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Effects of eliminating shallow hooks from tuna longline sets on target and non-target species in the Hawaii-based pelagic tuna fishery

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Effects of eliminating shallow hooks from tuna longline sets on target and non-target species in the Hawaii-based pelagic tuna fishery

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A B S T R A C T

A longline experiment consisting of 45 paired sets (90 sets total) was carried out to evaluate a technique which maintains target catch rates while reducing non-target catch rates. Control sets were compared to experimental sets which eliminates the shallowest hooks (~less than 100 m depth). Researchers hypothesized that by eliminating shallow hooks, target catch of deeper dwelling species such as bigeye tuna (*Thunnus obesus*) would be maximized while incidental catch of many other non-target, but marketable epi-pelagic species (e.g. billfish), bycatch (discards) of other fishes and elasmobranchs, and protected sea turtles and marine mammals would be simultaneously reduced. To control for differences in fishing power, gear, and deployment techniques; a single vessel was contracted to perform all 90 paired longline sets (45 experimental sets using no-shallow-hooks and 45 control sets using standard methods). Control sets consisted of longlines that were suspended by floats on typical 30 m long floatlines in catenary-type shapes that fished a range of depths, determined by temperature–depth recorders (TDRs) to be 44–211 m (27.5–11.2 °C). By contrast, elimination of shallow hooks in the upper 100 m of the water column (hereinafter referred to as experimental sets) was achieved by suspending the fishing portion of the mainline on 75-m long, 3 kg weighted vertical sections of mainline suspended by floats on 30 m floatlines. As determined by TDRs, this arrangement ensured that all hooks fished at depths >100 m (103–248 m; 24.8–11.3 °C). Thirty percent of hooks in control sets fished at depths less than 100 m while all hooks on experimental gear fished greater than 100 m. Because many factors influence catchability, longline sets are by nature multivariate, and statistical comparisons were made between the two set types using canonical discriminant analysis (CDA). Except for the depth of shallow hooks, operational characteristics between experimental and control sets were the same. The catch rates of bigeye tuna were similar on the two sets types but the catch rate of sickle pomfret (*Taractichthys steindachneri*) was significantly higher ($p = 0.011$) in the experimental sets as compared to control sets. However, statistically fewer wahoo (*Acanthocybium solandri*, $p = 0.019$), dolphinfish (*Coryphaena hippurus*, $p = 0.008$), blue marlin (*Makaira nigricans*, $p = 0.001$), striped marlin (*Kajikia audax*, $p = 0.018$) and shortbill spearfish (*Tetrapturus angustirostris*, $p = 0.006$) were captured on the experimental sets; thus longline interactions and impacts on these species were reduced with the experimental gear. The reason for the differences in catch rates between gear types is likely due to the vertical habitat preferences of the species involved; interactions with epi-pelagic species with shallow distributions in the uniform mixed layer were reduced by deploying hooks greater than 100 m. By logical extension, the experimental gear will also likely reduce interactions with sea turtles. Except for additional lead weights, floats, and floatlines, only slight modification of existing longline fishing gear and methods were required to deploy the experimental gear. The main drawback of this method was the increase in time to both deploy (≈0.5 h) and retrieve (≈2 h) the gear. Knowledge of species vertical distribution patterns can play an important role in modifying fishing gear to reduce bycatch and can also assist managers in regulating fishing practices with a higher degree of likelihood of predicting catch rates and species captured in different gear types.

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1. Introduction

Pelagic longlining is conducted in all the world's oceans and mainly targets tuna (*Thunnus* spp.) using standard "deep-set" gear, and swordfish (*Xiphias gladius*) using standard "shallow-set gear", respectively, but both techniques also incidentally capture other species with market value and bycatch species (Suzuki et al., 1977). Target species in the western and central Pacific Ocean include bigeye tuna (*T. obesus*), yellowfin tuna (*T. albacares*), albacore (*T. alalunga*), and swordfish. Non-target species can be grouped into two categories (incidental and bycatch). Incidentally caught species are not specifically targeted, but are retained for commercial value. In the Hawaii-based longline fishery, these include dolphinfish (*Coryphaena hippurus*), wahoo (*Acanthocybium solandri*), opah (*Lampris guttatus*), striped marlin (*Kajikia audax*), shortbill spearfish (*T. angustirostris*), blue marlin (*Makaira nigricans*), black marlin (*M. indica*), Indo-Pacific sailfish (*Istiophorus playpterus*), sickle pomfret (*Taractichthys steindchneri*), escolar (*Lepidocybium flavobrunneum*), shortfin mako (*Isurus oxyrinchus*), and bigeye thresher (*Alopias superciliosus*). Bycatch species are discarded because they either have no commercial value or because they are endangered and protected by law. Common bycatch species in the Hawaii-based longline fishery include longnose lancetfish (*Alepisaurus ferox*), snake mackerel (*Gempylus serpens*), pelagic stingray (*Pteroplatytrygon violacea*), some shark species (e.g. blue shark *Prionace glauca*), and undersized tunas and billfish.

Reducing the interaction and possible mortality (e.g. loss of parental biomass and genetic diversity) of incidental and bycatch species captured by longline fisheries has been identified as a fisheries management priority (Alverson et al., 1994) and has received much attention (Myers and Worm, 2003; Sibert et al., 2006). The capture of billfishes and other recreational species (e.g. dolphinfish, wahoo) by longline fisheries have recently received attention, especially where relatively large sport fisheries exist and there is concern of local depletion (e.g. New Zealand, Australia, Bromhead et al., 2004; Langley et al., 2006; Hawaii, Kitchell et al., 2004). Due to public scrutiny and their wide notoriety, longline interactions with sea turtles, birds and sharks often receive intense focus (Molony, 2005; Gilman et al., 2005, 2006; Watson et al., 2005). Turtle interactions are approximately 10 times greater in shallow set night longline gear than tuna (deep) set gear (SPC, 2001; Ito and Machado, 2001) because species such as loggerhead sea turtles (*Caretta caretta*) and olive Ridley sea turtles (*Lepidochelys olivacea*) spend the majority of their time in the upper 100 m of the water column (Polovina et al., 2003, 2004; Swimmer et al., 2006). Loggerhead sea turtles have also been found to feed predominately at the surface (Parker et al., 2005) and leatherback turtles (*Dermochelys coriacea*) have also been found to spend the majority of their time near the surface (Eckert et al., 1989).

In tuna longline fishing, one potential technique to reduce unwanted catch is to remove 'shallow hooks'. From a study using hook timers and temperature–depth recorders (TDRs) in the Hawaii longline fishery, Boggs (1992) showed that most shortbill spearfish and striped marlin were caught at depths within 120 m of the surface while most bigeye tuna were caught at depths greater than 200 m. Results from that study, and information from pelagic species' vertical habitat preferences from electronic tagging studies (Arnold and Dewar, 2001; Gunn and Block, 2001), suggested that eliminating shallow hooks could substantially reduce the catch rates of recreationally important billfish without reducing the fishing efficiency for bigeye tuna. Results of another study (Nakano et al., 1997) indicated that catch rates for albacore and bigeye tuna increased with depth while catch rates for all billfish (except swordfish) decreased with depth. Nakano et al. (1997) could also demonstrate catch rates of opah, longnose lancetfish, and sickle pomfret increased with depth while yellowfin tuna catch rates showed no trend.

The theoretical depth of the deepest hook (at the nadir position) for longlines can be calculated with catenary geometry and evaluated with TDRs (e.g. Bigelow et al., 2006) and the depth of a set can be controlled by altering the number of hooks between floats and boat speed relative to line setting speed (i.e. shortening rate). However, the true depth will be less than the theoretical catenary depth because of environmental factors such as current velocity that shoal the gear (Boggs, 1992; Mizuno et al., 1999; Bigelow et al., 2006). Many pelagic species have overlapping geographic ranges and the aim of this paper was to improve the vulnerability of longline fishing by creating mismatches in the vertical distribution of hooks and species' distribution patterns. Beverly and Robinson (2004) devised a relatively cost effective technique to achieve this goal by the elimination of hooks less than 100 m by using weighted sections of mainline on each end of longline baskets. Although preliminary results were encouraging, due to small sample sizes, however, it was decided to test this technique on a much larger temporal and spatial scale.

The objectives of this study were to compare operational details and catch rates between experimental longlines with no-shallow-hooks (reported in Beverly and Robinson, 2004; SPC, 2005) and control sets. Canonical discriminate analysis (CDA) was used to test differences in set details (e.g. hook depths, temperature) and to test for differences between experimental and control sets. A subsequent CDA compared the catch rates of each species (number of individuals per set) to identify which species were contributing to the discrimination between experimental and control sets.

2. Materials and methods

2.1. Fishing details

Gear modifications to configure experimental longline sets are provided in Beverly and Robinson (2004) and include 3 kg weighted branchlines to keep hooks below 100 m (Fig. 1). Ninety paired longline sets (45 experimental and 45 control) were made during seven fishing trips between June and December 2006 in the Hawaii-based tuna longline fishery (vessel based in Honolulu). To minimize variation in operational factors and catching power (i.e. catchability), a single vessel (F/V *Caroleigh*, 24 m in length) was chartered to undertake all sets. The captain and crew of the vessel was allowed to retain and sell their catch, choose their fishing areas, setting and hauling times, and the number of hooks deployed between floats on control sets. Control and experimental sets targeted bigeye tuna and setting time ranged from 07:10 to 10:49 (average start time was

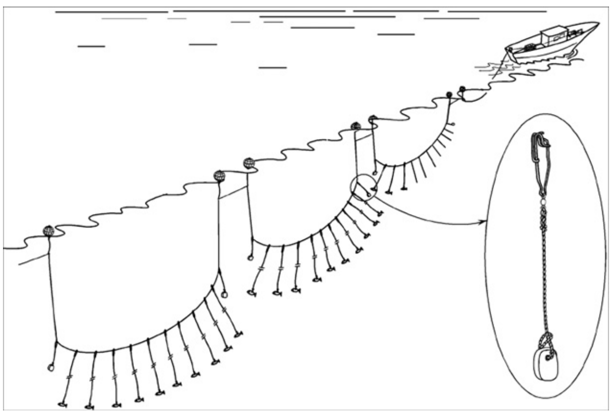

Fig. 1. Illustration of no-shallow-hooks gear (not to scale) showing lead weight in inset.

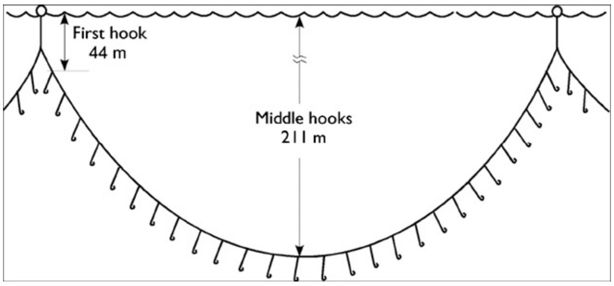

Fig. 2. Actual configuration of one segment of control gear.

8:15) and the start of haulback time ranged from 17:40 to 21:05 (average start time was 18:22). To ameliorate and control for differences in environmental factors and fish availability between set types, once the vessel began fishing operations, they were required to perform a control set (Fig. 2) on one day followed by an experimental set (Fig. 3) on the next day. The distance traveled from the end of a control set to the start of an experimental set ranged from 5 to 40 nm and the average distance traveled was 25 nm. Operational details of each longline set were recorded at deployment and haulback of the gear (Table 1). Two temperature–depth recorders (DST centi-ex, Star-Oddi, Reykjavik, Iceland) were placed within a single basket (section of hooks between floats) on each set near the first (shallowest position) and middle (nadir or deepest) branchline positions. Each TDR sampled temperature and depth at 10 min intervals and data were downloaded after each haul. To eliminate spurious data from the descent and ascent periods of gear deployment and retrieval, average depths were estimated after truncating the first and last 30 min of each depth temperature profile (Boggs, 1992; Bigelow et al., 2006).

Control gear had 27 hooks between floats while experimental gear had 30 hooks between floats, although the total number of hooks fished by each gear type remained the same at 2000 hooks per set. A total of 180,000 hooks were monitored during the experiment. Japanese tuna hooks with rings, size 3.6 sun (sun = 3.03 cm), were used and measured 3.2 cm across the narrowest profile with a slight (5–10°) point offset.

Table 1
Summary of operational variables (means and standards deviations (S.D.)) included in the canonical discriminant analysis (CDA) of the gear attributes. Data are from 45 control and 45 experimental (no-shallow-hooks) sets. Latitudes, longitudes and wind and current directions are in decimal format.

Variable	Control		Experimental	
	Mean	S.D.	Mean	S.D.
Start latitude (°N)	24.57	3.887	24.97	4.141
Start longitude (°W)	158.39	7.385	159.64	7.436
Haul latitude (°N)	24.55	3.899	24.92	4.146
Haul longitude (°W)	158.77	7.416	159.74	7.101
Sea surface temperature (°C)	26.06	1.720	26.62	1.663
Current speed (knots)	0.678	0.422	0.584	0.374
Current direction (°)	104.47	2.624	104.45	2.681
Wind speed (knots)	9.97	4.626	10.45	5.932
Wind direction (°)	102.14	1.457	102.13	1.384
Depth of first hook (m)	44.31	8.169	103.58	7.999
Temperature of first hook (°C)	23.64	2.580	20.41	2.907
Depth of middle hook (m)	209.11	28.987	250.45	29.647
Temperature of middle hook (°C)	15.55	2.318	14.01	1.706

2.2. Analyses

Two forward-stepwise CDAs (Tabachnick and Fidell, 1996; Manly, 2005) were performed. A forward-stepwise approach allows the model to add variables sequentially, choosing the variable that contributes most to the discrimination between the set types at each step. First, a comparison of operational details between experimental and control sets (Table 1) was conducted to identify which variable(s) discriminated between the two set types. Next, a second CDA analyzed the catches of the 18 most commonly reported species in this experiment (28 total species represented; Table 2) to determine which species contributed to the discrimination between set types. All CDAs were conducted in Statistic Software (StatSoft, 2004) using the discriminant analysis functions of the multivariate exploratory techniques module.

3. Results

3.1. Configuration of gear

All setting parameters (vessel speed, line setter speed, line-sagging ratio, distance between branchlines, length of floatline, length of branchline, bait type and hook type) remained constant throughout the experiment. Control sets took about 3.5 h to deploy (range, 3.2–3.6 h) and experimental sets took about 4 h to deploy (range, 3.75–4.2 h). Retrieval durations fluctuated (range, 8–14 h) and were a function of catch and weather conditions, but on paired sets where operational conditions were comparable (i.e. no change in wind, sea state, catch rates, or operational procedures), it took about 2 h longer to haul an experimental set than a control set. A total of 180 TDR recordings were made with half on experimental sets and half on control sets. On experimen-

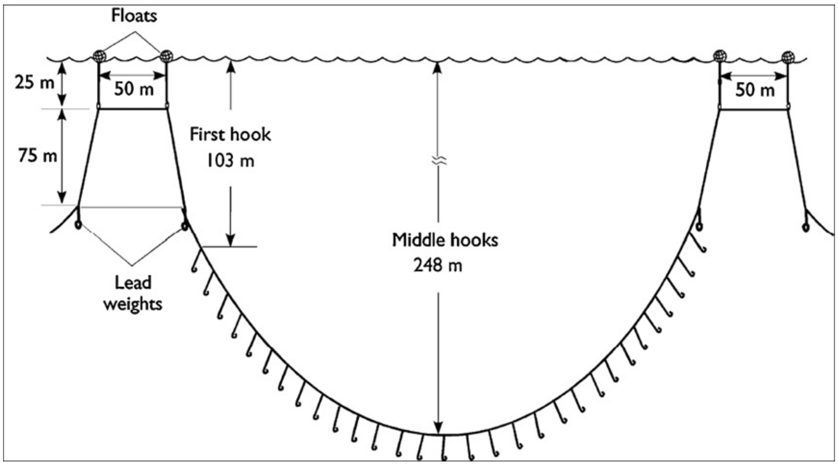

Fig. 3. Actual configuration of one segment of experimental (no-shallow-hooks) gear.

Table 2
Summary of catch totals by species and ratio of control ($n = 45$ sets) vs. experimental (no-shallow-hooks < 100 m, $n = 45$ sets) in the trial.

Species	Catch numbers			Ratio, control/exper.
	Control	Experimental	Total	
Tunas				
Bigeye (*Thunnus obesus*)	211	258	469	0.82
Albacore (*Thunnus alalunga*)	75	61	136	1.23
Skipjack (*Katsuwonus pelamis*)	32	17	49	1.88
Yellowfin (*Thunnus albacares*)	68	49	117	1.39
Billfish				
Striped marlin (*Kajikia audax*)	69	22	91	3.14
Blue marlin (*Makaira nigricans*)	17	6	23	2.83
Shortbill spearfish (*Tetrapturus angustirostris*)	25	6	31	4.17
Indo-Pacific sailfish (*Istiophorus platypterus*)	1	1	2	1.00
Swordfish (*Xiphias gladius*)	20	15	35	1.33
Other sportfish				
Dolphinfish (*Coryphaena hippurus*)	170	60	230	2.83
Wahoo (*Acanthocybium solandri*)	52	20	72	2.60
Sharks and rays				
Blue Shark (*Prionace glauca*)	218	227	445	0.96
Shortfin mako (*Isurus oxyrinchus*)	6	8	14	0.75
Oceanic whitetip (*Carcharhinus longimanus*)	0	1	1	0.00
Bigeye thresher (*Alopias superciliosus*)	2	6	8	0.33
Pelagic stingray (*Pteroplatytrygon violacea*)	14	14	28	1.00
Other species				
Opah (*Lampris guttatus*)	43	73	116	0.59
Oilfish (*Ruvettus pretiosus*)	3	1	4	3.00
Escolar (*Lepidocybium flavobrunneum*)	52	40	92	1.30
Sickle pomfret (*Taractichthys steindachneri*)	90	159	249	0.57
Dagger/Pacific pomfret (Family Bramidae)	4	7	11	0.57
Crestfish (Family Lophotidae)	3	1	4	3.00
Hammerjaw (*Omosudis lowii*)	0	1	1	0.00
Whiptail ribbonfish (*Desmodema lorum*)	1	0	1	
Ribbonfish (Family Trachipteridae)	2	0	2	
Great barracuda (*Sphyraena barracuda*)	1	0	1	
Snake mackerel (*Gempylus serpens*)	107	116	223	0.92
Longnose lancetfish (*Alepisaurus ferox*)	1056	1186	2242	0.89
Total of all species	2342	2355	4697	0.99

tal sets, the shallowest hooks averaged 103 ± 8.0 m (S.D.) (range, 83–127 m) in depth and 20.4 ± 2.9 °C (S.D.) (range, 24.8–15.7 °C) in temperature and the deepest hooks averaged 248 ± 27.8 m (range, 200–320 m) in depth and 14.0 ± 1.7 °C (range, 17.5–11.3 °C) in temperature (Figs. 4 and 5). On control sets, the shallowest hooks averaged 44 ± 7.7 m (range, 25–57 m) in depth and 23.6 ± 2.6 °C (range, 27.5–19.3 °C) in temperature and the deepest hooks averaged 211 ± 28.7 m (range, 140–260 m) in depth and 15.5 ± 2.3 °C (range, 21.5–11.2 °C) in temperature (Figs. 4 and 5). The experimental method did not dramatically change the vertical sag or shortening ratio of the amount of mainline deployed between successive floats, but simply shifted the whole profile down ~60 m at the first hook and ~40 m at the middle hook position. On average, estimation of hook depths in experimental and control sets using catenary geometry and TDRs indicated that at least four hooks in each shallow end of longline baskets in control sets (8 hooks out of 27 or 30%) were fishing at depths less than 100 m (Fig. 4). On average, hooks on experimental sets fished greater than 100 m (Fig. 4). For each pair of sets, the shallowest hook on experimental sets averaged 3.1 °C (range, −0.4 to 7.5 °C) colder than the

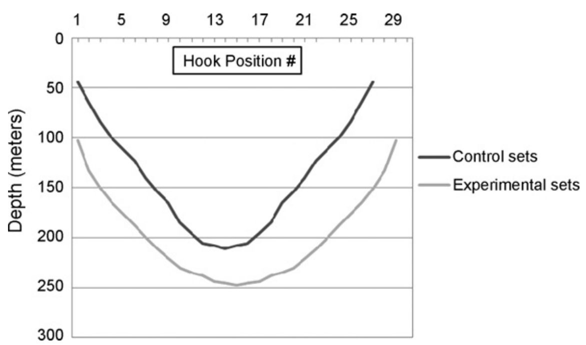

Fig. 4. Average temperature–depth recorder (TDR) depths for all sets by set type. Not all hook positions were monitored with TDRs on all sets, thus some hook depths averages were interpolated (along a catenary curve) between measured averages.

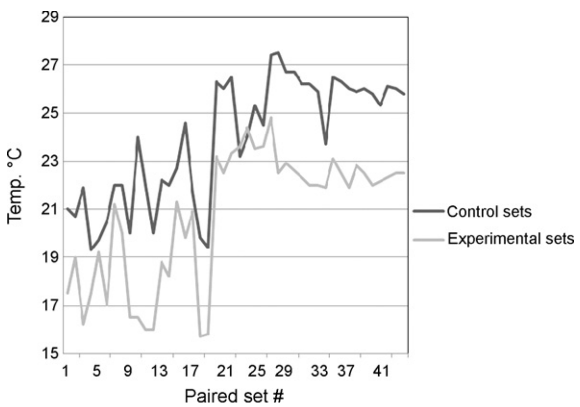

Fig. 5. Average temperature–depth recorder (TDR) temperatures for the shallowest hook positions (by paired set number) for control and experimental sets.

Table 3A
Results of the CDA of gear attributes discriminating between the two set types. Overall results of the statistical test (Chi-square) on the significance of the CDA between operational factors of control and experimental (no-shallow-hooks) sets. The value of Wilk's lambda (0.057) indicates that the discrimination between the two set types from this canonical root is very high (Wilk's Lambda ranges between zero (perfect discrimination) and 1 (no discrimination) (StatSoft, 2004).

Canonical roots removed	Eigenvalue	Canonical *R*	Wilk's lambda	χ^2	Degrees of freedom	*P*-Level
0	16.597	0.971	0.057	179.235	5	0.000

Table 3B
Results of the CDA of gear attributes discriminating between the two set types. Analysis of individual variables and their contribution to discriminating between set types in the CDA. Variables are listed in order of highest to lowest contribution to the discrimination of the two set types in the CDA. Only the depth of first hook (grey shading) was significant in discriminating between the two set types.

Variable	Wilk's lambda	Partial lambda	F-value	P (>F)	Tolerance
Depth of first hook	0.627	0.090	613.780	0.000	0.743
Current speed	0.060	0.953	2.993	0.089	0.754
Depth of middle hook	0.059	0.955	2.857	0.096	0.785
Current direction	0.060	0.956	2.899	0.094	0.901
Wind speed	0.058	0.980	1.240	0.270	0.835
Start of set latitude	0.057	0.999	0.032	0.859	0.915
Start of set longitude	0.057	0.999	0.002	0.967	0.806
Start of haul latitude	0.057	0.999	0.030	0.863	0.925
Start of haul longitude	0.057	0.999	0.001	0.975	0.815
Sea surface temperature	0.057	0.997	0.176	0.676	0.935
Wind direction	0.056	0.986	0.842	0.362	0.957
Temperature of first hook	0.057	0.999	0.045	0.832	0.925
Temperature of middle hook	0.056	0.992	0.455	0.502	0.672

shallowest hook on control sets (Fig. 5). On 6 of the 45 paired sets, the difference between the shallowest hook on control and experimental sets was than 1 °C (Fig. 5). Sea surface temperatures increased during the experiment reflecting a geographical shift in fishing locations from approximately 200 nm north of Oahu in July to over 500 nm south and west of Oahu by December.

Of the 13 operational factors measured (Table 1), only the depth of the first hook was identified as providing significant discrimination between control and experimental sets (Tables 3A and 3B). This single variable had a very strong unique discriminatory power (partial lambda = 0.090) suggesting that set types were almost perfectly discriminated by the depth of the first hook alone (Wilk's lambda = 0.057, 0 = perfect discrimination, 1 = no discrimination). Other variables had very little unique discriminatory power (partial lambdas > 0.95). Except for depth of the first hook, the two set types were indistinguishable and therefore extraneous operational variables do not corrupt catch rates.

3.2. Catch and effort

A total of 4697 individual fish comprising 28 species were caught on 180,000 hooks from 90 longline sets. Experimental gear caught 2355 fish on 45 sets while control gear caught 2342 fish on 45 sets (Table 2). Longnose lancetfish dominated the total catch (48%) while bigeye tuna, the target species, was the second most commonly captured species representing approximately 10% of the total catch (Table 2). Twenty-two percent more bigeye tuna were captured by experimental gear than control gear, while 164% more billfish species were captured on control gear than experimental gear. More valuable non-target species, such as sickle pomfret (77%) and opah (70%), were caught by experimental gear. In total, the experimental set gear generated an estimated 51.5% of all vessel revenue while the control set gear generated 48.5% of all revenue. There were no turtle or bird encounters on any of the sets but there was one observation of a false killer whale (*Pseudorca crassidens*) near the vicinity of the gear during haul back on one control set.

Six species of fish contributed to the discrimination between experimental and control sets (Tables 4, 5A and 5B) but the discriminatory power was moderate (Wilk's lambda = 0.534). Catch rates of wahoo, dolphinfish, striped marlin, shortbill spearfish, blue marlin, and sickle pomfret contributed significantly to the discrimination between the two set types (Tables 5A and 5B). Control sets caught more of these species (except for sickle pomfret), than experimental sets (Tables 2 and 4, Fig. 6). The unique discriminatory power of each of these species' contributions was low (partial lambdas between 0.851 and 0.932, Tables 5A and 5B) and catch rates based on single species comparisons could not discriminate between experimental and control sets. Other species could not discriminate between experimental and control sets with any degree of confidence (Table 5B). Of particular interest,

Table 4
Means and standards deviations (S.D.) of the catches for 18 species from 45 control and 45 experimental (no-shallow-hooks) sets.

Species	Control			Experimental		
	Mean	Median	S.D.	Mean	Median	S.D.
Tunas						
Bigeye	4.7	3	5.2	5.7	3	6.1
Albacore	1.7	0	3.8	1.4	0	3.1
Skipjack	0.7	0	1.4	0.4	0	0.7
Yellowfin	1.5	0	3.4	1.1	0	1.8
Billfish						
Striped marlin	1.5	1	1.9	0.5	0	0.8
Blue marlin	0.4	0	0.7	0.1	0	0.4
Shortbill spearfish	0.6	0	0.9	0.1	0	0.3
Other sportfish						
Dolphinfish	3.8	2	4.6	1.3	1	1.9
Wahoo	1.2	1	1.3	0.4	0	0.6
Sharks and rays						
Blue Shark	4.8	3	5.0	5.0	3	5.6
Shortfin mako	0.1	0	0.4	0.2	0	0.4
Pelagic stingray	0.3	0	0.6	0.3	0	0.6
Other species						
Opah	1.0	1	1.4	1.6	1	1.7
Swordfish	0.4	0	0.9	0.3	0	0.7
Escolar	1.2	1	1.3	0.9	1	1.1
Sickle pomfret	2.0	1	2.0	3.5	2	5.0
Snake mackerel	2.4	2	2.5	2.6	1	3.9
Longnose lancetfish	23.5	9	30.5	26.4	9	31.8

Table 5A
Results of the CDA of species captured (by number) by both set types ($n = 45$ sets for each set type). Overall results of the statistical test (Chi-square) on the significance of the CDA between catch rates of control and experimental (no-shallow-hooks) sets. The value of Wilk's lambda (0.534) suggest that the discrimination between the two set types from this canonical root is very high (Wilk's Lambda ranges between zero (perfect discrimination) and 1 (no discrimination) (StatSoft, 2004).

Canonical roots removed	Eigenvalue	Canonical *R*	Wilk's lambda	χ^2	Degrees of freedom	*P*-Level
0	0.872	0.682	0.534	52.037	10	0.000

Table 5B
Results of the CDA of species captured (by number) by both set types ($n = 45$ sets for each set type). Analysis of individual variables and their contribution to discriminating between set types in the CDA. Variables are listed in order of highest to lowest contribution to the discrimination of the two set types in the CDA. Grey highlighted species were significant in discriminating between the two set types. Bigeye tuna were the target species for all set types.

Species	Wilk's lambda	Partial lambda	F-value	P (>F)	Tolerance
Wahoo	0.574	0.931	5.815	0.018	0.910
Dolphinfish	0.628	0.851	13.838	0.001	0.844
Striped marlin	0.588	0.908	7.972	0.006	0.934
Shortbill spearfish	0.584	0.912	7.288	0.008	0.876
Blue marlin	0.573	0.932	5.758	0.019	0.866
Sickle pomfret	0.580	0.921	6.757	0.011	0.895
Opah	0.550	0.971	2.37	0.128	0.938
Swordfish	0.550	0.970	2.405	0.125	0.763
Snake mackerel	0.545	0.980	1.634	0.205	0.917
Blue shark	0.545	0.980	1.600	0.210	0.700
Yellowfin tuna	0.531	0.994	0.507	0.479	0.690
Bigeye tuna	0.531	0.994	0.503	0.480	0.890
Albacore	0.533	0.998	0.167	0.684	0.499
Skipjack tuna	0.532	0.995	0.415	0.521	0.948
Shortfin mako	0.533	0.998	0.152	0.698	0.897
Escolar	0.533	0.997	0.213	0.646	0.904
Pelagic stingray	0.533	0.999	0.109	0.742	0.914
Longnose lancetfish	0.533	0.998	0.133	0.716	0.714

detectable differences in catch rates of the target species, bigeye tuna (or any species of tuna) between the two sets types could not be demonstrated. Moreover, analysis of catch rates of sharks (blue and shortfin mako) and pelagic stingrays indicated no differences between the two set types.

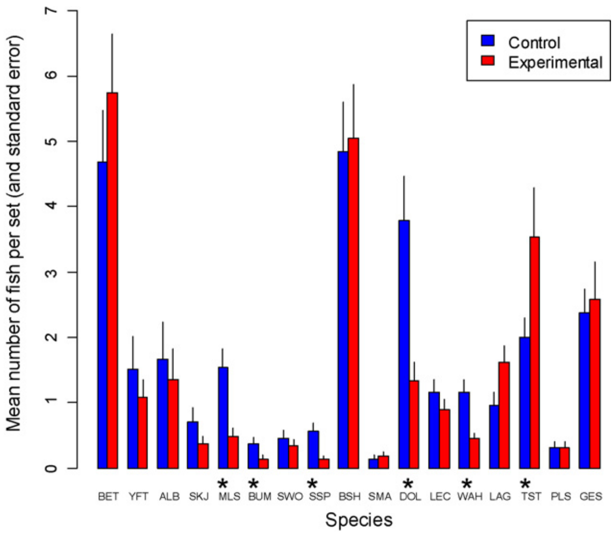

Fig. 6. Mean number of each species captured per control and experimental (no-shallow-hooks) sets. Vertical lines represent one standard error of the mean. Species identified with an asterisk (*) contributed significantly to the discrimination between the two set types. Species codes: BET, bigeye tuna; YFT, yellowfin tuna; ALB, albacore; SKJ, skipjack tuna; MLS, striped marlin; BUM, blue marlin; SWO, swordfish; SSP, shortbill spearfish; BSH, blue shark; SMA, short fin mako shark; DOL, dolphinfish; LEC, escolar; WAH, wahoo; LAG, opah; TST, sickle pomfret; PLS, pelagic stingray; GES, snake mackerel. Data for longnose lancetfish are not shown due to the much higher means for both set types (control: 23.47 ± 4.55 (S.D.); experimental: 26.36 ± 4.74 (S.D.)). See Tables 2 and 4.

4. Discussion

Temperature–depth recorder data indicated, on average, that the depth of the first hook was significantly deeper in the experimental gear than the control gear (Tables 3A and 3B) thus reinforcing the potential of this technique to reduce fishery interactions of epi-pelagic species. On average, the fishing portion of the experimental gear fished below 100 m (Fig. 4). By contrast, about 30% of the hooks on control gear (4 shallow hooks at each end of the longline basket) fished at depths less than 100 m (Fig. 4). Despite the difference in depth of shallow position hooks between gear types, both gear types targeted bigeye tuna and captured a similar species composition. Given the distribution pattern of bigeye tuna in Hawaii (Musyl et al., 2003), control and experimental gear caught similar numbers due to the availability of hooks beneath the thermocline where bigeye tuna forage during the daytime. However, there were significant differences in catch rates between the two gear types for five incidental epi-pelagic species. Significantly fewer wahoo, dolphinfish, striped marlin, shortbill spearfish and blue marlin were caught from the experimental gear than from the control gear. These species are generally reported to have shallow depth distributions with most movements within the uniform mixed layer (Collette and Nauen, 1983; Lasso and Zapato, 1999; Matsumoto et al., 2000; Arnold and Dewar, 2001; Gunn and Block, 2001; Domeier et al., 2003). By having the shallowest hooks below ~100 m, the experimental sets created more distributional "mismatches" with epi-pelagic species than the control gear. At fishing depths greater than 100 m, the experimental gear was mostly fishing at the juncture between the mixed layer and thermocline (de Boyer Montégut et al., 2004) thus eliminating hooks available to epi-pelagic species that do not make regular excursions beneath the thermocline (Arnold and Dewar, 2001; Gunn and Block, 2001; Brill and Lutcavage, 2001).

The potential to eliminate hooks less than 100 m to reduce interactions with epi-pelagic species on commercial longline gear has important management and conservation implications. There is particular concern in Hawaii and other areas of the Pacific about interactions between longline and sport fishing gears (Boggs, 1994; Bromhead et al., 2004; Langley et al., 2006). Sport and recreational fisheries target epi-pelagic species with shallow distributions usually by trolling gear in the upper 50 m of the water column which overlaps the depth distribution of typical tuna longline fishing. Therefore, the experimental technique reported in this study creates mismatches in distribution patterns of fishing gear with vertical dive patterns of epi-pelagic species and has important ramifications. Potential benefits to the longline fishery in adopting this experimental technique include: (1) reduction in catch rates of at least three epi-pelagic marlin species, dolphinfish, and wahoo, (2) reduction in fishery interactions between longline, sport fishing, and recreational sectors, and (3) an increase in the number of hooks available to deeper species such as bigeye tuna and sickle pomfret. In the long term, an economic disadvantage of using this experimental gear is the loss of revenue from these three marlin species, dolphinfish, and wahoo that have market value. The reduction in catch of epi-pelagic fish like wahoo, reduces the perceived interaction of longline activities with sport fishing activities. The increased catch in species that are marketable, but not targeted by the sport fish community (e.g. opah, pomfret), could provide managers with a tool to help alleviate allocation conflicts.

The additional gear needed to deploy the experimental sets resulted in a one-off cost of about US$3000 for the floats, lines, snaps, and lead weights. There was also a 'cost' in work time as it generally took 30 min longer to set experimental gear than control gear and it took approximately 2 h longer to haulback experimental gear than control gear. However, the 'perceived' loss of revenue could be compensated by an increase in landings of more valuable species. Although the numbers were too low to have a strong statistical impact in this study, never-the-less, experimental gear did capture 22% more bigeye tuna and 77% more sickle pomfret than control gear. From both a monetary cost: benefit and conservation perspective, if these numbers could be demonstrated to be constant over the long term, then this would make the experimental gear an extremely attractive alternative.

Many species were captured in similar numbers by both gear types due to the overlapping depth range of hooks in each set type. Most importantly, catches of bigeye tuna, the target species, were similar between the two set types. Additionally, other commercially important tuna species were also captured in similar numbers by both set types, although catches of yellowfin, albacore and skipjack were lower in the experimental sets (Table 2). Yellowfin and skipjack tuna are most common in surface waters (Nakano et al., 1997) and thus it was expected that control gear would catch more of these species than the experimental gear. Albacore are typically found at intermediate depths between those for bigeye and yellowfin (Gong et al., 1995; Ward and Myers, 2005) and catches were similar on both gear types as were the catch rates of sharks and pelagic stingrays. Thus, the experimental gear did not dramatically alter the catch rates with these species in the area examined.

Our results showed significant differences in catch rates of epi-pelagic species between the experimental and control sets when operational characteristics between the set types were virtually similar except for the depth of the shallow hooks. To control for differences in catching and fishing power (Hilborn and Walters, 1992), only a single vessel was used to deploy all 90 sets (45 of each set type). Additional trials over much greater temporal and spatial scales may strengthen the discrimination between the two set types and would also result in a more thorough comparison of the experimental setting technique with standard (control) setting techniques.

Based on our initial results, it is likely that the new experimental technique reported in this study would also significantly reduce longline–turtle interactions because electronic tagging studies reported marine turtles to spend the majority of their time in the upper 100 m of the water column (Polovina et al., 2003, 2004; Swimmer et al., 2006). Turtle interactions are considered "rare" events in the Hawaii-based tuna longline fishery (McCracken, 2004) and, as expected, no interactions occurred during this experiment. Elimination of hooks available in the upper 100 m of the water column effectively removes baited hooks within prime turtle foraging habitat.

The development and implementation of any mitigation technique should consider trade-offs for the species and industries impacted. The experimental (no-shallow-hooks) gear demonstrated a significant reduction in longline catches of epi-pelagic species while the catch rate of the target species, bigeye tuna, was similar between the two set types. The success of any mitigation technique should not be measured just by its ability to reduce catches of unwanted species, but also by its acceptance by the fishing industry (Gilman et al., 2005, 2006). Mitigation measures that are likely to be adopted by industry are those that provide operational benefits, do not increase safety hazards, and do not decrease fishing efficiency. We believe the catch results for the new experimental technique reported in this study meets these criteria and therefore, warrants further study.

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