Standardization of Striped Marlin *Kajikia audax* CPUE for the Hawaii-based Longline Fishery during 1995–2013 using Generalized Linear Models: An Update from 2011

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Abstract

This working paper presents descriptive catch statistics and catch-per-unit-effort (CPUE) standardizations for striped marlin *Kajikia audax* in the Hawaii-based pelagic longline fishery during 1995–2013. The results are intended for use in a striped marlin stock assessment to be conducted in 2015, which will update one from 2011. Analyses were conducted using catch and operational data reported by the NOAA Fisheries Pacific Islands Regional Observer Program. Catch rates were standardized using Poisson and delta-lognormal generalized linear models because the catch data were reported as counts (Poisson) and included many zeros (delta-lognormal). The fishing year, fishing (i.e., calendar) quarter, and fishing region were significant, important factor variables in the CPUE standardization models; the weekly mean sea surface temperature and the number of hooks per float were significant, important continuous predictor variables. Detailed tabulations of catch statistics, analyses of deviance for the fitted CPUE standardization models, and graphical presentations of the nominal with the standardized CPUE trends are presented in the results. The CPUE standardization model summaries and residuals plots used for diagnostics are presented in appendices.

Introduction

This working paper (WP) presents descriptive catch statistics and catch-per-unit-effort (CPUE) standardizations for striped marlin *Kajikia audax* in the Hawaii-based pelagic longline fishery during 1995–2013. It is intended for use as input about striped marlin relative abundance, in waters fished by the Hawaiian longline fleet, for a stock assessment to be conducted under the aegis of the ISC Billfish Working Group (ISC BILLWG) in 2015.

The 2015 stock assessment will update one conducted in 2011 (Lee et al. 2011). Therefore, the same types of CPUE standardization models (Poisson; delta-lognormal) were fitted, but to a time series with four additional years of catch and operational data reported by fishery observers.

The previously fitted CPUE standardization models (Walsh and Lee 2011) included the fishing year, fishing season (i.e., calendar quarter), fishing region, sea surface temperature (SST), the number of hooks per float, and the number of hooks deployed as significant predictors. This WP uses a similar suite of predictors; differences from the earlier procedures are noted.

Results include tables summarizing effort, catches, and nominal CPUE by fishing years, fishing seasons, fishing regions, and fishery sectors, summary analyses of deviance for the fitted generalized linear models, and the estimated abundance indices with their coefficients of variation. Temporal trends in nominal catch statistics by fishery sectors and nominal and standardized CPUE trends are presented graphically.

This WP has been written to conform to the guidelines adopted by the ISC concerning use of best available scientific information (Brodziak and Dreyfus 2011). The specific guidelines pertaining to this WP are related to the need for accurate species identifications (Table 1, Brodziak and Dreyfus 2011) and several aspects of CPUE standardizations (Table 2, Brodziak and Dreyfus 2011). The citations, diagnostics, and documentation required for guideline conformity are provided in the text or the appendices.

Methods

Data sources

Catch and operational data were collected by the NOAA Fisheries Pacific Islands Regional

Observer Program (PIROP). This WP uses data from 1995–2013 because 1995 was the first full year of PIROP activities, following its establishment early in 1994. All observer data were collected aboard Hawaiʻi-based pelagic longline vessels during commercial fishing operations.

Fishery observer data, rather than self-reported logbook data from vessel operators, were used to ensure that the analyses were conducted according to ISC guidelines regarding best available scientific information precepts (Table 1 *in* Brodziak and Dreyfus 2011). The specific purpose was to avoid use of the negatively biased striped marlin catch data in the commercial logbooks from this fishery (Walsh et al. 2005; 2007) that results from species misidentifications.

The analyses used species-specific catch tallies and operational descriptors (e.g., geographic position, number of hooks deployed, number of hooks per float) recorded by observers on each set. Observers followed protocols in the field manual published by the NOAA Fisheries Pacific Islands Regional Office (2009). Sea surface temperature (SST°C) was the other covariate used in the analyses; these data were weekly mean values measured by an advanced, very high resolution radiometer borne by a NOAA satellite (Walsh et al. 2007).

Each longline set was considered to be an independent fishing operation, as in Brodziak and Walsh (2013) and Walsh and Brodziak (in press). The underlying assumption is that within-trip relationships among the individual sets that might exert positive, negative, or indirect effects. Examples of negative or positive effects would include movements away from areas with low catches of target species but high bycatch or vice versa. Indirect effects could include private at-sea communications among cooperating vessels leading to ensuing movements to higher catch rate areas. Overall, using this approach may underestimate the uncertainty about standardized billfish CPUE of vessels for which within-trip catch correlations were important and lead to selection of overly complex models.

Fishery description

The Hawaii-based pelagic longline fishery is managed in two sectors, defined as deep-set (≥15 hooks per float) and shallow-set fishing (<15 hooks per float). The deep- and shallow-set sectors usually target bigeye tuna *Thunnus obesus* and swordfish *Xiphias gladius*, respectively.

Descriptions of the history, operations, and striped marlin catches in this fishery based upon data from longline logbooks are presented in Ito (ISC/BILLWG/15/01/01). Gilman et al. (2012) also recently presented a detailed study of the deep-set sector of this fishery based on the PIROP observer data.

Descriptive statistical summary

Catch and effort data were tabulated on a fishery-wide basis for all years combined and annually, and by fishing quarters and regions within fishery sectors for all years combined. The within-sector temporal trends in the annual mean values for catches per set, nominal CPUE, and percentages of zero catch sets are presented graphically.

CPUE standardization

Striped marlin CPUE was standardized with two types of generalized linear models (GLMs): Poisson and delta-lognormal. There was no model selection procedure *per se* because the specific intention was to fit GLMs similar to those from 2011, but differing in the length of the data series.

The CPUE standardization models were fitted similarly to the CPUE standardization for the 2011 stock assessment, except where noted (Walsh and Lee 2011). The delta-lognormal analysis was conducted by fitting a binomial GLM using the entire data set, and then fitting a lognormal GLM to the subset of longline sets with positive catch. The Poisson GLM was fitted as a single model, as it accommodates the zero catch sets.

Each GLM was fitted by forward entry step-wise variable selection, beginning with the factor variables, followed by the continuous variables. Because temporal trends were of primary interest, yearly (19 fishing years) and quarterly effects were the initial factor variable entries. Spatial effects were expected to be important so the fishing regions (eight fishing regions) were then entered. The sea surface temperature (SST) was expected to exert strong effects on striped marlin catch rates (Walsh et al., 2005; Walsh et al., 2007; Walsh and Brodziak, in press), so it was tested as a continuous variable (linear and quadratic) and considered an index of habitat suitability. The number of hooks per float was tested because of its influence on longline gear settling depth. The natural logarithm of the number of hooks deployed on each longline set was used as an offset in the binomial and Poisson GLMs as a measure of relative effort. This is the principal difference from the previous analysis (Walsh and Lee 2011), in which the number of hooks was used as a covariate. These alternative approaches were discussed in Maunder and Punt (2004). The other difference was that SST and hooks per float were previously tested as cubic functions. The reductions in the residual deviance and Akaike Information Criterion (AIC) were calculated after each entry. Chi-squared tests were computed at each entry stage to evaluate the statistical significance of explanatory variables.

Estimation of coefficients of variation

Non-parametric bootstrapping was conducted by resampling the data used in the CPUE standardizations in order to estimate the coefficient of variation (CV) of the standardized CPUE. The bootstrap samplings were conducted after stratifying the fixed yearly and quarterly effects and were repeated 1000 times.

Model diagnostics

Pearson residuals from the lognormal and Poisson GLMs were plotted as histograms, on the fitted values, and on the scale of the linear predictor. The quantile residuals from the binomial GLM were also plotted against the predicted values, the values of the explanatory variables.

General aspects of statistical methods

All statistical computations were performed in R (Version 3.1.2). GLM methodology followed Crawley (2007).

Results

Descriptive statistics

Striped marlin catch statistics and operational information spanning the 19-year study period are presented in Table 1. Data were collected aboard 188 longline vessels during 4443 commercial trips that deployed 60,315 sets. Striped marlin were caught on 37.1% of these sets; the total catch (51,122 striped marlin) comprised 1.8% and ranked tenth in the observed catch of all fishes. The ratio of the variance to the mean (VMR=3.32) of striped marlin catch per set was large and indicated that the counts data were overdispersed.

The fishery-wide (i.e., sectors pooled) striped marlin catches per set, nominal CPUE, percentages of sets with positive striped marlin catches, and CPUE on sets with positive catch decreased by 63%, 82%, and 69%, respectively, between 1995 and 2013. The frequencies of sets with positive catches also decreased by 21.1 percentage points during this interval.

The temporal catch trends (Figure 1) in the two sectors were compared after deleting 2001–2004 data because the shallow-set sector was closed during all or part of those years. The annual mean catches per set (r=0.609; df = 13; P=0.016), nominal CPUE (r=0.680; df = 13; P=0.005), and nominal CPUE on sets with positive catches (r=0.592; df = 13; P=0.020) decreased, while the percentages of zero catches increased (r=0.812; df = 13; P<0.006) in both sectors. Each of the trends was significantly correlated between sectors.

Fishery sector, quarterly, and regional effects on striped marlin catch rates are summarized in Table 2. Most (78.5%) observed sets were deployed and most striped marlin were caught (86.5%) in the deep-set sector. The mean catches per set in Regions 3, 4, and 6 during the first quarter and in Region 6 during the second and fourth quarters (1.23–1.96) were greater than those in all other quarterly-regional combinations. Striped marlin were caught on 56.5–68.7% of the sets in these regions during these quarters; the pooled catch represented 39.4% of the deep-set striped marlin catch from 36.7% of the effort. No other quarterly-regional combination had a positive catch rate ≥50%. The catches per set and mean CPUE in Region 6 were greater than those of other regions during all quarters. Striped marlin were caught least frequently in Region 1 and Regions 7 and 8 (combined) in the first quarter and Regions 1 and 2 in the second quarter.

In contrast to the deep-set sector, with some effort in every quarterly-regional combination, shallow-set activity was restricted to Regions 3–8, and there was no effort in Regions 3 and 4 during the first quarter. Nearly half (48.0%) of the sets were deployed during the first quarter, but only 12.2% of the shallow-set sector striped marlin catch was taken. The catch from Region 6 in the second quarter represented 50.4% of the sector and 6.9% of the fishery-wide totals, respectively. Another 18.2% of the shallow-set striped marlin catch was taken in Region 5 during quarter 2.

Maps showing spatio-temporal catch patterns during 2007–2011 are in Appendix III. It should be noted that the plotted data include two years from the previous stock assessment and do not cover the entire period for the update.

GLM fitting summary

Table 3 presents a summary of the fitting results for the binomial, lognormal, and Poisson GLMs. Full output from the R "summary" function for these GLMs is in Appendix I. Residuals plots for model diagnostics are presented in Appendix II.

The binomial GLM explained 12.1% of the null deviance of the presence or absence of positive striped marlin catches in the entire data set. The sequential entries of the fishing years, fishing quarters, and fishing regions yielded deviance reductions of 6.0, 2.6, and 2.9%, respectively. The SST effect was expressed as a quadratic function. The AIC and deviance reductions attained by entering the numbers of hooks per float were intermediate between those of the SST variables.

The lognormal GLM results differed from the other GLMs in two primary respects. First, entry of the number of hooks per float yielded a large deviance reduction and the largest AIC reduction, and was predominant per degree of freedom. The other principal difference was the relatively minor effect of SST. This indicated that SST primarily affects the presence or absence of catch, but in suitable habitat the SST exerts only minor effects on the positive catch rate.

The effects of fishing years, fishing quarters, fishing regions, and hooks per float were again important and significant in the Poisson GLM. Forward entry of these covariates into the GLM yielded deviance reductions of 1.3–14.1%. The AIC and deviance reductions per degree of freedom indicated that the effects of the fishing quarters and the number of hooks per float had comparably strong influences on striped marlin catch per longline set. The SST effect was again expressed as a quadratic function. The GLM *pseudo*-coefficient of determination was 25.2%.

Striped marlin relative abundance indices

The results of the delta-lognormal and Poisson analyses are presented in Table 4 and Figures 2 and 3, respectively. The CVs estimated by bootstrapping ranged from 2.03–7.37% for the delta-lognormal GLM and from 2.24–7.91% for the Poisson GLM, similar for both models. For both methods, the CVs were relatively high during 1995–2000, but decreased to around 3% during 2001–2013 following the expansion of observer effort that began in 2000 (Table 1).

Model diagnostics

The residuals plots (Appendix II) did not reveal serious problems, although the quantile-quantile plot for the lognormal GLM exhibited an upward inflection in the negative tail. The quantile residuals for the binomial GLM appeared to be normally distributed and homogeneously spread across the range of predicted values and on the scale of the linear predictor. Pearson residual plots showed non-normality in the distribution of residuals for the Poisson GLM, but the plots of the residuals on the values of the covariates showed no obvious patterns in the median values.

Discussion

This WP presents catch statistics and CPUE standardization analyses for striped marlin in the Hawaii-based pelagic longline fishery during 1995–2013. The statistical methodology was similar to that followed in 2011 (Walsh and Lee 2011), and the WP was written in conformity with ISC guidelines (Brodziak and Dreyfus 2011) in order to ensure that the results would prove comparable to the earlier work.

The descriptive catch statistics such as nominal CPUE and catch per set from 2010–2013 remained within ranges that began *ca*. 2000, except in 2001 and 2003 (Figure 1). In the former year, catch rates were relatively high and the percentage of zero catches was low. Gilman et al. (2012) related the 2001 increase in striped marlin catches to *La Niña*. These results suggest that the nominal indicators remained roughly stable for most of the last 14 years of the time series except when strongly influenced by environmental factors. The apparent increases in the shallow-set sector catch rates in 2013 (Figure 1) reflected two factors: 1) shallow-set effort in 2013 was at the lowest level for any full year since the re-opening in 2004; and 2) 66% of this effort was in Region 6 during May and June, meaning that much shallow-set effort was located further south and closer to the summer months than in many other years.

In the CPUE standardizations, the temporal factors were significant and important, with deviance reductions of 6−14.1% for annual and 1.7−4.0% for quarterly effects in the three GLMs. The quarterly deviance reductions per degree of freedom, however, were greater than the annual deviance reductions per degree of freedom in each model, which indicated that the seasonal effects were relatively stronger than interannual effects.

Regional effects in the GLMs were important and significant, as was expected. It was also noteworthy that striped marlin catches in 2007−2011 were always much lower than target species catches, but were sometimes the most numerous of the other incidentally caught billfishes in this fishery (Appendix III).

The continuous variables, SST and hooks per float, exerted their expected effects. The lognormal results indicated that SST primarily affects the presence or absence of catch, but in suitable habitat it exerts only minor effects on the positive catch rate. Also, expression of the SST effect as a curvilinear function (quadratic) was consistent with Gilman et al. (2012) and Walsh et al. (2007), who identified curved SST effects in generalized additive mixed model (GAMM) and generalized additive model (GAM) analyses, respectively. The linear hooks per float effect with a negative coefficient used herein was also consistent with prior experience and comprehensible with an epipelagic species; in the 2011 CPUE standardization, this variable was tested as a cubic function, but the second- and third-order terms were non-significant (Walsh and Lee 2011).

Langseth (2015) presents additional work on striped marlin CPUE standardization for the stock assessment update, including evaluations of distributional assumptions, inclusion of interactions in GLMs used for CPUE standardization, and comparisons of several relative abundance indices. Also, Walsh and Brodziak (in press) recently applied model selection and multimodel inference techniques (Brodziak and Walsh 2013) to the striped marlin catch data from this fishery. The selected model was a zero-inflated negative binomial model, which had also been selected as the best fitting model for oceanic whitetip shark *Carcharhinus longimanus* bycatch. Availability of multiple CPUE standardizations means that alternative relative abundance indices can be considered for use in the stock assessment update.

Conclusions

These CPUE standardization results obtained with a longer time series were generally consistent with previous results (Walsh and Lee 2011). Thus, we have presented relative abundance indices for striped marlin that are comparable to earlier work and potentially suitable for use in the 2015 stock assessment update.

The residuals plots from the GLMs (Appendix III) did not reveal serious problems. Hence, there is no apparent *a priori* reason not to consider these GLMs for use in the stock assessment update.

Because this work and additional CPUE standardizations (Langseth 2015) have been computed and their results compared for striped marlin in this fishery, we recommend deference to the judgment of the lead stock assessment analysts regarding the choice of relative abundance indices to be used as input.

References

Brodziak, J. and Dreyfus, M. 2011. Annex 11: Report on the Seminar on the Use of the Best Available Scientific Information. 22 July 2011. ISC.

Brodziak, J. and Walsh, W.A. 2013. Standardizing catch rates of bycatch species using multimodel inference: A case study of oceanic whitetip shark in the Hawaii longline fishery. Canadian Journal of Fishery and Aquatic Sciences 70: 1723−1740.

Crawley, M.J. 2007. The R Book. John Wiley & Sons, Ltd., The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, England.

Department of Commerce. 2004. Fisheries off West Coast states and in the western Pacific; highly migratory species fisheries. National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Federal Register 69(67): 50 CFR Parts 223, 224, and 660.

Gilman, E., Chaloupka, M., Read, A., Dalzell, P., Holetschek, J., and Curtice, C. 2012. Hawaii tuna longline fishery temporal trends in standardized catch rates and length distributions and effects on pelagic and seamount ecosystems. Aquatic Conservation: Marine and Freshwater Ecosystems 22: 446−488.

Ito, R.Y. 2015. US commercial fisheries for marlins in the North Pacific Ocean. ISC/15/BILLWG/1/01.

Langseth, B. 2015. Standardization of striped marlin (*Kajikia audax*) CPUE in the Hawaiian longline fishery II: Additional covariates, distribution, and use of data from the deep-set fishery sector only ISC/15/BILLWG/1/06.

Lee, H-.H, Piner, K.R., Humphreys, R., and Brodziak, J. 2012. Stock assessment of striped marlin in the western and central North Pacific Ocean. PIFSC Internal Report IR-12-035. (http://www.pifsc.noaa.gov/library/pubs/IR-12-035.pdf)

Maunder, M.N. and Punt, A.E. 2004. Standardizing catch and effort data: a review of recent approaches. Fisheries Research 70:141-159.

Pacific Islands Regional Office, 2009. Hawaii Longline Observer Program Observer Field Manual. Version LM.09.11. National Oceanic and Atmospheric Administration, Pacific Islands Region, Honolulu, Hawaii. (http://www.fpir.noaa.gov/Library/PUBDOCS/observer_manual_forms/obs_hawaii/obs_hi_manual_09_2011.pdf)

R Development Core Team (2006). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, http://www.R-project.org.

Walsh, W. A., Bigelow, K.A., and Ito, R.Y. 2007. Corrected catch histories and logbook accuracy for billfishes (Istiophoridae) in the Hawaii-based longline fishery. NOAA Technical Memorandum NMFS-PIFSC-13.

Walsh, W. A., Ito, R.Y., Kawamoto, K.E., and McCracken, M. 2005. Analysis of logbook accuracy for blue marlin (*Makaira nigricans*) in the Hawaii-based longline fishery with a generalized additive model and commercial sales data. Fisheries Research 75:175–192.

Walsh, W.A. and Brodziak, J. Billfish CPUE standardization in the Hawaii longline fishery: Model selection and multimodel inference. Fish.Res.(2014),http://dx.doi.org/10.1016/j.fishres.2014.07.015.

Walsh, W.A. and Lee, H.-H. 2011. Standardization of striped marlin, *Kajikia audax*, CPUE with generalized linear models fitted to pelagic longline observer data from the Hawaii-based fishery: 1995-2009. ISC/11/BILLWG/1/08.

Table 1. Summary of observed striped marlin *Kajikia audax* catch and effort data from the Hawaii-based pelagic longline fishery (January 1995–December 2013; *N*=60,315 observed sets). Nominal CPUE is fish per 1000 hooks. Parenthetical entries are standard deviations.

Year	Vessels	Trips	Sets	Hooks	Catch (Fish)	Sets with catch	Catch/set	Variance: mean	Nominal CPUE	Nominal CPUE: catch > 0
1995–2013	188	4443	60,315	113,894,720	51,122	37.1%	0.85 (1.67)	3.32	0.449	1.155
1995	44	48	547	615,858	1144	59.8%	2.09 (3.16)	4.78	1.858	2.881
1996	47	52	620	733,705	1007	49.2%	1.62 (3.08)	5.85	1.372	2.528
1997	33	37	461	545,715	512	44.9%	1.11 (1.83)	3.00	0.938	1.763
1998	40	47	549	729,228	638	43.0%	1.16 (2.12)	3.88	0.875	1.773
1999	36	39	433	649,489	487	49.7%	1.12 (1.61)	2.31	0.750	1.412
2000	71	113	1324	2,225,119	725	28.5%	0.55 (1.19)	2.58	0.326	1.136
2001	98	244	2782	5,087,928	4725	60.3%	1.70 (2.29)	3.09	0.929	1.522
2002	98	285	3487	6,716,209	2302	35.5%	0.66 (1.24)	2.34	0.343	0.959
2003	104	261	3167	6,384,022	7010	65.2%	2.21 (2.92)	3.85	1.098	1.677

Table 1, continued.

Year	Vessels	Trips	Sets	Hooks	Catch (fish)	Sets with catch	Catch/set	Variance: mean	Nominal CPUE	Nominal CPUE: catch > 0
2004	124	346	4048	7,963,851	3752	42.7%	0.93 (1.66)	2.96	0.471	1.056
2005	122	392	4995	8,236,979	4618	41.8%	0.92 (1.55)	2.59	0.561	1.296
2006	123	318	4143	7,643,864	4782	45.3%	1.15 (1.97)	3.37	0.626	1.228
2007	123	362	5092	9,061,320	1588	20.7%	0.31 (0.76)	1.85	0.175	0.785
2008	126	380	5362	10,079,044	4412	37.5%	0.82 (1.53)	2.83	0.438	1.100
2009	121	360	5144	9,442,943	1992	24.7%	0.39 (0.85)	1.87	0.211	0.843
2010	115	338	4900	9,095,717	930	14.8%	0.19 (0.52)	1.40	0.102	0.647
2011	121	310	4446	9,169,823	4686	43.9%	1.05 (1.81)	3.11	0.511	1.100
2012	124	326	4571	9,794,413	2523	32.7%	0.55 (1.04)	1.96	0.258	0.756
2013	126	311	4244	9,719,493	3289	36.7%	0.77 (1.53)	3.01	0.338	0.891

Table 2. Summary of striped marlin catch and effort statistics from 1995–2013, tabulated by fishery sectors, fishing (i.e., calendar) quarters, and fishing regions. Entries are the mean catches per set (numbers of fish) and nominal CPUE (fish/1000 hooks), the number of sets, and the percentage of sets with positive catches in each fishing quarter-fishing region combination.

Deep-set sector

Fishing Quarter	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6	Regions 7&8
1	Catch/set= 0.12 CPUE = 0.054 34 sets 11.8% > 0	Catch/set= 0.40 CPUE = 0.190 510 sets 26.3% > 0	Catch/set= 1.23 CPUE = 0.626 1854 sets 57.9% > 0	Catch/set= 1.37 CPUE = 0.641 3447 sets 56.5% > 0	Catch/set= 0.88 CPUE = 0.402 2857 sets 38.5% > 0	Catch/set= 1.76 CPUE = 0.819 1543 sets 63.3% > 0	Catch/set= 0.07 CPUE = 0.052 54 sets 3.7% > 0
2	Catch/set= 0.17 CPUE= 0.079 79 sets 13.9% > 0	Catch/set= 0.18 CPUE= 0.080 512 sets 11.9% > 0	Catch/set= 0.63 CPUE = 0.310 2065 sets 39.1% > 0	Catch/set= 0.82 CPUE = 0.391 4506 sets 42.4% > 0	Catch/set= 0.73 CPUE = 0.323 2269 sets 38.1% > 0	Catch/set= 1.86 CPUE = 0.845 1200 sets 68.7% > 0	Catch/set= 0.77 CPUE = 0.311 271 sets 40.6% > 0
3	Catch/set= 0.62 CPUE = 0.275 85 sets 20.0% > 0	Catch/set= 0.35 CPUE = 0.178 301 sets 21.3% > 0	Catch/set= 0.24 CPUE = 0.120 1100 sets 16.0% > 0	Catch/set= 0.26 CPUE = 0.124 1673 sets 17.8% > 0	Catch/set= 0.43 CPUE = 0.195 5870 sets 22.7% > 0	Catch/set= 0.77 CPUE = 0.359 640 sets 36.1% > 0	Catch/set= 0.44 CPUE = 0.187 2133 sets 26.1% > 0
4	Catch/set= 0.24 CPUE = 0.156 17 sets 23.5% > 0	Catch/set= 0.37 CPUE = 0.184 175 sets 18.3% > 0	Catch/set= 0.86 CPUE = 0.423 1959 sets 33.6% > 0	Catch/set= 0.80 CPUE = 0.369 2084 sets 38.1% > 0	Catch/set= 1.23 CPUE = 0.556 7074 sets 47.9% > 0	Catch/set= 1.91 CPUE = 0.882 2843 sets 59.7% > 0	Catch/set= 0.69 CPUE = 0.304 167 sets 31.7% > 0

Table 2, continued.

Shallow-set sector

Calendar Quarter	Region 3	Region 4	Region 5	Region 6	Region 7	Region 8
1	0 sets	0 sets	Catch/set= 0.44 CPUE = 0.497 385 sets 24.7% > 0	Catch/set= 0.19 CPUE = 0.209 743 sets 14.0% > 0	Catch/set= 0.11 CPUE = 0.119 4203 sets 9.4% > 0	Catch/set= 0.11 CPUE = 0.120 909 sets 10.5% > 0
2	Catch/set= 0.54 CPUE= 0.600 24 sets 33.3% > 0	Catch/set= 0.17 CPUE= 0.210 6 sets 16.7% > 0	Catch/set= 0.84 CPUE = 0.914 1523 sets 42.2% > 0	Catch/set= 1.34 CPUE = 1.401 2642 sets 52.2% > 0	Catch/set= 0.13 CPUE = 0.135 257 sets 11.3% > 0	Catch/set= 0.34 CPUE = 0.364 345 sets 18.6% > 0
3	Catch/set= 0.23 CPUE = 0.275 86 sets 19.8% > 0	Catch/set= 0.15 CPUE = 0.184 33 sets 15.2% > 0	Catch/set= 1.03 CPUE = 1.145 108 sets 56.5% > 0	Catch/set= 1.19 CPUE = 1.306 101 sets 48.5% > 0	Catch/set= 1.02 CPUE = 1.004 43 sets 48.8% > 0	Catch/set= 0.94 CPUE = 1.018 428 sets 49.5% > 0
4	Catch/set= 0.25 CPUE = 0.359 4 sets 25.0% > 0	Catch/set= 0.43 CPUE = 0.524 14 sets 28.6% > 0	Catch/set= 3.78 CPUE = 4.274 85 sets 67.1% > 0	Catch/set= 1.82 CPUE = 2.002 38 sets 78.9% > 0	Catch/set= 0.08 CPUE = 0.087 953 sets 6.8% > 0	Catch/set= 0.05 CPUE = 0.062 63 sets 4.8% > 0

Table 3. Summary of the forward selection GLM fitting results. Results include the residual deviance, deviance reduction, proportion of the null deviance, the test for the significance of the deviance reduction, the reduction of the Akaike Information Criterion (AIC) value and the proportion of the null model AIC attained by entering each covariate.

Binomial GLM: 60,315 longline sets; presence or absence of catch as response variable; Null deviance= 79,025; Null model AIC = 79,027

Parameter	Df	Residual deviance	Δ Residual deviance	Δ Residual deviance/df	Deviance reduction/ null deviance	AIC	ΔAIC	ΔAIC/Df	AIC reduction/ null model AIC
Intercept	1	79,025	---			79,027	---		
Fishing years	18	74,314	4711.3	261.74	0.060	74,352	4675.3	259.74	0.059
Fishing quarters	3	72,253	2061.1	687.04	0.026	72,297	2055.1	685.03	0.026
Fishing regions	7	69,967	2285.9	326.55	0.029	70,025	2271.9	324.56	0.029
Hooks per float	1	69,841	126.2	126.2	0.002	69,900.8	124.2	124.2	0.002
SST (linear)	1	69,732	108.8	108.8	0.001	69,794	106.8	106.8	0.001
SST (quadratic)	1	69,495	237.4	237.4	0.003	69,559	235.4	235.4	0.003

Binomial GLM *pseudo*-R^2 = 12.1%

Lognormal GLM: 22,407 longline sets; ln(catch/1000 hooks) as response variable; Null deviance= 12,310.6;Null model AIC = 50,172.4

Parameter	Df	Residual deviance	Δ Residual deviance	Δ Residual deviance/df	Deviance reduction/ null deviance	AIC	ΔAIC	ΔAIC/Df	AIC reduction/ null model AIC
Intercept	1	12,310.6	---			50,172.4	---		
Fishing years	18	10,980.1	1330.5	73.9	0.108	47,645.7	2526.7	140.4	0.050
Fishing quarters	3	10,776.1	204.0	68.0	0.017	47,231.4	414.3	138.1	0.008
Fishing regions	7	10,030.3	745.7	106.5	0.061	45,638.4	1592.9	227.6	0.032
Hooks per float	1	8783.2	1247.1	1247.1	0.101	42,665.4	2973.0	2973.0	0.059
SST (linear)	1	8777.4	5.8	5.8	<0.001	42,652.6	12.8	12.8	<0.001
SST (quadratic)	1	8773.2	4.2	4.2	<0.001	42,643.9	8.7	8.7	<0.001

Lognormal GLM *pseudo*-R^2 = 28.9%

Poisson GLM: 60,315 longline sets; catch per longline set as response variable; Null deviance= 131,078; Null model AIC = 187,442

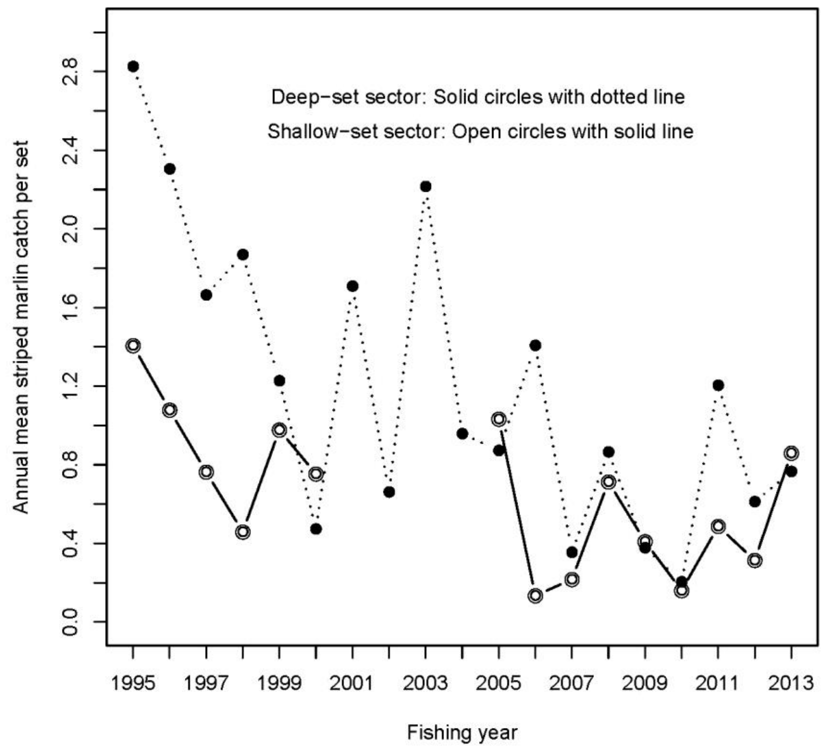
Parameter	Df	Residual deviance	Δ Residual deviance	Δ Residual deviance/df	Deviance reduction/ null deviance	AIC	ΔAIC	ΔAIC/Df	AIC reduction/ null model AIC
Intercept	1	131,078	---			187,442	---		
Fishing years	18	112,584	18,494.4	1027.5	0.141	168,983	18,458.4	1025.5	0.098
Fishing quarters	3	107,300	5283.4	1761.1	0.040	163,706	5277.4	1759.1	0.028
Fishing regions	7	100,564	6736.7	962.4	0.051	15,983	6722.7	960.4	0.036
Hooks per float	1	98,780	1763.9	1763.9	0.013	155,221	1761.9	1761.9	0.009
SST (linear)	1	98,453	346.4	346.4	0.003	154,877	344.4	344.4	0.002
SST (quadratic)	1	98,060	393.4	393.4	0.003	154,486	391.4	391.4	0.002

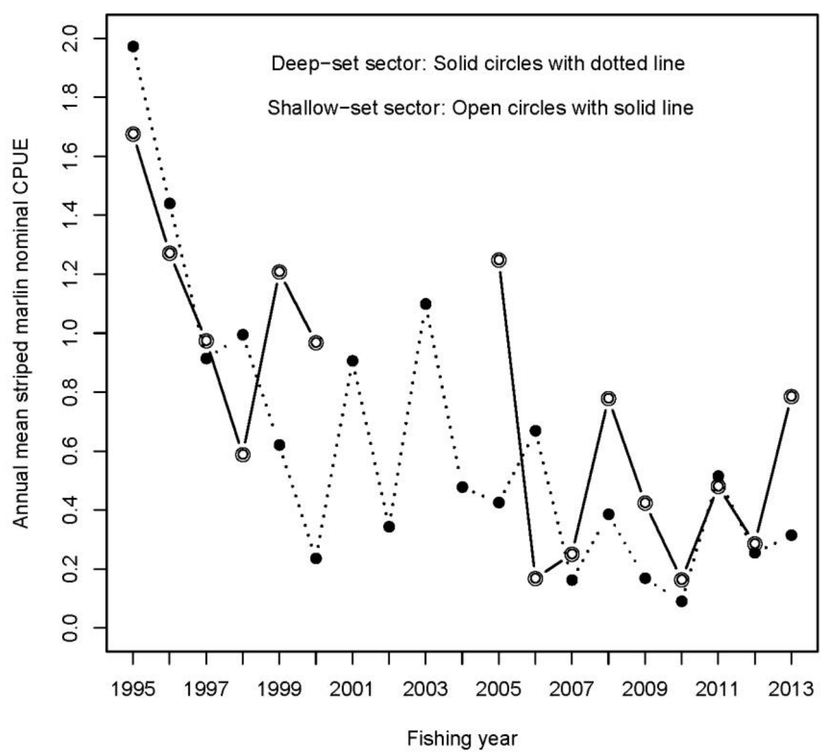
Poisson GLM *pseudo-*R^2 = 25.2%

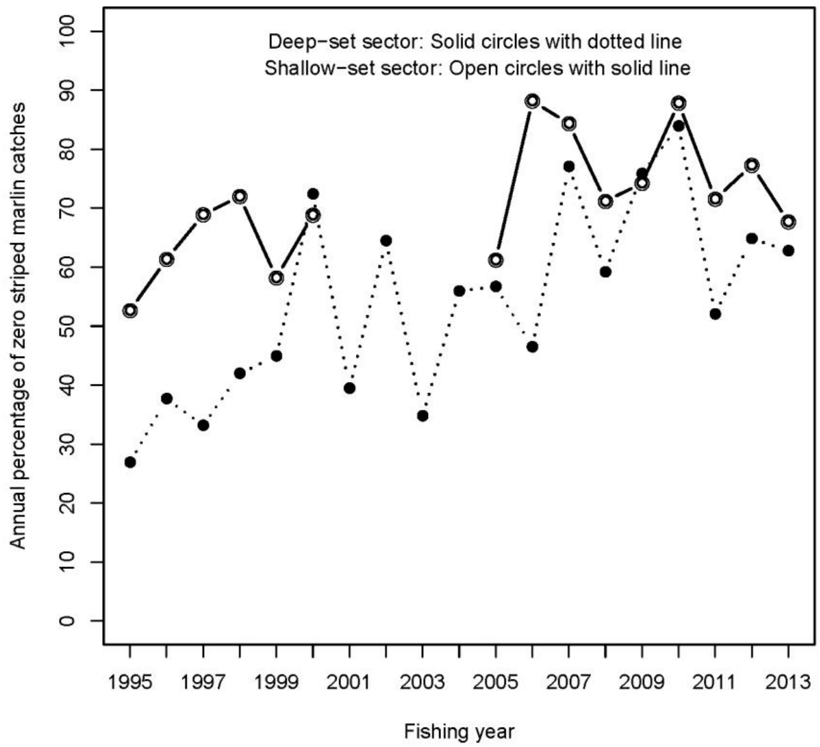
Table 4. Annual standardized CPUE (fish/1000 hooks) with coefficients of variation from the delta-lognormal model and annual standardized catch per longline set from the Poisson model with coefficients of variation, with values estimated by using the bootstrap approach.

Year	Delta-lognormal		Poisson	
	Index	CV	Index	CV
1995	1.28	5.88	2.09	6.69
1996	0.94	5.89	1.62	7.52
1997	0.69	7.37	1.11	7.85
1998	0.62	6.65	1.16	7.91
1999	0.65	6.74	1.12	6.58
2000	0.29	6.08	0.55	6.00
2001	0.73	2.33	1.70	2.50
2002	0.29	2.79	0.66	3.14
2003	0.83	2.03	2.21	2.26
2004	0.36	2.45	0.93	2.71
2005	0.48	2.51	0.92	2.24
2006	0.44	2.34	1.15	2.67
2007	0.16	3.31	0.31	3.41
2008	0.35	2.39	0.82	2.54
2009	0.20	2.96	0.39	3.09
2010	0.10	3.93	0.19	3.77
2011	0.40	2.38	1.05	2.61
2012	0.22	2.58	0.55	2.85
2013	0.27	2.69	0.77	3.17

Figure 1. Striped marlin (a) catches per set, (b) nominal CPUE, (c) percentages of sets with zero catches, and (d) CPUE on sets with positive catches by fishery sectors during 1995–2013.






Deep−set sector: Solid circles with dotted line
Shallow−set sector: Open circles with solid line
Annual percentage of zero striped marlin catches
0
10
20
30
40
50
60
70
80
90
100
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
Fishing year

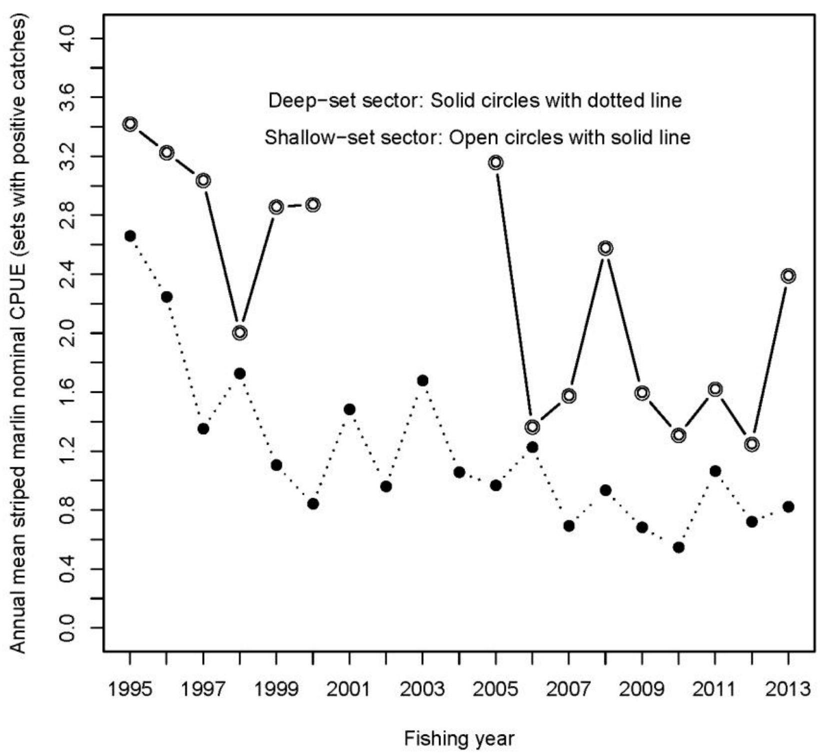

Deep−set sector: Solid circles with dotted line
Shallow−set sector: Open circles with solid line
Annual mean striped marlin nominal CPUE (sets with positive catches)
0.0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
4.0
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
Fishing year

Figure 2. Yearly effects on striped marlin standardized CPUE (fish/1000 hooks) as estimated with the delta-lognormal model. The black dashed line and shadow represent the means and 95% confidence intervals for the standardized CPUE, respectively. Open circles denote the nominal index (catch/1000 hooks).

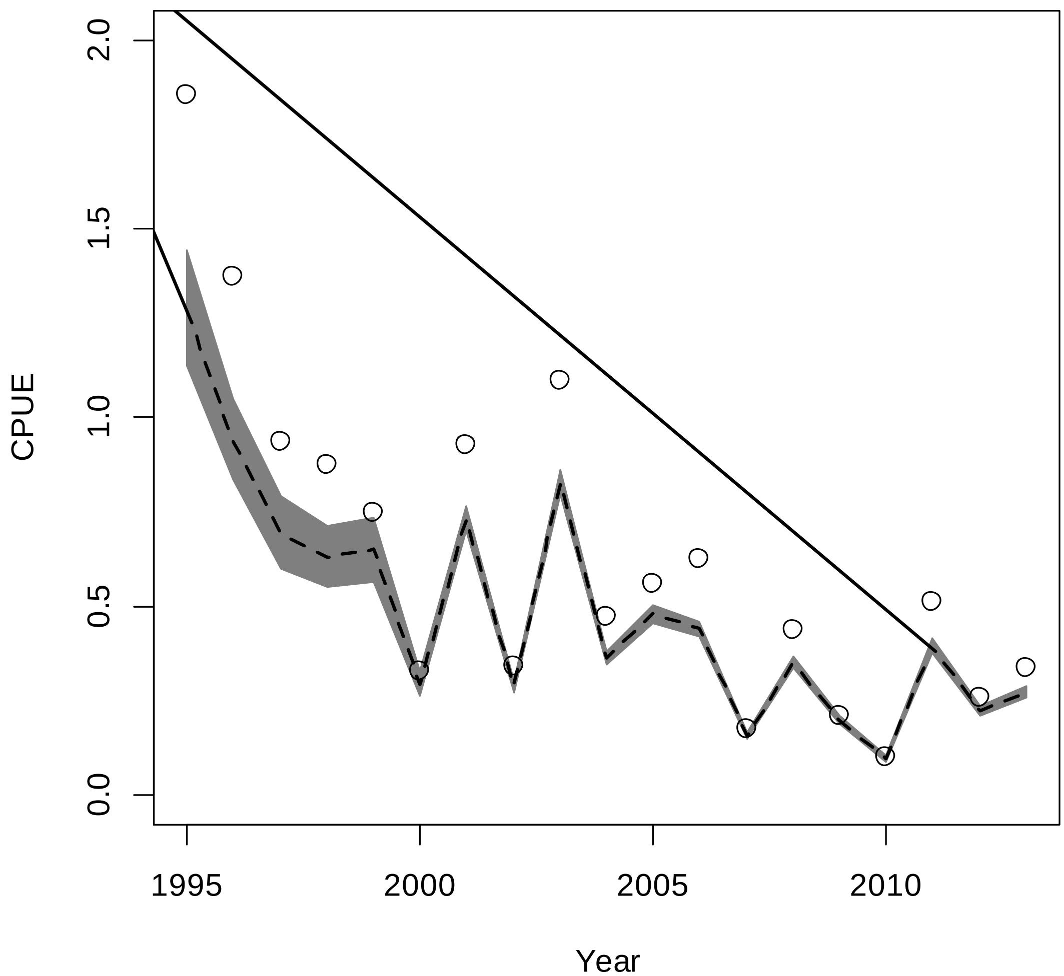
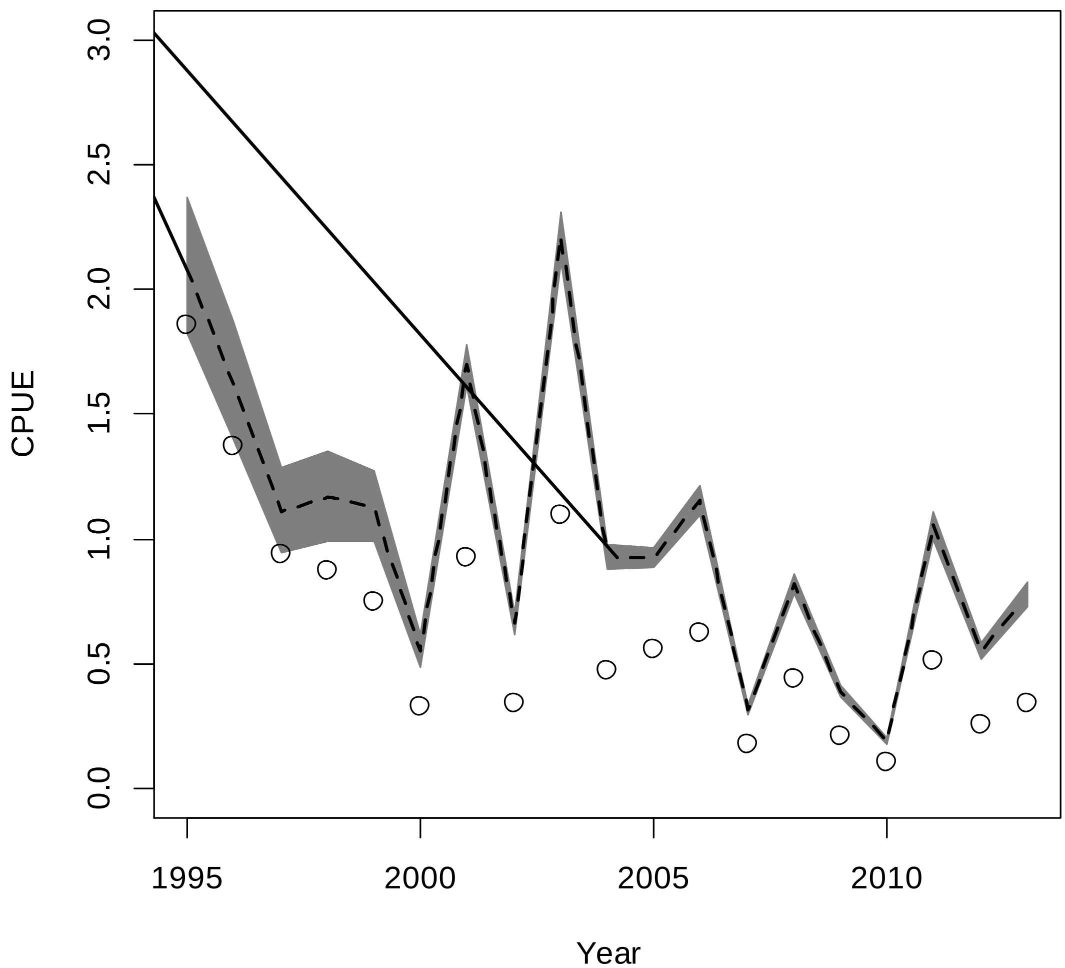


Figure 3. Yearly effects on striped marlin standardized CPUE (catch per standardized longline set) as estimated with the Poisson GLM. The black dash line and shadow represent the means and 95% confidence intervals for the standardized CPUE, respectively. Open circles denote the nominal index (catch per 1000 hooks).



APPENDIX I

GLM Model Summaries

The output from the R “summary” function is presented for each GLM.

Table AI 1. Summary of the binomial GLM from the delta-lognormal analysis.

Table AI 2. Summary of the lognormal GLM from the delta-lognormal analysis.

Table AI 3. Summary of the binomial GLM from the delta-lognormal analysis.

Delta-Lognormal Analysis: Binomial GLM

glm(formula = StrMar_yn ~ Haulyr1 + Quarter1 + Region1 + Hkpfl + SST + SST**2 + offset(log(Hooks)), family = "binomial", data = Observer)

Coefficients:

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	-17.621590	0.655520	-26.882	< 2e-16 ***
Haulyr11996	-0.596658	0.126185	-4.728	2.26e-06 ***
Haulyr11997	-0.807541	0.136524	-5.915	3.32e-09 ***
Haulyr11998	-0.640008	0.132274	-4.838	1.31e-06 ***
Haulyr11999	-0.775670	0.138866	-5.586	2.33e-08 ***
Haulyr12000	-1.750870	0.113882	-15.374	< 2e-16 ***
Haulyr12001	-0.341795	0.103265	-3.310	0.000933 ***
Haulyr12002	-1.380688	0.101766	-13.567	< 2e-16 ***
Haulyr12003	-0.222837	0.102291	-2.178	0.029371 *
Haulyr12004	-1.026984	0.100502	-10.219	< 2e-16 ***
Haulyr12005	-1.020822	0.098438	-10.370	< 2e-16 ***
Haulyr12006	-0.777435	0.099984	-7.776	7.51e-15 ***
Haulyr12007	-2.123352	0.100700	-21.086	< 2e-16 ***
Haulyr12008	-1.391025	0.098756	-14.086	< 2e-16 ***
Haulyr12009	-1.970859	0.099730	-19.762	< 2e-16 ***
Haulyr12010	-2.686840	0.102465	-26.222	< 2e-16 ***
Haulyr12011	-1.245791	0.099225	-12.555	< 2e-16 ***
Haulyr12012	-1.850657	0.099680	-18.566	< 2e-16 ***
Haulyr12013	-1.654585	0.099858	-16.569	< 2e-16 ***
Quarter12	-0.033850	0.026465	-1.279	0.200880
Quarter13	-0.920414	0.031623	-29.106	< 2e-16 ***
Quarter14	-0.082511	0.028334	-2.912	0.003590 **

Coefficients:

	Estimate	Std. Error	z value	Pr(>|z|)
Region12	0.009447	0.201706	0.047	0.962644
Region13	0.763583	0.193080	3.955	7.66e-05 ***
Region14	1.033906	0.192099	5.382	7.36e-08 ***
Region15	1.045306	0.192514	5.430	5.64e-08 ***
Region16	1.680583	0.193155	8.701	< 2e-16 ***
Region17	0.089758	0.196574	0.457	0.647950
Region18	0.965712	0.198684	4.861	1.17e-06 ***
Hkpfl	-0.019362	0.001429	-13.552	< 2e-16 ***
SST	0.908172	0.056912	15.957	< 2e-16 ***
SST**2	-0.019170	0.001256	-15.258	< 2e-16 ***

(Dispersion parameter for binomial family taken to be 1)

Null deviance: 79025 on 60314 degrees of freedom

Residual deviance: 69495 on 60283 degrees of freedom

AIC: 69559

Delta-Lognormal Analysis: Lognormal GLM

glm(formula = log(SM_cpue) ~ Haulyr1 + Quarter1 + Region + Hkpfl + SST + SST**2, family = "gaussian", data = SM_PosCatch)

Coefficients:

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	0.1794101	0.3219372	0.557	0.577340
Haulyr11996	-0.1196373	0.0499611	-2.395	0.016646 *
Haulyr11997	-0.3588157	0.0557119	-6.441	1.21e-10 ***
Haulyr11998	-0.3315590	0.0536866	-6.176	6.70e-10 ***
Haulyr11999	-0.4479145	0.0551091	-8.128	4.60e-16 ***
Haulyr12000	-0.6349260	0.0476131	-13.335	< 2e-16 ***
Haulyr12001	-0.2733873	0.0382321	-7.151	8.90e-13 ***
Haulyr12002	-0.5990938	0.0395496	-15.148	< 2e-16 ***
Haulyr12003	-0.1705108	0.0377728	-4.514	6.39e-06 ***
Haulyr12004	-0.5477453	0.0383237	-14.293	< 2e-16 ***
Haulyr12005	-0.5089072	0.0373786	-13.615	< 2e-16 ***
Haulyr12006	-0.4602009	0.0379630	-12.122	< 2e-16 ***
Haulyr12007	-0.8710250	0.0398240	-21.872	< 2e-16 ***
Haulyr12008	-0.6820230	0.0377253	-18.079	< 2e-16 ***
Haulyr12009	-0.8931112	0.0390565	-22.867	< 2e-16 ***
Haulyr12010	-1.0746096	0.0418753	-25.662	< 2e-16 ***
Haulyr12011	-0.7251841	0.0376380	-19.267	< 2e-16 ***
Haulyr12012	-0.9866008	0.0384657	-25.649	< 2e-16 ***
Haulyr12013	-0.8652666	0.0383576	-22.558	< 2e-16 ***
Quarter12	-0.0755113	0.0121381	-6.221	5.03e-10 ***
Quarter13	-0.2102724	0.0159102	-13.216	< 2e-16 ***
Quarter14	0.0155667	0.0127621	1.220	0.222570

Coefficients:

	Estimate	Std. Error	t value	Pr(>|t|)
Region2	-0.1964614	0.1110211	-1.770	0.076810 .
Region3	-0.0720480	0.1058102	-0.681	0.495931
Region4	0.0176952	0.1053816	0.168	0.866651
Region5	0.0439532	0.1053621	0.417	0.676563
Region6	0.2320934	0.1055359	2.199	0.027875 *
Region7	-0.1753919	0.1072221	-1.636	0.101900
Region8	0.0288353	0.1081656	0.267	0.789791
Hkpfl	-0.0359899	0.0006357	-56.615	< 2e-16 ***
SST	0.0971636	0.0274232	3.543	0.000396 ***
SST**2	-0.0019757	0.0006049	-3.266	0.001093 **

(Dispersion parameter for gaussian family taken to be 0.3920983)

Null deviance: 12310.6 on 22406 degrees of freedom

Residual deviance: 8773.2 on 22375 degrees of freedom

AIC: 42644

Poisson GLM

```
> summary(SM_Poisson_GLM)
glm(formula = Striped_Marlin ~ Haulyr1 + Quarter1 + Region +  Hkpfl + SST + SST**2 + offset(log(Hooks)), family = "poisson",  data = Observer)
```

Coefficients:

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	-1.406e+01	3.649e-01	-38.520	< 2e-16 ***
Haulyr11996	-3.022e-01	4.334e-02	-6.974	3.08e-12 ***
Haulyr11997	-7.371e-01	5.331e-02	-13.827	< 2e-16 ***
Haulyr11998	-5.493e-01	4.967e-02	-11.059	< 2e-16 ***
Haulyr11999	-8.157e-01	5.426e-02	-15.031	< 2e-16 ***
Haulyr12000	-1.578e+00	4.800e-02	-32.867	< 2e-16 ***
Haulyr12001	-4.503e-01	3.366e-02	-13.377	< 2e-16 ***
Haulyr12002	-1.280e+00	3.701e-02	-34.597	< 2e-16 ***
Haulyr12003	-2.082e-01	3.279e-02	-6.349	2.17e-10 ***
Haulyr12004	-9.635e-01	3.474e-02	-27.732	< 2e-16 ***
Haulyr12005	-9.370e-01	3.323e-02	-28.197	< 2e-16 ***
Haulyr12006	-6.670e-01	3.364e-02	-19.827	< 2e-16 ***
Haulyr12007	-2.089e+00	3.913e-02	-53.393	< 2e-16 ***
Haulyr12008	-1.199e+00	3.360e-02	-35.695	< 2e-16 ***
Haulyr12009	-1.927e+00	3.734e-02	-51.602	< 2e-16 ***
Haulyr12010	-2.683e+00	4.432e-02	-60.545	< 2e-16 ***
Haulyr12011	-1.120e+00	3.325e-02	-33.672	< 2e-16 ***
Haulyr12012	-1.818e+00	3.592e-02	-50.609	< 2e-16 ***
Haulyr12013	-1.478e+00	3.473e-02	-42.550	< 2e-16 ***
Quarter12	-1.549e-01	1.289e-02	-12.019	< 2e-16 ***
Quarter13	-8.039e-01	1.753e-02	-45.847	< 2e-16 ***
Quarter14	4.912e-02	1.316e-02	3.733	0.000189 ***

Coefficients:

	Estimate	Std. Error	z value	Pr(>|z|)
Region2	-2.445e-01	1.253e-01	-1.952	0.050958 .
Region3	3.959e-01	1.177e-01	3.364	0.000769 ***
Region4	6.684e-01	1.172e-01	5.703	1.18e-08 ***
Region5	7.279e-01	1.174e-01	6.200	5.65e-10 ***
Region6	1.178e+00	1.174e-01	10.032	< 2e-16 ***
Region7	-4.652e-01	1.209e-01	-3.849	0.000118 ***
Region8	4.711e-01	1.213e-01	3.885	0.000102 ***
Hkpfl	-3.268e-02	7.054e-04	-46.323	< 2e-16 ***
SST	6.436e-01	3.104e-02	20.732	< 2e-16 ***
SST**2	-1.323e-02	6.785e-04	-19.501	< 2e-16 ***

(Dispersion parameter for poisson family taken to be 1)

Null deviance: 131078 on 60314 degrees of freedom

Residual deviance: 98060 on 60283 degrees of freedom

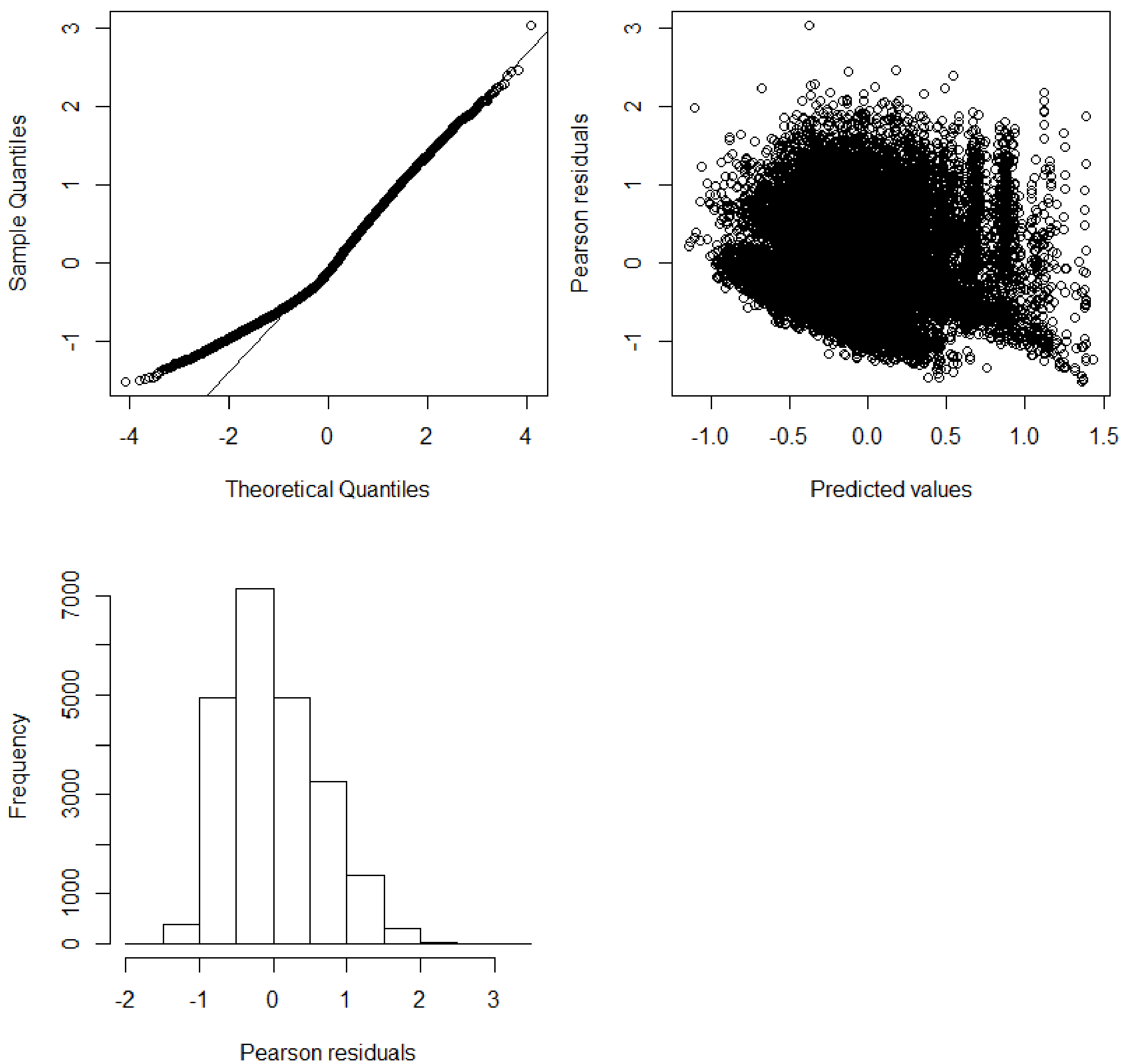
AIC: 154486

APPENDIX II

Residuals plots are presented for each GLM.

Figure AII 1. Residuals from the lognormal GLM in the delta-lognormal analysis are presented as (A) a normal probability plot, (B) a plot of the Pearson residuals on the fitted values, (C) a histogram of the Pearson residuals, and (D) the Pearson residuals plotted on the scale of the linear predictor.

A B



C

D

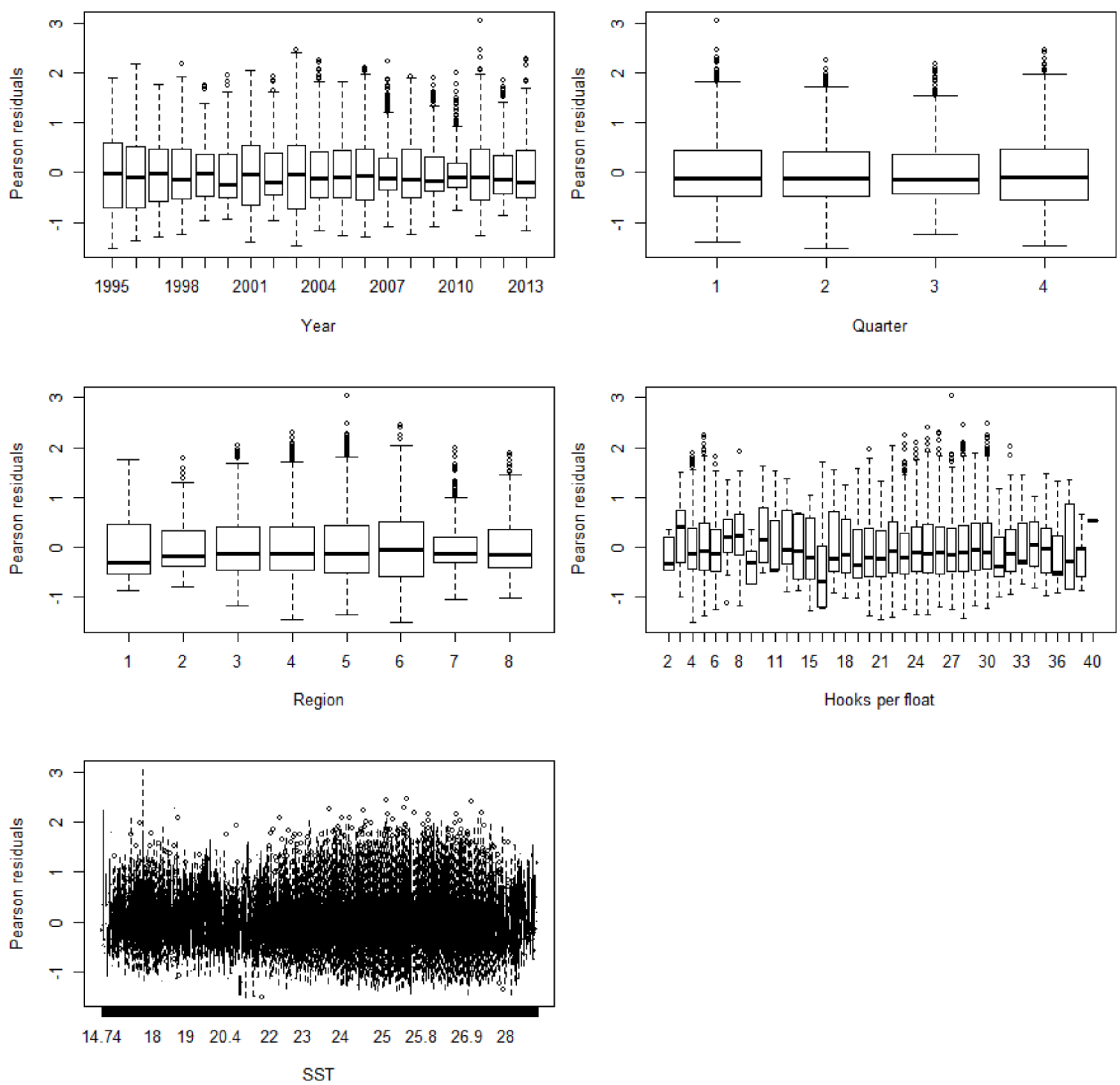
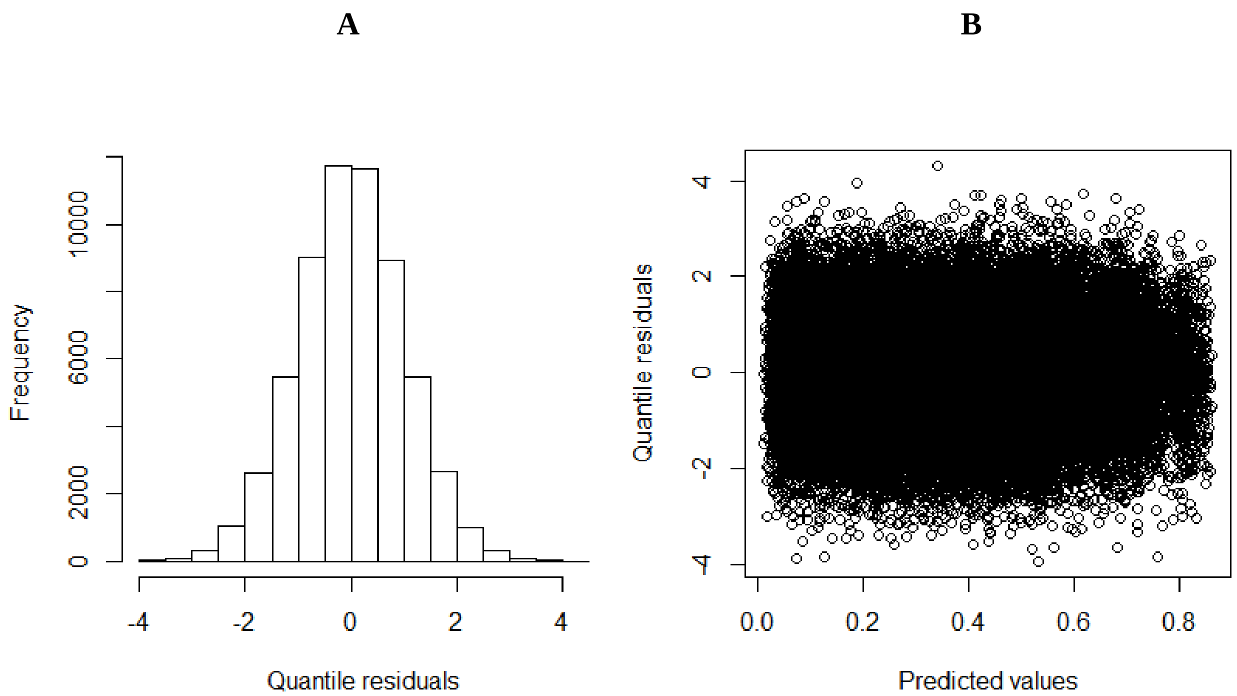

Pearson residuals
3
2
1
0
-1
1995
1998
2001
2004
2007
2010
2013
Year
1
2
3
4
Quarter
1
2
3
4
5
6
7
8
Region
2
4
6
8
11
15
18
21
24
27
30
33
36
40
Hooks per float
14.74
18
19
20.4
22
23
24
25
25.8
26.9
28
SST

Figure AII 2. Residuals from the binomial GLM in the delta-lognormal analysis are presented as (A) a histogram of the quantile residuals, (B) a plot of the quantile residuals on the fitted values, and (C) plots of the quantile residuals on the scale of the linear predictor,



C

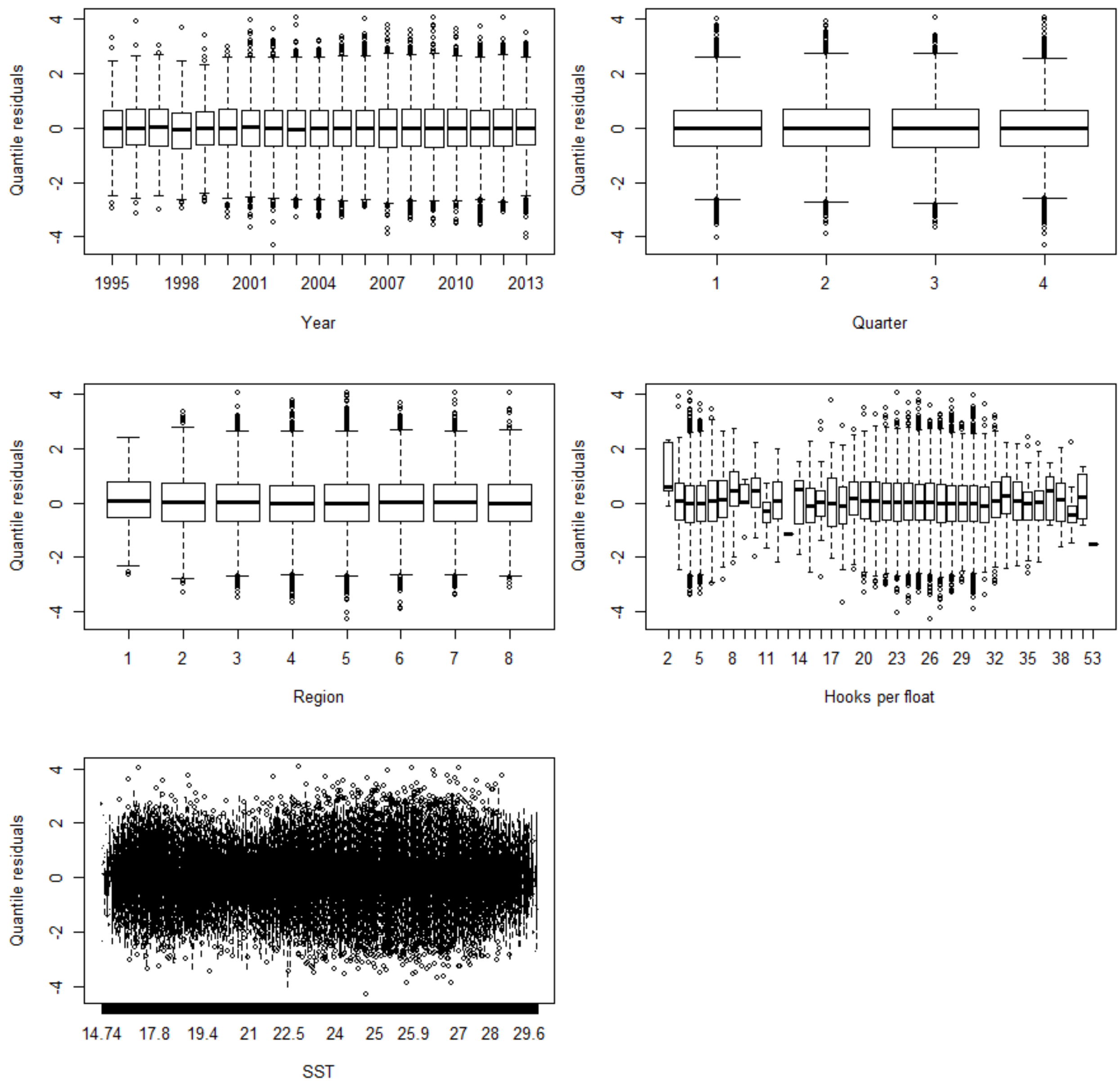
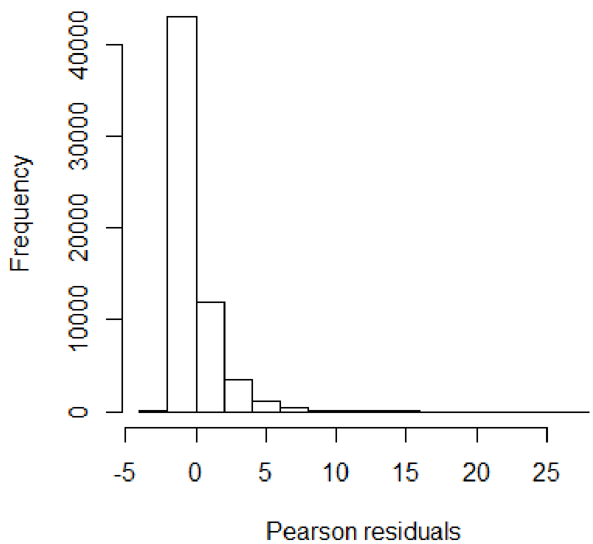
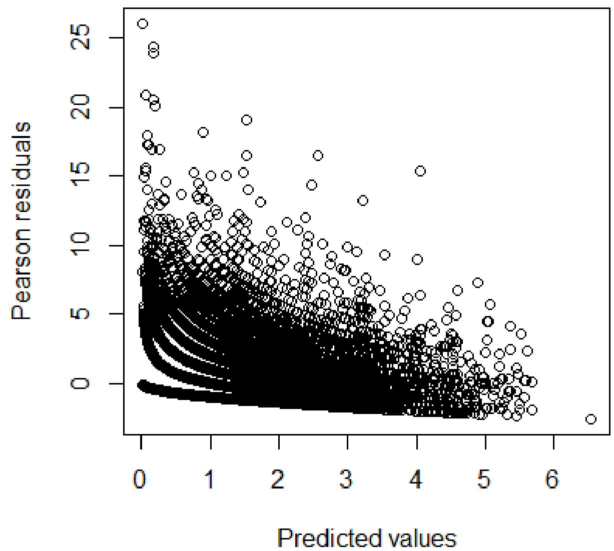

Quantile residuals
Year
1995 1998 2001 2004 2007 2010 2013
Quarter
1 2 3 4
Region
1 2 3 4 5 6 7 8
Hooks per float
2 5 8 11 14 17 20 23 26 29 32 35 38 53
SST
14.74 17.8 19.4 21 22.5 24 25 25.9 27 28 29.6

Figure AII 3. Residuals from the Poisson GLM analysis are presented as a (A) histogram of the Pearson residuals, (B) a plot of the Pearson residuals on the fitted values, and (C) plots of the Pearson residuals on the scale of the linear predictor.

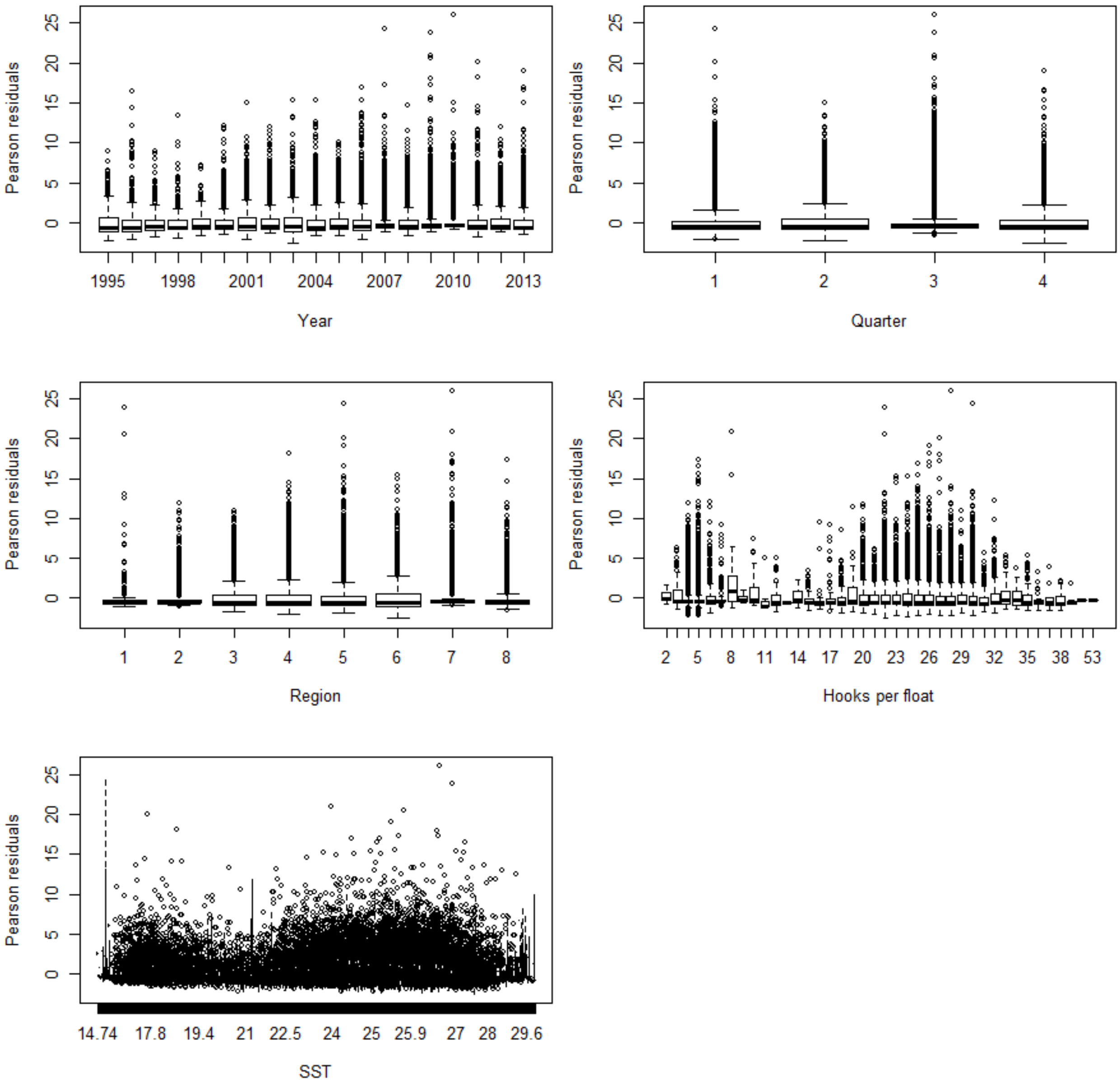
A



B



C


Pearson residuals
Year
1995 1998 2001 2004 2007 2010 2013
Quarter
1 2 3 4
Region
1 2 3 4 5 6 7 8
Hooks per float
2 5 8 11 14 17 20 23 26 29 32 35 38 53
SST
14.74 17.8 19.4 21 22.5 24 25 25.9 27 28 29.6
0 5 10 15 20 25

APPENDIX III

Maps of catches of target species and billfishes by fishery sector during 2007–2011

The following maps are reproduced from Walsh and Brodziak (in press).
Fish.Res.(2014),http://dx.doi.org/10.1016/j.fishres.2014.07.015.

Figure AIII 1. Incidental catches of billfishes and swordfish *Xiphias gladius* as well as target species bigeye tuna *Thunnus obesus* catches as reported by PIROP fishery observers in the deep-set sector of the Hawaii-based pelagic longline fishery during 2007−2011. Eight fishing regions are defined by 10° latitudinal increments and a longitudinal separation at 160°W. Results are by fishing quarters, denoted in the upper left corners of the panels.

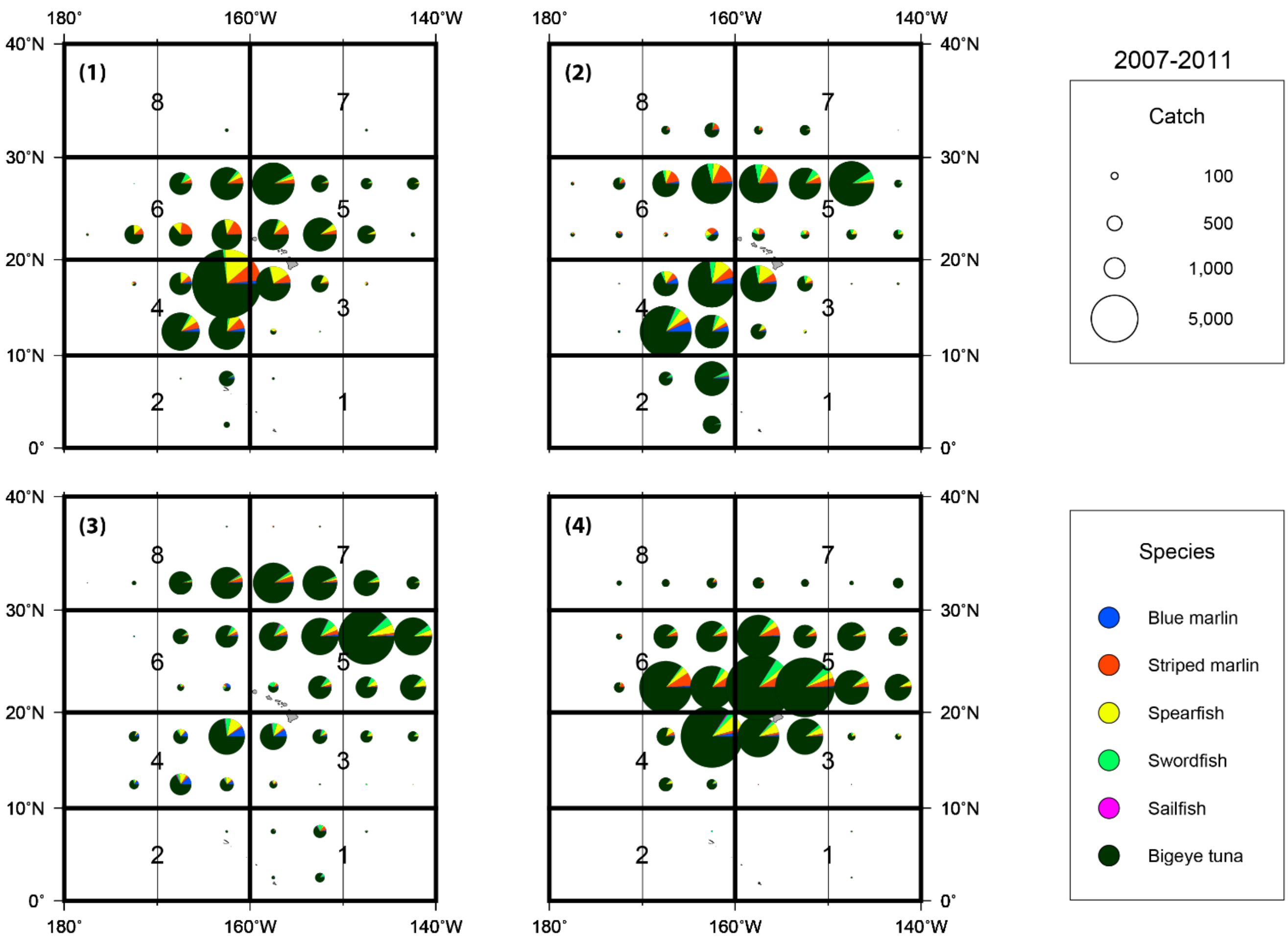


Figure AIII 2. Incidental catches of billfishes and bigeye tuna *Thunnus obesus* as well as target species swordfish *Xiphias gladius* catches as reported by PIROP fishery observers in the shallow-set sector of the Hawaii-based pelagic longline fishery during 2007−2011. Eight fishing regions are defined by 10° latitudinal increments and a longitudinal separation at 160°W. Results are by fishing quarters, denoted in the upper left corners of the panels.