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A Review of Shark Control in Hawaii with Recommendations for Future Research[1]

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ABSTRACT: In an attempt to allay public fears and to reduce the risk of shark attack, the state government of Hawaii spent over $300,000 on shark control programs between 1959 and 1976. Six control programs of various intensity resulted in the killing of 4,668 sharks at an average cost of $182 per shark. The programs furnished information on diet, reproduction, and distribution of sharks in Hawaii, but research efforts of the programs had a number of shortcomings. Analysis of the biological data gathered was not directed toward the tiger shark, *Galeocerdo cuvier* (Peron & LeSueur), which is responsible for most attacks in Hawaii. Reliable estimates of shark populations in Hawaii cannot be made based on catch data from control programs because of sampling biases. Most of the information gained from the control programs was not published in reviewed journals and is not readily available to the scientific community. The ability of the control programs to reduce shark populations and to remove large sharks from coastal waters appears to have been stated with more confidence than is warranted, considering seasonal changes observed in shark abundance and variable fishing effort. Shark control programs do not appear to have had measurable effects on the rate of shark attacks in Hawaiian waters. Implementation of large-scale control programs in the future in Hawaii may not be appropriate. Increased understanding of the behavior and biology of target species is necessary for evaluation of the effectiveness of small-scale control efforts, such as selective fishing after an attack. Acoustic telemetry, conventional tagging, and studies on population dynamics concentrating primarily on the tiger shark may be used to obtain data about activity patterns, distribution, and population parameters, providing information useful for reducing the risk of shark attack in Hawaii and elsewhere.

AS THE HUMAN POPULATION in Hawaii has risen, ocean resources have become increasingly exploited. In addition, Hawaii's increasing resident and tourist populations have placed a high priority on coastal recreation. Expanded recreational use of the ocean brings the potential for increasing shark-human interactions. Fear of shark attack, coupled with socioeconomic pressures of tourism, prompted the state of Hawaii to establish a shark control program in 1959 (Ikehara 1961), which was followed by other programs in 1966–1969 (Tester 1968, 1969, Norris and Harvey 1969), 1971 (Fujimoto and Sakuda 1971), and 1976 (Naftel 1976, Naftel et al. 1976). Two recent fatal shark attacks in Hawaii have prompted calls for reinstitution of a large-scale shark control program.

Because of the limited availability of data from past control programs and continued debate over the appropriateness of shark control in Hawaii, this paper provides a summary and critical review of past shark control programs in Hawaii with regard to: (1) objectives of the programs; (2) results and new information gained; (3) evaluation of success. This paper also assesses the potential for future shark control programs and provides suggestions for further research to increase under-

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standing of shark behavior and to provide information that may be useful for reducing shark-human interactions.

PAST SHARK CONTROL PROGRAMS IN HAWAII

The Billy Weaver Shark Research and Control Program, 1959–1960

On 13 December 1958 a teenage surfer, Billy Weaver, was fatally attacked by a shark off Lanikai, Oahu (Tester 1960). To minimize the hazard to surfers and swimmers posed by sharks, Hawaii's first shark control program (the Billy Weaver Shark Research and Control Program) was established. The intent of the program was to reduce shark populations in coastal waters around Oahu and to compile data for future use in controlling shark abundance. The Hawaii Board of Agriculture and Forestry was assigned to direct and supervise fishing operations and collection of biological and ecological data (Ikehara 1961).

TABLE 1

FISHING EFFORT, CATCH, AND CATCH PER UNIT EFFORT (CPUE) DURING EACH SEASON FOR EACH ISLAND FROM EACH CONTROL PROGRAM

	NO. OF HOOKS SET				NO. OF SHARKS CAUGHT				SHARKS PER 100 HOOKS (CPUE)				
ISLANDS	Wi	Sp	Su	Fa	Wi	Sp	Su	Fa	Wi	Sp	Su	Fa	TOTAL CPUE
Niihau													
Tester 1967–1969	192	360	1,272	344	10	90	180	42	5.2	25.0	14.1	12.2	14.8
												OA =	14.8
Kauai													
Tester 1967–1969	216	0	496	72	12	0	54	12	5.5	0	10.9	16.7	9.9
1971	0	288	288	0	0	13	8	0	0	4.5	2.8	0	3.6
1976	0	0	0	585	0	0	0	35	0	0	0	6.0	6.0
												OA =	6.9
Oahu													
Billy Weaver	3,312	2,064	2,640	2,988	120	173	238	166	3.6	8.4	9.0	5.5	6.3
Tester 1967–1969	2,141	2,808	2,224	2,088	89	148	175	122	4.1	5.3	7.9	5.8	5.8
1971	0	1,008	1,495	0	0	31	46	0	0	3.1	3.1	0	3.1
1976	0	0	141	0	0	0	3	0	0	0	2.1	0	2.1
												OA =	5.7
Molokai													
Tester 1967–1969	0	153	0	280	0	18	0	57	0	11.8	0	20.3	17.3
1971	0	216	240	0	0	19	13	0	0	8.8	5.4	0	7.0
												OA =	12.0
Maui													
Tester 1967–1969	0	157	72	72	0	25	9	20	0	21.0	12.5	27.8	20.1
1971	0	432	431	0	0	30	26	0	0	6.9	6.0	0	6.5
1976	0	0	988	0	0	0	57	0	0	0	5.7	0	5.7
												OA =	8.1
Lanai													
Tester 1967–1969	0	0	0	144	0	0	0	32	0	0	0	22.2	22.2
												OA =	22.2
Kahoolawe													
Tester 1967–1969	0	81	0	72	0	23	0	10	0	28.4	0	13.9	21.5
												OA =	21.5
Hawaii													
OI 1966–1967	640	96	96	96	64	3	15	10	10.0	3.1	15.6	10.4	9.9
Tester 1967–1969	504	218	408	576	25	6	20	35	5.0	2.7	4.9	6.1	5.0
1971	0	480	573	0	0	27	25	0	0	5.6	4.4	0	4.9
												OA =	6.2
Total	7,005	8,361	11,364	7,317	320	606	869	541	4.6	7.2	7.6	7.4	6.9

Wi, winter; Sp, spring; Su, summer; and Fa, fall. OI, Oceanic Institute; OA, overall average for all programs on each island.

Shark fishing was conducted aboard a tuna fishing boat during four circuits around the island of Oahu in 17 designated areas between 1 April 1959 and 31 March 1960 (Table 1). Sharks were caught using three 800-m sections of longline, with 24 hooks per section. The longlines were set parallel to shore in water about 45 m deep in the afternoon and were retrieved at dawn the next morning. Skipjack tuna, *Katsuwonus pelamis* (L.), was the primary bait used, although other types of bait were used in bait preference studies. Standard longlines of three 24-hook sections were used throughout each of the subsequent control programs (with the exception of the Oceanic Institute program) to allow comparison of catch rates between programs.

Nine species of sharks were caught, most of which were identified as "sand" sharks, *Carcharhinus* sp.; tiger sharks, *Galeocerdo cuvier* (Peron & LeSueur); and blacktip sharks, *Carcharhinus limbatus* (Valenciennes) (Table 2). Two great white sharks, *Carcharodon carcharias* (L.), were also caught. Although great white sharks are rare in Hawaii, they are responsible for attacks on humans and are

TABLE 2

SUMMARY OF THE SIX SHARK CONTROL PROGRAMS CONDUCTED IN THE STATE OF HAWAII

PROGRAM DATE	COST	COST PER SHARK	NO. OF SHARKS KILLED SANDBAR	TIGER	OTHER SPECIES	TOTAL
Billy Weaver 1959–1960	$27,440	$39	"sand sharks" 492	87	Blacktip, 81 Hammerheads, 18 Sixgill, 11 Prickly, 3 White, 2 Blue, 1 Mako, 1 Unidentified, 1	697 [641]
Oceanic Institute 1966–1967	$20,000	$217	52	32	Blacktip, 6 White, 2	92
Tester 1967–1969	$200,000	$116	789	280	Gray reef, 274 Galápagos, 206 Unidentified, 64 Blacktip, 47 Hammerheads, 35 Prickly, 9 Sixgill, 9 Bignose, 9 Mako, 2 False cat, 2 Silky, 1	1,727 [1,095]
1971 March–August	$50,000	$210	88	109	Galápagos, 19 Blacktip, 19 Gray reef, 2 Mako, 1	238 [83]
1976 10–20 June	$8,200	$283	14	15	None	29
1976 August–September	$15,000	$227	20	31	Galápagos, 12 Gray reef, 1 Blacktip, 1 Mako, 1	66
Totals	$320,640	avg. $182	1,455 (963)	554	838	2,849 [1,819]
Grand total						4,668

NOTE: Numbers in brackets represent the numbers of pups removed from pregnant females; numbers in parentheses represent the confirmed number of sandbar sharks killed in total.

considered one of the most dangerous species of shark (Taylor 1985). To determine whether or not sharks range over a limited area, 14 sharks were tagged and released. None was recaptured. A progressive decrease in sharks caught per 100 hooks was observed during successive circuits around Oahu (Ikehara 1961).

Oceanic Institute Shark Control Program, 1966–1967

Oceanic Institute, a privately funded scientific research organization, conducted a small-scale shark fishing program restricted to Kawaihae Bay on the island of Hawaii from January 1966 through March 1967 (Table 1). Longlines consisting of a total of 32 hooks were used through March 1967, at which time the program was merged with the Hawaii Cooperative Shark Research and Control Program and 72 hook lines were used to fish this area (Norris and Harvey 1969). A total of 92 sharks was caught in the bay, predominately sandbar, *Carcharhinus plumbeus* (Nardo), and tiger sharks (Table 2). Norris and Harvey (1969) estimated that the combined fishing programs had resulted in an 80–90% reduction in the shark population of Kawaihae Bay.

Hawaii Cooperative Shark Research and Control Program, 1967–1969

The Hawaii Cooperative Shark Research and Control Program was initiated based on advice from local fisheries scientists to respond to an increase in shark sightings around the main Hawaiian Islands. The primary objectives of this program were to determine the species composition of coastal sharks and to gather information on abundance, life history, movement, growth rate, diet, and fecundity. Additional objectives were to determine the effects of fishing on coastal shark populations and to recommend effective measures for future shark control. The program was headed by Dr. Albert L. Tester, professor of zoology, and run under the auspices of the Institute of Marine Biology, University of Hawaii, with support from federal, state, and private agencies (Tester 1969).

Shark fishing was conducted between 1 June 1967 and 30 June 1969, again aboard a single tuna fishing boat. Fishing was conducted within 77 stations designated around all eight of the main Hawaiian Islands, but was concentrated around Oahu (eight successive circuits, during each of which all the designated areas were fished once) (Table 1). In addition to standard longlines, light longlines (12 hooks, set between 18 and 118 m) and "timed" handlines (fished at 18–109 m) were used to target smaller sharks. Experimental fishing trials, which consisted of bait preference tests, sets perpendicular to shore, and deep-water sets, were conducted off the south shore of Oahu.

The majority of sharks captured were sandbar sharks, followed by tiger; gray reef, *Carcharhinus amblyrhynchos* (Bleeker); and Galápagos sharks, *C. galapagensis* (Snodgrass & Heller) (Table 2). Of 16 tiger sharks tagged, four were recaptured, one of which had traveled 73 km after 207 days at liberty.

Again, a progressive decrease in the number of sharks caught per 100 hooks in successive fishing circuits was observed. However, the extended period of sampling for this program revealed considerable seasonal fluctuation in catch rates (Wass 1971). Tester (1969) concluded that coastal shark populations were very susceptible to fishing pressure and suggested that "the state undertake a continuing shark research and control program, at least until a commercial fishery is developed." Tester further recommended a continuous control program that would reduce shark abundance by at least 50% along all populated coastlines utilized for recreation and coastal fisheries.

1971 Shark Control and Research Program

The 1970 Hawaii state legislature mandated the Hawaii State Department of Land and Natural Resources to oversee a fourth shark control and research program in Hawaii (Fujimoto and Sakuda 1971). The program was initiated to reduce "fear and apprehension against sharks felt by locals and tourists" that restricted the optimum potential of recreational usage of the state's coastal waters. The major goal of this program was to remove sharks from coastal waters "using the knowledge of shark behavior gained from the two previous programs." Additional objectives were to gather biological data on species composition, catch rates, sex ratios, length measurements, and diet of sharks. The potential hazards for commercial utilization of shark meat were investigated by measuring mercury and pesticide levels in shark tissue as well as the suitability of shark as food for cultured prawns.

Shark fishing using standard longlines began on 3 March 1971 and continued until 27 August 1971 (Table 1). Tiger sharks were caught in the greatest numbers followed by sandbar, blacktip, Galápagos, and gray reef sharks (Table 2).

It was concluded that the coastal shark population could be considerably reduced by control program fishing, based on decreases in catch rates observed in consecutive fishing rounds in the 1971 program and in the previous two programs. Fujimoto and Sakuda (1971) noted that the Billy Weaver program (1959–1960) and the 1967–1969 program (7 yr later) both had initial catch rates of about 11 sharks per 100 hooks, whereas the 1971 program had an initial catch rate of only 4.4 sharks per 100 hooks (2 yr after the previous program). Based on these comparisons Fujimoto and Sakuda concluded that between 2 and 7 yr were required for the coastal shark population to recover to maximum density. No specific recommendations for future shark control were offered except that "the best method of controlling the near shore shark population appears to be the institution of a systematic and continuous shark control program conducted by the state" (Fujimoto and Sakuda 1971).

1976 Control Programs

Two brief shark control programs that were carried out during the summer of 1976 were the Shark Abatement/Student Training Program, and the Shark Utilization/Student Training Program, funded by the State of Hawaii Department of Planning and Economic Development and the State Marine Affairs Coordinator's Office (Naftel 1976, Naftel et al. 1976). The intent of the programs was to control a suspected increase in the population of coastal sharks in selected areas, to provide training opportunities for community college marine technology students, and to supply biological data for graduate students at the University of Hawaii. Other objectives included the investigation of marketing shark meat for human consumption and the evaluation of the potential for establishing a shark fishery in Hawaii. The first program operated from 10 to 20 June 1976 and the second from 21 August through 18 September 1976. Fishing effort and number of sharks caught were both limited compared with the previous four control programs (Table 1). The majority of sharks caught were sandbar, tiger, and Galápagos sharks (Table 2).

Naftel et al. (1976) concluded that the first 1976 program had demonstrated the existence of "a serious shark danger in Hawaiian waters" and that "some form of control should begin soon." They further concluded that unless shark populations were reduced, sharks would "compete with local fishermen for commercial food fish" and that "it would only be a matter of time before the food fish would be decreased to a point where sharks would then begin to sample other available forms of food, such as man."

Recommendations of the second 1976 program included continued funding by the state for a shark fishing/student training program and the establishment of a well-managed shark fishery, which would provide an economical fish product and serve to maintain shark populations at "acceptable levels" (Naftel 1976).

INFORMATION GAINED FROM SHARK CONTROL PROGRAMS IN HAWAII

Species Composition

Fifteen species of sharks were caught during the control programs: sandbar; tiger;

gray reef; Galápagos; blacktip; mako, *Isurus oxyrinchus* Rafinesque; great white; bignose, *Carcharhinus altimus* (Springer); silky, *Carcharhinus falciformis* (Bibron); blue, *Prionace glauca* (L.); scalloped hammerhead, *Sphyrna lewini* (Griffith & Smith); smooth hammerhead, *S. zygaena* (L.); bluntnose sixgill, *Hexanchus griseus* (Bonnaterre); false catshark, *Pseudotriakis microdon* Capello; and prickly, *Echinorhinus cookei* Pietschmann (common and scientific names follow Compagno [1984]). The Galápagos, bignose, smooth hammerhead, bluntnose sixgill, and false catshark were new records for Hawaiian waters. The following sharks were typically caught in water deeper than 180 m off Oahu, with maximum depth recorded in parentheses: bignose (361 m), bluntnose sixgill (366 m), prickly (379 m), and false catsharks (375 m) (A. L. Tester, unpublished data).

Relative Abundance

A total of 36,122 hooks was set, with a catch of 2849 sharks, or eight sharks per 100 hooks. In addition, 1819 pups were removed from pregnant sharks, for a grand total of 4668 sharks killed (Table 2). The combined catch for all control programs (excluding unidentified sharks, unborn pups, and all sharks from the Billy Weaver program, because of lack of positive identification: a total of 2088 sharks) consisted of 46% sandbar, 22% tiger, 13% gray reef, and 11% Galápagos sharks. Catch rate of sharks (sharks per 100 hooks) was highest in waters off Lanai (22.2) and Kahoolawe (21.5), followed by Niihau (14.8), Molokai (12.0), Maui (8.1), Kauai (6.9), Hawaii (6.2), and Oahu (5.7) (Table 1).

However, comparison between islands is difficult because fishing techniques varied between islands and fishing outside of Oahu was limited. Fishing was conducted along the entire coastline of only two islands (Oahu and Niihau), and only two longline sets were made at Lanai and Kahoolawe during any of the control programs. Fishing at islands other than Oahu occurred mostly during the spring and summer, which may partially explain elevated catch rates at those locations. On Oahu, where fishing was conducted year-round, catch rates were higher during the summer (7.1 sharks per 100 hooks) than in winter months (3.8) (Wass 1971). Also, a majority of fishing at islands other than Oahu consisted of bait preference tests and sets perpendicular to the depth contour rather than standard sets (Tester 1969). Wass (1971) found that average catch rate of sandbar sharks per 100 hooks was 12.6 for all perpendicular sets compared with 5.7 for all sets made parallel to the depth contour when an area was fished for the first time.

Distribution

Comparison of catch rates from various locations during the 1967–1969 program revealed information on spatial distribution of shark species in Hawaiian waters. Catch rates of sandbar sharks were highest around Molokai and Lanai and lowest around Kauai (Wass 1971) and revealed evidence of segregation on the basis of sex and age class. Depth of capture for adult male sandbar sharks ranged from 27 to 278 m, with an average depth of 112 m. Capture depth of adult females ranged from 9 to 187 m, with an average depth of 68 m. Nearly three times more female (182) than male (63) sandbar sharks were caught off Oahu, although there were seasonal fluctuations in the ratio of females to males (Table 3). Wass (1971) reported a peak in catch of male sandbar sharks with sperm-laden claspers during the summer (May–September) and noted that mature males were caught more frequently at shallower depths during late spring and summer months, based on catch data from lines set perpendicular to the depth contour and from light longlines set at various depths. He theorized that males moved inshore to join females for mating in the late spring and returned to deeper water during the late summer. He offered as further evidence of offshore movement of males the observation that not a single mature male sandbar shark was caught off Oahu during the two fall quarters of fishing in the 1967–1969 program.

TABLE 3

FISHING EFFORT, CATCH PER UNIT EFFORT, AND SEX RATIO FOR SANDBAR SHARKS (*Carcharhinus plumbeus*) CAUGHT ON OAHU DURING THE TESTER 1967–1969 CONTROL PROGRAM

SEASON	NO. HOOKS	NO. FEMALES	NO. MALES	CPUE FEMALE	CPUE MALE	RATIO F : M
Summer	2,224	69	17	3.1	0.76	4.0 : 1
Fall	2,088	43	10	1.9	0.45	4.3 : 1
Spring	2,808	26	11	1.1	0.48	2.4 : 1
Winter	2,141	44	25	1.9	1.10	1.8 : 1

CPUE, number of sharks per 100 hooks. F : M represents the female to male ratio (data from Tester [1969]).

Catch rate of adult sandbar sharks was higher in fishing areas on the leeward coast of Oahu (4.6 sharks per 100 hooks) than in other fishing areas off Oahu (2.6) (Wass 1971). Catch rate of pregnant female sandbar sharks in Oahu waters was higher on the windward coast (Wass 1971). Juvenile sandbar sharks were abundant on the north and east coasts of Oahu in comparison with the south and west coasts, whereas subadults were found to be more uniformly distributed (Figure 1*a*). Mature male sandbar sharks also showed a fairly uniform distribution around Oahu, although samples sizes were low. Catch rate of mature females was highest on the west coast of Oahu and lowest along the east coast.

Catch rate of tiger sharks was highest on the south coast of Oahu and lowest on the west coast, with higher catch rates generally occurring during fall and winter months (Figure 2). Immature and adult tiger sharks appear to have similar distributions, most abundant on the south coast of Oahu and least abundant on the west coast (Figure 1*b*). Tiger sharks ranged from 11 to 371 m in depth, and Galápagos sharks were caught between 18 and 286 m (Tester, unpublished data).

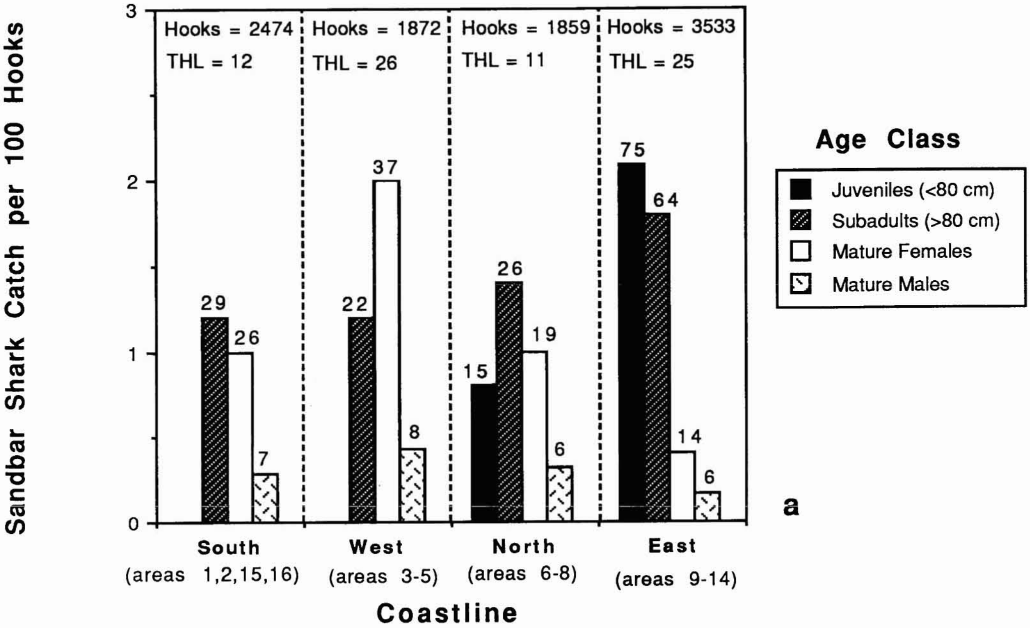
Gray reef sharks showed a restricted distribution: they were common off Niihau and Molokini Crater, but were rarely taken elsewhere (Tester 1969). Juveniles were caught in shallower water than adults (Table 4). Gray reef sharks were usually caught in areas where water visibility was higher (32 m) than visibility where sandbar sharks were common (22 m) (Wass 1971). Eleven gray reef sharks that were tagged and recaptured moved short distances (3–6 km) along the coastline over periods of 65–138 days (Tester 1969).

Biology

Total and precaudal lengths were measured for sharks caught in the control programs and were used to estimate size range for each species. Reproductive tracts of sharks were examined to quantify life history characteristics such as size at birth, size at maturity, mating and pupping seasons, and fecundity. Information gained on life history aspects of sandbar and gray reef sharks caught during the 1967–1969 control program is shown in Table 4. Diet of Hawaiian sharks was quantified by examination of stomach contents. Stomach contents of the most common species of sharks captured during the 1967–1969 program are summarized in Table 5.

EVALUATION OF SHARK CONTROL PROGRAMS

Each shark control program that has operated in Hawaii has been described as having been successful in controlling sharks. In these instances "success" refers to steady declines in catch rates of sharks and a reduction in the number of large sharks in the population. The following is an evaluation of the success of shark control efforts in Hawaii in terms of their success in increasing the body of knowledge useful for improving future control measures, decreasing shark populations, decreasing the number of large sharks, and, ultimately, success in reducing the risk of shark



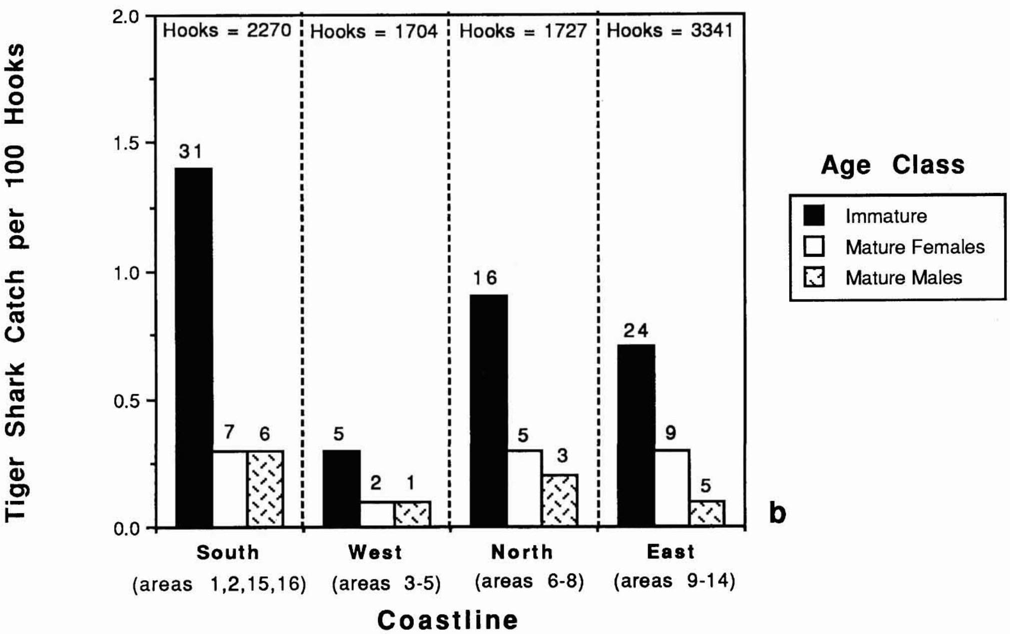


FIGURE 1. Catch rate per 100 hooks in coastal areas of Oahu with standard longlines during the 1967–1969 control program: *a*, for sandbar sharks (*Carcharhinus plumbeus*) of different age classes (based on precaudal length) (THL, timed handline fishing in each area—not included in fishing effort, data from Wass [1971]); *b*, for tiger sharks (*Galeocerdo cuvier*) (sharks > 305 cm total length considered mature) (data from Tester [1969] and Tester, unpublished data). Numbers above each bar represent number of sharks caught.

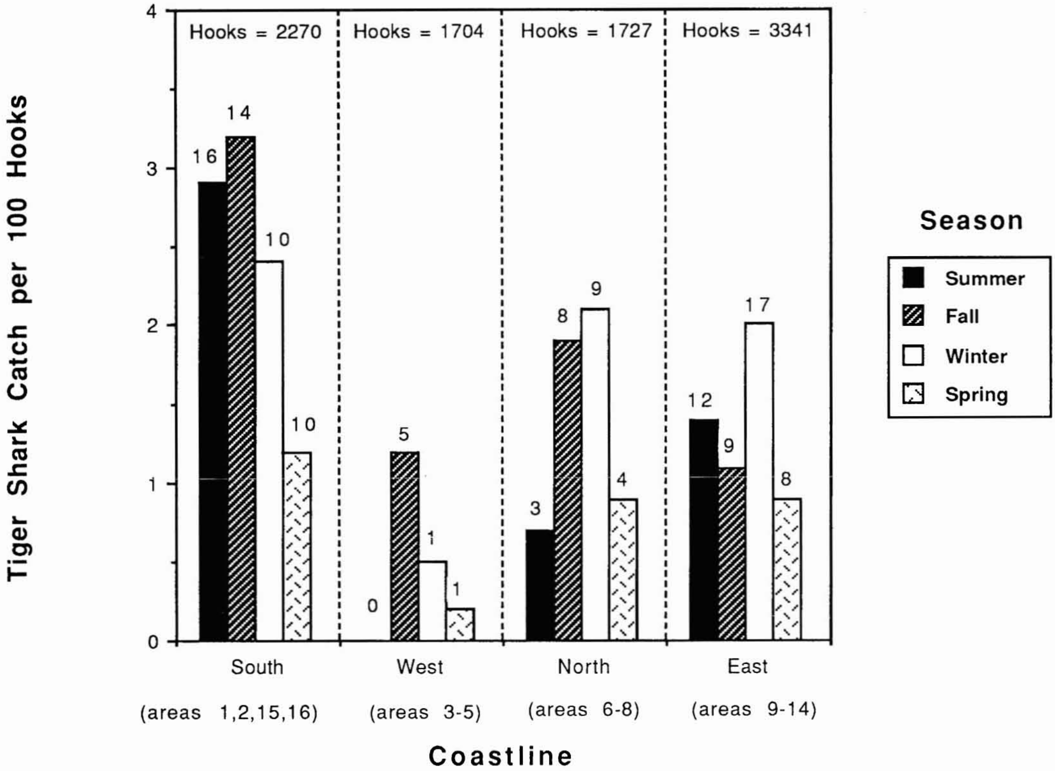


FIGURE 2. Catch rate per 100 hooks for tiger sharks (*Galeocerdo cuvier*) using standard longlines in different coastal areas of Oahu for each season during the 1967–1969 control program (data from Tester [1969]). Numbers above each bar represent number of sharks caught.

attack in Hawaiian waters. Our evaluation concentrates on sandbar and tiger sharks caught around Oahu during the 1967–1969 program, because these were by far the most abundant sharks caught and that was the first program where sharks were identified to species and the only program where fishing was conducted in all areas around Oahu for two consecutive years.

An objective of each of the control programs was to compile data that would add to the body of knowledge on sharks, and yet little of the information gathered during the control programs is available to the general scientific community. Wass (1973) reported a portion of his findings in the only peer-reviewed journal publication from any of the shark control programs. The validity of the control program reports has remained largely unquestioned although the reports did not receive the benefit of formal scientific peer review. Had the data been fully analyzed and the reports reviewed, it is unlikely that the influence of factors such as seasonality, annual fluctuations in abundance, weather, and variable fishing techniques on catch rate would have been ignored. Consequently, conclusions made about the effectiveness of the programs in reducing shark populations might well have been stated with less confidence.

Success in Reducing Shark Populations

Shark control programs in Hawaii have operated on the premise that by fishing for sharks, the population could be reduced to a level where the risk of shark attack was decreased. Each of the major control pro-

TABLE 4

LIFE HISTORY AND DISTRIBUTION DATA OF HAWAIIAN SANDBAR SHARKS (*Carcharhinus plumbeus*) AND GRAY REEF SHARKS (*C. amblyrhynchos*) FROM WASS (1971)

SHARKS	SIZE AT MATURITY: PRECAUDAL LENGTH (cm)	AGE (yr)	SIZE AT BIRTH: PRECAUDAL LENGTH (cm)	MATING SEASON MONTHS (GESTATION)	PUPPING SEASON MONTHS	AVG. NO. OF PUPS	AVG. DEPTH CAUGHT (m)
Sandbar Shark							
Male	110	10.2		July–September (12 months)	July–September		112
Female	115	13.1				5.5	68
Juvenile	—	—	45–51				79
Gray reef shark							
Male	100	7.4		February–April (unknown)	September–October		71
Female	105	7.2				5.0	56
Juvenile	—	—	45–50				38

NOTE: Juvenile sharks (<80 cm total length) were caught on light longlines or timed handlines.

grams referred to continual decreases in catch rates for consecutive fishing circuits as evidence that shark populations had been reduced and that control efforts had been successful (Ikehara 1961, Tester 1969, Fujimoto and Sakuda 1971). It was estimated that shark populations were reduced by as much as 50–90% after the moderate fishing effort of the control programs (Norris and Harvey 1969, Tester 1969). The removal of nearly 4700 sharks from Hawaiian waters over an 18-yr period undoubtedly resulted in a substantial decrease in the population, and declines in shark abundance are evident in reduced catch rates in long-running programs (Figure 3). However, factors such as seasonality, weather, and fishing effort also appear to have contributed to declines in catch rates observed during control programs. The following is an attempt to examine the influence that some of these factors might have had on catch rate and to obtain a more accurate estimate of the degree to which local populations of sharks were reduced by the control programs.

Results of the Billy Weaver program first appeared to indicate that a sudden decline in the shark population could be effected by continuous fishing circuits around Oahu (Ikehara 1961). Fishing in this program began in April and ended the following March. Inshore movement of sharks for mating and parturition during late spring and early summer has been documented for many species of sharks (Pratt and Casey 1990, Reid and Krogh 1992, Simpfendorfer 1992). Seasonal inshore and offshore movements have also been reported for sandbar sharks (Springer 1960, Medved and Marshall 1983, Stillwell and Kohler 1993). Although standard fishing in the control programs was conducted at an average of 45 m, male sandbar sharks range into much deeper water and were caught at depths of up to 278 m (Tester 1969, Wass 1971). Movement of large numbers of male sandbar sharks into water deeper than 45 m during fall and winter as noted by Wass (1971) would have contributed to decreased catch rates observed in later fishing rounds (fall and winter quarters) during the Billy Weaver program. Seasonal movements of sharks into

TABLE 5

SUMMARY OF STOMACH CONTENTS FOR HAWAIIAN SHARKS AS PERCENTAGE OCCURENCE FOR TIGER (*Galeocerdo cuvier*), SANDBAR (*Carcharhinus plumbeus*), GALÁPAGOS (*C. galapagensis*), AND GRAY REEF (*C. amblyrhynchos*) SHARKS FROM WASS (1971)

		TIGER		SANDBAR		GALÁPAGOS		GRAY REEF	
		n	%	*n*	%	*n*	%	*n*	%
STOMACH	NO. OF EMPTY STOMACHS	29	14	298	55	90	58	65	71
CONTENTS	FOOD PRESENT	181	86	243	45	65	42	27	29
Cephalopods		20	11	66	27	18	28	5	19
Crustaceans		47	26	44	18	6	9	1	4
Elasmobranchs		26	14	8	3	5	8	—	—
Teleosts		90	50	170	70	46	71	25	93
Sea turtles		20	11	—	—	—	—	—	—
Birds		42	23	—	—	—	—	—	—
Cetaceans		13	7	—	—	1	2	—	—
Indigestible items		32	18	2	1	2	3	—	—
Total no. examined		210		541		155		92	

deeper water during fall and winter would have biased catch rates reported for the 1971 control program in a similar manner. Cliff et al. (1988) found a predominance of female sandbar sharks caught in protective nets in South Africa and postulated that males inhabit deeper water, farther from netted areas. Cliff et al. (1988) also reported that the highest catches of both sexes in protective netting occurred during summer months and lowest catches were in autumn and winter. They theorized that male sandbar sharks move onshore and offshore seasonally.

Of the three major control programs, only the 1967–1969 program spanned more than 12 months and provided information permitting examination of the effects of season on catch rate. Seasonal fluctuations are evident in catch rate of the two species of sharks (sandbar and tiger) caught in the highest numbers during this program (Figure 3). Catch rate of sandbar sharks peaked during summer and was lowest in winter, coinciding with seasonal changes in the depth distribution of adult sandbar sharks (Wass 1971). In fact, the second highest catch rate of sandbar sharks was observed during the very last round of fishing. Considering that 46% of sharks caught in the 1967–1969 program were sandbar sharks, seasonal movements of sandbar sharks out of fishing areas may have contributed greatly to decreased catch rates in control programs over time. Seasonal fluctuations in catch rate and differential catch rates for male and female tiger sharks were observed by Paterson (1990) and Simpfendorfer (1992) in Australia and may also occur in Hawaii.

Season and weather may have influenced the actual fishing power of the gear and therefore the effective fishing effort and ensuing catch rate. Strong currents and rough seas during the fall and winter months resulted in fouled and tangled sections of longline more frequently than during the spring and summer, and these sections were not subtracted from the total effort in quantifying catch per unit effort. Of 20 references to fouled or tangled lines in the final report of the 1967–1969 program, only six occurred during the spring or summer (Tester 1969). The effectiveness of fishing in winter months also may have been reduced as a result of rapid dispersion of bait odor along strong, turbulent currents and more frequent stripping of bait from hooks. Reduced effective fishing in winter months resulting from rough weather would also have contributed to lower catch rates recorded during later fishing rounds in fall and winter.

Targeting larger sharks during later cir-

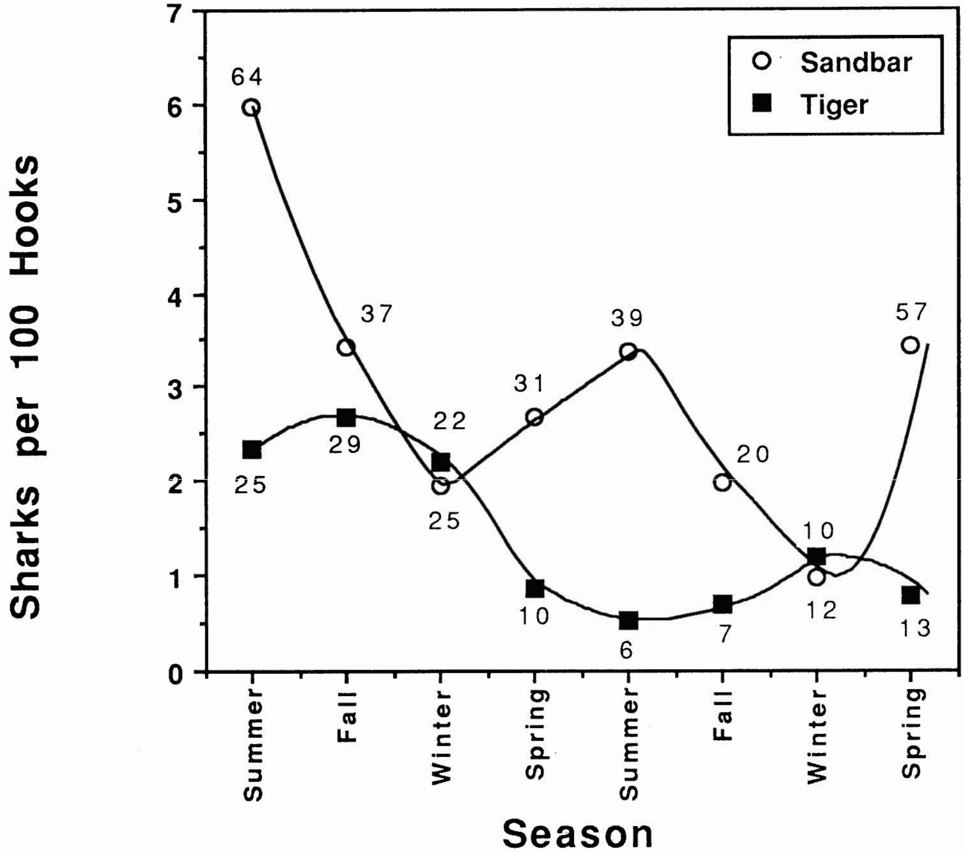


FIGURE 3. Catch rate for sandbar sharks (*Carcharhinus plumbeus*) and tiger sharks (*Galeocerdo cuvier*) captured off Oahu during each season in the 1967–1969 shark control program (data from Tester [1969]). Numbers adjacent to data points represent number of sharks caught.

cuits within a program by modification of fishing techniques could have resulted in the capture of fewer sharks because smaller individuals were excluded. This would have resulted in an underestimation of the number of sharks in fishing areas during later rounds and further complicates comparison of catch rates between fishing rounds.

In each of the major control programs, catch rate was used as an indicator of shark abundance, and catch rates of programs were compared to evaluate changes in the shark population (Ikehara 1961, Tester 1969, Fujimoto and Sakuda 1971). The assumption that catch rate was indicative of the shark population, without considering factors such as fishing technique, may lead to erroneous conclusions about changes in shark abundance. For example, if one assumes that catch rate of tiger sharks was directly proportional to the tiger shark population, one may conclude that continued shark fishing during control programs actually led to an increase in the tiger shark population. The catch rate of tiger sharks increased from 0.9 per 100 hooks during the Billy Weaver program to 1.4 in the

1967–1969 program and to 2.0 for the 1971 program. Tiger sharks made up only 12.5% of the catch in the Billy Weaver program, but increased to 16% in the 1967–1969 program and to 46% in the 1971 program. These changes in catch rate of tiger sharks were more likely the result of selectively catching larger sharks rather than an actual increase in tiger shark abundance.

Although each major control program reported drastic declines in shark abundance at the completion of fishing, the only attempt to estimate shark populations in Hawaii was made by Lawrie (1978), based on catch rate data from the 1967–1969 program. Using the Leslie and DeLury models, Lawrie estimated the tiger shark population in waters around Oahu to be between 80 and 130 individuals at the start of that program. Because 127 tiger sharks were caught around Oahu during that program, Lawrie's analysis appears to grossly underestimate the abundance of tiger sharks. Much of the catch data from the program was not included in Lawrie's analysis because it was inconsistent with the models. Bias was also created in each program by use of gear and bait that favored large sharks and by fishing within a limited portion of the full depth range inhabited by the sharks, thereby sampling a limited portion of the population. Removal of over 100 sharks from the south coast of Oahu during experimental fishing episodes further complicates attempts to determine declines in shark abundance using catch rates. These limitations make it virtually impossible to accurately estimate entire shark populations in Hawaii from the control program data.

Because of the short duration of each of the control programs, annual and long-term changes in the population could not be monitored. Annual variation in shark abundance in a given area may go undetected in the absence of long-term fishing. Cliff et al. (1988) recorded considerable annual variation in catch rate of sandbar sharks captured in South African shark nets. Although catches fluctuated, catch rates were highest during 3 of the last 4 yr of sampling and showed an increasing trend.

Success in Eliminating Large Sharks

Tester (1969) described a decrease in the average size of sharks caught in successive fishing rounds during the 1967–1969 program and suggested that the water was safer for humans because the larger, presumably more dangerous, sharks had been removed. However, decreased average size for sharks overall during the final fishing rounds referred to by Tester is largely due to a decrease in the average size of sandbar sharks during those rounds (Figure 4). The decrease in average size of sandbar sharks during the final circuits in 1969 was primarily due to an increased number of small sharks captured, which Tester attributed to reduced predation resulting from the elimination of large tiger sharks. However, other explanations may include immigration and/or the change of bait from large pieces of tuna in the first seven circuits to smaller akule, *Selar crumenophthalmus* (Bloch) during the final circuit. This change in bait may have affected the size distribution of all shark species in the catch. The highest catch rate of sharks other than sandbar and tiger sharks was recorded during the final fishing circuit. Bait tests conducted during the 1967–1969 program showed that composition of shark catch was influenced by the type of bait used. In bait tests using porpoise, 44% of sharks caught were Galápagos sharks, leading Tester (1969) to conclude that use of tuna for bait during most of the standard fishing was not providing an adequate estimate of Galápagos abundance.

Although changes in the number of large sandbar sharks may have occurred, the change in the size distribution of tiger sharks is of primary interest because these sharks present a much greater danger to humans than sandbar sharks (Compagno 1984). Tiger sharks showed substantial variation in average size over the eight circuits during the 1967–1969 program, with the largest average size recorded during the third to last round (Figure 4). The poor fit of the data to a linear regression model ($r^2 = 0.113$) and low sample sizes in later fishing rounds (Figure 4) do not support Tester's conclusion that the number

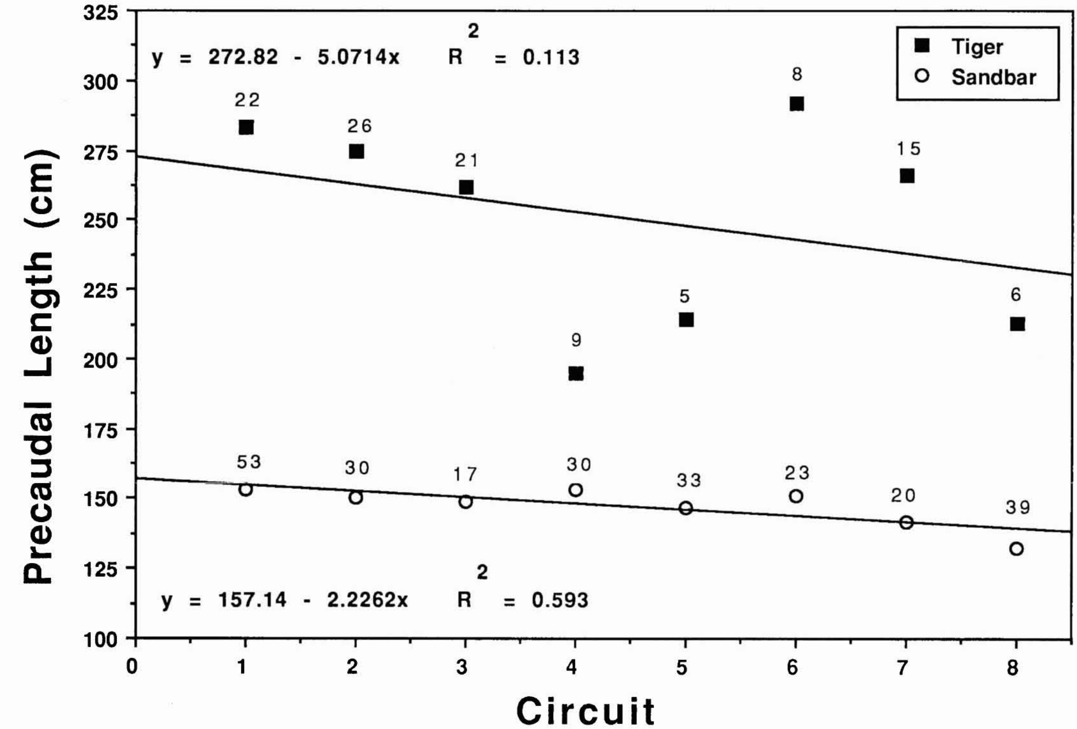


FIGURE 4. Average size of sandbar sharks (*Carcharhinus plumbeus*) and tiger sharks (*Galeocerdo cuvier*) caught in consecutive fishing circuits around Oahu during the 1967–1969 shark control program (data from Tester [1969]). Numbers above data points represent sample sizes.

of large tiger sharks was actually decreased as a result of fishing pressure.

Evidence from shark control programs in Australia indicates that tiger shark populations may be less affected by antishark measures than populations of other species of sharks. Simpfendorfer (1992) concluded that there was no significant reduction in the abundance or mean size of tiger sharks caught during an extensive meshing program in Australia between 1964 and 1986. He suggested that the lack of decline in the local tiger shark population examined was a result of light fishing pressure in relation to population size and movement of tiger sharks over a wide geographical range. Paterson (1990) and Reid and Krogh (1992) found that the number of tiger sharks caught in antishark nets in Australia actually increased between 1962 and 1990.

Based on the results of research conducted during the control programs in Hawaii, it is difficult to quantify the effect the programs actually had on shark abundance and size composition of the populations. However, the real test of success of these control programs is their effectiveness in reducing shark attacks.

Success in Reducing Attacks

Shark attacks dating back to the 1700s have been documented in Hawaii (Balazs and Kam 1981; G. Balazs, 1992, unpublished data), but abatement programs were not initiated until after the fatal attack on Billy Weaver in 1958. According to the International Shark Attack File (ISAF) (kept at Florida Museum of Natural History, University of Florida, Gainesville, by G. Burgess), an incident is considered a shark attack if confirmed as either a provoked or unprovoked attack on a live human in the shark's natural environment; therefore, attacks on dead humans are not considered (G. Burgess, pers. comm.).

Based on records of shark attacks in Hawaii that meet the criteria of the ISAF (drawn from a larger pool of incidents reported by G. Balazs [1992, unpublished data]), there was no difference between the average number of shark attacks per year for the 18 yr before control efforts (0.6) and during the 18 yr that control programs intermittently operated (0.6). A shark attack occurred 3 months before the completion of the 1967–1969 control program, and another attack occurred 5 months after the program had ended (G. Balazs, 1992, unpublished data). In the years following control programs, the rate of attack has increased to an average of 1.4 per year. Although there have been two confirmed fatal shark attacks in Hawaii since 1991, there were no fatal attacks during the 31-yr period between 1959 and 1990. Although the mean number of attacks after control programs seems large compared with numbers from the other periods, the data consist of highly variable, small, discrete numbers. One factor that has undoubtedly increased the number of documented attacks after control programs ended is a greater effort and interest in documenting shark attacks by Balazs since the implementation of an "official list" of Hawaiian shark incidents in 1979.

Rate of shark attacks appears to be better correlated with human population than with shark population. For example, in Florida the rate of shark attacks and the human population have increased in a similar fashion over the past century (Figure 5A). Recently, shark populations in Florida have been severely reduced as a result of overfishing (Manire and Gruber 1990), yet the rate of shark attacks has continued to increase. The resident population of Hawaii has increased from 520,000 in 1946 to 1.1 million in 1990 (Figure 5B). Over the same period of time the number of people visiting Hawaii annually has increased exponentially from 15,000 to 7 million (Hawaii Visitors Bureau, pers. comm.). Because many of the tourists that come to Hawaii engage in water-related activities, using population figures of the resident population grossly underestimates the number of people entering the water. The increasing popularity of water-related activities such as scuba diving and surfing has undoubtedly resulted in an enormous increase in the proportion of people that enter the water. Given this great increase in the number of humans entering the ocean, a concomitant increase in the number of shark attacks per year might be expected. Although there have been more shark attacks during the past few years, the rate of shark attacks in Hawaiian waters has remained fairly constant at less than one attack per year over the past 48 yr. Therefore, based on the available data, shark control programs and the associated reduction in coastal shark populations do not appear to have had a dramatic effect on the rate of shark attacks in Hawaii.

Shark Control Outside Hawaii

Shark control programs have been in operation in Australia since the 1930s and in South Africa since the early 1950s (Wallett 1983, Cliff and Dudley 1992, Reid and Krogh 1992). Longlining has not been used extensively as a method of shark control in other parts of the world. Longlining was abandoned after use for a few years in South Africa (Cliff and Dudley 1992) and has raised concerns about baited lines attracting sharks to regions that they would otherwise not frequent (Paterson 1990). A series of gill nets used to "mesh" beaches has been successful in reducing the number of shark attacks in Australia and South Africa (Cliff and Dudley 1992, Reid and Krogh 1992). However, these successful antishark measures are not without drawbacks. Dolphins, dugongs, turtles, birds, rays, tuna and other teleosts, nondangerous sharks, and even humpback whales are killed in the gill nets (Paterson 1979, Cliff and Dudley 1992, Reid and Krogh 1992). Reid and Krogh (1992) estimated that one dolphin was killed for every 30–40 sharks caught and that one ray was killed for every two or three sharks caught in gill nets off New South Wales.

Removing large numbers of apex predators from a marine area may have large-scale effects on the ecological balance of that region. Large-scale changes observed in the

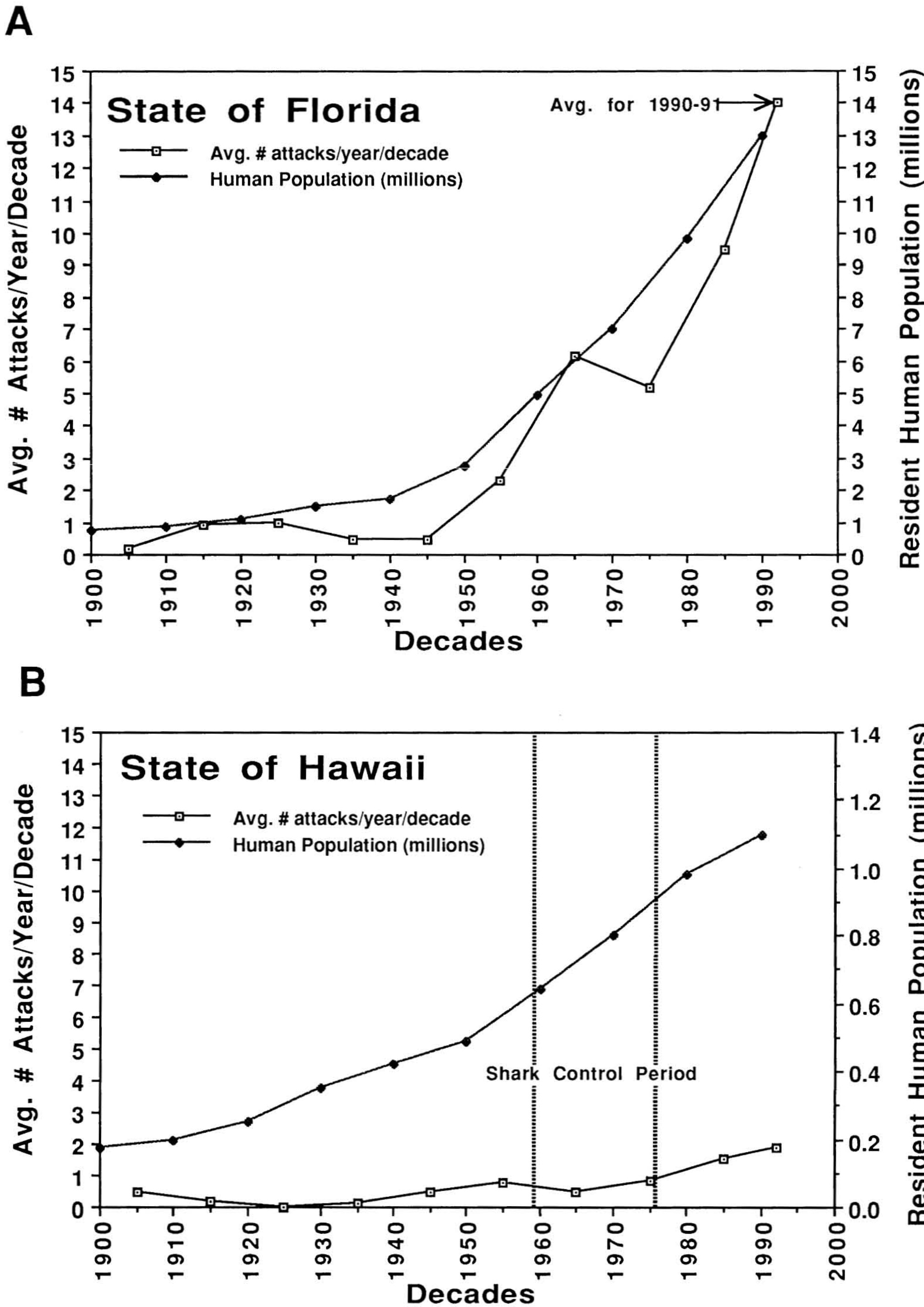


FIGURE 5. Average number of shark attacks per year per decade and resident human population between 1900 and 1992: A, in Florida; B, in Hawaii (Florida attack data from G. Burgess, pers. comm.; Hawaii attack data from G. Balazs, 1992, unpublished data per criteria of the International Shark Attack File).

composition of species of sharks captured in nets in Queensland and New South Wales have been attributed to antishark measures (Reid and Krogh 1992). In South Africa, competition between fishermen and sharks for important fish stocks may have increased because of a proliferation of small sharks as a result of the removal of larger predatory sharks by meshing (van der Elst 1979). Paterson (1990) noted that once introduced, control measures are likely to be permanent, and any deleterious ecological effects that they cause will generally be regarded as unfortunate consequences secondary to consideration of human safety. He recommends a coordinated biological program to monitor the effects of antishark measures both on target and nontarget species.

Shark meshing programs are expensive to initiate and maintain. Installation of gill nets necessary for protective meshing of a beach in South Africa costs roughly $100,000 (U.S.) in its first year, and annual government funding to the Natal Sharks Board for maintaining all antishark measures in South Africa is now over $2 million (U.S.) (Cliff and Dudley 1992). Despite substantial investment in widespread meshing of beaches, shark attacks still occur. With 44 km of nets in place at over 40 beaches in South Africa (and nearly 1500 sharks caught annually), the rate of shark attack was reduced to an average of one per year during the 1980s, but one-third of all attacks occurred at or near protected beaches (Cliff 1991, Cliff and Dudley 1992).

CONCLUSIONS

Control programs have contributed information on sharks, including data on diet, reproduction, species composition, and seasonal distribution. Diet of Hawaiian sharks has also been examined extensively during subsequent studies (Taylor and Naftel 1978, Okamoto and Kawamoto 1980, DeCrosta et al. 1984). Although information on diet and feeding habits can contribute to a greater understanding of the role that sharks play in marine ecosystems (Wetherbee et al. 1990), continued emphasis on examination of stomach contents of large numbers of dead sharks is unlikely to reveal further information useful for control measures.

Because only a small portion of the results of research conducted during control programs was published in reviewed journals, information gained is not available to the scientific community at large. Thus, the programs have made only limited contributions to the understanding of shark biology. Publication in reviewed journals would have resulted in a greater dissemination of information to a much wider audience, a more rigorous analysis of the data, and possibly more restricted endorsement of continued large-scale control efforts.

Because the primary purpose of the control programs was to remove as many sharks as possible, research conducted during the programs was limited largely to information that could be acquired from dead sharks. Although considerable information was obtained for sandbar and gray reef sharks, virtually no information was reported for the tiger shark in regard to depth distribution, population biology, seasonal movements, and sexual segregation. This type of information has particular importance because tiger sharks are responsible for most of the shark attacks in Hawaii (Randall 1992). Future studies involving shark-human interactions in Hawaii should be concentrated on the tiger shark and aspects of their biology that relate to control measures. Whether tiger sharks are far-ranging or site-attached has yet to be determined. Diurnal and seasonal movements of tiger sharks on- and offshore are also poorly understood. The possibility that tiger shark populations are less susceptible to control by antishark measures because of characteristics such as their high fecundity and widespread populations compared with other species remains to be investigated.

Past control programs have not adequately addressed a number of important questions concerning shark behavior that are relevant to shark-human interactions. An understanding of home range, diel activity patterns, social interactions, feeding periodicity, and depth distribution may provide a basis for effectively reducing the probability of shark attack. The above-mentioned aspects of shark behavior can be investigated using modern techniques such as acoustic telemetry and remote sensing (Myrberg 1987). Telemetered sharks can be tracked to determine activity patterns, space utilization, and short-term movements (Tricas et al. 1981, Nelson 1990, Holland et al. 1993). Until short-term behavior of sharks is better understood, the merits of control measures such as selective fishing in an area immediately after an attack remain uncertain. Given that the shark responsible for an attack may have already left an area when baited lines are set to catch the shark, the only value of such a response may be the psychological reassurance to those entering the area that the chances of a second attack are small (Cliff and Dudley 1992).

More extensive tag-and-release studies may be used to examine patterns of migration, distribution, and factors that influence the distribution observed (Casey and Kohler 1992). Tagging studies may also provide information on growth, population size, and segregation based on size or sex (Casey and Taniuchi 1990). Parameters useful for understanding population dynamics (fecundity, recruitment, mortality, age at maturity, DNA fingerprinting) are particularly relevant for managing a population and assessing the effects of human interactions on that population.

Because sharks play an important role as apex predators in marine ecosystems in Hawaii (DeCrosta 1984), removal of large numbers of sharks from an area could drastically affect the natural ecological balance, on a scale similar to what has occurred in Australia and South Africa (van der Elst 1979, Reid and Krough 1992). Dramatic declines in shark populations have occurred over short periods of time elsewhere in the world and are evidence of the susceptibility of sharks to overfishing (Manire and Gruber 1990). Carefully planned and focused trophic research would increase understanding of the importance of sharks in the marine environment and enable assessment of the ecological effects of large-scale shark control in Hawaii. All of these results would contribute to a better understanding of the ecology of sharks and their effects on the ecosystem.

Meshing beaches with gill nets has been effective in reducing the rate of shark attacks in Australia and South Africa and is an option for shark control in Hawaii. However, the high cost of meshing programs, unknown ecological impacts brought on by removing large numbers of sharks, and incidental catch of marine mammals, sea turtles, and other nontarget animals are undesirable aspects of such control measures. The rate of shark attacks in Hawaii is low in comparison with areas where meshing has been initiated, and attacks are rare at Hawaiian beaches most often frequented by tourists. Rough surf conditions at beaches frequented by oceangoers in Hawaii could also present a potential obstacle for maintenance of gill nets.

Public desire for protection against shark attacks is often an emotional issue and may also be a result of economic considerations in areas heavily dependent on tourism. Cliff (1991) attempted to put the threat of shark attack in perspective compared with other ocean-related fatalities by noting that there were only seven shark attacks (none fatal) in South Africa in 1989, while 139 people drowned. A similar situation exists in Hawaii, where there has been an average of less than one shark attack per year compared with an average of 40 drownings per year (State of Hawaii Health Department, pers. comm.).

Success of the past control programs in decreasing shark populations and removing large sharks from Hawaiian coastal waters seems uncertain and appears to have been overestimated in previous reports. The tentative conclusion that these sharks are territorial (based on limited tag-and-recapture data) contributed to the belief that sharks can effectively be eliminated from specific areas. However, long-term site fidelity has not been documented for any species of shark (McKibben and Nelson 1986, Myrberg 1987). Because there is little evidence that increasingly expensive shark control programs have been effective in reducing the already relatively low rate of shark attacks in Hawaii, such large-scale longlining programs may no longer be cost-effective.

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