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Exploratory Shrimp Trawling in the Hawaiian Islands

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ABSTRACT—The results of exploratory shrimp trawling in the Hawaiian Islands during six cruises of the RV Townsend Cromwell *are given. One species of shrimp,* Penaeus marginatus, *was found in quantities thought sufficient to sustain a small trawl fishery. Average catches in the four most productive areas ranged from 4.7 to 31.0 pounds (2.1 to 14.1 kg) per hour (heads-on weight) with a single 41-foot (12.5-m) shrimp trawl. Evidence is presented that individual shrimp move offshore into depths of 100-125 fathoms (185-230 m) during daytime, with most individuals returning to shallower depths of 35-100 fathoms (65-185 m) during night. Optimum trawling speed was between 2.3 and 3.0 knots with best catches being made at 2.5-2.8 knots. The size of the shrimp at most stations ranged from 16 to 19 individuals per pound (heads-on). In any given depth range the females tend to be larger than males. In depths greater than 100 fathoms (185 m) the males are 3-4 times more numerous than females. Small amounts of shrimps of the genera* Heterocarpus, Aristeus, Pandalus, *and* Pleisioneka *were taken in depths of 150-385 fathoms (275-705 m), but never in quantities sufficient to justify the sorting effort required. Catches of white crabs ranged up to 30 pounds (13.6 kg) per tow, while incidental catches of slipper lobsters, spiny lobsters, and kona crabs were also made.*

Figure 1.—A portion of a catch of *Penaeus marginatus* trawled in the Hawaiian Islands.

During the 1902 expedition of the U.S. Fish Commission's steamer *Albatross* to the Hawaiian Islands, large specimens of the penaeid shrimp, *Penaeus marginatus* Randall (Fig. 1), were taken with beam trawls in Pailolo Channel at depths of 122-141 fathoms (220-255 m) (Rathbun, 1906). Because contemporary charts indicated that Pailolo Channel and other areas of the Hawaiian Islands offered moderate amounts of grounds that might be trawlable in depths presumably inhabited by adult *P. marginatus*, the National Marine Fisheries Service (NMFS), in cooperation with the Hawaii Institute of Marine Biology, conducted four exploratory trawling cruises with the RV *Townsend Cromwell* during 1967 and 1968 to assess the demersal shrimp and fish resources of the main group of the Hawaiian Islands (Fig. 2). Yoshida (1972) reported on the shrimp catches for the first three cruises, while Struhsaker (1973) discussed the ichthyological results. The results of these four cruises and subsequent trawl surveys during 1971-72 are summarized here. We conclude from these investigations that *P. marginatus* occurs in sufficient quantities to support a small commercial trawl fishery.

GEAR AND METHODS

Most of the trawling effort during the first four cruises was conducted with 41-foot (12.5-m) headrope 4-seam flat shrimp trawls such as described by Bullis (1951) and Schaefers and Johnson (1957). Similarly constructed trawls with headrope lengths of 27 feet (8.3 m) and 71 feet (21.5 m) were also utilized during the first cruise, as was a 71-foot headrope fish trawl (Greenwood, 1958).

Trawling surveys conducted during 1971-72 utilized, almost exclusively, 41-foot headrope 4-seam flat and semiballoon shrimp trawls similar to those described by Greenwood (1959), with mud rollers mounted about every three feet (1 m) on the foot rope. A 60-foot (18.3-m) headrope semiballoon

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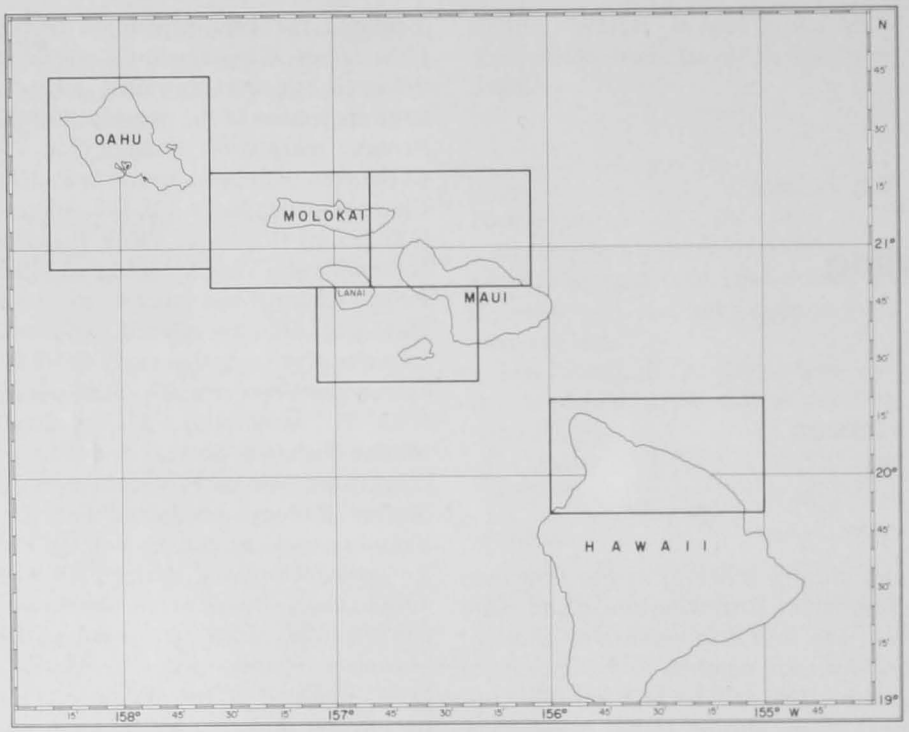

Figure 2.—General areas where trawl surveys were conducted in the main group of the Hawaiian Islands.

shrimp trawl with no mud rollers was briefly tested during fall 1972.

The shrimp trawls were all constructed of 1.5-inch (38-mm) stretched mesh nylon webbing throughout the body and cod end. The foot ropes were weighted with 0.25-inch (6-mm) loop-chain attached at 1-foot (0.3-m) intervals. Tickler chains of 0.25-inch stock were used on all shrimp trawls.

The 41-foot trawls were fished on a single wire with a 15-fathom (27-m) bridle. Although conventional Gulf of Mexico type wooden doors (Bullis, 1951) were tried initially, modified aluminum V-doors as described by Barraclough and Johnson (1960) were used at most of the stations. The aluminum doors were superior to the wooden doors, especially in the deeper sets. The 60-foot trawl was fished with two warps and spread with 7-foot (2.1-m) steel Chinese V-doors.

During the first four cruises, 225 shrimp trawl stations were conducted in the 35-385 fathom (66-705 m) depth range. At 161 stations the 41-foot flat trawl was used and fished correctly with little or no damage. Additional shrimp trawling stations were effected during spring 1971 (23 stations) and fall 1972 (29 stations). Single trawls were fished at all stations and towing times ranged from about 0.5 to 4.0 hours, with most hauls ranging from 1 to 2 hours in duration.

One advantage of deep-water trawling in areas similar to the Hawaiian Islands is that the nearness of the land masses provides fixed geographic reference points for accurate positioning of vessels not equipped with precision navigational systems. Position data are probably accurate to less than 0.1 mile. We considered that a tow began at "dog-off" and ended at the beginning of "haul-back." Although the actual times that the trawl began and ended fishing were not accurately known, it was assumed that the time lags at the start of both operations approximately canceled one another. This assumption is probably valid for shallow waters, but greater variance must be assumed with increased fishing depths. Stations where the gear fished satisfactorily and suffered no damage, or damage so slight that it was considered that the sampling efficiency of the trawl was not affected, were considered to be "quantitative." These stations were used in the calculation of catch rates of shrimp to determine the effects of trawling speed, depth of water, and time of day. For the determination of catch rates per unit area, it was assumed that the 41-foot trawls had an effective sampling width of 23 feet (7 m).

During the first cruise, emphasis was placed on becoming familiar with bottom trawling techniques and gaining an introductory knowledge of the bottom resources in depths greater than 100 fathoms (185 m). Two subsequent cruises during spring 1968 emphasized the exploration of additional areas that might have harvestable populations of *P. marginatus*. During the fourth cruise (fall 1968), four areas where *P. marginatus* was found to be most abundant during the previous cruises were extensively surveyed to determine the availability of the species in relation to the factors of depth and time of day.

Although some gear damage was experienced during all cruises, once the characteristics of the various areas were learned tear-ups were greatly reduced. During the last cruise when 119 trawling stations were effected, only four tows were unsuccessful: one was a water-haul; very light trawl damage was experienced at two stations; and heavy damage was experienced at one station. The last station was an attempt to sample a broken-bottom area in shallow water.

RESULTS

Trawling Areas and Shrimp Catches

The four areas where the best catches of *P. marginatus* were made are discussed first. The catch rates for these areas are summarized in Table 1. Most of the data are for fall 1968 when the greatest number of quantitative stations were made. The results of fishing during spring 1971 and fall 1972 in the Pailolo-Molokai area are also given. All catch weights (heads-on) are for single 41-foot shrimp trawls except for the 1972 samples when a 60-foot shrimp trawl was used. Areas where only small catches of *P. marginatus* were made, or where other species of shrimp were found are also discussed.

Northwest Molokai

Although the northeastern coast of the island of Molokai presents one of the world's most dramatic sea scarps, which continues in places to great depths, the undersea portion of the

northwest coast is a continuation of the low, gently sloping west Molokai Dome until the shelf break is encountered at about 95 fathoms (175 m). West of long. 157°05′W, trawlable bottom extends for about 10 nautical miles (18 km) in depths of 55-95 fathoms (100-175 m) (Fig. 3). The bottom type is muddy sand with moderate amounts of sponge. Although the surveys were restricted to an area estimated to be 5.5 square nautical miles (18.7 km^2), quite possibly this ground could be extended to a greater depth and farther westward.

Of the four most productive areas, northwest Molokai was the shallowest and produced the smallest catches. During fall 1968 the depths sampled ranged from about 65 to 70 fathoms (120 to 130 m). *P. marginatus* was only taken during night tows with catches ranging from 5 to 16 pounds (2.3 to 7.3 kg) per station (Table 1).

Table 1.—Catches of *Penaeus marginatus* with a 41-foot shrimp trawl in four areas of the Hawaiian Islands (heads-on weights).

Area and time	Year	No. of stations	Range of catch per station		Range of catch per hour		Average catch per station		Average catch per hour	
			lb	kg	lb	kg	lb	kg	lb	kg
Northwest Molokai	1968									
Night		9	5-16	2.3- 7.3	2.3- 7.6	1.0- 3.5	10.9	5.0	4.7	2.1
Penguin Bank	1968									
Night		16	11-33	5.0-15.0	5.5-19.4	2.5- 8.8	20.4	9.3	10.8	4.9
Pailolo Channel-Maui	1968									
Night		10	4-35	1.8-15.9	2.4-17.5	1.1- 8.0	15.3	7.0	7.6	3.5
Day		6	2-29	0.9-13.2	1.1-13.2	0.5- 6.0	18.8	8.5	9.5	4.3
Pailolo Channel-Molokai	1968									
Night		7	6-53	2.7-24.1	2.9-23.0	1.3-10.5	23.4	10.6	11.3	5.1
Day		7	33-105	15.0-47.7	17.4-47.7	7.9-21.7	59.1	26.9	31.0	14.1
	1971									
Night		4	23-58	10.5-26.4	11.6-27.2	5.3-12.4	34.8	15.8	18.1	8.2
Day		6	42-75	19.1-34.1	20.8-37.5	9.5-17.0	59.7	27.1	29.8	13.5
Day	1972	10	40-75	18.2-34.1	20.0-37.5	9.1-17.0	55.1	25.0	27.5	12.5

Penguin Bank

An 8-mile (14.8-km) long trawlable area of about 3.0 square miles (10.3 km^2), centered on the 100-fathom (185 m) depth curve between long. 157°22′W and 157°30′W, was located on the north edge of Penguin Bank west of Molokai (Fig. 3). The bottom type is coralline sand and rubble with moderate amounts of sponge and algae. A few subsequent stations during 1971 demonstrated that the depth limits and east-west boundaries of the area sampled may be extended somewhat.

This area was the second shallowest, with most tows being made in the 100-fathom (185-m) depth range. Again, almost all catches of *P. marginatus* were made at night, although frequently a few shrimps were taken during day stations (<1 pound per station). The night catches ranged from 11 to 33 pounds (5-15 kg) per tow (Table 1).

Pailolo Channel

Pailolo Channel, between the islands of Maui and Molokai (Fig. 4), may be likened to a dead-end canyon sloping gently to the northeast with a level floor of muddy sand at depths of 120-130 fathoms (220-247 m). Although the entire channel in these depths is generally trawlable, the best shrimp catches were made in depths of 110-120 fathoms (200-220 m) on the southeast edge of the channel near Maui and on the northwestern edge near Molokai. The "Pailolo Channel-Maui" ground extends from about lat. 21°03.2′N, long. 156°41′W to lat. 20°58.2°N, long. 156°46.3′W, a distance of about 7 miles (13 km), with an area of about 3 square miles (10.2 km^2). The "Pailolo Channel-Molokai" ground extends from about lat. 21°05.5′N, long. 156°42.5′W to lat. 21°01.5′N, long. 156°50′W, a distance of about 8 miles (14.8 km), with an area of about 4 square miles (13.7 km^2).

The better catches of *P. marginatus* were made in the 110-120 fathom (200-220 m) depth range in Pailolo Channel during both day and night hours. Catches on the Maui side of the channel ranged from 4 to 35 pounds (1.8-15.9 kg) during night stations and 2 to 29 pounds (0.9-13.2 kg) during day stations. However, the day stations yielded a higher average catch than the night stations (Table 1).

Stations made during 1968 on the Molokai side of Pailolo Channel produced the best catches of *P. marginatus*. They ranged from 6 to 53 pounds (2.7-24.1 kg) per tow at night and 33 to 105 pounds (15-47.7 kg) per tow during daylight hours (Table 1). During spring 1971, when a 41-foot

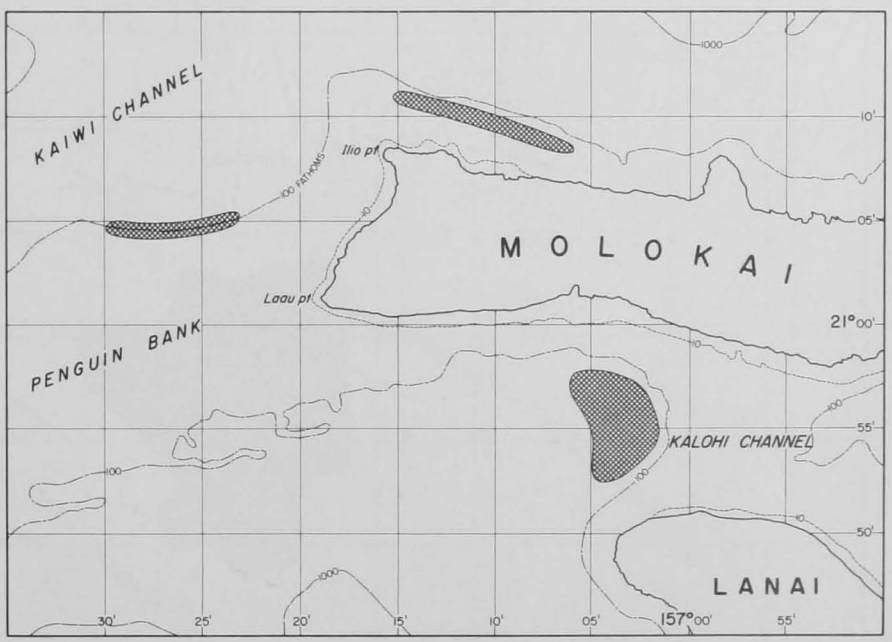

Figure 3.—Trawlable areas (hatched) in the vicinity of west Molokai.

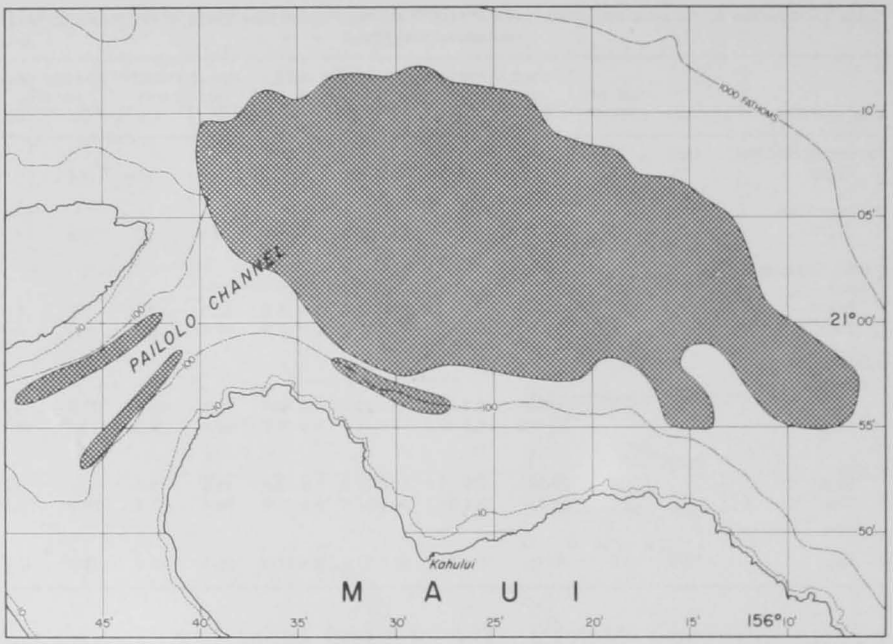

Figure 4.—Trawlable areas in Pailolo Channel and north of Maui.

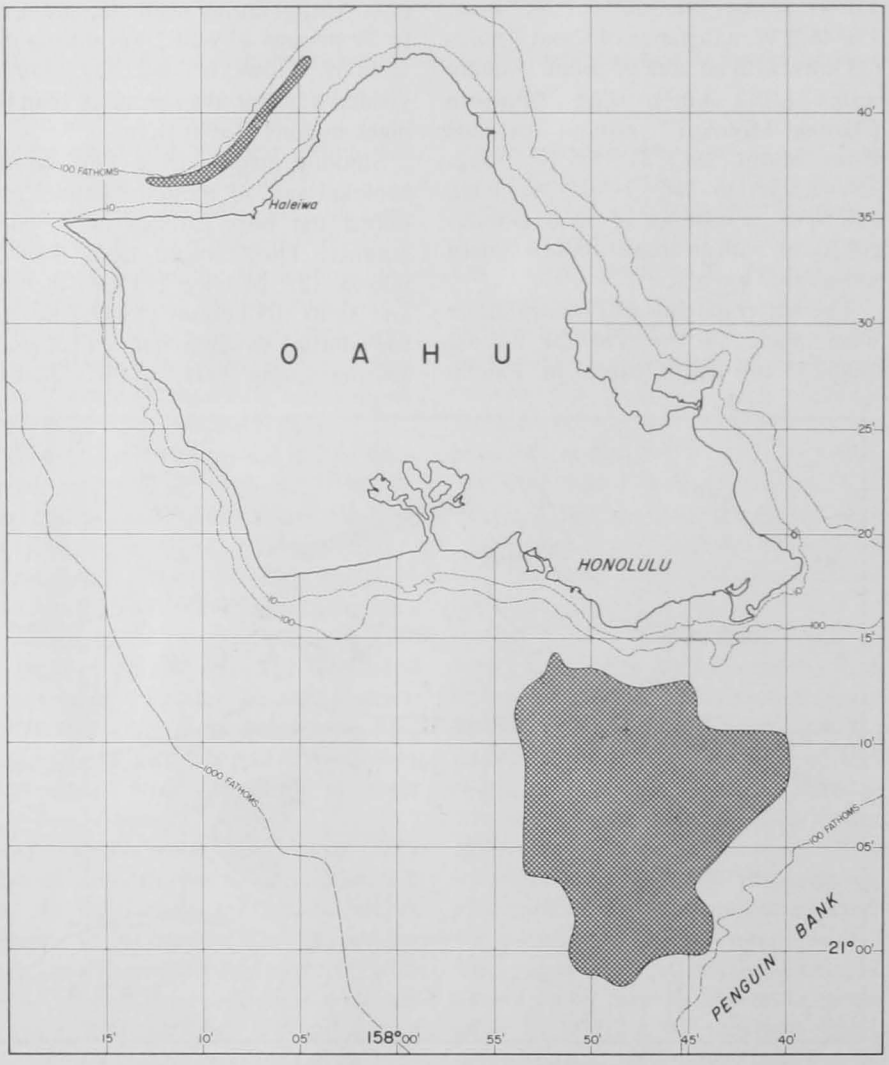

Figure 5.—Trawlable areas near Oahu.

semiballoon trawl with mud rollers was utilized, catches were similar. Night tows at that time produced catches of 23-58 pounds (10.5-26.4 kg), while day tows ranged from 42 to 75 pounds (19.1-34.1 kg). Finally, during fall 1972, 10 daylight stations with a 60-foot shrimp trawl without mud rollers produced catches of 40-75 pounds (18.2-34.1 kg). These stations with the larger trawl produced smaller average catches than the previous sampling with 41-foot trawls, probably because optimum trawling techniques with the gear were not yet fully developed during this series of stations.

Areas where only small catches of *P. marginatus* and other species of shrimp were taken are discussed below.

Haleiwa

Good trawlable bottom was located off the north coast of Oahu in the 55-65 fathom (95-115 m) depth range (Fig. 5) during the cruises conducted in 1968. Smooth sandy bottom extends from due north of Haleiwa northeast to the latitude of Kahuku Point and no trawling difficulties were experienced. A secondary area extends from off Haleiwa westward 5 miles to about long. 158°12'W consisting primarily of smooth sand bottom with some coral and rock outcrops. Trawling was generally successful, but occasional gear damage caused this latter area to be classified as "marginal." Live sponges often made up a large portion of the catches in both subareas.

A few subsequent stations during 1972 demonstrated that trawlable bottom extends out to depths of 120 fathoms (220 m) between Haleiwa and Waimea Bay.

Although substantial sampling was conducted at depths of 55-65 fathoms (95-115 m), catches of *P. marginatus* were made only at night and were considered to be spotty. Catches during fall 1968 ranged from 0.2 to 3.0 pounds (0.1-1.4 kg) per tow. Six night-trawl stations further offshore in depths of 80-120 fathoms (145-220 m) during 1972 produced catches ranging from 3 to 11.5 pounds (1.4-5.2 kg) per hour. Although further delineation of trawlable grounds in the deeper water portions off north Oahu is desirable, it would seem that moderately good catches could be made on a sustained basis.

Maui

An extensive area of trawlable grounds was located off the north coast of Maui (Fig. 4), but most of it lies in depths of 175-350 fathoms (325-650 m), below the depth range inhabited by *P. marginatus*. During the 1967-68 cruises, the bottom off north Maui in depths less than about 150 fathoms (275 m) was classified as only marginally trawlable. Several stations were effected in depths of 35-40 fathoms (65-75 m), resulting in a best catch of 4 pounds (1.8 kg) of *P. marginatus* for a 1-hour tow. Two additional stations made during 1971 indicated that trawlable grounds are present in the 95-120 fathom (175-220 m) depth range. This latter area extends from north of Kahului Harbor west-northwest for about 7 miles (13 km) along the 100-fathom (185 m) curve (Fig. 4). The stations were made during daylight hours and the best catch was 9.2 pounds (4.2 kg) for a 2-hour tow. Further explorations in this area seem warranted.

Kealaikahiki Channel

Good trawlable grounds were located in Kealaikahiki Channel between the islands of Lanai and Kahoolawe (Fig. 6). Approximately half of the area bounded by the 100-fathom (185 m) curve on the north, east, and south, and 250 fathoms (455 m) to the westward consists of smooth mud and sandy mud bottom.

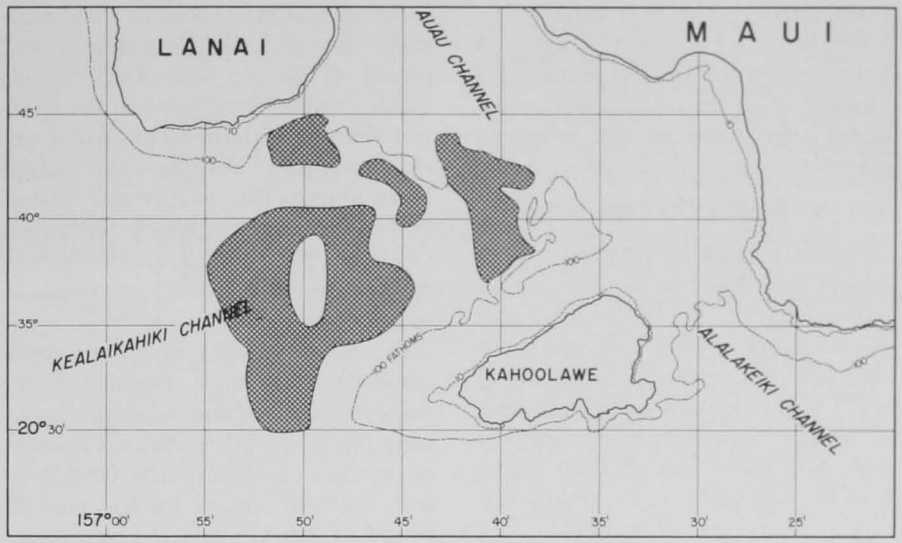

Figure 6.—Trawlable areas between the Islands of Lanai and Kahoolawe.

Small amounts of *P. marginatus* were taken off southeastern Lanai. All stations were made during the first cruise, and the sampling gear used here was less efficient than that used on later cruises. Best catches were made with a 27-foot shrimp trawl which resulted in 27 shrimps taken in a 60-fathom (108 m) night tow and 28 taken in a 124-fathom (226-m) day drag (both tows of 1-hour duration).

Hamakua Coast

The Hamakua Coast of northeast Hawaii (Fig. 7), between Waipio Valley and Hilo Bay, offers good trawling grounds in depths inhabited by *P. marginatus*. However, sugarcane plantations along the coast have been dumping cane trash directly into the ocean for many years. Large quantities of trash taken in the trawls (up to 3,000 pounds) so hampered the operations that extensive trawling was not undertaken. Our limited sampling was insufficient to determine what effect, if any, the cane debris has on the bathyal environment and associated animal communities. There is little doubt, however, that this area is an excellent example of a deep-sea environment extensively altered by

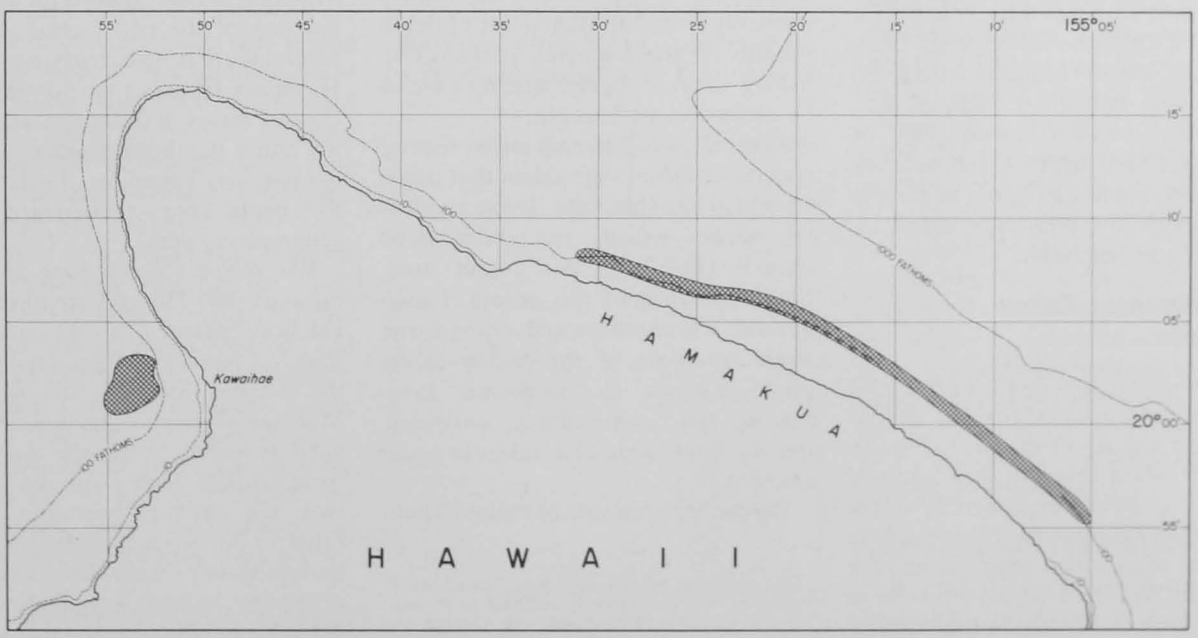

Figure 7.—Trawlable areas off the Island of Hawaii.

human activity. The best catch of *P. marginatus* was 7 pounds (3.2 kg) for a 1-hour daylight tow in 122 fathoms (225 m) during 1972. No catches of *P. marginatus* were made in the following three areas.

Kalohi Channel

A small portion of western Kalohi Channel was found to have a smooth mud bottom (Fig. 3). The trawlable area is bounded on the north, east, and south by the base of the recent shelf break at about 125 fathoms (230 m). The floor of the channel slopes gently westward to about the 165-fathom (330-m) curve where the bottom becomes broken and trawling conditions are marginal.

Kaiwi Channel

The portion of Kaiwi Channel between Honolulu Harbor and Makapuu Point (Fig. 5) was found to be trawlable in depths greater than about 300 fathoms (550 m). One tear-up was experienced when rough bottom was encountered at about 275 fathoms (500 m) on the north edge of Penguin Bank.

Kawaihae

A small trawlable area of smooth, sandy mud bottom in the 130-220 fathom (235-400 m) depth range was located due west of Kawaihae (Fig. 7). The 50-300 fathom (90-550 m) depth range off this coast between lat. 19°50′N and Malae Point (lat. 20°06′N) was extensively surveyed. Bottom conditions, for the most part, are very rough with reliefs of 25-30 fathoms (45-55 m) common in the 190-300 fathom (350-350 m) depth range. Bottom recordings indicated very heavy concentrations of fishes associated with the pinnacles in this region; limited attempts to sample these populations with traps and handlines were unsuccessful.

Other Species Taken In Trawls

Several other species of shrimp were taken in small amounts in the deeper trawling areas south of Oahu (Fig. 5), off north Maui (Fig. 4), and south of Lanai (Fig. 6). They generally occur deeper than 150 fathoms (275 m) and the problem of sorting them from the numerous fishes also taken in these depths renders trawling an impractical means of harvest. The penaeid *Aristeus semidentatus* was taken in small numbers, with catches ranging up to about 2 pounds (1 kg) per hour. Only slightly better catches were made of the caridean shrimps *Heterocarpus ensifer* and *H. laevigatus*, but they are readily taken in traps (Struhsaker and Aasted, 1974). Several small species belonging to the genera *Pandalus* and *Pleisioneka* were also present in small amounts in all of the deeper tows.

Incidental catches of other crustaceans were also made. During fall 1968 white crabs, *Portunus sanguinolentus*, were taken at every station off Haleiwa in depths of 54-66 fathoms (99-121 m) with catches ranging up to about 30 pounds (13.6 kg) and averaging 13.5 pounds (6.1 kg) per tow. This species was also present in every station off northwest Molokai in depths of 65-68 fathoms (120-124 m). Catches were smaller, however, averaging 5.8 pounds (2.6 kg). The size of the crabs ranged from about 3 to 7 individuals per pound (6-15 per kg).

During fall 1968, slipper lobsters, *Scyllarides squamosus*, were present at 6 of 11 stations off northwest Molokai. From 1 to 4 individuals were taken per tow and weighed 1-2 pounds each. At the same time six spiny lobsters, *Panulirus marginatus*,[1] were taken at three stations. Finally, individual kona crabs, *Ranina serrata*, were taken on several occasions at depths of 100 fathoms on the north edge of Penguin Bank. These catches are of interest primarily from the standpoint of depth records for these species: perhaps trap fishing at these depths would prove to be commercially feasible.

In the Pailolo Channel areas, several species of fishes were taken that might be sold in local markets. These incidental catches usually ran about 40-60 pounds (18-27 kg) per 2-hour drag. Small flatfishes of the genera *Taeniopsetta*, *Parabothus*, and *Arnoglossus* made up most of the finfish catch. Papio, *Caranx* sp.; aweoweo, *Priacanthus* spp.; and boarfish, *Antigonia steindachneri* were also taken in small amounts.

On the Molokai side of Pailolo Channel, dead "trees" of black coral, *Antipathes* sp., were often taken in the trawls: catches of 25 pounds (10 kg) were not unusual.

[1]This endemic species was long known as *P. japonicus* but was recently referred to *P. marginatus* (Quoy and Gaimard) by George and Holthuis (1965). Brock (1973) recently reported the species from Johnston Atoll.

Variation In Catch Rates

The reasonably accurate station position data obtained during the surveys permit an examination of the effects of time of day, depth of water, and towing speed on the catch rates of *Penaeus marginatus*. Only quantitative stations with a 41-foot 4-seam flat shrimp trawl (without mud rollers) from the first four cruises are considered. The estimated area sampled by a trawl was converted to hectares and catch rates are expressed as numbers of shrimp per hectare. The time of the station is considered to be the median between on- and off-bottom times.

It soon became apparent during the early cruises that the catches of *P. marginatus* varied markedly by time of day and depth of water fished. While catches were made at night in the shallower areas, shrimp were taken during both day and night in depths of 110-125 fathoms (200-230 m). However, in these deeper areas, daytime catches were higher than those of night catches (Table 1).

The effects of time of day and depth of water are summarized in Figure 8, where average catches are given for five depth zones for 3-hour periods throughout the day. Sampling effort ranged from one to nine stations for each combination of the two factors. Unfortunately, there is no extensive area in the Hawaiian Islands that permits a continuous series of trawling stations over the entire depth range inhabited by *P. marginatus*. Therefore, the data for the five depth zones treated are for five geographical areas.

The deepest depth zone of 110-125 fathoms (200-230 m) is represented by catches obtained at 42 stations in Pailolo Channel. For each time period, the catches for both the Maui and Molokai side of the Channel were averaged together. Although the catches were usually higher on the Molokai side, the day-night patterns in catch rates for the two areas were similar. Although shrimps were taken at all times of the day, catches were highest during daylight hours and considerably reduced during night.

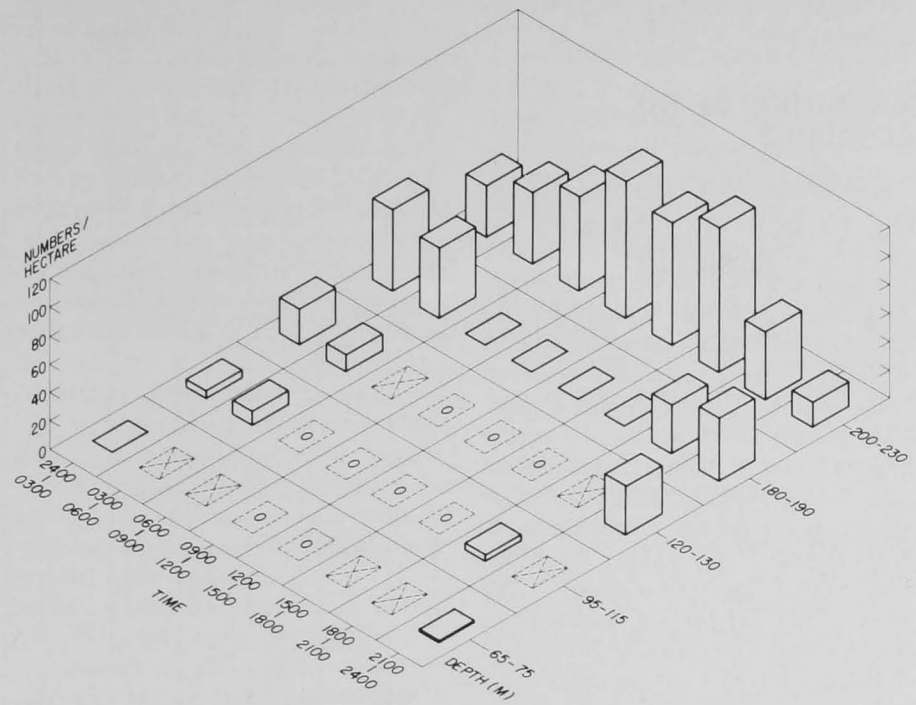

Figure 8.—Average catch rates (numbers per hectare) of *Penaeus marginatus* by time of day and depth. Cells with a dashed rectangle and an "O" indicate that no *P. marginatus* were taken for that combination of factors, while rectangles with an "X" indicate that no sampling was conducted for that combination of factors.

The data for the 99-104 fathom (180-190 m) depth range were obtained from 41 stations in the Penguin Bank area where the best catches were made at night. Only a few shrimps were taken during daytime, and catch rates averaged less than one shrimp per hectare.

The 65-70 fathom (120-130 m) depth range is represented by the northwest Molokai area where 22 stations were made. Shrimps were taken only during 2100-0600 hours. No stations were made during 0600-0900 hours and 1800-2100 hours, and while sampling was conducted during the three time periods between 0900 and 1800 hours, no shrimps were taken.

A total of 23 stations in the Haleiwa area provide the data for the 53-63 fathom (95-115 m) depth range. No daylight catches of shrimps were made and only small catches were made at night. No median sampling times fell within the 2100-2400 hours time period.

Five stations, all off north Maui, were made in the 35-40 fathom (65-75 m) depth range. Only small amounts of shrimps were taken during night in these depths.

We believe that the pattern of catches of *P. marginatus* can best be explained by a nocturnal movement of the shrimp into shallower depths. In the areas considered, the slope of the bottom is such that the shrimps would have to undertake horizontal movements of only about 1 mile (1.9 km) to effect depth changes of 40 fathoms (75 m). This is indicated by the reduced night catches in the deepest depth zone, higher night catches in the next deepest zone, and progressively smaller catches in each succeeding depth zone. As pointed out by Pearcy and Laurs (1966), strong evidence for vertical migration in midwater animals is provided in a case where daytime catches of an animal exceed those of the night catches in the same depth zone. Presumably, the animals can better avoid the trawl during daylight; thus, reduced nighttime catches are indicative of movement out of the depths being sampled.

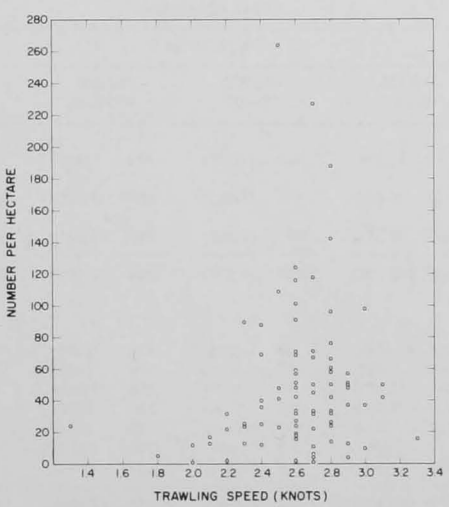

Figure 9.—Number of *Penaeus marginatus* taken as a function of trawling speed.

Thus *P. marginatus*, like most other species of the genus, appears to be negatively phototactic (avoids light). However, it seems as though most individuals of *P. marginatus* accomplish this by moving offshore into deeper water during daytime, rather than burrowing during daylight hours as do most other species of *Penaeus*. However, captive specimens of *P. marginatus* have been observed to burrow readily, and burrowing may also be an important behavioral component of this species. As discussed below, smaller shrimps occur in shallower depths. Possibly the smaller shrimps undertake more limited movements offshore and burrow to some degree. If the smaller shrimps occurring in the shallower depths burrowed during daytime and did not undertake any migratory movements, then we would expect to occasionally capture a few shrimps during daylight stations. However, not one *P. marginatus* was taken between 0600 and 1800 hours in depths of 70 fathoms (130 m) or less.

We also examined the effect of trawling speed on the catch rates of *P. marginatus*. Figure 9 shows the relationship between catch and towing speed for 83 stations. Zero-catch stations were not plotted. The optimum towing speed appears to range from about 2.3 to 3.0 knots, with the best catches being made at 2.5 to 2.8 knots. There is considerable variation in catch rates within the indicated optimum towing speeds. This is due to variation in the abundance of shrimps by depth and time of day as discussed above. We assume that at lower trawling speeds the shrimps avoid the trawl more readily, and at higher speeds the trawl lifts off the bottom, permitting the shrimp to escape under the trawl.

GENERAL OBSERVATIONS

At each station where *P. marginatus* was taken, the shrimp were counted and weighed. At 63 stations where the catch exceeded 5 pounds, the shrimp ranged

from 14 to 23 individuals per pound (heads-on). Shrimp in most of the catches (45 stations) ranged from 16 to 19 per pound, and the average for all stations was 17.7 per pound.

The percentage of the total weight of the shrimp contributed by the tail (shell on) was determined at eight stations; the tails make up 50 percent to 55 percent of the total weight.

The total lengths (tip of rostrum to tip of telson) were determined for many specimens of *P. marginatus*. Length frequencies for three stations are presented here to illustrate the main conclusions resulting from analysis of these data. At all stations during the surveys, female shrimp ranged to a larger size than the males (Fig. 10). The shrimp taken in the shallower portions of the Haleiwa area tended to be smaller than those from Pailolo Channel. Finally, there were no obvious seasonal differences in the size of shrimp inhabiting depths of 100-125 fathoms (185-230 m). This is shown for the Pailolo Channel in Figure 10, where a sample collected during fall (C and D) is compared with one collected during spring (E and F).

Although the numbers of male and female shrimp are about equal in lesser depths, the males consistently outnumber the females by ratios of 3-4 to 1 in depths of 100-125 fathoms (185-230 m). This is illustrated in Figure 10, for which random samples from Haleiwa (A and B) and Pailolo Channel (E and F) are presented. The other Pailolo Channel sample in the figure (C and D) is not a random one.

MAGNITUDE OF THE RESOURCE

An estimate of the standing biomass of *P. marginatus* available at any one moment on the four most productive fishing grounds was made by determining average catch rates per unit area (for fall 1968) and the area of each ground. A summary of these estimates is as follows: Pailolo Channel-Molokai side, 8,316 pounds (3,780 kg) for 4.0 square miles (13.7 km^2); Pailolo Channel-Maui side, 2,367 pounds (1,076 kg) for 3.0 square miles (10.2 km^2); Penguin Bank, 3,294 pounds (1,497 kg) for 3.0 square miles (10.3 km^2); Molokai, 1,784 pounds (811 kg) for 5.5 square miles (18.7 km^2); all four areas, 15,761 pounds (7,164 kg) for 15.4 square miles (52.9 km^2).

Although this standing biomass estimate of about 16,000 pounds (7,270 kg) is not impressive, it is a minimal estimate of the available resource for the following reasons. 1) There is no allowance in the estimate for trawl avoidance by the shrimp. 2) The available trawling areas of the four most productive grounds can probably be enlarged. 3) Additional trawling grounds appear available. 4) There may be movement of adults from untrawlable areas to the fishing grounds. 5) There is some evidence that this species spawns throughout the year. 6) Recruitment of young could be provided by adults inhabiting untrawlable areas.

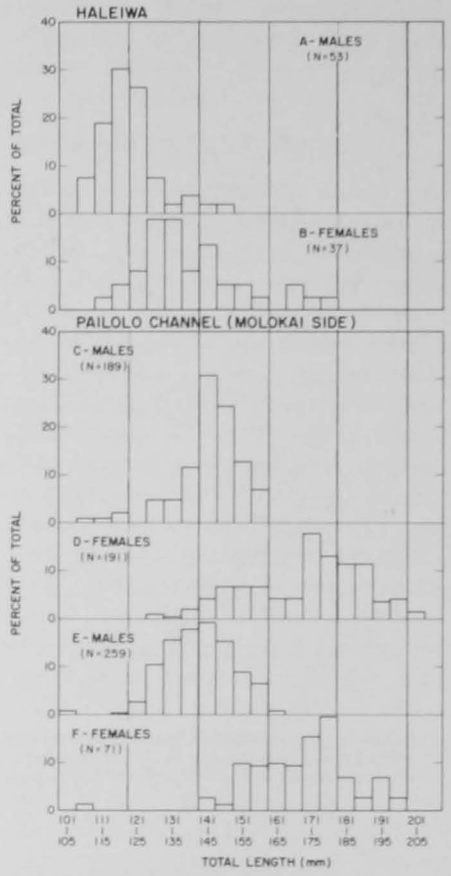

Figure 10.—*Penaeus marginatus* length-frequency data. A and B: Haleiwa area, 65-80 fathoms (118-146 m), October 1972. C and D: Pailolo Channel (Molokai side), 110-120 fathoms (201-219 m), October 1972. E and F: Same as preceding, March 1971.

In order to gain some idea of the total magnitude of the *P. marginatus*

Table 2.—Estimated areas of seven depth ranges in the Hawaiian Islands. Units are square nautical miles and kilometers (in parentheses). See text for further explanation.

Region	Depth range													
	Fathoms 0-10		10-100		100-200		200-300		300-400		400- 500		500-1,000	
	Meters 10-20		20-200		200-400		400-600		600-800		800-1,000		1,000-2,000	
Leeward Islands														
Kure Is.-Laysan Is.	308	(1,056)	979	(3,358)	343	(1,176)	131	(449)	222	(761)	290	(995)	1,797	(6,164)
Maro Reef-Gardner Pinnacles	114	(391)	1,347	(4,620)	317	(1,087)	357	(1,225)	297	(1,019)	456	(1,564)	3,368	(11,552)
St. Rogatien Bank-Nihoa Is.	109	(374)	1,257	(4,312)	871	(2,988)	881	(3,021)	485	(1,664)	587	(2,013)	1,980	(6,791)
Total: Leeward Is.	531	(1,821)	3,583	(12,290)	1,531	(5,251)	1,369	(4,695)	1,004	(3,444)	1,333	(4,572)	7,145	(24,507)
Main group														
Kaula Is., Niihau, and Kauai	82	(281)	225	(772)	83	(285)	176	(604)	198	(679)	228	(782)	862	(2,957)
Oahu	105	(360)	163	(559)	127	(436)	264	(906)	265	(909)	454	(1,557)	173	(593)
Molokai	51	(175)	447	(1,533)	177	(607)	296	(1,015)	247	(847)	239	(820)	411	(1,410)
Maui	48	(165)	296	(1,015)	163	(559)	267	(916)	127	(436)	76	(261)	447	(1,533)
Lanai	13	(45)	120	(412)	133	(456)	120	(412)	213	(731)	79	(271)	127	(436)
Kahoolawe	12	(41)	77	(264)	29	(99)	16	(55)	15	(51)	16	(55)	91	(312)
Hawaii	63	(216)	274	(946)	255	(875)	232	(796)	184	(631)	256	(878)	1,096	(3,759)
Total (main group)	374	(1,283)	1,602	(5,501)	967	(3,317)	1,371	(4,704)	1,249	(4,284)	1,348	(4,624)	3,207	(11,000)
Grand total	905	(3,104)	5,185	(17,791)	2,498	(8,568)	2,740	(9,399)	2,253	(7,728)	2,681	(9,196)	10,352	(35,507)

resource, as well as for other studies, we estimated the total amount of bottom area in the Hawaiian Islands for seven depth ranges to a depth of 1,000 fathoms (2,000 m). These estimates were obtained by contouring National Ocean Survey nautical charts (nos. 4115-4117 and 4181-4183) at the desired depths and then cutting out and weighing each depth range. The weights for each depth range were converted to area by reference to the weight of a known rectangular area for each chart. Checking this method by estimating known land areas indicated an error of less than 0.1 percent. The results are given in Table 2. Due to the subjectivity in plotting the contours, we feel that simply doubling the depths in fathoms to obtain depths in meters is justified.

To estimate the amount of bottom area that could be inhabited by adult *P. marginatus* in the island areas from Oahu to Hawaii, we assumed that 35 percent and 20 percent of the bottom areas in the 10-100 fathom (20-200 m) and 100-200 fathom (200-400 m) depth ranges respectively are available to this species. This results in an estimate of about 850 nautical square miles (2,915 km^2). Using an average standing biomass estimate of 1,023 pounds per square nautical mile (135 kg/km^2) from the four most productive trawling areas results in a total biomass estimate of about 870,000 pounds (395,500 kg) of *P. marginatus*. Considering the factors discussed above, it would not seem unreasonable to assume that 50,000 to 100,000 pounds (23,000 to 46,000 kg) of this species might be harvested annually.

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