per-recruit analysis of opakapaka from Penguin Bank provide a coherent assessment of the present status of bottomfish populations. Landings from the fishery were estimated to be somewhat less than maximal in the former treatment, ostensibly as a result of overfishing. The latter study, on the other hand, suggested that in terms of optimizing the harvest of opakapaka growth potential few improvements were possible. On face value these two conclusions seem somewhat contradictory although a brief examination of the literature will show otherwise.

Recall from the yield-per-recruit analysis that the natural mortality rate of opakapaka at Maro Reef was estimated to be 0.25 per year whereas the total mortality rate of this species at Penguin Bank was determined to be 0.73 per year. If natural mortality at these two sites is comparable, and at the present time there is no reason to think otherwise, this implies a fishing mortality rate at Penguin Bank which is nearly twice as high as that due to natural causes. Other studies suggest this may be excessively high if yields are to be maximized by avoiding recruitment/stock-overfishing.

Alverson and Pereyra (1969), based on the unpublished ideas of Gulland (1971) and an earlier Soviet study (Tiurin, 1962), first proposed that at MSY the optimum level of fishing mortality (F_{opt}) was approximately equal to natural mortality. This particular conclusion applied not only to surplus-production models such as the Graham-Schaefer formulation, but more loosely to the Beverton-Holt constant recruitment model as well (Gulland, 1971). Saetersdal (1973) also advocated using M as a direct estimate of F_{opt} when assessing unexploited resources and when catch statistics are unavailable.

Francis (1974) examined more critically the theoretical basis of this approximation within the framework of the logistic growth equation. He concluded that the equivalence of mortality factors held only when recruitment was density-independent over a range in stock size spanning unexploited levels to one-half the virgin level (i.e., $R_o = R_{opt}$). More generally if the stock-recruitment relationship is best described by a Beverton-Holt type of spawner-recruit curve, or any other asymptotic form, then F_{opt} would likely be constrained to values less than M. Conversely, only when a Ricker or dome-shaped spawner-recruit relationship applies will F_{opt} likely exceed M.

Deriso (1982) expanded on these ideas and showed analytically two other factors of importance. The first and most significant of these is that MSY fishing mortality is often restricted to values less than the fishing mortality which maximizes yield per recruit. Thus, the relatively efficient utilization of opakapaka growth potential which characterizes the fishery at Penguin Bank is compatible with the notion of overexploitation from the perspective of MSY. The second point is that when a spawner-recruit curve is dome-shaped, F_{opt} can exceed M in the logistic model, but only in the situation where recruitment is severely depressed in the unexploited state (i.e., the stock displays strong recruitment compensation) will F_{opt} exceed 1.5(M). Other models such as Deriso's delay-difference formulation are more conservative in their behavior.

In view of the conclusions of these other studies it would seem that the analysis of the MLKM fishery presented here is internally consistent. Fishing there is excessive relative to obtaining MSY but is near optimal in terms of maximizing yield per recruit. A danger of recruitment-overfishing likely exists in this situation and yet it is fortuitous that with the historical lack of any serious constraints on fishing the stocks of bottomfishes have been as stable as they have, given the extent of exploitation at the MLKM bank. The situation is tenuous, however, and management of bottomfish resources around the main Hawaiian islands should certainly be considered now.

In contrast, the resources of the NWHI apparently have much potential yet to offer. Estimates of the total mortality rate of opakapaka from Necker Island and French Frigate Shoals (Figure 3) indicate that further increases in fishing activity should be easily assimilated by the stocks. Other fishing grounds remain totally untapped to the northwest of Maro Reef, where little fishing has occurred to date. While conflicts between fishing activity and the conservation of other wildlife resources (e.g., monk seals) remain unresolved, there nevertheless exists a bottomfish resource in the NWHI capable of supporting increased harvests on biological grounds.

As a first approximation to the magnitude of bottomfish resources in the NWHI, we can assume productivity comparable with the main high islands and invoke the Ralston and Polovina (1982) estimate of MSY per unit of habitat area (272 kg/nmi of 100-fathom isobath per year) for the MLKM stock. Because this figure does not include the recreational catch it provides a very conservative estimate of the potential yield of bottomfishes from the NWHI. These islands have a combined habitat area equivalent to about 1,200 nmi of 100-fathom isobath. Thus, one might expect as a minimum a sustained bottomfish yield of 330 MT per year from the NWHI. Given that the ex-vessel price per pound for these species is currently averaging about $2.75, the value of the resource to the fishermen might be estimated to be roughly $2 million annually. This amounts to a harvest substantially greater than that currently being landed in the main high islands of the archipelago.

ACKNOWLEDGMENTS

This work was supported in part by the University of Hawaii Sea Grant College Program, "Development of a Biological Basis for Managing the Handline Fishery for Snapper and Grouper Populations in the Hawaiian Archipelago" project, NI/R-7 (under Institutional Grant Nos. 04-8-M01-178 and NA79AA-D-00085 from NOAA Office of Sea Grant, Department of Commerce). This is Sea Grant publication UNIHI-SEAGRANT-CP-84-04. Additional support was provided by the University of Washington Sea Grant College Program under Grant No. NA79AA-D-00054 and by the Southwest Fisheries Center Honolulu Laboratory, National Marine Fisheries Service.

I wish to thank Bud Burgner, Phil Helfrich, and the other members of my dissertation committee for the constant encouragement and guidance they provided as the research progressed. Rick Deriso, Jeff Polovina, and Bill Walsh were also a rich source of stimulating ideas from which this study benefited greatly.

REFERENCES

Alverson, D.L., and W.T. Pereyra. 1969. Demersal fish explorations in the northeastern Pacific Ocean - an evaluation of exploratory fishing methods and analytical approaches to stock size and yield forecasts. Journal of the Fisheries Research Board of Canada 26:1985-2001.

Beverton, R.J.H., and S.J. Holt. 1957. On the dynamics of exploited fish populations. Fishery Investigations Ministry of Agriculture Fisheries and Food (Great Britain), Series II, 19. 533 pp.

Deriso, R.B. 1980. Harvesting strategies and parameter estimation for an age-structured model. Canadian Journal of Fisheries and Aquatic Sciences 37:268-282.

Deriso, R.B. 1982. Relationship of fishing mortality to natural mortality and growth at the level of maximum sustainable yield. Canadian Journal of Fisheries and Aquatic Sciences 39:1054-1058.

Francis, R.C. 1974. Relationship of fishing mortality to natural mortality at the level of maximum sustainable yield under the logistic stock production model. Journal of the Fisheries Research Board of Canada 31:1539-1542.

Gulland, J.A., compiler and editor. 1971. The Fish Resources of the Ocean. Surrey, England: Fishing News (Books) Ltd.

Mohn, R.K. 1980. Bias and error propagation in logistic production models. Canadian Journal of Fisheries and Aquatic Sciences 37:1276-1283.

Pauly, D. 1980. On the interrelationships between natural mortality, growth parameters, and mean environmental temperature in 175 fish stocks. Journal du Conseil Conseil International pour l'Exploration de la Mer 39:175-192.

Pope, J. 1979. Stock assessment in multispecies fisheries, with special reference to the trawl fishery in the Gulf of Thailand. South China Sea Fisheries Development and Coordinating Programme, Manila, SCS/DEV/79/19. 106 pp.

Ralston, S. 1979. A description of the bottomfish fisheries of Hawaii, American Samoa, Guam, and the Northern Marianas. A report submitted to the Western Pacific Regional Fishery Management Council, Honolulu. 102 pp.

Ralston, S. 1980a. An analysis of the Hawaiian offshore handline fishery: A progress report. In Proceedings of the symposium on status of resource investigations in the Northwestern Hawaiian Islands, April 24-25, 1980, ed. R.W. Grigg, and R.T. Pfund, pp. 204-215. UNIHI-SEAGRANT-MR-80-04. University of Hawaii Sea Grant College Program, Honolulu.

Ralston, S. 1980b. A multispecies production analysis of Hawaii's offshore handline fishery. (Abstract) Pacific Science 34:336.

Ralston, S. 1981a. A new record of the pomacanthid fish Centropyge interruptus from the Hawaiian Islands. Japanese Journal of Ichthyology 27:327-329.

Ralston, S.V.D. 1981b. A study of the hawaiian deep sea hand line fishery with special reference to the population dynamics of Opakapaka, Pristipomoides filamentosus (Pisces: Lutjanidae). Ph.D. dissertation, University of Washington, Seattle.

Ralston, S. 1982. Influence of hook size in the Hawaiian deep-sea handline fishery. Canadian Journal of Fisheries and Aquatic Sciences 39(9):1297-1302.

Ralston, S., and G.T. Miyamoto. 1982. Estimation of the age of a tropical reef fish using the density of daily growth increments. In The reef and man. Proceedings of the Fourth International Coral Reef Symposium, 18-22 May 1981, Manila, Philippines, ed. E.D. Gomez, C.E. Birkeland, R.W. Buddemeier, R.E. Johannes, J.A. Marsh, Jr., and R.T. Tsuda 1:83-88. Quezon City: Marine Science Center, University of the Philippines.

Ralston, S., and G.T. Miyamoto. Analyzing the width of daily otolith increments to age the Hawaiian snapper, Pristipomoides filamentosus. Fishery Bulletin, U.S. In press.

Ralston, S., and J.J. Polovina. 1982. A multispecies analysis of the commercial deep-sea handline fishery in Hawaii. Fishery Bulletin, U.S. 80(3):435-448.

Ricker, W.E. 1975. Computation and interpretation of biological statistics of fish populations. Bulletin of the Fisheries Research Board of Canada. Vol. 191. 382 pp.

Saetersdal, G. 1973. Assessment of unexploited resources. Journal of the Fisheries Research Board of Canada 30:2010-2016.

Schnute, J. 1977. Improved estimates from the Schaefer production model: theoretical considerations. Journal of the Fisheries Research Board of Canada 34:583-603.

Shaklee, J.B., and P.B. Samollow. Genetic variation and population structure in a spiny lobster (*Panulirus marginatus*) and a snapper (*Pristipomoides filamentosus*) in the Hawaiian Archipelago. CSIRO Marine Laboratories, Division of Fisheries Research, P.O. Box 120, Cleveland, Queensland 4163, Australia. Unpublished manuscript.

Tiurin, P.V. 1962. Factor estestvennoi smertnosti ryb i ego znachenie pri regulirovanii rybolovstva (The natural mortality factor and its importance in regulating fisheries). *Voprosy Ikhtiologii* 2:403-427. (Fisheries Research Board of Canada, Translation Series 558.)