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Evaluation of longline mitigation to reduce catches of North Pacific striped marlin in the Hawaii-based tuna fishery[1]

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1 Introduction

Striped marlin in the North Pacific are primarily harvested in longline fisheries targeting species such as tunas (*Thunnus spp.*) and swordfish (*Xiphias gladius*). Annual catches have declcined from ~17,000 mt in the early 1960s to ~3,000 mt in 2006 (Figure 1). Striped marlin are primarily harvested by longline fisheries from Japan in the northwest Pacific and the USA in the central Pacific with smaller catches from Korea and Chinese-Taipei longline fleets and are also targeted in coastal fisheries off Japan and Chinese-Taipei and support valuable recreational fisheries off Australia, New Zealand, Mexico and the United States.

The International Scientific Committee for Tuna and Tuna-like species in the North Pacific (ISC) completed a striped marlin assessment in 2007 considering a stock in the entire North Pacific (Piner et al. 2007). The assessment was conducted in SS2 with a structure of 29 different fisheries, defined by region, country and gear. Nine fisheries, all of them longline fisheries from the western or central Pacific, provided reasonable measures of abundance. Two assessment scenarios were based on alternative assumptions about the steepness of the stock-recruitment relationship and under these two scenarios the spawning biomass of the North Pacific striped marlin stock was estimated to have been fished down to between 6% and 16% of its 1952 abundance. This low range of spawner abundance suggested that the stock was in a depleted condition and the ISC offered the following conservation advice (ISC 2007):

While further guidance from the management authority is necessary, including guidance on reference points and the desirable degree of reduction, the fishing mortality rate of striped marlin (which can be converted into effort or catch in management) should be reduced from the current level (2003 or before), taking into consideration various factors associated with this species and its fishery. Until appropriate measures in this regard are taken, the fishing mortality rate should not be increased.

Brodziak and Piner (2010) presented probable status of N. Pacific striped marlin by conducting two assessment scenarios to account for different hypotheses about the steepness of the stock-recruitment dynamics. Values of relative fishing mortality rates during 2001–2003 were 367% of F_{MSY} under scenario 1 and 190% of F_{MSY} under scenario 2. Corresponding estimates of striped marlin biomass were below S_{MSY} and ranged from 29% of S_{MSY} under scenario 1 to 44% of S_{MSY} under scenario 2. In relation to MSY-based reference points, striped marlin was experiencing overfishing and the stock was considered depleted under each steepness scenario.

Given the high estimated fishing mortality, the objectives of this study were to conduct analyses of potential longline catch reductions of N. Pacific striped marlin while maintaining target bigeye tuna catches. Longline mitigation was based on modification of longline gear and spatially closed areas. The analysis was conducted on the Hawaii-based longline fishery which comprises ~10% of the total N. Pacific catch of striped marlin since 2000 and is well suited to analyses of longline mitigation because detailed operational and catch data have been gathered by the Pacific Islands Regional Observer Program (PIROP) since 1994. The Hawaii-based pelagic longline fishery is composed of two sectors which target bigeye tuna (*Thunnus obesus*) with deep gear and swordfish (*Xiphius gladius*) with shallow gear. The median depth of the deepest hook on 266 deep sets was 248 m, whereas that on 333 shallow sets was 60 m (Bigelow et al. 2006). The study considered the deep set fishery due to larger striped marlin catches and potentially greater mitigation options as deep gear fishes at a greater range of depth and habitat than shallow gear targeting swordfish. Aspects of gear mitigation considered in the study were the efficacy of removing shallow hooks adjacent to longline floats and conversion of terminal gear from Japanese style tuna hooks to 18/0 circle hooks. A spatial and temporal analysis was conducted to investigate the existence of striped marlin catch rate (CPUE) hot spots. An evaluation of establishing tuna longline fishery closures was conducted with the trade-off between striped marlin catch reductions and loss of target bigeye catch.

2 Methods

2.1 Observer data

Levels of observer coverage increased from 4.7% of longline sets in 1995, nearly tripled in 2000 and averaged 24.4% during 2001–2006 (Walsh et al. 2009). The PIROP observers record operational details of the longline set and retrieval, species specific estimates of fish catch on a particular hook position, condition upon longline retrieval (i.e. live or dead), subsequent disposition (i.e. retained or discarded), and lengths. They also monitor interactions with protected or endangered species (PIRO 2010). Deep sets were characterized as a longline set with at least 15 hooks between floats and shallow sets used less than 15 hooks between floats. Catch data were gathered by PIROP observers on 33,049 deep longline sets north of the equator on 2,640 commercial fishing trips from March 1994 through December 2009.

2.2 Hook-at-capture

Observers recorded the particular hook position, numbered sequentially between two successive floats, for each animal caught. These hook-at-capture data are available even when depths are not recorded, and distributions of hook-at-capture were generated from the 33,049 observed sets that monitored 68,165,026 hooks. A total of 1,534,262 animals representing 125 fish, elasmobranch, turtle, mammal and bird species or species groups were caught. Hook-at-capture distributions by species and corresponding catch rate by hook number were only considered in the analysis if at least 5,000 individuals were caught. Some species were rarely encountered and this criterion reduced the analysis to 1,463,000 individuals of 19 species (Table 1). A proportion (~14%) of individuals was reported as caught but without a hook-at-capture number. In these cases, the available catch rate by hook number distribution for a species was expanded (raised) to represent all captures for the purposes of modeling the effects of eliminating particular hook numbers.

2.3 Longline catch scenarios with removing hooks adjacent to floats and redistribution of hooks

For modeling the removal of hooks near floats, sequential hook positions were renumbered from shallowest (nearest the float) to deepest (half way between floats) for each configuration of hooks between floats (the number of hooks between floats can vary). The catch and effort were then summed by hook number. Six scenarios based on catch rate by hook number were developed to portray the change in catches expected to occur by removing hooks adjacent to longline floats. Three scenarios considered the removal of hook #1, hooks #1−2 and hooks #1−3 adjacent to the float. Removal of hooks actually occurs on both sides of each float, thus the removal of hooks #1−3 constitutes a total of six hooks removed. An additional three scenarios considered the same sequence of hook removal though the removed hooks were redeployed in the deeper depth pattern by adding to the total length of the set (with additional mainline and floats). For example, if hooks #1−3 were removed, then they were deployed at position #4 and deeper in an extension to the length of the modeled set. Each scenario considered a hypothetical longline set with 2,800 hooks deployed and 28 hooks between floats.

The six scenarios were further stratified by catches kept (landed) and released (bycatch) to quantify changes expected by hook removal. Proportions of kept and released individuals by species were based on 33,049 observed sets (Table 1) and the scenarios assumed that proportions did not change through time.

2.4 Catchability of Japanese tuna and circle hooks

Sixteen Hawaii-based tuna longline vessels were contracted to alternate large non-ringed stainless steel circle hooks ("C" hooks size 18/0 made in Korea) with the vessel's conventional hooks (composed entirely of Japanese style tuna hooks size 3.6 sun (hereafter referred as a 'tuna' hooks) on all longline deployments. Vessels mixed two individual hook types (e.g. C, tuna, C, tuna) throughout the longline set in a 1:1 ratio, and there was no change in operational characteristics in order to minimize sources of variation. Vessels chose where they fished and were allowed to retain and sell their catch. At the beginning of the field trials, all vessels were mandated to mix the alternate hook types throughout the entire longline set and to maintain a 1:1 ratio of hook types throughout the trials. Branchline snaps with 10-cm cable ties allowed for easy identification of hook type and corresponding fish catch. Vessels conducted trips between July 2005 and February 2006.

Every trip was accompanied by a National Oceanic and Atmospheric Administration (NOAA) certified Pacific Islands Region observer who collected information on all catch by species, hook type, sequential hook number between two floats, life status, catch disposition (retained, discarded), and length measurements of some landed species. The observer conducted a daily tally of the numbers of each type of hook deployed, and evaluated the vessel's ability to follow experimental protocols. A total of 1,182 longline sets were analyzed. The most numerous 18 individual species were chosen for analysis representing a minimum catch rate of 0.14 fish per longline set.

Generalized Linear Mixed Models (GLMM) were applied to explicitly model the underlying processes in the catch rate (CPUE, number per 1,000 hooks) data and to estimate catchability of hook types. GLMMs were employed to accommodate the hierarchy in which longline sets within a trip are expected to be more similar than sets across trips. For each species, the GLMM predicts mean catch (μ_i) per set using three categorical and two continuous variables with a log link:

$$\log(\mu_i) = N_i + H_i + T_i + V_i + \beta_1 Lat_i + \beta_2 Lat_i^{\,2} + \beta_3 Lat_i^{\,3} + \beta_4 Lon_i + \beta_5 Lon_i^{\,2} + \beta_6 Lon_i^{\,3} + \log(E_i)$$

where N is the mean local abundance; H, hook type effect; T, time (year:quarter) effect; V, vessel effect; Lat and Lon are third order (cubic) effects of latitude and longitude and offset E is the number of hooks deployed during longline operation i. Catch rates are correlated within a trip, thus trip was assigned as the grouping variable in GLMMs with no estimated random effects. GLMMs were applied using the glmm.ADMB module in R (version 2.7.2 for Linux) and considered both poisson and negative binomial response distributions. Model selection was conducted by AIC.

2.5 Striped marlin catch rate (CPUE) hot spots and effects of spatially closed areas

Logbooks estimates of istiophorid catches in the Hawaii longline fishery are biased due to misidentification, especially blue marlin which was estimated to be inflated by 29.4% while catches of other marlin species are negatively biased (Walsh et al. 2005). A scientific database of corrected istiophorid catches from 1994 to 2003 was used to investigate spatial CPUE hot spots and evaluated tuna longline fishery closures. In order to predict the areas with high CPUE we applied generalized additive models (GAM) using penalized regression splines, estimated by penalized iterative least squares (Wood, 2006). Two models were fit to the data:

- Reduced model

$$\log(\mu_i) = s(Lon_i, Lat_i) + \log(E_i)$$

- Full model

$$\log(\mu_i) = Y_i + s(Lon_i, Lat_i) + s(M_i) + s(V_i) + s(HBF_i) + \log(E_i)$$

where μ_i is the number of striped marlin caught per set; *s* (*Lon, Lat*) represents the effect of the spatial location as an isotropic bivariate function (Wood and Augustin, 2002); *Y*, year effect as a factor; *M*, month effect; *V*, vessel effect; *HBF*, the number of hooks deployed between two successive floats and offset *E* is the number of hooks deployed during longline operation *i*. Initially the models were fit for the entire period (1994−2003) and also on a quarterly basis to assess seasonal variation. Moreover, in order to delineate and assess the persistence of the CPUE hot spot areas we also fit models for each year separately.

GAMs were fitted using the *mgcv* package (Wood 2006) in R 2.10.1 (R Development Core Team, 2009) with the optimum degrees of smoothing being estimated by the generalized cross-validation (GCV) criterion. The selection of predictors and the decision on entry or exclusion was based on AIC and the total deviance explained. Two error distributions (poisson and negative binomial) were considered and the decision of error distribution was based on the lowest values of AIC and BIC, total deviance explained and adjusted-R^2. The latter was defined as the proportion of variance explained, where original variance and residual variance were both estimated using unbiased estimators (Wood, 2006).

The spatial predictions were generated from the contribution of the smoothed latitude-longitude term and the predictions occurred uniformly across the locations of observed fishing and not exclusively over a regular spatial grid. Furthermore, spatial predictions with overall mean of +1 standard deviation were also illustrated to assess if high CPUE persisted spatially across years following the methodology in Watson et al. (2008).

Impact of fishery closures was estimated on a spatial grid from 180º to 128ºW and the equator to 40ºN (Figure 2). All possible contiguous squares and rectangles were considered which resulted in 79,380 closure options. The percentage reduction in striped marlin and bigeye catches was estimated for each closed area. There was no temporal structure for the closures and no redistribution of fishing effort was considered.

3 Results

3.1 Observer data and hook-at-capture

Attributes of gear configuration on observed deep sets were similar to previously values estimated for the longlines monitored during 1996−1999 (Table 1 in Bigelow et al. 2006). Hook-at-capture results are initially illustrated for two species – striped marlin and bigeye tuna (Figure 3). The hooks are numbered sequentially from one float to the subsequent float and indicate that striped marlin are caught on shallow hooks while bigeye are on deeper hooks. For each hook between float configuration, the hooks were renumbered from shallow to deep and catch and effort were summed by hook number. The resulting CPUE by hook number is illustrated for 19 species in Figure 4. The shallowest hooks, adjacent to the longline floats, have substantially higher CPUE for wahoo, four istiophorid species, oceanic white-tip shark and mahimahi. The deepest hooks have higher CPUE for bigeye tuna and bigeye thresher shark.

3.2 Longline catch scenarios with removing hooks adjacent to floats and redistribution of hooks

Table 2 summarizes the percentage of catch by species on hook#1 and hooks#1−2. There are differences by quarter for most species. Striped marlin had the lowest percentage in reductions during quarter 1 (12% on hook#1 and 23% on hooks#1−2) and highest percentage during quarter 4 (25% on hook#1 and 43% on hooks#1−2). Table 3 considers catch scenarios resulting from removal of hooks adjacent to floats and the redistribution of hooks to deeper depths. Catch reductions in Tables 2−3 differ slightly because estimates in Table 2 were from the entire hook-at-capture CPUE distribution (Figure 4) whereas Table 3 considered one particular gear type (28 HBF).

The largest catch reductions in terms of percentage occurred for striped marlin, spearfish and dolphinfish. Target bigeye catches declined 1.5%, 4% and 7.8% by removing hook #1, hooks #1−2 and hooks #1−3 adjacent to the float. Total catches of all landed fish declined at higher percentages (8%, 16% and 23%) mainly due to lower CPUE of mahimahi. Total bycatch declined at the lower percentages (5%, 12% and 19%) due to lower CPUE of blue shark and lancetfish. The redistribution of hook #1, hooks #1−2 and hooks #1−3 increased target bigeye catches by 6%, 12% and 17%. Albacore, bigeye thresher shark and sickle pomfret also had similar catch increases as bigeye tuna with removing and redistributing hooks. Total bycatch was largely unaffected by removing and redistributing hooks.

3.3 Catchability of Japanese tuna and circle hooks

Tuna hooks caught 4,630 bigeye and 642 striped marlin whereas 18/0 circle hooks caught 4,722 bigeye and 370 striped marlin. Details for the remaining 16 species are not discussed as results are included in another manuscript currently under review. The GLMM hook type coefficients are equivalent to catchability and interpreted as the magnitude of the CPUE differences between hook types considering the inclusion of other significant explanatory variables. The circle hook coefficients for bigeye tuna and striped marlin were 1.011 (95% CI 0.949−1.073) and 0.574 (95% CI 0.431−0.718), respectively. Bigeye CPUE was not significantly different between tuna and circle hooks. A coefficient of 0.574 indicates that striped marlin CPUE was ~42.6% reduced on circle hooks compared to tuna hooks.

3.4 Striped marlin catch rate (CPUE) hot spots and effects of spatially closed areas

Model results of the GAM analysis are provided in Table 4. A negative binomial error distribution was consistently preferred over a poisson distribution. The reduced models with only the smoothed latitude-longitude term explained ~13% of the deviance, whereas the full model with effects of month, vessel and gear (HBF) explained ~24% of the deviance. The spatial prediction aggregated over the entire time-series (1994−2003) indicated an area of high CPUE at 25ºN and 165ºW (Figure 5). The high CPUE occurred in the same area in quarters 1 through 3, but CPUE was lower and more dispersed in quarter 4 (Figure 6). However, when individual years were considered the spatial distribution of high CPUE was highly variable and not persistent, suggesting a lack of CPUE hot-spots (Figure 7).

The closure analysis did not identify areas of potentially high striped marlin reductions with minimal reductions of target bigeye catch (Figure 8), rather there is a co-occurrence in catch of both species. The lack of an optimal spatial closure is reflected in the high interannual spatial variation of CPUE (Figure 7).

4 Discussion

Analyses of the effects on removing shallow hooks and changing from tuna to circle hooks both demonstrated moderate striped marlin CPUE reductions with minimal or no reductions on target bigeye CPUE. Striped marlin CPUE hot-spots exist in the Baja California in the eastern Pacific, near New Zealand and in the northwest Pacific; however there were no hot-spots identified that were spatially persistent in the area fished by the Hawaii-based tuna fishery. Modifying longline gear to fish deeper has been demonstrated to provide conservation benefits to istiophorids by comparing CPUE on shallow and deep gear (Suzuki et al. 1977) and by experimental longline trials (Boggs 1992, Beverly et al. 2009). An estimated 16 and 30% reduction in striped marlin catch could occur if hook#1 and hooks#1−2 were not fished, respectively; and longline scenarios with a specific gear configuration of 28 HBFs indicated reductions of 18 and 34%. Three of the longline scenarios changed the gear configuration by redistributing hooks to deeper depths. While these scenarios indicate increased CPUE and catches of target bigeye, there are operational difficulties as more mainline will need to be deployed, thus increasing both the setting and retrieval times. Considering a longline with 2,800 hooks deployed and 28 hook positions between floats, if two hooks are removed adjacent to the float then 14% of the effort (4 of every 28 hooks) would have to be redistributed. Longline retrieval is typically completed by 2 am and the set commences again at 6:30 am thus there is little time for extending retrievals with the current observed operational patterns.

Using large (18/0) circle hooks had a larger effect on CPUE (42% reduction) than removing shallow hooks. Reduced catchability occurred for most species on large circle hooks and we contend that these reductions are a function of 18/0 circle hook morphology. Although there are a myriad of types, sizes, and shapes of hooks used within longline fisheries around the world, the minimum width appears to be the primary metric influencing catchability rather than gape or straight total length. The 18/0 circle hook had a minimum width (4.9 cm) that was 57% wider than the Japanese tuna (3.1 cm). The larger minimum width relates to a smaller probability of ingestion and probably accounts for the reduced catchability of non-bigeye species.

We assume that the there would be a multiplicative effect of a ~70% reduction in striped marlin CPUE by both removing shallow hooks and implementing large circle hooks. While there are demonstrated conservation benefits to a variety of species in not fishing shallow hooks or implementing large circle hooks, there is economic concern in the Hawaii-based tuna fishery of lost revenue due to lower catch rates of istiophorids, dolphinfish and some pelagic sharks that are often retained and marketed.

5 Acknowledgments

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Table 1. Catch of 19 most common species observed on 33,049 sets in the Hawaii-based tuna longline fishery with valid hook-at-capture and percentage retained.

Species	Catch	Valid hook-at-capture	Percentage retained
Bigeye tuna *Thunnus obesus*	286,621	275,351	94.54
Yellowfin tuna *Thunnus albacares*	72,184	69,636	90.72
Wahoo *Acanthocybium solandri*	32,149	21,272	94.78
Albacore *Thunnus alalunga*	47,425	45,947	97.51
Skipjack tuna *Katsuwonus pelamis*	61,026	59,803	82.84
Striped marlin *Kajikia audax*	34,365	33,611	94.40
Spearfish *Tetrapturus angustirostris*	28,612	28,012	92.21
Swordfish *Xiphias gladius*	12,367	11,854	58.45
Blue marlin *Makaira nigricans*	9,358	8,952	96.28
Blue shark *Prionace glauca*	146,307	142,834	0.33
Bigeye thresher *Alopias superciliosus*	11,646	11,129	8.63
Oceanic white-tip shark *Carcharhinus longimanus*	5,303	5,124	4.22
Pelagic stingray *Dasyatis violacea*	11,526	7,151	3.63
Dolphinfish *Coryphaena hippurus*	137,599	98,238	92.31
Opah *Lampris guttatus*	28,238	19,802	97.57
Sickle pomfret *Taractichthys steindachneri*	94,586	69,358	96.05
Lancetfish *Alepisaurus ferox*	314,747	246,916	0.02
Escolar *Lepidocybium flavobrunneum*	45,908	36,491	88.66
Snake mackerel *Gempylus serpens*	83,033	62,900	1.84

Table 2. Percentage of individuals taken on the first and first/second hooks closest to the longline float observed on 33,049 sets in the Hawaii-based tuna longline fishery.

Species	All quarters		1st quarter		2nd quarter		3rd quarter		4th quarter	
	Hook 1	Hooks 1-2	Hook 1	Hooks 1-2	Hook 1	Hooks 1-2	Hook 1	Hooks 1-2	Hook 1	Hooks 1-2
Bigeye tuna	1.13	2.89	1.12	2.97	1.09	2.77	1.43	3.44	1.01	2.68
Yellowfin tuna	3.69	8.78	2.93	7.32	4.71	10.57	3.69	8.56	3.80	9.20
Wahoo	12.31	25.07	9.75	20.40	12.23	25.62	14.11	27.87	12.11	23.98
Albacore	1.28	3.77	1.56	4.20	1.23	3.83	1.98	5.81	0.98	2.90
Skipjack tuna	8.23	18.54	5.76	13.50	9.74	21.71	13.10	28.44	8.98	20.14
Striped marlin	16.71	30.64	12.15	23.30	17.78	31.81	25.20	43.22	17.28	32.18
Spearfish	22.07	38.28	19.14	34.51	24.80	42.63	29.69	49.21	21.57	37.14
Swordfish	6.58	14.57	5.70	10.95	3.93	9.64	8.10	17.04	8.04	18.60
Blue marlin	14.10	25.52	11.87	21.46	13.93	25.62	15.95	27.37	14.14	26.51
Blue shark	4.73	10.69	4.95	10.79	4.72	10.58	5.57	12.25	4.16	9.80
Bigeye thresher	1.14	3.16	1.23	3.13	1.04	2.87	1.50	4.63	1.19	3.31
Oceanic white-tip shark	15.14	26.82	14.22	24.95	15.75	26.93	15.98	30.26	15.73	27.73
Pelagic stingray	3.89	9.99	2.55	7.24	3.77	9.15	5.36	12.59	3.22	9.10
Dolphinfish	22.82	38.42	26.74	43.56	25.51	42.94	19.98	34.35	21.28	35.91
Opah	1.02	2.86	0.58	1.74	1.08	3.45	0.92	2.48	0.92	2.54
Sickle pomfret	0.56	1.67	0.45	1.56	0.51	1.44	0.50	1.51	0.62	1.86
Lancetfish	3.30	8.48	2.88	7.25	2.88	7.67	3.97	9.71	2.41	6.83
Escolar	7.29	15.99	6.75	15.38	7.08	15.78	7.72	15.95	7.21	15.94
Snake mackerel	5.67	12.99	4.86	11.25	6.28	13.93	7.96	17.33	5.01	11.96

Table 3. Nominal CPUE (number per 1000 hooks) and percentage landed for 19 species observed on 33,049 longline sets in the Hawaii-based fishery. Six longline scenarios indicate hypothetical catches by removing various hooks with and without redistribution for a longline set with 28 hooks between floats and 2,800 hooks.

					Removing no hooks (status quo)			Removing hook #1 adjacent to float			
Common name	Species code	Nominal cpue	Percentage landed	Percentage bycatch	Catch	Landed	Bycatch	Catch	Catch percent of status quo	Landed	Bycatch
Bigeye tuna	916	4.15	94.54	5.46	11.63	11.00	0.64	11.47	98.56	10.84	0.63
Yellowfin tuna	1	1.06	90.72	9.28	2.96	2.68	0.27	2.81	95.22	2.55	0.26
Wahoo	57	0.47	94.78	5.22	1.33	1.26	0.07	1.15	86.97	1.09	0.06
Albacore	5	0.69	97.51	2.49	1.92	1.88	0.05	1.89	98.42	1.85	0.05
Skipjack tuna	2	0.90	82.84	17.16	2.52	2.08	0.43	2.26	89.97	1.88	0.39
Striped marlin	92	0.51	94.40	5.60	1.42	1.34	0.08	1.15	81.54	1.09	0.06
Spearfish	94	0.42	92.21	7.79	1.18	1.09	0.09	0.89	75.71	0.82	0.07
Swordfish	91	0.18	58.45	41.55	0.51	0.30	0.21	0.47	91.49	0.27	0.19
Blue marlin	93	0.14	96.28	3.72	0.39	0.37	0.01	0.33	84.45	0.31	0.01
Blue shark	167	2.15	0.33	99.67	6.01	0.02	5.99	5.68	94.57	0.02	5.66
Bigeye thresher	147	0.17	8.63	91.37	0.47	0.04	0.43	0.47	98.77	0.04	0.43
Oceanic white-tip shark	138	0.08	4.22	95.78	0.22	0.01	0.21	0.18	82.72	0.01	0.17
Pelagic stingray	193	0.17	3.63	96.37	0.47	0.02	0.45	0.45	95.72	0.02	0.43
Dolphinfish	914	2.03	92.31	7.69	5.68	5.24	0.44	4.26	75.04	3.93	0.33
Opah	467	0.41	97.57	2.43	1.15	1.13	0.03	1.14	99.13	1.12	0.03
Sickle pomfret	908	1.35	96.05	3.95	3.79	3.64	0.15	3.78	99.67	3.63	0.15
Lancetfish	909	4.64	0.02	99.98	13.00	0.00	13.00	12.57	96.66	0.00	12.56
Escolar	13	0.68	88.66	11.34	1.89	1.68	0.21	1.74	91.82	1.54	0.20
Snake mackerel	295	1.22	1.84	98.16	3.43	0.06	3.36	3.22	93.86	0.06	3.16
Total catch (numbers of fish)					**59.96**	**33.83**	**26.13**	**55.91**		**31.07**	**24.84**

Table 3 continued. Nominal CPUE (number per 1000 hooks) and percentage landed for 19 species observed on 33,049 longline sets in the Hawaii-based fishery. Six longline scenarios indicate hypothetical catches by removing various hooks with and without redistribution for a longline set with 28 hooks between floats and 2,800 hooks.

	Removing hooks #1-2 adjacent to float				Removing hooks #1-3 adjacent to float			
Common name	Catch	Catch percent of status quo	Landed	Bycatch	Catch	Catch percent of status quo	Landed	Bycatch
Bigeye tuna	11.17	96.04	10.56	0.61	10.73	92.20	10.14	0.59
Yellowfin tuna	2.61	88.43	2.37	0.24	2.36	79.89	2.14	0.22
Wahoo	0.97	73.35	0.92	0.05	0.81	60.83	0.76	0.04
Albacore	1.82	94.87	1.78	0.05	1.72	89.36	1.68	0.04
Skipjack tuna	1.94	77.20	1.61	0.33	1.62	64.40	1.34	0.28
Striped marlin	0.94	66.11	0.88	0.05	0.75	53.21	0.71	0.04
Spearfish	0.68	57.84	0.63	0.05	0.52	43.98	0.48	0.04
Swordfish	0.41	81.00	0.24	0.17	0.36	70.77	0.21	0.15
Blue marlin	0.28	71.86	0.27	0.01	0.23	60.19	0.22	0.01
Blue shark	5.26	87.58	0.02	5.24	4.77	79.33	0.02	4.75
Bigeye thresher	0.45	96.22	0.04	0.42	0.44	92.43	0.04	0.40
Oceanic white-tip shark	0.15	69.40	0.01	0.14	0.13	58.06	0.01	0.12
Pelagic stingray	0.42	88.72	0.02	0.40	0.38	80.58	0.01	0.37
Dolphinfish	3.29	57.95	3.04	0.25	2.60	45.80	2.40	0.20
Opah	1.12	97.17	1.09	0.03	1.08	93.80	1.06	0.03
Sickle pomfret	3.73	98.50	3.59	0.15	3.65	96.31	3.51	0.14
Lancetfish	11.85	91.12	0.00	11.85	10.91	83.89	0.00	10.91
Escolar	1.55	81.91	1.38	0.18	1.36	71.55	1.20	0.15
Snake mackerel	2.94	85.75	0.05	2.88	2.63	76.68	0.05	2.58
Total catch (numbers of fish)	**51.60**		**28.49**	**23.11**	**47.03**		**25.98**	**21.05**

Table 3 continued. Nominal CPUE (number per 1000 hooks) and percentage landed for 19 species observed on 33,049 longline sets in the Hawaii-based fishery. Six longline scenarios indicate hypothetical catches by removing various hooks with and without redistribution for a longline set with 28 hooks between floats and 2,800 hooks.

Re-distributing shallow hooks

	Removing hook #1 adjacent to float				Removing hooks #1-2 adjacent to float				Removing hooks #1-3 adjacent to float			
Common name	Catch	Catch percent of status quo	Landed	Bycatch	Catch	Catch percent of status quo	Landed	Bycatch	Catch	Catch percent of status quo	Landed	Bycatch
Bigeye tuna	12.35	106.14	11.67	0.67	13.04	112.05	12.32	0.71	13.65	117.35	12.91	0.75
Yellowfin tuna	3.03	102.55	2.75	0.28	3.05	103.17	2.77	0.28	3.01	101.67	2.73	0.28
Wahoo	1.24	93.66	1.18	0.06	1.13	85.57	1.07	0.06	1.03	77.42	0.97	0.05
Albacore	2.04	105.99	1.99	0.05	2.13	110.68	2.08	0.05	2.19	113.73	2.13	0.05
Skipjack tuna	2.44	96.89	2.02	0.42	2.27	90.06	1.88	0.39	2.06	81.97	1.71	0.35
Striped marlin	1.24	87.81	1.17	0.07	1.09	77.13	1.03	0.06	0.96	67.72	0.91	0.05
Spearfish	0.96	81.54	0.89	0.07	0.79	67.49	0.73	0.06	0.66	55.98	0.61	0.05
Swordfish	0.50	98.53	0.29	0.21	0.48	94.50	0.28	0.20	0.46	90.07	0.27	0.19
Blue marlin	0.35	90.94	0.34	0.01	0.32	83.84	0.31	0.01	0.30	76.60	0.28	0.01
Blue shark	6.12	101.85	0.02	6.10	6.14	102.18	0.02	6.12	6.07	100.97	0.02	6.05
Bigeye thresher	0.50	106.37	0.04	0.46	0.53	112.26	0.05	0.48	0.56	117.64	0.05	0.51
Oceanic white-tip shark	0.19	89.08	0.01	0.19	0.18	80.96	0.01	0.17	0.16	73.90	0.01	0.15
Pelagic stingray	0.49	103.09	0.02	0.47	0.49	103.51	0.02	0.47	0.48	102.56	0.02	0.47
Dolphinfish	4.59	80.81	4.24	0.35	3.84	67.61	3.54	0.30	3.31	58.28	3.06	0.25
Opah	1.23	106.76	1.20	0.03	1.31	113.36	1.28	0.03	1.38	119.39	1.34	0.03
Sickle pomfret	4.07	107.33	3.91	0.16	4.36	114.92	4.18	0.17	4.65	122.58	4.46	0.18
Lancetfish	13.53	104.09	0.00	13.53	13.82	106.31	0.00	13.82	13.88	106.77	0.00	13.88
Escolar	1.87	98.88	1.66	0.21	1.81	95.57	1.60	0.21	1.72	91.07	1.53	0.20
Snake mackerel	3.46	101.07	0.06	3.40	3.43	100.04	0.06	3.37	3.34	97.59	0.06	3.28
Total catch (numbers of fish)	**60.21**		**33.46**	**26.75**	**60.20**		**33.24**	**26.96**	**59.86**		**33.06**	**26.80**

Table 4. Model selection results for striped marlin CPUE for reduced and full Generalized Additive Models.

	Reduced Model					Full Model				
	GCV	% Dev.	AIC	BIC	R-sq (adjust)	GCV	% Dev.	AIC	BIC	R-sq (adjust)
Poisson (1994-2003)	2.56	12.90	298344.80	298615.10	0.08	2.11	28.10	264957.30	265546.60	0.22
Neg. Binomial (1994-2003)		12.20	243544.70	243815.10	0.08		26.10	229964.30	230556.50	0.21
Neg. Binomial (1° quarter, 1994-2003)		0.08	66974.18	67198.49	12.40		20.70	65183.98	65609.00	0.16
Neg. Binomial (2° quarter, 1994-2003)		12.70	54603.46	54821.31	0.07		0.18	52742.03	53114.34	21.70
Neg. Binomial (3° quarter, 1994-2003)		13.20	32209.07	32432.81	0.04		26.10	29802.98	30213.69	0.14
Neg. Binomial (4° quarter, 1994-2003)		8.88	83735.05	83959.78	0.06		26.20	78954.18	79397.45	0.24
Neg. Binomial (1994)		9.69	11405.00	11556.45	0.08		18.40	11083.81	11310.02	0.18
Neg. Binomial (1995)		11.50	26179.00	26371.47	0.14		26.80	25061.10	25411.29	0.27
Neg. Binomial (1996)		12.70	22695.00	22885.77	0.09		22.90	22023.39	22357.96	0.27
Neg. Binomial (1997)		7.70	20967.00	21159.25	0.07		24.70	19778.15	20080.49	0.21
Neg. Binomial (1998)		29.70	21444.00	21637.28	0.28		39.40	20523.13	20786.58	0.38
Neg. Binomial (1999)		12.60	26162.00	26348.46	0.11		20.90	25416.37	25783.76	0.23
Neg. Binomial (2000)		20.90	15761.66	15952.04	0.17		32.50	14826.31	15131.25	0.30
Neg. Binomial (2001)		14.00	27338.24	27539.24	0.09		24.80	26238.87	26605.34	0.18
Neg. Binomial (2002)		12.20	22442.22	22648.29	0.08		25.60	20984.31	21335.21	0.22
Neg. Binomial (2003)		18.00	38407.32	38615.91	0.16		27.20	37201.19	37594.69	0.27

Figure 1. Time-series of annual striped marlin catches by gear in the North Pacific, Source: ISC 2010. Note: Longline striped marlin catch is negatively biased due to species misreporting in the US fleet.

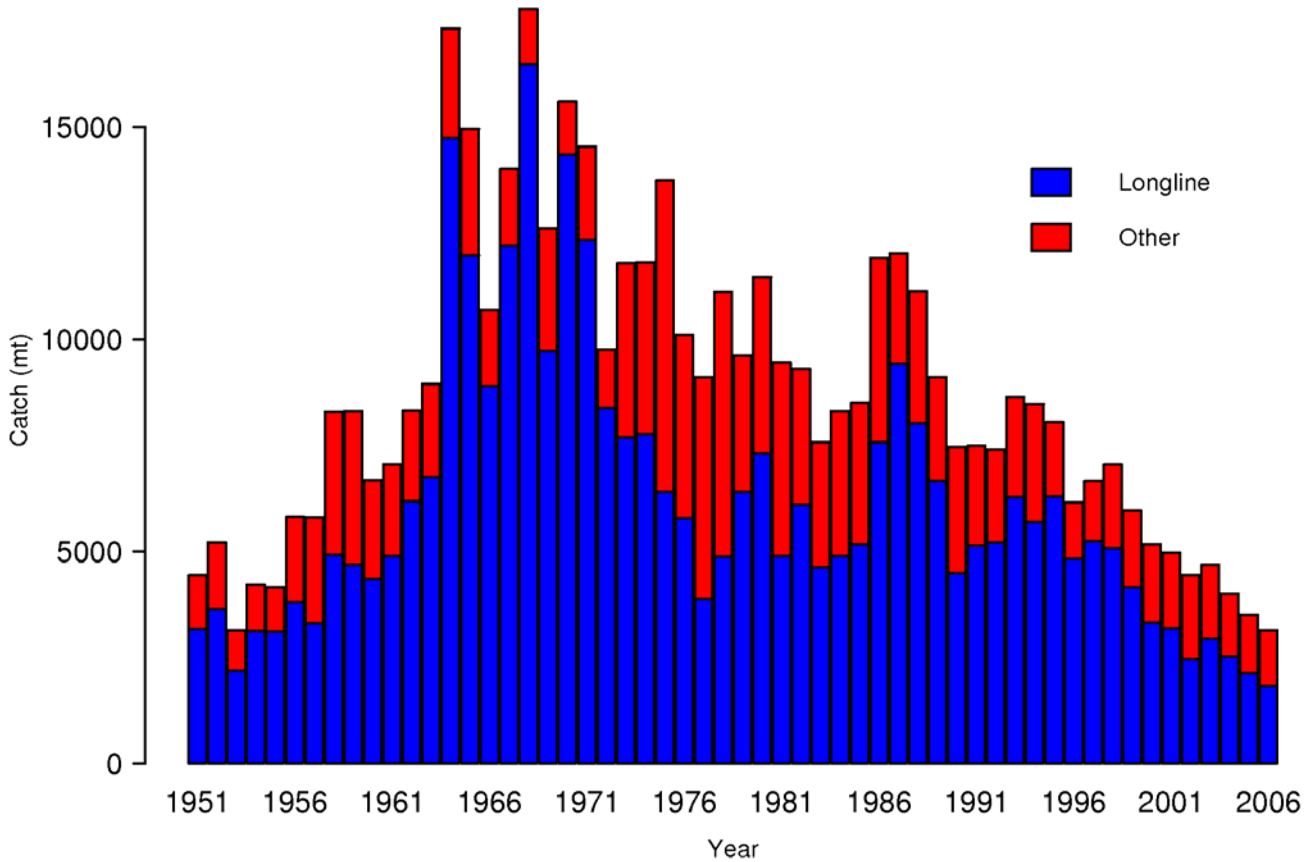

Figure 2. Spatial grids considered in an analysis of fishery closures.

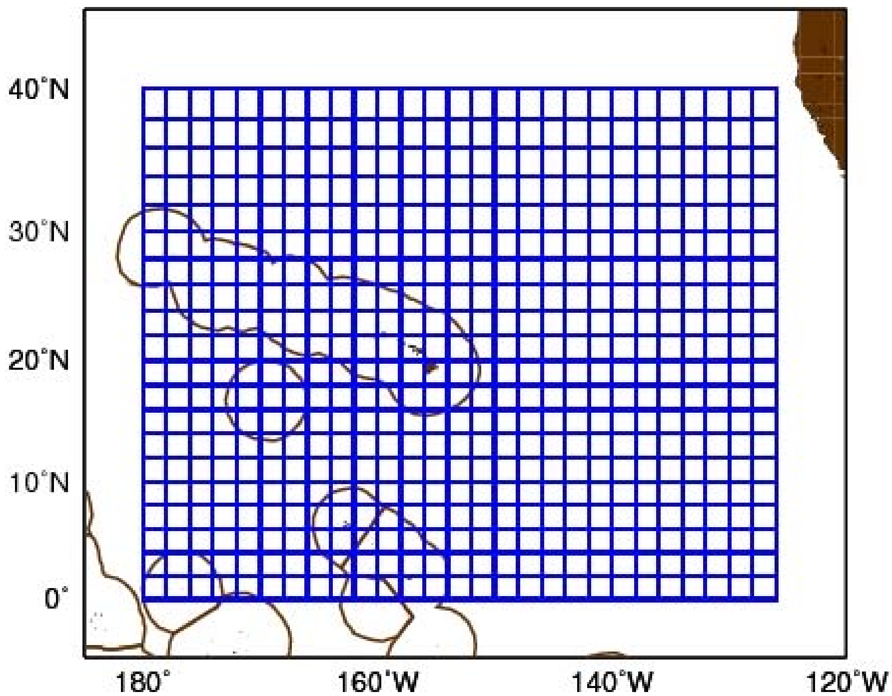

Figure 3. Frequency of hook-at-capture (horizontal axis) for two species in four commonly used longline gear configurations. (HBF: hooks between floats) observed in the Hawaii-based tuna fishery. Hooks are numbered sequentially from each float to the adjacent float.

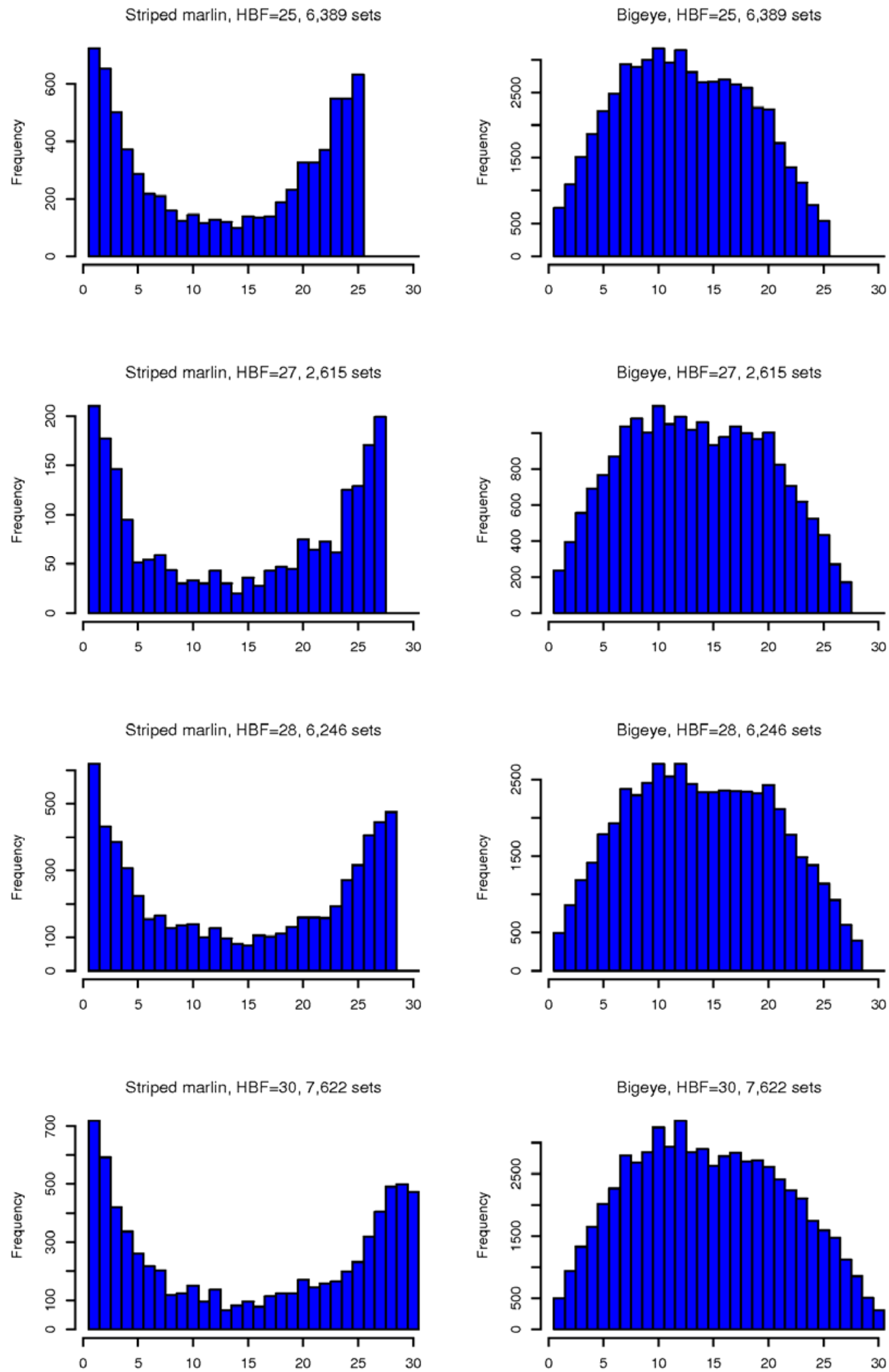

Figure 4. Comparison of catch rates by hook number for 19 species caught by the Hawaii-based tuna fishery (n=33,049 sets). Hook #1 is adjacent to the longline float while hook #19 is assumed to be the deepest hook.

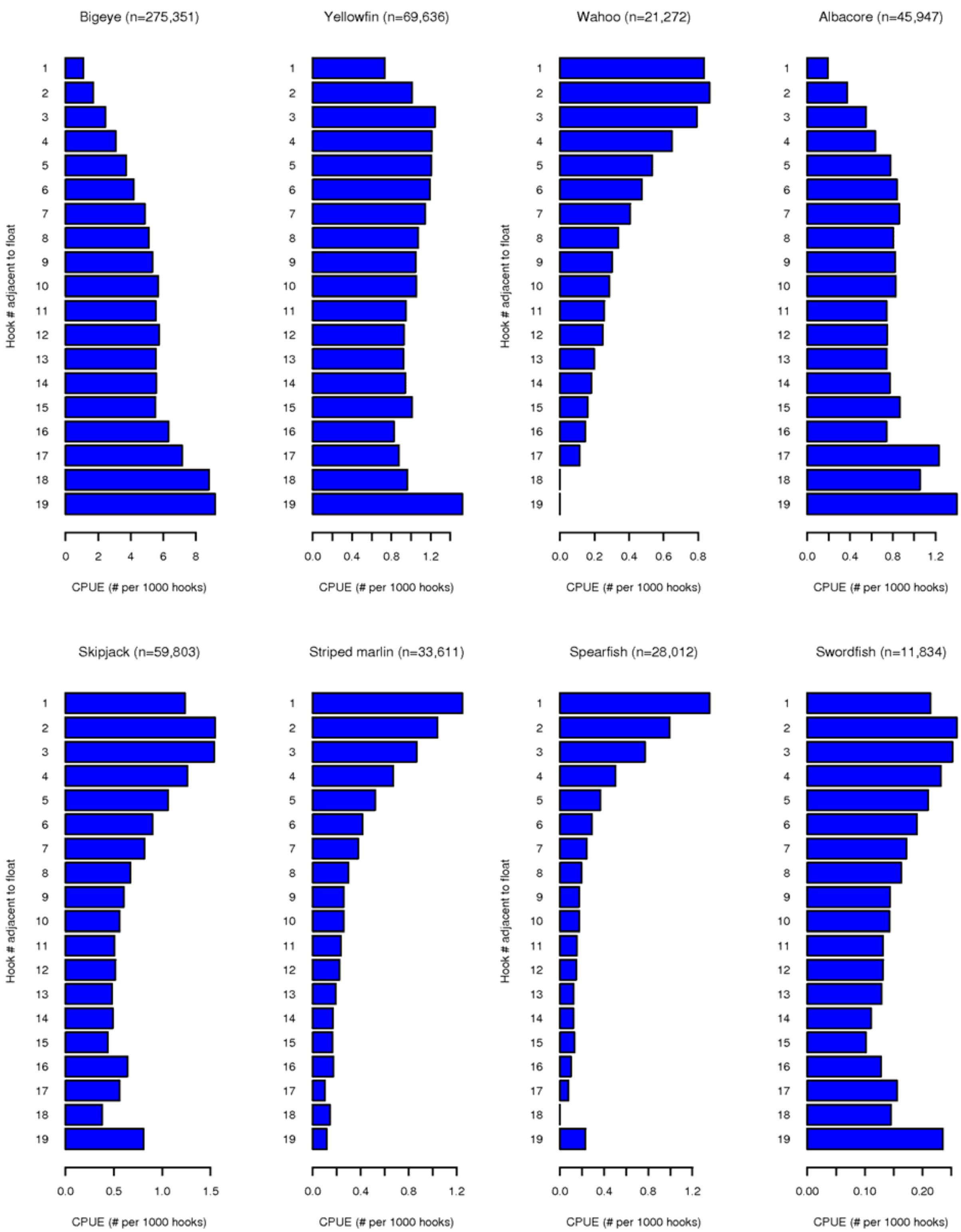

Figure 4 continued. Comparison of catch rates by hook number for 19 species caught by the Hawaii-based tuna fishery (n=33,049 sets). Hook #1 is adjacent to the longline float while hook #19 is assumed to be the deepest hook.

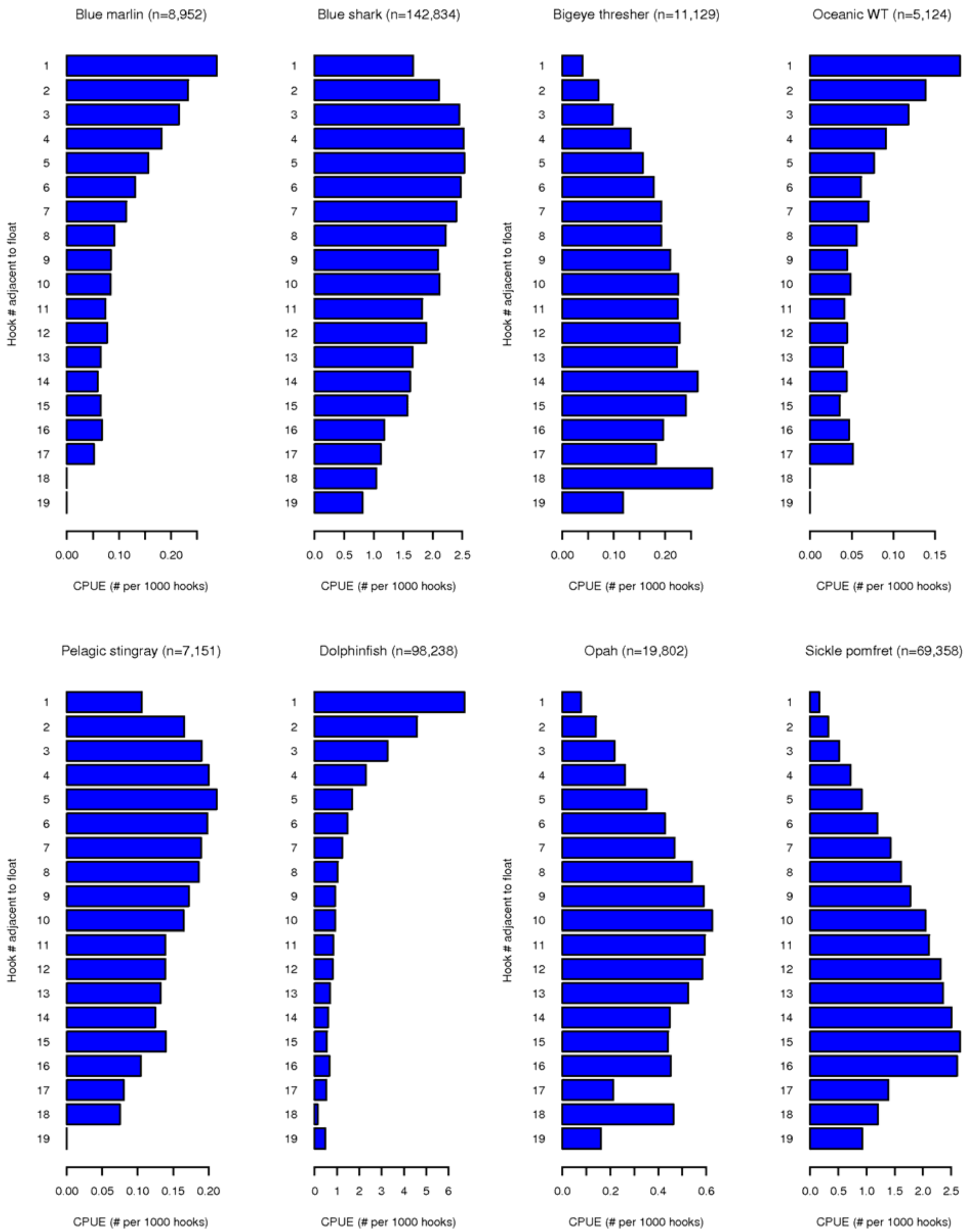

Figure 4 continued. Comparison of catch rates by hook number for 19 species caught by the Hawaii-based tuna fishery (n=33,049 sets). Hook #1 is adjacent to the longline float while hook #19 is assumed to be the deepest hook.

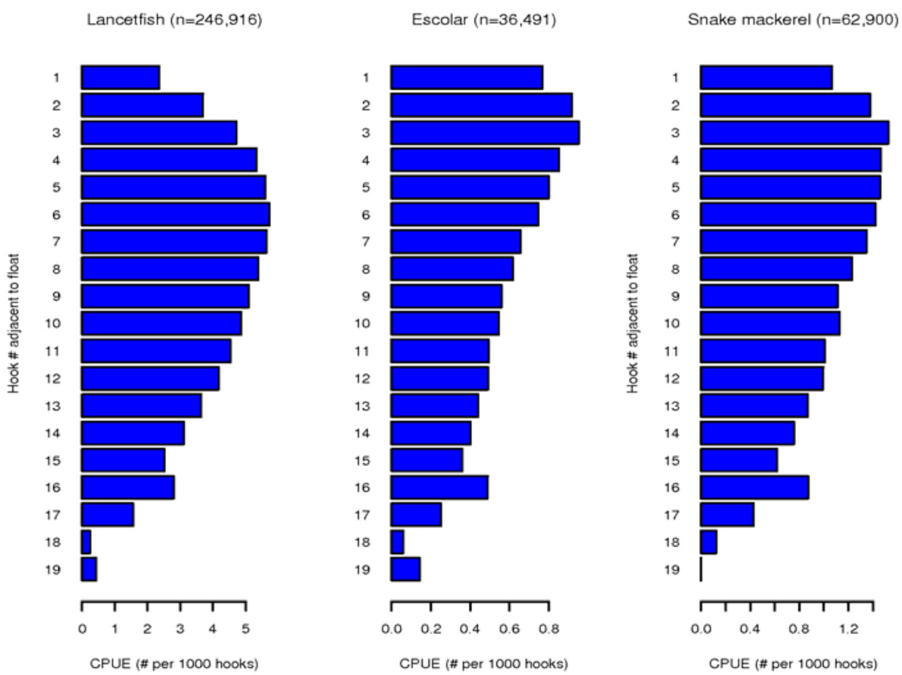

Figure 5. Spatial predictions of CPUE (number per 1,000 hooks) for striped marlin in the Hawaii-based tuna longline fishery based on reduced and full GAM models (1994−2003).

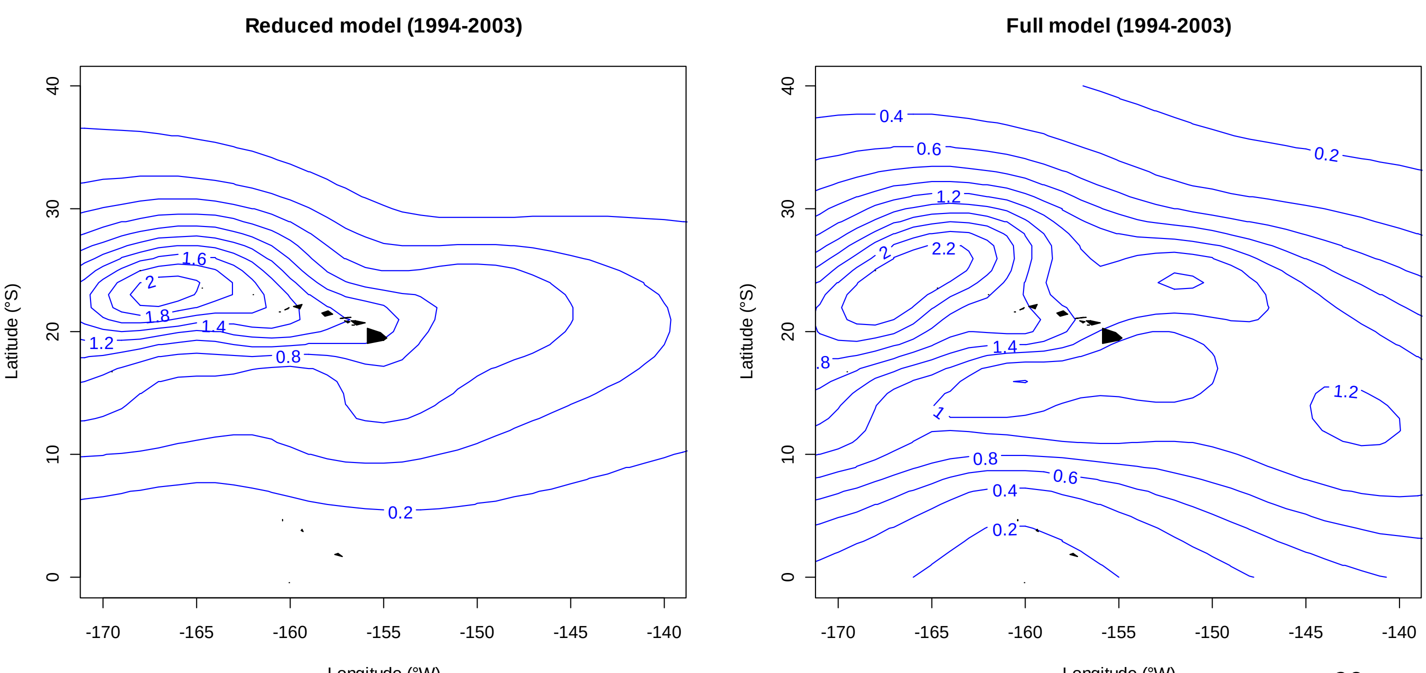

Figure 6. Quarterly spatial predictions of CPUE (number per 1,000 hooks) for striped marlin in the Hawaii-based tuna longline fishery based on reduced and full GAM models (1994−2003).

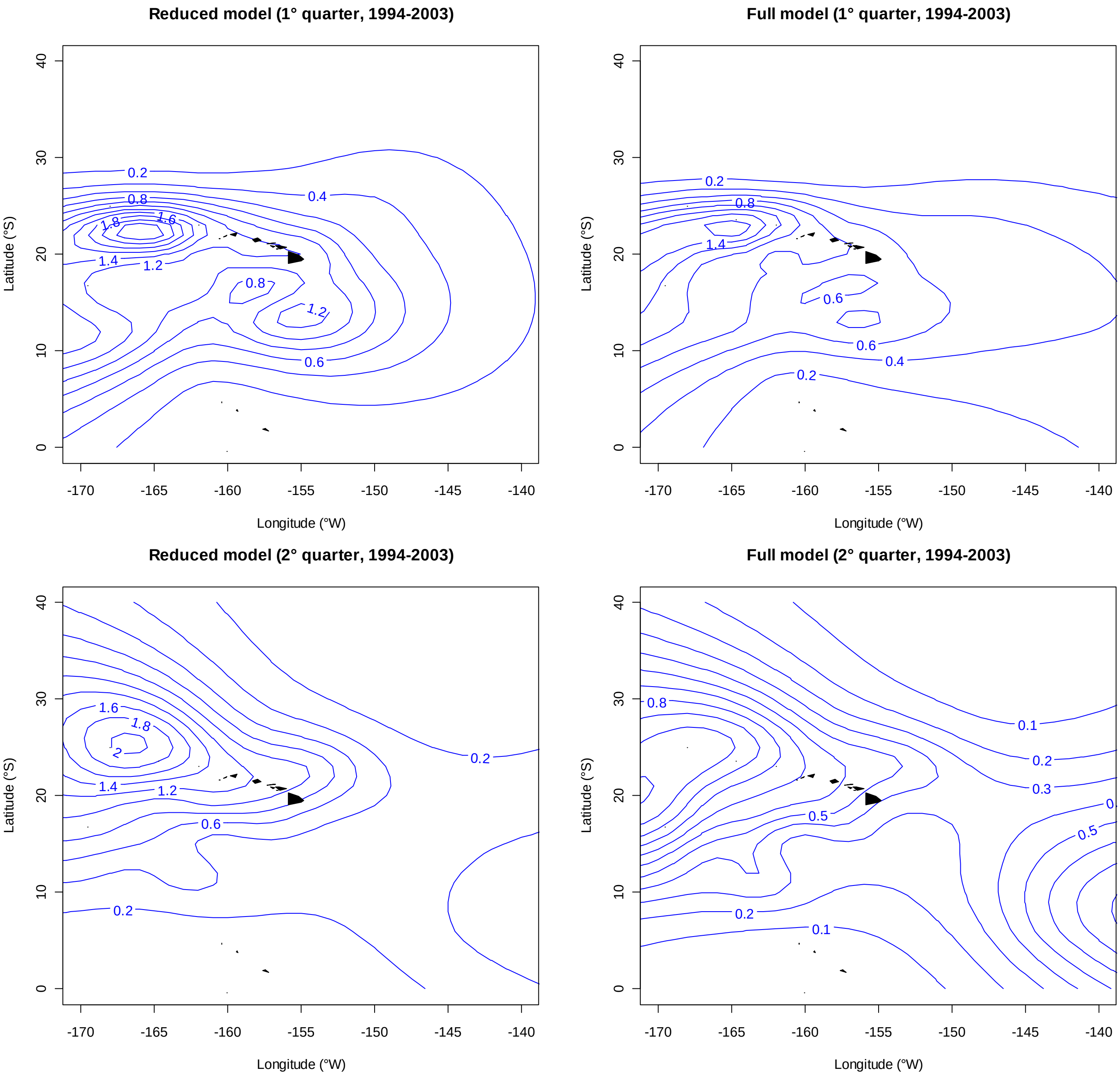

Figure 6 continued. Quarterly spatial predictions of CPUE (number per 1,000 hooks) for striped marlin in the Hawaii-based tuna longline fishery based on a reduced and full GAM models (1994−2003).

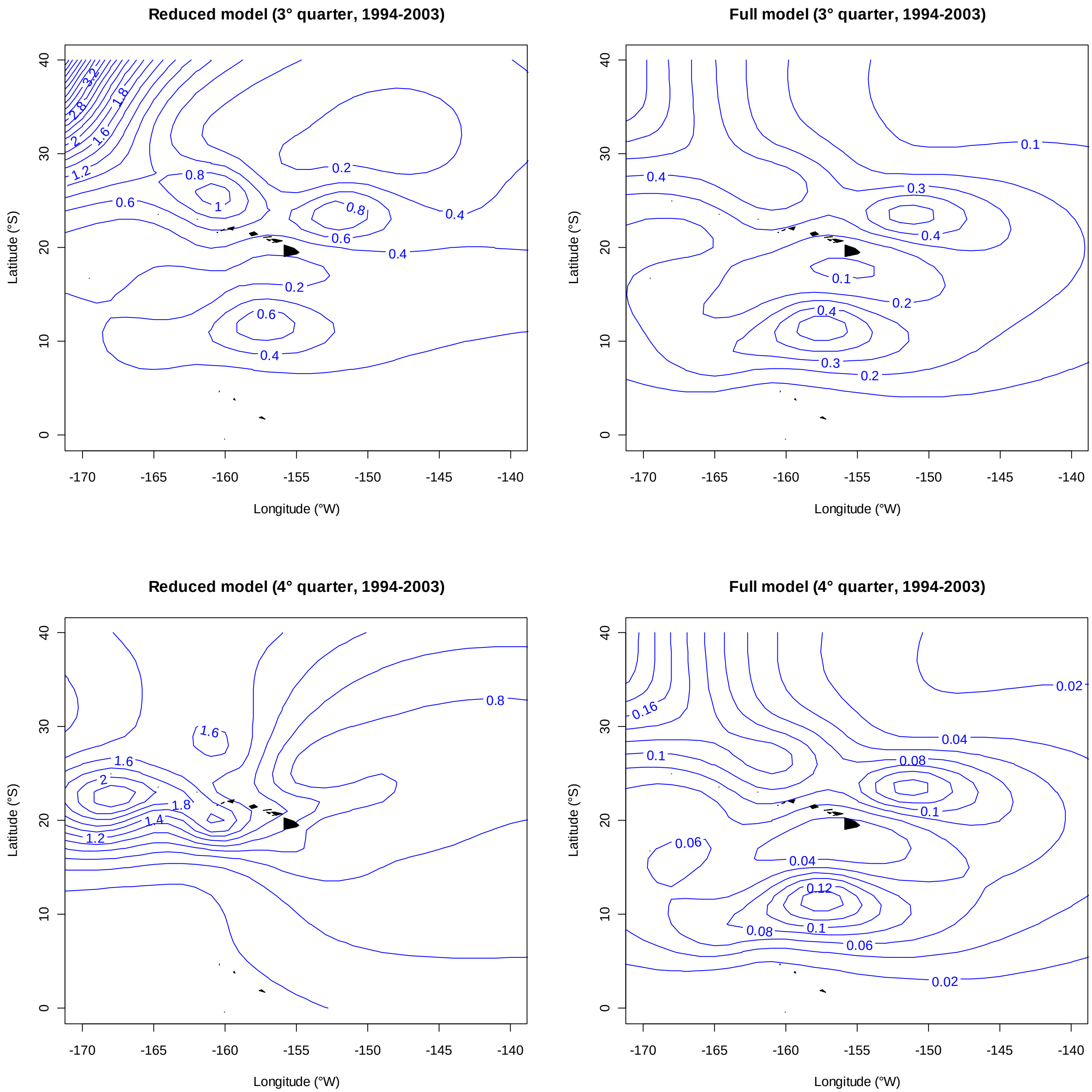

Figure 7. Spatial predictions of CPUE for striped marlin in the Hawaii-based tuna longline fishery based on reduced and full GAM models for individual years from 1994 to 2003. Contour lines are individual years with areas of high CPUE (mean + 1 standard deviation).

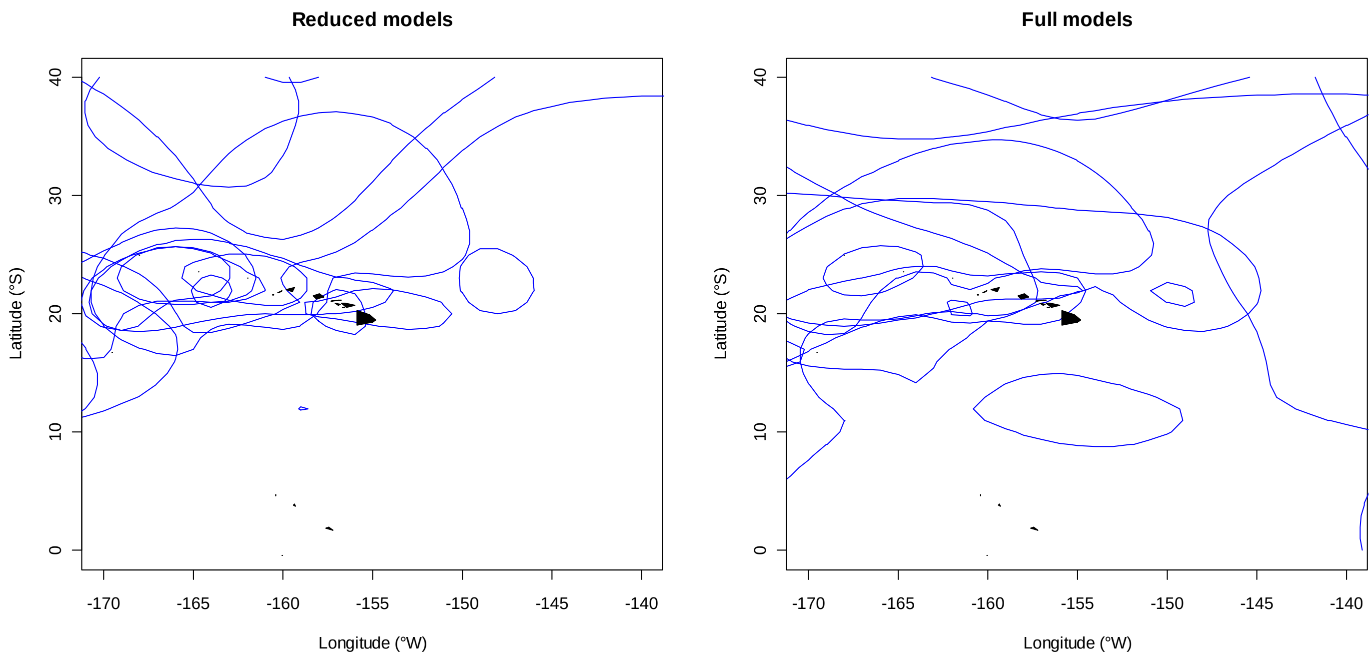

Figure 8. Trade-offs between the percentage reduction in striped marlin and bigeye tuna catch for spatial closures in the Hawaii-based tuna longline fishery. Each point represents a different closure for the period 1994−2003.