

Biology and Management of Deepwater Snappers of the Hawaiian Archipelago

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Introduction

Commercial exploitation of deep-water snappers in Hawaii began before the turn of the century (Cobb, 1903), and except for a hiatus during World War II, has continued to the present. The fishery operates throughout the Hawaiian archipelago, but the inhabited Main Hawaiian Islands (MHI) experience the highest exploitation by both commercial and recreational fishermen. The uninhabited islands and atolls northwest of Niihau, called the Northwestern Hawaiian Islands (NWHI) (Fig. 1), are fished mainly by commercial fishermen.

The deepwater handline fishery targets a multispecies group of fishes consisting of snappers (Lutjanidae),

groupers (Serranidae), and jacks (Carangidae). However, snappers are the most important group in the fishery, both by numbers and revenue.¹ Most of the commercially important species have a relatively high age at maturity, long life span, and slow growth rate. These factors, combined with considerable variation in larval recruitment, make these fishes highly susceptible to overfishing. Recent evidence suggests that some of the species may be overfished, and several others are approaching a level of concern^{1, 2} (Ralston and Polovina, 1982; Ralston, 1984).

Historically, minimum size limits have been the only measure used to manage both the MHI and NWHI stocks. Since 1989, the NWHI have been managed on a limited entry system. Minimum size limits remain the only management tool currently in effect in the MHI. Several management measures are being evaluated to maintain adequate spawning stock biomass in the future. These include changing minimum size limits, creating closed refuge areas, and imposing bag limits and closed fishing seasons.

This report presents a summary of available information regarding the biology, fishery, and management of these valuable species.

Species and Distribution

The commercially important deep-water snapper complex in Hawaii is composed of seven species of the lutjanid subfamily Etelinae: *Pristipoides filamentosus* (opakapaka), *P. seiboldii* (kalekale), *P. zonatus* (gindai), *Etelis carbunculus* (ehu), *E. coruscans* (onaga), *Aprion virescens* (uku), and *Aphareus rutilans* (lehi). Some commercial landings of an introduced snapper, *Lutjanus kasmira* (taape), are also made, but this species usually occurs in shallower water than the other species. The commercially important deepwater lutjanids inhabit the deep slopes of island coasts and banks at depths of 100 to 400 m. These banks and deep slopes comprise an area over 6 times that of shallow water reefs in the state. Biological production in these deepwater areas is thought to be quite different from shallow-water coral reef areas (Agegian et al., 1988).

Throughout their spatial and depth range, deepwater snappers in Hawaii are typically distributed in a clumped pattern, and are often associated with underwater headlands and areas of high relief. Four of the deepwater snapper species found in Hawaii were observed in situ from manned submersibles and an unmanned remotely operated vehicle (ROV) and were found to form large aggregations of up to 100 individuals near submerged promontories and areas of high relief (Brock and Chamberlain, 1968; Ralston et al., 1986; Haight, 1989). This clumped distribution pattern is also apparent when fishing from the surface.

A contributing factor in the distribution pattern of these fish may be that

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ABSTRACT — Commercial and recreational deepwater (100–400 m) bottom-fishing in Hawaii targets a multispecies group of lutjanid snappers. Relatively little is known about the life history of these species. Research in Hawaii and elsewhere in the tropical Pacific suggests that most of the species are slow growing, long lived, and have a relatively high age at sexual maturity. Stock assessment is difficult because of the multispecies nature of the fishery. However, recent analysis of commercial fishery data indicates that some of the species may currently be overexploited. Research is underway to determine the efficacy of management measures such as minimum-size limit changes or seasonal and spatial fishery closures to maintain optimal spawning biomass.

¹(WPRFMC) Western Pacific Regional Fishery Management Council. 1991. Annual bottomfish and seamount groundfish report, 85 p.

²S. Ralston and K. E. Kawamoto. 1985. A preliminary analysis of the 1984 size structure of Hawaii's commercial opakapaka landings and a consideration of age at entry and yield per recruit. U. S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fish. Cent., Admin. Rep. H-85-1, 9 p.

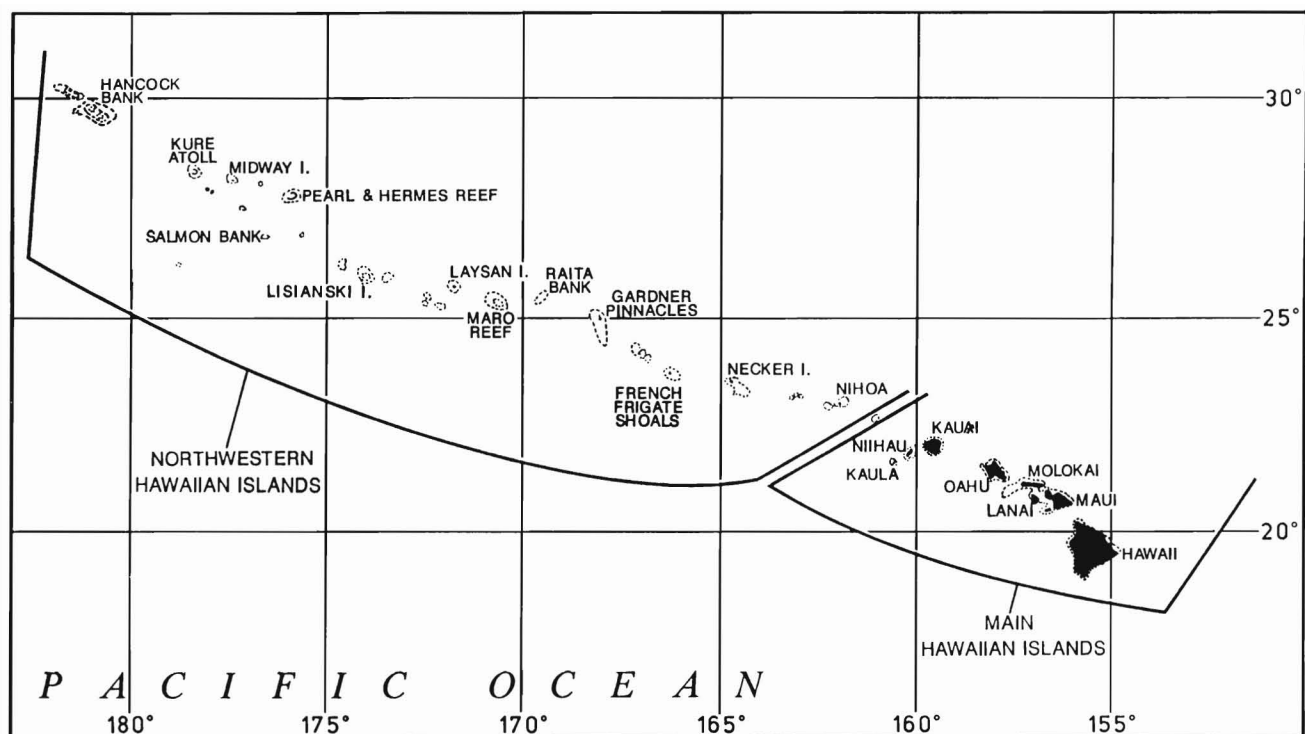


Figure 1. — The Hawaiian Archipelago

currents striking deepwater areas of high relief form localized zones of turbulent vertical water movement, increasing the availability of planktonic prey items (e.g. Brock and Chamberlain, 1968). In an ecological study of the bottomfish resources of Johnston Atoll, Ralston et al. (1986) found *P. filamentosus* in much higher densities on the upcurrent versus the down-current side of the atoll, and postulated that this was related to increased availability of allochthonous planktonic prey in the neritic upcurrent areas due to oceanic currents impacting the atoll. Although snappers throughout the world are generally thought of as top level carnivores, several snapper species in the Pacific are known to incorporate significant amounts of zooplankton, often gelatinous urochordates, in their diets (Parrish, 1987). Haight et al. (1993) found zooplankton to be an important prey item in four of the commercially important snappers in Hawaii. The same study found that the six snapper species studied were either primarily zooplanktivorous or prima-

rily piscivorous and showed little overlap in diet composition between trophic guilds.

Reproduction

Relatively little is known about the reproduction and early life history of deepwater snappers in Hawaii. Size at maturity has been estimated for only two species in the MHI and two species in the NWHI. In the MHI, uku reaches sexual maturity at 47 cm fork length (FL), which is 46% of maximum size (L_{∞}). Onaga reaches sexual maturity at 61 cm FL (62% L_{∞}) (Everson et al., 1989). In the NWHI, ehu reaches maturity at about 30 cm FL (46% L_{∞}) and opakapaka reaches maturity at around 43 cm FL (48% L_{∞}) (Everson, 1984; Kikkawa, 1984; Grimes, 1987).

There is a record of one anecdotal observation on the spawning behavior of opakapaka in Hawaii. A NWHI commercial fisherman using a chromoscope depth sounder observed an opakapaka aggregation at about 150 m become very dense during the mid-morning

hours. Catch rates decreased at this time, and egg masses were observed adhering to the fishing gear. By mid-afternoon the school became less compacted and catch rates increased. Opakapaka caught during this time were in spawning condition, some females released eggs and males released milt. Free-floating eggs were noted covering a large surface area around the vessel. The observations were made in mid-April.³

Gonadal studies on four of the species in Hawaii indicate that spawning may occur serially over a protracted period but is at a maximum during the summer months, and peaks from July to September (Everson et al., 1989; Uchida and Uchiyama, 1986). Estimated annual fecundity is 0.5 to 1.5 million eggs. The eggs are relatively small (0.7 to 0.8 mm) and are released into the water column.

³(WPRFMC) Western Pacific Regional Fishery Management Council. 1988. 1986 annual report of the fishery management plan for the bottomfish and seamount groundfish fisheries of the western Pacific region, 150 p.

Larval and Juvenile Stages

Newly hatched larvae of lutjanids in general are typical of those from fish with small pelagic eggs; the larvae have a large yolk sac, unpigmented eyes, and no mouth. The yolk sac typically lasts 3–4 days, after which the mouth is fully formed and the eyes become pigmented (Leis, 1987). The larval stages of snappers in Hawaii are poorly studied, perhaps because of their rarity in plankton samples. In a 16-month survey of the larval fishes near Oahu, snappers of the subfamily Etelinae were taken exclusively in the late summer and fall, and occurred in very low numbers, making up less than 0.5% of the 5,200 fish larvae identified (Clarke, 1991). Snapper larvae are thought to be planktonic and subject to advection by ocean current systems until benthic habitat suitable for metamorphosis is encountered (Munro, 1987). The duration of the pelagic phase is thought to be at least 25 days (Leis, 1987).

Little information currently exists on larval development, settlement, or early juvenile life history of deepwater snappers in Hawaii. Despite considerable research effort directed toward snapper productive processes in Hawaii, little is known about the ecology of juveniles from time of settlement to their appearance in the adult fishery. Age at entry to the fishery for the principal species is thought to be 2 to 3 years after settlement.⁴ In a three-year study of fish settlement on artificial reefs adjacent to adult snapper habitat in Hawaii, no recruitment of juvenile snappers to the reefs was observed, although adults aggregated at times around the reef structures (Moffitt et al., 1989).

Occasional reports of recreational fishermen taking juvenile opakapaka while fishing in depths less than 100 m prompted exploratory research fishing to be conducted in these nearshore areas. Results from a 13-month intensive fishing program off Kaneohe Bay, Oahu, Hawaii indicated juvenile

opakapaka first appear in the relatively shallow (60–100 m) nearshore areas at about 10 months of age (7–10 cm FL) during the fall and early winter months. The young opakapaka remain in this habitat for the next 7 months until they reach 18–24 cm FL.⁵ In situ scuba observations of the juvenile habitat found it to be a relatively flat, soft sediment substrate devoid of relief (Parrish, 1989). Recent trawl surveys suggest juvenile opakapaka are fairly widespread throughout the MHI in similar habitat and depths.⁶

Age, Growth, and Mortality

Tropical snappers in general are slow growing, long lived, and have low rates of natural mortality. Maximum ages exceed 10 years, and von Bertalanffy growth coefficients (K) are usually in the range of 0.10 to 0.25 per year (Manooch, 1987). Most aging studies of tropical snappers have depended on the enumeration of regularly formed marks on calcareous structures. The extended reproductive cycles and weakly expressed seasonality of growth in these fishes, however, confounds the accuracy of such studies. In Hawaii, Ralston and Miyamoto (1983) used daily growth increments deposited on the otoliths of immature *P. filamentosus* to determine its growth rate. Using in vivo tetracycline injection as a validation technique, they concluded that daily otolith increments were deposited in fish up to 3 years old (sexually mature), however, aging of fish greater than age 3 was difficult owing to episodic otolith deposition in sexually mature fish. Based on the growth of immature fish, the estimated growth coefficient of opakapaka was 0.145 per year, and asymptotic upper boundary on growth (L_{∞}) was 78 cm FL, which occurred at over 18 years of age.

⁵R. B. Moffitt and F. A. Parrish. In review. Temporal and spatial utilization of habitat by juvenile Hawaiian pink snapper, *Pristipomoides filamentosus*.

⁶D. A. Ellis, E. E. Demartini, and R. B. Moffitt. 1992. Bottom trawl catches of juvenile opakapaka, *Pristipomoides filamentosus* (F. Lutjanidae), and associated fishes, Townsend Cromwell cruise TC-90-10, 1990. U. S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fish. Sci. Cent. Admin. Rep. H-92-03, 33 p.

⁴S. Ralston and K. E. Kawamoto. 1987. An assessment and description of the status of bottom fish stocks in Hawaii. U. S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fish. Cent. Admin. Rep. H-87-7, 55 p.

Ralston (1987), in a comprehensive review of published reports on snapper growth and natural mortality, determined that for the 10 species studied, mortality and growth rates were highly correlated, with a mean M/K ratio of 2.0. Thus, if a value of K is available for a given species, its natural mortality rate can be estimated. Using an age-length probability matrix for opakapaka applied to length frequency samples, Ralston (1981) estimated the natural mortality rate for opakapaka in Hawaii to be 0.25, which when compared to the estimated K value for this species (0.145) is close to the value predicted by the M/K relationship derived for snappers in general.

Fishery Synopsis

Deepwater snapper in Hawaii have been commercially exploited since the early part of the century. In 1925, the Territorial Legislature, concerned with an increasing level of fishing pressure, imposed a one-pound minimum size limit for most of the deepwater snappers. By the 1930's, a fleet of vessels fished for bottomfish throughout the archipelago, with as many as five large (20 m) vessels venturing into the NWHI. After the hiatus imposed on the fishery by WWII, as many as nine vessels fished the NWHI. Landings peaked in the early 1950's at about 500 t, and declined steadily through the mid-1970's (Fig. 2). In the mid-1950's, poor fish prices and vessel losses reduced the number of fishermen in the NWHI; by the 1960's only one vessel remained in operation in the NWHI (Hau, 1984). There was renewed interest in the resources of the NWHI in the mid-1970's when state and federal agencies collaborated in a study focusing on the resources of this region. Bottomfish resources within this area were investigated during conducting an economic study of the fishery. The potential of the NWHI bottomfish resource prompted many new fishers to enter the fishery.

During the late 1970's, the fleet exploited banks closest to the MHI ports. As yields decreased, the fleet moved farther into the NWHI. A few vessels with extended fuel and hold capacity

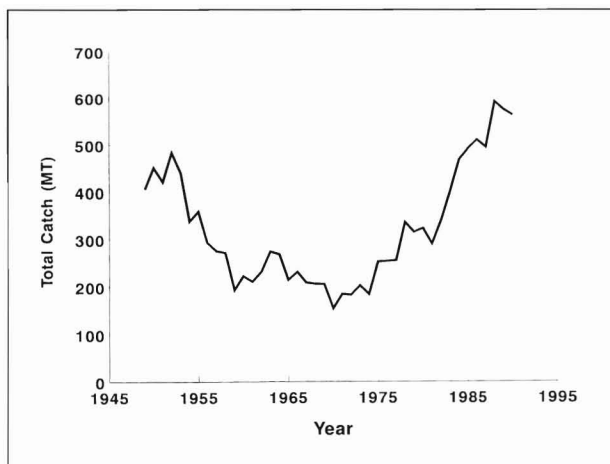


Figure 2. — Annual commercial bottomfish landings for the entire Hawaiian Archipelago, 1948–1990. (State of Hawaii, Division of Aquatic Resources data)

were fishing around Midway and Kure by 1988. The fishery expanded rapidly in the 1980's and landings peaked in 1987 (Fig. 2). Increased fishing pressure and fluctuating exploitation rates in the NWHI prompted the Western Pacific Regional Fishery Management Council (WPRFMC) to impose a limited access system for a large part of this area in 1989. Currently, effort in the portion of the NWHI west of Necker Island (Fig. 1) is limited to 6 vessels.

Fishing Gear

The Hawaiian snapper fishery utilizes various modifications of traditional Hawaiian handline gear. The gear consists of a main line with a 2–4 kg weight attached at the terminus. Several 40–60 cm sidelines with circle hooks are attached above the weight at 1 m intervals. The basic design of the handline gear used in the fishery has remained essentially unchanged from gear used by early, indigenous Hawaiians.

Commercial snapper fishermen in Hawaii mainly utilize vessels 10–20 m in length. The vessels are usually equipped with color video depth and fish echo sounders, satellite navigation receivers, Single Side Band (SSB) and VHF radios, EPIRB's, and hydraulic line-pulling equipment.

Vessels venturing into the NWHI tend to be in the upper end of the size range, as distance from ports and lack

of rough-weather shelter keep many of the smaller vessels closer to their home ports. The MHI vessels, although smaller than those used in the NWHI, are similarly equipped.

There are also many part-time recreational/commercial fishermen in the MHI. The boats involved in this fishery are smaller than the full-time commercial vessels and usually range from 5 to 15 m in length. Most of the part-time fishermen have color video depth/fish sounders, CB radios, and electric line-pulling equipment. Many also have satellite navigation equipment.

Since the late 1960's, the availability of improved navigational and fishing gear has greatly increased the fishing power of both commercial and recreational fishermen in Hawaii. It is now possible to return to a particular fishing spot with great accuracy in various weather conditions using electronic navigation equipment and to target single species using color video sounding equipment. In the past, triangulation from visible onshore landmarks was the most common method of relocating productive fishing grounds. This method can be very accurate, but depends on weather and other conditions beyond the control of the fisherman.

Until recently, many fishermen targeted individual species of snappers, but this strategy is not commonly practiced today. Most fishermen now diversify fishing effort because of de-

creased catch rates for some of the species. Targeting different species of snapper seasonally, or fishing for pelagic species when bottomfish are scarce, is now commonly practiced.

Seasons and Markets

The various snapper species are mainly caught during the months of November–February, with peak catches in December. Uku is an exception in that it is heavily exploited during the summer months when it aggregates in shallow water to spawn. Some uku are landed incidentally in December owing to increased fishing pressure on opakapaka which occurs at the same depths as uku.

A large portion of the MHI snapper landings is taken by recreational fishermen; therefore, the NWHI commercial fishery plays an important role in providing a consistent supply of fresh bottomfish to local markets. Generally the demand for fresh fish outstrips the supply. Snapper from various Pacific island nations are imported at times to supplement the supply of local fish. In the past these imports generally were of lower relative quality; however, in recent years the quality of these imports has improved dramatically. The price of these imported fish has also increased but is still lower than that of comparable local fish. The seasonal abundance of these imports can affect the price of the local bottomfish. However, most imports occur during the local low season for bottomfishing, which contributes to a year-round consistent supply of fish.

Most commercial fish in Hawaii are sold at wholesale fish auction houses. The demand for freshness and quality is high. Ex-vessel price can vary considerably depending on the quality of individual lots of fish. Snappers are generally separated into two categories at the auction: 1) large fish for the restaurant fillet market and 2) smaller whole fish for local consumers. Demand from local tourist-oriented restaurants is the major factor in bottomfish market economics. The local consumer market for smaller fish fluctuates to some extent, with peak demand occurring during traditional winter holidays.

Fishery Data Collection

In Hawaii, fishermen who sell all or part of their catch must be commercially licensed and submit a monthly catch report. These data have been available from the State of Hawaii Division of Aquatic Resources (HDAR) since 1948. In the MHI, incomplete reporting, and the "under-the-table" selling of fish by recreational fishermen confound the accuracy of the catch reporting system. In 1984 the WPRFMC initiated a monitoring program at the Honolulu fish auction to provide additional information on bottomfish landings in Hawaii. In 1986 the NMFS assumed responsibility for the program. In 1990, the HDAR began to share monitoring duties with the NMFS on a half-time basis. During the years 1984 through 1987, monitoring was conducted six days per week. This was reduced to five days per week in 1988, and three days per week in 1992. Information collected includes name of vessel or fisherman, date of sale, general area fished, species of fish, number of fish and corresponding weight, price per pound, and buyer. Information is recorded on a data sheet, coded and keypunched for analysis. Until recently, the majority of snapper sold in Hawaii passed through the monitored site. However, beginning in 1991, the majority of NWHI landings were not sold at the monitored site, which increased the difficulty in monitoring total archipelago landings.

An additional problem in obtaining total archipelago catch information is the large number of fish landed by recreational fishermen and not reported. The MHI recreational catch of snapper is impossible to accurately estimate. The large number of small trailerable boats currently registered in Hawaii gives an indication of the magnitude of the problem. Many of these "recreational" fishermen often sell their catch disregarding commercial fishing license requirements. The ease of selling privately to wholesalers, retail fishmarkets, restaurants, supermarkets, peddling, etc., without the proper licenses or reporting, leads to serious underestimation of total state catches.

Stock Status and Population Dynamics

Several different stock assessment approaches have been applied to the Hawaiian deepwater snapper fishery. These will be reviewed in approximate order of methodological complexity, which is similar to their chronological order in time because of developments in stock assessment methods and/or availability of additional data.

Simple catch per unit of fishing effort (CPUE) of commercial fishermen or research vessel surveys is commonly used as an index of stock abundance. CPUE alone can only provide estimates of relative changes in abundance; but, when coupled with certain assumptions and cast in the proper mathematical framework, it is possible to obtain measures of absolute abundance by estimating a catchability parameter. Catchability can be estimated in several different ways, and one of the more common approaches is to use the catch data in a surplus production model which will also estimate other fishery statistics such as maximum sustainable yield. Ralston and Polovina (1982) used a Schaefer surplus production model in one of the earliest attempts to assess MHI deepwater snapper stocks. The parameters for this model were estimated from a linear regression of yearly CPUE on yearly effort over the time period 1959–1978 (HDAR data). Rather than fit individual models to each species, Ralston and Polovina found that an intermediate level of species aggregation (from the species pool of 8 deepwater snappers) resulted in significantly improved fits to the model. This was apparently due to both depth segregation by species and the multispecies nature of the fishery where, since fishing effort (in fisherman-days) is not necessarily directed at a single species, single species CPUE, calculated by using the aggregate fishing effort, does not reflect that species abundance. Ralston and Polovina sought to aggregate species in the analysis to essentially mimic the aggregate nature of the fishing effort. This optimal level of species aggregation was objectively determined through

cluster analysis of species weight composition in HDAR daily commercial catch reports. The potentially complex effects of interaggregation interaction (i.e. predation, competition, and mutualism) were statistically examined and dismissed. Of the four MHI regions examined, statistically significant models were consistently achieved only for the Maui-Lanai-Kahoolawe-Molokai (MLKM) region (Fig. 1), an area which accounts for over 50% of the statewide bottomfish landings. This provided an estimate of MSY per habitat area which was then used in conjunction with other habitat area estimates to extrapolate other regional and total MSY's in the MHI and NWHI. Ralston and Polovina concluded that the MHI aggregate bottomfishery was operating at or near MSY in 1978, and in more recent years both MHI and NWHI landings have consistently exceeded estimates of MSY^{4,7} (Polovina, 1987), a situation difficult to interpret for purposes of stock assessment. The next level of stock assessment approaches for Hawaiian deepwater snappers attempted to utilize information on age and growth and patterns of size/age at entry to the fishery on a species-specific level.

Assessment of Hawaiian deepwater snappers in the 1980's relied heavily on the Beverton and Holt (1957) approach, also referred to as dynamic pool modelling. The normal methodology is simply to use the equations presented by Beverton and Holt (1957), inserting where necessary the von Bertalanffy growth coefficient (K) or asymptotic length (L_{∞}) parameters, values of total, natural, or fishing instantaneous mortality (Z , M , or F), and ages at maturity or entry to the fishery (t_m or t_e). Since this complete set of information is not available for many species of Hawaiian deepwater snappers, alternative methods must often be used to solve the yield equation.

The first alternative method is to estimate independently as many parameters as are within the limits of the

⁷S. Ralston and K. E. Kawamoto. 1988. A biological assessment of Hawaiian bottom fish stocks, 1984–87. U. S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fish. Cent. Admin. Rep. H-88–8, Honolulu, Hawaii, 60 p.

database, and then use empirical relationships to estimate the remaining parameters. Ralston and Kawamoto⁷ used this approach for five species of Hawaiian bottomfish (including four species of deepwater snappers: ehu, onaga, opakapaka, and uku), starting with estimates of L_∞ and the ratio Z/K from application of the Wetherall et al. (1987) method on catch length frequencies. These length frequencies were converted from Honolulu auction weight data by using the length-weight conversion parameters from Loubens (1980), Uchiyama et al. (1984), Brouard and Grandperrin (1984), and Ralston (1988). The empirical relationship presented in Manooch (1987) was used to estimate K from L_∞ , and the empirical relationship presented in Ralston (1987) was used to estimate M from K . The mortality parameters Z and F were deduced algebraically, where $Z=(Z/K)K$ and $F=Z-M$. Ages at entry were estimated from the ascending limbs of the weight frequency distributions, by using the length-weight conversion parameters and L_∞ and K (assuming $T_0=0$). The estimates of L_∞ and K were further used to construct a length converted catch curve from the length frequency distributions (also assuming $T_0=0$), resulting in another estimate of Z . Ralston (1984) also estimated M from L_∞ , K , and water temperature using the empirical formula given in Pauly (1980). Generally, multiple estimates of a parameter were averaged when they were in close agreement. Ralston and Kawamoto⁷ concluded that NWHI stocks were healthy, but most MHI stocks were being growth overfished by excessive harvesting of juvenile fish. They recommended some form of management regulation to counteract this.

The second alternative method is to modify the yield equation to a form which uses the ratios Z/K , M/K , or F/K rather than Z , M , F , or K since the former are readily calculable by using the Wetherall et al. method on weight-converted length frequency samples from a fished population (where $Z/K=M/K+F/K$) and an unfished population (where $Z/K=M/K$). F/K can then be solved for by subtraction, $F/K=Z/$

$K-F/K$. This was suggested by Polovina (1987) and implemented by Somerton and Kobayashi⁸ to calculate the spawning potential ratio (SPR =ratio of current spawning stock biomass per recruit to the virgin spawning stock biomass per recruit) for two species of MHI deepwater snappers (ehu and opakapaka). This analysis assumed that length frequencies of NWHI catch approximated a virgin unfished condition. Somerton and Kobayashi⁸ concluded that SPR values were in the 20–30% range which borders on the 20% value generally accepted as an indicator of recruitment overfishing (Beddington and Cooke⁹).

Both of these ad hoc applications of Beverton-Holt probably suffer from biases because of the variety of approximations and assumptions. One bias potentially affecting both approaches is due to use of the Wetherall et al. method to estimate initial parameters of the analyses. Somerton and Kobayashi (1991) used computer simulation to show that estimates of Z/K and L_∞ from the Wetherall et al. method can be either positively or negatively biased for many years while the population is adjusting to a change in fishing intensity or from a recruitment perturbation (however, bias due to recruitment seasonality per se can be negligible [Ralston, 1990]). Even under equilibrium conditions there can be substantial bias due to error in estimating the size at complete fishery selection and growth variability (Somerton and Kobayashi, 1991; Issac, 1990). In their assessment of the 1988 bottomfish stock, Somerton et al.¹⁰ abandoned the Beverton-Holt approach because of uncertainties regarding this type of

bias; however, as mentioned previously, Somerton and Kobayashi⁸ applied the Z/K , M/K , F/K version of Beverton-Holt to estimate SPR for ehu, which does appear to be in equilibrium, and for opakapaka, for which there are additional data on size at complete fishery selection.

Ralston and his coworkers^{2,4,7} (Ralston, 1981, 1984; Ralston and Miyamoto, 1983) have assembled an extensive database on the biology and fishery for opakapaka, which is by far the single best known species of Hawaiian deepwater snapper. For this reason, assessment approaches for opakapaka require fewer assumptions and approximations, and often there are multiple estimates available for a desired parameter. Ralston (1984) and Ralston and Kawamoto² applied yield-per-recruit analyses to opakapaka which made use of many independently estimated parameters. Von Bertalanffy parameters were obtained from a study of otolith microstructure (Ralston and Miyamoto, 1983), and Z and M were estimated from length converted catch curves from fished and unfished areas, and age at entry was estimated from the ascending limbs of catch weight frequency distributions, by using length-weight conversion and von Bertalanffy parameters.

Somerton and Kobayashi⁸ developed a computationally simple dynamic estimator of SPR that makes use of a time series of CPUE and catch size frequencies. Assuming that CPUE is an index of population size, changes in CPUE over time, coupled with the changes in the catch size composition, can be used to make estimates of SPR . Resorting to a similar strategy as that of Ralston and Polovina (1982), Somerton and Kobayashi⁸ aggregated species in the CPUE index and were able to calculate species-specific dynamic SPR for five MHI bottomfish species (including four species of deepwater snappers: ehu, onaga, opakapaka, and uku) by utilizing species-specific catch size frequency distributions and sizes at maturity. These dynamic SPR values were similar to the equilibrium SPR values, falling in the range of 20–40%. The earliest

⁸D. A. Somerton and D. R. Kobayashi. 1990. A measure of overfishing and its application on Hawaiian bottomfishes. U. S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fish. Sci. Cent. Admin. Rep. H-90-10, 18 p.

⁹J. R. Beddington and J. G. Cooke. 1983. The potential yield of fish stocks. FAO Fish. Tech. Pap. 242, 47 p.

¹⁰D. A. Somerton, B. S. Kikkawa, and A. R. Everson. 1989. Biological assessment of the Hawaii bottom fish stocks and the southeast Hancock Seamount armorhead stock, 1988. U. S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fish. Cent. Admin. Rep. H-89-6, 34 p.

(1948) CPUE data were considered virgin, but it is known that considerable bottomfishing may have been taking place at least as early as the 1930's (Polovina, 1987); and no attempt was made to correct for technological improvement in fishing efficiency. Clearly, there is a need for some type of dynamic stock estimator which does not rely on CPUE.

The logical alternatives are dynamic production modelling or age-structured models. The former approach is handicapped by incomplete landings and effort data, and the lack of a reliable CPUE. The latter approach may be more suitable, particularly since more age and growth data are available from ongoing otolith studies. Preliminary application of stock-synthesis, an age-structured model developed by Methot (1989, 1990), to NWHI opakapaka has been favorable¹¹, and a synthesis-like equilibrium approach called IMAGE (Somerton and Kobayashi, 1992) has been successfully used to estimate recruitment, fishing mortality, and the gear selection curve for MHI and NWHI opakapaka¹¹. Currently, the 1991 stocks are assessed with the CPUE-based dynamic *SPR* method.

Management and Regulation

Current fishing regulations for Hawaiian deepwater snappers include commercial minimum size limits of 1 pound for opakapaka, onaga and uku, and limited entry in the NWHI. There are no bag limits, closed seasons, or recreational minimum size limits for any deepwater snapper.

Somerton and Kobayashi^{12, 13} explored the possible consequences of increasing the minimum size limit for opakapaka from 1 to 3 pounds or initi-

ating a 1–3 month seasonal closure of the fishery. Their results from computer simulation indicated that both management strategies could substantially benefit the fish population in terms of increasing the spawning stock biomass. The potential increases ranged from 15–300% after a time period of 5–10 years, depending on the initial condition of the stock. Maximal benefits are attained if sublegal fishing mortality is minimal (i.e. small fish are avoided or released alive) in the case of a size limit increase, and if a seasonal closure effectively reduces the total annual fishing mortality (i.e. there is no compensatory increase in fishing effort during the open season). It is unlikely that the long-term equilibrium yield would increase; however, the population would be less vulnerable to recruitment overfishing and the associated catastrophic stock decline. The State of Hawaii is currently evaluating these and other management options (e.g. bag limits, areal closures) in response to concerns of deepwater snapper overfishing, primarily in the MHI.

Research Needs Pertaining to Management

Details of the reproductive biology are minimally adequate for most of the primary Hawaiian deepwater snapper species. More age and growth studies are needed, particularly for the younger and smaller fish, with enough data to better define the magnitude of growth variability. Discrepancies in growth estimation due to methodological differences in aging (e.g. Morales-Nin and Ralston, 1990; Radtke, 1987; Smith and Kostlan, 1991) need to be addressed and resolved, as this information forms the foundation for cohort/virtual population analysis, or stock synthesis assessment models. Movement patterns of adults and the extent of egg and larval dispersal need further study to clarify the identity of individual stocks, which would help determine the temporal and spatial scale for effective management.

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Literature Cited

- Agegian, C. R., F. T. Mackenzie, J. S. Tribble, and C. Sabine. 1988. Carbonate production and flux from a mid-depth bank ecosystem, Penguin Bank, Hawaii. In Agegian, C.R. (editor), Biogeochemical cycling and fluxes between the deep euphotic zone and other oceanic realms, p. 5–32. National undersea research program research Rep. 88–1, 176 p.
- Beverton, R. J. H., and S. J. Holt. 1957. On the dynamics of exploited fish populations. Fish. Invest., Minist. Agric. Fish. Food (G. B.) Ser. II 19:1–533.
- Brock, V. E., and T. C. Chamberlain. 1968. A geological and ecological reconnaissance off western Oahu, Hawaii, principally by means of the research submarine *Asherah*. Pac. Sci. 22:373–394.
- Brouard, F., and R. Grandperrin. 1984. Les poissons profonds de la pente récifale externe à Vanuatu. Notes et Doc. Ocean. 11, Mission ORSTOM, Port-Villa, Vanuatu, 131 p.
- Clarke, T. A. 1991. Larvae of nearshore fishes in oceanic waters near Oahu. U. S. Dep. Commer., NOAA Tech. Rep. NMFS 101, 19 p.
- Cobb, J. N. 1903. The commercial fisheries of the Hawaiian Islands in 1903. U.S. Fish Comm., Rep. 1903/04:433–512
- Everson, A. R. 1984. Spawning and gonadal maturation of the ehu, *Etelis carbunculus*, in the Northwestern Hawaiian Islands. In Grigg, R. W. and K. Y. Tanoue (Editors), Proceedings of the Second Symposium on Resource Investigations in the Northwestern Hawaiian Islands, p. 128–148, Vol. 2, University of Hawaii Sea Grant Miscellaneous Report UNIH-SEAGRANT-MR-84–01. Honolulu, Hawaii.
- Everson, A. R., H. A. Williams, and B. M. Ito. 1989. Maturation and reproduction in two Hawaiian Eteline snappers, Uku, *Aprion virescens*, and Onaga, *Etelis coruscans*. Fish. Bull. 87:877–888.
- Grimes, C. B. 1987. Reproductive biology of the Lutjanidae: A review. In J. J. Polovina and S. Ralston (editors), Tropical snappers and groupers: Biology and fisheries management, p. 239–294. Westview Press, Boulder, Colorado.
- Haight, W. R. 1989. Trophic relationships, density and habitat associations of deepwater snappers (Lutjanidae) from Penguin Bank, Hawaii. MS Thesis, University of Hawaii. 89 p.
- _____, J. D. Parrish, and T. A. Hayes. 1993. Feeding ecology of deepwater lutjanid snappers at Penguin Bank, Hawaii: depth, time of day, diet, and temporal changes. Trans. Am. Fish. Soc. 122(3):328–347.
- Hau, S. 1984. Economic analysis of deep bottomfishing in the Northwestern Hawaiian Islands. In Grigg, R.W. and K.Y. Tanoue (Editors), Proceedings of the Second Symposium on Resource Investigations in the Northwestern Hawaiian Islands, Vol. 2, University of Hawaii Sea Grant Miscellaneous Report UNIH-SEAGRANT-MR-84–01. Honolulu, Hawaii.
- Issac, V. J. 1990. The accuracy of some length-based methods for fish population studies. ICLARM Tech. Rep. 27, 81 p.

¹¹D. Kobayashi, Natl. Mar. Fish. Serv. Southwest Fish. Sci. Cent. 2570 Dole Street Honolulu, Hawaii 96822, unpublished data.

¹²D. A. Somerton, and D. R. Kobayashi. 1990. Some effects of increasing the minimum commercial size limit of opakapaka, *Pristipomoides filamentosus*. U. S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fish. Cent. Admin. Rep. H-90–3, 10 p.

¹³D. A. Somerton, and D. R. Kobayashi. 1990. Some effects of a seasonal fishing closure on opakapaka, *Pristipomoides filamentosus*. U. S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fish. Cent. Admin. Rep. H-90–16, 9 p.

- Kikkawa, B. S. 1984. Maturation, spawning, and fecundity of opakapaka, *Pristipomoides filamentosus*, in the Northwestern Hawaiian Islands. In Grigg, R.W. and K.Y. Tanoue (Editors), Proceedings of the Second Symposium on Resource Investigations in the Northwestern Hawaiian Islands, Vol. 2, p. 149-160. University of Hawaii Sea Grant Miscellaneous Report UNIHI-SEAGRANT-MR-84-01. Honolulu, Hawaii.
- Leis, J. M. 1987. Review of the early life history of tropical groupers (Serranidae) and snappers (Lutjanidae). In J. J. Polovina and S. Ralston (Editors), Tropical snappers and groupers: Biology and fisheries management, p. 189-237. Westview Press, Boulder, Colorado.
- Loubens, G. 1980. Biologie de quelques especes de poissons du lagon neo-caledonien. III. Croissance. Cah. Indo-Pac. 2(2):101-153.
- Manooch, C. S. III. 1987. Age and growth of snappers and groupers. In J. J. Polovina and S. Ralston (Editors), Tropical snappers and groupers: Biology and fisheries management, p. 329-373. Westview Press, Boulder, Colorado.
- Methot, R. D. 1989. Synthetic estimates of historical abundance and mortality for northern anchovy. Am. Fish. Soc. Symp. 6: 66-82.
- _____. 1990. Synthesis model: An adaptable framework for analysis of diverse stock assessment data. Proc. of the Symp. on Applic. of Stock Assess. Tech. to Gadids. INPFC Bull. 50:259-277.
- Moffitt, R. B., F. A. Parrish, and J. Polovina. 1989. Community structure, biomass and productivity of deepwater artificial reefs in Hawaii. Bull. Mar. Sci. 44(2):616-630.
- Morales-Nin, B., and S. Ralston. 1990. Age and growth of *Lutjanus kasmira* (Forsk.) in Hawaiian waters. J. Fish. Biol. 36:191-203.
- Munro, J. L. 1987. Workshop synthesis and directions for future research. In J. J. Polovina and S. Ralston (Editors), Tropical snappers and groupers: Biology and fisheries management, p. 639-659. Westview Press, Boulder, Colorado.
- Parrish, F. A. 1989. Identification of habitat of juvenile snappers in Hawaii. Fish. Bull. 87:1001-1005.
- Parrish, J. D. 1987. Trophic biology of snappers and groupers. In Polovina, J.J. and S.V. Ralston (Editors), Tropical snappers and groupers: Biology and fishery management, p. 405-463. Westview Press, Boulder, Colorado.
- Pauly, D. 1980. On the interrelationships between natural mortality, growth parameters, and mean environmental temperature in 175 fish stocks. J. Cons. Int. Explor. Mer 39: 175-192.
- Polovina, J. J. 1987. Assessment and management of deepwater bottom fishes in Hawaii and the Marianas. In J. J. Polovina and S. Ralston (editors), Tropical snappers and groupers: Biology and fisheries management, p. 505-532. Westview Press, Boulder, Colorado.
- Radtke, R. L. 1987. Age and growth information available from the otoliths of the Hawaiian snapper, *Pristipomoides filamentosus*. Coral Reefs 6:19-25.
- Ralston, S. 1981. A study of the Hawaiian deepsea handline fishery with special reference to the population dynamics of opakapaka, *Pristipomoides filamentosus* (Pisces: Lutjanidae). Ph.D. diss., Univ. Wash., Seattle, Washington, 204 p.
- _____. 1984. Biological constraints on production and related management issues in the Hawaiian deepsea handline fishery. In Grigg, R. W. and K. Y. Tanoue (Editors), Proceedings of the Second Symposium on Status of Resource Investigations in the Northwestern Hawaiian Islands, Vol. 1, p. 248-264. University of Hawaii Sea Grant Miscellaneous Report UNIHI-SEAGRANT-MR-84-01. Honolulu, Hawaii.
- _____. 1987. Mortality rates of snappers and groupers. In J. J. Polovina and S. Ralston (editors), Tropical snappers and groupers: Biology and fisheries management, p. 375-404. Westview Press, Boulder, Colorado.
- _____. 1988. Length-weight regressions and condition indices of lutjanids and other deep slope fishes from the Mariana Archipelago. Micronesica 21:189-197.
- _____. 1990. Effect of seasonal recruitment on bias of the Beverton-Holt length based mortality estimator. Am. Fish. Soc. Symp. 6: 190-197.
- Ralston, S., and J. J. Polovina. 1982. A multispecies analysis of the commercial deep-sea handline fishery in Hawaii. Fish. Bull. 80(3):435-448.
- Ralston, S., and G. T. Miyamoto. 1983. Analyzing the width of daily otolith increments to age the Hawaiian snapper, *Pristipomoides filamentosus*. Fish. Bull. 81(3):423-535.
- Ralston, S., R. M. Gooding, and G. M. Ludwig. 1986. An ecological survey and comparison of bottomfish resource assessments (submersible versus handline fishing) at Johnston Atoll. Fish. Bull. 84(1):141-155.
- Smith, M. K., and E. Kostlan. 1991. Estimates of age and growth of ehu *Etelis carbunculus* in four regions of the Pacific from density of daily increments in otoliths. Fish. Bull. 89(3):461-472.
- Somerton, D. A., and D. R. Kobayashi. 1991. Robustness of the Wetherall length-based method to population disequilibria. Fish. Bull. 89(2):307-314.
- Somerton, D. A., and D. R. Kobayashi. 1992. Inverse method for mortality and growth estimation: A new method for larval fishes. Fish. Bull. 90(2):368-375.
- Uchida, R. N. and J. H. Uchiyama (Editors). 1986. Fishery Atlas of the Northwestern Hawaiian Islands. U.S. Dep. Commer., NOAA Technical Report NMFS 38, 142 p.
- Uchiyama, J. H., S. M. Kuba, and D. T. Tagami. 1984. Length-weight and standard length - fork length relationships of deepsea handline fishes of the Northwestern Hawaiian Islands. In Grigg, R.W. and K.Y. Tanoue (Editors), Proceedings of the Second Symposium on Resource Investigations in the Northwestern Hawaiian Islands, Vol. 2, p. 209-225. University of Hawaii Sea Grant Miscellaneous Report-UNIHI-SEAGRANT-MR-84-01. Honolulu, Hawaii.
- Wetherall, J. A., J. J. Polovina, and S. Ralston. 1987. Estimating growth and mortality in steady-state fish stocks from length frequency data. In D. Pauly and G. R. Morgan (editors), Length-based methods in fisheries research. ICLARM Conference proc. 13, Manila, Philippines, and Kuwait Inst. for Sci. Res., Safat, Kuwait, p. 53-74.