Depth, capture time, and hooked longevity of longline-caught pelagic fish: Timing bites of fish with chips

Christofer H. Boggs
Honolulu Laboratory, Southwest Fisheries Science Center
National Marine Fisheries Service, NOAA
2570 Dole Street, Honolulu, Hawaii 96822-2396

Abstract.–To resolve the uncertainty in estimating capture depths of fish on pelagic longline gear, electronic microchip hook timers were attached to branch lines to record when bites occurred, and time-depth recorders (TDRs) were attached to longline gear, off Hawaii in January 1989 and January–February 1990. Hook timers indicated that 32% of the striped marlin *Tetrapturus audax*, 21% of the spearfish *T. angustirostris*, and 12% of the bigeye tuna *Thunnus obesus* were caught on sinking or rising hooks, demonstrating that capture time data are needed to correctly estimate capture depth. Recorded and predicted longline depths differed greatly, indicating that TDRs are essential for describing depth distributions of fish from longline catches. Most (>60%) of the spearfish and striped marlin were caught on settled hooks (not sinking or rising) at depths of <120 m, whereas most bigeye tuna were caught at depths of >200 m. This suggests that eliminating shallow hooks could substantially reduce the bycatch of spearfish, striped marlin, and other recreationally important billfish without reducing fishing efficiency for bigeye tuna. Bigeye tuna and striped marlin survived up to 6–9 hours after capture, and over 50% of 12 frequently-caught taxa were alive when retrieved, suggesting that the release of live fish can be an effective management option.

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Targeting specific depths can improve longline catches of desired species, such as bigeye tuna *Thunnus obesus* (Saito 1975, Hanamoto 1976, Suzuki et al. 1977, Suzuki and Kume 1982), and reduce bycatch of other species, such as billfish (Suzuki 1989). However, considerable uncertainty exists in estimating the fishing depth of longline gear. Predicted longline depth based on catenary geometry, line length, and distance between floats (Yoshihara 1954) differs from true depth (Saito 1973, Hanamoto 1974, Nishi 1990) because of currents and other factors, yet depth is often inferred rather than measured (Suzuki et al. 1977, Suzuki and Kume 1982, Hanamoto 1987, Grudinin 1989). Furthermore, fish may be caught while the hooks are sinking, during deployment of the gear, or rising during its retrieval (Saito 1973), making capture depths impossible to estimate accurately without known capture times.

Accurate estimates of fishing depth can be made if time-depth recorders (TDRs) are attached to longline gear. Longline studies using TDRs (Saito et al. 1970, Saito 1973, Yamaguchi 1989, Nishi 1990) have also interpreted TDR depth fluctuations as records of times of capture, but few such measurements exist. Instead, capture has been assumed to occur when the gear is settled, so capture depth has been estimated as settled hook depth (Hanamoto 1976, Suzuki and Kume 1982). Hook timers, designed to indicate when each hook is struck (Somerton et al. 1988), provide a way to measure capture times and survival times of hooked fish. Capture times, together with TDR records, can be used to estimate capture depths accurately.

Billfish catch rates in recreational fisheries may be negatively affected by nearby longline fisheries (Squire and Au 1990), and interest in finding ways to reduce the longline take of billfish without reducing fishing efficiency for target species is increasing (Rockefeller 1989). Information on capture depth, capture time, and hooked longevity can be used to design fishing methods that reduce billfish mortality. Data on the selectivity and efficiency of longline gear at various depths are also critical for stock assessments (Suzuki 1989).

The present study improves methods for estimating capture depths of fish on longline gear using electronic timing devices, and describes the depth distributions and capture times of tunas, billfishes, sharks, and other pelagic fishes in Hawaiian waters in winter. Water temperature and dissolved oxygen (DO) were measured to describe the physical habitat in the study area, since these variables appear to cause geographic variation in depth distributions of fish (Hanamoto 1975, 1987). Relative fishing efficiency and the bycatch of billfish were predicted for several gear configurations.

Table 1

Summary of longline fishing operations conducted by the NOAA ship *Townsend Cromwell* off Hawaii, January 1989 and January–February 1990, giving averages for three set types (ranges in parentheses). Baskets were intervals of continuous main line between floats with snap-on branch lines, not spliced units of gear. Shortening rate was the ratio between ship speed and thrower speed. Depths do not include branch line length. Predicted depths were calculated from the shortening rate and the main line length per basket, assuming a catenary shape. TDR = time depth recorder.

Year	Set type	Sets (no.)	Time		Hooks per set (no.)	Line per basket (m)	Shortening rate (ratio)	Predicted depth (m)	Deep TDR depth (m)	Middle TDR depth (m)
			Begin set	End retrieval						
1989	Regular	6	8:09 (4:31–10:05)	15:24 (14:20–16:41)	199 (128–278)	795 (640–1103)	0.80 (0.69–0.98)	222 (88–304)	111[1] (43–180)	82[2] (32–133)
	Deep	6	8:55 (5:29–12:47)	16:36 (10:34–20:40)	257 (185–392)	1085 (990–1146)	0.59 (0.46–0.83)	415 (273–489)	260 (241–303)	191[2] (178–224)
	Very deep	4	8:23 (8:16–8:41)	19:10 (17:58–20:40)	405 (356–474)	1117 (1053–1146)	0.54 (0.45–0.71)	447 (349–496)	367 (329–400)	270[2] (243–295)
1990	Regular	5	6:50 (6:14–7:18)	19:08 (16:24–22:07)	456 (212–591)	809 (611–1068)	0.78 (0.67–0.90)	243 (150–355)	142 (78–183)	104 (71–140)
	Deep	13	7:18 (6:12–10:04)	19:38 (17:57–20:42)	474 (173–594)	1069 (798–1265)	0.60 (0.40–0.70)	409 (298–499)	249 (193–318)	180 (122–232)
	Very deep	4	5:29 (4:45–6:21)	19:03 (15:30–21:05)	404 (219–600)	1165 (937–1427)	0.62 (0.50–0.74)	436 (303–592)	416 (340–517)	291 (251–381)

[1] TDR data obtained for only three sets.

[2] Calculated from the ratio (0.73) between middle and deep TDR depths of sets in which middle-position data were available.

Materials and methods

Longline fishing was conducted on board the NOAA ship *Townsend Cromwell* in January 1989 and January–February 1990. Sets were made between lat. 14° and 20°N, long. 148° and 159°W, 20–500 nmi from the main Hawaiian Islands, and within an area typically fished by Hawaii's domestic longline fishery. Gear was usually deployed in the morning and retrieved in the afternoon or evening (Table 1), or occasionally at midday to permit a second set on the same day. No sets were made at night. Except for the hook timers and TDRs, the fishing gear and operations were similar to commercial longline fishing methods for tuna in Hawaii (Kawamoto et al. 1989) prior to the advent of night fishing for swordfish *Xiphias gladius*. Both this study and the contemporary commercial longline fishery used a wide variety of fishing depths. Commercial fishermen used more gear (~1000 hooks), let it stay in the water longer (~12 h), and retrieved it faster than in this study.

The fishing gear consisted of 3.5 mm-diameter nylon monofilament main line deployed with a line thrower (Kawamoto et al. 1989). The main line was supported at intervals by vertical, 18 m lines with floats at the ends. Snap-on branch lines made of 2.1 mm-diameter clear-blue nylon monofilament (20 m long in 1989 and 11 m long in 1990) were baited with thawed saury *Cololabis saira* on curved tuna hooks (one hook/branch line) and attached to the main line between float lines. Hooks were size 3.6 (Japanese size is 10.9 cm from eye to point). Each portion of the longline between floats and the attached branch lines constituted a "basket," a term taken from older gear in which the number of branch lines is fixed. However, this study used varying numbers of snap-on branch lines (12, 14, 16, or 20/basket), depending on the length of main line per basket.

Hook position was controlled by timing the attachment of branch lines as the main line was thrown overboard mechanically at a controlled speed. A computer program was used to signal and record attachment times. Deviations from the programmed instructions were noted, providing a record of set times for each hook. The total number of hooks in each set was 128–600, and the amount of main line deployed per set was 9–44 km (Table 1). The amount of gear increased with crew experience but also varied because of inclement weather and equipment failures.

Set depths

Fishing depth was altered by varying the slack in the main line and the length of line per basket (Table 1) and by exogenous factors such as wind and currents. Line slack was quantified as the shortening rate (Saito 1973), or sagging rate (Suzuki et al. 1977), equal to the horizontal distance between floats divided by the length of line per basket (a dimensionless ratio). At deployment, the shortening rate was the same as the ratio of ship speed through the water to line-thrower speed: 0.40 (maximum slack) to 0.98 (no slack). The length of main line per basket was 640–1427m. The predicted maximum depth of the main line during each set was calculated from the shortening rate and the main line length per basket (Table 1), assuming a catenary shape (Yoshihara 1954).

The depth of each set was recorded with electronic TDRs (Wildlife Computers, models MKII and MKIII) programmed to sample depth once per minute. The TDRs were attached at the deep positions, defined as the attachment points for the branch line midway between floats (e.g., position 10 or 11 of 20 between floats). In 1990, TDRs were also attached at the middle positions between the deep positions and the float line (e.g., at position 5 or 15 of 20 between floats).

The time that the gear took to sink during deployment (0.5h) and to rise during recovery (0.5h) was quantified from TDR records. Set depth was described as the typical depth observed in records from the deep-positioned TDRs during the period after sinking and before rising. Recorded depth was examined after each set and compared with predicted depth. Shortening rate, the length of line per basket, or both were adjusted in the subsequent set to reach targeted depths.

Hook depths

The settled depth of each attachment point for the branch line was estimated by interpolating between (1) the TDR record for the deep and middle positions or (2) the latter point and the shallowest depth of the main line (assumed to equal the length of the float line). Settled hook depth was calculated by adding the branch line length to the interpolated depth of the branch line snap. Not enough TDRs were available (2 in 1989, 10 in 1990) to put 1 TDR on every basket. When fish were caught by baskets without TDRs, average TDR depths for that set were used to interpolate settled hook depths. For middle positions without TDRs in 1989, depth was estimated from the mean ratio of the middle position to deep-position TDR depths based on 1990 data.

Hook timers

Hook timers were made of a plastic resin cast around a battery-powered microchip clock controlled by a magnet (Somerton et al. 1988). They were attached to the branch lines near the snap, bridging a bend in the line (Fig. 1). A fish striking the hook pulled the magnet, thus triggering the timer. In 1989, a rubber band held the magnet in place against a test weight of about 1–2kg. In 1990, thread with a breaking strength of 4–5kg bridged the bend in the line, and the magnet was held in place by a weaker thread until the bridging thread was broken (Fig. 1). Some branch lines were set without timers (14% in 1989, 35.5% in 1990) to preclude interruptions in fishing when timers were tangled or otherwise unavailable.

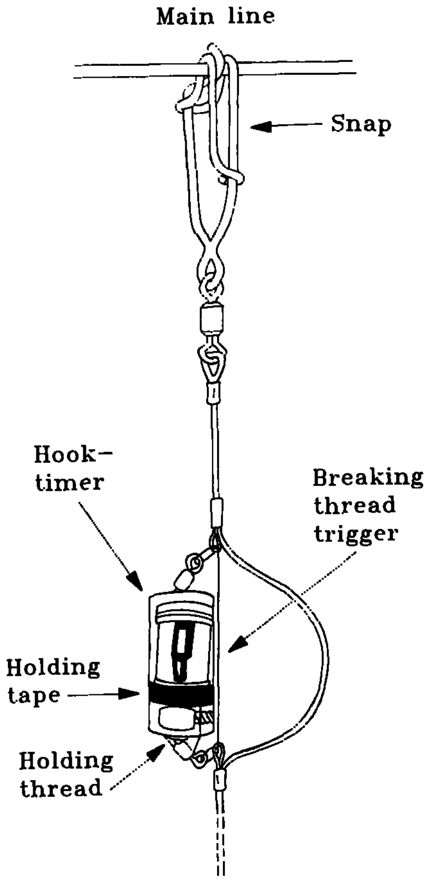

Figure 1
A hook timer and its trigger mechanism as arranged in 1990, when thread triggers were used. In 1989, rubber bands served as the trigger. The slack loop in the branch line was pulled taut when a fish struck the hook, breaking the trigger and pulling the magnet from its recess in the bottom of the hook timer.

Hook timers indicated elapsed time in whole minutes (e.g., 0min indicated 0–59s). Timers were read as the branch lines were recovered, or soon after, with corrections made for delays. Timers were categorized as being triggered (1) at recovery ($\leq$1min before removing the branch line snap), (2) while rising ($>$1min–0.5h before recovery), (3) while settled ($>$0.5–$<$1.0h, 1–$<$2, 2–$<$3h, and so on before recovery), (4) while sinking (<0.5h after gear deployment), (5) at deployment (⩽2 min after deployment), and (6) before deployment (timer triggered before setting commenced). Timers activated but without fish were categorized similarly except all settled categories (>0.5–9.0h) were combined. Untriggered hook timers with fish also were tallied, and hooks with timers that were damaged, broken loose, or tangled too badly to be triggered were counted as hooks without timers.

The numbers of fish caught while the gear was sinking, settled, and rising were summarized. The unconfirmed depth of capture of each fish was defined as the settled depth of the hook. Capture depths were considered confirmed only if hook timers indicated the capture occurred within the period in which the gear was settled.

Catch and effort

Live fish that were not needed as specimens were tagged and released. Steel head "H" type dart tags (Squire 1987) were applied using a 3m tagging pole while the fish remained in the water. Billfish were also injected with 5–20mg oxytetracycline/kg of fish using pole-mounted syringes (Foreman 1987) to mark hard parts for validation of growth increments. Fish were released by cutting the branch lines close to the hooks with a tree-trimming pole. The condition (alive or dead) of the retained fish was noted, and it was weighed to the nearest 0.5kg or measured to the nearest 0.1cm. For the five most-frequently-caught species of commercial importance, catch, number of hooks, and number of hooks with timers were stratified into 40m strata (40–<80m, 80–<120m, and so on) based on settled hook depths. The catch-per-unit-effort (CPUE) in each depth stratum was examined in two ways: (1) by confirmed capture depth ($CPUE_D$ in number of fish/1000 hooks with timers) representing the depth distribution of fish; and (2) by settled hook depth ($CPUE_H$ in number of fish/1000 hooks), representing the total effectiveness of hooks while sinking, settled, or rising.

The $CPUE_H$ for each depth was used to predict catch rates of "standardized" types of gear to illustrate the use of catch by hook position in estimating relative gear efficiency for different gear configurations. Total CPUE for each standardized gear configuration was estimated by calculating the weighted average $CPUE_H$, with weights corresponding to a given number of hooks per depth stratum for each configuration. Total CPUE was calculated from 1989 and 1990 data separately and averaged. Gear efficiency was calculated as the ratio of the predicted CPUE for each configuration to that of the regular configuration.

Standardized regular and deep longline gear configurations were assumed to have 6 and 13 hooks/basket, respectively. A shortening rate of 0.6 and the dimensions in Suzuki et al. (1977; without adjustment for currents) indicated hook depths of about 95, 140, and 170m (for regular gear) and 100, 145, 190, 230, 265, 290, and 300m (for deep gear). These depths correspond roughly to the midpoints of hook depth strata in the present study (100, 140, 180, 220, 260, and 300m).

In addition to regular and deep gear, CPUE values for two hypothetical gear types were predicted: (1) shallow gear for which hooks are limited to the first three depth strata of this study; and (2) a proposed new gear for which no hooks would be deployed in the first three depth strata and the distribution of deeper hooks would match that of deep gear. The shallow gear configuration may be representative of that achieved by Hawaii's longline fishermen in 1989 and 1990 when they first began using monofilament longline and had difficulty achieving the depths formerly fished with traditional rope gear. With the rope gear, slack was obtained by manually throwing the baskets with the main line partially coiled. The [predicted] CPUE for the new gear type was estimated to indicate the reduction in bycatch of some species by the elimination of shallow hooks.

To show CPUE as it would appear in a study of gear configurations without hook position, capture depth, or capture time information, $CPUE_S$ values were calculated from catch and effort by set type. Sets were categorized on the basis of depth (TDR depth plus branch line length) into three groups: 60–<200m (regular), 200–<330m (deep), and 330–530m (very deep). The first two groups contained depth ranges roughly comparable to those expected for regular and deep longline gear types, assuming a variety of shortening rates and variation due to ocean currents (Suzuki et al. 1977).

Oceanography

Vertical temperature structure in the area of each set was measured by expendable bathythermographs (XBTs; 400m depth) and conductivity-temperature-depth casts (CTDs; 500–1000m depth, usually 500m) before or after each set. Water samples were taken with Niskin bottles to measure DO and to calibrate DO measurements made by CTDs.

Many of the TDRs were equipped with a second channel to record temperature. The TDRs were attached to the CTD probe to calibrate depth and temperature measurements. The TDR temperature data were used to estimate set depths exceeding 400m (the lower limit for accurate range depth measurement from the TDRs).

Table 2

Catch data for 14 frequently-caught taxa in research longline sets off Hawaii, January 1989 and January–February 1990. Some weights were calculated from length measurements; some fish (i.e., those released) were not weighed.

Species	No. caught	No. weighed or measured	Weight (kg) Average	Weight (kg) Range	Alive (%)
Bigeye tuna *Thunnus obesus*	76	32	31.5	2.5–69.5	83
Yellowfin tuna *T. albacares*	16	11	39.5	7.5–62.5	63
Skipjack tuna *Katsuwonus pelamis*	5	5	9.0	7.0–11.0	20
Wahoo *Acanthocybium solandri*	4	3	17.5	7.5–25.0	0
Striped marlin *Tetrapturus audax*	67	20	18.0	9.5–37.0	71
Spearfish *T. angustirostris*	41	23	13.5	8.5–18.5	56
Mahimahi *Coryphaena hippurus*	90	60	6.5	2.5–16.0	88
Pomfrets (Bramidae)	17	15	5.5	2.0–10.0	86
Lancetfish *Alepisaurus ferox*	132	111	1.5	0.1–8.0	64
Ribbonfish *Trachipterus ishikawae*	4	2	8.0	7.0–8.0	75
Brown ray *Dasyatis violacea*	8	4	2.0	1.0–2.5	88
Whitetip shark *Carcharhinus longimanus*	26	—	—	—	85
Blue shark *Prionace glauca*	21	1	68.0	—	100
Thresher shark *Alopias* spp.	6	1	91.0	—	60

Results

A total of 16 longline sets caught 149 fish in 1989 and 22 sets caught 401 fish in 1990. Fishing effort totaled 14,410 hooks including 10,236 hooks with timers. There were 14 taxa for which more than 3 fish were caught (Table 2).

Achieving deep sets when intended was sometimes difficult. Backlash of the main line into the hydraulic line thrower created problems at high thrower speeds, and ship speed through the water was sometimes underestimated, reducing the shortening rate. Wind and currents reduced set depth by dragging floats and parts of the line in opposing directions. In particular, current shear between the surface and the waters below the thermocline, observed with an acoustic Doppler current profiler, seemed to prevent deep sets. Observed set depths were highly variable and usually less than the predicted depths (Table 1, Fig. 2). For example, at a predicted depth of about 490 m, observed depths were 200–400 m (Fig. 2). Sets averaged only 54% and 68% of the predicted depths in 1989 and 1990, respectively. For the first three sets in 1989, the TDRs failed, so depth was estimated as a percentage of the predicted depth based on the average percentage (49.3%) obtained from the next three sets with similar configurations.

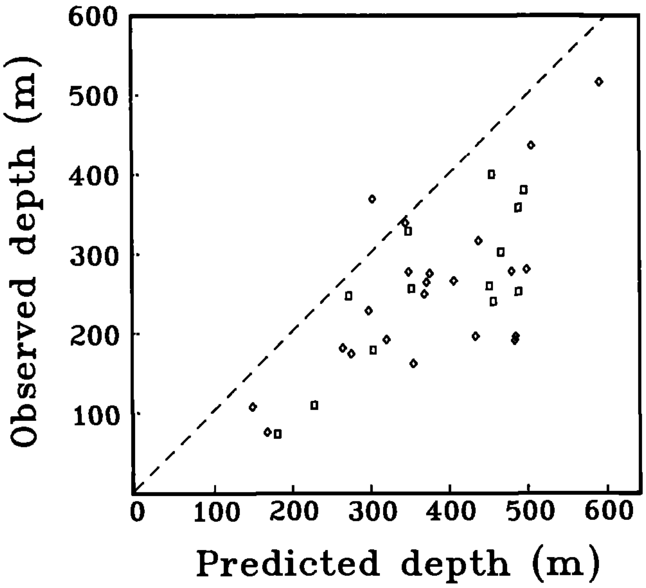

Figure 2

Relationship between predicted and observed set depths in 1989 (□) and 1990 (◇). Observed depths were measured with time-depth recorders, and predicted depths were calculated from the shortening rate and the main-line length per basket, assuming a catenary shape.

Capture depths

Capture depths were confirmed for those fish caught >0.5 h after deployment and >0.5 h before retrieval, because the TDR records showed that the main line usually took 0.5 h to sink to within about 90% of its settled depth and about 0.5 h to rise to the surface during retrieval (Fig. 3). Records of settled depth sometimes varied ≤100 m for the deep sets (e.g., set 14;

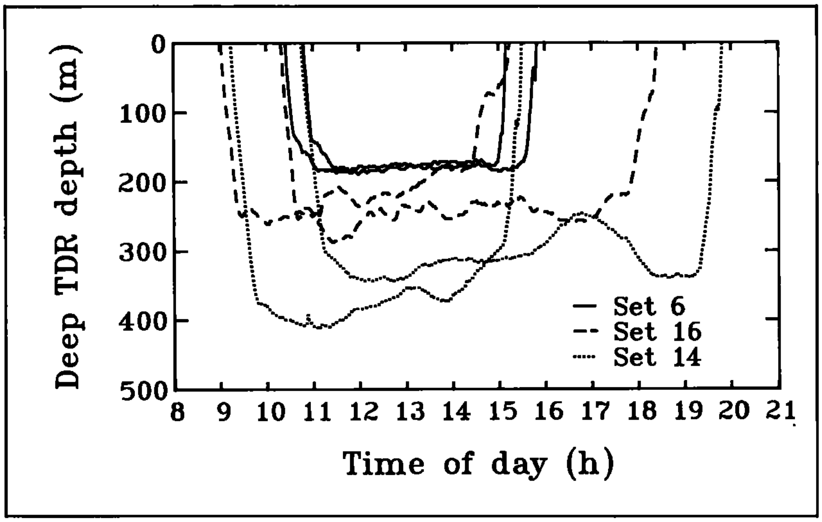

Figure 3 (left)
Sample records from time-depth recorders (TDRs) measuring the deep positions on three sets (each with two TDRs) in 1989, illustrating the typical sinking time (0.5 h), variation in settled depth, and typical rising time (0.5 h).

Figure 4 (below)
Hook depths for catches of 14 frequently-caught taxa in a study off Hawaii, winter 1989 and 1990 (combined). Settled hook depths are shown for all hooks that caught fish (unconfirmed) and for those hooks that caught fish while settled (i.e., not sinking or rising) as indicated by hook-timer data (confirmed).

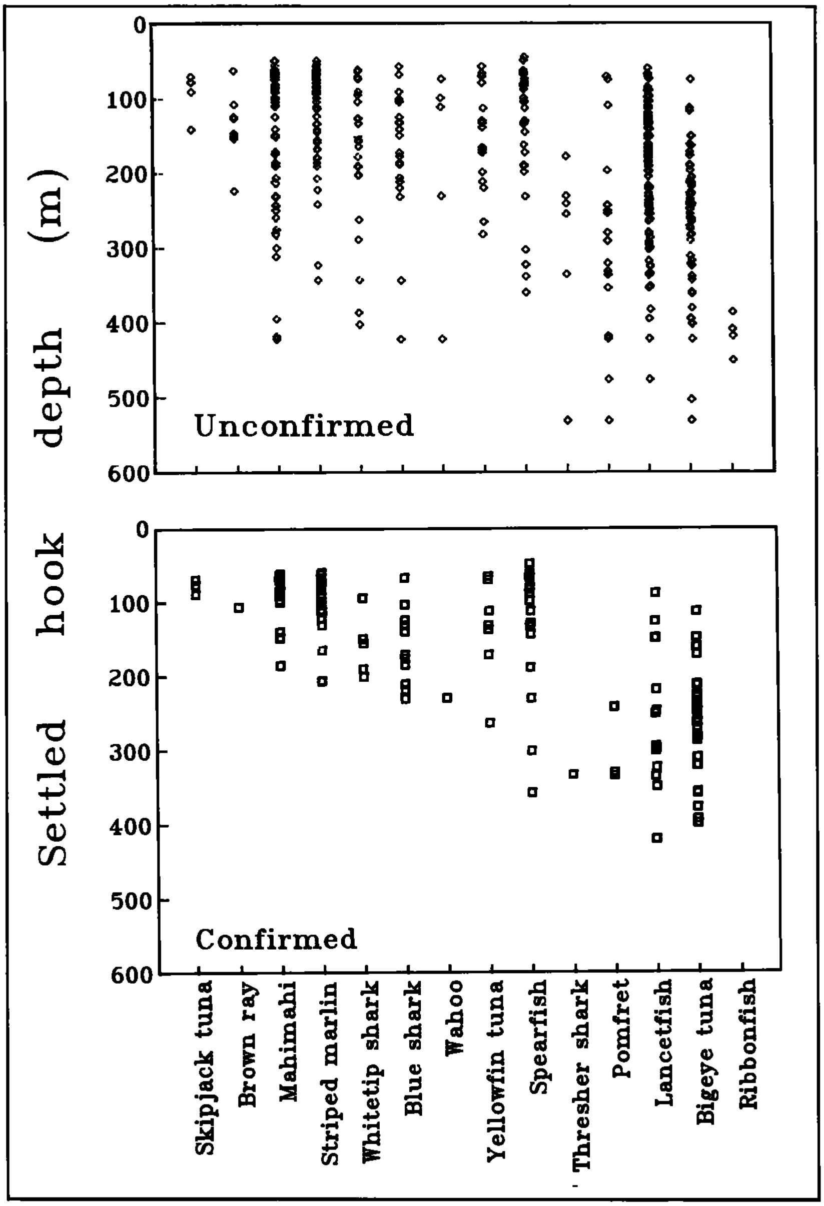

Fig. 3) and ≤40 m for the regular sets. Also, the gear sometimes took more than 0.5 h to rise (e.g., the first TDR on set 16; Fig. 3) or sink. Such deviations contributed to the variation in estimated capture depths. Capture depths of fish caught with hook timers on baskets with TDRs were based on the TDR depth at the time of capture; however, most catches were made by baskets without TDRs.

A comparison between the unconfirmed depths of all hooks that caught fish and those confirmed to have caught fish while settled (Fig. 4) showed that without hook-timer confirmation, many fish appeared to be caught at greater depths than they actually were. For example, mahimahi *Coryphaena hippurus* had unconfirmed capture depths of ≤420 m and confirmed capture depths of <190 m. Most confirmed capture depths were <100 m for mahimahi and skipjack tuna *Katsuwonus pelamis*. Striped marlin *Tetrapturus audax*, whitetip shark *Carcharhinus longimanus*, blue shark *Prionace glauca*, and wahoo *Acanthocybium solandri* had unconfirmed depths of ≤350–420 m and confirmed depths of <200–230 m. Species having a preponderance of confirmed capture depths of <150 m were yellowfin tuna *Thunnus albacares*, striped marlin, and spearfish *Tetrapturus angustirostris*. Most confirmed capture depths were >200 m for thresher shark *Alopias* spp., pomfrets (Bramidae; species included *Taractichthys steindachneri, Taractes rubescens, and Eumegistus illustris*), lancetfish *Alepisaurus ferox*, and bigeye tuna (Fig. 4).

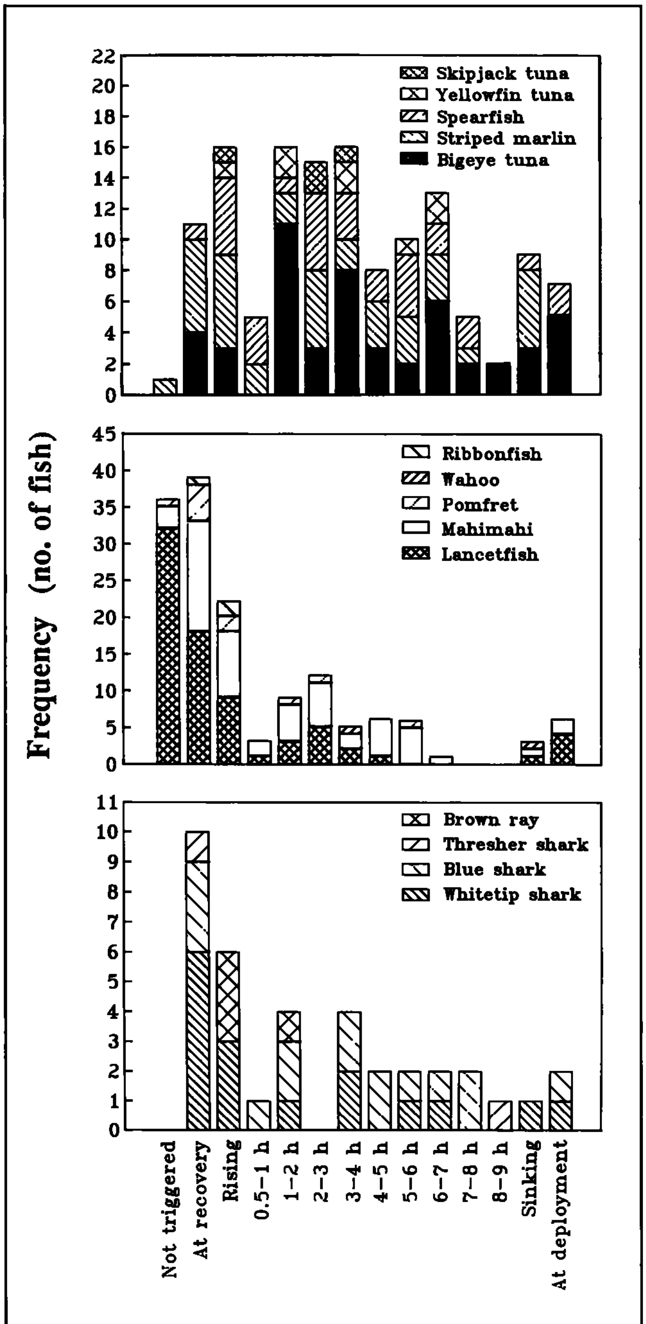

Figure 5

Hook-timer data for 14 taxa caught off Hawaii, winter 1989 and 1990 (combined). Height of each bar represents the sum of frequencies for each taxa (stacked bars). Hook timers were either not triggered, triggered while the gear was being set or recovered, or triggered by fish caught while gear was sinking, settled (0.5–9.0 h before recovery), or rising.

Capture times

Most of the fish (except ribbonfish *Trachipterus ishikawae* and brown ray *Dasyatis violacea*) were caught

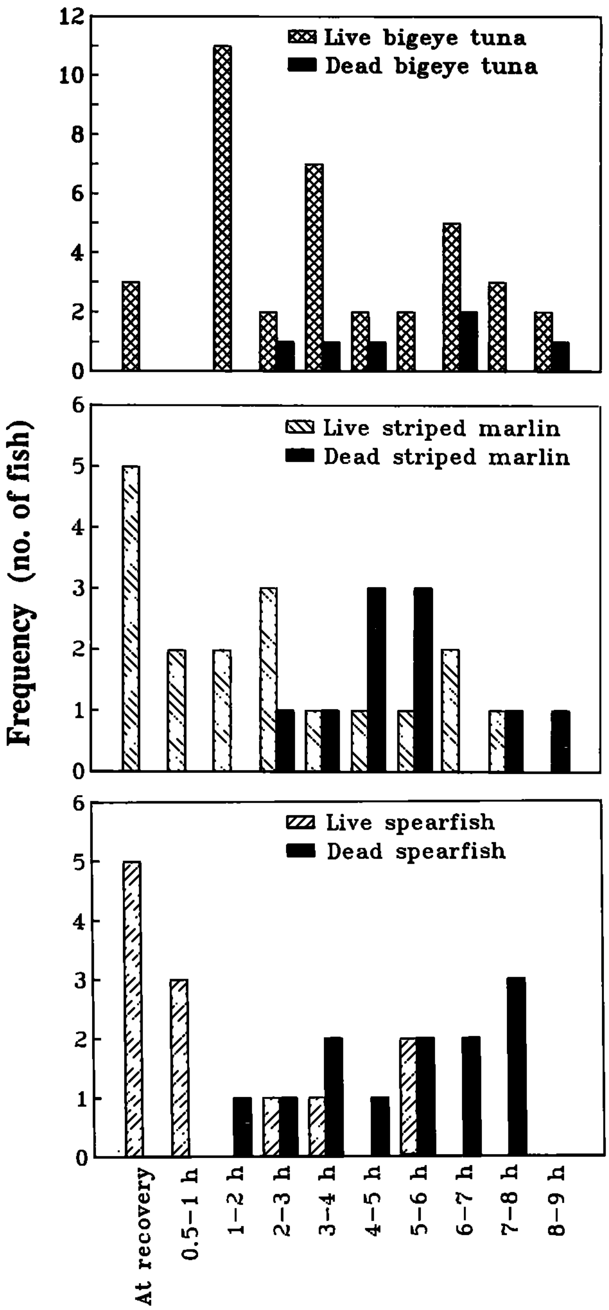

Figure 6

Condition (alive or dead) of three important species in relation to the elapsed time between capture and recovery as indicated by hook timers, during a study off Hawaii, winter 1989 and 1990 (combined).

while the gear was settled rather than while it was sinking or rising (Fig. 5), probably because the gear spent much more time in the settled position. However, substantial numbers of mahimahi, billfish, and other species were caught while the gear was rising (Fig. 5), which explains how fish were caught on deep-positioned hooks (unconfirmed depths) when their confirmed depth distribution was shallow (confirmed depths; Fig. 4).

For many species, catch-per-unit-time (CPUT) may have been highest while the gear was rising. The CPUT values at <3 and ≥3h before recovery were not directly comparable because short sets resulted in lower effort (number of hooks with timers) ≥3h before recovery. The catch in the 1–2h and 2–3h periods (Fig. 5) must be divided by 2 for comparison with the CPUT in the 0.5h and 0.5–<1.0h periods. For periods of 0.5–1.0, 1–2, and 2–3h before recovery, CPUT values were less than during the rising period for ribbonfish, pomfrets, mahimahi, lancetfish, striped marlin, spearfish, brown ray, and whitetip shark (Fig. 5). In contrast, the values for yellowfin and skipjack tunas were not much different between settled and moving gear and were highest for bigeye tuna 1–2h and 3–4h before recovery. Blue shark CPUT values were highest 1–2h before recovery.

Relatively large numbers of fish were categorized as caught at recovery (Fig. 5). However, estimates of the delay between recovery and reading each timer were not precise (± 1 minute). Thus some fish caught "at recovery" actually had timers triggered after recovery. Hook timers that did not catch fish were most often triggered "at recovery" (Table 3), suggesting that handling activated the timers. A similar lack of precision affected capture times "at deployment."

Hooks with timers triggered by small fish or without catching fish may have resulted in false capture times if larger fish were caught later on those hooks. Fortunately, small (<10kg) fish, particularly lancetfish (Table 2), were most frequently caught without triggering the timers (Fig. 5). It was unusual for larger (~10–90kg) fish, such as tunas, billfishes, or sharks (Table 2, Fig. 5), to be caught without triggering the timers. The increase in breaking strength of the triggers in 1990 (Fig. 1) decreased the relative number of small fish that triggered timers, and reduced the proportion of timers triggered without catching fish from 18.5% in 1989 to 9.7% in 1990 (Table 3).

Survival and release

Over 56% of the fish other than wahoo and skipjack tuna were alive when recovered, and for most species, survival was higher than 70% (Table 2). Based on fish with hook-timer data, over half of the bigeye tuna recovered up to 9h after capture were alive. None of the 11 bigeye tuna recovered 1–2h after capture were dead, and the shortest period between capture and recovery of dead bigeye tuna was 2–3h (Fig. 6). Striped marlin were less hardy, with over half recovered dead ≥3h after capture; nevertheless, many were recovered alive up to 6–8h after capture (Fig. 6). Spearfish were the least hardy: The longest survival time was 5–6h, and dead fish were recovered at <1–2h after capture (Fig. 6).

Of the 29 bigeye tuna, 35 striped marlin, and 11 spearfish tagged during the study, 2 bigeye tuna and 1 striped marlin were recaptured 3–10 months later. These three fish were tagged after having been on branch lines for 3–6h. The marlin had been injected

Table 3

Frequencies of activated hook timers on branch lines without fish (as percentage of total timers) categorized by elapsed time since the timers were triggered (range of values from individual sets in parentheses).

	Elapsed time							
	Before retrieval			After deployment				
Year	At retrieval (≤1 min)	Rising (>1–30 min)	Settled (≥30 min)	Sinking (≤30 min)	At deployment (≤2 min)	Activated before deployment	No. timers	Branch lines with timers (%)
1989	6.4	1.2	3.9	1.0	4.8	1.0	3744	86.0
	(–)*	(0–3.2)	(0.8–7.1)	(0–5.7)	(1.6–7.1)	(0–3.3)	(126–356)	(61–100)
1990	3.8	1.5	2.6	0.4	1.0	0.4	6492	64.5
	(1.1–6.2)	(0–4.8)	(0.8–6.5)	(0–1.1)	(0–2.6)	(0–2.4)	(167–418)	(34–99)
Combined	4.7*	1.4	3.1	0.6	2.4	0.6	10236	71.0

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* Number recorded only during the first set in 1989. To calculate the combined frequency (4.7%), frequency was assumed to be 6.4% throughout 1989.

with 6 mg/kg oxytetracycline, but no flourescent mark was found in the otolith or vertebrae.

Abundance in relation to depth

For bigeye tuna, the depth distribution of $CPUE_D$ values (number of fish/1000 hooks with timers) was similar in 1989 and 1990, with $CPUE_D$ highest at 360–400 m and relatively high at 200–400 m (Fig. 7). Hooks with timers triggered before or at deployment could not be subsequently triggered; therefore, they were counted as hooks without timers when $CPUE_D$ was calculated (Table 4). The data from wider depth ranges in both years were pooled to obtain sample sizes (number of hooks with timers; Table 4) large enough to determine whether significant differences existed between depths (Fig. 8). For bigeye tuna, $CPUE_D$ values were significantly higher at depths of >200 m than at depths of <200 m ($P<0.05$, based on 95% CI for the difference between proportions). Few (12%) of

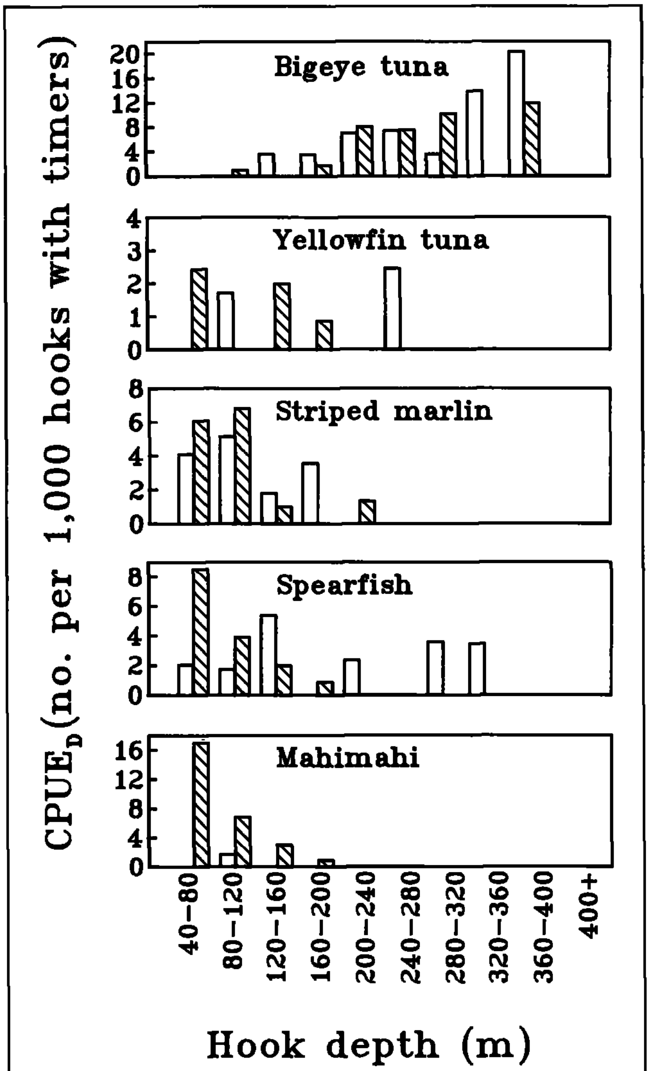


Figure 7

Indices of fish abundance vs. depth, calculated as the number of fish caught/1000 hooks with timers ($CPUE_D$) in ten depth strata. Indices for 1989 (open bars) and 1990 (crosshatched bars) are based on fish captured while the gear was settled (as confirmed by hook timers) (Table 4).

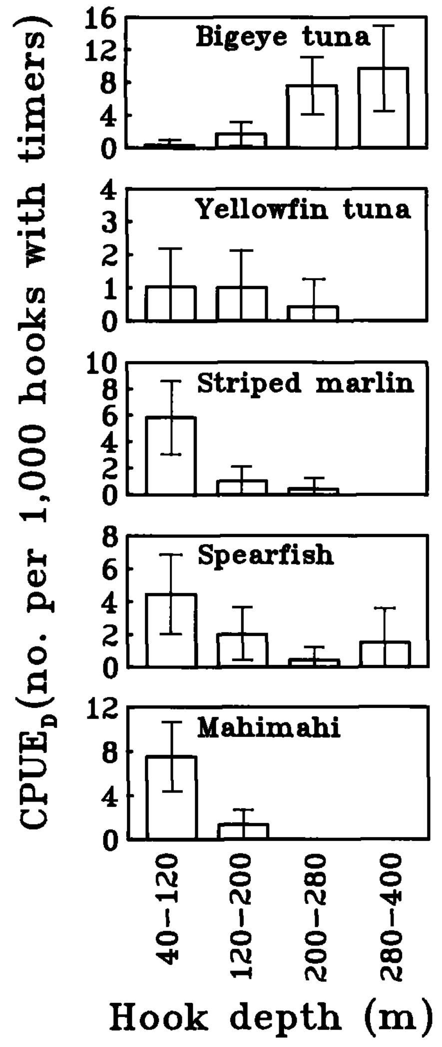


Figure 8

Indices of fish abundance vs. depth, calculated as the number of fish caught/1000 hooks with timers ($CPUE_D$) in four pooled hook-depth strata. Indices for 1989 and 1990 combined are based on fish captured while the gear was settled (as confirmed by hook timers) (Table 4). Error bars indicate 95% CI of the $CPUE_D$ values for each depth category.

the bigeye tuna with hook timers were caught while the hooks were moving (sinking or rising; Table 4). No clear relationship existed between depth and the proportion caught on moving hooks (Table 4).

Yellowfin tuna were not very abundant, which is typical for the winter months off Hawaii. The $\mathrm{CPUE_D}$ for yellowfin tuna was not the same in both years (Fig. 7), but the number of fish caught with timers was very small, particularly in 1989 (Table 4). Pooled $\mathrm{CPUE_D}$ was highest at 40–200 m (Fig. 8) although no significant difference in $\mathrm{CPUE_D}$ by depth was found. The 40 m end of the depth range did not indicate the shallowest depths preferred by any species, since no hooks fished depths of <40 m.

Timer-confirmed catches by settled hooks indicated the highest catch rates for striped marlin were at 40–120 m in both years (Fig. 7), and pooled $\mathrm{CPUE_D}$ was clearly the highest at this depth range (Fig. 8). The overall proportion of striped marlin caught on moving hooks was high (32%; Table 4) and increased with depth. At >120 m most striped marlin were caught by moving hooks, and at >200 m only one was caught by a settled hook (Table 4).

For spearfish, the pattern of $\mathrm{CPUE_D}$ vs. depth differed between years. In 1989, the highest $\mathrm{CPUE_D}$ was at 120–160 m although several fish were caught as deep as 280–360 m; however, in 1990 the highest $\mathrm{CPUE_D}$ was at 40–80 m, and no confirmed capture depths were recorded at >200 m (Fig. 7). Pooled data suggested that spearfish were more abundant at <120 m, but the $\mathrm{CPUE_D}$ at 40–120 m was not significantly different from that at 120–200 m (Fig. 8). In 1989, a large proportion (43%) of the spearfish were caught on moving hooks, but none were caught on moving hooks in 1990 (Table 4). Furthermore, for each of the major species, a higher proportion of fish were caught on moving hooks in 1989 than in 1990 (Table 4). An early report (Boggs 1990) on this research was based on 1990 data (Table 4) wherein only 12% of the tuna and billfish (combined) were caught on moving hooks.

Table 4

Catch of five commercially-important species in research longline sets off Hawaii, 1989 and 1990, giving fishing effort (number of hooks and timers) by depth strata, number caught (*N*) on known hook position, number confirmed by timers to be caught on moving (M; i.e., sinking or rising) and settled (S) hooks (in parentheses), and percentage of fish caught on moving hooks. Depth ranges include branch line length. Timers do not include those triggered at or before deployment. Catch totals are sometimes less than in Table 2 and Figure 5 because hook number and depth were not known for a few fish.

Hook depth (m)	Year	Hooks in stratum	Timers in stratum	Bigeye tuna		Yellowfin tuna		Striped marlin		Spearfish		Mahimahi	
				N (M, S)	Moving (%)	*N* (M, S)	Moving (%)	*N* (M, S)	Moving (%)	*N* (M, S)	Moving (%)	*N* (M, S)	Moving (%)
40–80	1989	546	489	1 (0,0)	—	0 (0,0)	—	5 (0,2)	0	4 (1,1)	50	3 (0,0)	—
	1990	1214	822	0 (0,0)	—	4 (0,2)	0	16 (1,5)	17	8 (0,7)	0	41 (5,14)	26
80–120	1989	684	586	0 (0,0)	—	1 (0,1)	0	9 (1,3)	25	4 (1,1)	50	2 (0,1)	0
	1990	1612	1026	2 (0,1)	0	0 (0,0)	—	15 (2,7)	22	5 (0,4)	0	14 (1,7)	12
120–160	1989	658	558	2 (0,2)	0	0 (0,0)	—	6 (2,1)	25	5 (1,3)	25	1 (0,0)	—
	1990	1611	1007	0 (0,0)	—	3 (0,2)	0	3 (1,1)	50	3 (0,2)	0	5 (1,3)	25
160–200	1989	350	281	1 (0,1)	0	0 (0,0)	—	2 (1,1)	50	1 (1,0)	100	0 (0,0)	—
	1990	1812	1151	6 (1,2)	33	4 (0,1)	0	5 (1,0)	100	5 (0,1)	0	6 (0,1)	0
200–240	1989	553	427	6 (1,3)	25	1 (1,0)	100	2 (0,0)	—	1 (0,1)	0	1 (1,0)	100
	1990	1160	748	11 (1,6)	14	1 (0,0)	—	1 (0,1)	0	0 (0,0)	—	4 (0,0)	—
240–280	1989	524	406	5 (0,3)	0	1 (0,1)	0	0 (0,0)	—	0 (0,0)	—	1 (0,0)	—
	1990	1321	795	11 (0,6)	0	1 (0,0)	—	0 (0,0)	—	0 (0,0)	—	6 (1,0)	100
280–320	1989	353	279	3 (0,1)	0	0 (0,0)	—	0 (0,0)	—	1 (0,1)	0	1 (0,0)	—
	1990	626	395	7 (0,4)	0	0 (0,0)	—	0 (0,0)	—	0 (0,0)	—	1 (0,0)	—
320–360	1989	384	288	7 (1,4)	20	0 (0,0)	—	2 (1,0)	100	4 (2,1)	67	0 (0,0)	—
	1990	198	152	0 (0,0)	—	0 (0,0)	—	0 (0,0)	—	0 (0,0)	—	0 (0,0)	—
360–400	1989	214	148	6 (1,3)	25	0 (0,0)	—	0 (0,0)	—	0 (0,0)	—	0 (0,0)	—
	1990	108	84	2 (0,1)	0	0 (0,0)	—	0 (0,0)	—	0 (0,0)	—	1 (0,0)	—
400+	1989	87	60	2 (0,0)	0	0 (0,0)	—	0 (0,0)	—	0 (0,0)	—	0 (0,0)	—
	1990	276	225	2 (0,0)	—	0 (0,0)	—	0 (0,0)	—	0 (0,0)	—	2 (1,0)	100
Total	1989	4352	3522	33 (3,17)	15	3 (1,2)	33	26 (5,7)	38	20 (6,8)	43	9 (1,1)	50
	1990	10,058	6402	41 (2,20)	9	13 (0,5)	0	40 (5,14)	26	21 (0,14)	0	80 (9,25)	26
Combined total		14,410	9924	74 (5,37)	12	16 (1,7)	12	66 (10,21)	32	41 (6,22)	21	89 (10,26)	28

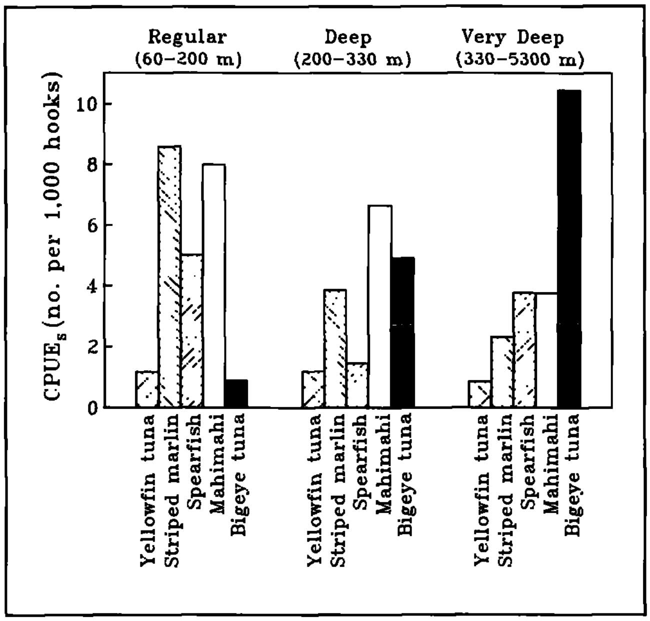
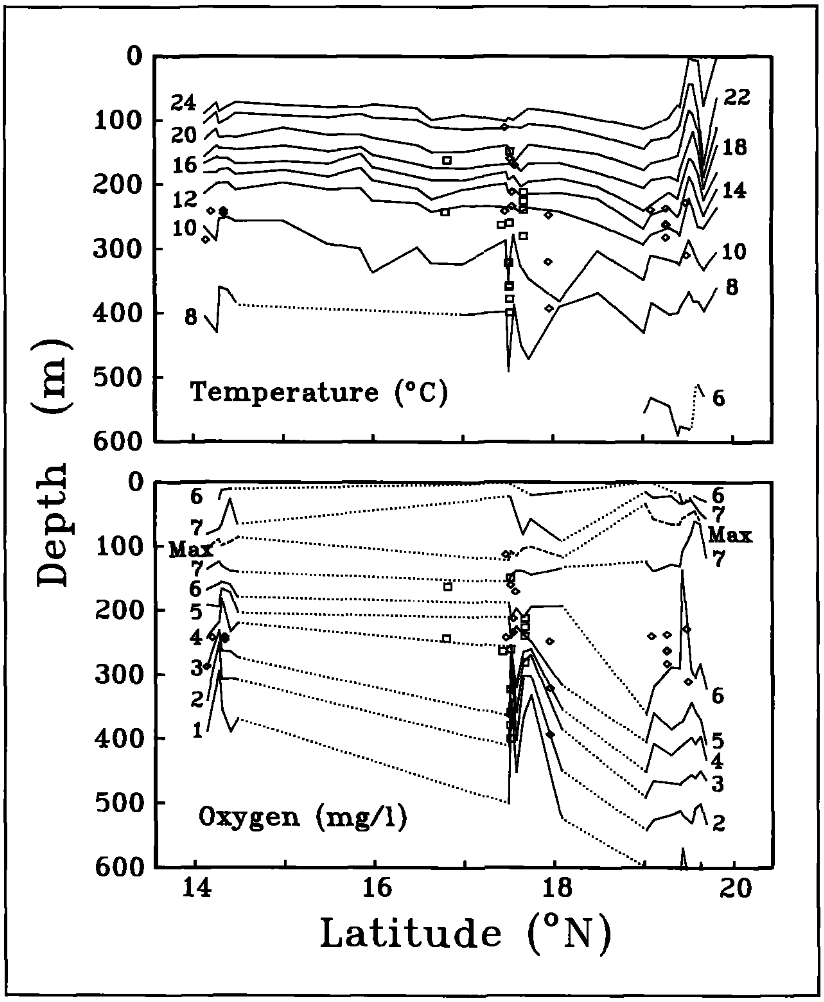


Figure 9

Comparison between indices of fish abundance from different types of longline sets, calculated as the number of fish caught/1000 hooks without regard to capture depth of individual fish (CPUE$_S$). Three types of longline sets were categorized on the basis of the deepest hooks, but every set contained some hooks as shallow as 40–80 m. Data are combined for 1989 and 1990.

Although relatively few mahimahi were captured with timer data, these data indicated maximum abundance was at 40–80 m in 1990 (only one fish was caught on a settled hook in 1989; Fig. 7, Table 4). Pooled data clearly indicated that CPUE$_D$ was highest at 40–120 m (Fig. 8). At >200 m, all mahimahi with timer data were caught on moving hooks.

Examining the CPUE$_S$ data as if the only available depth information were the set type (Fig. 9) made it difficult to correctly qualify the relative abundance of fish in relation to depth. For example, mahimahi appeared almost as abundant in deep sets as in shallow sets, and spearfish appeared more abundant in very deep than in deep sets, illustrating that it is impossible to correctly describe fish depth distributions without data on catch by hook position, hook depth, and capture time.



Oceanographic habitat

The temperature profile in 1990 (Fig. 10) was representative of the study area in both years, except the bottom of the thermocline (i.e., the 12°C isotherm) was ~40 m deeper in 1989. In both years, the highest catch rate of bigeye tuna with confirmed capture depths occurred at lat. 17°–18°N at 360–400 m in temperatures of 8°–10°C (Fig. 10).

The oxycline in 1990 (Fig. 10) also was similar to that in the previous year (i.e., the 3.0 mg/L isopleth was only 10–20 m deeper in 1989). Most bigeye tuna were caught at DO concentrations of 2–6 mg/L. In both years, the highest catch rate was at 2–3 mg/L.

Figure 10

Temperature and dissolved oxygen profiles of the study area (lat. 14°–20°N, long. 148°–159°W) in 1990 (similar to 1989). Confirmed capture depths of bigeye tuna in 1989 (□) and 1990 (◊) are indicated.

Table 5

Standardized distribution of hooks by depth stratum for four standardized gear types and predicted catch-per-unit-effort (CPUE) for each gear type based on the weighted average observed CPUE by hook depth for five commercially-important species in research longline sets off Hawaii, 1989 and 1990. For each species, relative gear efficiency is given as the ratio between the CPUE for each gear type and for regular gear (too few yellowfin tuna (*N* 3) were caught in 1989 to warrant calculating relative gear efficiency).

Model gear type	Hook number by depth (m)							Year	Bigeye tuna		Yellowfin tuna		Striped marlin		Shortbill spearfish		Mahimahi	
	40–80	80–120	120–160	160–200	200–240	240–280	280–320		CPUE	CPUE ratio	CPUE	CPUE ratio	CPUE	CPUE ratio	CPUE	CPUE ratio	CPUE	CPUE ratio
Regular	0	2	2	2	0	0	0	1989	1.93	1.00	0.47		9.30	1.00	5.37	1.00	1.43	1.00
								1990	1.52	1.00	1.36	1.00	4.83	1.00	2.57	1.00	5.03	1.00
								$\bar{x}$	1.73	1.00	0.91		7.07	1.00	3.97	1.00	3.23	1.00
Deep	0	2	2	2	2	2	3	1989	5.95	3.08	0.78		4.85	0.52	3.50	0.65	1.88	1.31
								1990	6.02	3.97	0.88	0.65	2.36	0.49	1.19	0.46	4.45	0.88
								$\bar{x}$	5.99	3.53	0.83		3.60	0.51	2.34	0.56	3.16	1.10
Shallow	2	2	2	0	0	0	0	1989	1.60	0.83	0.47		10.43	1.12	6.83	1.03	3.23	2.26
								1990	0.41	0.27	1.72	1.27	8.12	1.68	3.85	1.50	15.18	3.02
								$\bar{x}$	1.01	0.55	1.09		9.28	1.40	5.34	1.39	9.21	2.64
New	0	0	0	2	2	2	3	1989	7.93	4.10	0.82		2.04	0.22	2.09	0.39	1.76	1.22
								1990	8.42	5.55	0.85	0.63	0.93	0.19	0.61	0.24	3.81	0.76
								$\bar{x}$	8.18	4.82	0.84		1.49	0.20	1.35	0.32	2.78	0.99

The area (lat. 17°–18°N) of highest catch rates for bigeye tuna was on the south edge of a northward transition to a deeper thermocline and oxycline (Fig. 10). The north-south pattern is typical of the central Pacific Ocean at these latitudes, whereas the highly variable pattern in the thermocline between lat. 19.4° and 20°N was probably caused by the proximity to the lee side of the island of Hawaii.

With regard to the other species, the thermal structure of the habitat (Fig. 10) and the confirmed depth distribution of fish (Figs. 4, 7, and 8) suggested that yellowfin tuna were most abundant in the mixed layer (24°–25°C) and the steepest part of the thermocline down to about 15°C. Striped marlin appeared to be most abundant in the mixed layer and the top of the thermocline to ∼20°C. Spearfish appeared to occupy a habitat between that of yellowfin tuna and striped marlin, and mahimahi occupied the mixed layer.

Standardized gear efficiency

For bigeye tuna in 1989–90, the CPUE ranges for standardized deep gear and proposed new gear were about 3.1–4.0 and 4.1–5.6 times, respectively, as great as those for regular gear (Table 5). Shallow gear on average was about half as efficient as regular gear in catching bigeye tuna, whereas it was about 40% more efficient than regular gear in catching spearfish and striped marlin. Deep gear was only about half as efficient as regular gear in catching striped marlin and spearfish, and the proposed new gear was only about 20% as efficient for striped marlin and about 30% as efficient for spearfish.

The numbers of yellowfin tuna and mahimahi caught in 1989 were much lower than in 1990, so the latter year provided better data for calculating gear efficiency for these species (Table 5). Shallow gear was about 3.0 times as efficient at catching mahimahi, and deep and new gear reduced efficiency to about 90% and 75% in comparison with regular gear. For yellowfin tuna, shallow gear was about 25% more efficient than regular gear, whereas the deep and new gear types were each about 65% as efficient.

Discussion

Habitat depth

Hook timers are useful in confirming whether fish are caught while longline hooks are sinking, settled, or rising. Combined with capture depths from TDRs, hook timers offer a new method for establishing the habitat depth of large pelagic fishes. Stock assessments (Suzuki 1989) depend on the estimation of effective effort, defined as fishing effort corrected for differences in efficiency due to gear and habitat depth (Suzuki et al. 1977). Improving the definition of tuna and billfish habitats and the estimation of effective effort in those habitats should lead to significant improvements in assessing true abundance.

Comparisons of CPUE by two gear types provide only qualitative information on habitat depth. For example, since deep gear is more efficient than regular gear for bigeye tuna, this species must occupy a relatively deep habitat (Suzuki et al. 1977). More specific information on habitat depth is provided by catches and $CPUE_H$ by hook position (Hanamoto 1979 and 1987, Hanamoto et al. 1982, Suzuki and Kume 1982), especially when TDRs are used to record gear depth (Saito 1973 and 1975, Hanamoto 1974, Nishi 1990). Capture depth estimates without TDR records ignore major variations in actual gear depth (Fig. 2; Nishi 1990), and those without hook timers are biased by the inclusion of inappropriate hook depths.

A possible source of bias in the present study is the inclusion of some falsely confirmed depths due to fish being caught with timers already activated. The proportion of false estimates should be similar to the frequency of timers that were without fish and were triggered while settled, which was only 3.9% in 1989 and 2.6% in 1990 (Table 3). Thus it is unlikely that >4% of confirmed capture depths in this study are incorrect because of false timer readings.

Many pelagic longline studies (Saito 1975, Hanamoto 1976, Yang and Gong 1988) assume that fish are caught while hooks are at settled depths. Supporting this assumption, Saito (1973) has shown that albacore *Thunnus alalunga* are caught almost exclusively by settled hooks, based on capture times indicated by fluctuations in TDR records. Using hook timers, the present study adds new information: Almost 90% of bigeye and yellowfin tuna also are caught while hooks are at settled depths (Table 4). However, hook timers indicate this generalization does not extend to striped marlin, spearfish, mahimahi (Table 4), and most of the commercially unimportant species (Fig. 5). Although most of these fish are also caught on settled hooks, a substantial fraction are not, and this must be considered when quantifying their depth ranges (Fig. 4).

Besides the present study, little information exists on longline capture depths for mahimahi, spearfish, and striped marlin. In the study area, $CPUE_D$ values for these species (Fig. 7) indicate maximum abundance at depths in the mixed layer for mahimahi (<100 m, 24°–25°C; Fig. 10), extending into the top of the thermocline for striped marlin (120 m, 20°C) and into the middle of the thermocline for spearfish. Striped marlin are reported to be caught most frequently on longline hooks closest to the surface (60–90 m) in the eastern tropical Pacific and Indian Oceans, but they may be more abundant above this depth (Hanamoto 1979, Hanamoto et al. 1982). Mahimahi and spearfish may also be more abundant above the uppermost stratum (40–80 m) in the present study, since their catch rates appear to increase towards the surface (Fig. 7).

Striped marlin are also reported caught on deep longline hooks (~200 m; Hanamoto et al. 1982) and at the deep end of vertical longline gear (336 m; Saito 1973); but in the present study, their deepest confirmed capture depth is 210 m. Tracking data on striped marlin off California indicate a shallow (<60 m) depth distribution with most of the daytime spent within 10 m of the surface (Holts and Bedford 1989).

The depth distribution (200–400 m) of bigeye tuna in the present study is deeper than in many previous reports (Hanamoto 1974, 50–160 m; Saito 1975, 207–245 m; Suzuki and Kume 1982, 170–300 m; Yang and Gong 1988, 260–300 m; Nishi 1990, 140–180 m), although these studies have found bigeye tuna are most abundant on the deepest hooks fished. Hanamoto (1987) hypothesizes a habitat depth of 250–400 m for the central Pacific Ocean at latitude 25°N, based on the observed maximum longline CPUE at temperatures of 10°–15°C. The highest $CPUE_D$ values in the present study are at the cold, deep end of this range (Fig. 7), deeper than most hooks used in commercial fishing gear. However, the $CPUE_D$ value at 280–400 m is not significantly different from that at 200–400 m (Fig. 8). Although these results may be specific to January and February, perhaps commercial CPUE could be improved by increasing fishing depth, at least during winter months.

Seasonal and geographic variation in temperature and DO profiles may affect the depth preferences of pelagic fish. Hanamoto (1975, 1987) has hypothesized that the deep end of bigeye tuna habitat is limited by DO concentrations below 1 mL/L (1.4 mg/L) and by temperatures below 10°C. Results of the present study suggest that bigeye tuna are seldom caught in waters with a DO concentration of ~<2 mg/L (Fig. 10). Oxygen concentrations of ~2–3 mg/L cause significant reductions in bigeye tuna cardiac output (1.9–2.6 mg/L) and heart rate (2.7–3.5 mg/L), suggesting that bigeye tuna cannot maintain a full range of activity at lower DO concentrations (Bushnell et al. 1990).

Longline data to support the hypothesis of a 10°C temperature limit independent of the DO limit are sparse. Few hooks have been deployed in waters colder than 9°–10°C with DO concentrations of >1 mL/L (Hanamoto 1975, 1987). In the present study, the only area with DO values >2 mg/L and temperatures <8°C was at lat. 10°–20°N (Fig. 10). Currents prevented hooks from reaching cold (6°–8°C) water in this area.

Sonic tracking of bigeye tuna around Hawaii indicates a depth distribution slightly shallower than that in longline studies (Hanamoto 1987, 250–400 m; present study, 200–400 m). Holland et al. (1990) have reported that tracked bigeye tuna spend most of the daytime at 200–240 m in 14°–17°C water. This may be due to the association of the tracked bigeye tuna with fish aggregating devices or due to a size-related difference. The 72- to 74 cm bigeye tuna studied by Holland et al. (1990) weighed ~10–12 kg, whereas longline-caught bigeye tuna in the present study averaged >30 kg.

Results of the present study apply predominantly to daytime habitat depths, but an important difference apparently exists between the daytime and nighttime depth distributions of bigeye tuna (Holland et al. 1990). At night, tracked bigeye tuna move upward to ~70–90 m at temperatures of 23°–25°C. Confirmation of this nocturnal behavior comes from a new nighttime longline swordfish fishery that has recently developed in Hawaii using chemical light sticks. Although this fishery deploys very shallow (generally <90 m) gear, the bycatch of bigeye tuna is surprisingly high (S. Pooley, NMFS Honolulu Lab., pers. commun., April 1991), indicating that bigeye tuna have a shallow nighttime depth distribution.

The small number of yellowfin tuna caught in this study makes estimated habitat depth (40–200 m) less certain, but it does not differ much from the 90–230 m depth found in Suzuki and Kume (1982) and Yang and Gong (1988). Tracking studies (Carey and Olson 1982, Holland et al. 1990) show yellowfin tuna spend most of their time at depths <100 m. Depths of the highest longline $CPUE_D$ for yellowfin tuna in the present study (40–80 m; Fig. 7) are similar to the depths (30–80 m) at which tracked yellowfin tuna in Hawaii spend over 50% of their time during the day (Holland et al. 1990), tending to confirm that yellowfin tuna habitat is mostly in the mixed layer.

Methods for estimating habitat depths in the present study could be improved by increasing the number of TDRs deployed or by developing a model, calibrated with TDRs, to predict gear depth based on wind and current measurements, divergence or convergence of floats, and stops and starts in deployment and retrieval. Procedures to estimate the capture depths of fish caught while hooks are sinking or rising could also be developed, but would depend on very accurate timekeeping, since the gear rises rapidly during retrieval (Fig. 3).

Catch by moving hooks

The catch of shallow-swimming species on deep hooks moving through shallower depths could reduce the selectivity of gear designed to catch deep-swimming species. The results show that moving longline hooks are more effective (per unit time) than settled hooks at catching billfish, mahimahi, some sharks, and most other non-tuna species. However, the majority of these fish are caught on settled hooks, because of the longer time that hooks are settled (Fig. 5). The relative amount of time hooks are moving vs. settled is the only aspect of the commercial daytime tuna longline operations that differs much from the fishing method used in this study. The gear is left in the water longer and then retrieved more rapidly during commercial fishing, so hooks spend less time moving and more time settled. This may result in greater proportions of fish being caught on settled hooks by commercial fishermen than in the present study.

Eliminating shallow-settled hooks should greatly reduce the catch of shallow-swimming species. For non-tuna species, deploying and retrieving the gear less often (as in commercial operations) should decrease the CPUT (catch-per-unit-time), but would increase the CPUE because the latter increases with set duration. In contrast, bigeye tuna CPUT and CPUE should increase with less frequent deployment and retrieval, because CPUT is highest for settled hooks.

The mechanism for increased CPUT on moving hooks for non-tuna species is unclear. Moving bait may be more attractive than settled bait, but the low number caught on sinking hooks (Fig. 5) suggests that gear motion alone is not responsible for increased catch rate. Perhaps a gradual aggregation of fish around the gear (or the vessel) while the gear is settled contributes to the catch rate by rising hooks.

Although hook timer data provide a reliable way to confirm when fish are caught on settled hooks, such data may be less reliable as a measure of fish caught on moving hooks, because of the uncertainty regarding fish with timers triggered at recovery (Fig. 5). These fish are not included in the number captured on moving hooks (Table 4); their timer readings cannot be distinguished from ones triggered after being brought aboard. Therefore, the estimates of fish caught on moving hooks (Table 4) may be too low. Alternatively, if these readings indicate a tendency for some fish to not activate timers until they struggle during recovery, then the estimates of fish caught on moving hooks may be too high. In either case, only inferences regarding CPUT on moving and non-moving hooks, and the estimated proportions of fish caught on moving hooks, are affected by this uncertainty. The estimates of catches on non-moving hooks are conservative, and confirmed capture depths are not affected.

The higher proportion of fish caught on moving hooks in 1989 compared with 1990 (Table 4) could have been caused by moving hooks being less visible in 1990, since branch lines were more often recovered after dark (Table 1). Sets also lasted longer in 1990 (Table 1); this may have increased the relative proportion of catches on settled vs. moving hooks. The CPUT in relation to sinking, settled, and rising gear, and to the time of day, should be explored further using the techniques developed in the present study.

A TDR attached to vertical and regular rope longline gear sometimes records abrupt depth changes as a fish is caught, making the TDR equivalent to a hook timer if it is close to a branch line that catches a fish (Saito et al. 1970, Saito 1973, Yamaguchi 1989). The records of TDRs at positions close to fish caught with hook timers in the present study were checked to see whether they indicated the time of capture, but the depth of the monofilament longline gear was much less stable (Fig. 3) than in the depth records of Saito et al. (1970), Saito (1973), and Yamaguchi (1989) using TDRs on rope gear. On monofilament longline gear, frequent depth changes resembling fish captures occur even when no fish are caught, making TDRs unreliable as substitutes for hook timers.

Viability of released fish

Before the present study, it was believed that fish would survive only a few hours after capture on longline gear (Grudinin 1989, Yamaguchi 1989) despite large pelagic species being known to survive capture and release from other types of gear (Foreman 1987, Squire 1987, Holts and Bedford 1989). Commercial longline fishermen in Hawaii speculated that much of their catch was made as hooks were sinking or rising, because most were alive or appeared long dead (F. Amtsberg, Der Fischen Co., Honolulu, HI 96822, pers. commun., March 1988). Based on TDR data from fish on regular longline gear (Yamaguchi 1989), vertical movements stop 1.0–1.5h after capture for yellowfin tuna, 1.5–4.0h for bigeye tuna, and ~0.5h for spearfish and shark. This cessation of vertical movement has been interpreted as death (Yamaguchi 1989). Grudinin (1989) has reported on the diurnal periodicity of bigeye and yellowfin tuna catch rates based on the proportion recovered alive, assuming that tuna survive ≤2h on longline gear. However, hook-timer results (Fig. 6) show that fish survive much longer than this, suggesting that vertical movement is not a reliable indicator of survival. Alternatively, the results of the present study could be specific to monofilament gear, which could have less resistance to moving through the water than does rope gear.

Clearly the high proportion of live fish (Table 2) is not primarily the result of capture during the 0.5h rising period. The viability of longline-caught fish is indicated by their hooked longevity and the recovery of tagged fish. As a management option, non-retention of striped marlin and spearfish could reduce fishing mortality due to longline fishing. The importance of the reduction would depend on the length of the fishing operation; but in the present study, longline fishing mortality for striped marlin could have been reduced by 70% (Table 2) if all live fish had been released and had survived.

Gear efficiency and selectivity

Gear efficiency, defined as the dimensionless ratio of the CPUE of one gear type (i.e., deep gear) divided by the CPUE of the regular gear type, is the factor used to calculate effective effort by gear fishing at different depths (Suzuki et al. 1977). Total effective effort can then be used to calculate indices of relative abundance and to model stock production (Suzuki 1989). The most thorough approach thus far has been to calculate gear efficiency by area and season (Suzuki and Kume 1982). A better understanding of the variables that alter habitat depth would permit gear efficiency to be predicted as a function of environmental conditions, and help account for variation in abundance indices caused by environmental anomalies.

The relative efficiency of standardized deep gear (Table 5) follows the pattern observed in previous studies (Suzuki et al. 1977, Yang and Gong 1988) in which deep gear is more efficient at catching bigeye tuna and less efficient at catching yellowfin tuna and istiophorid billfish. However, the estimated efficiency of the standardized deep gear for bigeye tuna in the present study is greater (ratio 3.1–4.0 over the 2 years; Table 5) than that reported by Suzuki et al. (1977) for the central and western equatorial Pacific (1.8) or by Yang and Gong (1988) for the Atlantic (1.9). Suzuki and Kume (1982) have presented graphs of deep and regular CPUE for bigeye tuna on a quarterly basis by area throughout the Pacific, and these data indicate very little difference between gear types in the central Pacific north of lat. 15°N. The high efficiency estimated for deep gear in the present study may partly result from using measured depths rather than inferred depths to define deep and regular gear types. Also, a high relative efficiency for deep gear may be specific to the Hawaii area in the winter season.

The relative efficiency of deep gear for yellowfin tuna in the Atlantic (0.95, Yang and Gong 1988) is greater than in the central and western equatorial Pacific (0.73, Suzuki et al. 1977) and in the present study (0.65, Table 5). Relative efficiency of deep gear for striped marlin in the central and western equatorial Pacific (0.28, Suzuki et al. 1977) is much lower than in the central Pacific north of Hawaii (0.74, Suzuki 1989), nicely bracketing the estimate from the present study (0.51, Table 5).

The model estimates of gear efficiency (Table 5) are not meant to supplant earlier estimates based on much larger data sets (Suzuki et al. 1977, Suzuki and Kume 1982, Yang and Gong 1988, Suzuki 1989), but rather to show how catch by hook position can be used to estimate CPUE by different gear configurations, especially hypothetical configurations for which no real data exist. Efficiency estimates (Table 5) suggest that shallow sets of the type hypothesized to represent early use of monofilament longline gear in Hawaii would be expected to catch about 40% more billfish and 160% more mahimahi than would regular longline gear. Large increases in longline catches of these fish in Hawaii have occurred in recent years (1989–90, Boggs 1991) as the expanding Hawaii fishery adopted a new type of gear. The proposed new gear configuration would be an effective way to reduce the catch of spearfish and striped marlin by ~70–80% below that of regular gear.

Hook timers and TDRs are useful in documenting the depth distribution and habitat of pelagic fish and in showing how different configurations of longline gear and the release of live fish can be effective means of reducing fishing mortality for some species. Better methods of identifying the habitats of pelagic fishes should make it easier to estimate real changes in fish abundance by accounting for changes in fishing methods and the environment.

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