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Analyses of Catch Data for Oceanic Whitetip and Silky Sharks Reported by Fishery Observers in the Hawaii-based Longline Fishery in 1995−2010

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Analyses of Catch Data for Oceanic Whitetip and Silky Sharks Reported by Fishery Observers in the Hawaii-based Longline Fishery in 1995–2010

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ABSTRACT

This report presents descriptive statistical summaries and generalized linear model (GLM) analyses of catch data for oceanic whitetip shark, *Carcharhinus longimanus,* and silky shark, *C. falciformis,* in the Hawaii-based pelagic longline fishery. This paper is a collaborative effort begun at the Secretariat of the Pacific Community in New Caledonia and completed at the NOAA Fisheries Pacific Islands Fisheries Science Center in Hawaii. The data were collected by fishery observers aboard commercial vessels in 1995–2010. Oceanic whitetip shark mean annual nominal catch-per-unit effort (CPUE) decreased significantly from 0.428/1000 hooks in 1995 to 0.036/1000 hooks in 2010. This reflected a significant decrease in nominal CPUE on longline sets with positive catch from 1.690/1000 hooks to 0.773/1000 hooks, and a significant increase in longline sets with zero catches from 74.7% in 1995 to 95.3% in 2010. Oceanic whitetip shark CPUE was standardized by delta-lognormal and zero-inflated Poisson GLM methods. The latter method was employed because 90.1% of the longline sets caught zero oceanic whitetip sharks. Four factors (16 haul years, calendar quarters, deep- and shallow-set fishery sectors, 8 fishing regions) were significant explanatory variables in these analyses. Sea surface temperature was a significant continuous explanatory variable in a binomial GLM of the presence or absence of oceanic whitetip shark catches. The haul-year effect coefficients from these models were used to compute indices of relative abundance. These time series were highly correlated, and each was also highly correlated with the time series of nominal CPUE. The silky shark catch data differed from the oceanic whitetip shark data in four major respects. The first was that nearly all silky sharks are caught on deep sets. The second was that most (62.5%) of the silky shark catch was taken from 0° to 10°N, although only 3.4% of the observed fishing occurred in those latitudes. The third difference was that sample sizes were very small prior to 2000. Finally, although 46.3% of the longline sets from 0° to 10°N caught zero silky sharks, 54.5% of the silky shark catch in these waters was taken on 11.5% of the longline sets, which caught $\geq$ 5 silky sharks. These differences led to use of the data from 0° to 10°N in the deep sector from 2000 to 2010 in the GLM analyses, which were fitted by delta-lognormal and quasi-Poisson (i.e., overdispersed) methods. These GLM analyses had low explanatory power. Silky shark CPUE has ranged from 0.034/1000 hooks to 1.840/1000 hooks, but with no significant trend. Therefore, it is concluded that the relative abundance of silky shark in tropical waters exploited by this fishery, particularly near the Line Islands, has remained fairly stable since 2000. This was not the case with oceanic whitetip shark, which has apparently undergone a highly significant decline in relative abundance in this fishery since 1995.

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CONTENTS

Introduction 1
Methods 3
- Data Source 3
- Descriptive Statistics 3
- Oceanic Whitetip Shark: Catch Rate Standardizations 3
- Silky Shark: Catch Rate Standardizations 4
- General Aspects of Analyses 5

Results 5
- Observer Effort 5
- Oceanic Whitetip Shark: Distribution of Catches 6
- Descriptive Statistics 6
- Catch Rate Standardizations 7
- Silky Shark 8
- Catch Rate Standardizations 8
- Shark Fork Lengths 9

Discussion 9
Conclusions 11
Acknowledgments 12
References 13
Tables 17
Figures 31
Appendices
- Appendix A. Residuals from Oceanic Whitetip Shark GLM Analyses A-1
- Appendix B. Residuals from Silky Shark GLM Analyses B-1

INTRODUCTION

This report presents descriptive statistical summaries and generalized linear model analyses of fishery data for oceanic whitetip shark, *Carcharhinus longimanus,* and silky shark, *C. falciformis*. The catch and operational data used were collected by the NOAA Fisheries Pacific Islands Regional Observer Program (PIROP) in the Hawaii-based pelagic longline fishery in 1995–2010.

Estimation of shark catches by pelagic longline fisheries is difficult because data are generally limited in quantity and quality. In fisheries that target tunas *Thunnus* spp. or swordfish, *Xiphias gladius*, sharks are usually taken as bycatch or incidental catch. These catches may be reported as total sharks if reported at all (Camhi et al., 2008; Pikitch et al., 2008). When reported, catch data are likely to be biased by underreporting, inaccurate estimates of the effects of finning and nonreporting of discards (Camhi, 2008). Significant under- and nonreporting of blue shark, *Prionace glauca*, in the Hawaii longline fishery have been documented (Walsh et al., 2002) despite virtually optimal monitoring circumstances (Walsh et al., 2005; 2007). In addition, when catches are reported in the aggregate, estimation of catch composition or population trends among multiple shark species may prove difficult or impossible.

In contrast to such difficulties, the NOAA Fisheries Pacific Islands Fisheries Science Center has access to the PIROP longline observer data for use in investigations of pelagic shark catches. The PIROP was established in 1994 and has since become the largest national pelagic observer program in the Pacific Ocean (Walsh et al., 2009). The PIROP currently has high coverage rates in this fishery, with 100% on shallow-set trips (Pacific Islands Regional Office, 2011a) and 21.1% on deep-set trips in 2010 (Pacific Islands Regional Office, 2011b). The observers record catch totals by species and operational details for each set, which permits estimation of discards, underreporting, catch composition and catch trends of multiple species.

Walsh and Kleiber (2001) used the fishery observer data to fit generalized additive models (GAMs) of blue shark catches, with operational parameters (e.g., sea surface temperature, geographic position, number of hooks) as explanatory variables. The GAM coefficients were then applied to the corresponding predictor values from the logbooks of unobserved trips. Regression analysis of the relationship between reported and predicted catches demonstrated that a statistical model fitted to observer data could serve as a comparison standard for self-reported shark catches in the absence of an observer (Walsh et al., 2002).

More recently, the species-specific catch data were used to present a quantitative description of shark catches in the Hawaii-based pelagic longline fishery in 1995–2006 (Walsh et al., 2009). The shark catch included at least 20 species from 11 genera in 7 families from 3 orders, and comprised 15.6% of the observed catch (Walsh et al., 2009).

Requiem sharks (Carcharhinidae) were the predominant family, with three genera represented. They comprised 89.0% of the observed sharks catch (Walsh et al., 2009). Blue shark alone comprised 84.5% of all sharks and 13.2% of the entire catch. *Carcharhinus* was the most speciose (7) genus (Walsh et al., 2009). Oceanic whitetip shark, *Carcharhinus longimanus,* and silky shark, *C. falciformis,* were relatively common, at 2.9% and 1.6% of the sharks catch, respectively.

Oceanic whitetip shark is a large carcharhinid with a circumglobal distribution in tropical and warm-temperate open waters, usually found above 20ºC (Compagno, 1984; Compagno, 1988; Compagno and Niem, 1998; Musick et al., 2004; Mundy, 2005; Bonfil et al., 2008). It is primarily oceanic (Mundy, 2005) and considered one of the two most abundant oceanic sharks, along with blue shark (Bonfil et al., 2008).

Silky shark, which is one of the largest species in this genus, is another common carcharhinid species with a circumglobal distribution in all tropical oceans (Bonfil, 2008). It also occurs in some warm-temperate waters, usually above 23ºC (Bonfil, 2008; Compagno, 1984; Compagno, 1988; Compagno and Niem, 1998; Mundy, 2005). It has been described as semipelagic because it is often taken in coastal and insular regions (Bonfil, 2008). Strasburg (1958) reported that silky sharks were most abundant near the Line Islands between 0°–10° N and 155°–165°W in the central Pacific Ocean.

Both of these sharks are taken as bycatch and target species in oceanic or coastal fisheries (Camhi et al., 2008). Oceanic whitetip shark is one of the most common bycatch species in offshore tropical tuna longline fisheries and is also targeted in small-scale fisheries (Bonfil et al., 2008). Silky shark is targeted in many intensive fisheries and taken in large but unknown numbers as bycatch in tropical tuna longline and purse seine fisheries (Bonfil, 2008). Because the typical life history traits of sharks (e.g., slow growth, relatively late maturation, low fecundity) cause sensitivity to fishing pressure (Smith et al., 1998; Cortés, 2004), the population status of species that are subject to fishing pressure as both bycatch and target species may be of particular concern to fishery scientists and managers.

Despite scientific and management interest, little is known about the relative abundance of these species in Hawaiian waters. Walsh et al. (2009) reported mean nominal catch-per-unit effort (CPUE) values for oceanic whitetip shark and silky shark in 1995–2000 and 2004–2006 in the shallow-set (swordfish-targeted) and deep-set (tuna-targeted) sectors of the Hawaii longline fishery. Matsunaga and Nakano (1999) presented shark CPUE data from Japanese tuna longline cruises in 1967–1970 and 1992–1995. Strasburg (1958) reported CPUE data for these species from a longline survey conducted in the central Pacific Ocean in 1952–1955.

This paper presents results of catch and catch rate analyses for oceanic whitetip and silky sharks to be used as background information and input to stock assessments. These results should prove timely because both oceanic whitetip and silky sharks have been designated as priority species for assessment by the Inter-American Tropical Tuna Commission and the Western and Central Pacific Fisheries Commission (Clarke and Harley, 2010).

METHODS

Data Source

The catch and operational data used in this paper were collected by PIROP observers from January 1995 through December 2010. Observers were aboard Hawaii-based longline vessels during 3524 commercial fishing trips. Total observed effort was 47,140 longline sets.

Observers recorded catch tallies by species and a large suite of operational details on each set (Pacific Islands Regional Office, 2009). They measured shark fork lengths (FL) and total lengths (TL) when circumstances permitted.

Descriptive Statistics

Fishery-wide catch statistics for oceanic whitetip shark and silky shark were tabulated on an annual basis or plotted on an annual scale to illustrate general trends. Plots for oceanic whitetip shark present fishery-wide data from 1995 to 2010, but those for silky shark are limited to 2000–2010 because sample sizes were small in the earlier years. Quarterly catch statistics were also tabulated to show seasonal patterns in shark catch rates. Length data are presented as histograms.

The distributions and magnitudes of the catches of these species are illustrated on maps gridded on $5^{o} \times 5^{o}$ squares. These plots show nonconfidential data pooled across sectors, calendar quarters and years.

Oceanic Whitetip Shark: Catch Rate Standardizations

Generalized linear models (GLMs) were computed to standardize catch and CPUE for oceanic whitetip sharks. The initial sample size for these analyses was 45,023 because 2117 sets had missing values for explanatory variables of potential interest.

A delta lognormal analysis was conducted by fitting two models. The first was a binomial GLM of the presence or absence of catch using all sets. The second was a lognormal GLM of CPUE from sets with positive catch. The lognormal model coefficients were corrected for bias according to Beauchamp and Olson (1973). The natural logarithm of the number of hooks per set was used as an offset in the binomial model. The lognormal model had no offset because the unit of effort was thousands of hooks.

The factor variables tested for significance in the delta lognormal analysis were time (as haul year and haul quarter) fishing regions, and set type (i.e., deep or shallow). Eight regions[1] were defined by 10° latitudinal increments and a longitudinal separation at 160°W. These longitudinal ranges were defined in order to include as much observed effort north of the equator in the western hemisphere as possible. The two set types, which correspond to the sectors of this fishery, are described in the *Federal Register* (Department of Commerce, 2004). Deep sets use ≥ 15, whereas shallow sets use < 15 hooks per float.

Five continuous variables were also tested for significance. Sea surface temperature (SST°C) was considered an indicator of habitat suitability. Vessel length (m) was regarded as a proxy for fishing power. Begin-set time (Hawaii Standard Time) was used to indicate whether fishing operations proceeded normally. The distance from land (nautical miles) was also considered a possible indicator of habitat preferences. The El Niño-Southern Oscillation Index (ENSO) was tested to assess whether catch rates varied in relation to this climatic phenomenon.

GLM fitting was conducted by using reductions of the null deviance and the deviance reductions per degree of freedom as criteria to indicate the relative importance of explanatory variables. Sample sizes were large so some explanatory variables were expected to be statistically significant but of little practical importance. Therefore, a deviance reduction ≥ 0.5% (Maunder and Punt, 2004) and a reduction in the Akaike Information Criterion (AIC) ≥ 5 were required to retain any explanatory variable in a GLM.

A zero-inflated Poisson analysis was also computed for comparative purposes. A theoretical explanation and code to compute this analysis are in Zuur et al. (2009). All sets were included in both the counts and binomial models. This differed from the lognormal model, which included only sets with positive catch.

The back-transformed coefficients from both analyses were plotted against time to illustrate trends in the annual indices of relative abundance. The nominal CPUE was included to show the effects of standardization.

Silky Shark: Catch Rate Standardizations

Analytical procedures for silky shark were identical to those for oceanic whitetip shark with the following exceptions. The preliminary data examination revealed that although only 3.4% of the

[1] 1) 0–10°N, 140–160°W. 2) 0–10°N, 160–175°W. 3) 10–20°N, 135–160°W. 4) 10–20°N, 160–180°W; 5) 20–30°N, 135–160°W. 6) 20–30°N, 160–180°W. 7) 30–45°N, 125–160°W. 8) 30–45°N, 160–180°W.

observed sets were deployed between 0° and 10°N, 62.5% of the silky sharks were caught there. It also revealed that 98% of the silky shark catch was taken on deep sets. Therefore, the GLM analyses were limited to silky sharks caught on tropical deep sets between 0° and 10°N. This reduced the degrees of freedom to 1516 in the counts models and 815 in the lognormal model.

A quasi-Poisson was computed for silky shark because the preliminary examination also documented that although there were many zero catches (46.3%), most (53.7%) of the tropical sets caught at least one silky shark and 11.5% caught five or more. This method was chosen because of this apparent overdispersion.

General Aspects of Analyses

The GLM analyses are presented as summary tables and in the complete R format. Details regarding theory and implementation are in Crawley (2007). Residuals from the GLM analyses were plotted against fitted values and the values of explanatory variables and presented in Appendices A and B.

All computations were performed in R Version 2.12.2 for Windows or R Version 2.10.0 for Linux. The zero-inflated model was computed with the "pscl" library in R. The significance criterion for statistical tests was $P < 0.05$ except for contrasts of GLM coefficients, which were controlled at $P \leq 0.05$ by the Bonferroni principle.

Temporal trends in nominal statistics are described by linear regressions. The slopes and associated significance are presented.

RESULTS

Observer Effort

Observer effort increased almost ninefold from 1995 (549 sets) to 2010 (4918 sets). Observer effort in 1995–2006 is summarized in detail in Walsh et al. (2009). In 2007–2010, the average number of observed sets was 5133 per year, with deep sets comprising 69.5% of the total.

The geographic extent of observer coverage increased considerably after the PIROP completed its expansion (Walsh et al., 2009). In 1995, observer coverage spanned 30.8° of latitude and 39.6° of longitude (mean: 23.8°N; 156.8°W). In 2000, when the coverage rate was 10.3%, there was observer coverage across 31.8° of latitude and 33.9° of longitude (mean: 20.2°N; 161.8°W). By 2010, observer coverage spanned 42° of latitude and 51.4° of longitude (mean: 24.6°N; 156.6°W).

Oceanic Whitetip Shark: Distribution of Catches

The distribution and approximate magnitudes of oceanic whitetip shark catches are presented in Figure 1. The largest catch in any individual 5° × 5° square came from 5–10°N and 160–165°W (17.7% of all oceanic whitetip sharks). An additional 38.6% of the total oceanic whitetip shark catch was taken within the 10° × 10° square bounded by 15–25°N and 155–165°W.

Descriptive Statistics

The large majority (90.1%) of observed sets caught zero oceanic whitetip sharks (Table 1; Fig. 2). Most sets with catch yielded small numbers, with 94.4% of the oceanic whitetip sharks taken on sets that caught ≤ 5. The mean nominal CPUE was 0.088/1000 hooks (SD 0.386), and the coefficient of variation (CV) was 439%.

Oceanic whitetip shark nominal CPUE (b = -0.028; P = 1.250e-07) and nominal CPUE on sets with positive catch (b = -0.062; P = 0.0002) decreased significantly in 1995–2010 (Fig. 3). The mean nominal CPUE decreased by 91.6%, from 0.428 sharks/1000 hooks in 1995 to 0.036 sharks/1000 hooks in 2010, while the mean nominal CPUE from sets with positive catch decreased by 54.3%. Zero catches increased from 74.7% in 1995 to 95.3% in 2010 (b = 0.017; P = 7.091e-09).

The effects of fishery sectors, fishing regions and calendar quarters on oceanic whitetip shark catches and nominal CPUE are summarized in Table 2 using data from all years. The deep-set sector operated in all regions and quarters, but with only 42 sets and zero oceanic whitetip sharks caught in the first quarter above 30°N. There was no observed shallow-set fishing below 10°N.

The annual mean nominal CPUE in the deep- and shallow-set sectors (Fig. 4) decreased significantly by 91.5% and 89.6%, respectively, in 1995–2010. The two linear trends (shallow-set: b = -0.030; deep-set: -0.025) were significantly correlated (r = 0.778; P = 0.0004).

The highest mean nominal CPUE values with the fishery sectors pooled were in Regions 1 and 2 (Fig. 5). Although greater nominal CPUE values were measured in the shallow-set sector in Region 3 (Table 2), shallow-set activity comprised only 1.6% of the sets in that region. The nominal CPUE in the deep-set sector in Region 3 was approximately an order of magnitude lower (0.066–0.106 sharks/1000 hooks), which reduced the pooled mean.

The relationship between oceanic whitetip shark CPUE and SST is presented in Figure 6. A Wilcoxon rank sum test demonstrated that the distribution of SST values from sets with positive catch (median SST = 26.2°C) was significantly shifted (P < 2.2e-16) relative to the SST distribution from all sets, including those with zero catches (median SST = 25.1°C). At SST < 24°C, only 1.7% of the sets caught oceanic whitetip sharks.

The quarterly pattern of nominal CPUE (Fig. 7), with sectors and regions pooled, was an apparent cycle that began with a maximum in the second quarter followed by decreases through the following first quarter. The first quarter mean SST (21.9^{o}C) was considerably less than those in the other quarters (24.6–25.9^{o}C).

Catch Rate Standardizations

The delta lognormal analysis of oceanic whitetip shark catch rates (Table 4) demonstrated that four factor variables significantly affected both the probability of catch (binomial model) and CPUE on sets with positive catch (lognormal model). SST had a positive effect on the probability of catch, but did not influence CPUE on sets with positive catch.

In the binomial GLM, all years except 1997 and 1999, which had the two smallest annual set totals, had significant negative coefficients relative to the reference year. All quarterly effects were significant, and demonstrated that the percentage of positive catch in the first quarter was significantly less than during the other three. The significant difference between set types reflected higher proportions of positive catch on shallow than on deep sets in Regions 3–6. The significant regional effects were primarily attributable to latitude rather than longitude. Thus, Region 1 was not significantly different from Region 2, nor was Region 3 different from Region 4, but Region 1 was different from Region 3 and Region 2 was different from Region 4.

The principal difference between the binomial and lognormal model results was that SST was not a significant predictor of log-transformed CPUE. This reflected the lower degrees of freedom in the lognormal model, which resulted from eliminating the zero catches. Many of the zero catches came from sets deployed at relatively low SST.

The other continuous variables tested as candidate explanatory variables (begin-set time; vessel length; the ENSO; distance from land) were not significant in either the binomial (four *z*-tests: all $P > 0.05$) or lognormal models (four *t*-tests: all $P > 0.15$). These variables also did not reduce the AIC sufficiently to warrant retention in either or both model(s).

The zero-inflated Poisson analysis (Table 5) produced slightly different results. The four factor variables and SST were statistically significant in both the counts and zeroes models. The significance of SST reflected the inclusion of all sets in both models. The sign of the set type coefficient differed between the count and binomial models. The positive sign in the counts model reflected higher catches on shallow sets in Regions 3–6 than on deep sets. The negative sign in the zero-inflation model reflected the lower proportion of zero catches in these regions.

The indices of relative abundance computed from these models are shown in Figure 8. The two indices were highly correlated ($r = 0.894$; $P = 6.855e\text{-}06$), and each was significantly correlated with the nominal trend (delta-lognormal and nominal CPUE: $r = 0.972$; $P = 1.429e\text{-}09$; zero-inflated Poisson and nominal CPUE: $r = 0.942$; $P = 1.546e\text{-}07$).

Silky Shark

Silky shark catch data (Table 1) included many zeroes (96%), but 0.4% of the sets yielded large catches (5–38) that comprised 39% of the total. This caused the coefficient of variation for nominal CPUE to be very large (CV = 768%). A large percentage (34%) of the silky shark catch was taken in 6 successive quarters (April 2001–August 2002).

Figure 9 illustrates the distribution of silky shark catches used in the GLM analyses. The greatest fraction of these catches was taken between 5–10°N and 165–170°W.

Silky shark catches (Fig. 10) included many zeroes (46.2%) as well as some large catches (i.e., ≥ 10 per set). The mean nominal CPUE from 2000 to 2010 (Fig. 11), with an average sample size of 138 sets per year, was 0.85/1000 hooks. The major cause of variation in nominal CPUE was the zero catches (mean: 63.9%; range: 10.0–92.9%) as indicated by their highly significant negative correlation (r = -0.910; df = 9; P = 0.0001). The mean CPUE for sets with positive catch was 1.59 per 1000 hooks.

Catch Rate Standardizations

Table 8 summarizes the fitting of the silky shark delta lognormal analysis. Haul year, hooks per float, and distance from land were significant explanatory variables in the binomial GLM. These variables explained 6.4%, 0.8% and 0.6% of the null deviance, respectively. The GLM of log-transformed CPUE (N = 815 sets) included two significant explanatory variables. The year of fishing explained 7.0% of the null deviance. The effect of hooks per float was significant and negative, but it explained only 0.9% of the null deviance.

The complete silky shark delta-lognormal analysis in R format is presented in Table 9. The coefficients in the binomial GLM revealed that the probability of positive catch in 2 years with small sample sizes (2003: 20 longline sets; 2005: 14 longline sets) differed significantly from the reference year. The probabilities of positive catch were lower than in the reference year in 2004, 2005 and 2007, when 62.6–92.9% of the sets yielded zero silky sharks. The lognormal model coefficients demonstrated that CPUE on sets with positive catch was significantly lower in 6 subsequent years (2001; 2002; 2004; 2007; 2009; 2010) than in the reference year 2000.

A quasi-Poisson analysis of catch (Table 10) also detected significant effects of haul year, hooks per float, and distance from land on silky shark catches. The haul year coefficients from 2002, 2004, and 2007 in the quasi-Poisson model were significantly different from the reference year. In 2002, the nominal CPUE on sets with positive catch was 1.410/1000 hooks, compared to 2.312/1000 hooks in 2000, although the percentages of zero catches were similar (2000: 44.2%; 2002: 45.8%). The significant difference in 2004 reflected the second highest annual percentage of zero catches, whereas the nominal CPUE on sets with positive catch was the median of the annual values. In 2007, significance reflected the third highest percentage of zero catches and the second lowest CPUE on sets with positive catch. The coefficients of hooks per float and distance from land were negative, indicating that catch rates would vary inversely with these explanatory variables.

The back-transformed coefficients from the delta-lognormal and quasi-Poisson analyses (Table 11) are presented as indices of relative abundance in Figure 12. The two indices were significantly correlated with the nominal CPUE (delta-lognormal and nominal CPUE: $r = 0.966$; $P = 5.67e\text{-}06$; quasi-Poisson and nominal CPUE: $r = 0.991$; $P = 2.598e\text{-}08$) and with each other ($r = 0.977$; $P = 1.147e\text{-}06$). The linear regressions of the annual coefficients on time were not significant (both $P > .75$).

Shark Fork Lengths

Fork lengths of oceanic whitetip and silky sharks are presented in Figure 13. A preliminary data evaluation revealed apparent sampling artifacts with both species. In oceanic whitetip sharks, the annual mean FL was 125.8–136.9 cm from 1995 to 2001. In 2000, however, Hawaii Revised Statute 188-40.5 and the federal Shark Finning Prohibition Act (U.S. Public Law 106-557) were enacted. These laws affected the disposition of shark catches by prohibiting finning in most circumstances unless the carcass was retained. The annual mean FL decreased to 111.4 cm in 2002 and ranged from 98.2 to126.7 cm thereafter. In silky sharks, the data evaluation indicated that variation in FL measurements was associated with interannual differences in the months with observed fishing in tropical waters. For these reasons, the size measurements for each species were pooled using data from all years.

The mean and median oceanic whitetip shark FLs differed by 1 cm. The third quartile, 140.2 cm, corresponded to 170.5 cm TL. The mean and median silky shark FLs differed by 2 cm, and the third quartile, 123 cm, corresponded to 149.1 cm TL.

DISCUSSION

The principal finding of this study is that oceanic whitetip shark CPUE has decreased by > 90% since 1995 in the Hawaii-based pelagic longline fishery. These GLM analyses revealed significant, comprehensible effects of four factor variables and one continuous variable on oceanic whitetip shark catch rates.

The delta-lognormal analysis revealed three noteworthy features of the oceanic whitetip shark catch rate patterns. The first was that SST exerted a significant, positive effect on the probability of catch, but did not affect CPUE on sets with positive catch. This suggests that low SST acted as a thermal barrier for this species, but that within the preferred range CPUE was largely independent of SST. Moreover, SST appeared to act as a thermal barrier ca. 24°C, which is a higher temperature than might be expected from the literature (Bonfil et al., 2008). A second difference was that the percent deviance reductions and deviance reductions per degree of freedom revealed that set type (i.e., fishery sector) was an important explanatory variable in relation to the probability of catch, as exemplified by the greater proportions of positive catch on shallow rather than deep sets in Regions 3–6, but was the predominant influence relative to CPUE on sets with positive catch. The third was that regional effects were primarily latitudinal. This seems reasonable, given the oceanic distribution of this species.

Identification of a preferred SST range ca. 25–29°C for oceanic whitetip shark is pertinent to a previously reported decrease in nominal CPUE between 1995–2000 and 2004–2006 (Walsh et al., 2009). These authors reported a 54.1% decrease in nominal CPUE between these periods in the shallow-set sector, but an operational change in this sector probably contributed to this result. In 1995–2000, 37.8% of the shallow sets were deployed at SST > 24°C, and the nominal CPUE was 1.036/1000 hooks. Shallow sets deployed at SST ≤ 24°C during these years had a mean nominal CPUE of 0.088/1000 hooks. In 2004–2006, however, only 17.2% of the shallow sets were deployed at SST > 24°C, and the mean nominal CPUE was 0.808/1000 hooks. Shallow sets with SST ≤ 24°C in 2004–2006 yielded a mean nominal CPUE of 0.028/1000 hooks. These results suggest that the annual mean shallow-set CPUE for oceanic whitetip shark in recent years probably reflects both relative abundance and the spatiotemporal distribution of shallow-set effort.

The decrease in relative abundance of oceanic whitetip shark in Hawaiian waters probably began prior to 1995. Strasburg (1958) presented the results from central Pacific shark surveys conducted in 1952–1955, and reported identical mean CPUE values of 2.7 per 1000 hooks within 0–10°N and 155–165°W and 10–20°N and 155–165°W. In 1995–2000, however, the means in these 10° × 10° squares were 1.219/1000 hooks (0–10°N) and 0.348/1000 hooks (10–20°N), respectively.

The only significant factor variable in the silky shark analyses was the haul year, but this effect consisted largely of interannual fluctuations that probably reflected differences in the months with observed deep-set fishing in tropical waters and did not represent a negative, linear trend. The silky shark analyses also showed little explanatory power. As such, it is not clear whether the selections of candidate predictors for silky shark were appropriate. One exception was the significant, negative effect of the distance from land, which seemed consistent with the semipelagic distribution of this species. The significant negative effect of hooks per float as a continuous variable was also reasonable because this indicated that the silky shark catch rate should vary inversely with depth in tropical longline fishing.

These results suggest that identification of additional significant explanatory variables for both of these species will be difficult. For oceanic whitetip sharks, this would probably entail identifying extrinsic or intrinsic variables that affect very low catch rates, whereas the twofold problems with silky sharks are that a low percentage of effort goes to the preferred relatively constant tropical habitat, meaning that relatively low degrees of freedom are available to estimate effects of narrow ranges of candidate explanatory variables.

The fork length measurements did not reveal any pattern of decreasing sizes in these species in 1995–2010. These data did show, however, that most measured sharks of both species were probably immature. Seki et al. (1998) reported that most male and female oceanic whitetip sharks attain maturity at 175–189 cm, which suggests that at least 75% of the measured oceanic whitetip sharks from this fishery were immature. Similarly, both male and female silky sharks in the eastern and central Pacific Ocean mature ca. 180 cm TL (Bonfil, 2009). This indicates that at least 75% of the measured silky sharks were also immature. It must be recognized, however, that these mean and median sizes are probably negatively biased to some unknown extent because there has been little if any incentive to bring large sharks aboard a fishing vessel since the finning prohibition.

CONCLUSIONS

The decreases in oceanic whitetip shark nominal and standardized CPUE probably reflect real change in relative abundance in the Hawaii-based pelagic longline fishery in 1995–2010. The reason is that both the probability of positive catch and CPUE on sets with positive catch decreased, as shown by the binomial and lognormal models, respectively.

The SST results suggest that if the shallow-set sector of this fishery continues to operate as it has since 2004, with 51% of the activity in the first quarter of the year, catches of oceanic whitetip shark should remain low as a result of habitat unsuitability. Although the results were from a single year, Walsh et al. (2009) documented substantial catches of swordfish from 25° to 35°N in 2005. Thus, if bycatch reduction measures for oceanic whitetip shark are deemed necessary, one possibility might be to promote or if necessary limit shallow-set fishing to the first quarter of the year in temperate waters.

The silky shark analyses revealed no significant CPUE trend in 2000–2010. Hence, the relative abundance of this species in the tropical waters exploited by this fishery appears to have been stable during this interval.

Substantial catches of both species were taken in tropical waters, particularly silky sharks. This suggests that management measures in low latitude waters might be beneficial to both. Moreover, because the percentage of effort by this fishery in tropical waters is low, it might be possible to design and implement effective management measures that cause minimal economic losses to this fishery.

Because the fork length measurements for both species were pooled over the years, months, and regions, it was not possible to determine whether the sizes of caught sharks were decreasing systematically. It does appear, however, that most sharks of these species taken by this fishery are immature.

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Table 1.-- Summary of catch statistics for oceanic whitetip shark, *Carcharhinus longimanus,* and silky shark, *C. falciformis,* in the Hawaii-based longline fishery in 1995–2010. Results for both species were computed with all data (*N* = 47,140 longline sets).

Species	Total catch	Catch per set	Nominal CPUE (Catch per 1000 hooks)
Oceanic whitetip shark	6639	Mean: 0.141 SD: 0.527 Maximum: 15 Zeroes: 42,493 (90.1%)	Mean: 0.088 SD:0.386 Maximum: 18.456
Silky shark	4105	Mean: 0.087 SD: 0.686 Maximum: 38 Zeroes: 45,252 (96.0%)	Mean: 0.044 SD: 0.338 Maximum: 18.849

Table 2.--Summary of oceanic whitetip shark catches (upper entry) and mean nominal CPUE (middle entry; expressed as sharks/1000 hooks) in the Hawaii-based longline fishery by sectors (i.e., set types), quarters and regions of fishing. Numbers of sets (*N*) are in parentheses. Data from 1995 to 2010 are pooled. "NA" denotes not available.

Deep-set sector				Shallow-set sector			
Quarter 1	Quarter 2	Quarter 3	Quarter 4	Quarter 1	Quarter 2	Quarter 3	Quarter 4
Region 1 36 0.460 (35)	Region 1 55 0.271 (91)	Region 1 104 0.505 (95)	Region 1 21 0.808 (18)	Region 1 NA	Region 1 NA	Region 1 NA	Region 1 NA
Region 2 509 0.527 (469)	Region 2 377 0.447 (414)	Region 2 251 0.451 (293)	Region 2 266 0.818 (173)	Region 2 NA	Region 2 NA	Region 2 NA	Region 2 NA
Region 3 231 0.066 (1796)	Region 3 257 0.070 (1986)	Region 3 165 0.088 (1032)	Region 3 340 0.106 (1852)	Region 3 NA	Region 3 18 1.058 (22)	Region 3 150 1.965 (88)	Region 3 0 0.000 (5)
Region 4 368 0.014 (2256)	Region 4 603 0.006 (3358)	Region 4 365 0.014 (1367)	Region 4 419 0.028 (1660)	Region 4 NA	Region 4 4 0.856 (5)	Region 4 22 0.138 (26)	Region 4 9 0.120 (9)
Region 5 52 0.014 (2034)	Region 5 23 0.006 (1779)	Region 5 113 0.014 (3904)	Region 5 300 0.028 (5411)	Region 5 6 0.018 (374)	Region 5 196 0.157 (1411)	Region 5 62 0.731 (107)	Region 5 43 0.559 (88)
Region 6 113 0.058 (1022)	Region 6 112 0.080 (772)	Region 6 59 0.058 (539)	Region 6 336 0.081 (2166)	Region 6 5 0.009 (664)	Region 6 498 0.319 (1845)	Region 6 50 0.852 (77)	Region 6 6 0.166 (39)
Region 7 0 0.000 (11)	Region 7 0 0.000 (40)	Region 7 9 0.004 (1101)	Region 7 0 0.000 (86)	Region 7 6 0.002 (3,504)	Region 7 0 0.000 (195)	Region 7 9 0.063 (53)	Region 7 1 0.001 (906)
Region 8 0 0.000 (31)	Region 8 0 0.000 (61)	Region 8 7 0.006 (491)	Region 8 4 0.030 (64)	Region 8 1 0.002 (602)	Region 8 6 0.023 (267)	Region 8 57 0.171 (383)	Region 8 1 0.019 (63)

Table 3.--Summary of GLM fitting in the oceanic whitetip shark delta-lognormal analysis. The first is the binomial model; the second is the lognormal model. "NA" denotes not applicable.

Parameter	Df	Residual deviance	Deviance reduction	Deviance reduction per df	Percent reduction of null deviance	AIC & ΔAIC	Median residual
Intercept	1	28,429.76	NA	NA	NA	28,431.76 NA	-0.4571
Haul year	15	26,181.46	2248.30	149.89	7.91%	26213.46; -2218.30	-0.3557
Calendar quarter	3	25,902.40	279.06	93.02	0.98%	25,940.40; -273.06	-0.3499
Fishing region	7	23,717.31	2185.09	312.16	7.64%	23,769.31; -2171.09	-0.3120
Set type	1	23,006.69	710.62	710.62	2.50%	23,060.69; -708.62	-0.3084
SST	1	22,110.11	896.58	896.58	3.15%	22,166.11; -894.58	-0.2782

Binomial GLM null deviance = 28,429.76. Explanation of null deviance: 22.2%. *N* = 45,023.

Parameter	Df	Residual deviance	Deviance reduction	Deviance reduction per df	Percent reduction of null deviance	AIC & ΔAIC	Median residual
Intercept	1	1464.78	NA	NA	NA	7540.12 NA	-0.2478
Haul year	15	1220.08	244.69	16.31	16.71%	6792.75; -747.38	-0.1490
Calendar quarter	3	1153.01	67.07	22.36	4.58%	6558.27; -234.48	-0.1165
Fishing region	7	1070.82	82.19	11.74	5.61%	6257.75; -300.52	-0.0950
Set type	1	800.75	270.07	270.07	18.44%	5023.69; -1234.06	-0.0961

Lognormal GLM null deviance = 1464.78. Explanation of null deviance: 45.3%. *N* = 4,253.

Table 4.--Delta-lognormal analysis of oceanic whitetip shark catch rates in the Hawaii-based longline fishery in 1995–2010. Haul year (Haulyr), calendar quarter (Quarter), region of fishing (Region) and set types (settype) are factor variables. Sea surface temperature (SST) is a continuous variable. Results are presented in R format.

Binomial GLM

Deviance Residuals:	Min	1Q	Median	3Q	Max
	-2.1182	-0.4596	-0.2782	-0.1162	3.7921

Coefficients:	Estimate	Std. Error	z value	Pr (> |z|)
(Intercept)	-2.006e+01	5.408e-01	-37.086	< 2e-16 ***
Haulyr 1996	-5.691e-01	1.659e-01	-3.431	0.000602 ***
Haulyr 1997	-2.772e-04	1.815e-01	-0.002	0.998781
Haulyr 1998	-5.859e-01	1.678e-01	-3.492	0.000479 ***
Haulyr 1999	-2.171e-02	1.857e-01	-0.117	0.906936
Haulyr 2000	-1.184e+00	1.469e-01	-8.061	7.54e-16 ***
Haulyr 2001	-5.842e-01	1.291e-01	-4.524	6.06e-06 ***
Haulyr 2002	-1.375e+00	1.336e-01	-10.292	< 2e-16 ***
Haulyr 2003	-1.157e+00	1.301e-01	-8.889	< 2e-16 ***
Haulyr 2004	-1.684e+00	1.283e-01	-13.127	< 2e-16 ***
Haulyr 2005	-1.533e+00	1.272e-01	-12.044	< 2e-16 ***
Haulyr 2006	-2.162e+00	1.367e-01	-15.815	< 2e-16 ***
Haulyr 2007	-2.179e+00	1.334e-01	-16.333	< 2e-16 ***
Haulyr 2008	-2.197e+00	1.406e-01	-15.623	< 2e-16 ***
Haulyr 2009	-2.380e+00	1.368e-01	-17.394	< 2e-16 ***
Haulyr 2010	-2.110e+00	1.357e-01	-15.553	< 2e-16 ***
Quarter 2	-1.491e-01	5.698e-02	-2.616	0.008888 **
Quarter 3	-4.493e-01	7.092e-02	-6.335	2.38e-10 ***
Quarter 4	-1.788e-01	6.478e-02	-2.761	0.005767 **
Region 2	-3.381e-01	1.622e-01	-2.084	0.037124 *
Region 3	-1.042e+00	1.591e-01	-6.549	5.78e-11 ***
Region 4	-1.051e+00	1.543e-01	-6.812	9.60e-12 ***
Region 5	-1.975e+00	1.645e-01	-12.009	< 2e-16 ***
Region 6	-1.192e+00	1.635e-01	-7.293	3.04e-13 ***
Region 7	-3.099e+00	3.026e-01	-10.243	< 2e-16 ***
Region 8	-1.976e+00	2.176e-01	-9.077	< 2e-16 ***
settypeS	2.497e+00	7.025e-02	35.547	< 2e-16 ***
SST	5.136e-01	1.904e-02	26.976	< 2e-16 ***

(Dispersion parameter for binomial family taken to be 1)

Null deviance: 28,430; df = 45,022. Residual deviance: 22,110.11; df = 44,995. AIC: 22,166.

*** = .001 ** = .01 * = .05

Lognormal GLM

Deviance Residuals:	Min	1Q	Median	3Q	Max
	-1.03426	-0.26614	-0.09614	0.15111	2.57725

Coefficients:	Estimate	Std. Error	t value	Pr (> |t|)
(Intercept)	0.08852	0.06210	1.425	0.154096
Haulyr 1996	-0.12508	0.05499	-2.274	0.022991 *
Haulyr 1997	-0.25058	0.05800	-4.320	1.59e-05 ***
Haulyr 1998	-0.14679	0.05588	-2.627	0.008653 **
Haulyr 1999	-0.14647	0.06103	-2.400	0.016435 *
Haulyr 2000	-0.30600	0.05061	-6.046	1.61e-09 ***
Haulyr 2001	-0.33213	0.04351	-7.633	2.81e-14 ***
Haulyr 2002	-0.41789	0.04557	-9.169	< 2e-16 ***
Haulyr 2003	-0.42080	0.04480	-9.393	< 2e-16 ***
Haulyr 2004	-0.42495	0.04366	-9.733	< 2e-16 ***
Haulyr 2005	-0.43957	0.04373	-10.053	< 2e-16 ***
Haulyr 2006	-0.58571	0.04817	-12.160	< 2e-16 ***
Haulyr 2007	-0.56511	0.04645	-12.166	< 2e-16 ***
Haulyr 2008	-0.60646	0.05081	-11.936	< 2e-16 ***
Haulyr 2009	-0.63372	0.04866	-13.023	< 2e-16 ***
Haulyr 2010	-0.59307	0.04817	-12.312	< 2e-16 ***
Quarter 2	0.06396	0.02114	3.025	0.002498 **
Quarter 3	0.07486	0.02255	3.320	0.000909 ***
Quarter 4	0.04888	0.02173	2.249	0.024538 *
Region 2	0.06331	0.04846	1.306	0.191519
Region 3	-0.22392	0.04758	-4.706	2.60e-06 ***
Region 4	-0.26381	0.04648	-5.675	1.48e-08 ***
Region 5	-0.37091	0.04880	-7.601	3.60e-14 ***
Region 6	-0.23477	0.04884	-4.807	1.59e-06 ***
Region 7	-0.40681	0.11520	-3.531	0.000418 ***
Region 8	-0.46029	0.07384	-6.234	5.00e-10 ***
settypeS	0.95440	0.02528	37.753	< 2e-16 ***

(Dispersion parameter for gaussian family taken to be 0.1894814)

Null deviance: 1464.78; df = 4,252. Residual deviance: 800.75; df = 4,226. AIC: 5023.7.

*** = .001 ** = .01 * = .05

Table 5.--Zero-inflated Poisson analysis of oceanic whitetip shark catches in the Hawaii-based longline fishery in 1995–2010. The first section is the count model; the second section is the binomial model. Haul year (Haulyr), calendar quarter (Quarter), region of fishing (Region) and set types (settype) are factor variables. Sea surface temperature (SST) is a continuous variable. Results are presented in R format.

Pearson residuals:

Min	1Q	Median	3Q	Max
-1.60808	-0.31595	-0.19744	-0.08642	34.04182

Count model coefficients (poisson with log link):

	Estimate	Std. Error	z value	Pr (> |z|)
(Intercept)	-18.29197	0.45439	-40.256	< 2e-16 ***
Haulyr 1996	-0.51355	0.14085	-3.646	0.000266 ***
Haulyr 1997	-0.77250	0.15192	-5.085	3.68e-07 ***
Haulyr 1998	-0.28628	0.13801	-2.074	0.038039 *
Haulyr 1999	-0.01800	0.14695	-0.122	0.902518
Haulyr 2000	-0.56725	0.13886	-4.085	4.41e-05 ***
Haulyr 2001	-0.82398	0.12398	-6.646	3.02e-11 ***
Haulyr 2002	-1.12531	0.13255	-8.490	< 2e-16 ***
Haulyr 2003	-1.16378	0.14186	-8.204	2.33e-16 ***
Haulyr 2004	-1.26296	0.12522	-10.086	< 2e-16 ***
Haulyr 2005	-1.21937	0.14288	-8.534	< 2e-16 ***
Haulyr 2006	-1.76641	0.16885	-10.462	< 2e-16 ***
Haulyr 2007	-1.30968	0.14520	-9.020	< 2e-16 ***
Haulyr 2008	-1.87239	0.20922	-8.949	< 2e-16 ***
Haulyr 2009	-1.68714	0.17194	-9.813	< 2e-16 ***
Haulyr 2010	-1.55116	0.15358	-10.100	< 2e-16 ***
Quarter 2	-0.04194	0.07311	-0.574	0.566183
Quarter 3	-0.53907	0.08755	-6.157	7.40e-10 ***
Quarter 4	-0.43169	0.08006	-5.392	6.97e-08 ***
Region 2	-0.14481	0.11471	-1.262	0.206835
Region 3	-0.28271	0.12976	-2.179	0.029350 *
Region 4	-0.42809	0.12084	-3.543	0.000396 ***
Region 5	-0.80021	0.15395	-5.198	2.02e-07 ***
Region 6	-0.23368	0.13790	-1.695	0.090164 .
Region 7	-2.39463	0.69210	-3.460	0.000540 ***
Region 8	-0.57961	0.26689	-2.172	0.029875 *
settypeS	1.61432	0.10413	15.503	< 2e-16 ***
SST	0.44287	0.01570	28.204	< 2e-16 ***

*** = .001   ** = .01   * = .05

Zero-inflation model coefficients (binomial with logit link):

	Estimate	Std. Error	z value	Pr (> |z|)
(Intercept)	-1.43886	0.39127	-3.677	0.000236 ***
Haulyr 1996	0.02622	0.35503	0.074	0.941117
Haulyr 1997	-4.32936	11.03755	-0.392	0.694881
Haulyr 1998	0.48363	0.32841	1.473	0.140847
Haulyr 1999	-0.03009	0.37183	-0.081	0.935505
Haulyr 2000	0.98472	0.29200	3.372	0.000745 ***
Haulyr 2001	-0.39943	0.31165	-1.282	0.199964
Haulyr 2002	0.44685	0.28199	1.585	0.113044
Haulyr 2003	0.03583	0.30585	0.117	0.906740
Haulyr 2004	0.69479	0.26282	2.644	0.008203 **
Haulyr 2005	0.57187	0.30459	1.878	0.060444 .
Haulyr 2006	0.68903	0.32103	2.146	0.031847 *
Haulyr 2007	1.40532	0.27605	5.091	3.57e-07 ***
Haulyr 2008	0.68456	0.38164	1.794	0.072856 .
Haulyr 2009	1.12407	0.31453	3.574	0.000352 ***
Haulyr 2010	0.97571	0.29908	3.262	0.001105 **
Quarter 2	0.09210	0.13841	0.665	0.505782
Quarter 3	-0.33030	0.16423	-2.011	0.044303 *
Quarter 4	-0.56692	0.14746	-3.844	0.000121 ***
Region 2	0.18168	0.30895	0.588	0.556485
Region 3	1.41129	0.30355	4.649	3.33e-06 ***
Region 4	1.16976	0.29520	3.963	7.41e-05 ***
Region 5	2.20607	0.32185	6.854	7.17e-12 ***
Region 6	1.78680	0.31409	5.689	1.28e-08 ***
Region 7	1.73981	1.24234	1.400	0.161384
Region 8	2.67798	0.45716	5.858	4.69e-09 ***
settypeS	-1.42911	0.21949	-6.511	7.46e-11

Log-likelihood: -1.444e+04 on 55 Df

AIC: 28,986.13

*** = .001 ** = .01 * = .05

Table 6.--Back-transformed coefficients of the annual effects from the delta-lognormal and zero-inflated Poisson analyses of oceanic whitetip shark catch rates. The back-transformed coefficients from the two models in both analyses are the upper entries; the index values are the lower, centered, bold-face entries. The reference year was 1995.

<table>
<tr><th></th><th colspan="2">Delta-lognormal analysis</th><th colspan="2">Zero-inflated Poisson analysis</th></tr>
<tr><th>Haul year</th><th>Binomial model: Back-transformed coefficient</th><th>Lognormal model: Back-transformed coefficient</th><th>Counts model: Back-transformed coefficient</th><th>Binomial model: Back-transformed coefficient</th></tr>
<tr><td rowspan="2">1996</td><td>0.269316</td><td>0.969557</td><td>0.598368</td><td>0.465346</td></tr>
<tr><td colspan="2">0.261117</td><td colspan="2">0.278445</td></tr>
<tr><td rowspan="2">1997</td><td>0.284091</td><td>0.855202</td><td>0.461857</td><td>0.454542</td></tr>
<tr><td colspan="2">0.242955</td><td colspan="2">0.209933</td></tr>
<tr><td rowspan="2">1998</td><td>0.273756</td><td>0.948732</td><td>0.751052</td><td>0.529469</td></tr>
<tr><td colspan="2">0.259721</td><td colspan="2">0.397659</td></tr>
<tr><td rowspan="2">1999</td><td>0.241477</td><td>0.949037</td><td>0.982161</td><td>0.485836</td></tr>
<tr><td colspan="2">0.229170</td><td colspan="2">0.477169</td></tr>
<tr><td rowspan="2">2000</td><td>0.180961</td><td>0.809091</td><td>0.567083</td><td>0.301141</td></tr>
<tr><td colspan="2">0.146414</td><td colspan="2">0.170772</td></tr>
<tr><td rowspan="2">2001</td><td>0.231408</td><td>0.788232</td><td>0.438682</td><td>0.347983</td></tr>
<tr><td colspan="2">0.182403</td><td colspan="2">0.152654</td></tr>
<tr><td rowspan="2">2002</td><td>0.142290</td><td>0.723447</td><td>0.324552</td><td>0.220419</td></tr>
<tr><td colspan="2">0.102939</td><td colspan="2">0.071537</td></tr>
<tr><td rowspan="2">2003</td><td>0.135536</td><td>0.721345</td><td>0.312303</td><td>0.167205</td></tr>
<tr><td colspan="2">0.097768</td><td colspan="2">0.052219</td></tr>
<tr><td rowspan="2">2004</td><td>0.132284</td><td>0.718361</td><td>0.282816</td><td>0.179004</td></tr>
<tr><td colspan="2">0.095028</td><td colspan="2">0.050625</td></tr>
<tr><td rowspan="2">2005</td><td>0.087383</td><td>0.707929</td><td>0.295416</td><td>0.112564</td></tr>
<tr><td colspan="2">0.061861</td><td colspan="2">0.033253</td></tr>
<tr><td rowspan="2">2006</td><td>0.059831</td><td>0.611677</td><td>0.170946</td><td>0.071600</td></tr>
<tr><td colspan="2">0.036597</td><td colspan="2">0.012240</td></tr>
<tr><td rowspan="2">2007</td><td>0.055904</td><td>0.624407</td><td>0.269906</td><td>0.071773</td></tr>
<tr><td colspan="2">0.034907</td><td colspan="2">0.019372</td></tr>
<tr><td rowspan="2">2008</td><td>0.032420</td><td>0.599117</td><td>0.153756</td><td>0.035745</td></tr>
<tr><td colspan="2">0.019423</td><td colspan="2">0.005496</td></tr>
<tr><td rowspan="2">2009</td><td>0.045843</td><td>0.583005</td><td>0.185048</td><td>0.058051</td></tr>
<tr><td colspan="2">0.026727</td><td colspan="2">0.010742</td></tr>
<tr><td rowspan="2">2010</td><td>0.046970</td><td>0.607196</td><td>0.212002</td><td>0.057652</td></tr>
<tr><td colspan="2">0.028520</td><td colspan="2">0.012222</td></tr>
</table>

Table 7.--Summary of silky shark catches (upper entry) and mean nominal CPUE (middle entry; expressed as sharks/1000 hooks) in the deep-set sector of Hawaii-based longline fishery by regions of fishing and calendar quarters. Numbers of sets (*N*) are in parentheses. Data from 1995–2010 are pooled.

Region 1				Region 2			
Quarter 1	Quarter 2	Quarter 3	Quarter 4	Quarter 1	Quarter 2	Quarter 3	Quarter 4
58 0.748 (35)	144 0.740 (91)	234 1.015 (95)	53 2.011 (18)	775 0.769 (469)	259 0.697 (414)	616 1.189 (293)	667 0.778 (173)
Region 3				**Region 4**			
Quarter 1	Quarter 2	Quarter 3	Quarter 4	Quarter 1	Quarter 2	Quarter 3	Quarter 4
57 0.015 (1796)	139 0.031 (1986)	120 0.045 (1032)	89 0.039 (1852)	132 0.029 (2256)	159 0.024 (3358)	165 0.042 (1367)	117 0.046 (1660)
Region 5				**Region 6**			
Quarter 1	Quarter 2	Quarter 3	Quarter 4	Quarter 1	Quarter 2	Quarter 3	Quarter 4
4 0.001 (2034)	56 0.002 (1779)	6 0.004 (3904)	31 0.005 (5411)	25 0.012 (1022)	17 0.010 (772)	16 0.015 (539)	75 0.017 (2166)
Region 7				**Region 8**			
Quarter 1	Quarter 2	Quarter 3	Quarter 4	Quarter 1	Quarter 2	Quarter 3	Quarter 4
0 0.000 (11)	0 0.000 (40)	0 0.000 (1,101)	0 0.000 (86)	0 0.000 (31)	0 0.856 (61)	0 0.138 (491)	2 0.120 (64)

Table 8.--Summary of GLM fitting in the delta-lognormal analysis for silky shark. The first is the binomial model; the second is the lognormal model. "NA" denotes not applicable.

Parameter	Df	Residual deviance	Deviance reduction	Deviance reduction per df	Percent reduction of null deviance	AIC & ΔAIC	Median residual
Intercept	1	2091.23	NA	NA	NA	2093.2; NA	0.9992
Haul year	10	1957.53	133.70	13.37	6.39%	1979.5; -113.7	0.6362
Hooks per float	1	1941.58	15.95	15.95	0.76%	1965.575; -13.95	0.6590
Distance from land	1	1928.91	12.67	12.67	0.61%	1954.9; -10.675	0.6330

Binomial GLM null deviance = 2091.23. Explanation of null deviance: 7.76%. *N* = 1516.

Parameter	Df	Residual deviance	Deviance reduction	Residual deviance reduction per df	Percent reduction of null deviance	AIC & ΔAIC	Median residual
Intercept	1	498.54	NA	NA	NA	1916.3; NA	-0.0879
Haul year	10	463.73	34.81	3.48	6.98%	1877.3; -39.0	-0.0779
Hooks per float	1	459.28	4.45	4.45	0.89%	1871.5; -5.8	-0.0716

Lognormal GLM null deviance: 498.54. Explanation of null deviance: 7.87%. *N* = 815.

Table 9.--Delta-lognormal analysis of silky shark catch rates in the Hawaii-based longline fishery in 2000–2010 from 0° to 10°N. Haul year (Haulyr) is a factor variable. Hooks per float (Hkpfl) and distance from land (landdist) are continuous variables. Results are presented in R format.

Binomial GLM

Deviance Residuals:	Min	1Q	Median	3Q	Max
	-2.255	-1.190	0.633	1.059	2.277

Coefficients	Estimate	Std. Error	z value	Pr (> |z|)
(Intercept)	-4.690204	0.635759	-7.377	1.61e-13 ***
Haulyr 2001	0.071424	0.249967	0.286	0.775082
Haulyr 2002	-0.119373	0.237966	-0.502	0.615922
Haulyr 2003	1.922167	0.781455	2.460	0.013904 *
Haulyr 2004	-1.235792	0.284049	-4.351	1.36e-05 ***
Haulyr 2005	-2.879084	1.059245	-2.718	0.006567 **
Haulyr 2006	1.053625	0.324475	3.247	0.001166 **
Haulyr 2007	-0.930023	0.269616	-3.449	0.000562 ***
Haulyr 2008	0.884515	0.686926	1.288	0.197870
Haulyr 2009	0.267949	0.312965	0.856	0.391906
Haulyr 2010	0.137981	0.375177	0.368	0.713040
Hkpfl	-0.089360	0.020880	-4.280	1.87e-05 ***
landdist	-0.001459	0.000419	-3.482	0.000498 ***

(Dispersion parameter for binomial family taken to be 1)

Null deviance: 2091.2; df = 1515. Residual deviance: 1928.9; df = 1503. AIC = 1954.913

*** = .001 ** = .01 * = .05

Lognormal GLM

Deviance Residuals:	Min	1Q	Median	3Q	Max
	-1.50022	-0.64466	-0.07162	0.49462	2.97457

Coefficients:	Estimate	Std. Error	t value	Pr(> |t|)
(Intercept)	1.238375	0.30409	4.072	5.12e-05***
Haulyr 2001	-0.26132	0.12452	-2.099	0.03617 *
Haulyr 2002	-0.42623	0.11906	-3.580	0.000364***
Haulyr 2003	-0.18680	0.21147	-0.883	0.377338
Haulyr 2004	-0.57933	0.15753	-3.678	0.000251 ***
Haulyr 2005	-1.18606	0.76413	-1.552	0.121015
Haulyr 2006	-0.08446	0.13581	-0.622	0.534192
Haulyr 2007	-0.70322	0.14543	-4.835	1.59e-06 ***
Haulyr 2008	0.02023	0.25289	0.080	0.936264
Haulyr 2009	-0.59251	0.14317	-4.139	3.86e-05 ***
Haulyr 2010	-0.59079	0.17605	-3.356	0.000828 ***
Hkpfl	-0.02789	0.01000	-2.788	0.005430 ***

Dispersion parameter for gaussian family taken to be 0.5719602)

Null deviance: 498.54; df = 814. Residual deviance: 459.28; df = 803. AIC = 1871.5.

*** = .001 ** = .01 * = .05

Table 10.--Quasi-Poisson analysis of silky shark catches in the Hawaii-based longline fishery in 2000–2010. Haul year (Haulyr) is a factor variable. Hooks per float (Hkpfl) and distance from land (landdist) are continuous variables. Results are presented in R format.

Deviance residuals:

	Min	1Q	Median	3Q	Max
	-3.4972	-1.6801	-0.9018	0.3380	13.7841

	Estimate	Std. Error	*t* value	Pr (> |t|)
(Intercept)	-4.8636293	0.4774159	-10.187	< 2e-16***
Haulyr 2001	-0.3015074	0.1790290	-1.684	0.092365 .
Haulyr 2002	-0.4728851	0.1698159	-2.785	0.005425 **
Haulyr 2003	0.3784950	0.3041050	1.245	0.213466
Haulyr 2004	-1.0397346	0.2348906	-4.426	1.03e-05 ***
Haulyr 2005	-3.6105250	2.1762809	-1.659	0.097317 .
Haulyr 2006	0.2675259	0.1877646	1.425	0.154424
Haulyr 2007	-1.2680028	0.2408188	-5.265	1.60e-07 ***
Haulyr 2008	0.2049863	0.3417235	0.600	0.548700
Haulyr 2009	-0.2551783	0.2195152	-1.162	0.245232
Haulyr 2010	-0.6620863	0.2960456	-2.236	0.025470 *
Hkpfl	-0.0605188	0.0157957	-3.831	0.000133 ***
landdist	-0.0013956	0.0003966	-3.519	0.0004466 ***

(Dispersion parameter for quasi-Poisson family taken to be 4.981414)

Null deviance: 5437.4 on 1515 degrees of freedom

Residual deviance: 4835.0 on 1503 degrees of freedom

Number of Fisher Scoring iterations: 6

*** = .001 ** = .01 * = .05

Table 11.--Back-transformed coefficients of the annual effects from the delta-lognormal and quasi-Poisson analyses of silky shark catch rates. The back-transformed coefficients from the two models in the delta-lognormal analysis are the upper entries; the index values are the lower, centered, bold-face entries. The quasi-Poisson entries in bold-face are the index values. The reference year was 2000.

	Delta-lognormal analysis			Quasi-Poisson analysis
Haul year	Binomial model: Back-transformed coefficient	Lognormal model: Back-transformed coefficient		Quasi-Poisson model: Back-transformed coefficient
2001	0.581081	1.021018	**0.593294**	**0.739702**
2002	0.542443	0.865785	**0.469639**	**0.623202**
2003	0.90000	1.100011	**0.990010**	**1.460086**
2004	0.302632	0.742887	**0.224821**	**0.353549**
2005	0.071429	0.404970	**0.028927**	**0.027038**
2006	0.800000	1.218543	**0.974914**	**1.306727**
2007	0.354286	0.656319	**0.232525**	**0.281393**
2008	0.785714	1.353027	**1.063092**	**1.227508**
2009	0.646018	0.733156	**0.473632**	0.**774778**
2010	0.625000	0.734417	**0.459011**	**0.515774**

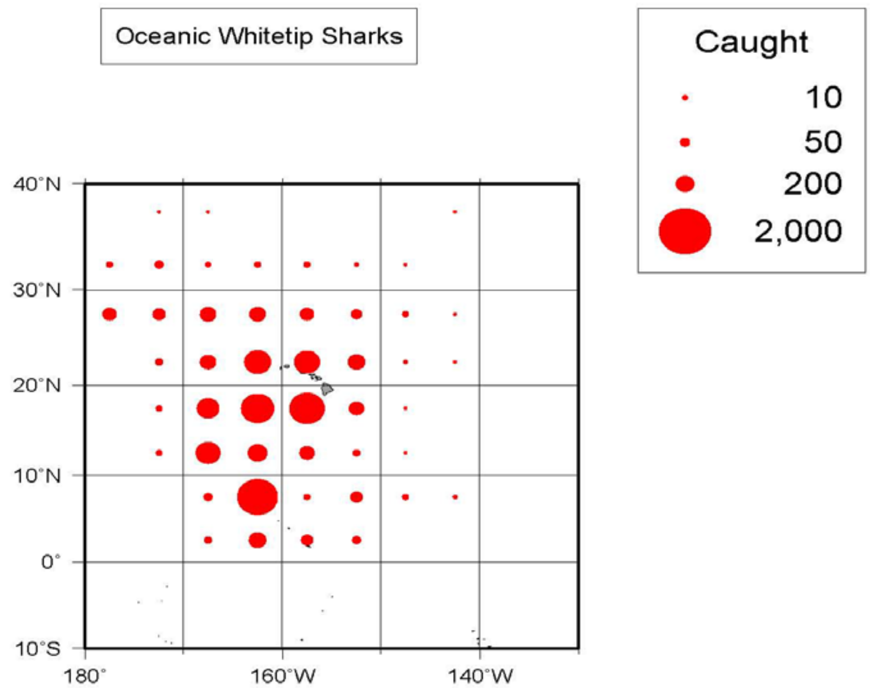


Figure 1.--Oceanic whitetip shark catches in the Hawaii-based pelagic longline fishery in 1995–2010. Data are nonconfidential and the catches from the two fishery sectors are pooled.

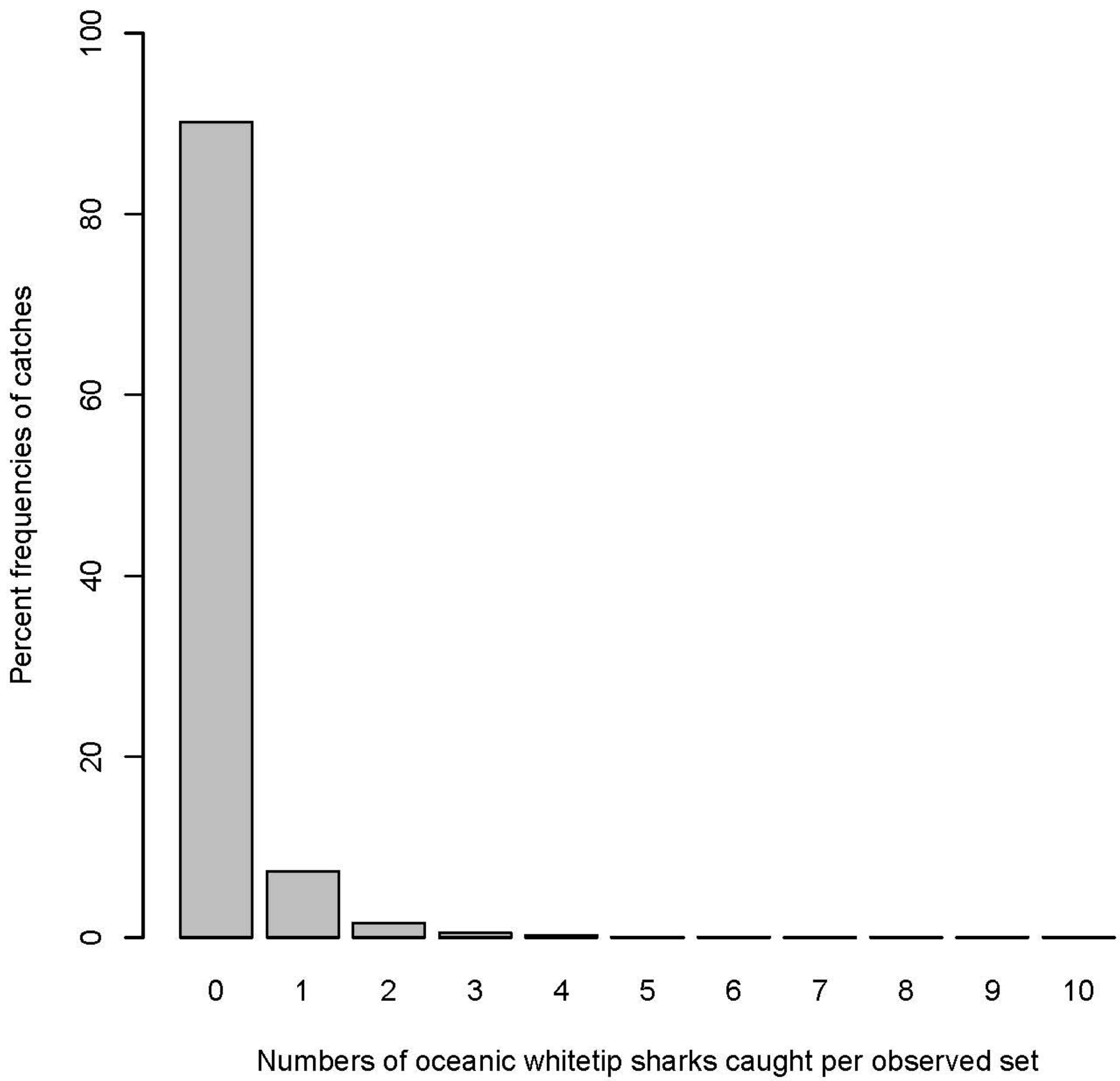


Figure 2.--Percent frequency plot of oceanic whitetip shark catches in the Hawaii-based pelagic longline fishery in 1995–2010. The rightmost bar represents catches ≥ 10 (5 sets).

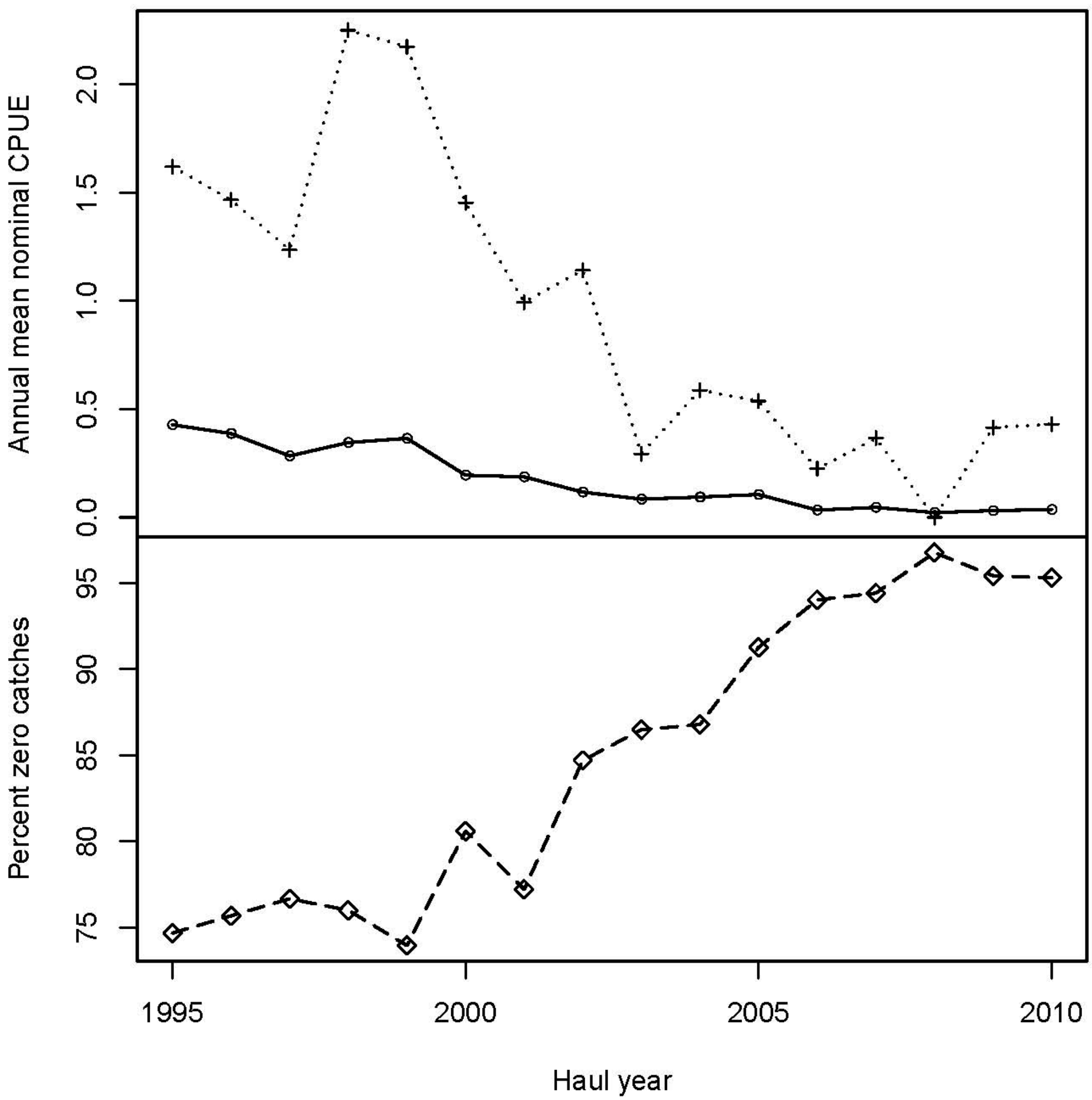


Figure 3.--Oceanic whitetip shark nominal CPUE and percentages of sets with zero catches in the Hawaii-based pelagic longline fishery in 1995–2010. The upper panel presents the annual mean nominal CPUE (solid line) and the mean annual nominal CPUE on sets with positive catch (dotted line). The lower panel presents annual percentages of zero oceanic whitetip shark catches.

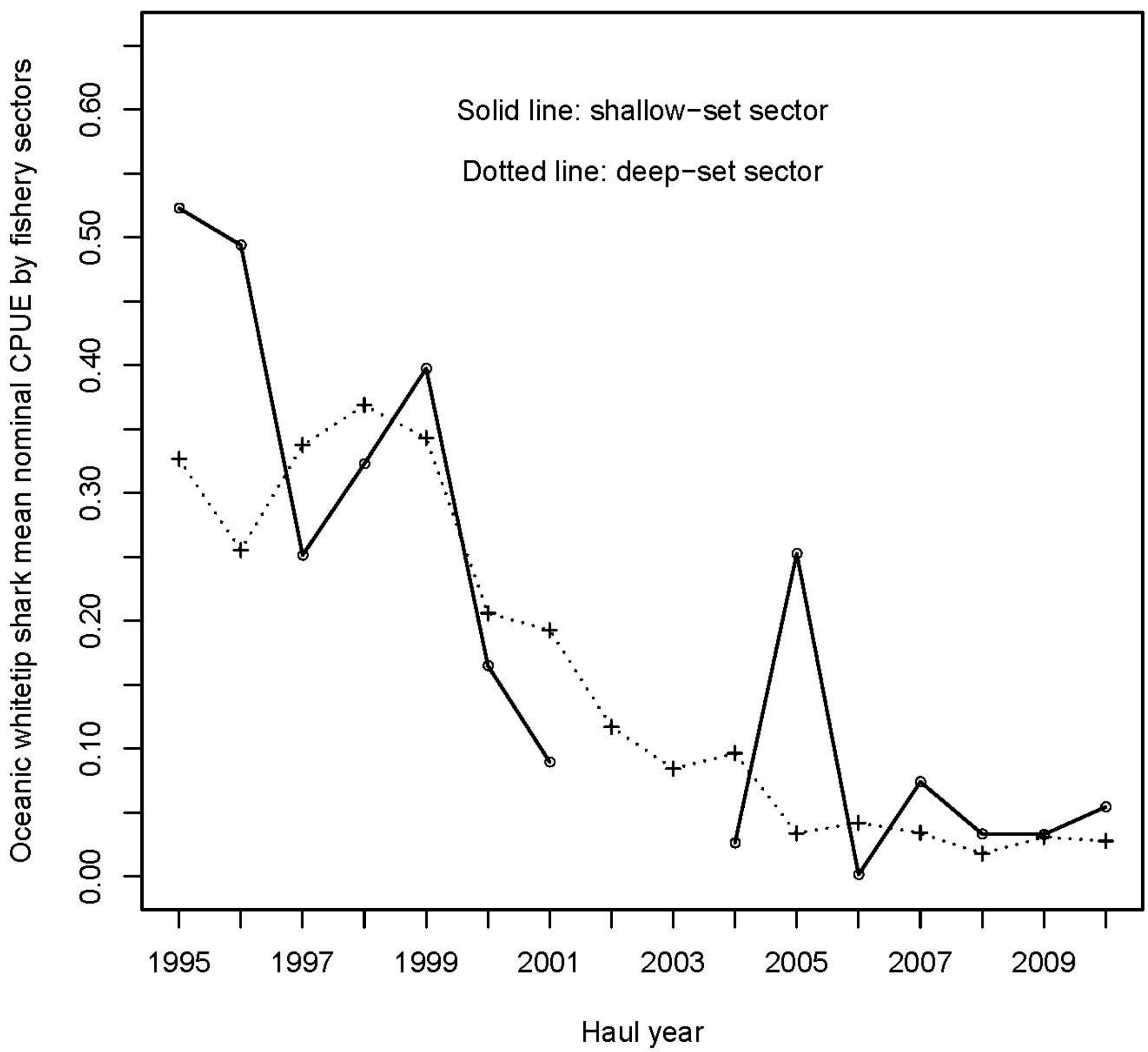


Figure 4.--Oceanic whitetip shark CPUE by fishery sectors in the Hawaii-based pelagic longline fishery in 1995–2010. Missing data for 2002–2003 reflect a closure of the shallow set sector.

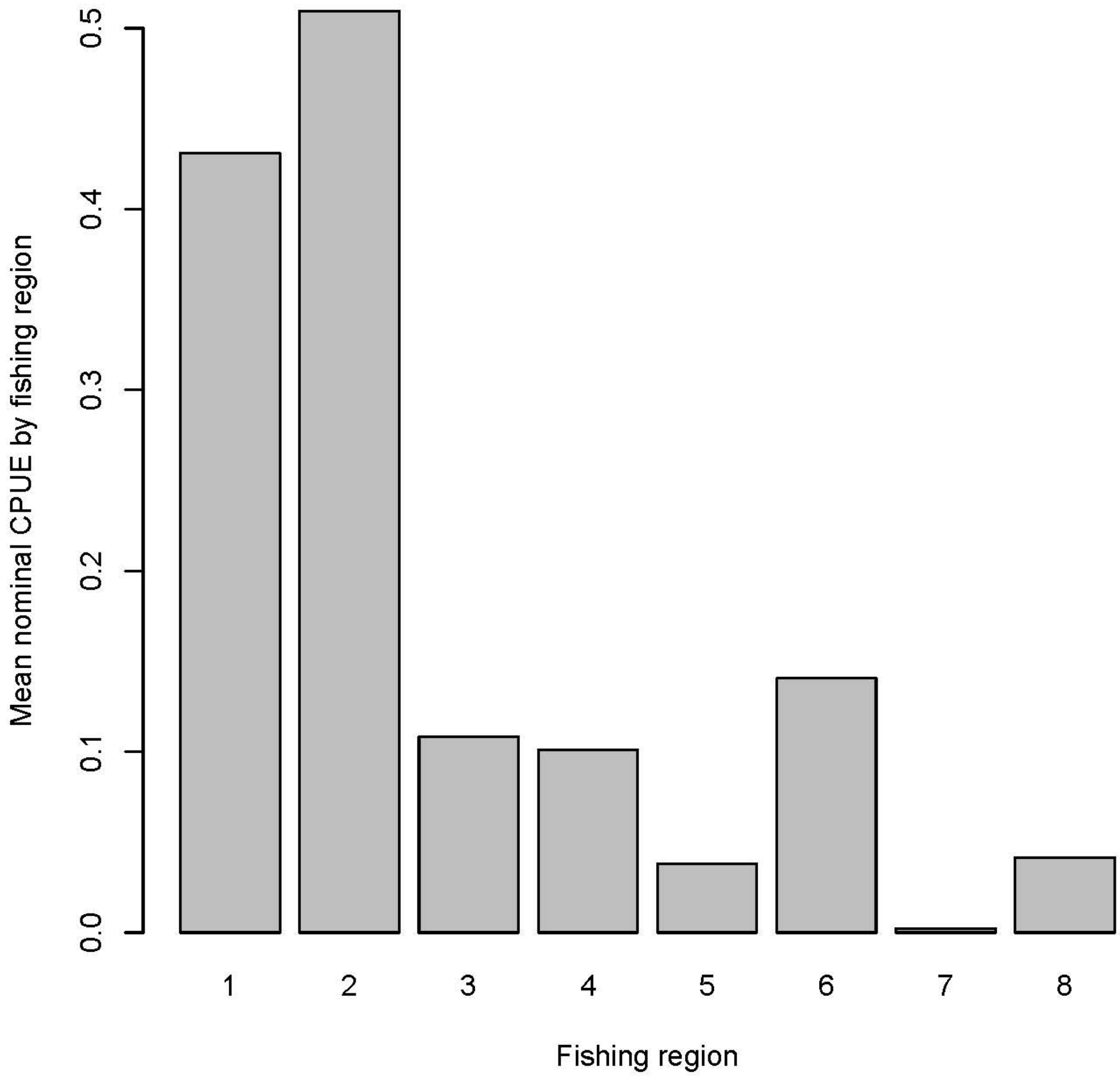


Figure 5.--Oceanic whitetip shark CPUE by regions in the Hawaii-based pelagic longline fishery in 1995–2010.

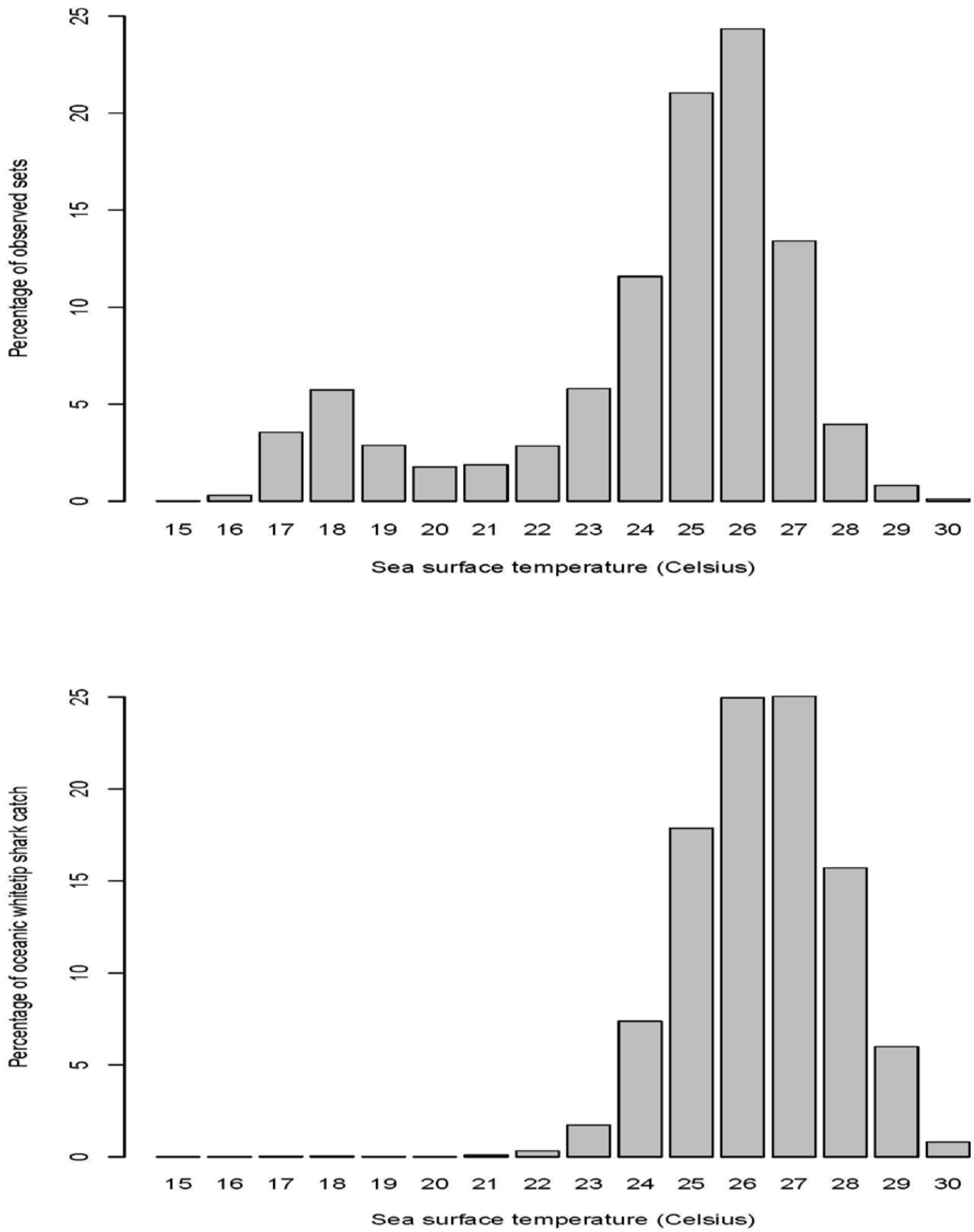


Figure 6.--Oceanic whitetip shark catches and SST in the Hawaii-based pelagic longline fishery in 1995–2010. The upper panel presents the percent frequency distribution for SST from all sets; the lower panel presents percentages of the oceanic whitetip shark catch relative to SST.

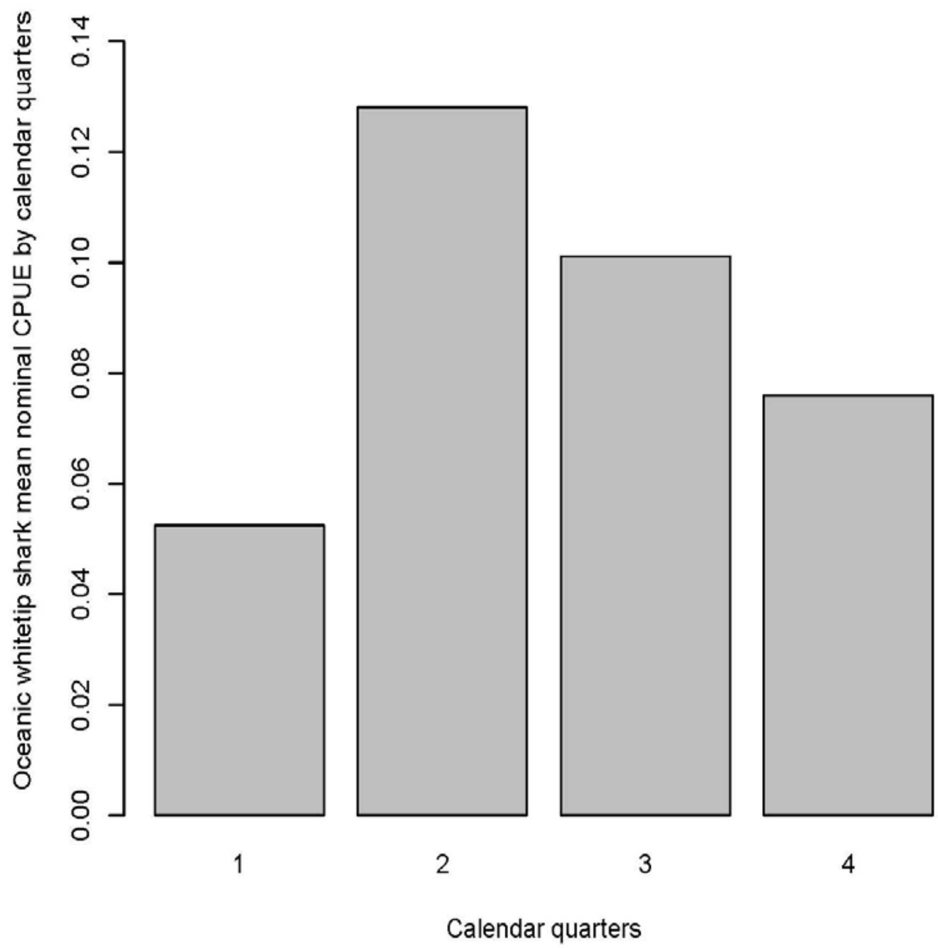


Figure 7.--Oceanic whitetip shark CPUE by calendar quarters in the Hawaii-based pelagic longline fishery in 1995–2010.

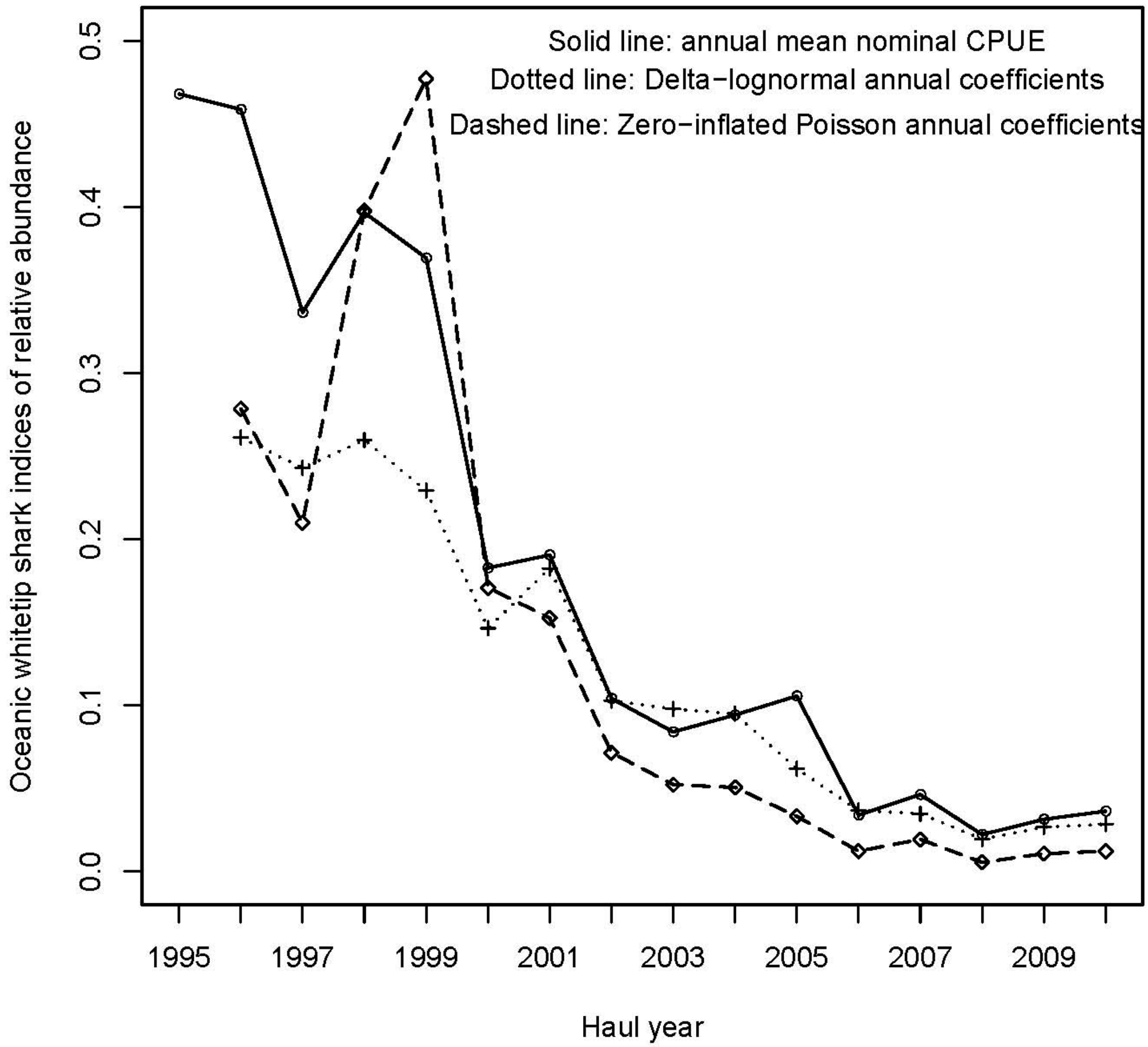


Figure 8.--Annual indices of relative abundance from the delta lognormal and zero-inflated Poisson analyses of oceanic whitetip shark CPUE in the Hawaii-based pelagic longline fishery in 1995–2010. The nominal CPUE trend is included for comparison.

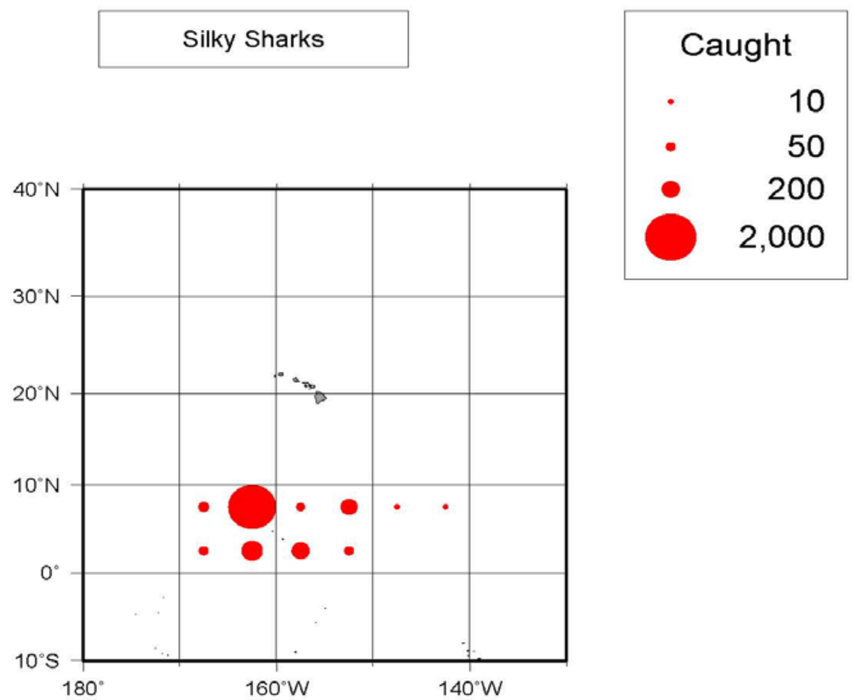


Figure 9.--Silky shark catches in the deep-set sector Hawaii-based pelagic longline fishery in 2000–2010. Data are nonconfidential. The plotted catches were used in the GLM analyses. Silky sharks caught above 10°N or on shallow sets are not shown.

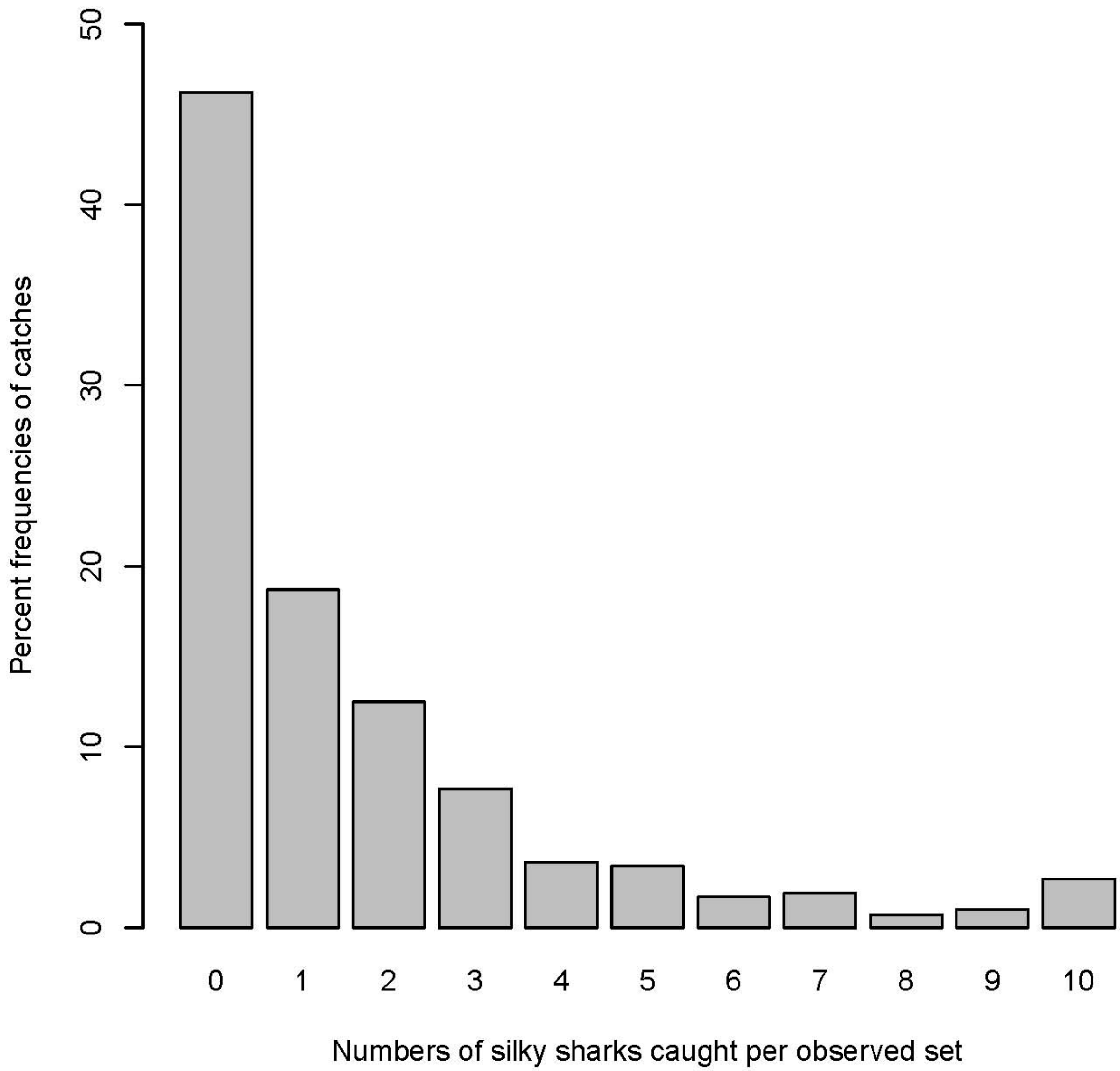


Figure 10.--Percent frequency plot of silky shark catches in the Hawaii-based pelagic longline fishery in 2000–2010 between 0–10°N. The rightmost bar represents catches ≥10 (41 sets).

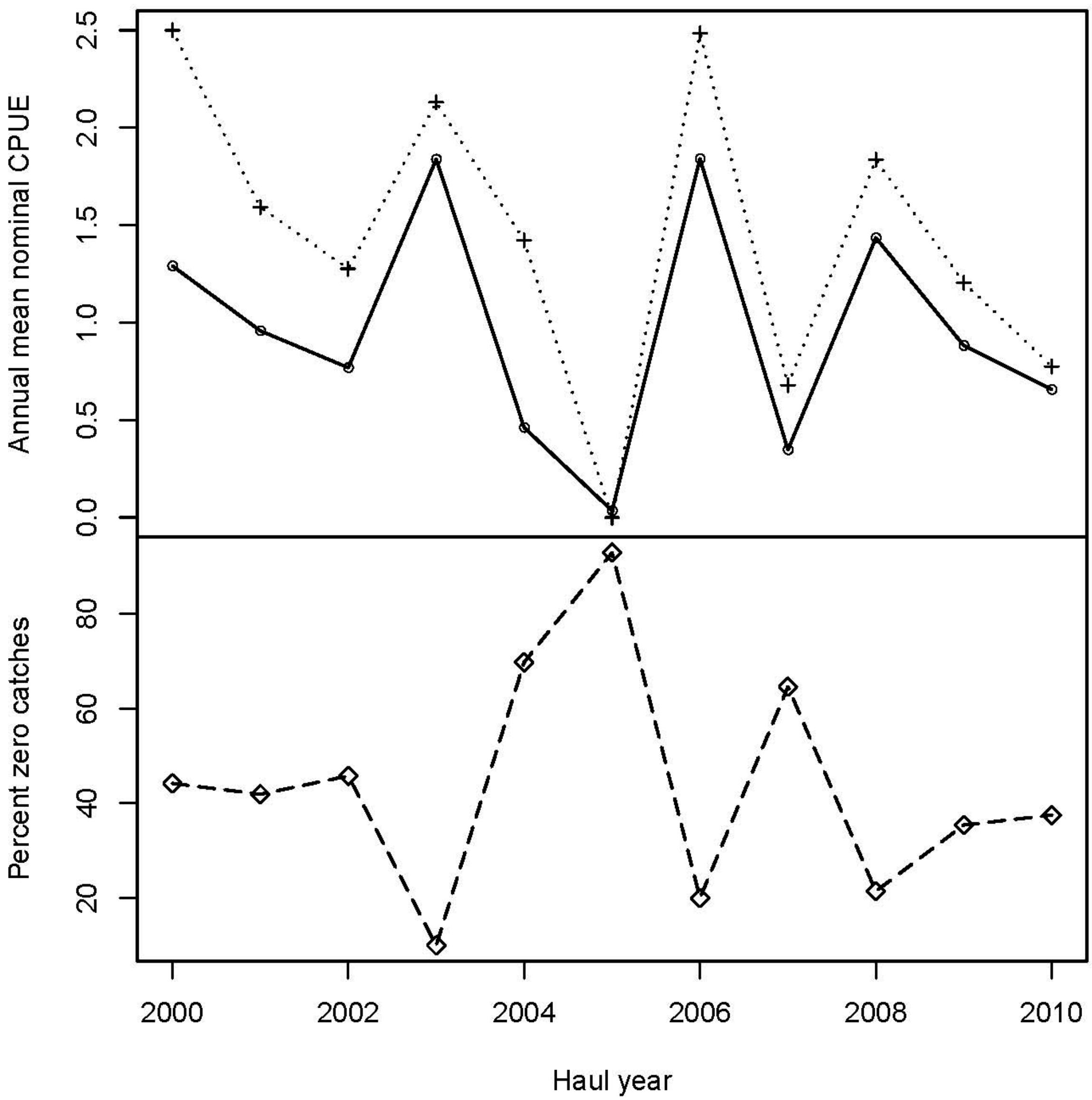


Figure 11.--Silky shark nominal CPUE and percentages of sets with zero catches in the Hawaii-based pelagic longline fishery in 2000–2010. The upper panel presents the annual mean nominal CPUE (solid line) and the mean annual nominal CPUE on sets with positive catch (dotted line). The lower panel presents annual percentages of zero oceanic whitetip shark catches.

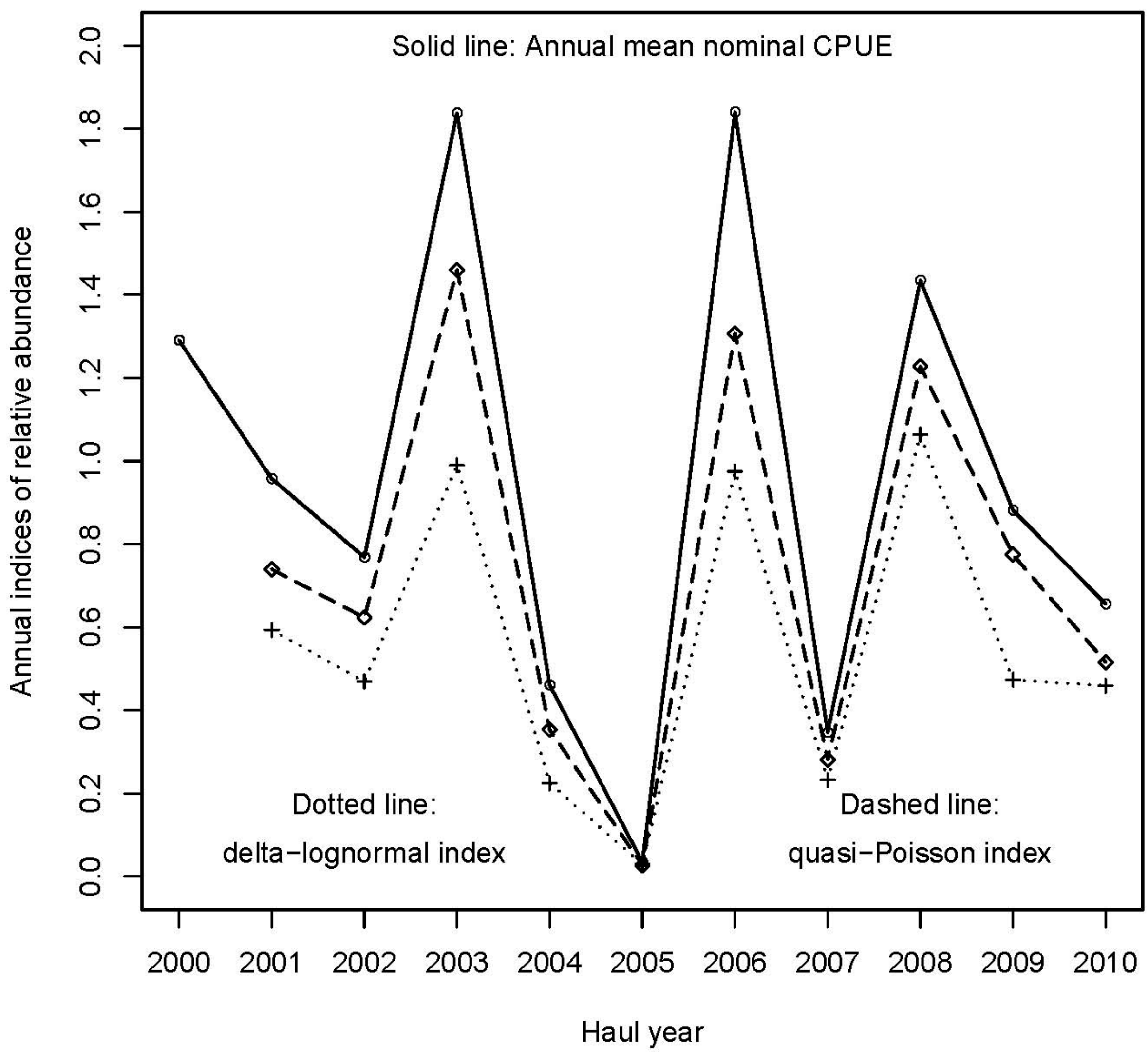
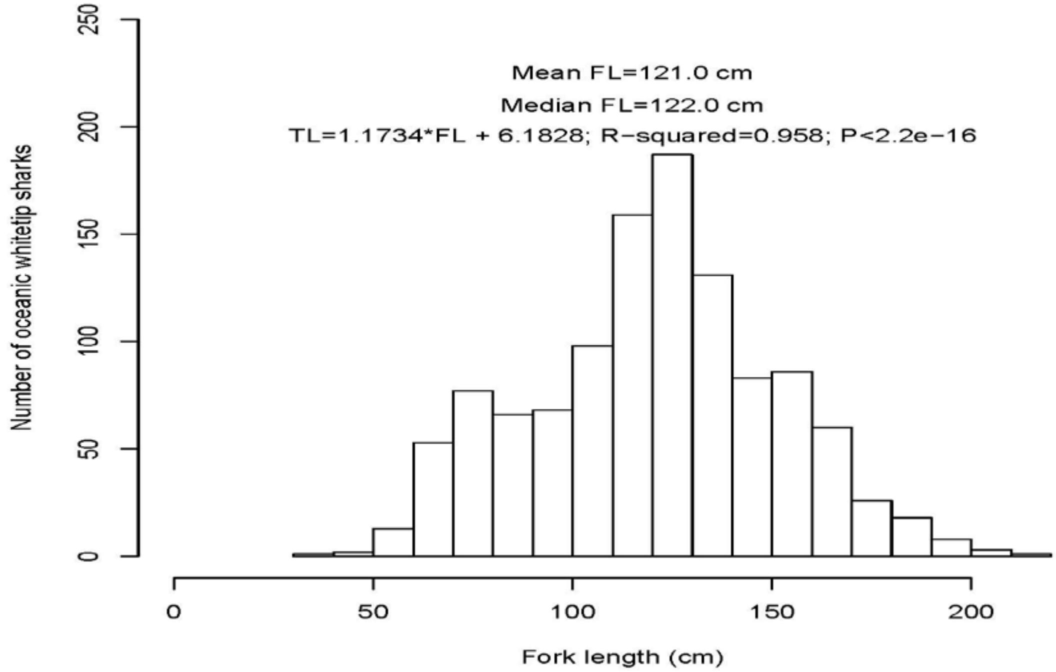


Figure 12.--Annual indices of relative abundance from the delta lognormal and quasi-Poisson analyses of silky shark CPUE in the Hawaii-based pelagic longline fishery in 1995–2010. The nominal CPUE trend is included for comparison.



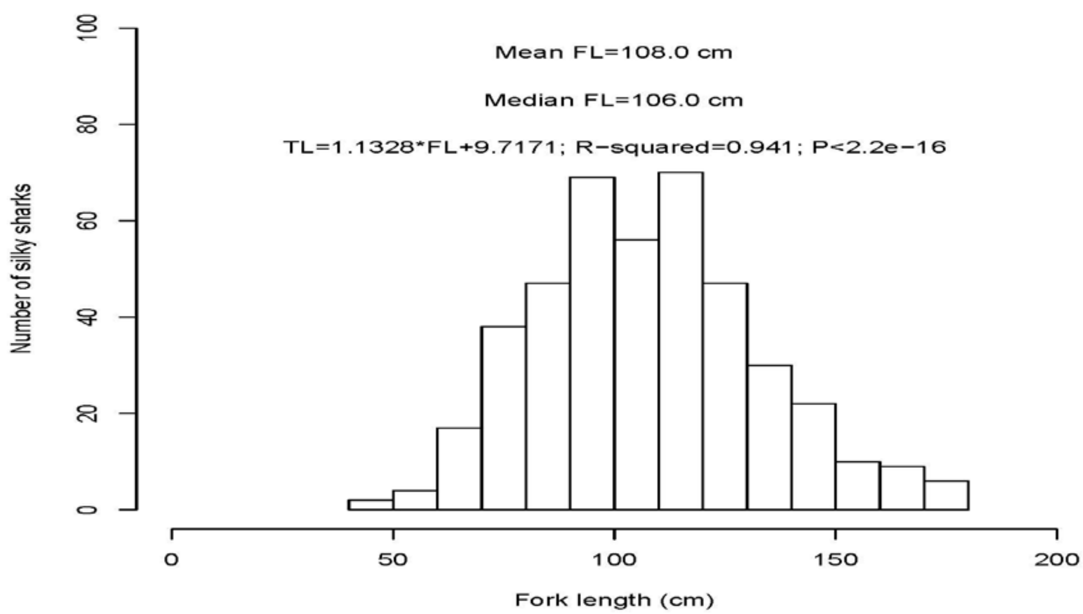


Figure 13.--Fork lengths of oceanic whitetip sharks (upper panel) and silky sharks (lower panel) from the Hawaii-based pelagic longline fishery in 1995–2010. The mean FL, median FL and linear regression to convert FL to TL is included for each species.

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APPENDIX A

Residuals from Oceanic Whitetip Shark

GLM Analyses

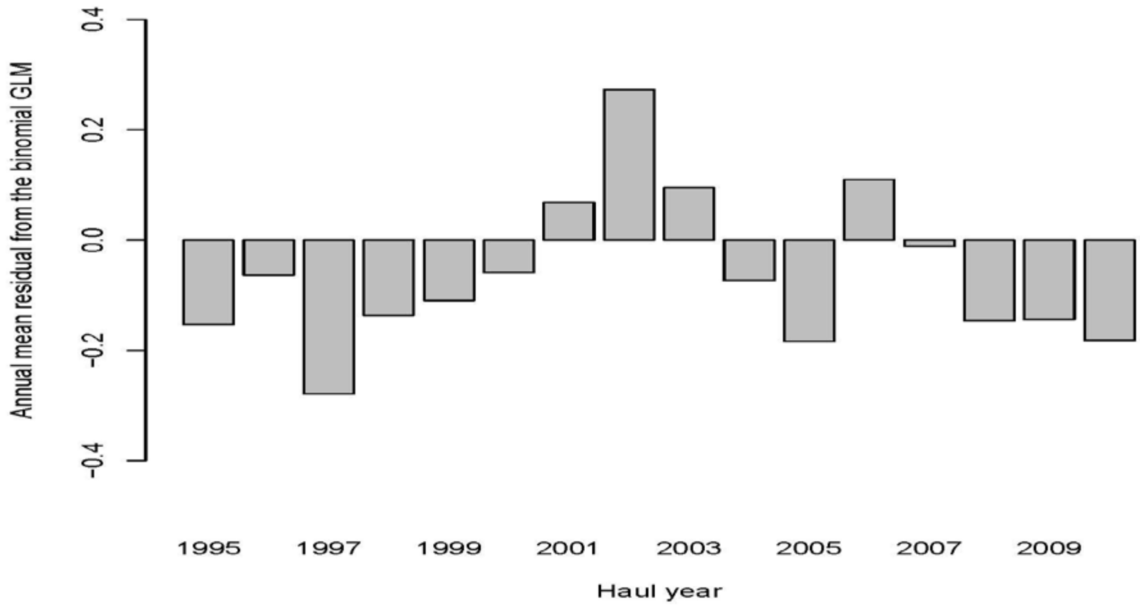

Figure A1.--Annual mean residuals from the oceanic whitetip shark binomial GLM in the delta-lognormal analysis.

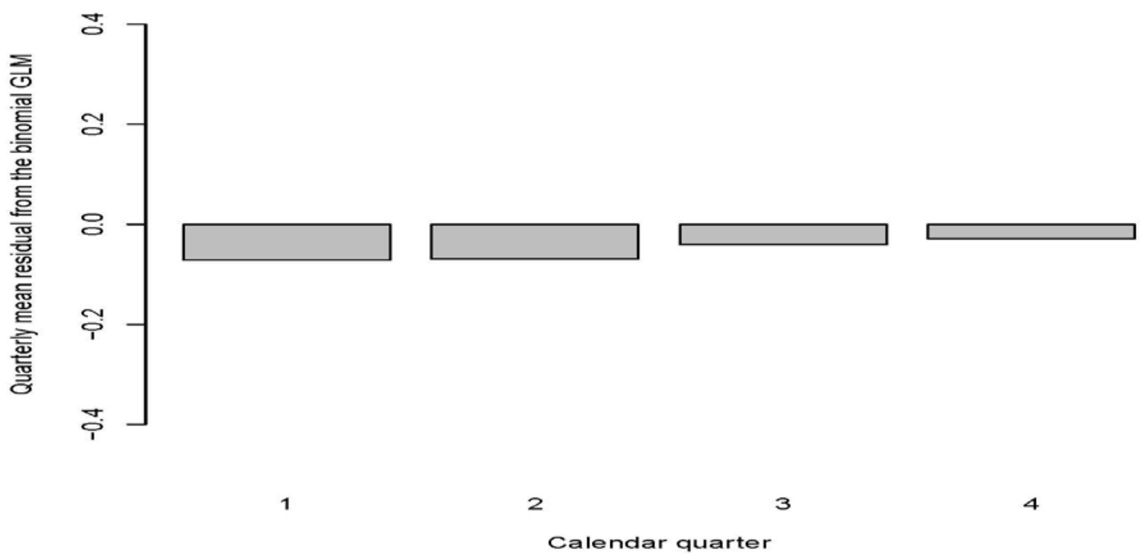

Figure A2.--Quarterly mean residuals from the oceanic whitetip shark binomial GLM in the delta-lognormal analysis.

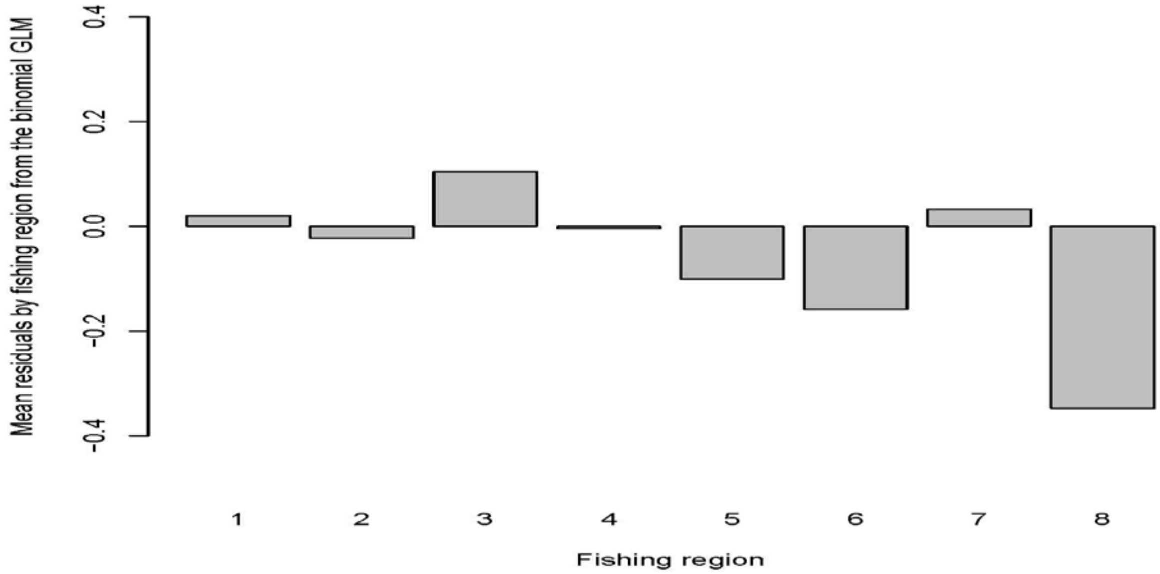

Figure A3. Mean residuals by fishing regions from the oceanic whitetip shark binomial GLM in the delta-lognormal analysis.

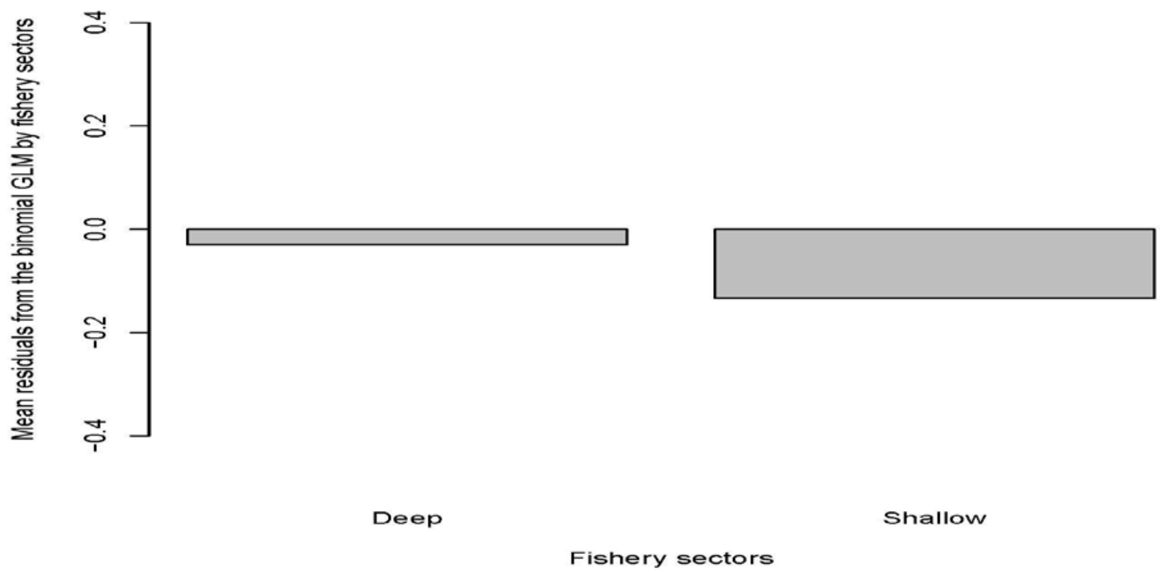

Figure A4. Mean residuals by fishery sector (i.e., set types) from the oceanic whitetip shark binomial GLM in the delta-lognormal analysis.

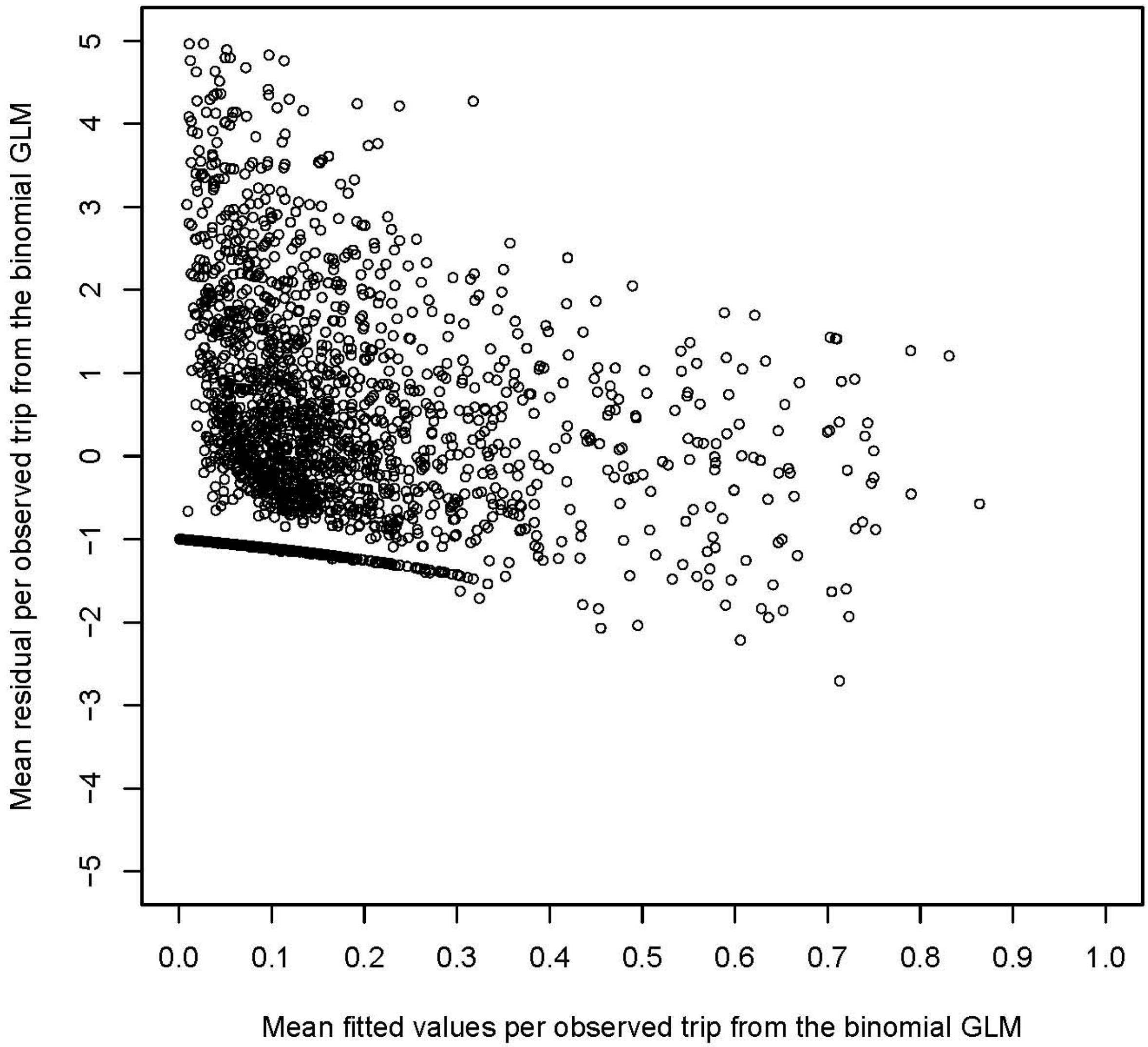

Figure A5.--Mean residuals from the oceanic whitetip shark binomial GLM in relation to the fitted values. Plotted values are means per observed trip. A total of 67 trips (1.9%) were deleted from the plot as positive outliers.

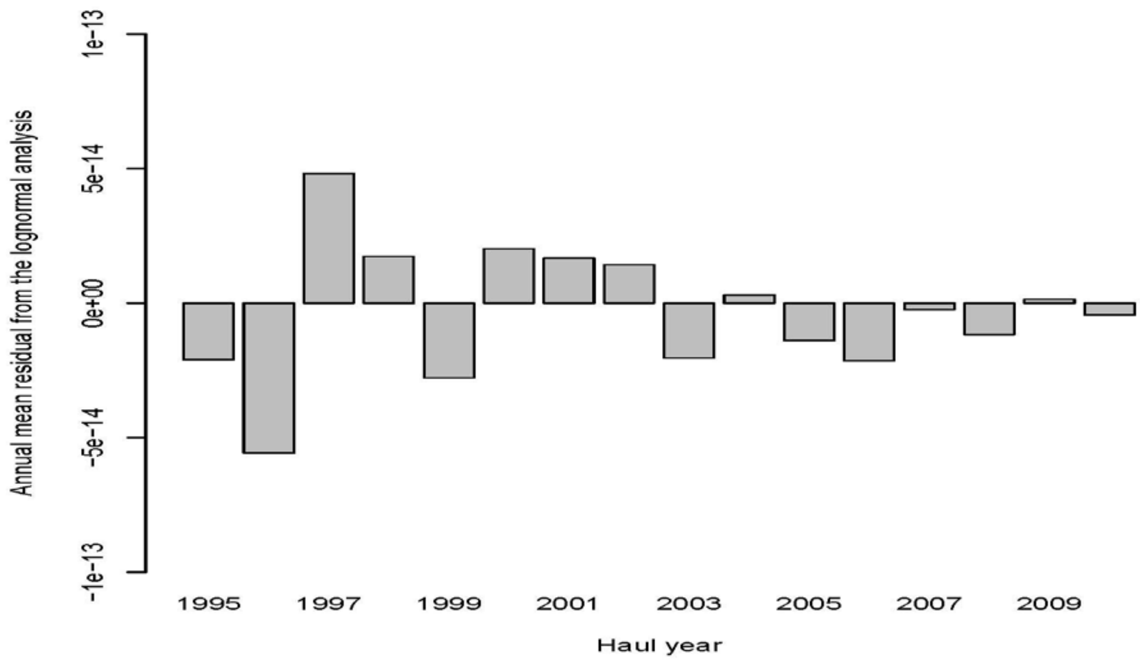

Figure A6.--Annual mean residuals from the oceanic whitetip shark lognormal GLM in the delta-lognormal analysis.

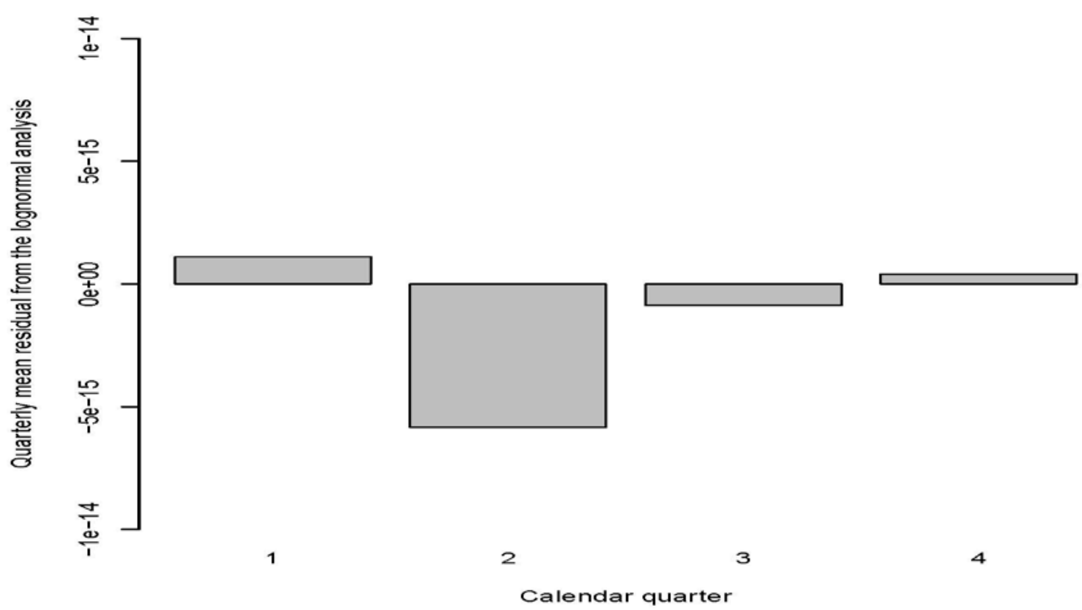

Figure A7.--Quarterly mean residuals from the oceanic whitetip shark lognormal GLM in the delta-lognormal analysis.

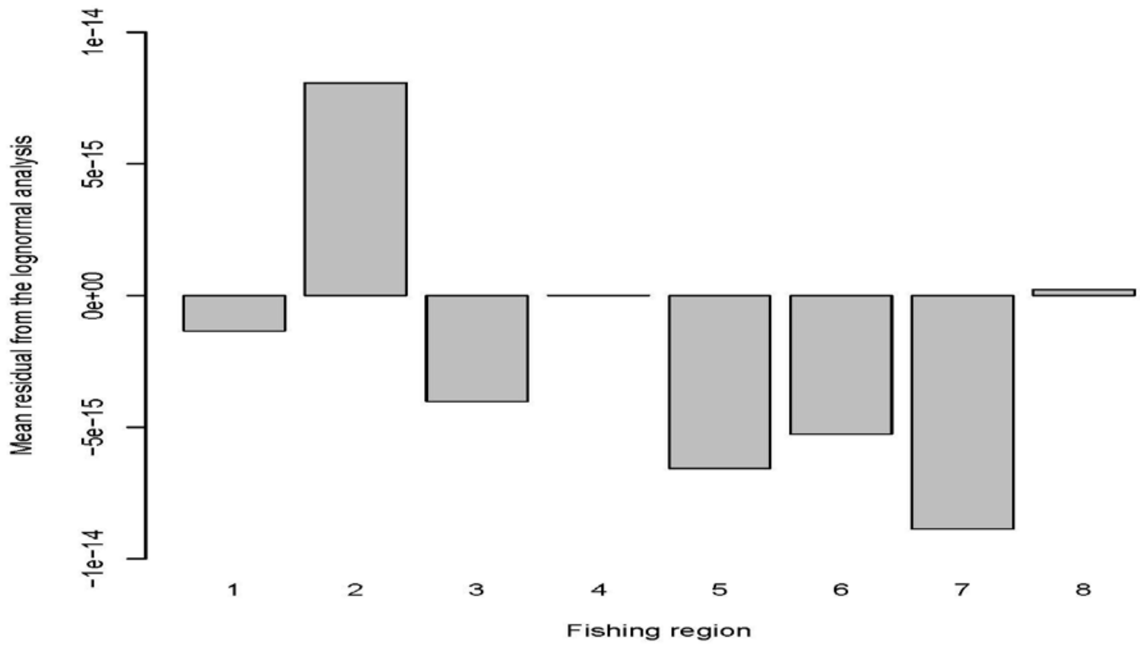

Figure A8.--Mean residuals by fishing regions from the oceanic whitetip shark lognormal GLM in the delta-lognormal analysis.

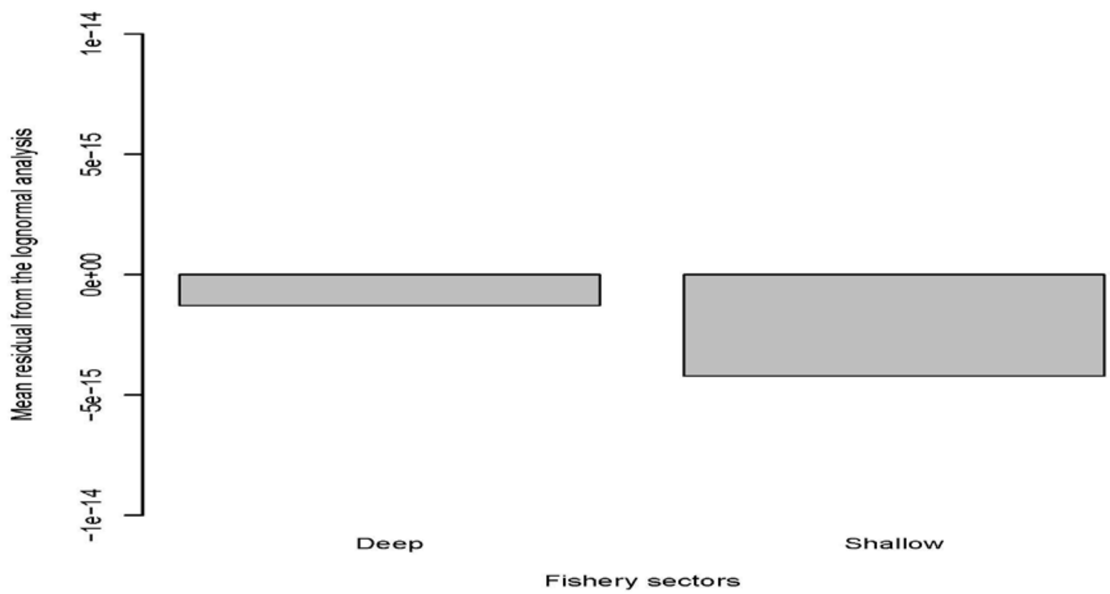

Figure A9.--Mean residuals by fishery sector (i.e., set types) from the oceanic whitetip shark lognormal GLM in the delta-lognormal analysis.

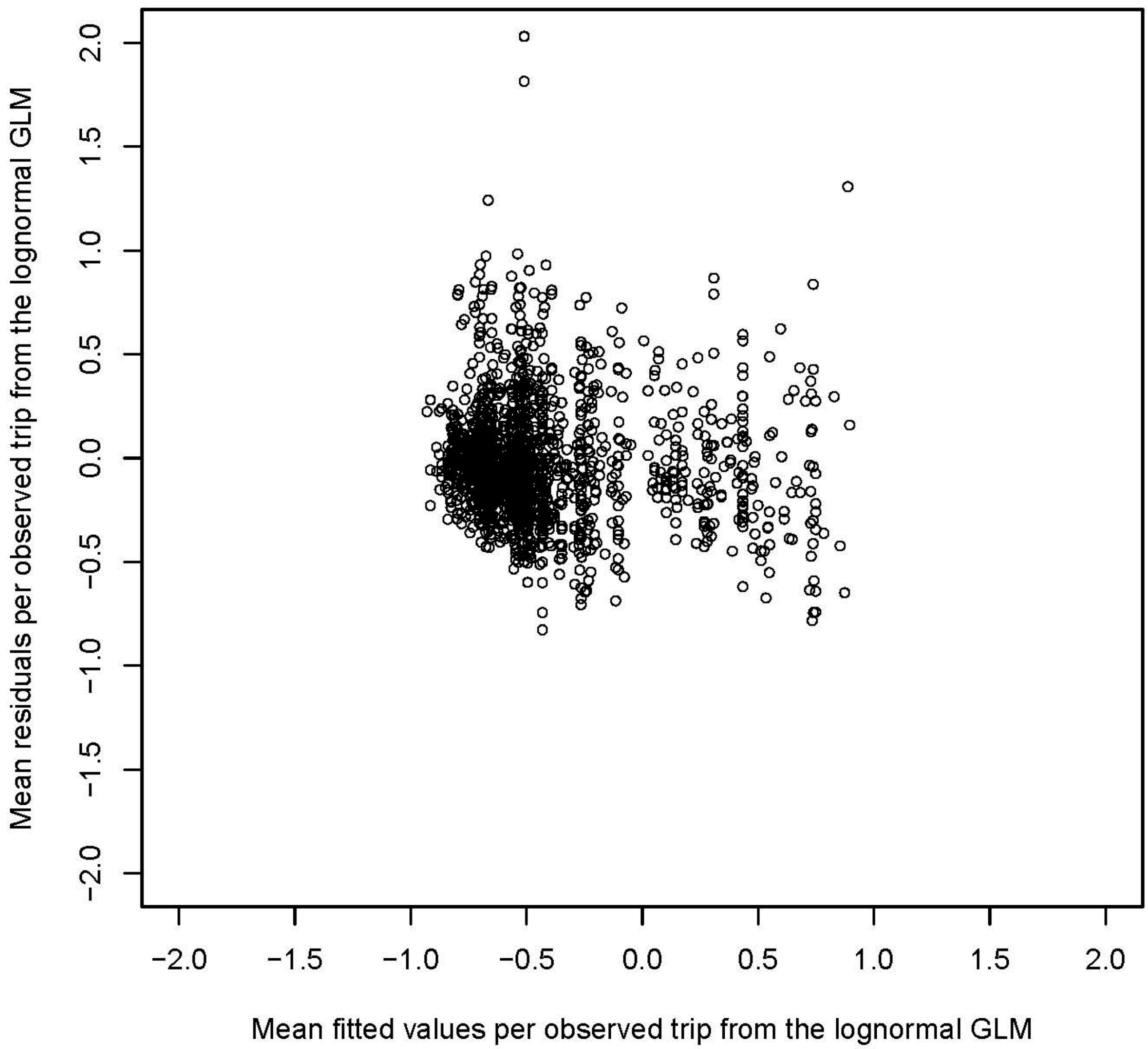

Figure A10.--Mean residuals from the oceanic whitetip shark lognormal GLM in relation to the fitted values. Plotted values are means per observed trip.

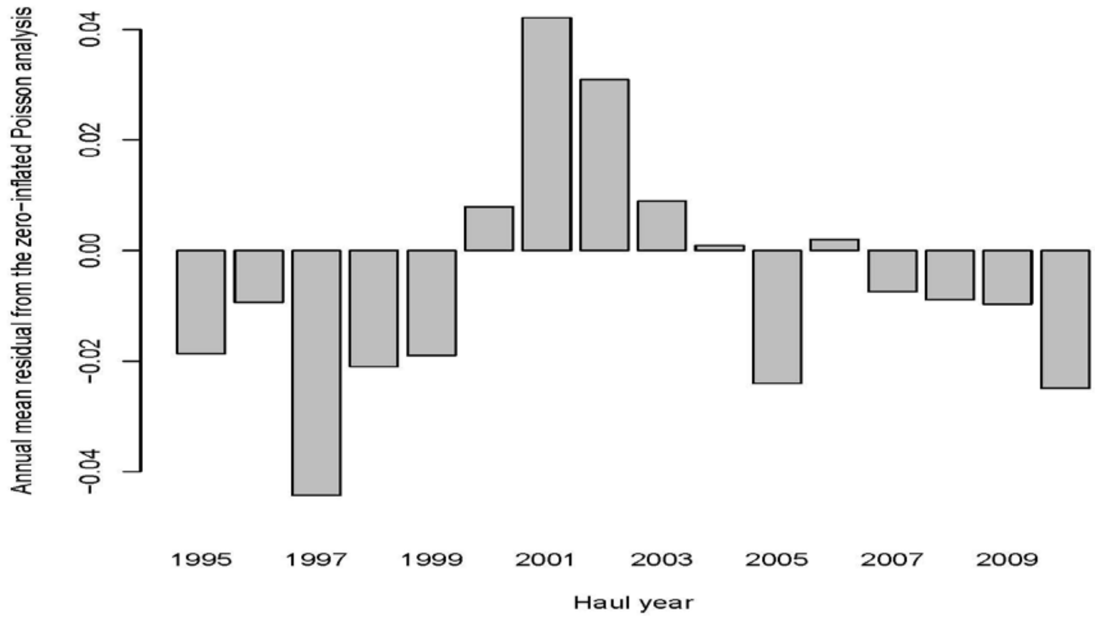

Figure A11.--Annual mean residuals from the oceanic whitetip shark zero-inflated Poisson analysis.

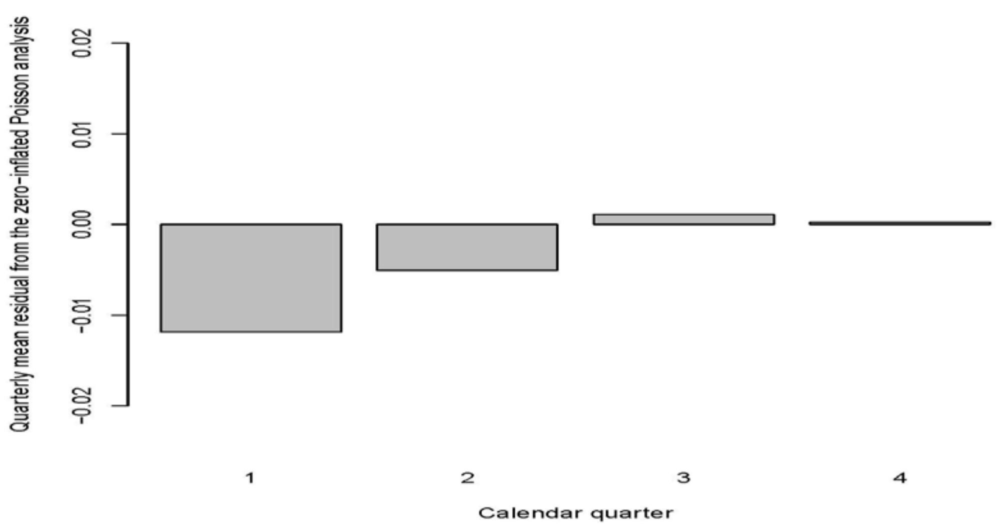

Figure A12.--Quarterly mean residuals from the oceanic whitetip shark zero-inflated Poisson analysis.

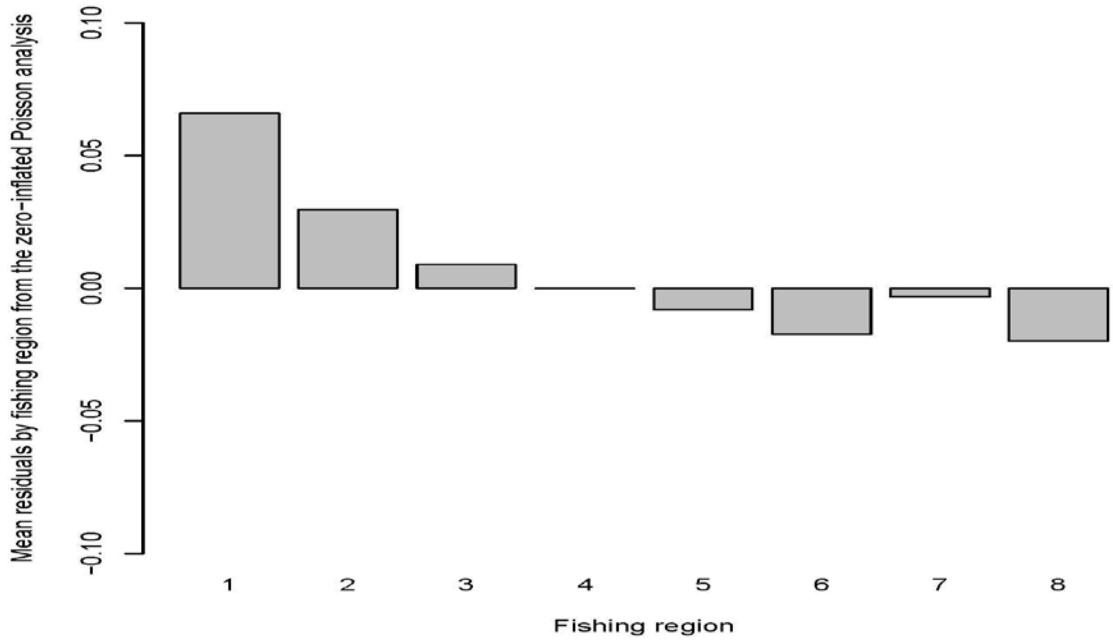

Figure A13.--Mean residuals by fishing regions from the oceanic whitetip shark zero-inflated Poisson analysis.

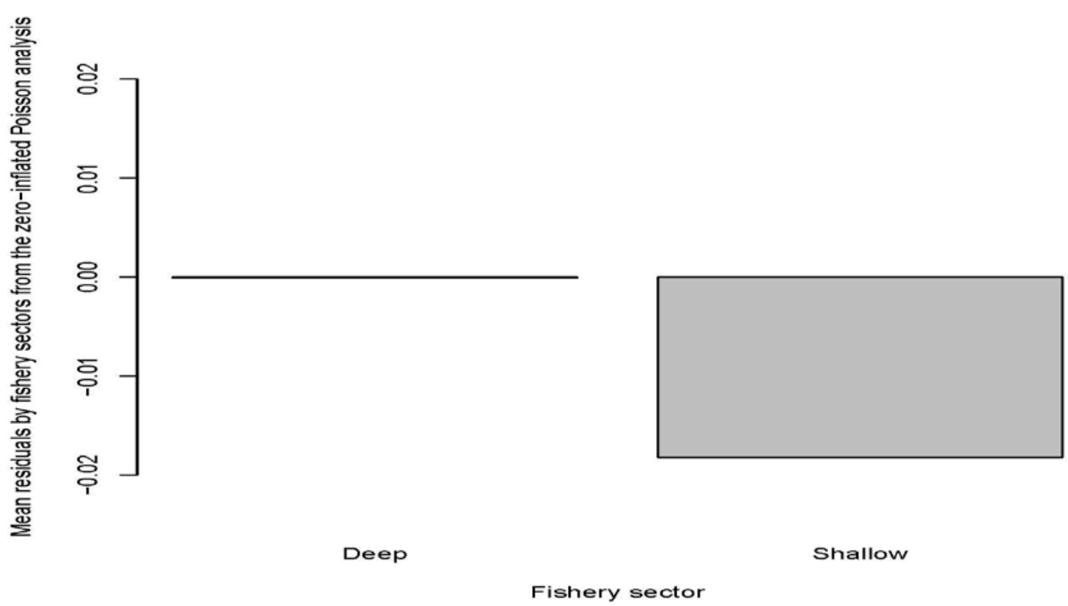

Figure A14.--Mean residuals by fishery sector (i.e., set types) from the oceanic whitetip shark zero-inflated Poisson analysis.

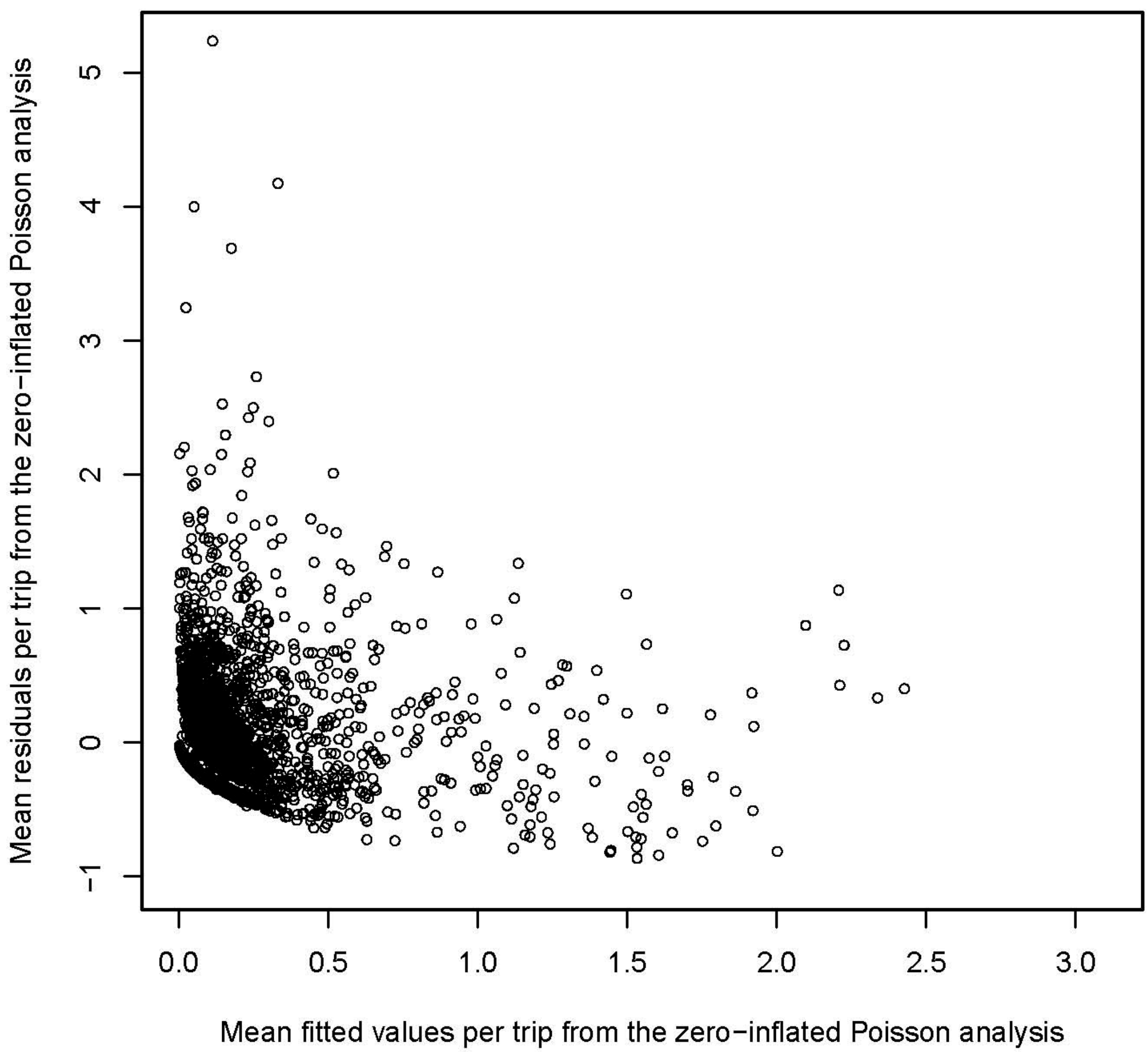

Figure A15.--Mean residuals from the oceanic whitetip shark zero-inflated Poisson analysis in relation to the fitted values. Plotted values are means per observed trip.

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APPENDIX B

Residuals from Silky Shark GLM Analyses

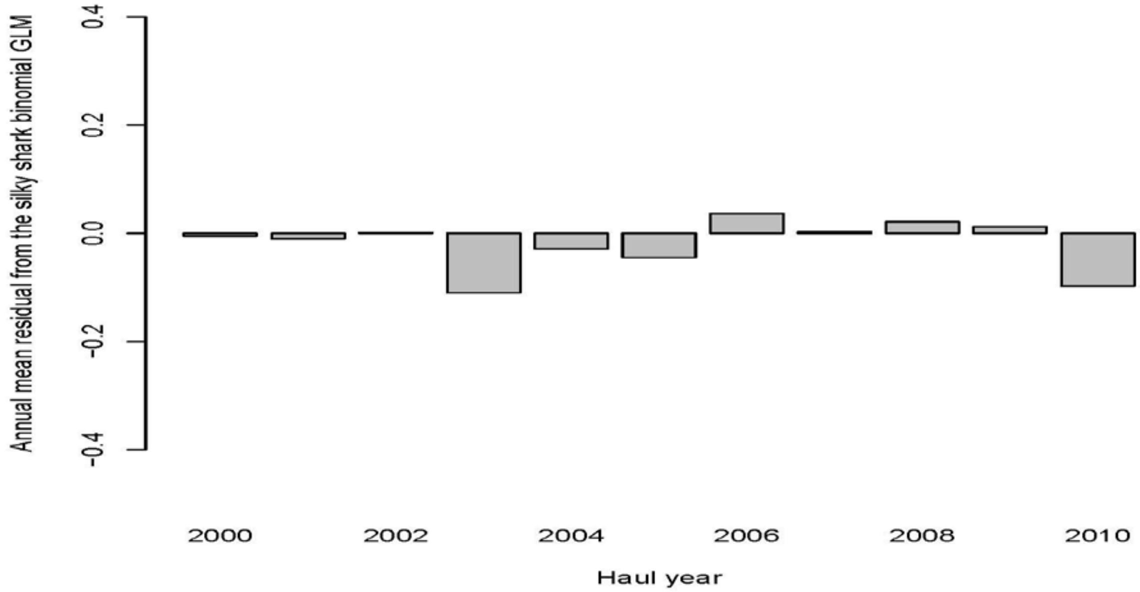

Figure B1.--Annual mean residuals from the silky shark binomial GLM in the delta-lognormal analysis.

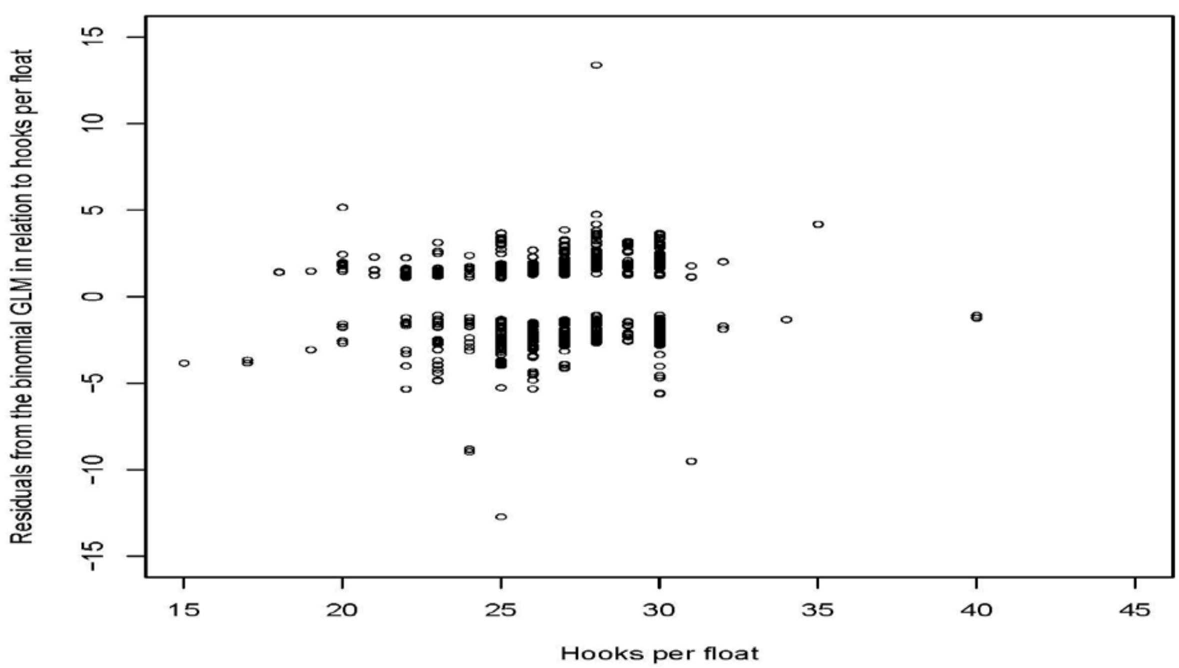

Figure B2.--Residuals from the silky shark binomial GLM in relation to hooks per float.

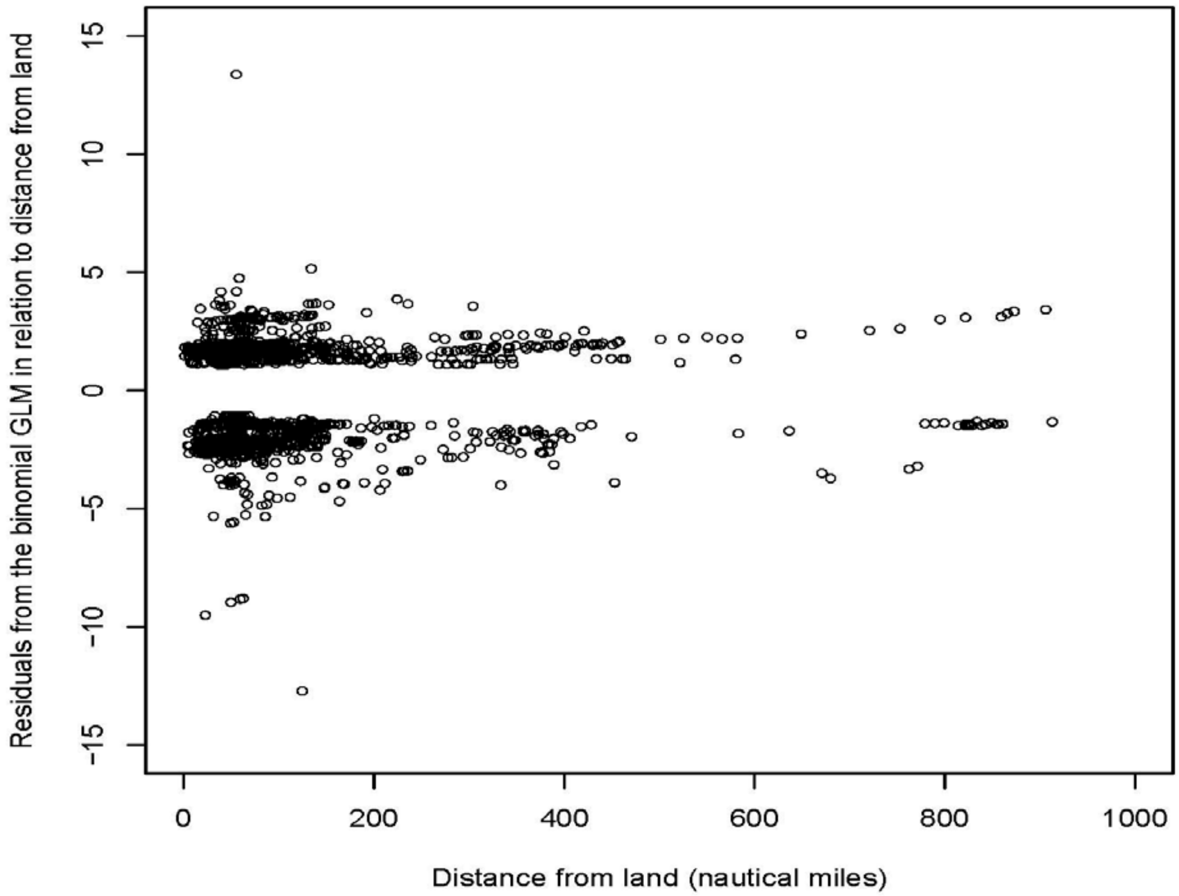

Figure B3.--Residuals from the silky shark binomial GLM in relation to distance from land.

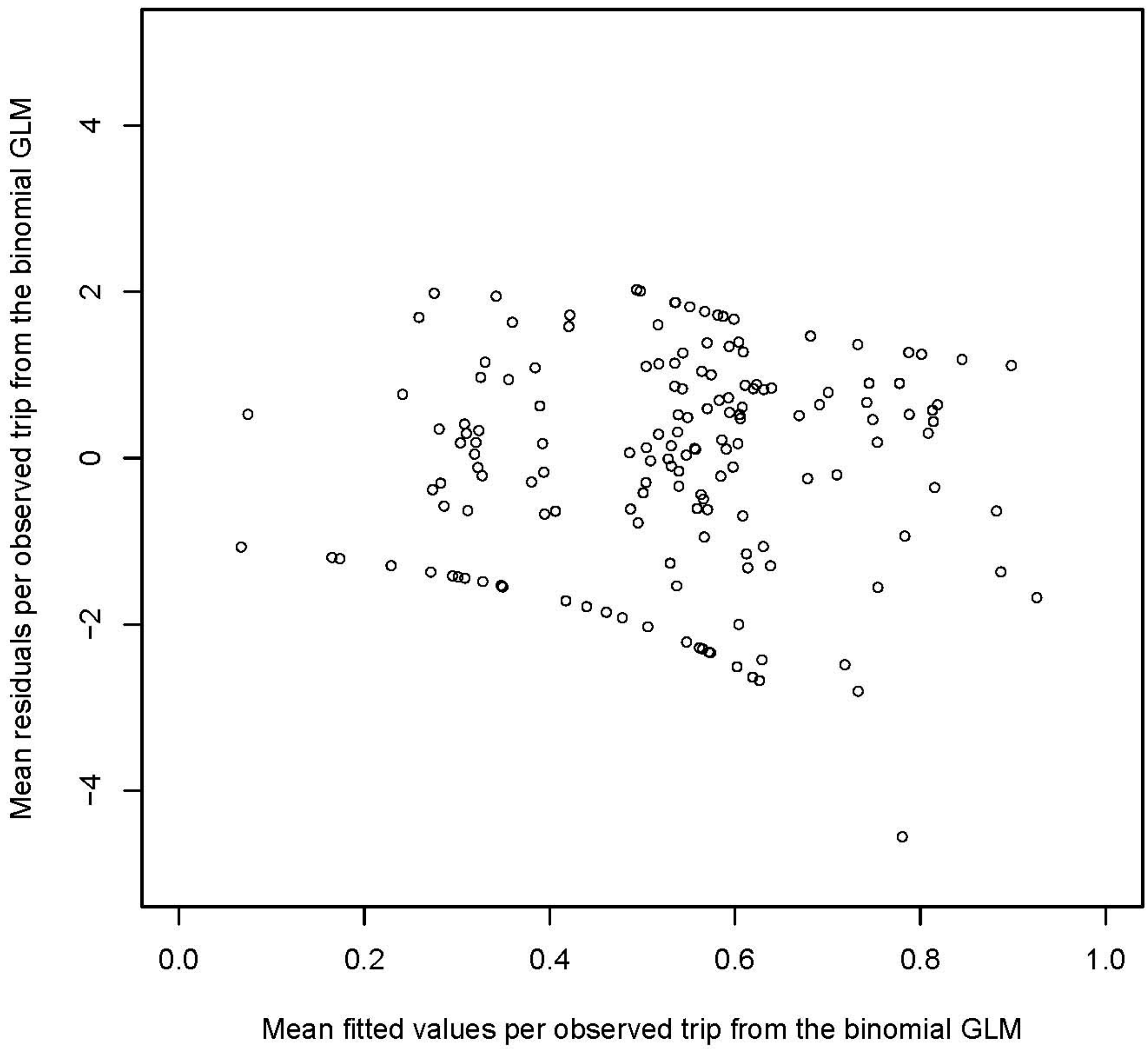

Figure B4.--Mean residuals from the silky shark binomial GLM in the delta-lognormal analysis in relation to the fitted values. Plotted values are means per observed trip.

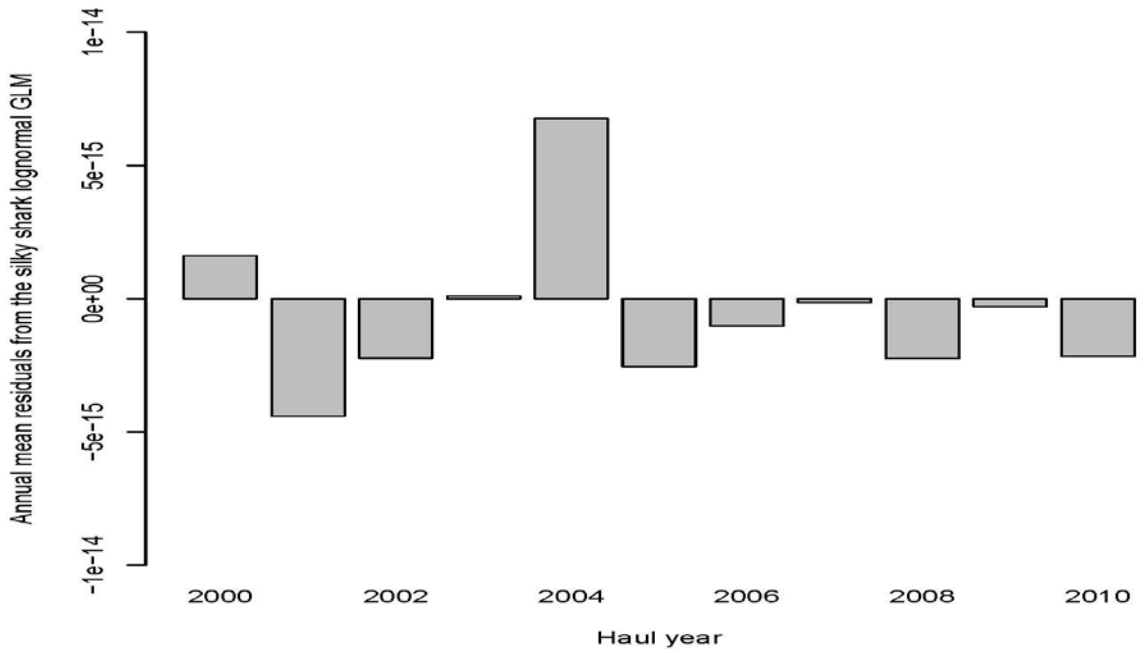

Figure B5.--Annual mean residuals from the silky shark lognormal GLM in the delta-lognormal analysis.

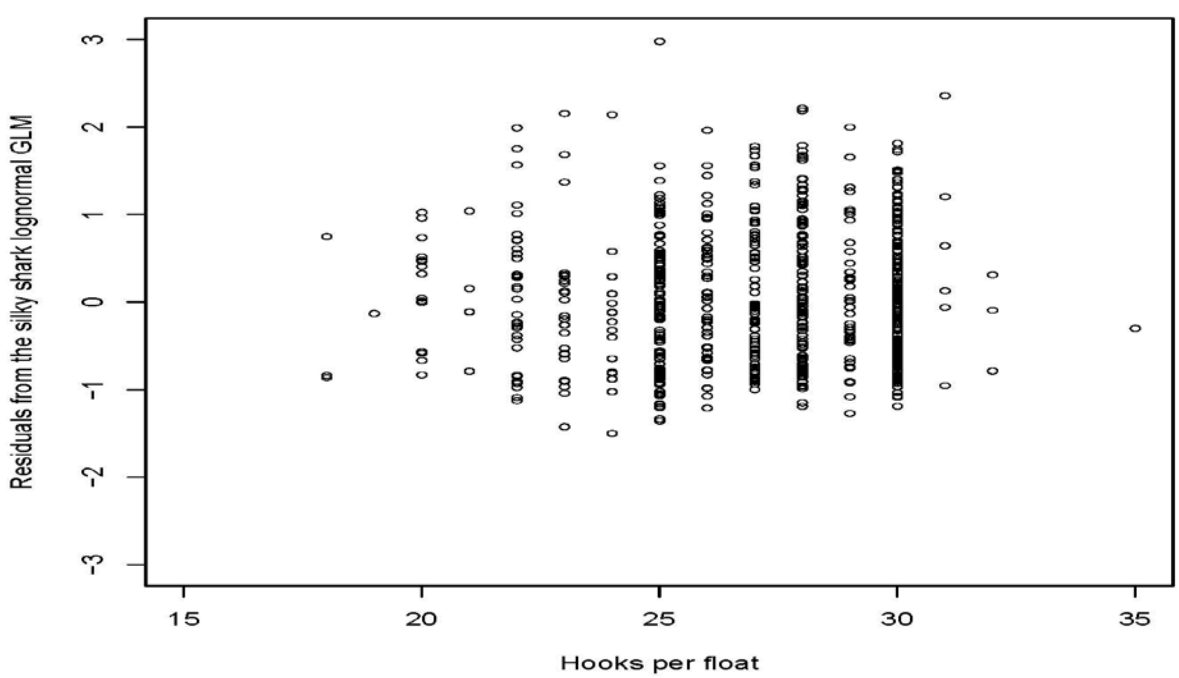

Figure B6.--Residuals from the silky shark lognormal GLM in relation to the number of hooks per float.

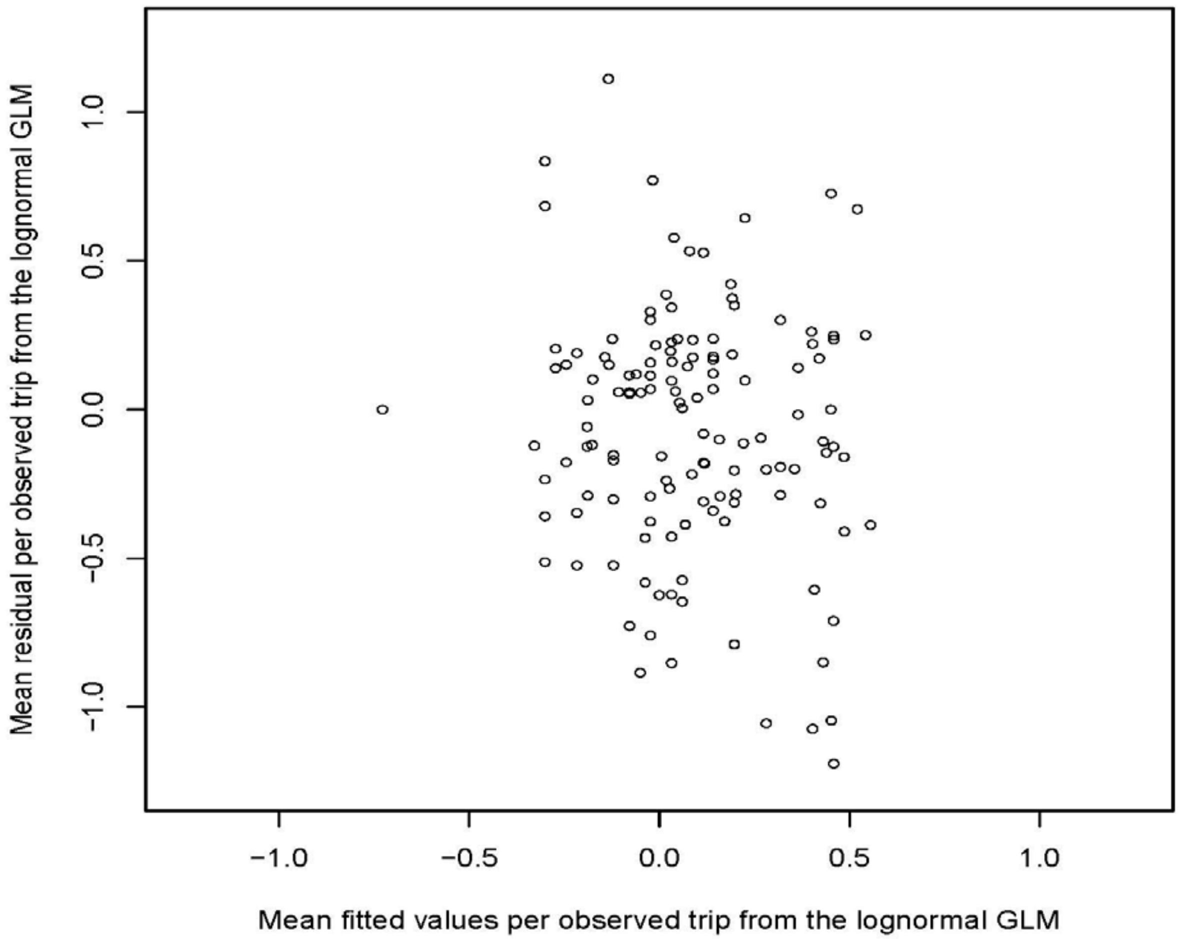

Figure B7.--Mean residuals from the silky shark lognormal GLM in relation to the fitted values. Plotted values are means per observed trip.

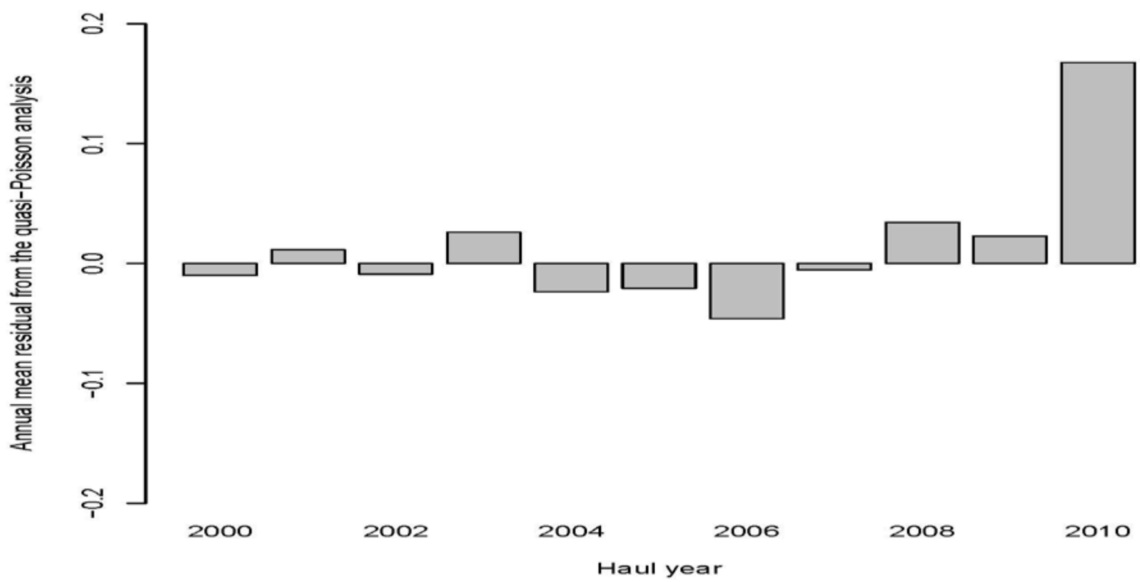

Figure B8.--Annual mean residuals from the silky shark quasi-Poisson analysis.

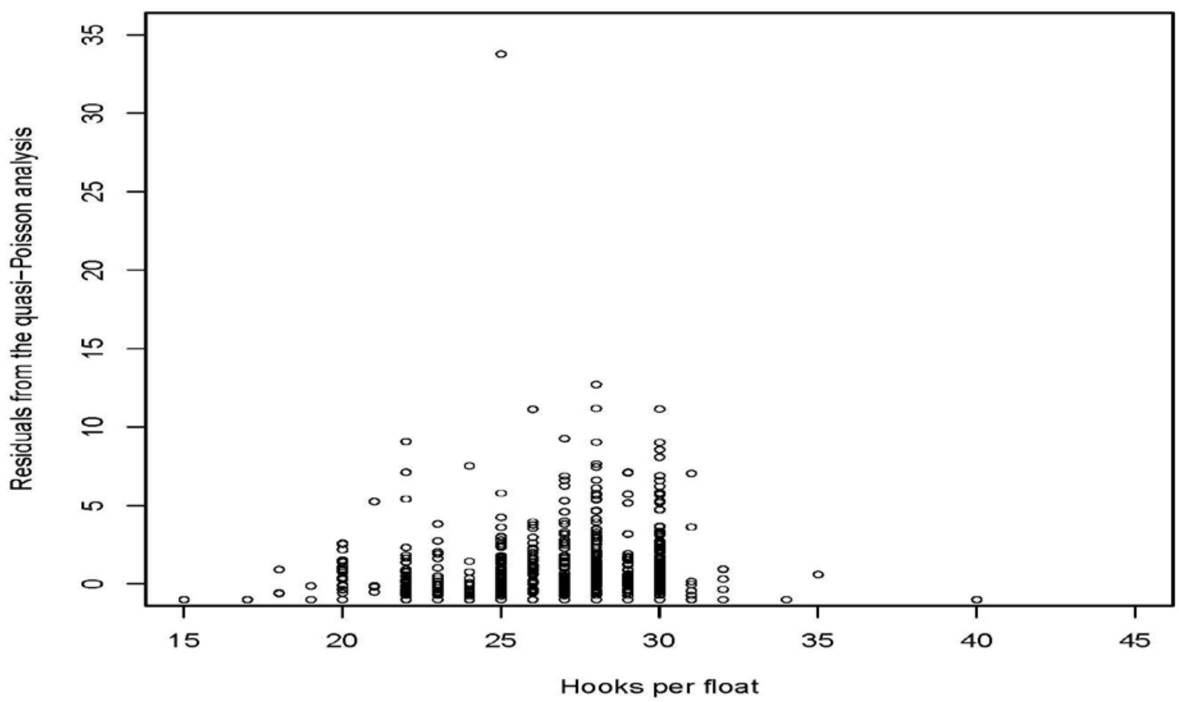

Figure B9.--Residuals from the silky shark quasi-Poisson analysis in relation to the number of hooks per float.

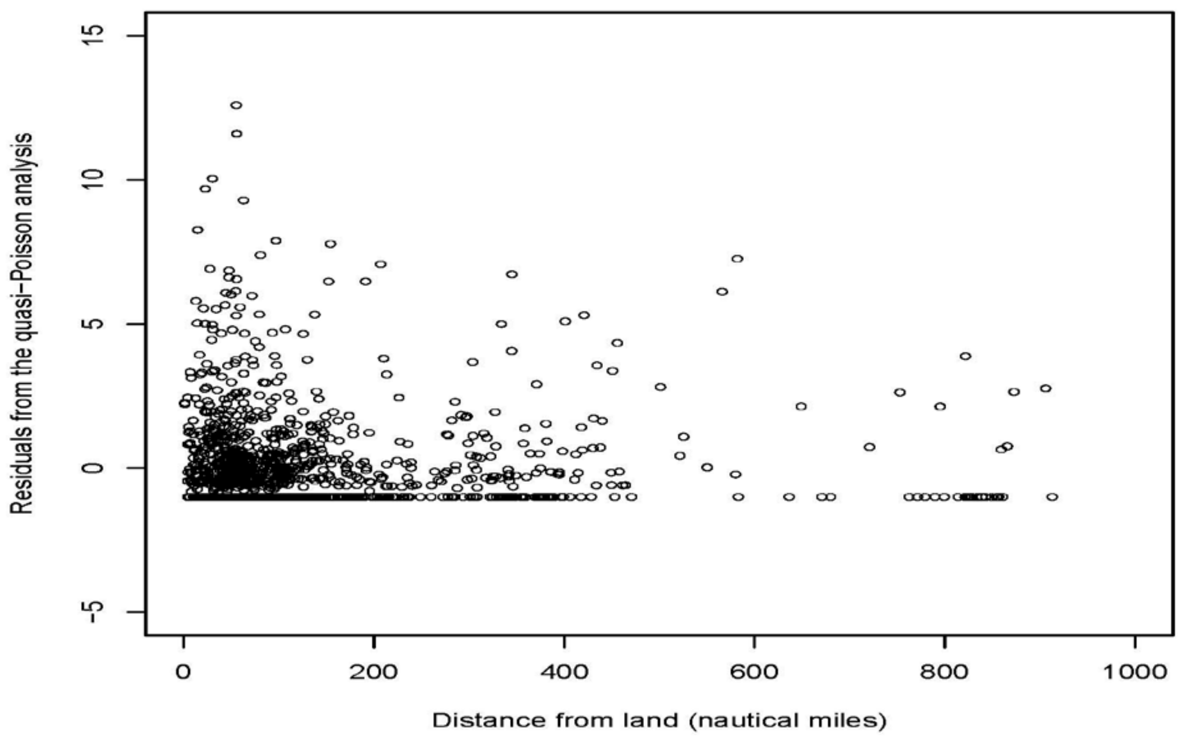

Figure B10.--Residuals from the silky shark quasi-Poisson analysis in relation to the distance from land.

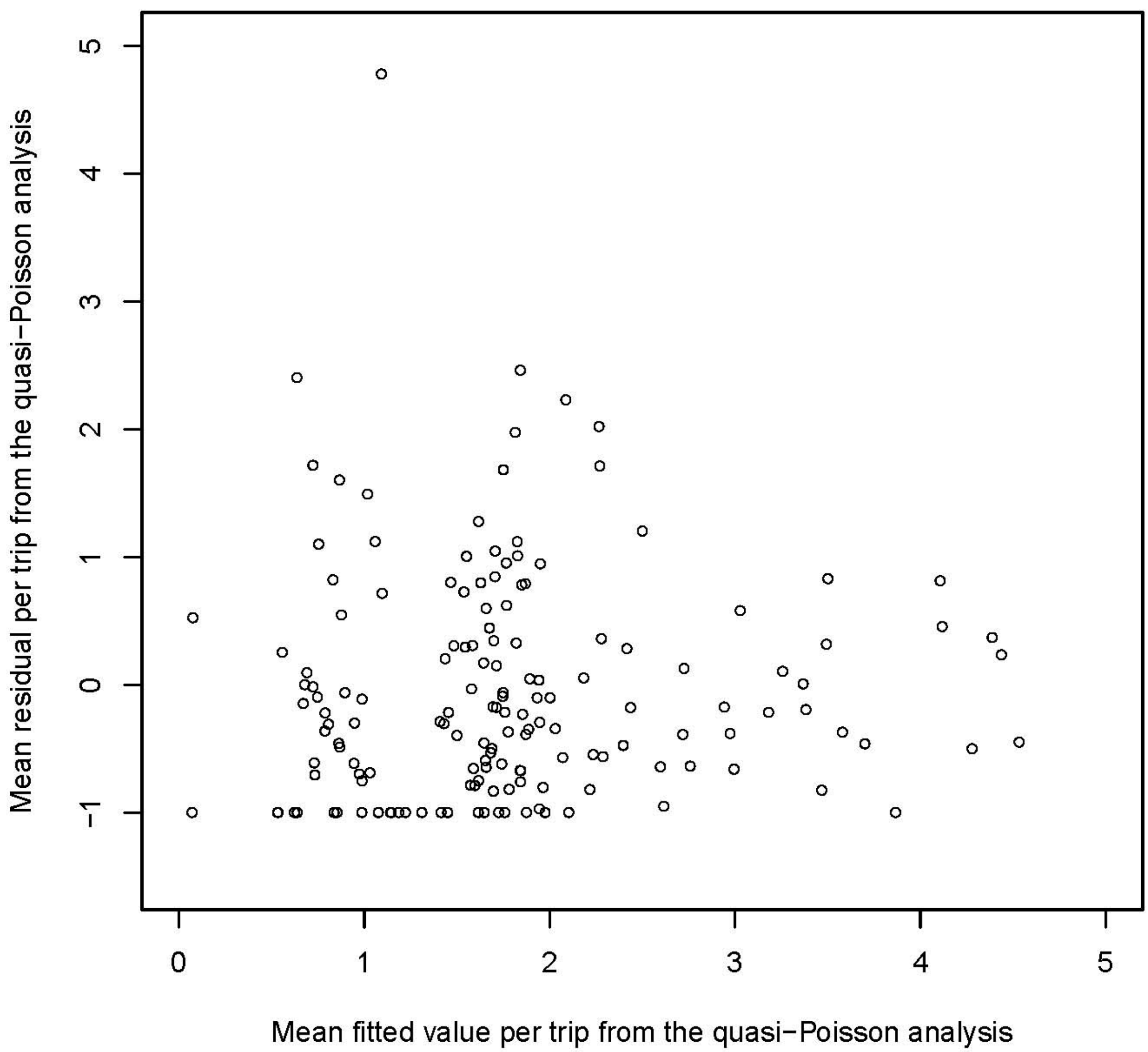

Figure B11.--Mean residuals from the silky shark quasi-Poisson analysis in relation to the fitted values. Plotted values are means per observed trip.

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