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Decreases in Shark Catches and Mortality in the Hawaii-based Longline Fishery as Documented by Fishery Observers

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Abstract

This paper summarizes catch data for sharks collected by fishery observers during 1995–2000 and 2004–2006 in the Hawaii-based pelagic longline fishery, which targets swordfish, *Xiphias gladius*, and bigeye tuna, *Thunnus obesus*, in shallow-set and deep-set sectors, respectively. The blue shark, *Prionace glauca*, was the predominant shark species caught throughout the study period (84.5% of all sharks). Five other species (bigeye thresher, *Alopias superciliosus*, oceanic whitetip shark, *Carcharhinus longimanus*, shortfin mako, *Isurus oxyrinchus*, silky shark, *C. falciformis*, crocodile shark, *Pseudocarcharias kamoharai*) were relatively common (1.0−4.1%). Two major developments affected shark catches in this fishery during the study period. The first was the prohibition in 2000 of shark finning in most circumstances. The second development, management measures taken in 2000 and 2001 to protect sea turtles, included a closure of the shallow-set swordfish-targeted sector for more than three years. This closure caused decreases in shark catches because this sector was typically characterized by high catch rates. The shallow-set sector was reopened in 2004. Comparisons of nominal catch-per-unit-of-effort (sharks per 1000 hooks) revealed significant differences in catch rates between the two fishery sectors and the two periods. Blue shark and shortfin mako catch rates were significantly greater in the shallow-set sector than in the deep-set sector of the fishery, whereas the opposite was true for the deeper-dwelling bigeye thresher and crocodile shark. Catch rates for blue shark, oceanic whitetip shark, bigeye thresher and crocodile shark were significantly lower in 2004–2006 than

in 1995–2000. For blue shark in particular, the combination of reduced catch rates, the finning ban and an apparent capacity to resist the stress of capture on longline gear resulted in low (4%–5.7%) minimum mortality estimates. Therefore, we conclude that the Hawaii-based pelagic longline fishery has made substantial progress in reducing shark mortality.

Introduction

Sharks are of considerable interest from at least three important scientific or practical perspectives. First, many aspects of the biology of these fishes have not yet been studied in detail (Carrier et al. 2004; Grogan and Lund 2004). Second, they are ecologically important as predators in pelagic food webs (Kitchell et al. 2002; Schindler et al. 2002; Compagno 2008). Third, sharks comprise much of the nontarget catch in many commercial fisheries (Beerkircher et al. 2004; Gilman 2007a; Pikitch et al. 2008; Erickson and Berkeley 2008) and are vulnerable to overfishing because their typical life history traits include slow growth, relatively late maturation and low fecundity (Smith et al. 1998; Cortés 2004). Moreover, because most sharks are of low value, they may be under-reported or not reported at all in logbooks (Walsh et al. 2002; Nakano and Clarke 2006), which can increase the difficulty of discerning population trends and introduce uncertainty into stock assessment models.

The Hawaii-based pelagic longline fishery, which targets bigeye tuna, *Thunnus obesus*, in the deep-set sector, and swordfish, *Xiphias gladius*, in the shallow-set sector, takes sharks, especially blue sharks, *Prionace glauca*, in substantial numbers (Kleiber et al. 2001; Walsh et al. 2002; Dalzell et al. 2008). Unlike most other fisheries that take sharks, the Hawaii-based longline fishery is very well suited to analyses of shark catches because detailed operational and catch data are gathered by the Pacific Islands Regional Observer Program (PIROP). This program was established as the Hawaii Longline Observer Program in March 1994 for the purpose of monitoring interactions between fishing vessels and protected or endangered sea turtles (DiNardo 1993). At the present time, PIROP observers monitor interactions with protected or endangered species, record a large suite of operational details (e.g., position, number of hooks, set and haul times, target species, bait type), obtain species-specific tallies of the catch including its condition on retrieval (i.e., live or dead) and subsequent disposition (i.e., retained or discarded), and measure fish (Pacific Islands Regional Office 2006). The PIROP is now the largest pelagic observer program for longline fisheries in the Pacific Ocean, representing at least 59% of such observer effort (P. Williams, Secretariat of the Pacific Community, personal communication).

This paper provides a detailed quantitative description and analysis of catch data for sharks from the Hawaii-based pelagic longline fishery as reported by PIROP observers from January 1995 through December 2006. These detailed catch and operational data are particularly important to the interpretation of trends because management decisions taken by the Western Pacific Regional Fishery Management Council[1] (WPRFMC) during this period probably affected shark catches in several ways. Specifically, regulations promulgated in 2001 in response to high interaction rates between the shallow-set sector and sea turtles led to a closure of the swordfish fishery for more than three years. The closure caused the Hawaii-based longline fleet to begin targeting bigeye tuna almost exclusively, using deep-set gear (Walsh et al. 2005). This entailed a southward shift in effort away from the main swordfish and blue shark habitat in temperate waters toward tropical and semitropical regions where other shark species (e.g., oceanic whitetip shark, *Carcharhinus longimanus*) might be expected to be more common than the blue shark (Nakano and Seki 2003; Bonfil et al. 2008). The swordfish sector was reopened in 2004, but with operational requirements intended to protect sea turtles (e.g., 100% observer coverage; use of circle hooks and thawed, dyed bait) some of which may also have affected catches of sharks and swordfish. Finally, Hawaii State and Federal laws[2] enacted in 2000 affected the disposition of shark catches by prohibiting finning in most circumstances unless the carcass was retained.

The dual objectives of this paper are to provide quantitative information needed for management of sharks in the Hawaii-based longline fishery and other pelagic fisheries and to contribute to the fundamental knowledge of these fishes. We met these goals by presenting results that include a description of the shark catch composition, species-specific catch statistics such as nominal catch rates and minimum mortality estimates; and biological and distributional information, including the catches of sharks and target species in 2005. Moreover, these data were collected in a fishery that operates throughout a vast region, from near the equator to the North Pacific transition zone, in pelagic habitats and near seamounts or insular areas, using two distinct types of operational techniques according to the target species. These results are also directly relevant to efforts to reduce the mortality of sharks taken as nontarget species by U.S. pelagic longline fisheries (Beerkircher et al. 2004) as mandated by the Magnuson-Stevens Fishery Conservation and Management Act (MSA)[2,3]. This paper summarizes progress attained by the Hawaii-based longline fishery relative to the MSA mandate from January 1995 through December 2006.

Methods

Data Source and Observer Effort

Catch data were gathered by PIROP observers on 26,507 longline sets during 2,121 commercial fishing trips from January 1995 through December 2006. Observer coverage rates were computed on the fleet-wide basis and by set types defined according to gear configuration[4].

Deep sets used either a monofilament mainline and at least 15 hooks per float or basket gear with any number of hooks per float (one vessel); shallow sets used a monofilament mainline and less than 15 hooks per float. In addition, the most commonly used bait on deep sets (47% of all deep sets) was sauries, *Cololabis* sp., whereas squid were used as bait on 90% of shallow sets in 1995–1999 and mackerel-like fish on 93% after 2004. The mean begin-set times also differed, at 0752 h and 1837 h on deep and shallow sets, respectively. 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 initial quality control of the catch data was conducted by the PIROP. The data were first entered and checked by the observer and then re-checked by a debriefer. Logical and numerical tests were computed and a final data examination was performed by a third individual. Additional detailed evaluations based on observer notes, photographs and published distributional accounts, which focused on species identifications and catch sizes, were later conducted at the Pacific Islands Fisheries Science Center (PIFSC). All catch statistics were computed with these corrected data. Detailed descriptions of use of observer data are presented in Walsh et al. (2002; 2005; 2007).

Categorization of Shark Condition and Collection of Size Measurements

Observers categorized sharks as live or dead at the time of release. Any responsiveness led to categorization as alive.

Observers measured the fork lengths (FLs; cm) of sharks after they were caught and brought aboard fishing vessels according to the PIROP observer field manual (2006). From January 1995 through January 2006, the protocol called for as many intact sharks, tunas, swordfish and istiophorid billfishes to be measured as possible, subject to time and safety constraints. As of February 2006, every third fish brought aboard was measured, regardless of species.

Statistical Methods

Descriptive statistics on species composition, catch per set, nominal catch-per-unit-of-effort (nominal CPUE; i.e., sharks per 1000 hooks), and catch frequencies were initially tabulated for all species from all years. Statistics for those shark species that comprised at least 1% of the total shark catch were next tabulated by set type (shallow-set sector; deep-set sector) and by two time intervals (1995–2000; 2004–2006), representing the periods before the closure and after the reopening of the shallow-set sector[5]. The effects of set type and time period on nominal CPUE of six species were tested by two-way analysis of variance with interaction (ANOVA) using the natural log-transformed annual means as observations. Shark FLs were also log-transformed and tested for the main effects of time period, set type, and sex and the three linear interactions using three-way ANOVA. Means comparisons were performed by Bonferroni *t*-tests. Sex ratios and various other proportions were evaluated with chi-squared tests. Relationships between blue shark sizes and latitude were assessed in terms of their correlations. All statistical procedures were conducted in S-PLUS, Version 6.2.1 (Insightful Corporation, 2002). The significance criterion for statistical tests was $P < 0.05$, or for the Bonferroni *t*-tests, $P \leq 0.05$.

The minimum mortality of these species was estimated as the proportion of sharks caught that were not released alive. Hence, for 1995–2000, the estimates reflect the effects of finning. Another source of mortality throughout the study was retention for sale or consumption (primarily makos and threshers). The tabulated values represent minimum estimates because any responsiveness by the shark led to categorization as alive at release and because sharks could not be monitored for post-release mortality. No significance tests were attempted because of this uncertainty. Sample sizes for minimum mortality estimates were $N \geq 50$ sharks.

Results

Observer Coverage

Levels of observer effort increased greatly during the 12-year study period from an initial rate of 4.7% in 1995 followed by four more years at similar levels (Table 1). Observer effort nearly tripled in 2000 and averaged 24.4% coverage thereafter (2001–2006).

The allocation of observer effort changed markedly during the study period. The initial emphasis was on the shallow-set sector, in keeping with the monitoring objective. The closure led to a near total allocation of observers (96.7–99.9%) to the deep-set sector in 2002–2004.

The geographic distribution of observer coverage also changed during the study period. Shallow sets were deployed east of 130°W in 1996, 1998 and 2000, but there was no shallow-set activity in these waters in 2004–2006. Deep sets were deployed across 23° of longitude in 1995–2000 but 33° of longitude in 2004–2006.

Catch Composition

Sharks comprised 15.6% of the observed catch, with at least one species taken on 95.1% of the observed sets (Table 2). The shark catch included 20 or 21 species from seven families in three orders. *Carcharhinus*, with seven species, was the most speciose genus. *C. altimus* and *C. plumbeus* were combined because of uncertainty about these species identifications. Blue shark ranked third in the observed catch (13.2%), behind bigeye tuna (16.4%) and the longnose lancetfish, *Alepisaurus ferox* (15.9%), a teleost bycatch species.

Blue shark was predominant (84.5% of all sharks), taken on 90.7% of the observed sets. Five other species (oceanic white-tip shark, silky shark, *C. falciformis*, shortfin mako, crocodile shark, *Pseudocarcharias kamoharai*, and bigeye thresher, *Alopias superciliosus*) were relatively common (1.0–4.0%). Most sets that caught sharks (77.2%) took either blue sharks or blue sharks and one other common species. All other sharks comprised less than 1% of the total catch.

Several uncommon species were taken primarily in the peripheral areas of this fishery, and occasionally with relatively large catches. For example, certain requiem sharks (e.g., gray reef shark, *C. amblyrhynchos*, and blacktip shark, *C. limbatus*) were caught exclusively in tropical waters (1°S–8°N). Most (53.3%) salmon sharks, *Lamna ditropis*, were taken on five sets at relatively high latitudes (29–34°N).

Figure 1 depicts the catch rates for the common shark species by sectors and time periods. In the shallow-set sector (Figure 1a), the pooled CPUE for all sharks in 1995–2000 was 19.9 per 1000 hooks (Figure 1a), with blue shark representing 92.5% of the pooled value. The ranking of the shark CPUE in the shallow-set sector in 1995–2000 was blue shark > oceanic whitetip shark > shortfin mako > bigeye thresher. By 2004–2006, the pooled CPUE had decreased to 14.5 per 1000 hooks, with blue shark at 90.3% of the total. The shortfin mako CPUE was greater than that for oceanic whitetip shark in 2004–2006, reflecting the 389% increase between periods. Only 3.4% of the shallow sets were deployed south of 20°N, but a change in the species composition was apparent with 71.5% blue sharks and 17.0% oceanic whitetip sharks.

The nominal mean blue shark CPUE was 3.753 per 1000 hooks and those of five other common species were 0.064–0.272 per 1000 hooks in the deep-set sector in 1995–2000 (Figure 1b). The CPUE ranking in this sector in 1995–2000 was blue shark > oceanic whitetip shark > bigeye thresher > silky shark > shortfin mako > crocodile shark. The pooled shark CPUE decreased by 43.7% between 1995–2000 and 2004–2006; the nominal mean CPUE values of the individual species decreased by 12.5–77.9%. The CPUE ranking in 2004–2006 was blue shark > bigeye thresher > shortfin mako > oceanic whitetip shark > silky shark > crocodile shark.

The species composition varied latitudinally within this sector. Above 20°N, blue sharks and shortfin mako comprised 92.5% of the shark catch. Blue shark remained predominant between 10–20°N (81.6% of all sharks); the remainder consisted primarily of bigeye thresher (7.7%), oceanic whitetip sharks (3.5%), and crocodile sharks (1.9%). Silky shark comprised the greatest fraction (29.3%) of the shark catch from tropical and insular areas (i.e., south of 7°N).

Effects of Fishery Sectors and Time Periods on Nominal CPUE, Disposition, and Mortality

Nominal CPUE of five species (Table 3) differed significantly between set types, time periods or both. The nominal CPUE values for blue shark and shortfin mako were significantly greater in the shallow-set than the deep-set sector (both tests: $P < 0.001$) and greater in 1995–2000 than during 2004–2006 (blue shark: $P < 0.05$; shortfin mako: $P < 0.005$). The differences between sectors for shortfin mako were 3.25- and 14.5-fold in 1995–2000 and 2004–2006, respectively. Shortfin mako CPUE also differed significantly ($P < 0.01$) between 1995–2000 and 2004–2006, reflecting high catch rates in the shallow-set sector in 2004–2006. The nominal CPUE values for both bigeye thresher and crocodile shark were significantly greater in the deep-set than the shallow-set sector (bigeye thresher: $P < 0.001$; crocodile shark: $P < 0.01$) and in 1995–2000 than during 2004–2006 (bigeye thresher: $P < 0.01$; crocodile shark: $P < 0.01$). Oceanic whitetip shark nominal CPUE was also significantly greater ($P < 0.001$) in 1995–2000 than in 2004–2006.

The disposition of sharks (Table 3) varied between sectors and among species in 1995–2000. A significantly greater percentage of blue sharks was finned in the deep-set than in the shallow-set sector (chi-squared test: $P <0.0001$). Both oceanic whitetip and silky sharks were finned at high rates (45–100%). Bigeye threshers and shortfin makos were usually kept for consumption or sale or else released.

Minimum mortality estimates decreased substantially for several species in both fishery sectors after the finning prohibition. The estimates for blue sharks decreased from 51.1% to 5.7% and 61.9% to 4.0% in the shallow-set and deep-set sectors, respectively. These minimum estimates included sharks that were released dead. The range for blue sharks (4.0–8.5%) was considerably less than those of the other species, all of which exceeded 20% in either sector or period.

Effects of Fishery Sector, Time Period, and Sex on Shark Sizes

Blue shark mean fork lengths (FLs; Table 4) differed significantly between periods and sexes (both tests: $P < 0.001$). The mean FL in 1995–2000 (177.9 cm FL), including both sexes, was significantly greater than in 2004–2006 (170.8 cm). The mean FL of males (180.7 cm), including both time periods, was significantly greater than that of females (173.2 cm). The sizes of blue sharks also exhibited spatial, seasonal and sexual variation. Blue shark FLs were negatively correlated with latitude in the shallow-set sector above 35°N (r = -0.408; df = 163; P < 0.001). The sex ratio (♂:♀) from these waters was 6.8:1. In temperate waters (20–35°N), 46.0% of the measured blue sharks were >180 cm FL. Bivariate regressions using data from sharks with measurements of both FL and total length (TL) predicted a mean TL of 215 cm for a 180 cm FL female (N = 102; R^2 = 0.998) and 212 cm for a 180 cm FL male (N = 74; R^2 = 0.906). Most (69.1%) of these large sharks were caught in the first or second quarters of 1996–1999, with a 1.6:1 sex ratio. In contrast to the shallow-set sector, the FLs of blue sharks of both sexes caught in the deep-set sector were positively correlated with latitude (females: r = 0.308; df = 1511; P < 0.001; males: r = 0.093; df = 1714; P < 0.001). Above 20°N, 58.1% of the blue sharks were >180 cm FL; the sex ratio among these large sharks was 1.9:1. South of 20°N, 43.0% of the blue sharks were >180 cm FL, with a 2.0:1 sex ratio.

Shortfin mako FLs varied significantly between periods, set types, and sexes (three tests: all P < 0.01). Shortfin makos from the deep-set sector were significantly larger than those caught on shallow sets. Shortfin makos caught in 1995−2000 were significantly larger than caught in 2004−2006. The significant effect of sexes actually reflected an interaction with sectors; i.e., females were larger than males in the deep-set sector and vice versa.

Bigeye threshers, silky sharks, and crocodile sharks were caught primarily on deep sets, and only five FL measurements of oceanic whitetip sharks were obtained from the shallow-set sector in 2004–2006. Therefore, FLs of these species were not tested for differences between sectors. Male oceanic whitetip sharks were significantly larger than females, and sharks caught in 1995−2000 were significantly larger than those caught in 2004−2006 (both tests: P < 0.01). Silky sharks caught in 1995−2000 were also significantly larger than those caught in 2004−2006 (P < 0.01). The FLs of bigeye threshers caught in 1995−2000, however, were smaller and significantly different from those caught in 2004–2006. Crocodile shark FLs did not differ significantly between periods or sexes (both tests: P > 0.50); the pooled mean FL was 85.0 cm.

There were three patterns in the sex ratios of these species. Males comprised the majority of the shortfin makos caught by the shallow-set sector in 1995–2000 and 2004–2006 (two chi-squared tests: both $P < 0.01$). Males also dominated the catches of bigeye thresher (two chi-squared tests: both $P < 0.0001$) and crocodile sharks (two chi-squared tests: both $P < 0.01$) from the deep-set sector. Crocodile shark exhibited the greatest sexual segregation of any species.

Distributions of the Catches of Sharks and Target Species

Figure 2 depicts the distribution and species composition of longline catches in 2005, when both fishery sectors remained open throughout the year. In the shallow-set sector (Figure 2a) during the first quarter, the swordfish CPUE (19.2 per 1000 hooks) in the most heavily fished region (30–35°N; 150–160°W) was less than the combined CPUE for blue shark (18.8 per 1000 hooks) and shortfin mako (1.3 per 1000 hooks). A much higher ratio of swordfish (22.0 per 1000 hooks) to blue shark CPUE (9.4 per 1000 hooks) was attained to the southwest (25–30°N; 165–170°W). During the second quarter, the nominal swordfish CPUE (16.3 per 1000 hooks) was again more than double that for blue sharks (7.7 per 1000 hooks). The mean sea surface temperature on these shallow sets during the first two quarters was 20.9°C. There was very little shallow-set activity in the third quarter, and in the fourth quarter (35–40°N; 140–150°W), the swordfish CPUE (12.4 per 1000 hooks) was less than that of blue shark (15.7 per 1000 hooks). Shortfin mako CPUE reached its annual maximum, 1.4 per 1000 hooks, in the fourth quarter.

Substantial catches of bigeye tuna were taken across 10 degrees of latitude and 20 degrees of longitude (15–25°N; 150–170°W) in the deep-set sector (Figure 2b) during the first quarter. The ratio of bigeye tuna (5.5 per 1000 hooks) to blue shark CPUE (1.4 per 1000 hooks) was 3.9:1. Second quarter activity was concentrated in two areas. The ratio of bigeye tuna to blue shark CPUE in the more northerly (25-30°N; 150-155°W) was 3.6:1, versus 1.4:1 in the more southerly area (15-20°N; 150-165°W). The largest fraction of the bigeye thresher catch (45.5%) was also taken in the second quarter, primarily within 10–20°N and 155–165°W. Third quarter activity was concentrated within 20-25°N and 145-160°W. The bigeye tuna to blue shark CPUE ratio remained low at 1.6:1. During the fourth quarter between 15-20°N and 155-165°W, more blue sharks were caught than the target species. Other bycatch and incidentally-caught species comprised most (73.9%) of the total catch in this sector.

Discussion

Shark Catch Composition

The predominance of blue shark was expected (Walsh et al. 2002) and consistent with general accounts of its distribution and abundance (Compagno 1988; Nakano and Stevens 2008) and published descriptions of this fishery (He et al. 1997; Gilman 2007b; Dalzell et al. 2008). The observed shark catch in this fishery could still be aptly described by Strasburg's (1958) statement that "the great blue shark is wide ranging throughout the area considered, whereas certain of the other species live within rather narrowly circumscribed limits." The predominance of blue shark in this fishery is usually so great that in addition to under- and non-reporting biases (Walsh et al. 2002), logbooks from observed trips are sometimes inaccurate with all sharks logged as blue sharks when observers report multiple species, apparently because captains are accustomed to the shark catch consisting entirely of blue sharks (Walsh, unpublished data).

Oceanic whitetip and silky sharks were among the common species, but the percentages of sets with catches of these species were very low. The oceanic whitetip shark is an abundant, epipelagic oceanic species with a circumglobal distribution in tropical waters, usually above 20°C (Bonfil et al. 2008). The silky shark is one of the most common semipelagic sharks of all tropical oceans, usually found at ambient temperatures above 23℃ (Bonfil 2008). The mean sea surface temperature (SST) during shallow-set activity in 2005 (20.9°C) indicates that much of the activity of this sector occurred at times and in locales outside the thermal ranges of these species, especially silky shark. Thus, decreases in nominal CPUE for these species in 2004–2006 in the shallow-set sector appear to reflect to some unknown degree the timing and location of fishing. If so, and this sector continues to operate primarily in the same general areas during the first half of the year, catch rates for these tropical carcharhinids will probably remain low.

This fishery catches both species of makos (*I. oxyrinchus*: *I. paucus*) and all three species of threshers (*A. superciliosus*; *A. pelagicus*; *A. vulpinus*). The shortfin mako catch was 25-fold greater than that of longfin mako, and the bigeye thresher catch was 11 times that of pelagic thresher. The individual catches of pelagic and common threshers are uncertain. The occurrence of common thresher in Hawaiian waters is enigmatic (Mundy 2005) and some common thresher identifications from the early years of the PIROP were later deemed to be uncertain. Therefore, these catches were combined, assuming that any misidentifications would only involve common and pelagic threshers because bigeye thresher is so distinctive in appearance.

Most shark species (10) comprised less than 0.1% of the shark catch. These species were caught occasionally to very rarely and were apparently minimally affected by this fishery.

Blue Shark

The blue shark size data and sex ratios appeared consistent with hypotheses about the life history and distribution of this species in the North Pacific (Nakano 1994; Nakano and Seki 2003; Nakano and Stevens 2008) in at least one major respect. The highly skewed sex ratio above 35°N and the significant negative correlation between size and latitude support the suggestion that latitudes from 35–40°N are important in the early life history of males.

The relatively large sharks (i.e., >180 cm FL) caught from 20–35°N in the first and second quarters of 1996–1999 were probably mature because 200 cm TL is considered the approximate size at maturity for both sexes in the North Pacific (Nakano and Stevens 2008). These catches may have reflected seasonal movements because many of the measured blue sharks were caught in or near the North Pacific Transition Zone (Roden 1991). This would also be consistent with Nakano and Stevens (2008), who described seasonal movements to higher latitudes into highly productive oceanic convergence or boundary zones.

Effects of Fishery Sectors

The two fishery sectors were characterized by qualitative differences in the species composition of the shark catch and quantitative differences in CPUE, sizes and sex ratios. The signs of the correlations between size and latitude also differed between sectors in blue shark, reflecting the preponderance of small males taken above 35°N in the shallow-set sector and possibly reflecting movements of large sharks to feeding areas in the deep-set sector. Such effects can be complex, as in shortfin mako, which exhibited sector-specific size differences between sexes. Sector-specific effects and their associated complexities may create opportunities for fishery managers. If, for example, it were deemed important to conserve adult female shortfin makos, the focus would be on the deep-set sector. If the intention was to reduce shark bycatch in the aggregate, emphasis would be placed on the shallow-set sector early in the year at high latitudes where large numbers of small male blue sharks are likely to be caught.

Nominal CPUE of Common Sharks

Nominal CPUE values for five species exhibited significant decreases from 1995–2000 to 2004–2006. Interpretation of the shallow-set results from 2004–2006 is complicated by the fact that the changes in hook and bait types were confounded. The months with the greatest activity and the geographic distribution of sets also differed between time periods. The distributional changes in particular would have introduced sampling variation. Nonetheless, it appears that the switch to mackerel as bait probably contributed to the reduced blue shark catch rates in this sector. In the Atlantic, Watson et al. (2005) employed a two-way experimental design and determined that circle hooks affected catch rates for swordfish and blue shark positively, whereas mackerel bait did so negatively. Changes in bait types may also have contributed to the decrease in nominal blue shark CPUE in the deep-set sector. Although not mandatory, use of sauries decreased from 76–100% each year in 1995–1999 to 48% in 2000 and 49–55% in 2004–2006.

The most serious possible explanation for a decrease in nominal CPUE of one or more species would be population decline(s). The most recent North Pacific blue shark assessment (Kleiber et al. 2009) indicated that the population increased by 6.5% in 1995–2002. Because the duration of this study is greater than that of the assessment, however, the latter cannot be used to address the possibility that blue shark may be or may have been undergoing population decline.

Shortfin mako exhibited a large increase in nominal CPUE between 1995–2000 and 2004–2006, the only increase among the common species. This may also have been related to the switch to mackerel bait, though in a manner opposite to blue shark. Stillwell and Kohler (1982) examined gut contents of 399 shortfin makos caught in fishing tournaments and on longlines in the Northwest Atlantic and identified Atlantic mackerel, *Scomber scombrus*, in 2.2% of the samples. Bluefish, *Pomatomus saltatrix*, was the only teleost identified from more samples (43.8%). Scott and Scott (1988) described shortfin mako as feeding mostly on fishes, especially mackerels and other scombrids, in Canadian Atlantic waters. It appears that bait types may have strong, species-specific effects on shark bycatch rates**.** In practical terms, however, any treatment or technique that reduces blue shark CPUE significantly in fisheries that catch both species would probably yield a large net reduction in bycatch because shortfin mako catches are usually about 3–13% of the blue shark catches (Stevens 2008).

Shark Conservation

The very large reductions in the minimum mortality estimates for 2004–2006 after the finning ban are critically important from the perspective of shark conservation. Because blue shark was by far the predominant species and a major bycatch species in many high-seas longline fisheries (Nakano and Stevens 2008), it appears that shark mortality from fishing could be reduced considerably if finning prohibitions were adopted elsewhere.

Bycatch mortality in this fishery now consists primarily of sharks caught and subsequently released dead. The percentages of blue sharks caught and released dead in 2004–2006 (4.0–5.7%) were very low, but exceeded 20% in all other common species in either sector or period. This suggests that blue sharks are much less sensitive to the stress associated with capture by longline gear than the other common shark species.

It must be emphasized that these mortality estimates were minima because the post-release fate of sharks could not be monitored, but high survival rates among longline-caught blue sharks have been reported previously. Moyes et al. (2006) estimated that 90–95% of all blue sharks and up to 100% of apparently healthy blue sharks could survive capture. Kerstetter and Graves

(2006) reported a 7.4% mortality rate for blue sharks caught on longlines with circle hooks in the western North Atlantic. Thus, even if the minimum mortality estimates are low by an order of magnitude, about half of all released blue sharks would be expected to survive.

Sizes of Sharks

Several differences in mean sizes between sectors or periods were statistically significant but probably not biologically important. For example, the mean sizes indicate that about half of all blue sharks of both sexes were mature in both sectors in 1995–2000 and in the deep-set sector in 2004–2006. The relatively small mean sizes of male blue sharks and female shortfin makos in 2004–2006 in the shallow-set sector were influenced by catches in restricted locales during short intervals. It is also likely that decreases in mean sizes reflected sampling bias because there was little incentive to bring large sharks aboard fishing vessels after the finning prohibition. The decreases in oceanic whitetip and silky sharks cannot yet be explained. It would be useful to assess whether changes in the distribution of fishing effort underlay these decreases.

Distributions of Catches of Target Species and Sharks

Distributional information on shark catch may help fishers increase the ratio of target species catch to shark bycatch. Though from a single year, the 2005 data suggest that shifting shallow-set operations during the first quarter from the most heavily fished area (30–35°N; 155–160°W) toward the southwest (25–30°N; 165–170°W) might increase this ratio. In the deep-set sector, fishers might wish to remain above 20°N during the third and fourth quarters because blue shark catches exceeded those for bigeye tuna south of this latitude. A second possible use is to permit informed conjecture about effects on sharks of management measures intended for other purposes (e.g., time-area closures to protect endangered species). Such management measures could cause spillover effects on the distribution of fishing effort, which in turn might influence bycatch rates positively or negatively, depending upon the final location of the redirected effort.

Conclusions

The shark catch in this pelagic longline fishery was aspeciose, with blue shark as the predominant species. Management efforts in this fishery can therefore be directed toward blue shark and a few other common species.

The estimates of minimum mortality for blue shark were very low in 2004–2006 (4%–5.7%). The combination of reduced catch rates, the finning ban and the apparent capacity of this species to resist the stress of capture on longline gear contributed to these low estimates. By reducing blue shark mortality in particular, the Hawaii-based pelagic longline fishery has made substantial progress in reducing shark mortality in keeping with the mandates of the MSA.

All other common sharks exhibited greater sensitivity to the stress of capture or handling than blue shark. As such, reductions in bycatch mortality attained by finning prohibitions would probably be species-specific, and for most species, smaller than those attained with blue shark.

Shark bycatch in the two fishery sectors differed both qualitatively and quantitatively. Higher nominal CPUE values for blue shark and shortfin mako in the shallow-set and bigeye thresher and crocodile shark in the deep-set sector indicate that set depth is highly influential on shark catch rates. Setting longline gear deep may prove to be an effective bycatch mitigation technique for epipelagic species. The extent to which deep-setting is adopted commercially will probably depend upon whether catch rates for target species can be maintained. Manipulation of bait types and comparison of target species to bycatch CPUE ratios may also be potentially useful mitigation techniques.

The nominal mean CPUE values for oceanic whitetip shark and silky shark were negatively biased, and probably to a considerable degree, because these species are not distributed throughout the area exploited by this fishery. Nominal catch rates for the other common species, except blue shark and possibly shortfin mako, were probably similarly biased and would not accurately reflect relative abundance. Indices of relative abundance could be improved by standardizing CPUE with appropriate predictor variables (e.g., time, latitude, longitude, bait types). We (WAW; KAB) are currently engaged in this research.

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Footnotes

[1] The WPRFMC is one of eight regional fishery management councils established in 1976 by the Magnuson Fishery Conservation and Management Act, also known as the Magnuson Act.

[2] Finning was prohibited in most circumstances by State of Hawaii law HRS 188-40.5 and The Shark Finning Prohibition Act (U.S. Public Law 106-557) unless the carcass was retained.

[3] 'Bycatch' is defined herein according to the MSA as sharks caught but not retained for sale or consumption. 'Incidental catch' follows prior usage (Walsh et al. 2002) as sharks retained for sale or processing, including finning.

[4] Federal Register, Volume 69, Number 64, April 2, 2004.

[5] The duration of shallow-set activity varied each year after the reopening. In 2004, shallow-set activity began in June and continued through December. This sector remained open throughout 2005. It was closed after March 2006 for the remainder of the year because the fleet reached the limit on incidental takes of loggerhead turtles, *Caretta caretta*.

Table 1. Summary of observed effort in the Hawaii-based pelagic longline fishery, January 1995–December 2006[a].

Year	Trips	Sets	Vessels	Observers	Set Types (%)		Fleet-wide Observer Coverage (%)
					Deep	Shallow	
1995 – 2006	2,121	26,507	170	294	82.8	17.2	16.0
1995	48	548	44	11	48.5	51.5	4.7
1996	52	617	47	16	44.2	55.8	5.3
1997	37	463	33	8	38.4	61.6	3.9
1998	47	549	40	15	49.9	50.1	4.4
1999	39	436	36	17	59.2	40.8	3.4
2000	114	1,331	71	51	73.3	26.7	10.3
2001	244	2,787	98	84	94.7	5.3	22.9
2002	286	3,472	99	61	98.9	1.1	24.6
2003	258	3,146	103	55	99.9	0.1	21.2
2004	346	4,053	124	78	96.7	3.3	25.3
2005	393	4,970	122	99	66.9	33.1	27.3
2006	318	4,135	123	75	80.1	19.9	23.9

[a] The sum of the annual trip totals exceeds the overall total because 61 trips that began in December ended in January. Tabulations are based on haul dates.

Table 2. Summary statistics for observed shark catches in the Hawaii-based longline fishery, January 1995–December 2006. CPUE (nominal) is defined as fish per 1000 hooks.

Species	Catch	Sets with catch (%)	Catch/set	Nominal CPUE	Sharks (%)	All fishes (%)
Blue shark (*Prionace glauca*)	159,922	90.7	6.033	4.623	84.5	13.2
Bigeye thresher shark (*Alopias superciliosus*)	7,842	17.0	0.296	0.156	4.1	0.6
Oceanic whitetip shark (*Carcharhinus longimanus*)	5,494	14.0	0.207	0.131	2.9	0.5
Shortfin mako (*Isurus oxyrinchus*)	5,243	14.7	0.198	0.165	2.8	0.4
Silky shark (*Carcharhinus falciformis*)	3,119	5.2	0.118	0.061	1.6	0.3
Crocodile shark (*Pseudocarcharias kamoharai*)	1,927	4.8	0.073	0.037	1.0	0.2
Pelagic thresher (*Alopias pelagicus*)	705	1.4	0.027	0.015	0.4	0.1
Velvet dogfish (*Zameus squamulosus*)	247	0.8	0.009	0.005	0.1	< 0.1
Longfin mako (*Isurus paucus*)	211	0.7	0.008	0.004	0.1	< 0.1

Table 2, continued.

Salmon shark (*Lamna ditropis*)	92	0.2	0.003	0.004	< 0.1	< 0.1
Tiger shark (*Galeocerdo cuvieri*)	61	0.2	0.002	0.002	< 0.1	< 0.1
Scalloped hammerhead (*Sphyrna lewini*)	56	0.2	0.002	0.001	< 0.1	< 0.1
Galapagos shark (*Carcharhinus galapagensis*)	50	0.2	0.002	0.001	< 0.1	< 0.1
Smooth hammerhead (*Sphyrna zygaena*)	49	0.2	0.002	0.001	< 0.1	< 0.1
Cookiecutter shark (*Isistius brasiliensis*)	33	0.1	0.001	0.001	< 0.1	< 0.1
Gray reef shark (*Carcharhinus amblyrhynchos*)	26	< 0.1	0.001	0.0004	< 0.1	< 0.1
Common thresher (*Alopias vulpinus*)	7	< 0.1	0.0003	0.0003	< 0.1	< 0.1
Blacktip shark (*Carcharhinus limbatus*)	2	< 0.1	0.00008	0.00004	< 0.1	< 0.1
Bigeye sandtiger shark (*Odontaspis noronhai*)	2	< 0.1	0.00008	0.00004	< 0.1	< 0.1

Table 2, continued.

Unidentified Thresher sharks (*Alopias vulpinus*/ *A. pelagicus*)	1,246	3.7	0.047	0.025	0.7	0.1
Unidentified Requiem sharks (*Carcharhinus* sp.)	152	0.4	0.006	0.004	0.1	< 0.1
Unidentified Requiem sharks (*Carcharhinus altimus*/ *C. plumbeus*)	110	0.3	0.004	0.003	0.1	< 0.1
Unidentified Makos (*Isurus* sp.)	109	0.4	0.004	0.003	0.1	< 0.1
Unidentified Hammerhead sharks (*Sphyrna* sp.)	38	0.1	0.001	0.001	< 0.1	< 0.1
Other sharks (Identified or Unidentified)	2,511	6.2	0.095	0.071	1.3	0.2

Table 3. Summary of sector- and period-specific observed catches of common sharks taken by the Hawaii-based longline fishery. Parenthetical entries are the percentages of sharks released dead.

Species	Sector	Period	Sets with catch (%)	Catch/set	Nominal CPUE	Disposition: Finned (%)	Disposition: Kept (%)	Disposition: Released (%)	Minimum Mortality (%)
Blue shark	Deep	1995 – 2000	94.3	6.984	3.753	54.6	1.2	44.2 (6.1)	61.9
		2004 – 2006	88.4	4.417	2.186	0.0	0.0	100.0 (4.0)	4.0
	Shallow	1995 – 2000	96.2	14.080	18.425	42.5	0.1	57.4 (8.5)	51.1
		2004 – 2006	98.7	10.460	13.124	0.0	0.0	100.0 (5.7)	5.7
Shortfin mako	Deep	1995 – 2000	11.1	0.129	0.072	13.8	63.8	22.4 (3.0)	80.6
		2004 – 2006	11.2	0.131	0.063	0.1	39.4	60.5 (7.5)	47.0
	Shallow	1995 – 2000	15.2	0.184	0.234	33.5	19.3	47.2 (15.2)	68.0
		2004 – 2006	43.7	0.743	0.911	0.1	11.0	88.9 (20.5)	31.6

Table 3, continued.

Oceanic whitetip shark	Deep	1995 – 2000	28.3	0.488	0.272	72.3	2.2	25.5 (7.4)	81.9
		2004 – 2006	9.4	0.118	0.060	0.0	4.9	95.1 (20.7)	25.6
	Shallow	1995 – 2000	15.6	0.286	0.351	52.7	2.9	44.4 (5.7)	61.3
		2004 – 2006	8.9	0.135	0.161	0.0	1.7	98.3 (7.4)	9.1
Bigeye thresher shark	Deep	1995 – 2000	23.0	0.469	0.259	23.3	6.3	70.4 (19.0)	48.6
		2004 – 2006	21.2	0.374	0.187	0.0	7.6	92.4 (16.5)	24.1
	Shallow	1995 – 2000	4.4	0.049	0.059	11.0	12.2	76.8 (24.4)	47.6
		2004 – 2006	1.9	0.020	0.026	0.0	13.2	86.8 (22.6)	35.8
Silky shark	Deep	1995 – 2000	7.9	0.201	0.105	45.0	1.8	53.2 (19.9)	66.7
		2004 – 2006	4.8	0.097	0.048	0.0	5.1	94.9 (21.8)	26.9
	Shallow	1995 – 2000	1.0	0.013	0.016	100.0	0.0	0.0	-----
		2004 – 2006	1.0	0.013	0.016	0.0	3.0	97.0	-----

Table 3, continued.

		1995 – 2000	8.3	0.110	0.064	0.8	5.7	93.5 (42.2)	48.7
	Deep	2004 – 2006	5.4	0.076	0.036	0.0	1.0	99.0 (13.6)	14.6
		1995 – 2000	1.9	0.022	0.028	0.0	25.0	75.0	-----
Crocodile shark	Shallow	2004 – 2006	0.5	0.003	0.004	0.0	0.0	100.0	-----

Table 4. Summary of mean lengths and sex ratios of common sharks caught in the Hawaii-based longline fishery by set type (fishery sector) and time period. Sample sizes are in parentheses.

Species	Sector	Period	Mean Fork length (cm) ♀	Mean Fork length (cm) ♂	Sex Ratio (♀: ♂)
Blue shark	Deep	1995 – 2000	171.3 (1324)	183.3 (1539)	46.2 : 53.8 (2863)
		2004 – 2006	168.8 (116)	187.6 (119)	49.4 : 50.6 (235)
	Shallow	1995 – 2000	175.0 (1744)	179.8 (2845)	38.0 : 62.0 (4589)
		2004 – 2006	170.4 (75)	143.2 (63)	54.3 : 45.7 (138)
Shortfin mako	Deep	1995 – 2000	191.0 (92)	179.3 (68)	57.5 : 42.5 (160)
		2004 – 2006	185.8 (151)	181.0 (156)	49.2 : 50.8 (307)
	Shallow	1995 – 2000	153.2 (96)	163.8 (142)	40.3 : 59.7 (238)
		2004 – 2006	133.1 (136)	157.3 (184)	42.5 : 57.5 (320)
Oceanic whitetip shark	Deep	1995 – 2000	127.0 (213)	131.0 (176)	54.8 : 45.2 (389)
	Deep	2004 – 2006	104.5 (104)	114.6 (57)	64.6 : 35.4 (161)
Bigeye thresher shark	Deep	1995 – 2000	134.8 (63)	155.3 (141)	30.9 : 69.1 (204)
	Deep	2004 – 2006	171.0 (116)	165.4 (172)	40.3 : 59.7 (288)

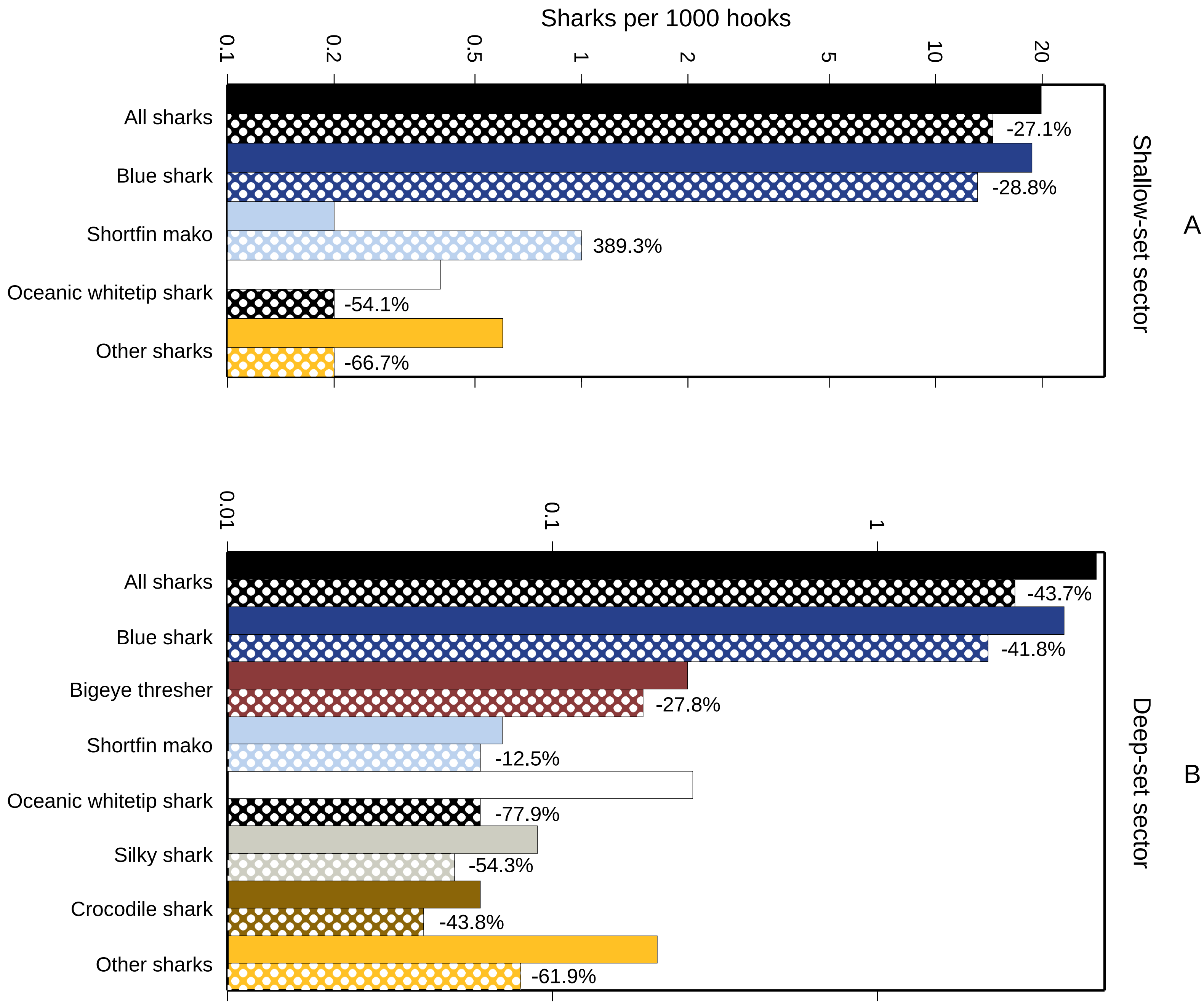
Table 4, continued

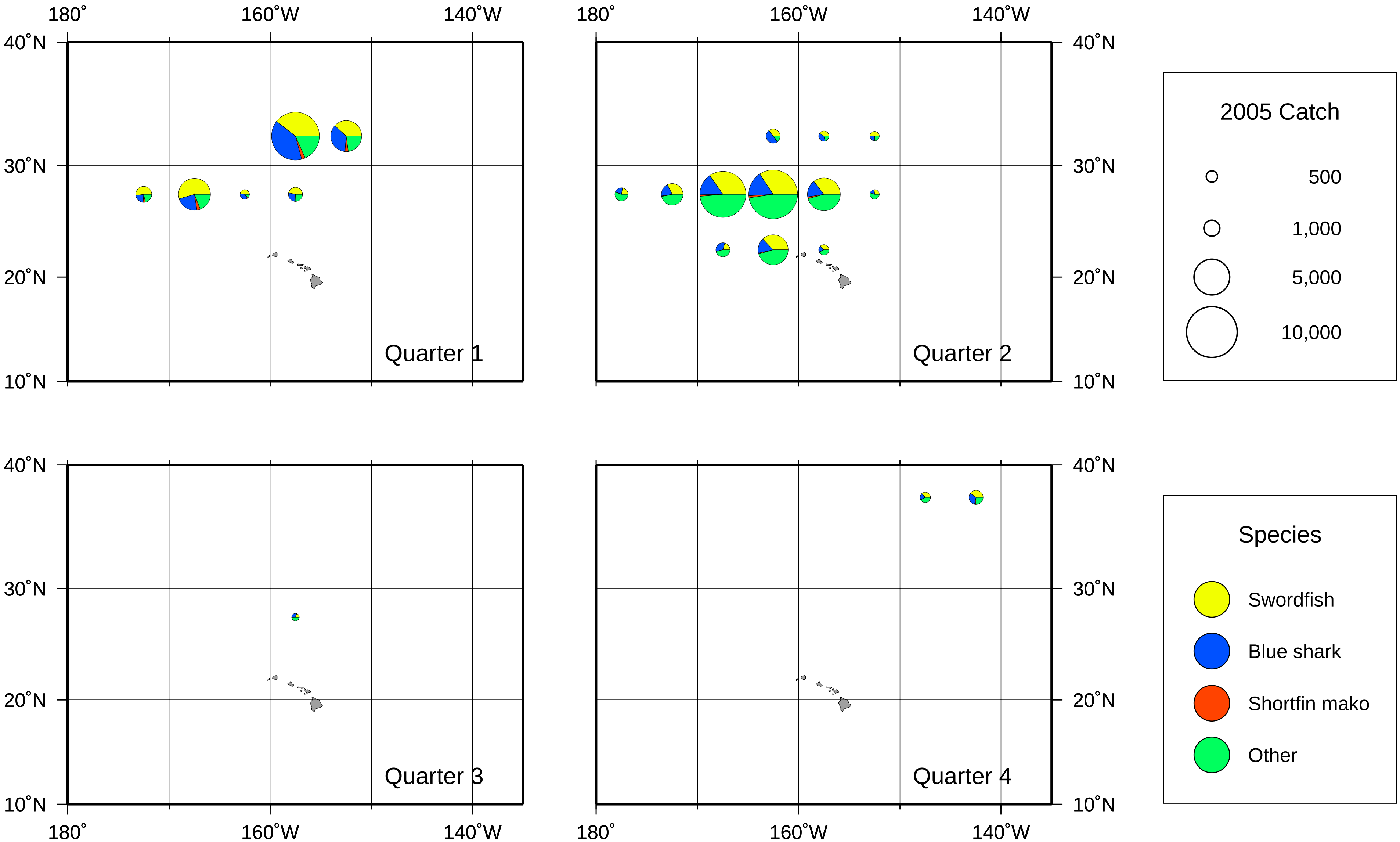
	Deep	1995 – 2000	132.9 (91)	134.3 (103)	46.9 : 53.1 (194)
Silky shark	Deep	2004 − 2006	118.9 (52)	127.2 (32)	59.8 : 40.2 (87)
	Deep	1995 – 2000	83.2 (13)	85.2 (81)	13.8 : 86.2 (94)
Crocodile shark	Deep	2004 − 2006	85.3 (32)	84.9 (125)	20.4 : 79.6 (157)

Figure Captions

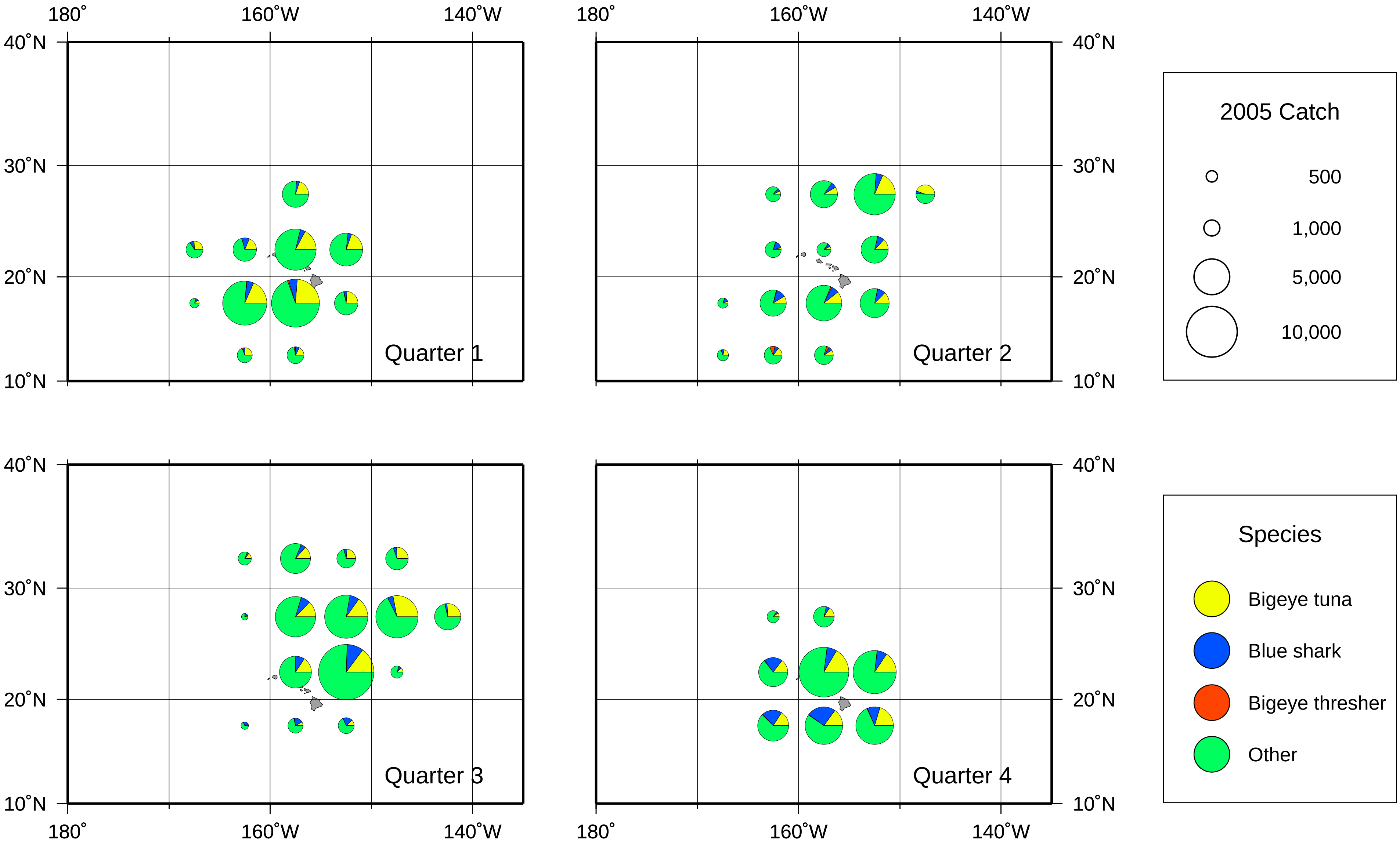
Figure 1. Catch-per unit-of-effort (sharks per 1000 hooks) plotted on a logarithmic scale for common sharks caught in the (a) shallow-set and (b) deep-set sectors of the Hawaii-based longline fishery. Solid bars represent mean CPUE values from 1995–2000; cross-hatched bars represent 2004–2006. The percentages represent the change in CPUE between the two periods.

Figure 2. Species composition of catches in the (a) shallow-set and (b) deep-set sectors of the Hawaii-based longline fishery in 2005 (5° latitude × 5 longitude° squares; nonconfidential data). The sizes of the circles are scaled by numbers of fish caught; the slices represent percentages of the catch. 'Other' denotes all other bycatch and incidentally-caught species (i.e., sharks and teleosts).


Sharks per 1000 hooks
0.1
0.2
0.5
1
2
5
10
20
All sharks
-27.1%
Blue shark
-28.8%
Shortfin mako
389.3%
Oceanic whitetip shark
-54.1%
Other sharks
-66.7%
Shallow-set sector
A
0.01
0.1
1
All sharks
-43.7%
Blue shark
-41.8%
Bigeye thresher
-27.8%
Shortfin mako
-12.5%
Oceanic whitetip shark
-77.9%
Silky shark
-54.3%
Crocodile shark
-43.8%
Other sharks
-61.9%
Deep-set sector
B



180°
160°W
140°W
40°N
30°N
20°N
10°N
Quarter 1
Quarter 2
Quarter 3
Quarter 4
2005 Catch
500
1,000
5,000
10,000
Species
Swordfish
Blue shark
Shortfin mako
Other



Quarter 1
Quarter 2
Quarter 3
Quarter 4
180°
160°W
140°W
10°N
20°N
30°N
40°N
2005 Catch
500
1,000
5,000
10,000
Species
Bigeye tuna
Blue shark
Bigeye thresher
Other