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Assessment and Management of Deepwater Bottom Fishes in Hawaii and the Marianas

Jeffrey J. Polovina
Southwest Fisheries Center Honolulu Laboratory
National Marine Fisheries Service, NOAA
Honolulu, Hawaii 96822-2396

ABSTRACT

Stocks of deepwater snappers, groupers, and jacks in the Mariana Archipelago are just beginning to be exploited, and it is estimated from a 5-year fishery assessment program that the annual equilibrium yield for this resource will be 109 metric tons (MT). Stocks of deepwater bottom fishes in the Hawaiian Islands have a long history of exploitation and have been fished very heavily in recent years, especially around the populated islands. Commercial landings for 1984 are estimated at 414 MT from the populated islands and 662 MT for the entire archipelago. There is some evidence that the high fishing pressure at least around the populated islands has so substantially reduced the spawning stock biomass for at least one of the major species that the recent levels of yield may not be sustainable.

The Beverton and Holt yield equation is used to evaluate the impact of fishing mortality on spawning stock biomass, and some general guidelines are proposed: When the size of entry to the fishery exceeds the size of sexual maturity, fishing mortality should not exceed twice natural mortality; and when the size of entry to the fishery is less than or equal the size of sexual maturity, fishing mortality should not exceed natural mortality. The Beverton and Holt equation is also used to simulate multispecies interactions for a developing fishery that arise when fishing mortality applied to one species impacts another. As fishing mortality increases and concurrently the size of entry to the

fishery decreases, the catches of species with higher natural mortality to growth ratios will increase relative to those with lower natural mortality to growth ratios.

INTRODUCTION

The Hawaiian and Mariana Archipelagos support deepwater bottom fishes, which are a multispecies group consisting principally of snappers (Lutjanidae) and groupers (Serranidae), but also including jacks (Carangidae) in depths from 125 to 360 m. In Hawaii there is a long history of fishing for deepwater bottom fishes; currently the resource is fished throughout the archipelago and heavily fished around the populated islands (Ralston and Polovina 1982). In the Marianas the fishery for the deepwater bottom fishes is a much more recent development, and the stocks around many of the islands and banks are still unexploited. The first section of this chapter presents an estimate of the potential yield of the deepwater bottom fishes in the Marianas based on a recently concluded 5-year fishery assessment program by the Southwest Fisheries Center Honolulu Laboratory, National Marine Fisheries Service, NOAA. The next section treats the trends and estimated yield of the bottom fish fishery in the Hawaiian Islands, based primarily on a time series of commercial landings. The final section gives general guidelines on assessment and management of the deepwater bottom fishes for Pacific islands.

DEEPWATER BOTTOM FISH FISHERY IN THE MARIANAS AND ITS POTENTIAL YIELD

The Mariana Archipelago consists of a chain of islands and banks on a north-south axis, beginning with Galvez Banks and Santa Rosa Reef at the southernmost end and extending northward to Farallon de Pajaros, and a chain of seamounts also on a north-south axis about 120 nmi west of the high island chain (Figure 11.1).

The fishery for deepwater bottom fishes in the Marianas grew out of a program of exploratory fishing for deepwater snappers and groupers initiated in 1968 (Ikehara et al. 1970). The bottom fishing fleet consists of vessels 6 to 15 m long based primarily in Guam or Saipan. The vessels typically use electric or hydraulic gurdies

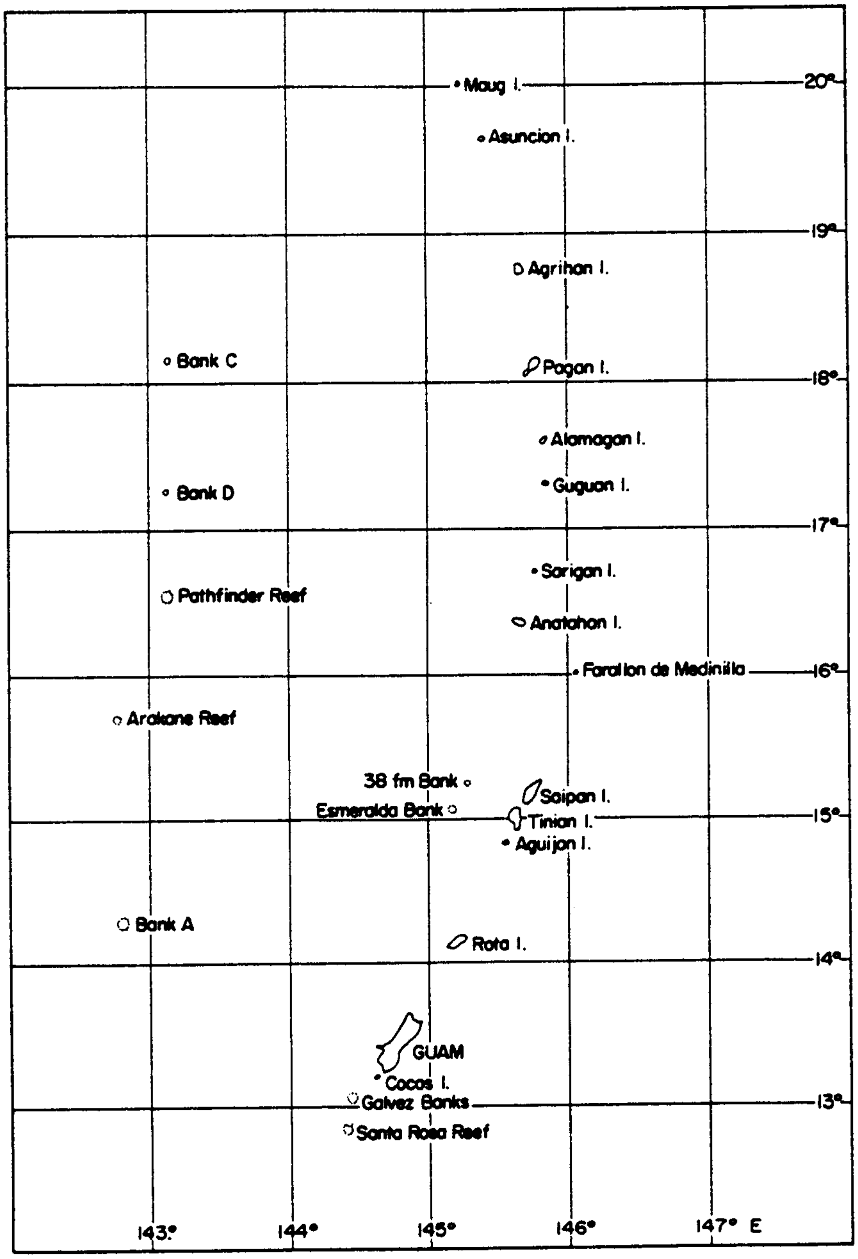

Figure 11.1 The Mariana Archipelago with the 22 islands and banks sampled

with a terminal rig consisting of a weight and four to six hooks, each attached to the mainline with a leader and spaced about a meter apart. From 1980 to 1984, the landings of deepwater bottom fishes in Guam have increased from 6 metric tons (MT) in 1980 to an estimated 20 MT in 1984. About 65 to 90% of the landings come from the waters around Guam.[1] The estimated commercial landings in Saipan for the period 1981 to 1984 ranged from 2 to 10 MT.[1]

In 1980, a 5-year fishery assessment was begun in the Marianas, and the deepwater snappers, groupers, and jacks were one of the resource groups targeted. A total of 7,621 deepwater bottom fishes were caught with handline gear during six assessment cruises. *Pristipomoides zonatus* accounted for 51.2% of the catch and three species (*P. zonatus*, *P. auricilla*, and *Etelis carbunculus*) accounted for 79.1% of the total catch (Table 11.1).

The resource is relatively unexploited except around a few of the islands and banks where the collection of catch and effort data has recently been initiated. Thus, any approach to yield assessment must be independent of catch and effort data. In recent years, there have been a number of new methods and modifications of existing methods to estimate growth and mortality parameters, standing stock, and yield for fish stocks particularly in the absence of a time series of commercial catch and effort data (Beddington and Cooke 1983; Munro 1983a; Pauly 1983; Polovina 1986; Wetherall et al. In press). A number of these methods have been combined to produce an integrated approach to yield assessment that was applied to the multispecies resource of deepwater bottom fishes in the Marianas (Polovina and Ralston In press) (Figure 11.2). This approach to equilibrium yield estimation assumes: (1) that growth follows the deterministic von Bertalanffy curve with parameters K and L_∞; (2) that the mortality of fish above the smallest length fully represented in the catch (L_c) occurs at a constant instantaneous rate (Z); (3) that recruitment is constant (R recruits entering the first age class annually); and (4) that the resource is essentially unexploited. Departures from some of these assumptions are discussed in Polovina and Ralston (In press).

The resource in the Marianas is essentially unexploited; thus an estimate for each species of the unexploited biomass that is recruited to the fishery and can be harvested with handline gear for each species was obtained from a systematic survey, and an estimate of

TABLE 11.1
List of species caught with bottom handline gear in the Mariana Archipelago during the period April 1982 to May 1984

Species	Number Caught	Percentage of Catch
Lutjanidae		
Aphareus rutilans	81	1.06
Aprion virescens	7	0.09
Etelis coruscans	202	2.65
E. carbunculus	952	12.49
Pristipomoides sieboldii	57	0.75
P. filamentosus	191	2.51
P. auricilla	1,170	15.35
P. flavipinnis	502	6.59
P. zonatus	3,904	51.23
P. amoenus	26	0.34
Carangidae		
Seriola sp.	60	0.79
Carangoides orthogrammus	9	0.12
Caranx lugubris	272	3.57
Serranidae		
Serranidae sp.	102	1.34
Epinephelus morrhua	15	0.20
Cephalopholis iqarasihensis	11	0.14
Variola louti	13	0.17
Saloptia powelli	47	0.62
Total	7,621	100

catchability was obtained from an intensive fishing experiment on a small isolated pinnacle (Polovina 1986). For each of the major species, an estimate of the von Bertlanffy growth parameter (K) was obtained from otolith data (Ralston and Williams Unpub.). Estimates of natural mortality (M) were obtained from large length-frequency samples by applying a regression model to the standard Beverton and Holt relationship for M/K in an unexploited stock, expressed as:

$$M/K = (L_\infty - \bar{\ell}) / (\bar{\ell} - L_c) \quad ,$$

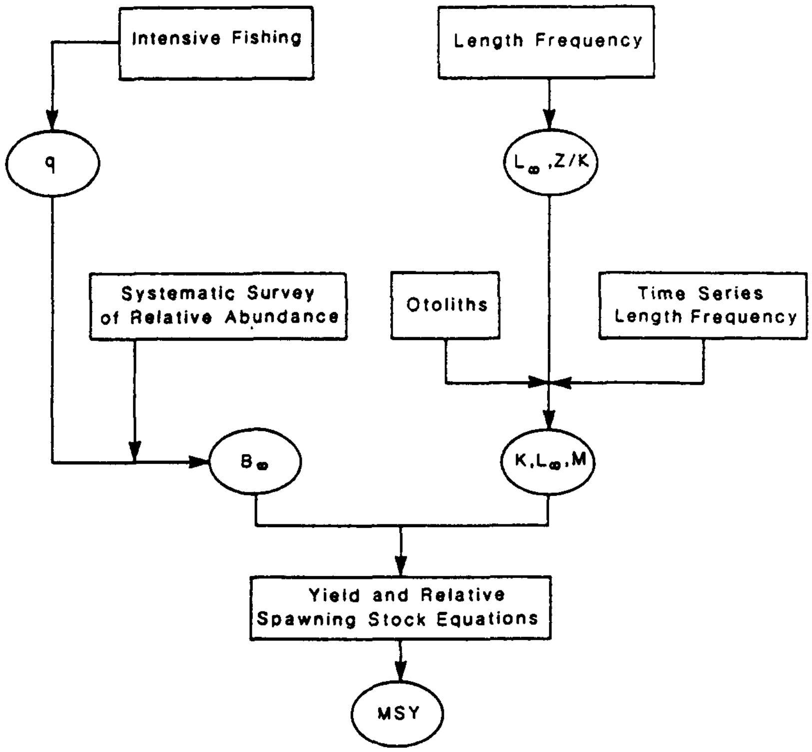

Figure 11.2 A schematic of the yield assessment approach--a more general approach to fishery assessment--which includes a treatment of catch and effort data as well is given in Munro (1983b); this figure represents a detailed subset of Munro's (1983b) figure 1

where L_c is the smallest length fully represented in the catch and $\bar{\ell}$ is the mean length of all fish greater than L_c (Beverton and Holt 1956). The regression approach constructs a series of L_c values at intervals beginning with the smallest L_c and going up to L_∞, together with the corresponding set of $\bar{\ell}$ values. By solving the M/K equation for $\bar{\ell}$ as a function of L_c, the following relationship is obtained:

$$\bar{\ell} = L_\infty \;/\; ((M/K) + 1) + L_c(M/K) \;/\; ((M/K) + 1) \quad .$$

Thus, regressing a sequence of $\bar{\ell}$ values on the corresponding L_c values (with the appropriate weighting) produces estimates for the slope and intercept that can be solved for L_∞ and M/K (Wetherall et al. In press).

The yield assessment approach is based on the Beverton and Holt yield equations, where equilibrium yield (Y) can be expressed as a function of growth (K), natural mortality (M), age of entry to the fishery (T_r), and fishing mortality (F) as:

$$Y = RF \int_{T_r}^{\infty} e^{(-tM-(t-T_r)F)} w(t)dt \quad ,$$

$$\text{with } w(t) = W(1-e^{(-Kt)})^{a} \quad ,$$

where W is the asymptotic weight and a is the coefficient of allometry. The unexploited biomass recruited to the fishery (B_∞) can be expressed as:

$$B_\infty = R \int_{T_r}^{\infty} w(t)e^{(-tM)}dt \quad .$$

The ratio of equilibrium yield to unexploited recruited biomass (Y/B_∞) is independent of W and R and depends only on K, M, T_r, F, and a. Once an estimate of B_∞ is available, the equilibrium yield is estimated for a given level of fishing mortality as the product of Y/B_∞ and B_∞.

Further, if the age of the onset of sexual maturity (T_m) is known, the spawning stock biomass (SSB) that corresponds to a given level of fishing mortality is:

$$SSB = R \int_{T_m}^{\infty} w(t)e^{-(t-T_r)F}e^{-tM}dt \quad \text{where } T_m \geq T_r$$

$$\text{and} \qquad SSB = R \int_{T_m}^{T_r} w(t)e^{-tM}dt + R \int_{T_r}^{\infty} w(t)e^{-(t-T_r)F}e^{-tM}dt$$

when $T_m < T_r$.

The ratio of the SSB for a specific level of F to the spawning stock biomass in the absence of exploitation (SSB_0) is a useful measure of the relative impact that F has on the SSB and under the assumption of constant recruitment is independent of R, depending only on T_m, K, T_r, M, F, and a.

In the systematic survey of the resource in the Marianas, seven species, one jack, Caranx lugubris, and six snappers, Pristipomoides zonatus, P. auricilla, P. filamentosus, P. flavipinnus, Etelis carbunculus, and E. coruscans, accounted for 92% of the catch (Table 11.1). Yield assessment was performed for each of these seven species plus an eighth group that consisted of all other species. For this latter group, the ratio (Y/B_∞) is estimated as the ratio of total yield for the seven species divided by their total unexploited recruited biomass. In this analysis, the age of entry for each species is the age that maximizes their yield per recruit.

The total equilibrium yield is computed as a function of F for the multispecies bottom fish complex fished with handline gear in the 125 to 275 m depth range for 22 islands and banks of the Mariana Archipelago. At each bank, the equilibrium yields are summed over the eight species groups to produce the bank equilibrium yield. The bank equilibrium yields then are summed over the 22 islands and banks surveyed. This archipelago yield increases rapidly as a function of fishing mortality to a

TABLE 11.2
Annual sustainable handline yield for the Marianas for the age at entry that maximizes the yield per recruit for each species in metric tons (MT)

Fishing Mortality (F)	Total Yield (MT)
0.1	35
0.5	91
1.0[a]	109[a]
1.5	114
2.0	116
2.5	116

[a] $F_{0.1}$ and $Y_{0.1}$ as defined by Gulland (1983).

level of about 100 MT, exhibits only a gradual increase with increasing F (Table 11.2). The yield curve assumes constant recruitment; of course when F is sufficiently large, this assumption will no longer hold, the yield will decline. Ideally, a spawner-recruit relationship is needed to determine the sustainable yield curve. However, in the absence of that relationship, the maximum level of F that will be sustained before a serious reduction in recruitment occurs can be estimated from the ratio of spawning stock biomass under F relative to the unexploited spawning stock biomass. In the absence of any species-specific knowledge, it has been suggested that a substantial reduction in recruitment will occur if the spawning stock biomass of a species is reduced below 20% of its unexploited level (Beddington and Cooke 1983). With F of 1.0 and the age of entry that maximizes their yields per recruit, the spawning stock biomasses for the seven species are reduced to levels ranging from 20 to 42% of their unexploited levels, suggesting that recruitment will not be reduced significantly if the lower bound of 0.20

TABLE 11.3
The ratio of spawning stock biomass to unexploited spawning stock biomass as a function of F with the ages of entry for each species taken at the age that maximizes the yield per recruit[a]

	Spawning Stock Biomass Relative to Its Level in the Absence of Exploitation		
Species	F = 0.5	F = 1.0	F = 1.5
Caranx lugubris	0.44	0.26	0.17
Pristipomoides filamentosus	0.46	0.33	0.28
P. auricilla	0.45	0.29	0.23
P. flavipinnis	0.45	0.26	0.17
P. zonatus	0.39	0.24	0.18
Etelis coruscans	0.31	0.20	0.15
E. carbunculus	0.58	0.42	0.34

[a] Based on length of maturity (L_m) estimated as $L_m = 0.576\ L_{max}$ (Anonyme 1977 in Brouard and Grandperrin 1984).

suggested by Beddington and Cooke is valid for these species (Table 11.3). As an alternative approach, the maximum sustainable yield (MSY) from the Beverton and Holt yield equation can be taken as the yield corresponding to that level of fishing mortality where an increase of one unit of fishing mortality will increase the catch by 0.1 of the amount caught by the very first unit of fishing mortality (Gulland 1983, 1984). This fishing mortality and corresponding yield have been denoted as $F_{0.1}$ and $Y_{0.1}$, respectively. The value of $F_{0.1}$ for the bottom fish resource in the Marianas based on this marginal yield approach is also estimated to be F = 1.0.

The annual equilibrium yield corresponding to F = 1.0 is 109 MT (an approximate 95% confidence interval is 81 to 137 MT (Polovina and Ralston In press)). About 70% of this yield would come from the southern islands and banks that include Guam and Saipan, 27% would come from the northern islands and banks, and only 3% from the seamounts (Table 11.4). This yield estimate can be converted to a yield per unit of bottom fish habitat. It is difficult to compute an area measure for the steep-sloped Pacific islands, and since the bottom fishes are found along the steep dropoff zones centered around the 200-m isobath, the length of the 200-m contour around an island or bank has been used as an index of bottom fish habitat. The means of the annual sustainable yield per nautical mile of 200-m contour for the northern banks, southern banks, and western seamounts are 212.9, 228.5, and 264.4 kg, respectively; a ratio of total yield for the archipelago to the total length of the 200-m contour is 222.4 kg/nmi of 200-m contour (95% confidence interval of 165.3 to 279.6 kg/nmi 200-m contour) (Table 11.4; Polovina and Ralston In press). There is, however, detailed bathymetry data from Guguan Island, one of the Northern Mariana Islands, where it is estimated that 1 nmi of 200-m isobath corresponds to 0.23 nmi^2 of habitat in the 125 to 275 m depth range (Polovina and Roush 1982). Based on this correspondence the unit MSY of 222.4 kg/nmi of 200-m contour for the Marianas is equivalent to approximately 1.0 MT/nmi^2 or 0.3 MT/km^2, which is at the lower end of the sustainable yield estimates for the bottom fish resources of the northwest Australian shelf (Sainsbury 1986).

There are two approximations to estimate MSY that express it as a fraction of the unexploited recruited biomass. Gulland (1969) uses a formula that estimates MSY as 0.5 MB_∞, where M is the instantaneous natural mortality and B_∞ the unexploited biomass, and while Pauly (1983)

TABLE 11.4
Annual sustainable yield and yield per nautical mile of 200-m contour for the age at entry that maximizes the yield per recruit at a level of fishing mortality of F = 1.0 (MT = metric tons)

Location	Total Yield (MT/Year)		Yield (kg/year)/nmi of 200-m Contour
	Northern Islands and Banks		
Maug	2.7		262.2
Asuncion	2.1		188.4
Agrihan	5.6		303.6
Pagan	7.7		255.1
Alamagan	2.0		177.6
Guguan	1.7		179.0
Sarigan	1.6		193.8
Anatahan	2.5		144.2
38-Fathom	0.5		187.3
Esmeralda	2.9		237.4
Total	29.3	Mean	212.9
	Southern Islands and Banks		
Farallon de Medinilla	16.7		216.6
Saipan	13.4		254.1
Tinian	8.8		303.9
Aguijan	4.2		266.7
Rota	6.1		192.2
Guam	17.2		201.6
Galvez and Santa Rosa	8.6		164.2
Total	76.0	Mean	228.5
	Seamounts		
Bank C	0.9		288.2
Bank D	1.1		351.2
Pathfinder	0.9		303.5
Arakane	0.6		199.6
Bank A	0.6		179.7
Total	4.1	Mean	264.4
Total yield from all banks	109 MT/year		

estimates MSY as $(2.3w^{-0.26})B_\infty$, where w is the mean of the weight at sexual maturity and the asymptotic weight. A comparison of both these approaches with the values of Y/B_∞ produced with the Beverton and Holt equation for the seven species shows that in four out of the seven the Y/B values estimated with the Beverton and Holt equation lie between the values obtained from the Pauly and Gulland approximations. For the other three species, the Y/B_∞ values fall slightly below the Pauly and Gulland estimates for two and substantially above for the third (Table 11.5). Thus, for at least six out of the seven species, the mean of the two estimates provides a useful approximation of Y/B_∞ computed from the Beverton and Holt equation. Further, the means of these estimates for Y/B_∞ are all in very close agreement.

Based on the estimate of catchability derived from the intensive fishing experiment, which represents lower bound for a commercial vessel, a fleet of 15 small vessels with two hydraulic or electric gurdies fishing 12 h a day, 200 days per year can produce the fishing effort approximately equal to the optimum fishing mortality of F = 1.0. The catch rate for this fleet would be about 1.5 kg per line-hour, and the average annual landing per vessel would be 7.3 MT.

TABLE 11.5
Annual maximum sustainable yield as a fraction of unexploited recruited biomass at F = 1.0 together with 0.5M and $2.3w^{-0.26}$

Species Groups	Y/B_∞	0.5M	$2.3w^{-0.26}$
Caranx lugubris	0.261	0.335	0.252
Pristipomoides filamentosus	0.262	0.270	0.296
P. auricilla	0.306	0.325	0.403
P. flavipinnis	0.680	0.475	0.348
P. zonatus	0.280	0.270	0.363
Etelis coruscans	0.201	0.175	0.226
E. carbunculus	0.375	0.515	0.289
Mean	0.338	0.338	0.311

DEEPWATER BOTTOM FISH FISHERY IN HAWAII AND ITS POTENTIAL YIELD

The Hawaiian Archipelago stretches from the Island of Hawaii to Hancock Seamounts 1,500 nmi to the northwest. The populated islands in the southern portion of the chain are often referred to as the main Hawaiian Islands, and the small, uninhabited islands, atolls, and seamounts that begin north of Niihau and extend northwest to Kure Atoll and Hancock Seamounts are called the Northwestern Hawaiian Islands (NWHI) (Figure 11.3).

There are 13 species groups that are harvested with deep-sea handline gear by the fishery (Table 11.6). Opakapaka, P. filamentosus, is the single most important species by weight, and the other major species consist of ulua (Caranx and Carangoides spp.), kahala, Seriola dumerili, uku, Aprion virescens, and onaga, Etelis coruscans. In 1984 opakapaka constituted 23% of the catch, and together onaga, opakapaka, uku, and ulua accounted for almost 70% of the landings.

Unlike the situation in the Marianas, there is a long history of commercial fishing for deepwater bottom fish in the Hawaiian Islands. There was a fleet of vessels that fished the deepwater bottom fishes throughout most the archipelago at least as early as the 1930s. Catch records from 1945 to 1982 indicate that the commercial landings

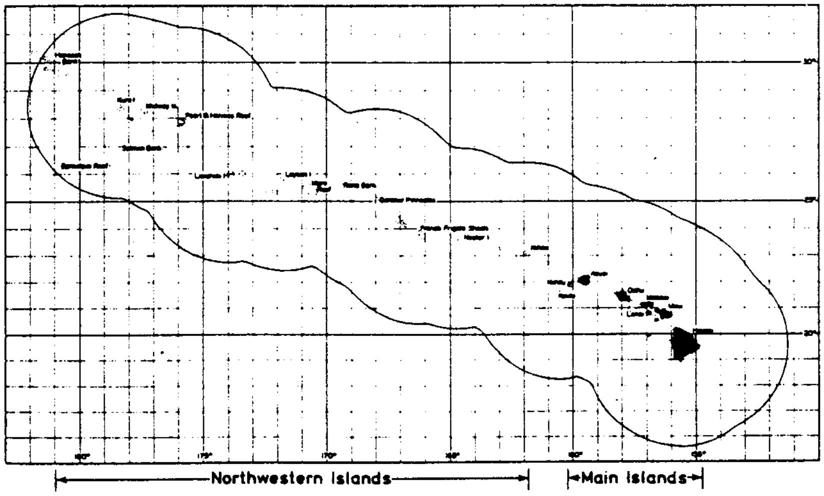

Figure 11.3 The Hawaiian Archipelago

TABLE 11.6
Principal species of fish landed in the Hawaiian offshore handline fishery

Family	Species	Common Name	Range of Landed Weight (kg)
Lutjanidae	*Aphareus rutilans*	Lehi	3-8
	Aprion virescens	Uku	2-8
	Etelis coruscans	Onaga	2-8
	E. carbunculus	Ehu	0.5-2
	Lutjanus kasmira	Taape	0.5
	Pristipomoides filamentosus	Opakapaka	1-6
	P. sieboldii	Kalekale	0.5
	P. zonatus	Gindai	0.5-2
Carangidae	*Caranx* and *Carangoides* spp.	Ulua	1-10
	Seriola dumerili	Kahala	3-10
Serranidae	*Epinephelus quernus*	Hapuupuu	3-10
Labridae	*Bodianus* spp.	Aawa	1-3
Scorpaenidae	*Pontinus macrocephala*	Nohu	1-2

for the State began at about 450 MT after the hiatus imposed by World War II, declined rapidly to a level of about 180 MT by 1959, and remained relatively stable at around 180 MT until 1974, when landings began steadily increasing (Figure 11.4). These catch data come only from fishermen with commercial fishing licenses and do not include the catches from the recreational fishermen, which may be substantial around the populated islands. An estimate of the commercial landings for the State for 1984 is 662 MT, which indicates that commercial landings have continued their rapid increase and are now greater than at any time since World War II (Figure 11.4).[2] The high catches from 1948 to 1953 correspond to catches for a period when both the NWHI and main Hawaiian Islands were fished. However, from the mid-1950s until about 1975, when there was renewed interest in the stocks of the NWHI,

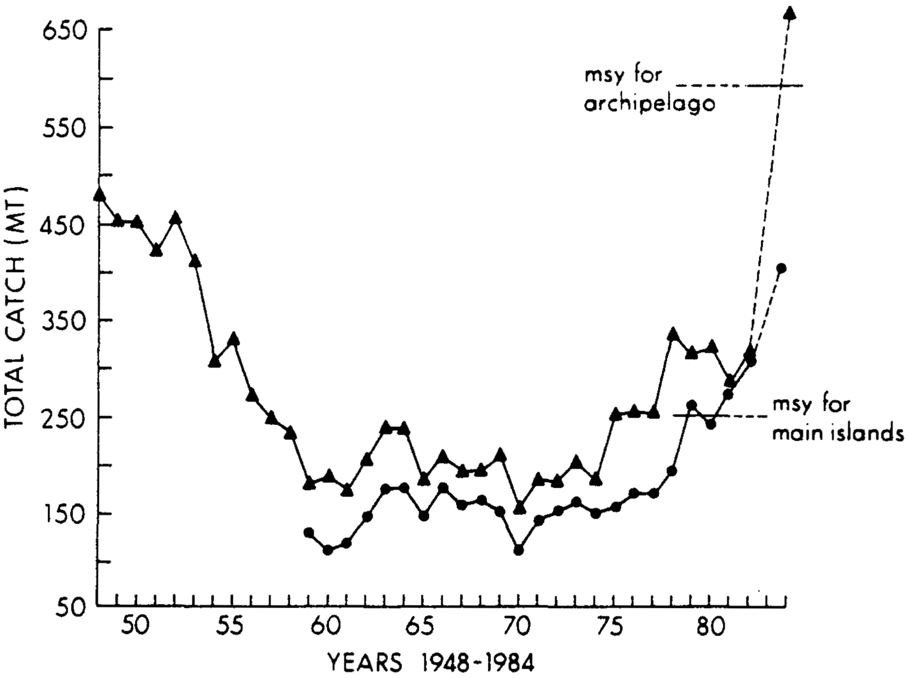

Figure 11.4 The annual commercial landings for deepwater bottom fishes from the main islands and the entire archipelago for 1948-1984. Data reported by State of Hawaii, Division of Aquatic Resources. ▲ = archipelago landings; ● = main island landings

most of the fishing was restricted to the main Hawaiian Islands. Records of landings from the main Hawaiian Islands are available only since 1959. Landings have fluctuated in the range of 100 to 200 MT from 1959 to 1978 while since 1978 have shown rapid growth. The estimated catch for 1984 is 413.6 MT. The rapid increase in landings from the main Hawaiian Islands and from the entire State since 1978 is a direct result of an expansion of the local market for fresh bottom fishes at a relatively stable and strong price (Pooley 1986). In 1984 the wholesale prices for bottom fishes averaged \$5.83/kg, and onaga and opakapaka commanded the highest prices at \$8.80 and \$7.37/kg, respectively.[2]

The species composition of the commercial landings from the main islands does not show any radical changes from 1959 to 1984, but some of the species do exhibit substantial relative increases or decreases (Table 11.7). Some of these changes are readily explainable, such as a decline of kahala (grouped in the Others category) due to its implication in ciguatera poisoning, the relative increase of onaga, the deepest water species, due to increasing fishing pressure in deeper habitat as the total fishing pressure increases, and the corresponding relative decline of the shallower water species ulua and uku due to overfishing in shallow waters.

The first approach to yield assessment for this multispecies fishery was fitting a Schaefer surplus production model to the commercial catch and effort data (measured in vessel days) for 1959-1978 (Ralston and Polovina 1982). For this analysis the main islands were grouped into four banks that are separated by deep channels and hence assumed to represent closed populations since adults and juveniles are not known to move across deep channels. The Islands of Oahu and Hawaii each formed their own bank; Kauai, Niihau, and Kaula Islands were pooled as one bank because of their proximity to each other; and the Islands of Maui, Lanai, Kahoolawe, and Molokai (MLKM) were treated as a single bank since the depths between them were <200 m. At first, single species surplus production models were applied to all 13 species for each of the 4 banks, but most of the fits were not

TABLE 11.7
Commercial landings of deepwater bottom fishes from the main Hawaiian Islands (in metric tons)

Species	1964	(%)	1974	(%)	1984	(%)
Ehu	9.3	(5.2)	9.4	(6.3)	16.7	(4.0)
Gindai	0.7	(0.4)	0.5	(0.3)	2.1	(0.5)
Hapuupuu	4.0	(2.3)	8.5	(5.7)	25.1	(6.1)
Kalekale	7.1	(4.0)	2.2	(1.5)	10.8	(2.6)
Lehi	0.4	(0.2)	1.9	(1.3)	7.4	(1.8)
Onaga	21.7	(12.2)	17.7	(11.8)	86.7	(21.0)
Opakapaka	42.4	(23.9)	48.7	(32.4)	96.2	(23.2)
Uku	40.1	(22.6)	35.0	(23.3)	66.4	(16.1)
Ulua	13.8	(7.8)	12.0	(8.0)	27.1	(6.6)
Others	38.0	(21.4)	14.1	(9.4)	75.0	(18.1)
Total	177.5		150.0		413.6	

statistically significant. The poor fit of the single species models was probably a result of using effort measured in vessel-days, because a vessel-day produces a multispecies catch; hence this represented a measure of multispecies effort more than effort directed toward any particular species. Next, 2 aggregated multispecies surplus production models were applied, 1 to the 13 species pooled together, the total biomass Schaefer model, and the other to 3 separate species groups formed by aggregating the species according to their depth distribution.

The MLKM bank, which accounts for over 50% of the State bottom fish landings, is the only bank where both approaches produced statistically significant results. The application of the Schaefer model to the three aggregated species groups explained only slightly more of the total variation in catch than the total biomass Schaefer model. As a first approximation, treating the 13 species bottom fish resource with the total biomass model is appealing. All the species occupy a very similar range of habitat, all the species appear to be high level carnivores with no evidence of prey-predator interactions among them, and fishing for one species also exerts pressure on other species.

The estimated MSY based on the total biomass Schaefer model for the MLKM bank is 106 MT, which corresponds to a unit MSY of 272 kg/nmi of 200-m contour (Ralston and Polovina 1982). This estimate is a lower bound since it includes only commercial landings and not the recreational catch, which could be substantial.

The lengths of the 200-m contour for the main islands and the NWHI are 977 and 1,231 nmi, respectively. Based on the annual MSY estimate of 272 kg/nmi of 200-m contour, the MSY is estimated at 266 MT for the main islands, 335 MT for the NWHI, and 601 MT for the entire archipelago. Since 1979 the landings from the main islands have exceeded the estimated MSY level, and the 1984 estimated landings of 414 MT were 55% above the MSY. Landings from the NWHI for 1984 were 74% of the MSY.

It is difficult to obtain an accurate measure of fishing mortality for the resource. Over the period 1959-1978, where a measure of effort in vessel-days is available, there was a threefold increase in vessel days (Ralston and Polovina 1982). However, technological changes such as electric or hydraulic gurdies, fathometers, chromoscopes, and loran have increased the fishing power of the vessel so that the trend in vessel days underestimates the real trend in fishing mortality. In addition to the considerable increase in fishing mortality in recent years, there is evidence, at least for opakapaka in the main islands, of substantial decrease in the age of entry to the fishery between 1980 and 1984 (Ralston and Kawamoto 1985). A yield-per-recruit analysis indicates that in 1980 the age of entry and fishing mortality for opakapaka on Penguin Bank were 4 years and 0.48/year, respectively, which placed it on the eumetric line of the yield-per-recruit isoplath (Ralston 1984). By 1984, however, a weight-frequency distribution for fish landed from the main Hawaiian Islands indicated that the age of entry was 1.8 years, which, with a fishing mortality of 0.48/year, results in a 17% reduction from the 1980 yield-per-recruit level (Ralston and Kawamoto 1985). When the approach used in the Marianas analysis to compute the ratio of the exploited to unexploited spawning stock biomass is applied to opakapaka stocks in the Hawaiian Islands with an age of entry of 1.8 years and a fishing mortality of 0.5/year, it is estimated that the spawning stock biomass is reduced to 10% of its unexploited level. This compares with 28% of its unexploited level when the age of entry is 4 years and the level of fishing mortality remains the same.

MANAGEMENT IMPLICATIONS

If the range of annual sustainable yield of 165 to 280 kg/nmi of 200-m contour estimated in the Marianas is taken as an archipelago range for Pacific islands and applied to the main Hawaiian Islands, an upper bound of sustainable yield is estimated at 274 MT annually. The landings from the main islands have exceeded this level since 1980, and by over 55% in 1984. This raises questions about the general nature of the range. However, given the evidence of growth overfishing, at least for opakapaka, and the reduction of its spawning stock biomass to as low as 10% of its unexploited level, it also suggests that these high levels of yield may not be sustainable.

Whereas the total biomass approach for multispecies bottom fish stocks is useful as a first step for assessment and management, it can be refined with a species specific approach based on the Beverton and Holt yield equation. This equation, appropriately formulated, requires only estimates of Z/K, F/M, L_c/L_∞ and L_m/L_∞ for yield-per-recruit and relative spawning stock analyses

(Beverton and Holt 1966; Beddington and Cooke 1983). Given that some of the recent length-based methods produce efficient estimators of Z/K when applied to large length-frequency samples, it is possible to develop species specific management of deepwater bottom fishes for Pacific islands based only on length-frequency samples. Even heavily fished archipelagos such as Hawaii have relatively unfished areas that can be sampled to estimate M/K. Fished banks will provide an estimate of Z/K that, together with M/K, provides an estimate of F/M. These estimates, together with estimates of L_c/L_∞ and L_m/L_∞, which are also easy to obtain from length-frequency samples and maturation studies, can be used to determine if the stock departs from the eumetric line and to estimate relative spawning stock biomass. Further, a time series of species specific estimates of Z or even Z/K obtained from length-frequency data, together with total catch data, can be used as the basis for single species production modelling (Csirke and Caddy 1983).

Based on the Beverton and Holt yield equation, upper bounds on F relative to M can be established as a function of L_c/L_∞. Consider the bottom fishes that have M/K values falling within the range of 1.0 to 4.0, which appears to include a large number of the snappers and groupers (Munro 1983b; Bannerot 1984; Ralston 1986; Polovina and Ralston In press). Further, suppose that the size of the onset of sexual maturity is estimated as $L_m = 0.5\ L_\infty$, which appears valid for most snappers (Grimes 1986). The ratio of spawning stock biomass under exploitation to the spawning stock biomass in the absence of fishing, computed as a function of F/M with the Beverton and Holt yield equation, is presented in Figure 11.5. Calculations were performed for two levels of M/K, 1.0 and 4.0, and for three levels of L_c/L_∞, 0.4, 0.5, and 0.6. When M/K is 4.0 and L_c/L_∞ is 0.6, the stock can sustain high levels of exploitation with minimal impact on the spawning stock. This is because when M/K is high and harvesting occurs above the size of sexual maturity, most of the contribution to the spawning stock comes from fish between the sizes L_m and L_c. However, when harvesting occurs at or below L_m, or if harvesting is above L_m and M/K is low, there is an exponential decline in the relative spawning stock biomass as a function of F/M. If L_c is greater than L_m, it appears that the relative spawning stock biomass for a fixed level of exploitation (F/M) increases with increasing M/K. Conversely, when L_c is less than L_m, the greater M/K, the lower the relative spawning stock biomass. If it is

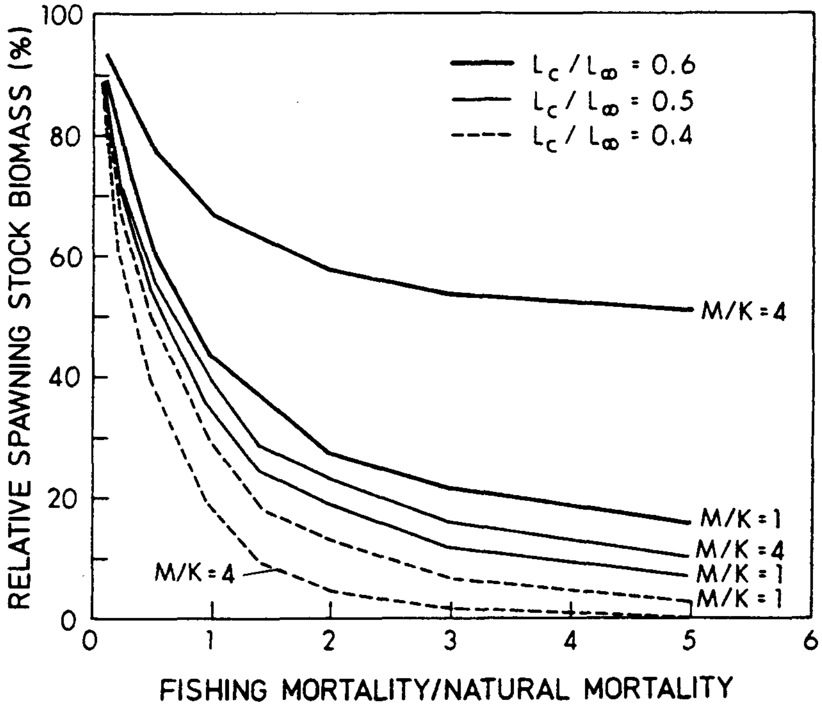

Figure 11.5 The ratio of spawning stock biomass as a function of fishing mortality to spawning stock biomass in the absence of exploitation for two levels of M/K and three levels of L_c/L_∞ when $L_m/L_\infty = 0.5$

determined that the exploited spawning stock biomass should not fall below about 20% of its unexploited level, then for fishes with M/K values in the range of 1 to 4 and when L_m is 0.5 L_∞, F should not exceed 2M if L_c is greater than or equal to L_m and F should not exceed M if L_c is below L_m.

Prey-predator interactions do not appear to be strong for the bottom fish community (Parrish 1986), and hence multispecies interactions are probably negligible (Ralston and Polovina 1982). However, multispecies interaction in the form of changes in relative species abundance may occur. For example, based on the Beverton and Holt equation it can be shown that in a multispecies fishery as F increases from a lightly exploited situation to a heavily exploited situation and concurrently the age of entry decreases, the yield per recruit of those stocks

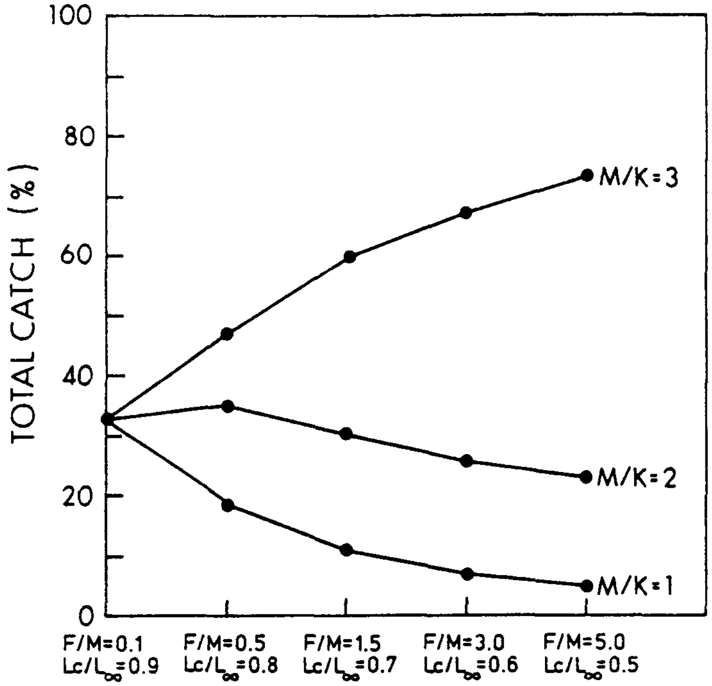

Figure 11.6 The relative contribution to the total catch for a multispecies group consisting of three species with different M/K values as a function of fishing mortality to natural mortality (F/M) and relative age of entry L_c/L_∞

with the higher M/K values will increase relative to the yield per recruit of those stocks with the lower M/K values. Simulation on a three-species group with M/K values of 1, 2, and 3, which represents a reasonable range for the bottom fishes in Hawaii, begins with F/M equal to 0.1, size of entry equal to 90% L_∞, and each species accounting for one-third of the landings. When F/M has increased to 3 and size of entry to 60% L_∞, (and assuming no change in recruitment for each species), the species with M/K of 3 will account for 67% of the landings while the species with M/K of 1 will only account for 7% (Figure 11.6). Further, the ratio of the exploited spawning stock biomass to unexploited spawning stock biomass will decline more rapidly for the species with low M/K values than for the species with higher M/K values (when L_c is greater than L_m), possibly adding further to the reduction of the relative contribution of low M/K species (Figure 11.5). It is the change in the age of entry more than the change in fishing mortality that is responsible for the change in relative yield.

Once the age of entry has been reduced substantially below the optimum value based on yield per recruit and relative spawning stock biomass analysis, as it appears to be for opakapaka in the main Hawaiian Islands, management recommendations that increase the age of entry must be sensitive to the dynamic or short-term response of the fishery. Even though yield-per-recruit analysis indicates that the long-term equilibrium yield will be increased with an increased age of entry, the short-term loss may exceed the long-term gain to the fishermen while the population structure of the stock is readjusting to the higher age of entry (Huntsman and Waters 1986). In such situations, management may find that a gradual increase in the age of entry through small annual increments is preferable to a single step increase to the optimal age of entry.

Although the mean level of the exploited spawning stock biomass relative to the unexploited level has been used to determine the level of exploitation that can be sustained, the variation in spawning stock biomass about this mean level has not been considered. If variation in recruitment is substantial, it may induce variation in the spawning stock biomass, which may have a greater impact on the sustainability of a level of yield than the mean value of the spawning stock biomass (Beddington and Cooke 1983). If it is assumed that recruitment is random and annual values are independent and identically distributed about a mean R with a coefficient of variation (standard deviation divided by mean) of s, and if it is assumed that the year-to-year variance in growth and mortality are negligible, then variances for annual yield, spawning stock biomass, and recruited biomass can be derived by computing the variance of yield, spawning stock, or biomass for a cohort of age t and integrating that variance with respect to t (Beddington and Cooke 1983). For example, the variance of the recruited biomass (V(B)) in the absence of exploitation is:

$$V(B) = R^2 s^2 W^2 \int_{T_r}^{\infty} \exp(-2tM)(1 - \exp(-Kt))^6 \, dt \quad .$$

Beddington and Cooke (1983) provide an approximation based on the Beverton and Holt equation that expresses the coefficient of variation (c.o.v.) of either the catch, the recruited biomass, or the spawning biomass as the same function of the coefficient of variation of recruitment (s) and total mortality (Z) as:

$$\text{c.o.v.} = (2/3)s(Z)^{0.5} \qquad (1)$$

Thus, if catch data are available for a period where Z is relatively constant and known, the c.o.v. of recruitment can be estimated, and the c.o.v. of the spawning stock biomass determined as a function of Z. With this latter relationship, confidence intervals of the relative spawning stock biomass can be computed as a function of F. In a number of instances it appears that annual recruitment and hence spawning stock biomass has a lognormal distribution, so the appropriate transformation must be applied to the variance of the spawning stock biomass before confidence intervals based on normal theory can be used.

This approach will be applied to estimate the lower bound of a 90% confidence interval of the relative spawning stock biomass for opakapaka when F is 0.5/year, age of entry to the fishery is 1.8 years, and age of sexual maturity is 3.25 years (the parameters that appear to represent the condition of the stock around the main islands in 1984 (Ralston and Kawamoto 1985)). The c.o.v. of the catch for the opakapaka fishery was estimated at 0.23 by using annual landings from just the main island catch for 1959 to 1970, when fishing effort was relatively constant. From Equation 1 with Z estimated to be 0.5 (M = F = 0.25) over the period 1959-1970 and the c.o.v. for opakapaka catch of 0.23, s is estimated to be 0.49. An estimate of the c.o.v. for opakapaka spawning stock biomass (SSB) is then estimated from Equation 1 as:

$$\text{c.o.v. (SSB)} = (0.49)\ (2/3)\ \sqrt{0.25 + F}\ .$$

When the mean spawning stock biomass is at 10% of the unexploited spawning stock biomass (SSB_0), which corresponds to F = 0.5, Equation 1 becomes:

$$\text{c.o.v.(SSB)} = 0.28$$

$$\begin{aligned} \text{or standard deviation (SSB)} &= 0.28 \text{ mean (SSB)} \\ &= 0.28\ (0.1)(SSB_0) \\ &= 0.028\ SSB_0 \quad . \end{aligned}$$

$$\text{Thus, variance } \left(\frac{SSB}{SSB_0}\right) = 7.84 \times 10^{-4} \quad .$$

A confidence interval for the relative spawning stock biomass can be obtained by transforming the lognormally distributed spawning stock biomass into a normally distributed variable. When the mean value for the spawning stock biomass is 10% of its unexploited value, the lower bound of the 90% confidence interval is 6% of its unexploited level. Thus, when recruitment variation is not considered, it is estimated that the spawning stock biomass of opakapaka around the main islands in 1984 was at about 10% of its unexploited level, but when variation in recruitment is taken into account, the relative spawning stock biomass could have been as low as 6%. It is interesting that the c.o.v. of recruitment for opakapaka estimated at 0.49 is slightly less than most of the estimates of the c.o.v. of recruitment for 18 temperate species that typically exceeded 0.6 (Hennemuth et al. 1980).

Beyond the conventional management approaches such as regulating the age of entry to the fishery and the fishing pressure, fishery enhancement may provide opportunities to increase yields of deepwater bottom fishes around Pacific islands. One approach to fishery enhancement in Hawaii has been the introduction of species groups that were underrepresented among the native fauna of the Hawaiian Islands, with the idea that these groups would fill a niche in the ecosystem and add to the total fishery yield. Between 1955 and 1961, 11 species of Serranidae, Lutjanidae, and Lethrinidae were introduced. Only three species have established significant populations: the grouper, *Cephalopholis argus*, and a snapper, *Lutjanus fulvus*, which only constitute a minor component of the commercial landings, and taape, *Lutjanus kasmira*, which has spread widely throughout the archipelago. The commercial catch of taape is 30 MT, and most probably would be considerably greater if market prices were higher (Oda and Parrish 1981). Although the introduction of taape appears to have increased the total yield of the bottom fish fishery and there does not appear to be a major dietary overlap between taape and any native species, some fishermen complain that it competes aggressively and successfully for fishing gear so that catches of more desirable native species are reduced (Oda and Parrish 1981).

Artificial reefs represent another fishery enhancement approach that may increase the production of deepwater bottom fishes. In Hawaii, many banks that support populations of snappers and groupers along their perimeters have flat, sandy tops in the 50 to 90 m depth range that support very low densities of fish. If the low densities of fish over the tops of these banks are a result of the lack of suitable habitat, and recruitment is not limiting, artificial reefs placed on these banks can offer appropriate habitat to support an increased standing stock and hence a yield of commercially valuable bottom fishes. The total area of habitat utilized by deepwater snappers and groupers in the Hawaiian Archipelago is about 2,000 nmi^2. Penguin Bank alone offers an area of 500 nmi^2 of level, sandy habitat which currently supports only a very low density of commercially valuable fishes. If appropriate habitat is a limiting factor, artificial reefs placed on Penguin Bank alone can increase the productive bottom fish habitat in the State by 25%.

NOTES

1. Data on file with Western Pacific Fishery Information Network, Southwest Fisheries Center Honolulu Laboratory, National Marine Fisheries Service, NOAA, Honolulu, HI 96822-2396.

2. Data from Western Pacific Regional Fishery Management Council.

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