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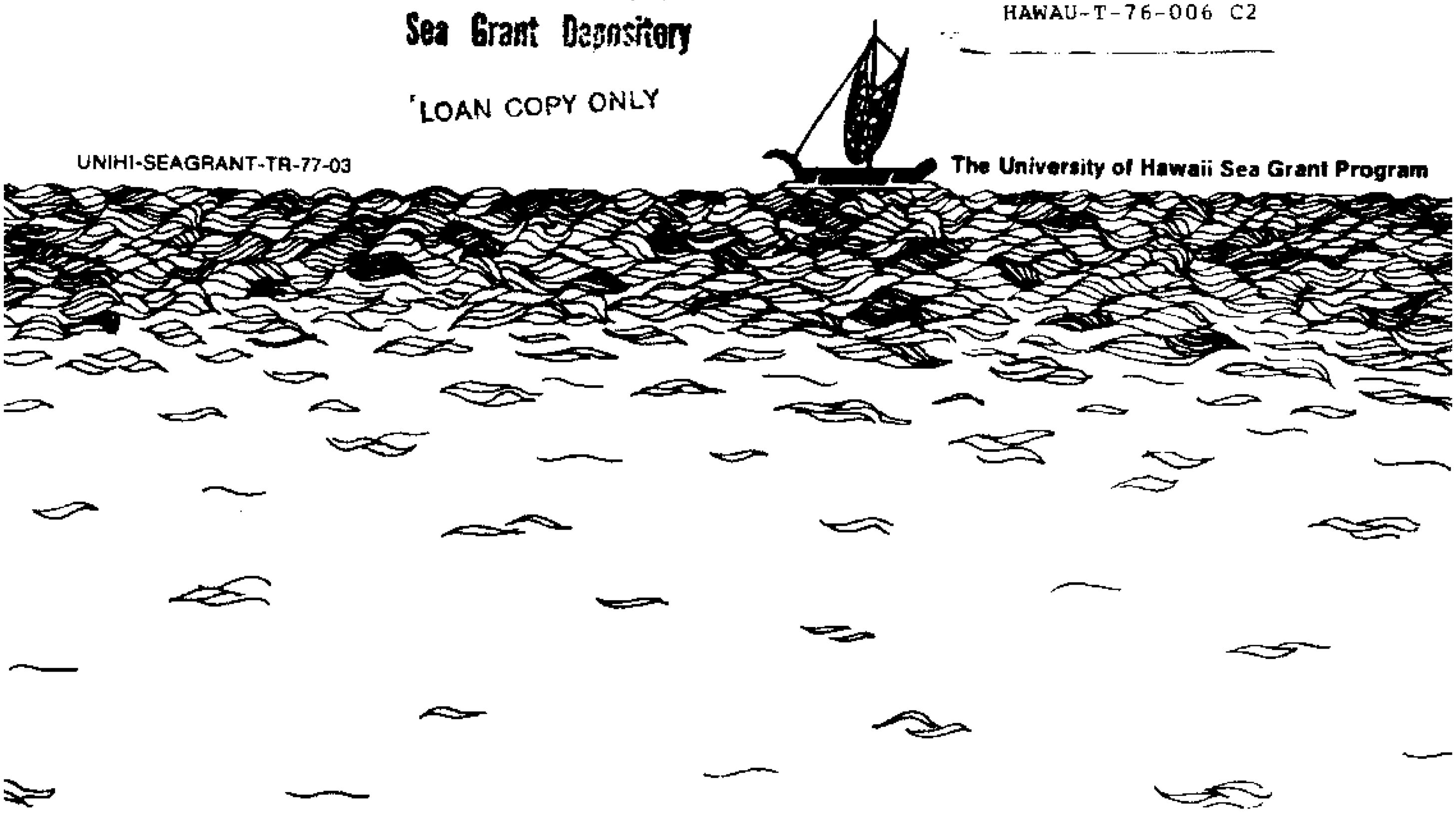

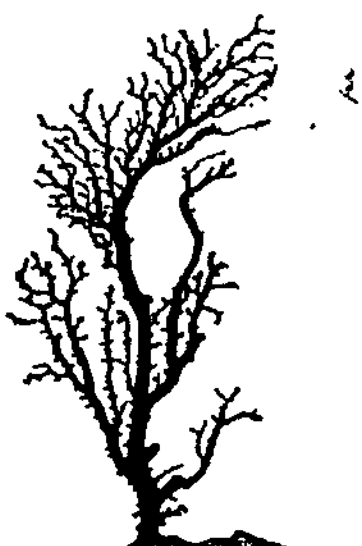

Fishery Management of Precious and Stony Corals in Hawaii

Richard W. Grigg

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FISHERY MANAGEMENT OF PRECIOUS AND STONY CORALS IN HAWAII

by

Richard W. Grigg

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ABSTRACT

Although the precious coral fishery dates back to antiquity, there has been little attempt throughout history to manage its exploitation. An often repeated pattern of the fishery has been exploration, discovery, exploitation, and depletion in different parts of the world. In recent years, shallow water reef-building stony corals have also come under heavy fishing pressure, especially in Florida and the Philippines. In this report, the life history patterns of several commercially important corals in Hawaii are analyzed for the purpose of developing a strategy of resource management. Major emphasis is placed on the stony reef-building coral, Pocillopora meandrina, *the black coral,* Antipathes dichotoma, *and the pink coral,* Corallium secundum. *An analysis of supply (natural production) and demand (sales) revealed that of the three species the latter two may be in jeopardy of overexploitation in Hawaii and thus require some form of management. Utilizing the method of Beverton and Holt (1957), yield curves were generated for both species by applying natural rates of growth and mortality to cohorts over their longevity. Estimates of maximum and optimum sustainable yield are given for both species and are compared with landings. These results, in combination with data concerning the ages of reproductive maturity, are used to develop management guidelines which include size limits and annual quotas.*

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INTRODUCTION

Skeletons of precious coral have been objects of curiosity and a source of commerce to man since Paleolithic times (Tescione, 1965). Artifacts unearthed in prehistoric European archaeological sites suggest that precious coral was used for trinkets or decoration as early as 25,000 years B.C. Commercial activity on an industrial scale can be traced back to the Neolithic period (ca. 7,000 years ago) in the Mediterranean Sea. In the 19th century, the center of the coral jewelry industry shifted to the Pacific Ocean where approximately 95 percent of the world's catch is now harvested (Grigg, 1974a). In 1970, one estimate of world retail sales of precious coral jewelry placed the total at $300 million (H. Ozawa, 1970: personal communication).

Initially, it is important to distinguish between the precious corals or so-called corals of commerce and other varieties of corals. Precious corals include species primarily in the families Gorgoniidae (*Corallium* spp., *Keratoisis* sp., *Acanella* sp., *Callogorgia* spp., and *Narella* spp.) and Antipathidae (*Antipathes* spp.). A recently discovered species of gold coral (Grigg, 1974a), *Parazoanthus* (= *Gerardia*) sp., is a member of the order Zoanthidae. All precious corals are ahermatypic (non-reef building) and generally occur in relatively deep water. Their skeletons consist of a complex of proteins and/or calcium carbonate.

Other varieties of coral that are of commercial value to man include the stony ($CaCO_3$) or scleractinian corals and certain other species in several groups that are of importance to medicine. Stony corals include both hermatypic (reef building) and ahermatypic species; however, only the shallow water hermatypic species are of commercial importance. The curio industry is the major source of demand for stony corals, although private collecting is on the increase in many parts of the tropical world. Recently (September 10, 1975) in the United States, the Department of Interior placed a 1-year ban on the collecting of stony corals on the outer continental shelf, where past activity has threatened the viability of some reefs off Key Largo, Florida.

Several varieties of coral are of commercial importance for pharmaceutical purposes. In the early 1970's the gorgonian *Plexaura homomalla* was harvested on a commercial scale by the UpJohn Chemical Company in order to obtain prostaglandin, a hormone with a number of useful medical applications including the inducement of abortion (Bayer and Weinheimer, 1974). Recently, prostaglandin has been produced synthetically, replacing *P. homomalla* as its source. Interestingly enough, *Corallium*, which is also a gorgonian, was used in ancient times for medicinal purposes and was believed effective in the treatment of gout and inflammation and as an antidote to all manner of stings, poisons, and enchantments, not the least of which was to neutralize the dreaded magic of the evil eye.

Palytoxin-producing zoanthids are another group of corals of potential importance for the production of pharmaceuticals (Kaul et al., 1974). Another intriguing application of coral products for medical purposes is the use of their skeletons as biomaterials or templates for developing porous synthetic solids such as artificial bones and teeth (J.N. Weber, 1973: personal communication).

The use of dead coral for sand, building material, and/or concrete is an activity in need of management but is not included in this report because the principles developed here can be applied only to living renewable resources.

While living corals are indeed renewable resources, by and large they have not been treated so historically. Management of the precious coral industry, in fact, has been almost completely lacking. The pattern of fishing has been one of exploration, discovery, exploitation, and depletion. Only for a brief period during the Middle Ages did coral fishermen practice a form of conservation, i.e., rotation of fishing grounds. More often, conservation was an unwitting occurrence due to interruption by war (Tescione, 1965). As a result, the future of the industry depends on the discovery of new harvesting grounds.

One problem is that corals, like many creatures of the sea, are often considered common-property resources. Ownership is vested in the heritage of mankind. Sovereign limits, of course, determine whether ownership is state or international, but this simply affects the size of the fishing fleet. Fishermen are frequently compelled to overexploit common-property resources for fear that if they don't their competitors will. Both recognition of this problem (Hardin, 1967) and the sad experience of its consequences have led to increasing efforts on the part of many nations to develop a conservation ethic. Now emerging as a fundamental issue in the law of the sea proceedings is the concept of full and wise utilization.

Basic to the implementation of wise utilization of living marine resources in the broadest sense is an analysis of supply and demand. Supply includes information on the basic biology of exploited species as well as estimates of maximum sustainable yield. Demand takes into account the consumer, the socioeconomics of the fishery, and an analysis of optimum sustained yield. It is the purpose of this report to apply this approach to several species of exploited corals in Hawaii with the aim of producing information that will be useful in managing these fisheries.

THE HAWAIIAN CORAL INDUSTRY

In Hawaii at the present time, four different types of living corals are currently under exploitation--stony or reef-building corals, black corals, pink corals, and gold corals.

Of the stony corals, the following species form the basis of the white coral curio industry: *Pocillopora meandrina*, *P. damicornis*, and *Fungia (Pleuractis) scutaria*. All are harvested by scuba divers. Current state law prohibits the taking of stony corals from the shoreline area and the ocean inside of 304 m (1,000 ft) offshore and at depths of less than 9 m (30 ft). Outside of these limits the harvesting of stony coral for domestic or curio purposes is legal in all counties. Commercial harvest is legal in all counties except the City and County of Honolulu.

although a permit is required. However, because the state does not have the manpower for adequate patrol, it is virtually impossible to determine where corals are collected and for what purpose. For this reason, the existing law relating to where corals are collected is unenforceable.

Prior to 1974, the harvest and sale of stony coral in Hawaii were of such minor importance as to hardly warrant mention. Sales in 1974 were estimated at $70,000 at the retail level, barely worth attention as a fishery were it not for the fact that the industry was estimated to have doubled during a 6-month period in that year. Consideration of this industry now is based on its potential for growth and thereby future management requirements.

Black corals (Figure 1) are also harvested by scuba divers but at greater depths (generally between 30 and 75 m) than stony corals. While black coral is primarily used in the manufacture of jewelry, the sale of undersized colonies for curio purposes is an activity of increasing frequency, especially in Lahaina, Maui, If this practice is not prohibited soon, serious depletion of the black coral resources off Lahaina may occur.

Figure 1. A large colony of black coral (*A. dichotoma*) at 58-m depth in the Auau Channel. It is approximately 2 m high and 3.5 m across. (Photo by Ron Church.)

The black coral industry began in Hawaii in 1958 when Jack Ackerman and Larry Windley discovered the beds off Lahaina, Maui. Since that time, harvest of the resource has been variable from year to year but is gradually increasing (Poh, 1971). The majority of the harvest is taken from the Auau Channel off Maui and off the southern half of the island of Kauai. While divers are required to possess commercial fishing licenses, there are no regulations to date that restrict the taking of this resource. The problem of management is complicated, at least off Maui where a portion of the coral beds lies outside of the traditional 3-mile territorial sea.

Pink and gold corals in Hawaii are presently harvested with the use of a small two-man submersible, *Star II*. In 1971, with support from the National Sea Grant Program, the feasibility of harvesting precious coral with a submersible was determined (Grigg et al., 1973). Since that time, Maui Divers of Hawaii, Ltd. has harvested approximately 1,200 kg of pink coral annually (Figure 2).

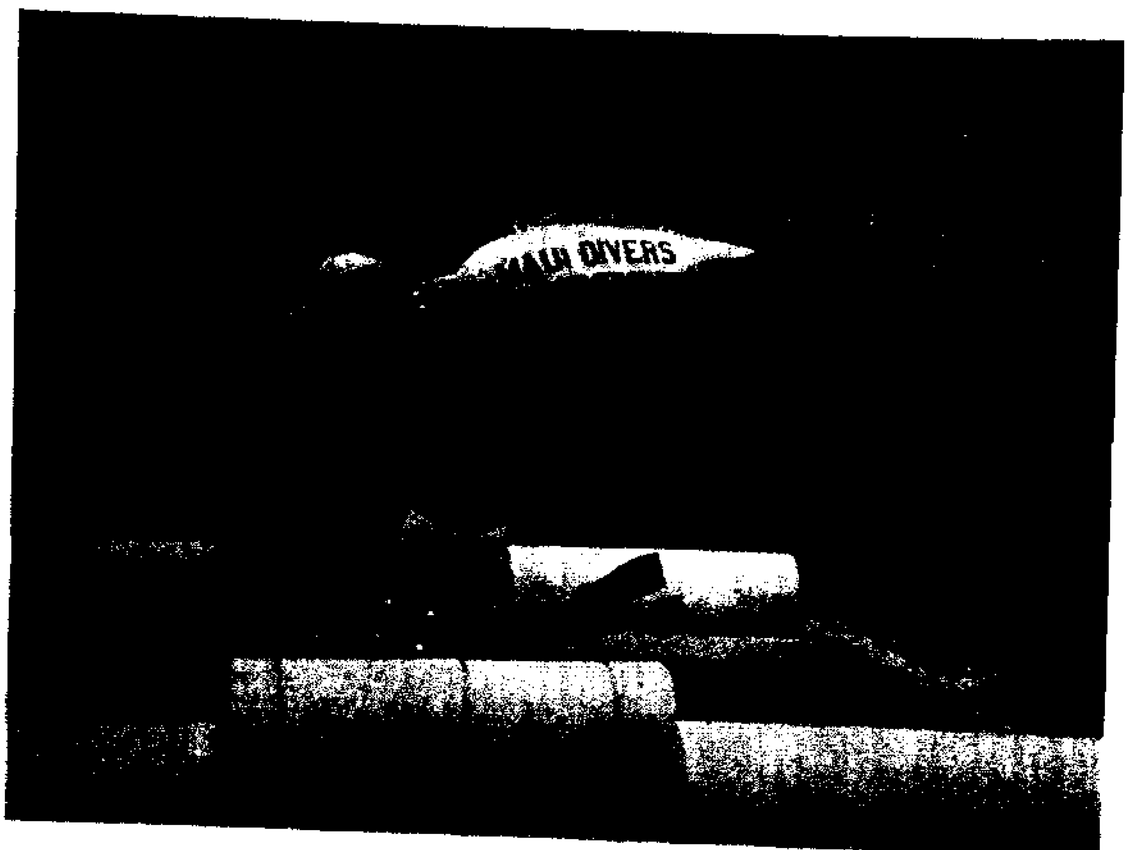

Figure 2. Returning from a precious coral harvesting dive off Makapuu, Oahu, *Star II* is recovered on the launching platform just below the surface. Note that the coral basket is about half full. (Photo by John Nordlum, courtesy of Maui Divers of Hawaii, Ltd.)

Prior to 1972, the precious coral industry in Hawaii was primarily dependent on sources of pink coral from Japan. All sales were conducted through closed auctions in Japan and were tightly governed by the coral cartel (All Nippon Coral Fishermen's Association).

The development of natural resources of pink coral off Hawaii has essentially freed the local industry from dependence on Japan. Furthermore, development of the pink coral fishery led to the discovery of gold coral and its use in the manufacture of exotic jewelry. Gold coral was first introduced on the market in late 1974; since that time sales have been brisk. Landings of gold coral in Hawaii in 1974 were about 300 kg, but since its successful acceptance by the consumer, landings can be expected to increase.

In 1975 gross retail sales of the precious coral industry (black, pink, and gold corals) in Hawaii were about $11 million (Thompson, 1975). This represents an increase by a factor of three over gross retail sales in 1972 when the industry was still dependent on Japanese sources for pink coral. Ironically, a significant part of this rapid growth can be attributed to the influx of Japanese tourists to Hawaii in recent years.

Both pink and gold corals in Hawaii are harvested at depths between 350 and 400 m, generally at distances greater than 3 miles from shore. Although both are now classified as creatures of the continental shelf under the Bartlett Act, jurisdiction remains moot. The state of Hawaii now has authority to regulate landings, but cannot prevent U.S. nationals from harvesting the resources outside of 3 miles. Foreign fleets may now harvest corals outside of 12 miles. With the passage of the Fishery Conservation and Management Act of 1976, federal jurisdiction over creatures of the continental shelf will be extended to 200 miles and beyond to the edges of the continental shelf beginning on March 1, 1977.

This brief review of the coral industry in Hawaii is intended to establish the need for developing management guidelines for the fishery as well as stress the urgency of their implementation.

OBJECTIVES

The specific objectives of this analysis are to investigate the natural history of selected species of commercially important corals in Hawaii and to develop estimates of their rates of natural production (supply) and consumption (demand) by the industry. This information will be used to provide an assessment of environmental impact of fishing activities and to furnish guidelines for wise management and conservation. Species selected for study include the stony coral, *Pocillopora meandrina*, the black corals, *Antipathes dichotoma* and *A. grandis*, and the pink coral, *Corallium secundum*. Several other species of commercially important corals in Hawaii include the stony reef-building corals, *Pocillopora damicornis* and *Fungia (Pleuractis) scutaria*, and the gold coral, *Parazoanthus* (= *Gerardia*) sp. These species await further study.

METHODS

Before it is possible to produce estimates of production, it is necessary to determine the distribution, abundance, and rates of turnover for individual species. Records of annual sales provide estimates of rates of consumption. Taken broadly, the relationship between the rates of production and consumption is a measure of the environmental impact of harvesting each species.

Distribution, Abundance, and Size Frequency

Estimates of the distribution and abundance of stony corals are based on diving surveys off windward and leeward Oahu. Representative stations were selected at four locations, two windward and two leeward, where quantitative transects were conducted at depths of 4.5 and 9 m. At each station a transect line, previously marked at 10 random points, was placed on the reef parallel to the appropriate isobath. A 1-meter square quadrat was placed on the bottom, over and normal to the line at each random point (situated mid-quadrat).

The number of species, along with visual estimates of percentage of coral cover, was recorded. Color photographs of each quadrat were taken with a camera-tripod assembly mounted above the quadrat. In the laboratory, photographs were projected against a calibrated grid on which the horizontal cover of each species was integrated.

Surveys of black coral (*A. dichotoma* and *A. grandis*) were also performed with scuba; however, because of depth and limitations in bottom time, surveys were less quantitative. Almost 150 dives were taken over a 3-year period at depths between 25 and 70 m off Kauai and Maui. At all stations observations of distributional patterns and relative abundance were recorded. Bathymetric profiles were run off Maui and Kauai in order to estimate the area of suitable habitat. The lower depth limit of both species was determined by observations from the submersible, *Star II*. Thirty-one submersible dives distributed almost equally between Kauai, Oahu, Molokai, Maui, and Hawaii were conducted. Although the most commonly surveyed depths ranged between 300 and 400 m, depths between 75 and 300 m were observed frequently during descent and ascent.

Estimates of the distributional patterns and density of pink coral are based on videotape records of three bottom surveys taken with a television camera assembly (Figure 3) and on in situ observations and counts from two dives with the submersible, *Star II*. In both instances, bottom area was calculated as the product of transect width and length. (See Grigg, 1974a for further details of the method.)

During both the black and pink coral surveys, measurements of size and frequency were collected in unfished (virgin) areas. For black coral this was done by simply measuring the height of every colony present along a 5-m swath of reef (between 44 and 53 m deep) at an inaccessible location within the coral bed off Lahaina, Maui. The size-frequency

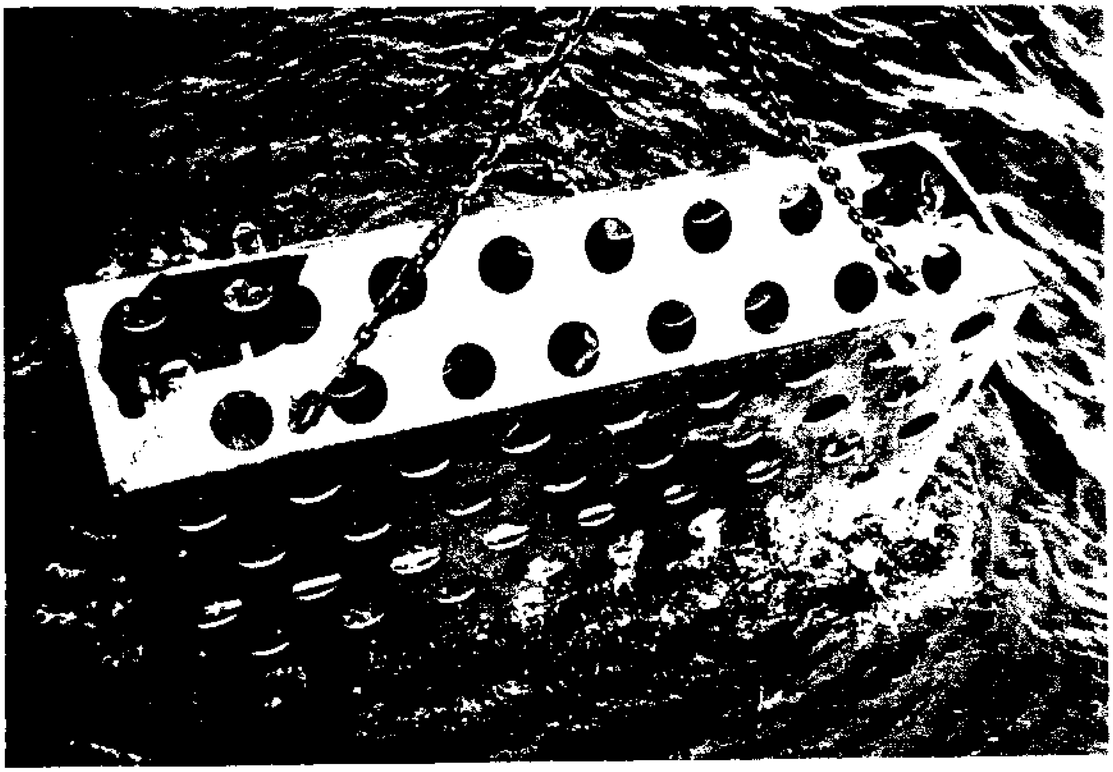

Figure 3. The TV-camera survey vehicle encased in a perforated steel shield in the process of being lowered from the R/V *Teritu*. It consists of two Edgerton 35-mm cameras, two strobes, a TV camera (Hydro Products model T.C. 303), a quartz-iodide light, and a pinger. The depth limit of the vehicle is 750 m.

distribution for pink coral was obtained in 1971 in the Makapuu coral bed (Grigg, 1974a) in a section not previously fished. Nine transects approximately 5 m wide by 300 m in length were taken, over which visual estimates of the height of all colonies were recorded on audiotape. The hydraulic claw was positioned near the bottom in front of the viewing window to provide a comparitive scale. Nevertheless, because of the common problem of underwater magnification which causes objects to appear about one-third larger, visual estimates were purposely conservative.

Growth

Knowledge of the rate and pattern of growth is prerequisite to developing a relationship between size and age. This must be determined before the age of reproductive maturity and production (yield) can be estimated. Growth rates for stony, black, and pink corals were obtained from literature, from direct field measurements, and by growth ring analysis, respectively. The use of a single rate is based on several commonly made assumptions: that individuals grow at the same rate and that effects due to changes or differences in the environment are inconsequential or tend to cancel one another. While this is never exactly true, for the sake of computation, the growth patterns for black and pink corals are described by simple mathematic expressions. Growth is defined as the change in colony height over time. Twenty-one colonies of black coral were "tagged" and measured at two stations, Upper and Lower Stone Wall Reef, 4.6 and 4.9 km off Lahaina Maui, respectively, at depths between 45 and 58 m. Upper and Lower Stone Wall Reef are 400 m apart but are sections of the same reef dropoff which runs parallel to shore. Stearns (1974) referred to Stone Wall Reef as Lahaina Roads.

In situ colony heights and widths were measured using a canvas tape (Figure 4). Each colony was measured twice at intervals of 1 year over a 3.5-year period. Colonies were tagged by placing numbered subsurface weighted floats in close proximity to each colony (Figure 4). Stations were relocated using triangulation methods.

Figure 4. Diver measuring height of a colony of *A. dichotoma* at a depth of 52 m (170 ft) on Stone Wall Reef off Lahaina, Maui. The subsurface floats are numbered to identify colonies; they have remained in place for over 4 years. (Photo by Mike Palmgren.)

Growth rings are present in the skeletons of both *A. dichotoma* and *A. grandis*. Their periodicity was analyzed in the laboratory where 48 thin sections cut from six colonies of *A. dichotoma* were prepared and X-radiographed. Preparation consisted of grinding and polishing thin sections to a thickness of 0.5 mm. The black coral wafers were then placed on Type R Kodak X-ray film and exposed to 20 kilovolt potentials for 1.3 minutes. Prints were overexposed and underdeveloped to achieve better contrast. Skeletal growth rings were counted in each section and plotted as a function of the length of the branch from which the section was cut. A ring is defined as one distinct dark line or distinct bundle of dark lines followed by a light zone made of indistinct light lines.

It was not possible to collect repetitive field measurements of growth for *C. secundum*; therefore a size-age relationship for pink coral was developed using growth ring analysis. The sectioning and X-radiographic procedure was the same as described for black coral, except that the rings were defined by annular discontinuities in the skeleton. The rings present in each thin section were counted under a microscope four times by two independent observers. This was done because rings are often very difficult to discern. Assuming ring formation is annual, the number of rings provides a measure of age. The validity of this assumption rests on the observation that ring formation is annual in related species (Grigg, 1974b). A plot of rings versus length produced an equation for annual growth.

Age-frequency distributions of *A. dichotoma* and *C. secundum* were constructed by dividing colony height by their growth rates.

The relationship between height and weight for both black coral (*A. dichotoma*) and pink coral (*C. secundum*) was obtained by weighing a large number of colonies of all sizes of each species and curve fitting the length-weight data.

Natural Mortality, Fishing Mortality, and Yield

If an unexploited natural population can be aged, the coefficient of natural mortality can be calculated by measuring the diminution of the numbers in a cohort over time or, assuming steady-state recruitment, the diminution of age-specific cohorts over 1 year. (See Deevey, 1953 for a complete discussion.) Taking the latter approach, one can consider the decrease between age classes of a population at any instant in time to be an estimate of age-specific natural mortality. The instantaneous mortality coefficient m is defined by the following equation:

$$N_t = N_o e^{-mt} \qquad (1)$$

where:

N_t = numbers at time t
N_o = numbers at time zero
t = years
m = instantaneous annual rate of mortality

Solving for m:

$$\text{Ln } N_t = \text{Ln } N_o - mt \tag{2}$$

$$m = \frac{\text{Ln } N_o - \text{Ln } N_t}{t}$$

Therefore, the regression of the natural logarithm of N versus time produces an equation of the form:

$$\text{Ln } N_t = a - mt \tag{3}$$

where:

m = the coefficient of natural mortality
a = a constant equal to Ln N_o

This method was used for both *A. dichotoma* and *C. secundum* to estimate natural mortality. N_o is taken as the age at which recruitment is "complete," meaning that very early ages which may be underrepresented (overlooked because of small size) are not included in the calculation.

Fishery mortality can be calculated as the difference in slope of the equation Ln N_t = a - mt between virgin and fished populations.

The use of this method relies on the explicit assumptions of steady-state recruitment and constant mortality and that the age composition of the samples are truly representative of the age composition of the whole population. The relatively stable age structure of both *A. dichotoma* and *C. secundum* suggests the first two assumptions are not badly violated. As for the third, this was met by taking as many and as large samples as practical.

Following the approach of Beverton and Holt (1957), production curves were generated by applying natural rates of growth and mortality to a cohort over its longevity. The cohort gains weight until a point is reached where growth gains are overtaken by mortality losses. This is the age at which maximum production (yield) occurs. Maximum production is converted to maximum yield per recruit by simply dividing maximum production by the original number in the cohort. As the cohort ages, its yield eventually declines to a negligible quantity at which point the process is terminated. If steady-state conditions prevail in nature, the yield curve of a single cohort over its longevity will model the yield of the entire population in any one year. In other words, given steady-state conditions, the production of a single cohort over its longevity will equal the production of all year classes present in any single year. If the assumptions are not badly violated, a model of annual production of the population is produced upon which different combinations of fishing mortality and age at first capture can be imposed. Theoretically, fishing mortality can be complete, in which case every age class above a certain size is harvested. In practice, however, fishing is never 100 percent successful, but rather operates at some lower level depending on effort.

Yields were calculated by imposing different combinations of fishing mortality and age at first capture on the production models for both *A. dichotoma* and *C. secundum*. This was done by adding together for each time interval the products of the number of colonies harvested and their average weight. These yields were then plotted as a function of fishing mortality and age at first capture to produce yield-isopleth (lines of equal value) diagrams (see results and discussion section, Figures 12 and 19). This method is useful in developing a strategy for management.

If an estimate of the absolute number of recruits entering the population each year were available, it can be multiplied by the maximum yield per recruit to give an estimate of maximum production of the population. If recruitment does not diminish after fishing mortality is imposed on the production model, then the yields produced are sustainable. It is also possible that harvesting may cause some small compensatory changes in growth, natural mortality, and even recruitment. Recruitment, of course, is the main factor relative to achieving sustainable yield. To attain maximum sustainable yield (MSY), the time or reproductive cushion between age at reproductive maturity and age at first capture must be substantial. For this reason, the age at reproductive maturity of each species was determined.

Age at Reproductive Maturity

For stony, black, and pink corals, the relative size of the gonads (oocytes or spermaries) within a colony was considered an accurate index of its relative reproductive maturity. Research on the reproductive behavior of many marine invertebrates has shown that gonads continue to enlarge up to the time of their maturity (Giese and Pearse, 1974).

Samples of colonies of all sizes were collected for each species under study. From each sample a number of polyps, generally about 10, were carefully dissected under a microscope and the diameter of the largest oocyte or spermary present was recorded. For all species the mean and standard deviation of these data, when plotted against colony size, showed that gonad diameter continued to increase in size with colony age until an upper maximum was reached after which no further increase in gonad size was apparent. This point on each curve served as an estimate of the size of reproductive maturity. These values were converted to age by dividing by the growth rates.

For *Pocillopora meandrina*, care was taken to collect all colonies at the same lunar phase since spawning of a closely related species is known to follow a lunar cycle throughout the year (Harrigan, 1972). Samples were collected in July of 1974 and 1975. All samples were preserved in Bouin's solution which partially dissolves the skeleton and facilitates excision of the polyps. After the skeleton softens, polyps can easily be teased or lifted from their otherwise highly septate calyxes. Examination of the aboral surface of the polyps under a binocular microscope generally revealed the gonads without further dissection.

Samples of *A. dichotoma* and *C. secundum* were initially preserved in formalin and later transferred to alcohol. Samples of *A. dichotoma* of various sizes were collected in July of 1974 and March of 1975 and samples of all sizes of *C. secundum* were taken in April of 1975. The gonads of *A. dichotoma* and *C. secundum* were more difficult to locate than those of *P. meandrina*. Enumeration and measurement required tedious dissection under a microscope. Histological sections of polyps were also prepared in order to determine anatomical relationships. Counting and measuring gonads using histological sections are impractical because of the number of sections that must be prepared and the scanning time required to examine all the sections.

In 1974 the coral industry provided samples of *C. secundum* on a monthly basis, enabling the annual reproductive cycle of this species to be analyzed. Samples were taken from the largest colonies available in order to obtain reproductively mature specimens.

Demand

Estimates of rates of annual consumption are based on interviews with sales persons and divers as well as records of annual landings available from the Federal Bureau of Mines (Poh, 1971) and the State Division of Fish and Game. While records for black coral date back to 1963 (Poh, 1971), only 3 years of data are available for pink coral and no official records exist for stony coral.

RESULTS AND DISCUSSION

Stony Coral

Pocillopora meandrina was the only species of commercial importance that was abundant on the transect surveys. Both *P. damicornis* and *Fungia (Pleuractis) scutaria* are generally found in shallower water in more protected environments inshore of the breaker zone. The latter two species are particularly abundant in Kaneohe Bay, Oahu where concentrations of *F. (Pleuractis) scutaria* up to 50 colonies/m^2 have been found on patch reefs at the north end of the bay. Species of *Fungia* are highly aggregated which makes them quite vulnerable to overexploitation; in fact, populations in Kaneohe Bay have declined substantially in recent years (J.E. Maragos, 1976: personal communication) although the cause is unknown.

Data for all species of coral present on the transects are given in Table 1. While *total* coral cover was generally higher at depths of 9 m than at 4.5 m, the density of *P. meandrina* was greater on every shallow transect. This pattern of distribution for *P. meandrina* is further evidence that this species is relatively light dependent and wave resistent as first reported by Maragos (1972). With regard to distribution and abundance around the island, total coral cover and density of *P. meandrina* were higher at leeward stations. Since harvesting effort is reported to be actually greater on leeward coasts, the greater abundance of *P. meandrina* and other corals there is probably a reflection of differences in natural rates of recruitment and/or mortality between leeward and windward stations. At windward stations, relatively smaller and more dead colonies of *P. meandrina* were observed.

TABLE 1. DISTRIBUTION AND ABUNDANCE OF STONY CORALS ON TRANSECT SURVEYS

Transect Location	Wind and Wave Exposure	Depth (m)	Total Living Coral Cover (%)	Percentage of Coral Cover, *P. meandrina*	Density of *P. meandrina* (numbers/m²)	No. of Species
Ala Moana Beach Park	Leeward	4.5	7.0	71.4	2.3	4
Ala Moana Beach Park	Leeward	9	17.6	0.5	0.1	3
Oneula Beach	Leeward	4.5	8.0	33.1	2.6	3
Oneula Beach	Leeward	9	22.1	3.3	1.3	6
Chinaman's Hat	Windward	4.5	3.8	93.0	0.9	3
Chinaman's Hat	Windward	9	14.2	3.9	0.4	3
Kahana Bay	Windward	7.5	3.8	31.6	0.9	5

Grigg and Maragos (1974) also found larger colonies of *P. meandrina* to be more abundant on the leeward reefs of the island of Hawaii. These findings suggest that the size frequency, distribution, and abundance of *P. meandrina* may be generally more dependent on natural mortality than fishery mortality. This conclusion may also apply to species less frequently harvested.

The minimum diameter of colonies of *P. meandrina* in which well-developed (100μ) oocytes were observed was 16 m. This diameter represents a minimum estimate of size at reproductive maturity. However, no spermaries were positively identified in any male colonies, leaving the question of size at sexual maturity for males unanswered. Furthermore, since samples were collected on only two dates and represented only 48 colonies, further research is required before an accurate estimate of size at sexual maturity can be made. At this point, the 16-cm estimate must be considered as an approximate figure.

Demand for stony corals was determined by conducting interviews with salespersons and shopowners on Oahu, Maui, and Hawaii. The results showed that Oahu is the only island where intensive harvesting occurs at the present time. The most commonly sold species in their order of importance are: *Pocillopora meandrina*, *Pocillopora damicornis*, *Fungia (Pleuractis) scutaria*, and occasionally *Porites lobata* and *Montipora verrucosa*.

Estimates of demand for local stony corals were often hindered by an unwillingness on the part of the vendors to discuss their business volume or to produce records of sales. It is also suspected that in some cases records do not exist. Another difficulty encountered was separating sales of local species from sales of imported species (Philippine coral). Total retail sales for both local and imported species based on reported sales was $70,000 in 1974. This must be considered a *very* conservative estimate. An equally conservative estimate of the number of colonies of all species of local origin sold was placed at 8,000 in the same year. This represents about a doubling of the industry in less than 1 year.

Eight thousand coral colonies are trivial relative to the standing crop of even one species off Oahu. A qualitative continuous survey of the standing crop of *P. meandrina* on the reef between Chinaman's Hat and Laie Point on Oahu (30 km) in July of 1975 produced an estimate of 4×10^6 colonies of which about 1×10^6 were larger than 16 cm in diameter. The standing crop of this species for the entire island of Oahu is probably ten times this number. Therefore, the total yearly harvest of all species in 1974 is on the order of one-tenth of 1 percent of the standing crop of *P. meandrina* off Oahu which is close to sexual maturity. Thus *P. meandrina* does not appear to be in jeopardy of being overharvested. However, the selective harvest of small colonies of *P. meandrina* and other rarer species such as *P. damicornis* and *F. (Pleuractis) scutaria* which aggregate may cause future problems. Small colonies of all species are the most desirable for a number of reasons. They are very symmetrical, inexpensive, and light in weight. They are also cheaper to ship and less inclined to break than larger colonies.

For these reasons and because growth rates of all corals are characteristically low (ca. 2 to 4 cm/yr increase in diameter for *P. meandrina*; Maragos, 1975), local areas subject to intensive harvesting pressure could easily be depleted. As the industry grows and spreads to the outer islands, increasing demand could produce excessive pressure on these resources. Therefore, it is clearly advisable to formulate and enact management guidelines before excessive demand is created.

In this regard, a number of steps can be taken now. First, since the present state law (Act 107), which prohibits the taking of stony coral within 304 m (1,000 ft) offshore and/or in water less than 9 m (30 ft) deep, is unenforceable, it should be amended. The author understands that the original intent of this act was to restrict the taking of dead coral rock for use by the construction industry. If Act 107 were amended to refer to only dead coral, this would legalize the harvesting of living coral in areas where harvesting takes place and enable the State Division of Fish and Game to regulate fishing activity. If commercial fishing licenses were required, the present law would require that all landings be reported. These data would be very useful for making future management decisions.

Interviews with stony coral divers and sellers revealed that few were aware of or concerned about existing laws relative to their activity. Clearly, a public information program is needed especially if future regulations are to be promulgated. Given the present lack of enforcement personnel at the State Division of Fish and Game, thought should be given to developing guidelines that could be exercised at the sales level; for example, a third copy of the receipt might be required for all sales.

Of equal importance is the need for more precise information on the patterns of distribution and abundance, reproductive biologies, natural mortality rates, and the impacts of harvesting stony corals. Harvested reefs should also be monitored on a continuing basis. If the stony coral industry continues to expand in the future, certain stringent controls may be necessary to avoid overexploitation of these resources.

Black Coral

Distribution and abundance

The known geographic range for both *Antipathes dichotoma* and *A. grandis* in the Hawaiian Islands extends between the islands of Hawaii and Niihau (Grigg, 1974a). A large species closely resembling *A. dichotoma* or *A. grandis* has been observed with the use of remotely controlled television cameras off Brooks Banks at a depth of 90 m (Grigg, 1974a). Therefore, it is likely that one or both species extend northwest of Niihau island. With the exception of *A. ulex* (fern coral), all other species of *Antipathes* in the Hawaiian Archipelago are much smaller and occur in deeper water (Grigg and Opresko, "The Antipatharia--black corals of Hawaii, in *Reef and Shore Fauna*, Bishop Museum Press, in press).

The depth ranges of *A. dichotoma* and *A. grandis*, 30 to 85 m and 45 to 146 m, respectively (Grigg, 1974a), require modification at the lower limit. Based on recent observations from *Star II* off Hawaii, Maui, Molokai, and Kauai, it is now reasonably certain that the lower depth limit of both species is about 110 m (Table 2).

Since 110 m is close to the top of the major thermocline in Hawaiian waters, temperature may play a role in determining the lower depth limit of these species.

Within their depth ranges, both species are highly aggregated and are most frequently found on or under vertical dropoffs. Such features are commonly associated with terraces and undercut notches relict of ancient sea level still stands (Stearns, 1974). Where such features are common, such as off Kauai and Maui, both species are particularly abundant. This suggests that their abundance is related to habitat space and that a

TABLE 2. *STAR II* DIVES AND OBSERVATIONS OF BLACK CORALS

Dive	Location	Date	Range Bottom Depth Surveyed	Observations
II-SII	Auau Channel, Maui	08-12-73	88 - 225 m 290 - 740 ft	*A. dichotoma* observed shallower than 107 m, small colonies, sparse
VI-SII	Penguin Bank, Molokai	09-12-73	70 - 375 m 230 - 1,230 ft	Several small colonies of *A. dichotoma* observed at 95 m
VII-SII	Koko Head, Oahu	10-01-73	84 - 369 m 275 - 1,210 ft	Large colonies of *A. dichotoma* and *A. ulex* observed at 91 m
VI-SIII	Kawaihae, Hawaii	04-25-75	61 - 134 m 200 - 440 ft	*A. dichotoma* and *A. grandis* colonies small, abundant, not found below 110 m

positive relationship may exist between abundance and recruitment, at least until the habitat is fully saturated. Off Oahu, sediments have covered many submarine terraces and notches (Coulbourn et al., 1974), thereby significantly reducing the habitat of *A. dichotoma* and *A. grandis*. This may explain the relative scarcity of both species off Oahu.

An attempt was made to estimate the accessible portion of standing crop of the entire bed of *A. dichotoma* in the Auau Channel. This was done by analyzing bathymetric profiles of the channel and integrating the area judged to be suitable habitat, i.e., steep dropoffs at depths between 40 and 70 m. This procedure produced an estimate of suitable habitat of 1,680,000 m^2 (56 km of dropoff reef x 30 m slope). Multiplying this figure by an average density of 0.05 colonies/m^2 (Grigg, 1965) yielded an estimate of 84,000 colonies. Conversion to weight required that this number be multiplied by the weight of a colony of mean longevity, i.e., 14 years. (See section on age structure and yield.) This procedure produced an estimate of the standing crop in weight of 166,000 kg for *A. dichotoma* in the Auau Channel. Given the patchiness in distribution and the variability in growth rate, the precision of estimate is probably not better than 33 percent. A similar procedure was followed to estimate the standing crop of *A. dichotoma* off Kauai which turned out to be about 40,000 kg, roughly 25 percent of the Auau Channel population. Data are insufficient to calculate similar figures for *A. grandis*. A subjective estimate of the relative abundance of *A. grandis* is about 10 percent the abundance of *A. dichotoma* off Maui and 0.2 percent the abundance off Kauai.

Growth

Records of all colonies "tagged" and measured at approximately yearly intervals are given in Figures 5 and 6. Of the 21 colonies monitored, 16

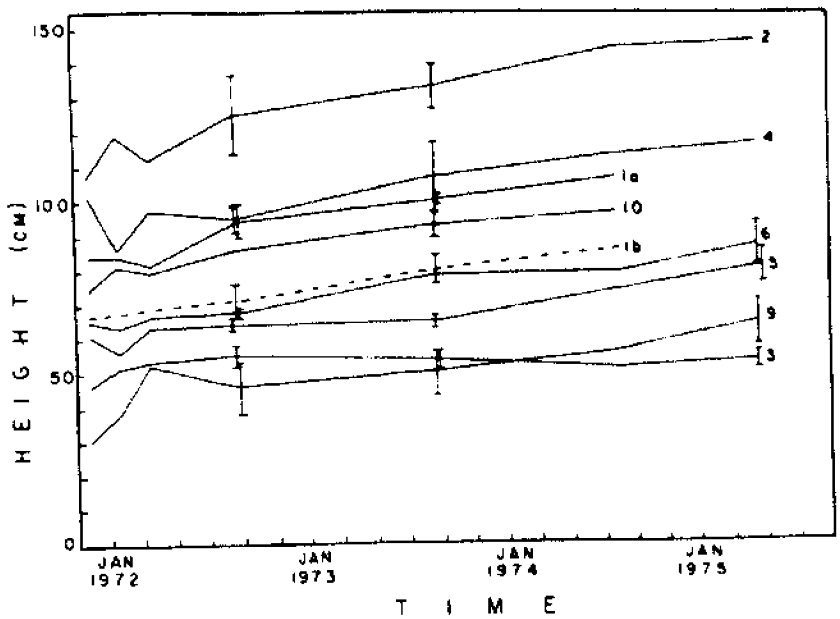

Figure 5. Heights of colonies of *A. dichotoma* (solid lines) and *A. grandis* (dashed lines) at Lower Stone Wall Reef are plotted over a 3.5-year period. The lines connect single measurements or the means of two measurements.

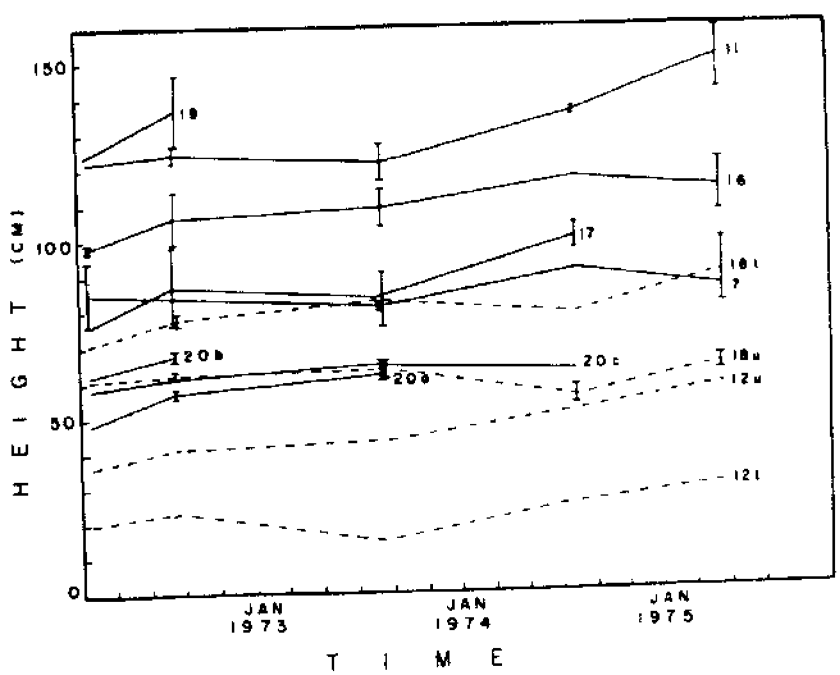

Figure 6. Heights of colonies of *A. dichotoma* (solid lines) and *A. grandis* (dashed lines) at Upper Stone Wall Reef are plotted over a 3.5-year period. The lines connect single measurements or the means of two measurements.

were *A. dichotoma* and 5 were *A. grandis*. Presentation of the data graphically illustrates several important characteristics of both the patterns of growth and the method of measurement. First, the relatively large differences in colony height measurements, which were especially apparent at Lower Stone Wall Reef during the first 3 months of the study, are presumably due to measurement error since there is no consistent trend. This result is not surprising since it is quite physically demanding to carry out research at the depths where these data were collected. A certain amount of practice and routine are required before data can be collected reliably. For this reason, the first 3 months' data were discarded. A second possible error, this time a systematic one, is evident in the data collected at Upper Stone Wall Reef in the summer of 1973 (Figure 6). Most measurements appear to be too low. These data were collected during a period when the bottom current was relatively strong (about 0.6 knots), causing colonies to bend in the direction of the current, and appears to have produced a downward bias on most measurements. By using a cumulative value of growth over a much longer period of time, these sorts of errors are offset.

The average annual rate of increase in height over the 3.5-year period was 6.42 cm for *A. dichotoma* and 6.12 cm for *A. grandis*. Growth rates for both species which were reported in an earlier report (Grigg, 1974a; *A. dichotoma* at 5.86 cm/yr and *A. grandis* at 2.92 cm/yr) must be revised in view of these data which represent a longer period of growth. The means between species are not significantly different ($P = .40$). While it is clear that some colonies appear to be consistently fast or slow growers (compare colonies 12u and 18u in Figure 6 and colonies 3 and 9 in Figure 5), differences do not appear to be due to size or placement on the reef. For example, the mean annual increase in height of *A. dichotoma* at Upper and Lower Stone Wall Reef was 6.35 cm and 6.50 cm, respectively; the difference is not significant ($t_{14} = .86$, $P = .41$).

Differences in growth between colonies may be intrinsic or related to the "health" of a colony. Colony 3 (Figure 5), for example, grew very little over the 3.5-year study and was observed to consistently have bits of mucus clinging to terminal branch tips. This is not to say that differences in growth rate may not be caused by environmental differences which, as in the case between Upper and Lower Stone Wall Reef, may simply have been too small to "show up." Differences in the growth rate of widely separated hermatypic corals of the same species have often been attributed to differences in temperature (Stoddart, 1969), day length, or other environmental factors (Knutson et al., 1972).

Because the growth rates of both species did not appear to be related to their size, their patterns of growth were assumed to be linear for purposes of calculating age. However, since colonies larger than 1.5 m were not measured (due to logistic difficulties), it is not possible to say whether or not the pattern is linear over the entire lifespan.

Further indication that the growth rate of *A. dichotoma* is linear up to a size of about 1.5 m was provided by a straight line fit ($Y = 9.4 \times 4.75 X$) between a plot of growth rings and branch length (Figure 7).

Within single colonies a linear fit was sometimes extraordinary (Figure 8). Furthermore, close examination of the X-radiographs (Figure 9) revealed that the distance between growth lines is approximately constant, again suggesting that growth is indeterminant, i.e., it does not change with age.

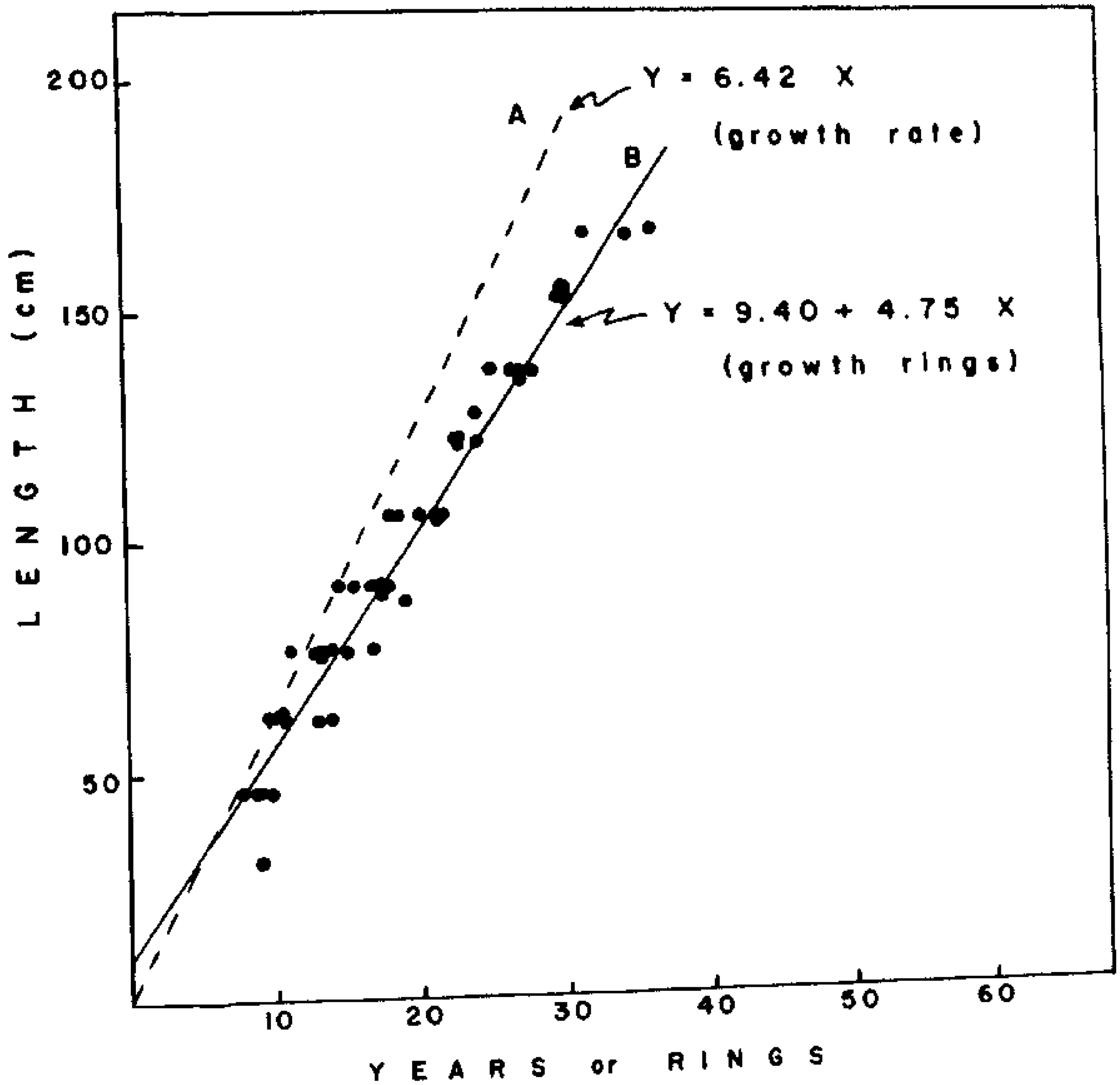

Figure 7. Plot of length (height) of *A. dichotoma* as a function of years or growth rate (curve A) and number of growth rings (curve B). Growth ring counts represent 47 thin sections cut from six colonies collected in the Auau Channel.

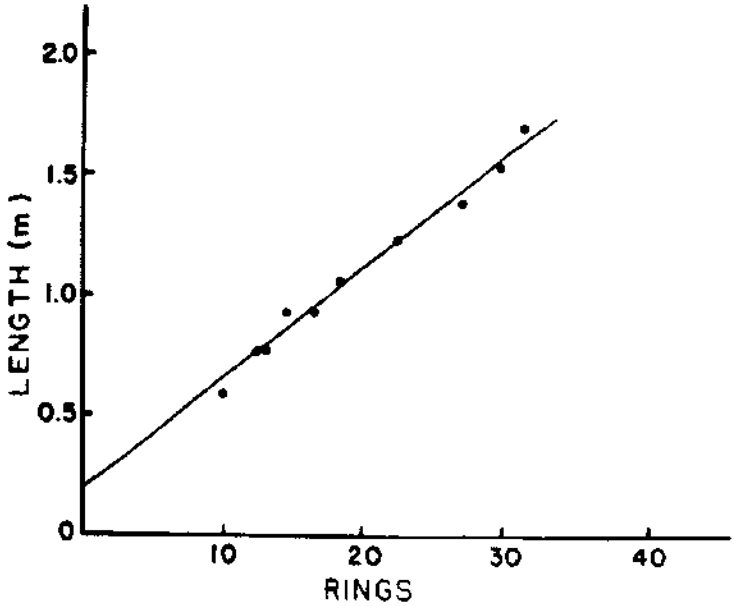

Figure 8. Relationship between colony height (length) and number of growth rings of *A. dichotoma* within a single colony collected in the Auau Channel. The best fit equation is: Y = 0.18 + 4.48 X.

Figure 9. X-radiograph of a basal cross-section of *A. dichotoma* showing growth rings in the skeleton. Colony height was 1.67 m; growth rings number 36. (Note area of faster growth around branch.)

A comparison of the number of growth rings present in the skeletons of *A. dichotoma* with estimates of its age based on the average growth rate indicates that the periodicity of ring formation is probably annual (Figure 7); this relationship characterizes several other coral taxa (Knutson et al., 1972; Grigg, 1974b). The slight disagreement between the growth rate curve (A) and the growth ring curve (B) may be due to real differences in growth rate between the two groups of colonies or a periodicity of ring formation which is slightly greater than 1 year. Since the six colonies that were analyzed for growth rings were not collected from Stone Wall Reef, but rather from a reef about 2 miles further offshore, the first explanation--that growth rate is different because of environmental differences--would appear most plausible. It is also of interest that growth rate within a colony may speed up in the region of branch formation or foreign inclusions (Figure 9). For the purpose of converting size into age, a growth rate of 6.42 cm/yr is used because it is based on the most information available.

Age structure

The age-frequency distribution of an unfished or virgin sample population of *A. dichotoma* off Lahaina, Maui is shown in Figure 10. The underrepresentation of young colonies is probably a consequence of the difficulty in seeing colonies of this size, since larvae frequently settle in the shaded interstices of the reef. While there is some apparent fluctuation between the size of age classes, compared with many other invertebrates (Coe, 1956), the age structure is relatively stable. The assumption of steady state for purposes of calculating natural mortality does not appear to be badly violated. Therefore, the regression of the natural logarithm of N versus time can be expected to produce a reasonable estimate of the instantaneous rate of natural mortality, m. The equation is as follows:

$$Y = 2.50 - 0.07\,X \qquad (4)$$

where:

Y = the natural logarithm of N at time X
X = years
2.50 = the natural logarithm of recruitment at time 2 years
0.07 = the instantaneous rate of natural mortality

Assuming steady state, the rate of recruitment would be equal to the mortality rate.

Yield

In order to calculate production curves in terms of biomass, a relationship between size and colony weight must be developed. For many species weight is roughly proportional to the cube of length (von Bertalanffy, 1938). However, this was not the case for *A. dichotoma* in which weight is more closely related to the square of length. This relationship

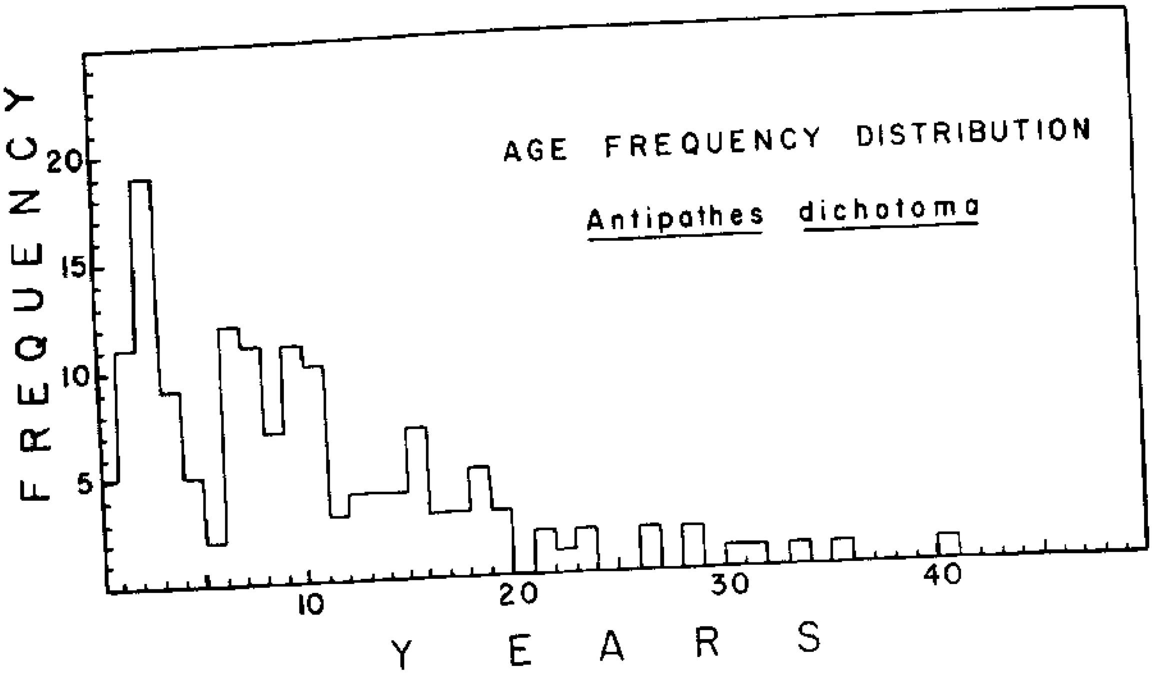

Figure 10. Age-frequency distribution of 152 colonies of *A. dichotoma* in an unfished section of the Auau Channel bed. Data were collected in April 1975.

is probably due to the branching dichotomy and planar growth form of these animals. The best fit equation is:

$$Y = 0.19\ X^{2.05} \qquad (5)$$

where:

Y = weight (gm)
X = height (cm)

Applying the above parameters for growth and natural mortality to a cohort over its longevity produced a yield curve shown in Figure 11. The absolute value of yield is expressed in units per recruit. It is immediately clear that a small change in natural mortality makes a large difference in potential yield per recruit. A decrease or increase in natural mortality of only 0.02 either doubles or halves potential yield. Fortunately, the calculation of natural mortality is based on data that span the longevity of the species, about 40 years. Therefore, differences in annual recruitment and age-specific mortality rates should be smoothed (differences between years should be offsetting) to a large extent. A range of natural mortality rates between 0.05 and 0.09 would produce colonies with asymptotic ages of between 27 and 50 years, corresponding to colonies 1.7 and 3.2 m high, respectively. Since the largest colonies observed in unfished populations almost always fall within these limits, it is reasonable to assume that natural mortality is generally between 0.05 and 0.09.

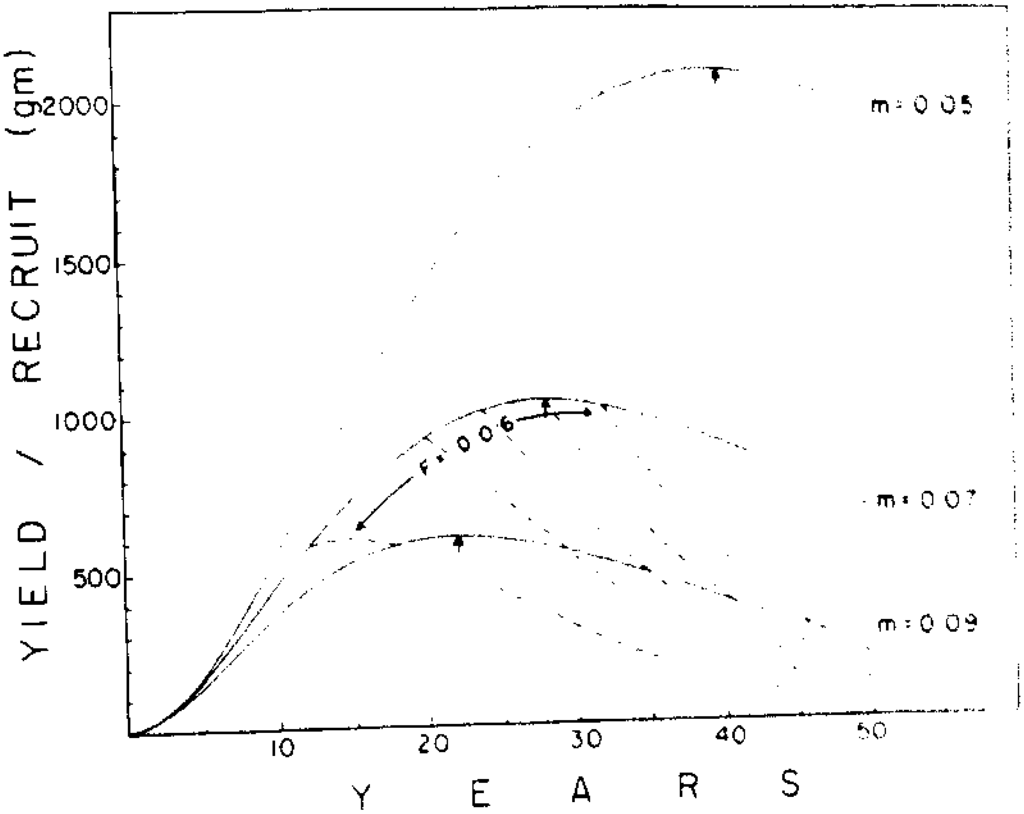

Figure 11. Yield curves for *A. dichotoma* at different rates of natural mortality (solid lines). Dashed lines represent yield curves of a cohort subject to a natural mortality of 0.07 and fishing mortality of 0.06 beginning at different ages of first capture. The arrows below each solid line signify the maximum yield per recruit with no fishing mortality.

The maximum yields per recruit as a function of different values of natural mortality are given in Table 3.

TABLE 3. NATURAL MORTALITY AND YIELD PER RECRUIT OF A. [illegible]

Mortality Coefficient	Yield Per Recruit (gm)	Age at Maximum Yield Per Recruit
0.05	2,100	40
0.07	1,050	28
0.09	600	22

If the number of recruits entering the population were known, it is possible to use the figures in Table 3 to calculate the maximum yield in weight of the population. Again, assuming steady state and that the rate of recruitment equals the rate of natural mortality, the estimated standing crop of the Auau Channel population (84,000 colonies) can be multiplied by 0.05, 0.07, and 0.09 to give estimates of the absolute number of recruits. The absolute number of recruits times the corresponding values of maximum yield per recruit produces a range of the maximum yields of between 4,536 and 8,820 kg (or between about 10,000 and 19,000 lb/yr) for the Auau Channel population. The calculations are as follows:

1. 0.05 x 84,000 rec x 2,100 gm/rec = 8,820 kg
2. 0.07 x 84,000 rec x 1,050 gm/rec = 6,174 kg
3. 0.09 x 84,000 rec x 600 gm/rec = 4,536 kg

The above estimates of maximum yield for the population can only be sustained if harvesting does not significantly diminish recruitment. It is of course possible that harvesting may result in some small compensatory changes in growth, natural mortality, or even recruitment.

Past practice of the fishermen has been to only harvest colonies larger than about 1.2 m (4 ft) in height. This would represent colonies older than about 20 years. If an age at first capture of 20 years is combined with the yield for the best estimate of natural mortality (0.07), the maximum yield would be about 5,000 kg (11,000 lb) for the Auau Channel population. Therefore, if the above assumptions are not badly violated and given the present circumstances of the fishery, 5,000 kg can be considered the best estimate of optimum sustainable yield (OSY) for this area. This figure might serve as a reasonable annual quota for the Auau Channel population of *Antipathes dichotoma*. Future catch per unit effort statistics can be used to judge whether this estimate is under or over conservative. A less precise estimate for an annual quota of *A. dichotoma* off Kauai might be 25 percent of this value, or 1,250 kg (2,750 lb).

Colonies of *A. grandis* are not distinguished from *A. dichotoma* by the industry. Further, because of its relative scarcity, the most reasonable policy might be to include its landings within the above estimates.

Up until now it has been assumed that fishing effort acted instantaneously and was completely successful, i.e., all corals beyond the age at first capture were harvested. This procedure, of course, produces catches larger than MSY until all older age classes have been caught. After that catch is dependent on what is entering the first exploitable year class. In most accessible areas in Hawaii this is roughly the present status of the fishery. The potential catch entering the first exploited year class is the value that has been calculated above as an estimate of OSY.

In practice, fishing does not operate instantaneously and is not completely successful, but rather operates at some level dependent on effort. For this reason, it is useful to compare the yield per recruit that would be obtained given different combinations of fishing mortality and age at first capture on a virgin fishery. In Figure 11, the yields obtained by fishing at a level of 0.06 per year starting at ages 12, 20, 24, 28, and 32 are graphically represented as the difference between the unfished (solid line) and fished (dashed line) cohort. The difference is what is caught and will gradually accumulate over time. In the model, fishing is terminated when what is caught per year is a small fraction of total past catch; in this case 1 percent.

The yields are depicted in a comprehensive fashion in yield-isopleth diagrams (Figure 12). The effect on yield of varying one or the other of the two parameters (fishing mortality or age at first capture) separately, while the other is held constant, can also be examined (Figures 13 and 14). The latter plots are easier to understand since only one factor is varying at a time. For example, as is shown in Figure 13, it makes little sense to fish at a level beyond 0.06 because of diminishing returns. Also by fishing more intensely, the age at first capture must be postponed in order to maximize yield (Figure 14). This is necessary to allow time for the younger colonies to grow. In Figure 12, looking at the middle case where m = 0.07, it is clear that doubling catch requires more than quadrupling effort. Also apparent in Figure 12 is the little difference that age at first capture makes on yield at lower fishing levels. However, changing the natural mortality rate (compare top, middle, and bottom yields in Figure 12) dramatically affects yield as well as the optimum strategy of first capture.

It is important to stress that the yield-isopleth analysis has been done assuming the fishery is in a virgin state simply for the purpose of developing a management strategy. Even so, it does not pinpoint a single best combination of fishing effort and age at first capture, but rather indicates the consequences of various fishing strategies. In this case, the most economical strategy is to fish at a low level of intensity and to catch the coral at an early age. Given a natural mortality coefficient of 0.07 and a fishing mortality coefficient of not greater than 0.06, the best yield is obtained at an age of first capture of about 20 years or less. This suggested age at first capture is realistic in terms of the present status of the fishery. However, it is re-emphasized that this combination may not produce a sustainable harvest unless recruitment is undiminished. Therefore, it is equally important to consider the reproductive behavior of the species.

<u>Age at reproductive maturity</u>

Sexes are separate in *Antipathes dichotoma*. Oocytes or spermaries, as the case may be, are located at the base of the primary tentacles (Figure 15). A plot of gonad diameter versus colony height for 12 samples collected in July of 1974 revealed that reproductive maturity is reached at a size of about 64 to 80 cm in height (Figure 16). This size corresponds to an age between 10 and 12.5 years old, which is very similar to the gorgonian *Muricea californica* in California (Grigg, 1970). A collection of *A. dichotoma* ranging in size between 0.1 m and 2.0 m taken in March of 1975 contained only immature gonads. While further study is needed to determine the periodicity and phasing of the reproductive cycle, there is a suggestion that it is annual, culminating in summer months.

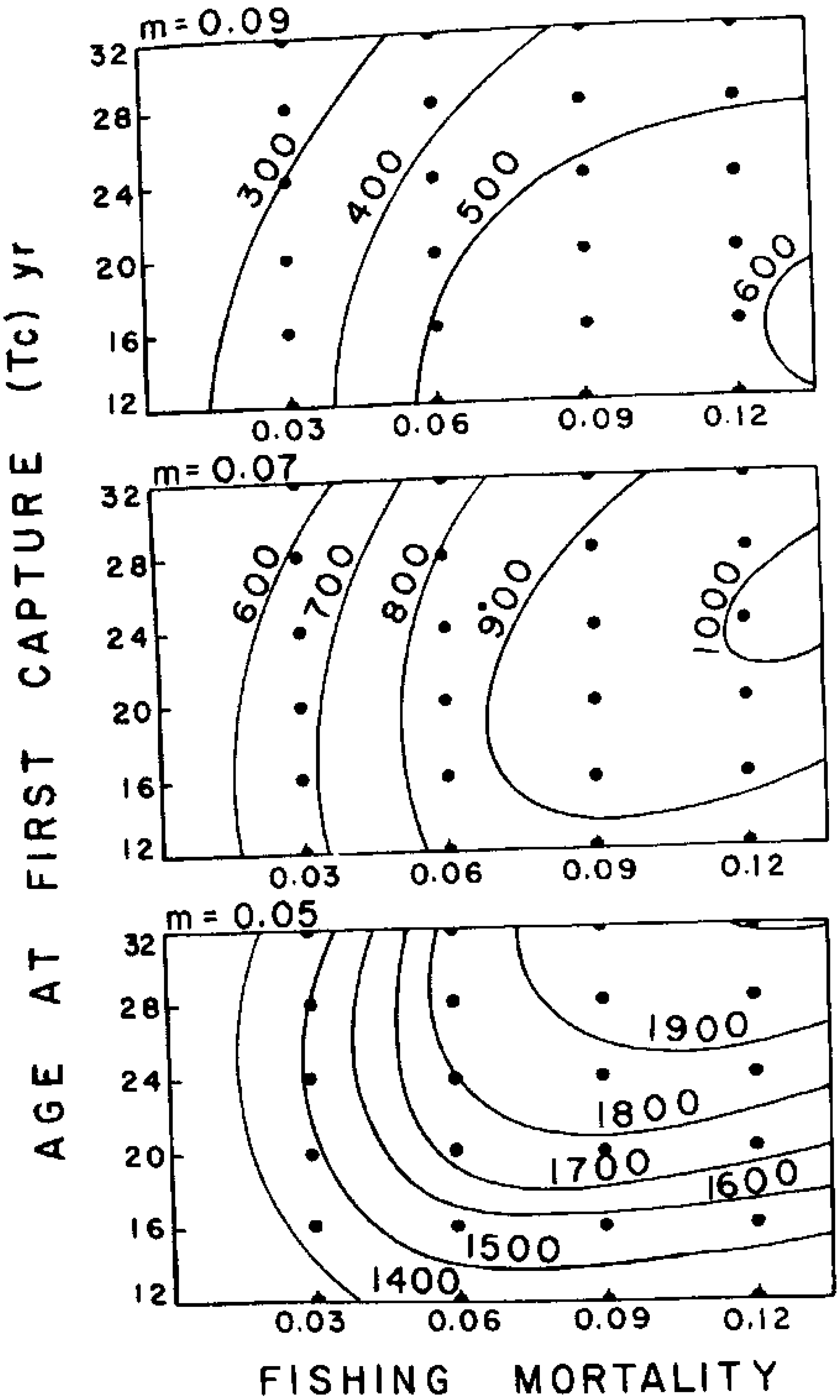

Figure 12. Yield-isopleth diagrams for *A. dichotoma* at different values of m in the Auau Channel. Contour units are grams per recruit.

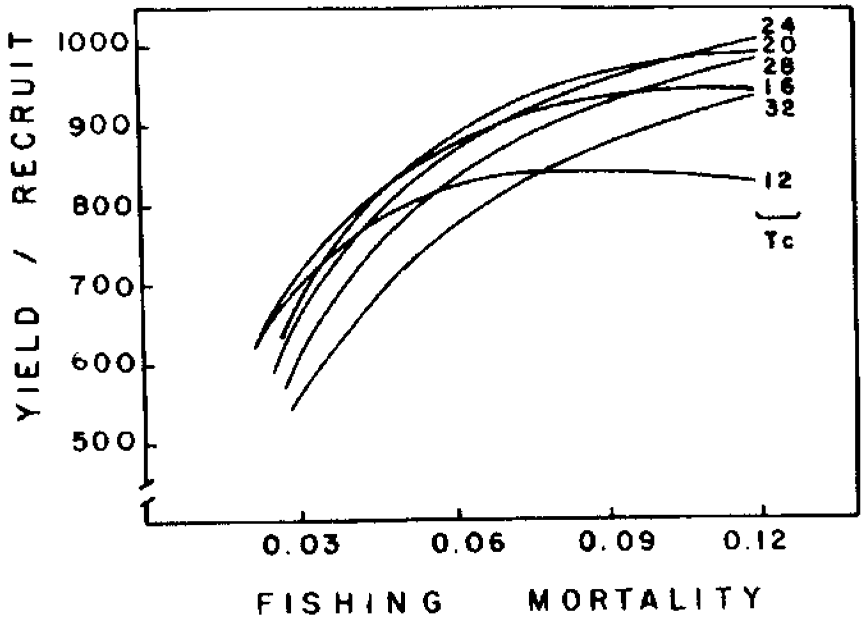

Figure 13. Plots of yield per recruit for *A. dichotoma* as a function of fishing mortality showing the effect of age at first capture (Tc).

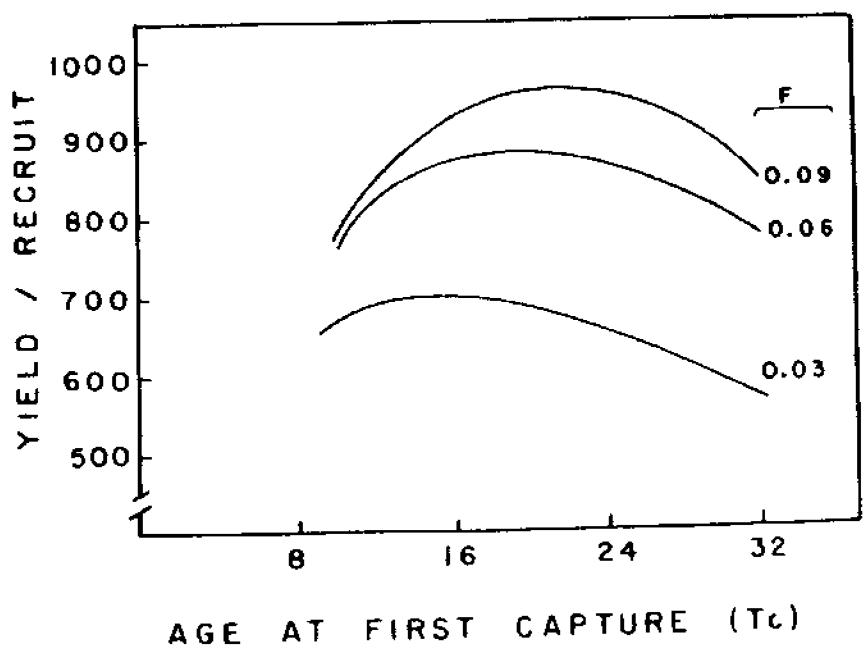

Figure 14. Plots of yield per recruit for *A. dichotoma* as a function of age at first capture showing the effect of different rates of fishing mortality (F).

Figure 15. Oocytes of *A. dichotoma*; largest cells are 100 micra.

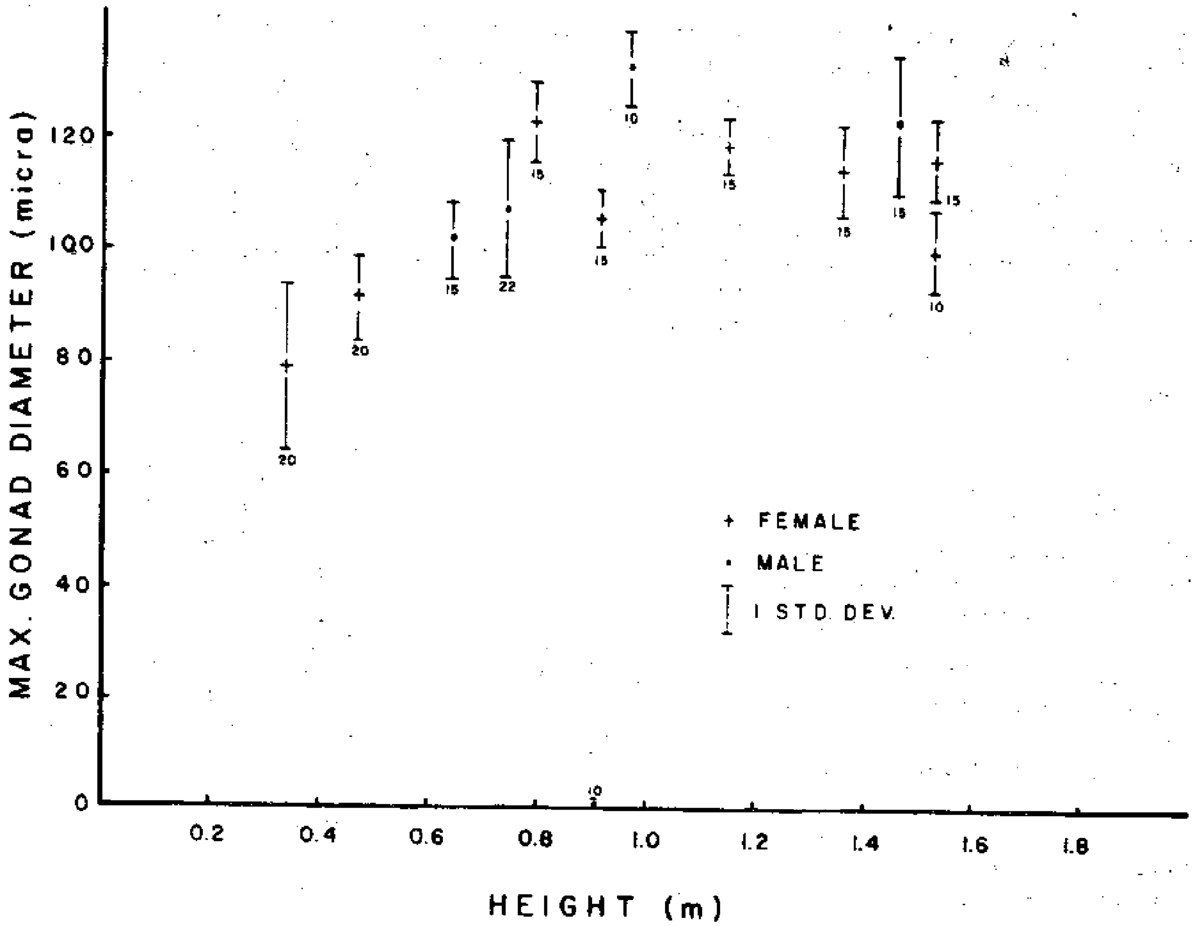

Figure 16. Relationship between maximum gonad diameter and colony height of *A. dichotoma*. Colonies were collected in July of 1974.

Returning to the question of size or age limit, a size of 1.2 m (about 4 ft) or 20 years would allow about 8 to 10 years for reproduction to occur. There is no precise way of knowing if this reproductive "cushion" is adequate to sustain production. Rather, it is a question that must be answered empirically. From past field observations, it would appear adequate since the rate of recruitment on some reefs which have been heavily harvested does not appear to have diminished. However, this may in part be due to the fact that a good fraction of the population of *A. dichotoma* exists below the present limits of scuba (about 75 m) and is therefore inaccessible. The segment of the population below 75 m may represent a reservoir for recruitment. If advances in future technology were to "expose" this portion of the population to the fishermen, a minimum size larger than 1.2 m may be more appropriate.

Landings and resource management

The amount of black coral landed in Hawaii annually primarily depends on local consumer demand. In 1970, a survey revealed that about 85 percent of local black coral jewelry sales were to tourists (Poh, 1971). Poh also presented data showing that visitor expenditures increased at an average annual rate of 18 percent between 1959 and 1969. This trend has continued in recent years although at a much less dramatic pace. Reported annual landings of black coral (*A. dichotoma* and *A. grandis*) between 1963 and 1970 averaged about 3,000 kg (6,360 lb) (Poh, 1971). Personal communication by the author with the industry reveals that since 1970, total annual landings have varied from about 5,000 to 7,000 kg (10,000 to 15,000 lb). These figures are very close to estimates of the combined MSY in the Auau Channel and off Kauai. The resources on other islands have not been included in the above calculation because they do not represent substantial quantities.

Because it appears likely that demand for black coral will continue to increase, some form of resource management may be necessary. While establishing an annual quota based on MSY is logical from the standpoint of conserving the resource, it may be very difficult to enforce. Divers may stockpile landings and/or attempt to create an export market. A more practical approach would be to establish a size limit.

A reasonable size limit would prevent the harvest of very small colonies and their sale as "displays" on the curio-collector market. As mentioned in the introduction, this activity is increasing, especially in Lahaina, Maui, and poses a potential threat to the jewelry industry.

If the size limit is sufficiently greater than the size at reproductive maturity, a protected period for reproduction is assured. This period is sometimes referred to as a reproductive cushion.

A size limit of 1.2 m (4 ft) in height, which corresponds to a basal stem diameter of 2.5 cm (1 in.) and 20 years of age, is recommended because (1) it is close to a level of maximum yield in the production model; (2) it appears to provide for an adequate reproductive cushion; and (3) it maximizes socioeconomic benefits. If a height of 1.2 m were introduced into the production model, an equilibrium yield of about 5,000 kg (11,000 lb) is produced for the Auau Channel population. This is close to maximum yield which, as predicted by the model, is 6,174 kg and occurs at a size limit corresponding to 28 years. Socioeconomic benefits are maximized at a size limit of 1.2 m in height and/or 2.5 cm in stem diameter because a minimal disturbance to present fishing practices is created and because a reasonable compromise between reproductive requirements of the species and economic efficiency is achieved. Thus, a size limit of 1.2 m and/or 2.5 cm would accomplish two things: it would eliminate the taking of immature "display" colonies and it would appear to produce an optimum sustainable yield.

Since a large fraction of colonies larger than the 1.2 m/2.5 cm size limit has already been harvested throughout the state, the present fishery is now operating close to the recommended size limit. Even so, regulations will inevitably reduce catch per unit of effort in the short term because divers will be unable to harvest display and nearly mature-sized colonies. If, for example, a diver "lands" in an area on the bottom where there are no legal-sized colonies, he will no longer be able to compensate by collecting displays. Therefore, imposition of a size limit may put an upward pressure on the price of raw coral.

Finally, the question of jurisdiction of the resource needs to be considered. Although a portion of the black coral beds in Hawaii exists outside of 3 miles, the fishery is predominantly located inside of this boundary. For this reason, jurisdiction and management of the black coral fishery are the responsibility of the State Division of Fish and Game. Passage of the Fishery Conservation and Management Act of 1976 (PL 94-265), which extends federal jurisdiction outward from the territorial seas of the states to 200 miles and requires management plans for most all commercial fisheries located in this zone, should not directly affect the black coral fishery in Hawaii.

Pink Coral

Distribution and abundance

The distribution, abundance, and depth range of *Corallium secundum* in Hawaii have been described by Grigg (1974a). Briefly, the geographic range extends from Hawaii island to Milwaukee Banks, approximately 3,800 km (2,400 miles). The depth range is generally 350 to 475 m although isolated colonies have been observed as shallow as 230 m. The pattern of distribution is extremely patchy. Commercial concentrations have only been found in areas exposed to strong bottom currents. Such areas at the southeastern end of the chain are limited to channels between the islands. The Makapuu bed, for example, lies at the apex of the 200-fathom contour on the Oahu side of the Molokai Channel. Bottom currents in the Makapuu "bed" are bi-directional and range between 0 and 150 cm/sec (0 and 3 knots). While other beds exist, at this writing the Makapuu bed is the only significant source of *Corallium* under exploitation in the Hawaiian Islands.

Television camera surveys and observations from the submersible, *Star II*, indicate that the areal coverage of the Makapuu bed is 3.6 km^2. The density of *C. secundum* within the bed varies between about 0.01 and 0.05 colonies/m^2. Data based on videotape records and submersible observations are summarized in Table 4. Videotape records which reflect higher values than submersible observations are probably too high by a factor of two since they undoubtedly include colonies of *Dendrophyllia* which in some areas are equally abundant and very difficult to distinguish from colonies of *Corallium*. Because the observations from the submersible are considered more reliable, the mean of the density estimates (0.022 colonies/m^2) is used to calculate the standing crop of the entire bed.

Extrapolation of the mean density over the entire bed gives a standing crop estimate of 80,000 colonies. The 95 percent confidence limits of the standing crop are 47,000 to 111,000 colonies. Conversion of the mean standing crop of colonies to biomass required multiplication of abundance by the weight of colony of mean age (300 gm). This procedure produced an estimate of 26,000 kg (57,000 lb) for the standing crop of *C. secundum* in the Makapuu bed.

TABLE 4. DENSITY OF *C. SECUNDUM* IN THE MAKAPUU BED

Transect	Date	Density of *C. secundum* (colonies/m^2)
TV-I	01-26-71	0.05
TV-II	01-27-71	0.04
TV-III	03-25-71	0.12
Star II Dive 5	10-01-71	0.009
Star II Dive 5	10-01-71	0.015
Star II Dive 5	10-01-71	0.005
Star II Dive 5	10-01-71	0.012
Star II Dive 7	10-28-71	0.035
Star II Dive 7	10-28-71	0.034
Star II Dive 7	10-28-71	0.029
Star II Dive 7	10-28-71	0.028
Star II Dive 7	10-28-71	0.032

Growth

As mentioned in the section on methods, it was not possible to collect repetitive measurements of growth for *C. secundum*. Therefore, an equation for size versus age was developed by using growth rings which are assumed to form annually. The data for 29 colonies of various height are presented in Figure 17. The best (least squares) fit to the data is:

$$Y = 2.63 + 0.89\ X \qquad (6)$$

where:

Y = colony height (cm)
X = number of growth rings

This equation suggests that after the first several years growth in height is linear and proceeds at a rate of about 0.9 cm/yr. However, as is the case with *A. dichotoma*, a considerable amount of variability around the best fit curve exists. The variability may be due to growth and/or ring formation. In fact, only 61 percent of the variability is accounted for by fitting the above equation to the data. It is clear that using an equation for growth based on growth rings is not a very precise method. Unfortunately, it is the only one available. An analysis of bomb carbon (C^{14}) was conducted but was so imprecise that one can only say that cores of large colonies are greater than 10 years of age (Buddemeier, 1973: personal communication). While this does not shed much light on the problem, it at least fits with ages that would be given by dividing the height of large colonies by the growth rate.

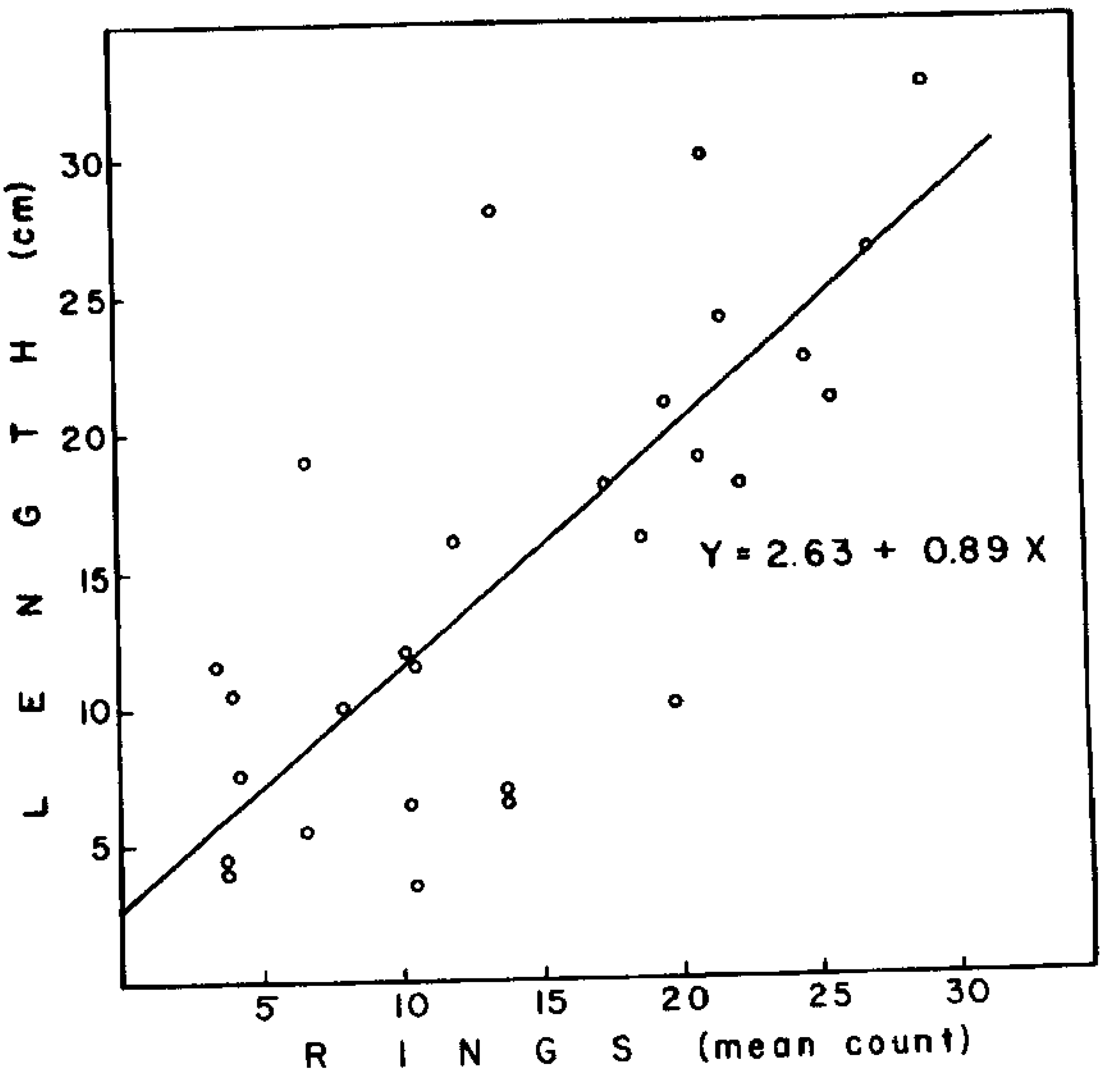

Figure 17. Relationship between colony height (length) and growth rings for *C. secundum*. Each data point represents the mean of four independent counts.

Age structure

The size-frequency distribution of *C. secundum* in the Makapuu bed, obtained by scaled visual estimates of colony heights, was converted to an age-frequency distribution by dividing by a growth rate of 0.9 cm/yr (Table 5).

Similar to the black coral example, there is an underrepresentation of very young colonies. Again this is believed to be an artifact of small colonies having been overlooked. The gradual diminution in number of colonies in the older age categories suggests that age structure is relatively stable and that the assumption of steady state in order to calculate

TABLE 5. AGE-FREQUENCY DISTRIBUTION OF *C. SECUNDUM*

Age Group	No. of Colonies
0-10	44
10-20	73
20-30	22
30-40	12
40-50	7
50-60	0

natural mortality is not unreasonable. Normally natural mortality is calculated on age classes *after* recruitment has been completed, so as not to introduce an error from having missed young colonies. In this case, because the data are grouped into categories representing 10 years, natural mortality was calculated twice, first using all the data and second using only the data after recruitment had been completed. The reason year classes are grouped as to avoid being more precise than the data warrant, considering the apparent variability in the growth rate.

The two expressions of the regression of the natural logarithm of N over time are as follows:

$$Y = 4.49 - 0.055\ X \qquad (7)$$

$$Y = 5.24 - 0.077\ X \qquad (8)$$

where:

Y = the natural logarithm of N at time X
4.49 and 5.24 = the natural logarithm of recruitment
0.055 and 0.077 = the rates of instantaneous mortality

The two estimates of natural mortality are fairly close. In fact, because age 10 is probably too long to wait before considering recruitment complete, the best estimate of m that can be obtained from these data is probably an intermediate value. Therefore, for purposes of calculating yield, a value of 0.066 is used.

Yield

Before a yield curve for *C. secundum* can be generated, it is first necessary to present the best fit equation generated by curve fitting length-weight data, which is:

$$Y = 0.8\ X^{2.27} \qquad (9)$$

where:

Y = colony weight (gm)
X = colony height (cm)

Like *Antipathes dichotoma*, weight is more closely related to the square than the cube of the length.

Yield or production curves were generated using equations (6) and (9) for growth and natural mortality coefficients of 0.055, 0.066, and 0.077 (Figure 18). The results share several similarities with the production of *A. dichotoma*. Perhaps this is to be expected since their life history phenomena are very similar. First, it is clear that a small change in natural mortality makes a relatively large difference in yield. Second, it is not likely that the rate of natural mortality deviates more than ± 0.01 since to do so would produce asymptotic colonies inconsistent with colonies observed in nature. This may seem surprising; however, because of the longevity of these animals, those differences in annual recruitment and age specific mortality that do exist tend to offset one another. For this reason, the estimates of natural mortality of both *A. dichotoma* and *C. secundum* are probably quite accurate.

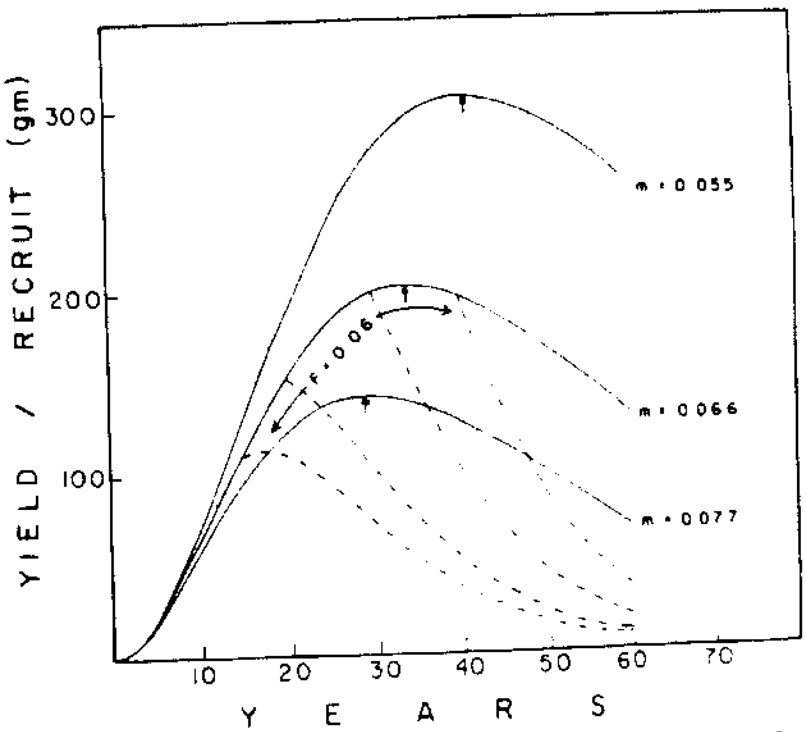

Figure 18. Yield curves for *C. secundum* at different rates of natural mortality (solid line). Dashed lines represent yield-curves of a cohort subject to a natural mortality of 0.066 and a fishing mortality of 0.06 beginning at different ages of first capture. The vertical arrows below each solid line signify the maximum yield per recruit with no fishing mortality.

Maximum yields per recruit at the different rates of natural mortality are given in Table 6.

TABLE 6. NATURAL MORTALITY AND YIELD PER RECRUIT FOR *C. SECUNDUM*

Mortality Coefficient	Yield Per Recruit (gm)	Age at Maximum Yield Per Recruit
0.055	306	41
0.066	203	34
0.077	143	29

Following the same procedure used in the black coral example, if the size of the population and the recruitment rate (if steady state, same as mortality rate) are known, then the values of maximum yield per recruit can be used to calculate potential maximum sustainable yield. The word potential is inserted because of the implicit assumption that harvesting will not diminish future recruitment. The calculations are as follows:

1. 80,000 x 0.055 x 306 = 1,346 kg (2,962 lb)
2. 80,000 x 0.066 x 203 = 1,072 kg (2,358 lb)
3. 80,000 x 0.077 x 143 = 880 kg (1,936 lb)

The middle value (1,072 kg) indicates that about 1/26 of the standing crop of the virgin fishery (26,000 kg) can be harvested each year. This is an estimate of the maximum potential sustainable yield. It is the amount entering the fishery each year at age 34 which corresponds to a size of about 30 cm (1 ft). To catch this amount would require setting a size limit of 30 cm and harvesting every colony equal to or larger than this amount each year. In practice this would require infinite fishing effort. It is more realistic to consider the consequences of fishing at a lower effort.

Yield-isopleth diagrams show the yield per recruit of a virgin fishery at various levels of fishing mortality (effort) and age at first capture (Figure 19). Plotting each variable separately as a function of the other is also useful (Figures 20 and 21). The most economical strategy is to fish light and early, that is harvest younger colonies. For example, at a natural mortality level of 0.066 in combination with a fishing mortality equal to 0.06 and an age at first capture of 20 years, the yield per recruit is 150 gm. Given 5,280 recruits (80,000 x 0.066), the maximum yield would be about 800 kg (1,700 lb), which is not much different than 1,000 kg in the above example. A number of combinations such as this can be worked out, but all are somewhat less than 1,000 kg/yr, which in this sense might be considered an estimate of the upper limit. A consideration of age at reproductive maturity is necessary to determine what a reasonable age at first capture might be.

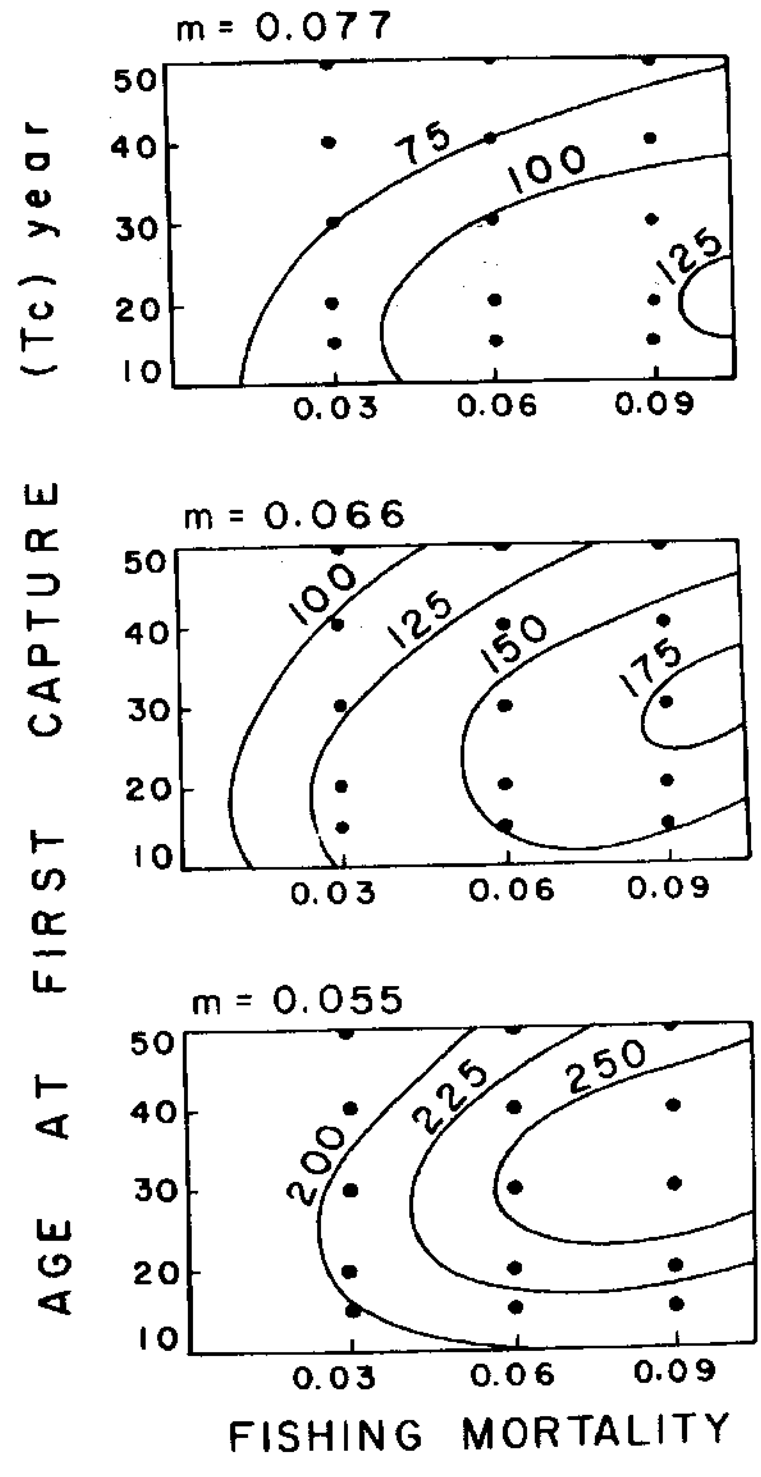

Figure 19. Yield-isopleth diagrams for *C. secundum* at different values of m. Contour units are grams per recruit.

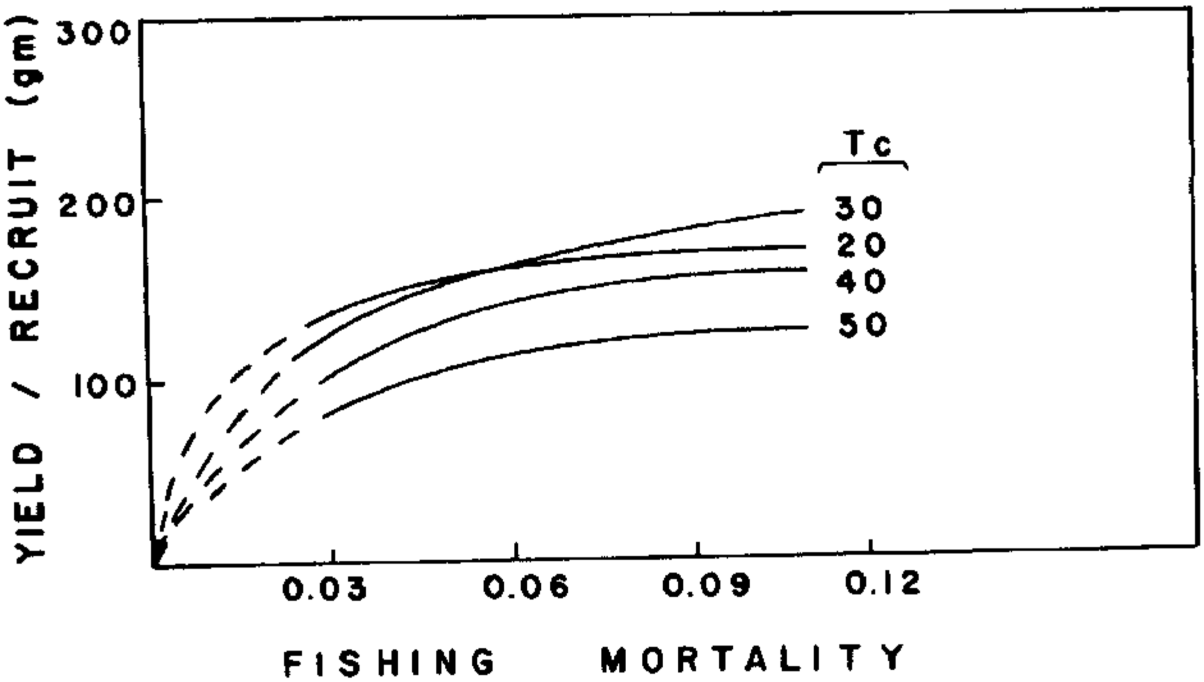

Figure 20. Plots of yield per recruit for *C. secundum* as a function of fishing mortality showing effect of different ages at first capture (Tc).

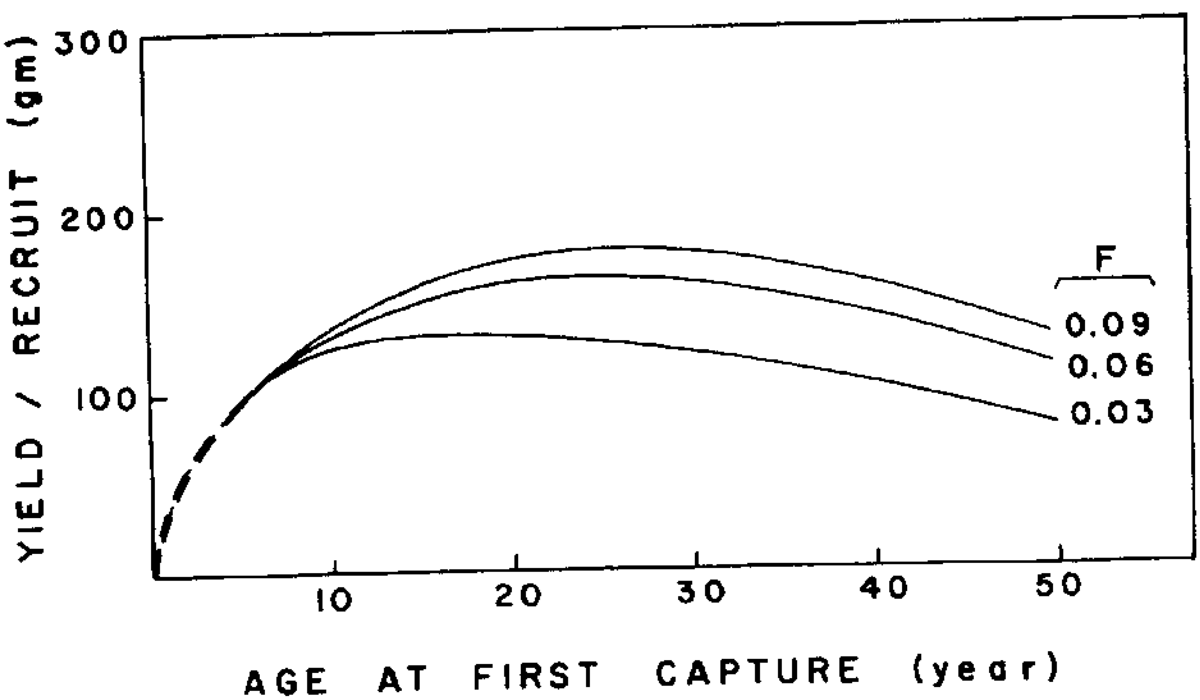

Figure 21. Plots of yield per recruit for *C. secundum* as a function of age at first capture showing effect of different rates of fishing mortality (F).

Age at reproductive maturity

The reproductive cycle of *C. secundum* is considered first. It has been mentioned that the industry provided samples every month for 1 year. In Figure 22, the maximum diameters of the gonads present in each sample are plotted according to the time of year they were collected. From this figure it is immediately clear that (1) the reproductive cycle is annual; (2) sexes are separate (male = 0, female = +); (3) the largest oocytes are about 600μ before spawning; and (4) spawning appears to take place between June and July.

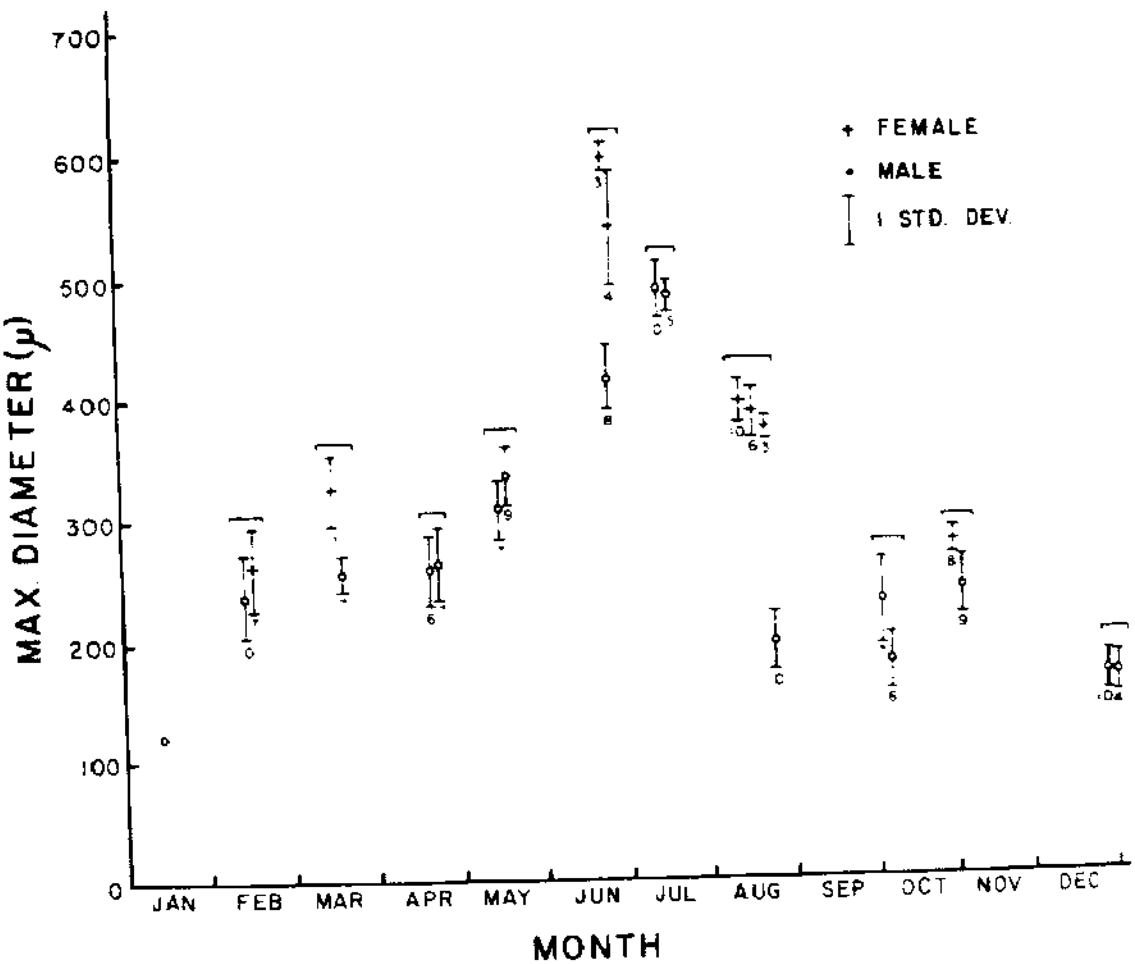

Figure 22. Annual reproductive cycle of *C. secundum* showing the size of the maximum diameter of the gonads at monthly intervals for 1 year. The number of polyps examined in each colony is indicated below the bar limits which represent one standard deviation for the gonad measurements.

Having established the pattern of the reproductive cycle, the relationship between size and reproductive maturity can be examined. Unfortunately, the samples analyzed for this purpose were collected in April before any of the colonies reached sexual maturity. Gaging from Figure 22, gonads or spermaries between 230 and 300μ were considered mature for this stage of development. In the April collection the smallest colony with gonads of this size was 12 cm high (Figure 23) or about 13 years old, not unlike the results obtained for *A. dichotoma*. It is clear that more data are needed to pin down age at reproductive maturity more precisely. At this time perhaps the best strategy would be to set the age at first capture fairly high, say at the level of maximum yield per recruit (MYR) for a mortality coefficient of 0.066. This would require setting a size limit of 30 cm (12 in.) and would allow about 1,000 kg (2,200 lb) to be harvested annually.

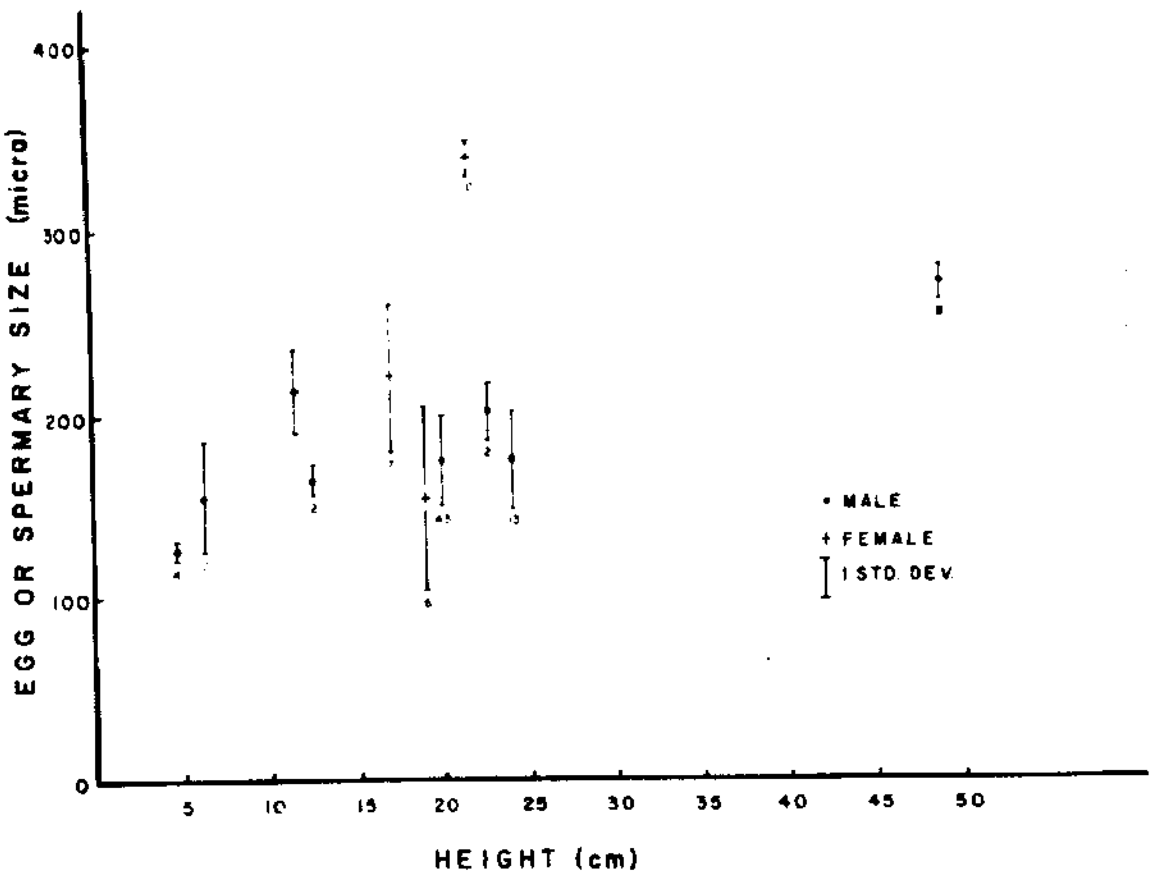

Figure 23. Relationship between maximum gonad diameter and colony height for *C. secundum*. The number of polyps examined in each colony is indicated below the bar limits. Collection was made on April 4, 1975.

Landings and resource management

As with black coral, the major source of consumer demand for pink coral is tourists. The breakdown between tourist and resident consumer spending is about 70:30 (Poh, 1971). With both the visitor and local populations as well as their expenditures increasing, a trend of gradually increasing demand for pink coral can be expected.

The recent past history of the pink coral industry in Hawaii has been described (Grigg, 1970; Poh, 1971; Grigg et al., 1973; Grigg, 1974a). Briefly, after its discovery in 1966 off Makapuu, Oahu, a small number of fishermen began dredging for the resource on a limited scale. This activity continued on and off for about 3 years until high costs of operation and bad weather led to its discontinuation. About 1,800 kg (4,000 lb) were harvested during this period. After an abortive attempt in 1969 at harvesting with a remote TV camera assembly by a Seattle firm (the Jacobsen brothers), research by the Sea Grant Program at the University of Hawaii led to the development of a harvesting system utilizing a submersible. This approach proved to be economically feasible and was incorporated by the local industry in late 1972.

Since 1972, Maui Divers of Hawaii Ltd. has been harvesting *C. secundum* in the Makapuu bed. Landings over the past 3 years have averaged about 1,200 kg, slightly greater than the most probable estimate of maximum yield. It is not surprising that early landings have been higher than the estimated maximum yield. This is because large, old colonies are initially more abundant in a virgin or unfished population. As they are gradually harvested, yield depends more on production entering the fishery at the age of first capture.

Maximum yield on the most probable m curve (0.066) is about 1,000 kg/yr and occurs at an age of 34 which corresponds to a size of about 30 cm (12 in.) (Figure 18). Setting a size limit of 30 cm should insure an adequate reproductive cushion for sustained recruitment. If so, this size limit should produce a MSY of about 1,000 kg in the Makapuu bed. Both a 30-cm size limit (height) and a 1,000-kg annual quota are recommended regulations for the harvest of *C. secundum* in the Makapuu bed.

At the present time, there is no need to limit entry since this is accomplished quite naturally by the high capitalization costs of operating a submersible. More useful would be the prohibition of all forms of dredging for precious coral since dredging is highly destructive of the habitat.

The question of jurisdiction requires further elaboration. While it is clear that the Exclusive Fishing Act of 1966 allows the federal government to promulgate regulations and gives the states authority to regulate the activity of its citizens in the contiguous zone, the depth of the pink coral resource (400 m) raises some question as to whether or not it is in the contiguous zone, even though it may be between 3 and 12 miles offshore. Under the Bartlett Act (Public Law 88-308 as amended), *C. secundum* is defined as a creature of the continental shelf, the depth limit of which is generally agreed to be 200 m. However, the wording of the 1958 Geneva Convention on the Continental Shelf defines its depth limit as "200 m., or beyond that limit, to where the depth of the superjacent waters admits of the exploitation of the natural resources of the said areas...," which permits the interpretation that exploitation of the resource, in fact, establishes a jurisdictional base even though it exists at 400 m.

On March 1, 1977, federal jurisdiction over creatures of the continental shelf will be extended from 3 to 200 miles, or beyond that distance in areas where the continental shelf is wider than 200 miles. As far as depth is concerned, under the act (PL 94-265) the continental shelf is defined as 200 m, but the same interpretation referred to above for exploited resources below 200 m still applies. Since precious coral fishing in Hawaii is predominently outside of the state's territorial sea but inside of 200 miles, formulation of a management plan should be the responsibility of the Western Pacific Regional Council. Resources both deeper than 200 m and outside of 200 miles in the Hawaiian Archipelago may be included in the management plan if they are exploited by U.S. fishermen.

MANAGEMENT PHILOSOPHY

It should be re-emphasized that the management plans developed in this report are based on equilibrium models which require assumptions of steady-state recruitment, growth, and natural mortality of fishery stocks. While such a model is relatively well suited to certain species of precious coral, because of their great longevity and relatively stable population dynamics, it is equally important to emphasize the well-recognized fact that nature is "never" static but rather an ever-changing dynamic paradigm.

In the models developed in this report, the accuracy of prediction with regard to yield is inversely related to the variability of recruitment, growth, and mortality of particular stocks. The variability of these parameters for species investigated here appears to be small. Even so, it may be useful if not necessary to convert the static models presented in this report to dynamic models in the future. This can be done if time lags are taken into account, by introducing into the models, year specific estimates of recruitment, growth, and mortality. Of the three parameters, recruitment would be expected to be by far the most variable and therefore the most important to monitor. The problem of time lags, especially for longevous species, reduces the flexibility of the model for management purposes. Even so, should significant changes in population dynamics of one or another species occur in the future, it may be necessary to adjust the parameters of the model accordingly. In this way the management plans based on cohort production models can be adjusted to more accurately predict future yields.

SUMMARY AND RECOMMENDATIONS

Stony corals

1. The most common species of stony corals harvested and sold in Hawaii, in order of importance, are: *Pocillopora meandrina, P. damicornis, Fungia (Pleuractis) scutaria, Porites lobata,* and *Montipora verrucosa.*

2. No species of endemic stony coral at this time appears to be in jeopardy of overexploitation; however, small colonies of *P. meandrina, P. damicornis,* and *F. (Pleuractis) scutaria* are preferred for a number of reasons and can be locally depleted.

3. Recommendations for future management of these resources include:

   a. Amendment of Act 107 to only refer to dead coral--this will legalize present fishing practices and enable the State Division of Fish and Game to manage the resource

   b. The requirement of a commercial fishing license for all commercial coral harvesters

   c. A requirement that all buyers furnish a third copy of receipts for all purchases, indicating the identity of the person selling

   d. The collection of catch and effort statistics by the State Division of Fish and Game

   e. Contingent upon significant expansion of the fishery, a minimum size limit well above the size of reproductive maturity for respective species

   f. A public information program to educate coral harvesters and sellers of existing laws

   g. A program to monitor harvested reefs and more research on the reproductive biology and population dynamics of exploited species

Black coral

1. The known geographic distribution of *A. dichotoma* and *A. grandis* is between the big island of Hawaii and Niihau, but most probably extends throughout the leeward islands. The depth ranges are 30 to 110 m and 45 to 110 m, respectively.

2. Abundance of both species appears to be positively correlated with the size of the habitat.

3. Field measurements show that average rates of increase in height of *A. dichotoma* and *A. grandis* are 6.42 cm/yr and 6.12

cm/yr, respectively. Both field measurements and growth ring analysis indicate that the patterns of growth are constant and indeterminant. The periodicity of ring formation in *A. dichotoma* appears to be annual.

4. Sexes are separate in *A. dichotoma*. Reproductive maturity appears to be reached at an age roughly between 10 and 12.5 years. There is a suggestion that the reproductive cycle is annual.

5. The standing crop of *A. dichotoma* in the Auau Channel is estimated to be 166,000 kg; four times larger than the estimate for the Kauai grounds (about 40,000 kg).

6. A yield per recruit curve is presented for *A. dichotoma*. Yield is calculated as the product of natural mortality and growth of a cohort each year over its longevity. The "top of the curve" or maximum yield per recruit is the point at which mortality-losses overtake growth-gains. Assuming steady state, this value can be multiplied by estimates of absolute recruitment to, in turn, produce estimates of maximum yield which range between about 4,500 and 8,800 kg for the Auau Channel population. If fishing activity does not diminish recruitment, the maximum yield will be sustainable.

7. Estimates of optimum sustainable yield based on current practices of the fishermen, economics, and reproductive requirements are also given. Fishermen now generally harvest colonies of black coral larger than about 1.2 m (4 ft) in length. This limit is set somewhat naturally by the economics of the fishery. First, buyers don't like buying coral smaller than this because most of it is unusable for jewelry. Second, fishermen may spend as much time harvesting a small colony as they do a large one. Dives are time-limited because of risks associated with the bends. Considering the expenses and the risks of diving, it doesn't "pay" to take colonies smaller than about 1.2 m (4 ft) for the jewelry market. However, the display market pays much more per pound for smaller colonies. A nicely shaped display colony weighing one pound might bring $50 or more, compared with $10 for coral sold to the jewelry market. Because the display market provides an incentive to harvest immature colonies, its prohibition is strongly recommended.

   The relationship between age at first capture and fishing effort is such that the most economical strategy is to fish lightly and catch the coral at an early age. This simple strategy, however, does not take into account the reproductive requirements of *A. dichotoma*. Since harvesting may adversely affect recruitment, the age at reproductive maturity must be considered. Empirical evidence of recruitment of *A. dichotoma* on harvested reefs off Maui indicates that recruitment there is occurring at a sustainable rate, suggesting that the current height limit of 1.2 m (4 ft) set by the economics of the jewelry industry can be considered optimum and sustainable. This would require setting formal size limits of 1.2 m (4 ft) in height and/or 2.5 cm (1 in.) in stem diameter. The establishment of these size limits, then, accomplishes two things: it eliminates the taking of immature "displays" and appears to produce an optimum sustainable yield, which in this case is about 5,000 kg (11,000 lb) for the Auau Channel population and 1,250 kg (2,750 lb) for Kauai.

Because the black coral fishery is located predominantly inside of 3 miles, jurisdiction and management are responsibilities of the state. The extended jurisdiction bill (PL 94-265) is not expected to directly affect management of the resource.

8. A final consideration which concerns the asexual reproductive behavior of *A. dichotoma* may have important implications for future management of the fishery. Asexual reproduction occurs naturally by way of fragmentation of branch ends. It is not known what causes branch tips to fragment, nor is it now possible to quantify this process in terms of recruitment. Nevertheless it may be possible to take advantage of this behavior by artificially fragmenting large colonies and "replanting" the branches. In practice, it might be possible to transport a colony to a depth just below the surface where divers could systematically remove all branch ends. If an inert weight were attached to the bases of the branches, they might be dropped from the surface over areas of suitable depth and substrata. This practice would represent no loss to the jewelry industry since small branches of less than 1/8 inch in diameter are discarded as waste anyway. Pruned colonies, of course, would necessitate a higher price to the fishermen so as not to diminish their profits. While artificial seeding as a tool for resource management may seem far-fetched, the method is sufficiently intriguing to warrant an experimental trial and could easily be tested on a small scale.

Pink coral

1. *Corallium secundum* is found throughout the Hawaiian Archipelago at depths between 350 and 475 m.

2. The only "bed" of *C. secundum* under exploitation is situated in the Molokai Channel off Makapuu, Oahu. The standing crop of the bed is estimated to be 26,000 kg (57,000 lb).

3. A growth equation is developed on the assumption of annual ring formation.

4. The reproductive cycle of *C. secundum* is annual, with spawning taking place in June or July. Reproductive maturity occurs at a size of about 12 cm or about 13 years old; however, more data are needed to precisely define this parameter.

5. The best estimate of maximum sustainable yield for *C. secundum* in the Makapuu bed is about 1,000 kg annually. This quota should not be exceeded over the long term if a size limit of 30 cm (12 in.) is set. The size limit should also be more than adequate to provide a reproductive cushion (the difference between age at reproductive maturity and the age at first capture) for recruitment. While setting a size limit may accomplish MSY, as a management tool it may not be sufficient by itself because the coral is broken up during collection. Therefore, both a size limit and an annual quota of 1,000 kg for the Makapuu bed are recommended regulations.

6. There is no need to limit entry at the present time.

7. Prohibition against all forms of dredging for precious coral is strongly recommended.

8. A jurisdictional base for management of the pink coral fishery by the United States has been established by the 1958 Geneva Convention on the Continental Shelf. On March 1, 1977, federal jurisdiction over creatures of the continental shelf will be extended from 3 to 200 miles and beyond where continental shelves are wider than 200 miles. Since the pink coral fishery is predominantly outside of the state's territorial sea, its management should become the responsibility of the Western Pacific Regional Council.

9. The recommendations given for stony corals concerning a third receipt requirement for purchases, catch-effort statistics, a public information program, and more research also apply to commercial species of black and pink corals in Hawaii.

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