International Scientific Committee for Tuna and Tuna-like Species in the North Pacific Ocean

ISC/09/BILLWG-1/04

Generalized Additive Model Analyses to Standardize Swordfish (Xiphias gladius) Catch Rates in the Hawaii-based Pelagic Longline Fishery, 1995-2007, for use in Stock Assessment

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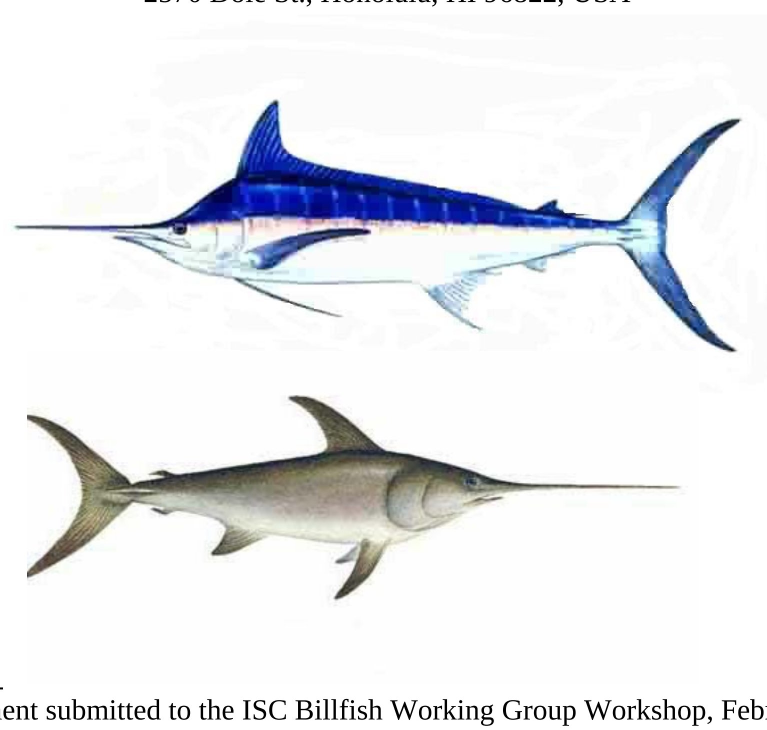

Working document submitted to the ISC Billfish Working Group Workshop, February 3-10, 2009, Honolulu, Hawaii, USA. Document not to be cited without author's written permission.

Generalized Additive Model Analyses to Standardize Swordfish (*Xiphias gladius*) Catch Rates in Hawaii-based Longline Fisheries, 1995 – 2007

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Abstract

This working paper presents analyses to standardize swordfish (*Xiphias gladius*) catch rates in two Hawaii-based longline fisheries, a shallow set fishery and a deep set fishery, during 1995-2007. In the Hawaii-based longline fishery, shallow-sets generally target swordfish, while deep-sets target other species and catch swordfish incidentally. Fishery data used to standardize catch rates included information on environmental conditions and fishing operations and was applied in an attempt to remove the effects of these factors on observed catch rates. Three generalized additive models (GAMs) were fit. Each GAM included the same response and predictor variables. The first GAM was fit to all observed sets (shallow and deep combined). The second GAM was fit to shallow sets separately. The third GAM was fit to deep sets separately. The deviance residuals for the GAM fit to all sets (shallow and deep combined) were not normally distributed and were heteroskedastic when plotted against the predictors. As a result, predicted catch rates were estimated from GAMs fit separately to shallow sets and to deep sets. Two time series of swordfish CPUE are recommended for consideration in stock assessment: Nominal CPUE from observed plus unobserved shallow sets, and GAM-predicted CPUE from observed plus unobserved shallow sets. Two additional time series of swordfish CPUE may be useful for exploratory purposes: Nominal CPUE from observed plus unobserved deep sets, and GAM-predicted CPUE from observed plus unobserved deep sets.

Introduction

This working paper presents analyses to standardize swordfish (*Xiphias gladius*) catch rates in two Hawaii-based longline fisheries, a shallow set fishery and a deep set fishery, during 1995-2007. Swordfish catch rate standardization was based on observer data collected by the Hawaii Longline Observer Program of NOAA Fisheries. Fishery data used to standardize catch rates included information on environmental conditions and fishing operations. In general, the catch rate standardization was applied to attempt to remove the effects of these other factors on observed catch rates. A generalized additive model (GAM) was fit to swordfish catch per set on observed sets. Coefficients from the fitted GAM were applied to unobserved sets from the Hawaii-based longline fishery logbook program of NOAA Fisheries.

In the Hawaii-based longline fishery, shallow-sets generally target swordfish, while deep-sets target other species and catch swordfish incidentally. Swordfish targeted shallow-sets typically begin in the late afternoon/evening, use relatively low numbers of hooks and hooks per float (i.e., < 15 hooks per float) and result in relatively shallow sets. In contrast, deep-sets typically target bigeye-tuna (*Thunnus obesus*) and begin around dawn, use relatively high numbers of hooks and hooks per float (i.e., ≥ 15 hooks per float) and result in relatively deeper sets.

Effort in the Hawaii-based longline fishery has changed during the years 1995 – 2007 as a result of management restrictions designed to reduce turtle bycatch in the swordfish target sector. Prior to December 23, 1999, the longline fishery was unrestricted. From December 23, 1999 to March 14, 2001, the longline fishery was subject to effort limitations, area restrictions, and increased observer coverage on the swordfish target sector. From March 14, 2001 to April 2, 2004 there was a complete prohibition of Hawaii-based longline fishing that targeted swordfish. After April 2, 2004 until the present, the swordfish target sector has been allowed to resume under new guidelines that establish a turtle catch cap and mandate 100% observer coverage and a requirement of circle hooks and fish bait. Prior to management restrictions, swordfish targeted sets were typically prosecuted with j-hooks and squid. The turtle cap was reached in 2006 and Hawaii-based longline fishing that targeted swordfish was prohibited after March of 2006 for the remainder of the year. The turtle cap was not reached in 2005 or 2007.

Observed swordfish catches presented in this report were provided by the NOAA Fisheries Observer Program which places biological observers on-board commercial fishing vessels. The percentage of commercial vessels covered by NOAA observers has changed during the years 1994 – 2007. Observer coverage began in 1994. Observers covered roughly half of the swordfish targeted sets in 1994 (48%). From 1995–1999, the allocation of observer coverage was reduced to approximate fleet-wide effort and about 1/10 of swordfish targeted sets were observed (10-13% by year). Observer coverage increased on swordfish targeted sets in 2000 and 2001, but the fishery was subject to effort and area restrictions as outlined above until April 2004. After April 2004, swordfish targeted sets resumed under mandatory 100% observer coverage. The deep-set sector has had 20% observer coverage since April, 2004.

Unobserved swordfish catches presented in this report were provided by commercial fishing vessels to the NOAA Fisheries Logbook Program. Logbook catch and effort data for swordfish in the Hawaii-based longline fishery were available from 1990 – 2007. However, several predictors used in the GAM analysis, were not available prior to 1995. As a result, this GAM analysis of observed and unobserved swordfish catches in the Hawaii-based longline fishery was necessarily limited to the years 1995 – 2007.

Methods

Three GAMs were fit. Each GAM included the same response and predictor variables. The first GAM was fit to all observed sets (shallow and deep combined). The second GAM was fit to shallow sets separately. The third GAM was fit to deep sets separately.

GAMs were fit to observed swordfish catch rates (log(catch)) using procedures outlined in Walsh et al. (2002; 2005; 2006)

$$\log(\mu) = \sum_{j=1}^{p} S_j\left(x_j, d_j\right),$$

where

μ represents the conditional mean catch for the set of predictors ($x_1, x_2, \ldots x_p$),

S_j represents the smoother function, and

d_j represents the degrees of freedom.

Catch per set was the response variable. An overdispersed Poisson model for catch rates was assumed, with a natural log link function, and with the overdispersion parameter estimated automatically.

Seven predictive variables were included in the GAM analyses: (1) begin-set time as a factor with 6 levels, one for every 4 hrs; (2) date of fishing as a factor with one level for each year/quarter; (3) latitude; (4) number of hooks per float; (5) number of hooks total; (6) sea surface temperature (SST°C), and (7) longitude. Order of entry was predicated upon reduction in the Akaike Information Criterion (AIC).

Predictors were chosen from a combination of operational and environmental predictors based on analogy with blue marlin, *Makaira nigricans* (Walsh et al. 2006). Walsh et al. (2006) demonstrated that the operational predictor hooks per float was informative and significantly affected longline catch of blue marlin. Hooks per float has not been used earlier because it was correlated with the number of hooks and was not recorded as consistently in logbooks prior to 2005. Bigelow et al. (1999) and Walsh et al. (2006) also demonstrated that environmental predictors such as sea surface temperature were informative and significantly affected longline catch of swordfish and blue marlin. As a result, hooks per float and sea surface temperature were included here. Yellowfin tuna/set and bigeye tuna/set were not included as potential swordfish predictors because these variable explained relatively little deviance (<1%) in Walsh et al. (2006)'s analyses.

Some predictive variables were correlated, as expected. For example, SST and latitude, were significantly negatively correlated (r = -0.367; df = 29654; P < 0.001). Similarly, hook numbers, hooks per float, and begin-set time were operational variables designed to serve as a proxy for the species targeted by the longline set.

The degrees of freedom were chosen based upon a sensitivity analysis conducted with the same predictors for blue marlin (Walsh et al. 2006). The initial blue marlin GAM was allotted 4 degrees of freedom per year per predictor. The final blue marlin GAM was allotted 70% fewer degrees of freedom for each predictor, except date. The sensitivity analysis showed that the final GAM with fewer degrees of freedom was both more parsimonious and had more accurate predictions (Walsh et al. 2006). The degrees of freedom for the swordfish GAM presented here are consistent with the final blue marlin GAM.

Maunder and Punt (2004) note that there is no standard inference for generalized linear model (GLM) or GAM performance. In practice, Maunder and Punt (2004) suggest that relative model fit is measured by deviance. Venables and Dichmont (2004) define the deviance as the difference, distributed as a chi-squared statistic under the null hypothesis, that the reduced model explains as much variability as the full model. Maunders and Punt (2004) also recommend an ad-hoc way to deal with adding variables based on relative increases in deviance by only adding explanatory variables if the deviance is reduced by a pre-specified percentage (e.g., 0.5 or 2%).

Here, an analysis of deviance was conducted following Walsh et al. (2006) by fitting the GAMs one-step-ahead. For each GAM, a pseudo-R^2 value (ρ^2) was evaluated to measure the goodness of model fit from the null deviance (D_{NULL}) and residual deviance ($D_{RESIDUAL}$) as

$$\rho^2 = \left(D_{NULL} - D_{RESIDUAL}\right) / D_{NULL} .$$

The deviance explained was then the difference in ρ^2 from the full and reduced (or Null) model. Similarly, change in AIC (ΔAIC) and change in residual deviance (ΔResidual deviance) were also calculated from the full and reduced (or Null) model. A deviance percentage for adding explanatory variables was not pre-specified. Instead, the reduction in deviance from the addition of each explanatory variable was reported as the percentage of deviance explained.

Diagnostics for model fit were evaluated using the deviance residuals from each fitted GAM. Venables and Dichmont (2004) note that there are many definitions for residuals in GAMs and suggest that the most widely used residuals are deviance residuals. The deviance residual for an observation is defined by Venables and Dichmont (2004) as the signed square root of the deviance increment for that observation; then just as the squares of the residuals in a linear model add to the residual sum of squares, the squares of the deviance residuals add to the deviance in a GAM. Venables and Dichmont (2004) suggest that once the deviance residuals are calculated, diagnostics are analogous to those for linear regression except that residuals from linear regression are replaced with deviance residuals from GAMs. Venables and Dichmont (2004) caution that deviance residuals may be unsatisfactory for binary data and other frequency data with small numbers, but otherwise, discreetness in the data is not a problem.

Coefficients from the GAM fitted to observed sets were applied to unobserved sets from the Hawaii-based longline fishery NOAA Fisheries logbook program. Predicted catch per set was obtained by applying coefficients from the fitted GAM to observed and unobserved sets. Predicted catch per set was divided by the number of hooks and re-expressed as catch-per-unit-effort (CPUE with units of swordfish per 1000 hooks). Mean predicted catch rates were examined separately for shallow-sets (i.e., $<$ 15 hooks per float) and deep-sets (i.e., $\geq$ 15 hooks per float). Predicted swordfish catch rates were compared to nominal catch rates on both observed and unobserved sets with correlations of both raw data and mean data at quarterly time step.

Trends in standardized CPUE were computed separately for the shallow sets and deep sets to depict the swordfish targeted and incidental catches respectively. Trends in standardized CPUE were estimated from the exponent of the fitted coefficients for year/quarter multiplied by the mean CPUE in 1995 Q1. Linear regression was used to evaluate the slope of the resulting standardized trend in observed CPUE (swordfish per 1000 hooks) relative to 1995 Q1.

Results

31,622 observed longline sets were available for the analysis during the years 1995 – 2007. The data were limited to 29,736 sets by removing sets with missing predictors. The data were further limited to a total of 29,654 observed sets by removing sets below the equator. As a result, a total of 29,654 observed sets were included in the GAM analysis for shallow and deep sets combined (Table 1-A).

An additional 56 observed shallow-sets were removed during Hawaii-longline prohibition on shallow-sets for swordfish (2001 Q2 – 2004 Q3, and 2006 Q2 – 2006 Q4). The shallow sets in the database corresponded to rope-gear rather than monofilament, or were misclassified sets. Rope-gear should probably be re-classified as deep-sets because the gear sinks deeper than monofilament with the same number of hooks per float. As a result, a total of 5,866 observed shallow sets were included in the GAM analysis for shallow sets (Table 1-B). A total of 23,732 observed deep sets were included in the GAM analysis for deep sets. (Table 1-C).

152,038 unobserved longline sets were available for the analysis during the years 1995 – 2007. For GAM analysis, the data were limited to 143,429 sets by removing sets with missing predictors. The data were further limited by removing unobserved sets with predictor values that were outside the range of predictor values for observed sets (e.g., Appendix A). As a result, a total of 143,091 unobserved sets were included in the GAM analysis for shallow and deep sets combined (Table 2-A). A total of 25,729 unobserved shallow sets were included in the GAM analysis for shallow sets (Table 2-B). A total of 116,983 unobserved deep sets were included in the GAM analysis for deep-sets (Table 2-C).

40% of all observed sets (shallow and deep combined) captured at least one swordfish, 96% of observed shallow-sets captured at least one swordfish, and 26% of observed deep-sets captured at least one swordfish (e.g., Appendix A, Figure 1-A). 25% of unobserved sets (shallow and deep combined) captured at least one swordfish, 84% of unobserved shallow sets captured at least one swordfish, and 12% of unobserved deep sets captured at least one swordfish (e.g., Appendix A, Figure 1-B).

GAM Fits

The swordfish GAM fit to all sets (shallow and deep combined) explained 83% of the null deviance of observed swordfish catch per set (Table 3-A). All predictors yielded highly significant deviance reductions (all F-tests, $P < 0.001$), but only the predictors begin set time and year/quarter each individually explained more than 1% of the null deviance (Table 3-A).

The swordfish GAM fit separately to shallow sets explained 45% of the null deviance of observed swordfish catch per set (Table 3-B). All predictors yielded highly significant deviance reductions (all F-tests, $P < 0.001$). The predictors begin set time, year/quarter, latitude, number of hooks, longitude, and hooks per float each individually explained more than 1% of the null deviance (Table 3-B).

The swordfish GAM fit separately to deep sets explained 18% of the null deviance of observed swordfish catch per set (Table 3-C). All predictors yielded highly significant deviance reductions (all F-tests, $P < 0.001$). Only the predictors year/quarter, latitude, sea surface temperature, and number of hooks each individually explained more than 1% of the null deviance (Table 3-C).

GAM Diagnostics

Smoother plots were produced for each predictor to depict the effect of individual predictors on the logarithm of catch (Appendix B). The relative influence of each predictor on the response variable can be inferred by comparing the scale of the change on the y-axis between predictors. The stippled lines represent one standard error. Rug plots along the x-axis depict the distribution of the values (sample size) of the predictors.

Qqnorm plots of deviance residuals were produced for each fitted GAM (Appendix C). The deviance residuals were normally distributed for the GAM fit to observed shallow sets (Appendix C; Figure 1-B). The deviance residuals were not normally distributed for the GAM fit to all sets (shallow and deep combined) or for the GAM fit separately to deep sets (Appendix C; Figures 1-A, and 1-C). The deviance residuals for these GAMs had a larger than expected proportion of residuals piled up over a narrow region, possibly suggesting difficulty estimating the large number of zero catches (Appendix C; Figures 1-A, and 1-C).

Deviance residuals were plotted against each predictor for each fitted GAM (Appendix C). Deviance residuals were heteroskedastic for the GAM fit to all sets (shallow and deep combined) for the predictors latitude, hooks per float, and number of hooks (Appendix C – Figure 2). The heteroscedasticity in deviance residuals was largely removed by fitting the GAMs separately for shallow and deep sets (Appendix C – Figures 3 and 4).

GAM Predicted Catch Rates

Predicted catch rates were estimated from GAMs fit separately to shallow sets and to deep sets. The GAM fit to all sets (shallow and deep combined; not shown here) yielded a large discrepancy between predicted and nominal catches for the deep-sets and indicated that there was a mismatch between the fitted GAM and the observed values for deep-sets. The GAM fit to all sets (shallow and deep combined) had more accurate predictions of shallow set catches. Given that most of the swordfish catch (>90%) is taken on directed shallow sets, we interpreted the poor predictive capacity of the fitted GAM (shallow and deep combined) on deep-sets to indicate model misspecification. This result along with the heteroscedastic residuals of the fitted GAM (shallow and deep combined) suggested that GAMs be fit separately for shallow and deep sets.

For the GAM fit separately to shallow sets, mean nominal and predicted CPUE per quarter from observed sets were highly correlated ($r = 0.99$, df = 34, $P < 0.001$, Figure 1-A). Nominal and predicted CPUE per quarter for unobserved sets were also highly correlated ($r = 0.84$, df = 29, $P < 0.001$, Figure 1-B). There were no predictions for shallow-set longline CPUE between 2001 Q2 and 2004 Q3 and again between 2006 Q2 and 2006 Q4 coinciding with the prohibition of swordfish targeted sets in the Hawaiian longline fishery. The relatively large sample sizes and small standard errors for the predictor year/quarter beginning in 2004 Q4 reflect the nearly 100% observer coverage for the shallow set swordfish target sector beginning in 2004 Q4 (Appendix A, Figure 3-A). In contrast, there were very few unobserved shallow sets after the 2000 Q2 (Appendix A, Figure 3-B). This may explain the relatively large discrepancies between predicted CPUE and nominal CPUE for unobserved shallow-sets beginning in year 2000 (Figure 1-B.)

For the GAM fit separately to deep sets, mean nominal and predicted CPUE per quarter from observed sets were not significantly correlated (r = 0.29, df = 50, P = 0.03, Figure 2-A). Nominal and predicted CPUE per quarter for unobserved sets were significantly correlated (r = 0.42, df = 50, P = 0.001, Figure 2-B). There were relatively large discrepancies between predicted CPUE and nominal CPUE prior to year 2000 for both observed and unobserved deep sets (Figures 2-A, and 2-B.). The discrepancies prior to year 2000 may reflect the relatively low number of observed deep sets prior to 2000 (Appendix A, Figure 3-B).

For the GAMs fit separately to shallow sets and to deep sets, the linear trends in CPUE were not significant, P = 0.2 and P = 0.5 respectively (Figures 3-A, and 3-B).

Discussion

Walsh et al. (2006) concluded that GAMs for blue marlin, with relatively fewer degrees of freedom were both more parsimonious and had more accurate predictions. Walsh et al. (2006) demonstrated that the operational predictor hooks per float was informative and significantly affected longline catch of blue marlin. Hooks per float has not been used earlier because it was correlated with the number of hooks and was not recorded as consistently in logbooks prior to 2005. Bigelow et al. (1999) and Walsh et al. (2006) also demonstrated that environmental predictors such as sea surface temperature were informative and significantly affected longline catch of swordfish and blue marlin. The GAM used here was similar to the reduced degrees of freedom model (predictive model) of Walsh et al. (2006) with an additional operational predictor for hooks per float and an environmental predictor for sea surface temperature.

The deviance residuals for the GAM fit to all sets (shallow and deep combined) were not normally distributed (Appendix C; Figures 1-A) and were heteroskedastic when plotted against the predictors latitude, hooks per float, and number of hooks (Appendix C – Figure 2). The heteroscedasticity in deviance residuals was largely removed by fitting the GAMs separately for shallow and deep sets (Appendix C – Figures 3 and 4). Additionally, there were large differences in catch rates between the shallow- and deep-set sectors of the Hawaii-based longline fishery, reflecting the fact that swordfish is targeted by the former and taken incidentally in the latter (Figures 1 and 2). The large difference in catch rates suggests that the variability in the response variable (swordfish catch) likely differs between target sectors. The heteroskedastic residuals from the GAM fit to all sets (shallow and deep combined) and the large difference in catch rates between target sectors support the separate GAM analysis for the shallow and deep sets.

The GAM fit separately to shallow sets, suggests that there was not a significant linear trend in shallow-set CPUE during the years 1995 – 2007 (Figure 3-A). The GAM predicted CPUE for both observed and unobserved sets appeared to increase in 2000 (Figures 1-A and 1-B). However, the apparent increase in swordfish CPUE was coincident with management actions beginning December 23, 1999 and extending to March 14, 2001 which included effort limitations, area restrictions, and increased observer coverage on the swordfish target sector. Swordfish targeted sets were prohibited from March 14, 2001 until April 2, 2004. After April 2, 2004 until the present, the swordfish target sector has been allowed to resume under new guidelines that establish a turtle catch cap, mandated 100% observer coverage, required use of circle hooks and fish bait. Prior to management restrictions, swordfish targeted sets were typically prosecuted with j-hooks and squid. We don't know the effect on CPUE of changing to circle hooks and fish bait as there was no overlap with previous tuna hooks and squid bait. These apparent increases in CPUE coincident with management restrictions in place after Dec 23, 1999 suggest that management actions may have affected the catchability of swordfish in the Hawaii-based longline fishery beginning in 2000 Q1. These changes in catchability may not be accounted for by the set of variables used in the standardization.

The GAM fit separately to deep sets suggests that there was not a significant linear trend in deep-set CPUE during the years 1995 – 2007 (Figure 3-B). However, the deviance residuals for the GAM fit to deep sets were not normally distributed (Appendix C; Figures 1-C). Deviance residuals plotted against the predictors year quarter and begin set time were not normally distributed (Appendix C – Figure 4). The deviance residuals were also somewhat heteroskedastic when plotted against the predictor latitude (Appendix C – Figure 4). Together, these diagnostics suggest that the GAM fit separately to deep sets may not have fit the large number of zero catches accurately and that caution should be used when interpreting the predictions from the GAM fit to deep sets.

Conclusions

Two time series of swordfish CPUE are recommended for consideration in stock assessment: Nominal CPUE from observed plus unobserved shallow sets, and GAM-predicted CPUE from observed plus unobserved shallow sets. Two additional time series of swordfish CPUE may be useful for exploratory purposes: Nominal CPUE from observed plus unobserved deep sets, and GAM-predicted CPUE from observed plus unobserved deep sets.

GAM	Type	Year Quarter	Excluding
Shallow-set	Nominal CPUE	1995 Q1 – 2007 Q4	2001 Q2 – 2004 Q3 2006 Q2 – 2006 Q4
Shallow-set	GAM predicted CPUE	1995 Q1 – 2007 Q4	2001 Q2 – 2004 Q3 2006 Q2 – 2006 Q4
Deep-set	Nominal CPUE	1995 Q1 – 2007 Q4	Exploratory purposes only
Deep-set	GAM predicted CPUE	1995 Q1 – 2007 Q4	Exploratory purposes only

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Tables

Table 1. Data included in the GAM analyses from observed sets.

A. Observed Sets (Shallow and Deep Combined)

Variable	N	Min.	Max.	Mean	Stdev	CV
Swordfish catch (n)	29,654	0.00	73.00	2.79	6.07	217.79
Begin-set time (hrs)	29,654	0.00	2359.00	978.65	486.88	49.75
Year/Quarter	29,654	1995.125	2007.875			
Latitude (°N)	29,654	0.22	44.51	21.84	6.65	30.46
Hooks (n)	29,654	19.00	4,110.00	1,777.59	588.24	33.09
Hooks per float (n)	29,654	2.00	53.00	22.64	9.51	42.01
Longitude (°W)	29,654	-179.96	-137.95	-158.72	5.58	-3.52
SST (°C)	29,654	14.71	30.31	25.47	2.30	9.04
Vessel length (m)	29,654	32.00	94.00	71.03	10.25	14.43

B. Observed Shallow Sets

Variable	N	Min.	Max.	Mean	Stdev	CV
Swordfish catch (n)	5,866	0.00	73.00	12.51	8.06	64.46
Begin-set time (hrs)	5,866	0.00	2359.00	1867.99	358.40	19.19
Year/Quarter	5,866	1995.125	2007.875			
Latitude (°N)	5,866	15.08	44.51	29.82	3.97	13.31
Hooks (n)	5,866	19.00	1,285.00	825.18	153.74	18.63
Hooks per float (n)	5,866	2.00	14.00	4.31	0.78	18.00
Longitude (°W)	5,866	-179.96	-138.11	-158.26	7.64	-4.83
SST (°C)	5,866	14.71	28.28	23.19	3.15	13.59
Vessel length (m)	5,866	52.10	91.40	77.62	6.04	7.78

C. Observed Deep Sets

Variable	N	Min.	Max.	Mean	Stdev	CV
Swordfish catch (n)	23,732	0.00	24.00	0.38	0.86	225.30
Begin-set time (hrs)	23,732	0.00	2358.00	758.37	139.16	18.35
Year/Quarter	23,732	1995.125	2007.875			
Latitude (°N)	23,732	0.22	35.45	19.86	5.63	28.34
Hooks (n)	23,732	19.00	4,110.00	2,015.06	379.56	18.84
Hooks per float (n)	23,732	15.00	53.00	27.20	2.94	10.79
Longitude (°W)	23,732	-173.68	-137.95	-158.83	4.93	-3.11
SST (°C)	23,732	16.74	30.31	26.03	1.60	6.14
Vessel length (m)	23,732	32.00	94.00	69.40	10.42	15.02

Table 2. Data included in the GAM analyses from unobserved sets.

A. Unobserved Sets (shallow and deep combined)

Variable	N	Min.	Max.	Mean	Stdev	CV
Swordfish catch (n)	143,091	0.00	62.00	1.55	4.28	277.03
Begin-set time (hrs)	143,091	0.00	2400.00	927.11	453.62	48.93
Year/Quarter	143,091	1995.125	2007.875			
Latitude (°N)	143,091	0.23	45.43	21.10	6.07	28.76
Hooks (n)	143,091	21.00	4,100.00	1,734.29	563.07	32.47
Hooks per float (n)	143,091	2.00	53.00	23.68	9.40	39.71
Longitude (°W)	143,091	-179.95	-138.00	-159.37	5.61	-3.52
SST (°C)	143,091	14.71	30.31	25.06	2.44	9.72
Vessel length (m)	143,091	32.00	94.00	68.46	10.80	15.78

B. Unobserved Shallow Sets

Variable	N	Min.	Max.	Mean	Stdev	CV
Swordfish catch (n)	25,729	0.00	62.00	7.77	7.23	93.00
Begin-set time (hrs)	25,729	0.00	2400.00	1725.28	514.82	29.84
Year/Quarter	25,729	1995.125	2007.875			
Latitude (°N)	25,729	1.15	45.43	27.51	4.88	17.72
Hooks (n)	25,729	40.00	2,200.00	800.92	149.38	18.65
Hooks per float (n)	25,729	2.00	14.00	4.69	1.45	30.97
Longitude (°W)	25,729	-179.95	-138.00	-160.18	8.28	-5.17
SST (°C)	25,729	14.71	28.36	22.23	3.14	14.13
Vessel length (m)	25,729	44.30	92.70	74.17	8.10	10.92

C. Unobserved Deep Sets

Variable	N	Min.	Max.	Mean	Stdev	CV
Swordfish catch (n)	116,983	0.00	38.00	0.18	0.71	400.36
Begin-set time (hrs)	116,983	0.00	2359.00	750.85	142.65	19.00
Year/Quarter	116,983	1995.125	2007.875			
Latitude (°N)	116,983	0.23	41.27	19.68	5.35	27.19
Hooks (n)	116,983	21.00	4,100.00	1,942.11	381.72	19.65
Hooks per float (n)	116,983	15.00	53.00	27.89	3.18	11.41
Longitude (°W)	116,983	-177.85	-138.50	-159.20	4.81	-3.02
SST (°C)	116,983	16.44	30.31	25.69	1.71	6.66
Vessel length (m)	116,983	32.00	94.00	67.20	10.93	16.26

Table 3. Analysis of deviance of observed swordfish catches, January 1995 – December 2007. Entries are the reductions in the Akaike Information Criterion and residual deviance, the *F*-test and its significance, and the stepwise percent deviance reductions.

A. Swordfish GAM fit to Shallow and Deep Sets Combined

Predictor	AIC	Δ AIC	Δ Residual deviance	Pesudo R^2	d.f. (npar)	F_{enter}	*P*	Deviance explained
Null	244,085.6		244,083.6					
Begin-set time (Factor)	51,542.2	192,543.4	192,553.4	78.9	5	21,071.0	< 0.001	**78.89**
Year/Quarter (Factor)	47,126.9	4,415.4	4,517.4	80.7	51	50.9	< 0.001	**1.85**
Latitude (°N)	45,466.0	1,660.8	1,680.2	81.4	8.8	101.3	< 0.001	0.69
Hooks (n)	44,229.7	1,236.3	1,245.9	81.9	3.8	152.8	< 0.001	0.51
Hooks per float (n)	43,185.6	1,044.2	1,053.7	82.4	3.8	134.5	< 0.001	0.43
Longitude (°W)	42,708.6	476.9	496.4	82.6	8.7	31.1	< 0.001	0.20
SST (°C)	42,311.8	396.8	406.8	82.7	3.8	52.0	< 0.001	0.17
Vessel length (m)	42,269.1	42.7	52.5	82.8	3.9	6.9	< 0.001	0.02
Total								**82.7**

B. Swordfish GAM fit to Shallow Sets

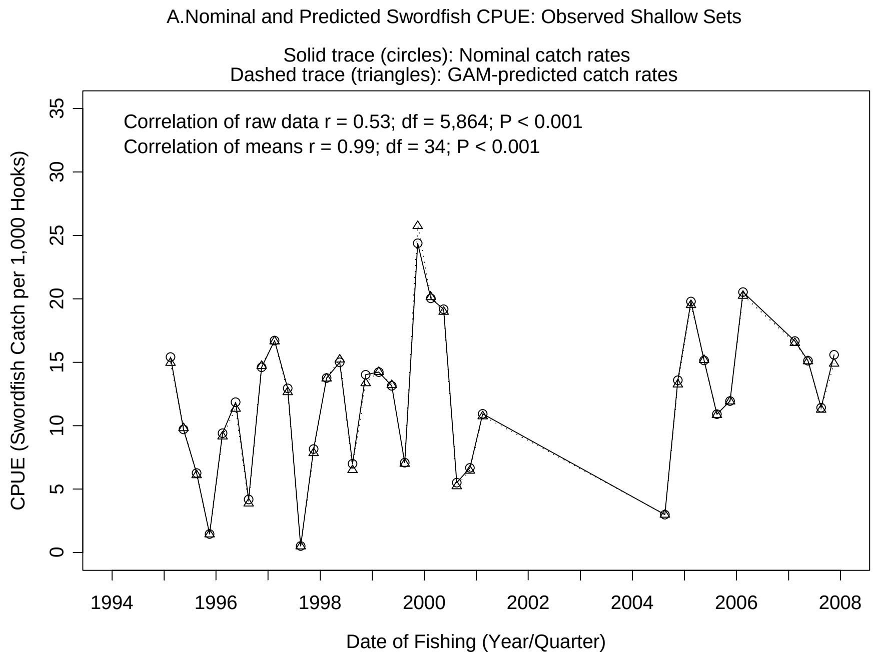
Predictor	AIC	Δ AIC	Δ Residual deviance	Pesudo R^2	d.f. (npar)	F_{enter}	*P*	Deviance explained
Null	31,861.1		31,859.1					
Begin-set time (Factor)	24,558.2	7,302.9	7,312.4	23.0	4.8	410.7	< 0.001	**23.0**
Year/Quarter (Factor)	21,564.1	2,994.1	3,059.7	32.6	32.8	28.5	< 0.001	**9.6**
Latitude (°N)	20,173.9	1,390.2	1,409.8	37.0	9.8	47.1	< 0.001	**4.4**
Hooks (n)	19,055.2	1,118.7	1,128.8	40.5	5.1	76.7	< 0.001	**3.5**
Longitude (°W)	18,266.8	788.4	808.4	43.1	10.0	29.5	< 0.001	**2.5**
Hooks per float (n)	17,735.0	531.7	541.6	44.8	4.9	40.7	< 0.001	**1.7**
SST (°C)	17,606.2	128.8	138.7	45.2	5.0	10.4	< 0.001	0.4
Vessel length (m)	17,548.7	57.5	67.6	45.4	5.0	5.0	< 0.001	0.2
Total								**45.1**

C. Swordfish GAM fit to Deep Sets

Predictor	AIC	Δ AIC	Δ Residual deviance	Pesudo R^2	d.f. (npar)	F_{enter}	*P*	Deviance explained
Null	27,681.9		27,679.9					
Year/Quarter (Factor)	24,599.4	3,082.5	3,184.5	11.5	51	44.8	< 0.001	**11.5**
Latitude (°N)	24,049.2	550.2	570.2	13.6	8.5	40.7	< 0.001	**2.1**
SST (°C)	23,536.2	513.0	523.0	15.5	3.7	81.8	< 0.001	**1.9**
Hooks (n)	23,255.4	280.8	290.8	16.5	4.0	45.8	< 0.001	**1.1**
Hooks per float (n)	23,032.0	223.3	230.8	17.3	3.7	51.7	< 0.001	0.8
Begin-set time (Factor)	22,863.5	168.5	179.4	18.0	5	27.2	< 0.001	0.6
Longitude (°W)	22,825.2	38.3	56.7	18.2	8.5	5.1	< 0.001	0.2
Vessel length (m)	22,811.5	13.7	23.2	18.3	3.7	4.1	< 0.001	0.1
Total								**18.2**

Figures

Figure 1. Nominal (solid trace) and predicted (dashed trace) swordfish CPUE from the swordfish GAM fit to observed shallow-sets.



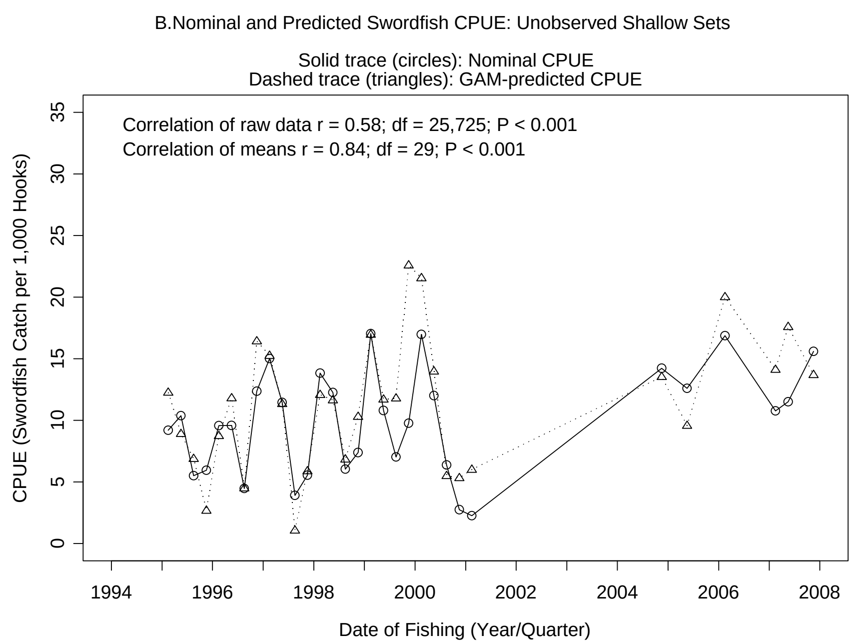
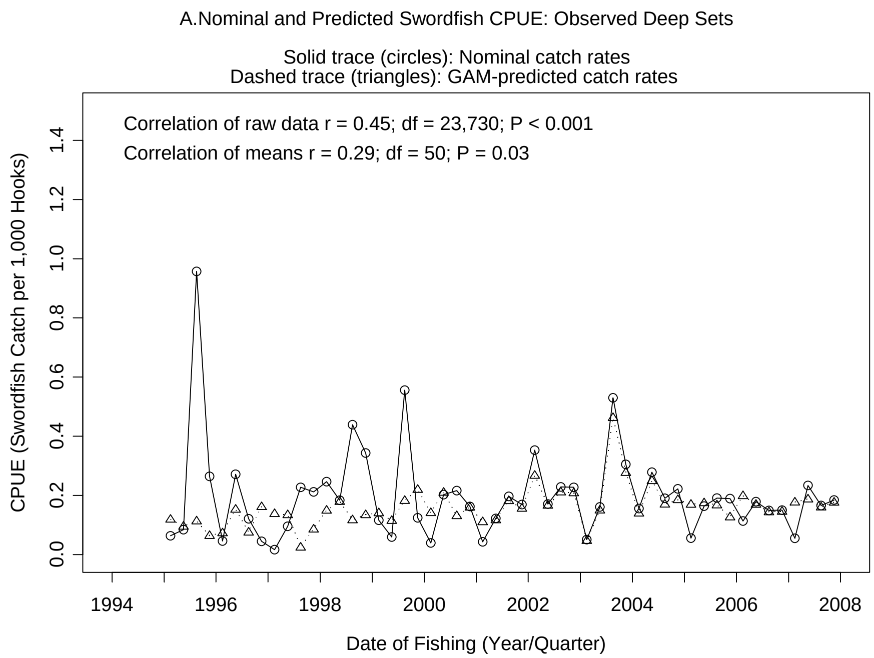


Figure 2. Nominal (solid trace) and predicted (dashed trace) swordfish CPUE from the swordfish GAM fit to deep-sets.



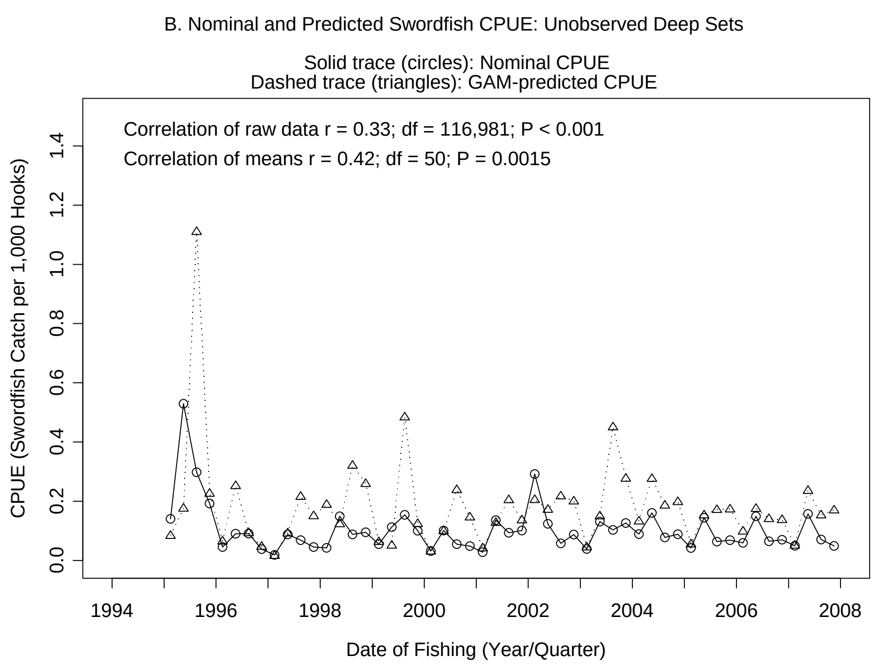
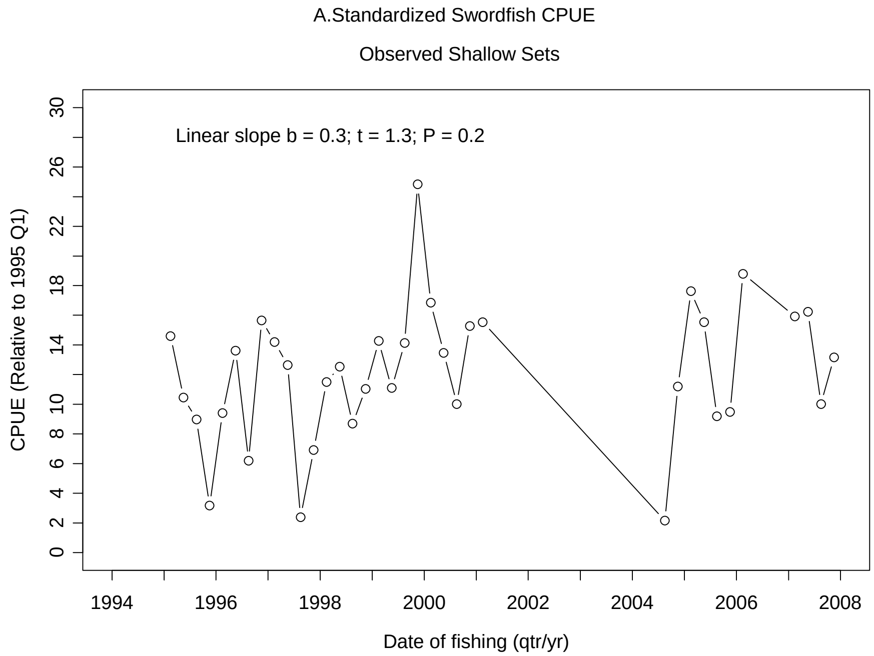
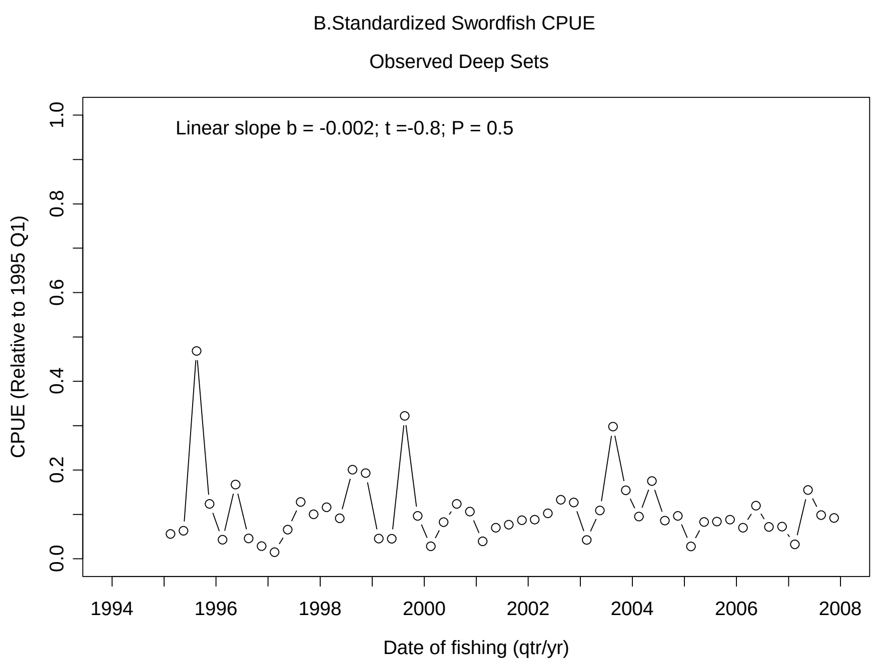


Figure 3. Standardized trends in swordfish CPUE from GAMs fit separately to observed shallow sets and to observed deep sets.





Appendix A – Frequency of Occurrence (Sets) by Predictor

Figure 1-A. Swordfish Catch: Observed Sets.

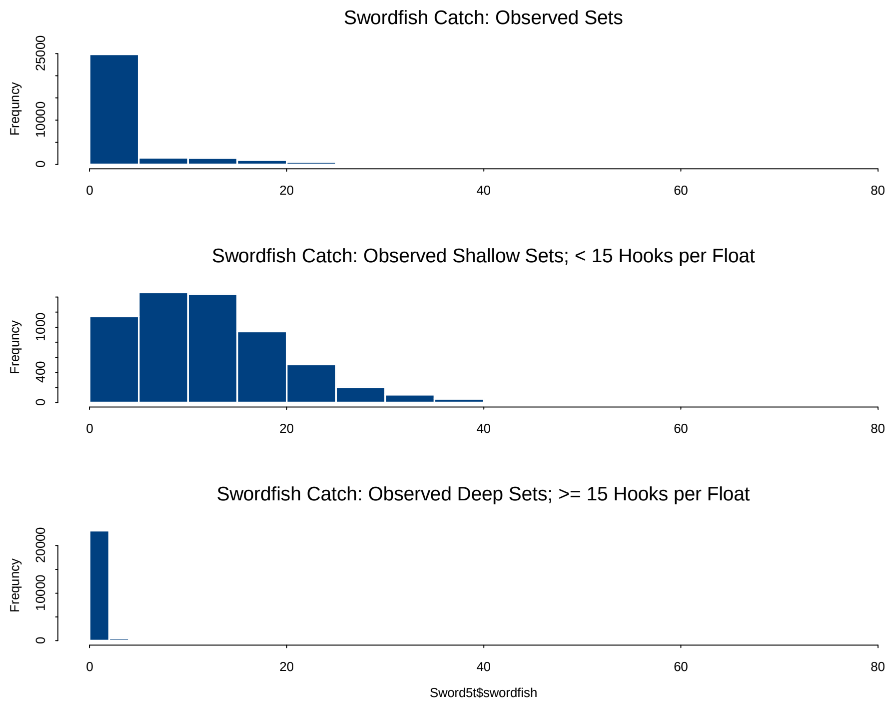


Figure 1-B. Swordfish Catch: Unobserved Sets.

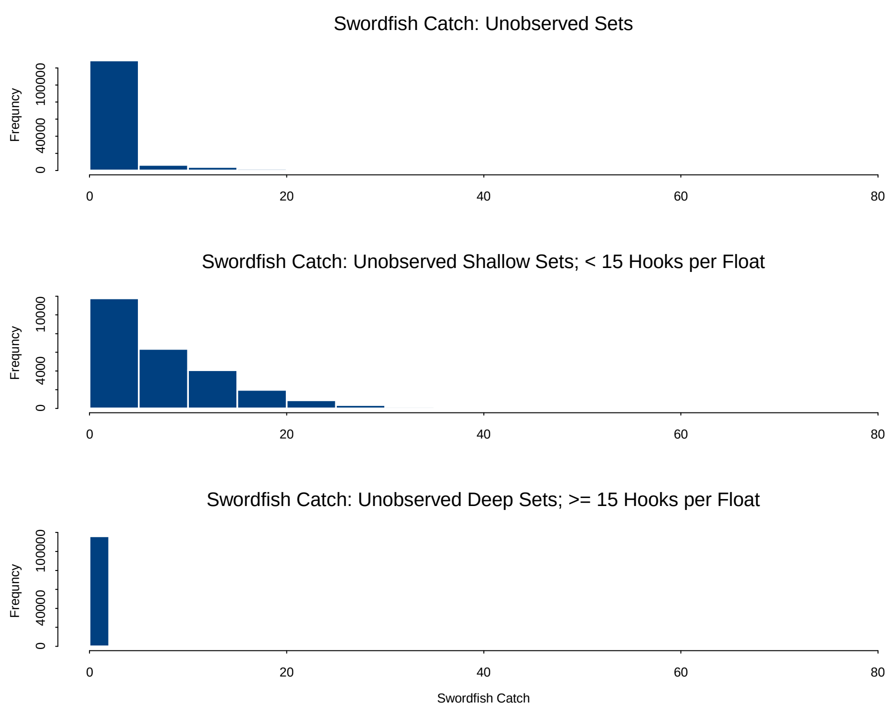


Figure 2-A. Begin Set Time: Observed Sets.

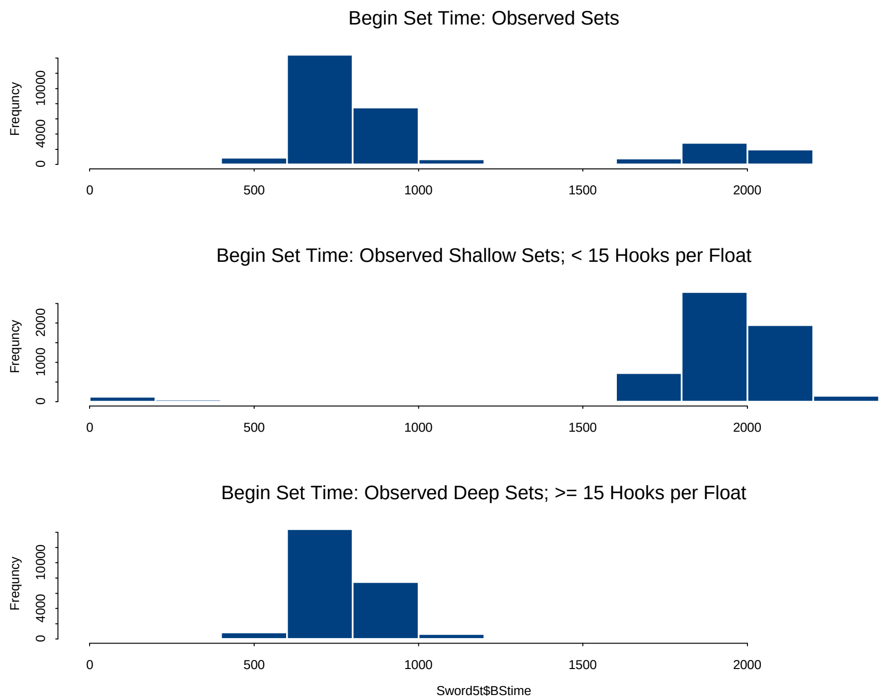


Figure 2-B. Begin Set Time: Unobserved Sets.

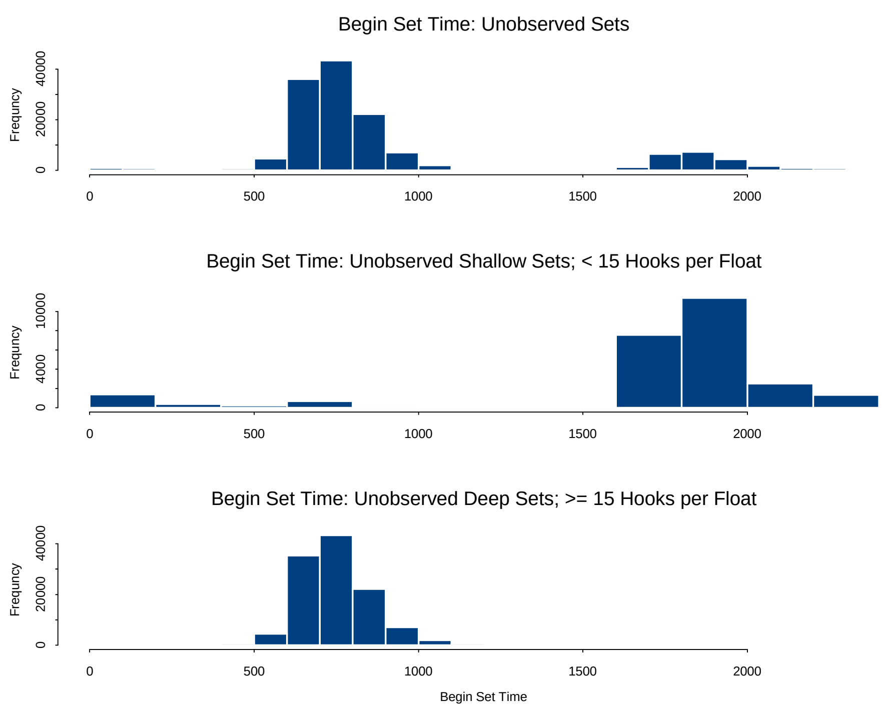


Figure 3-A. Year/Quarter: Observed Sets.

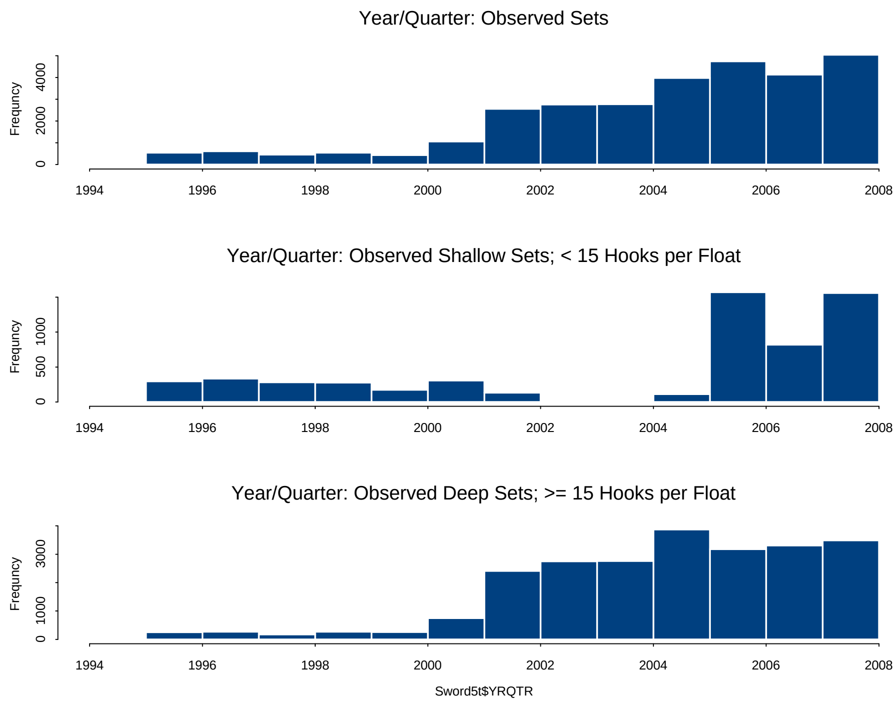


Figure 3-B. Year/Quarter: Unobserved Sets.

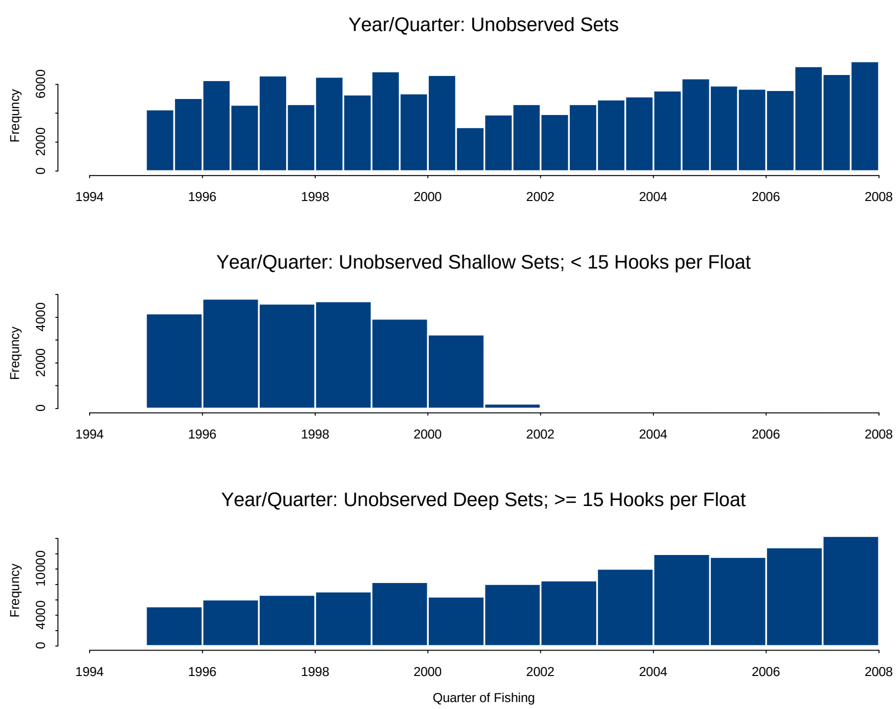


Figure 4-A. Latitude: Observed Sets.

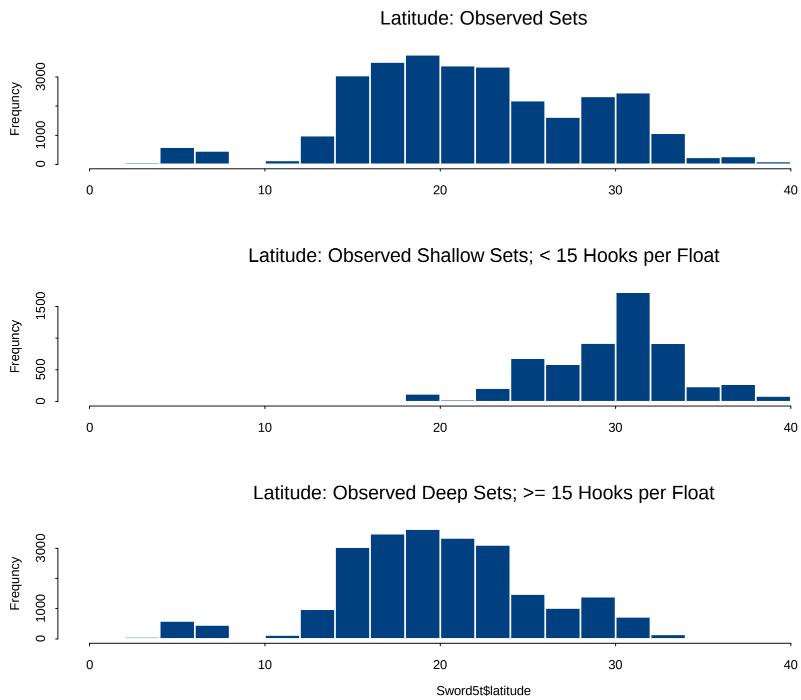


Figure 4-B. Latitude: Unobserved Sets.

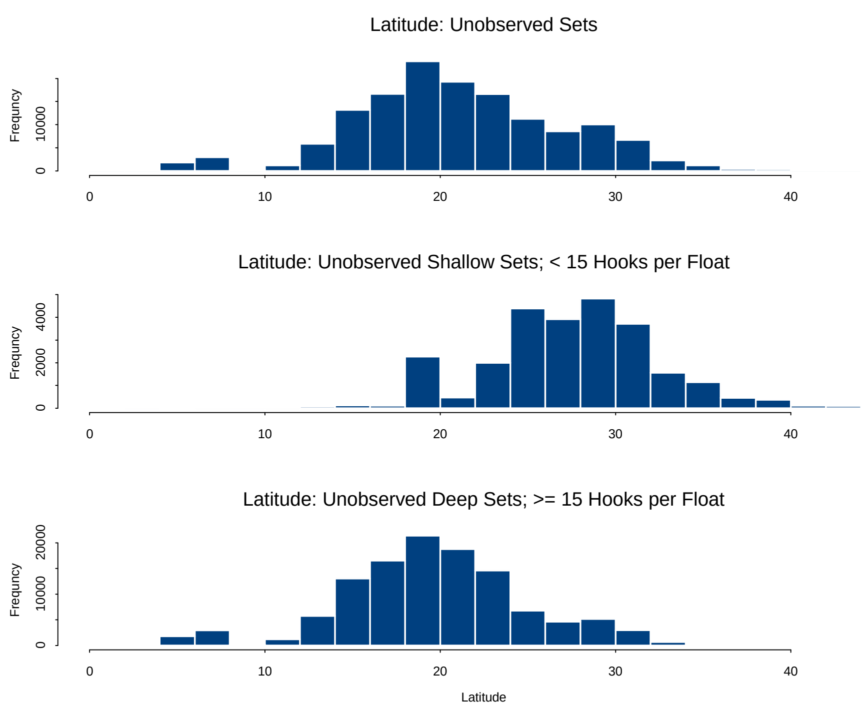


Figure 5-A. Longitude: Observed Sets.

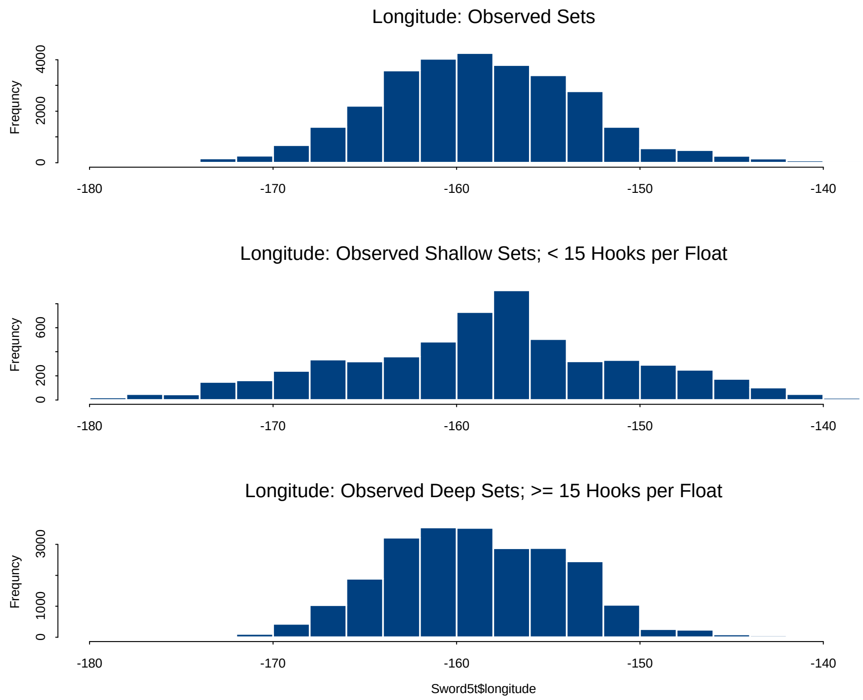


Figure 5-B. Longitude: Unobserved Sets.

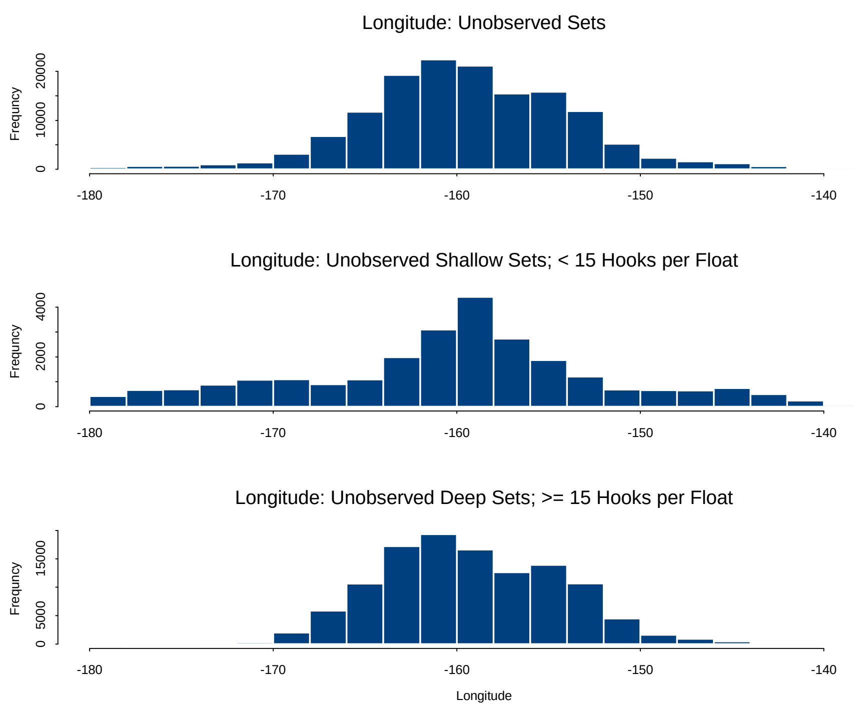


Figure 6-A. Number of Hooks: Observed Sets.

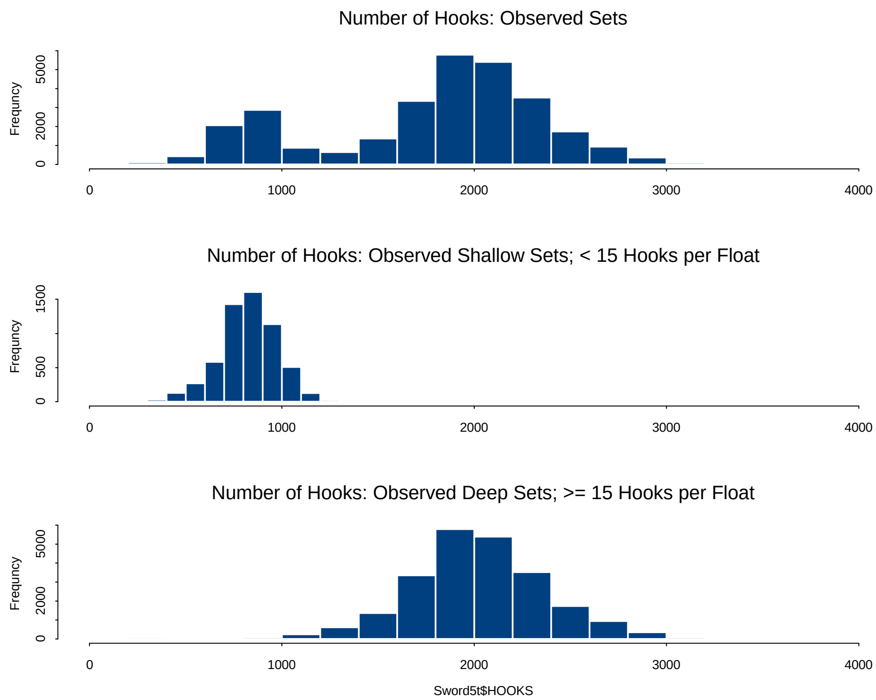


Figure 6-B. Number of Hooks: Unobserved Sets.

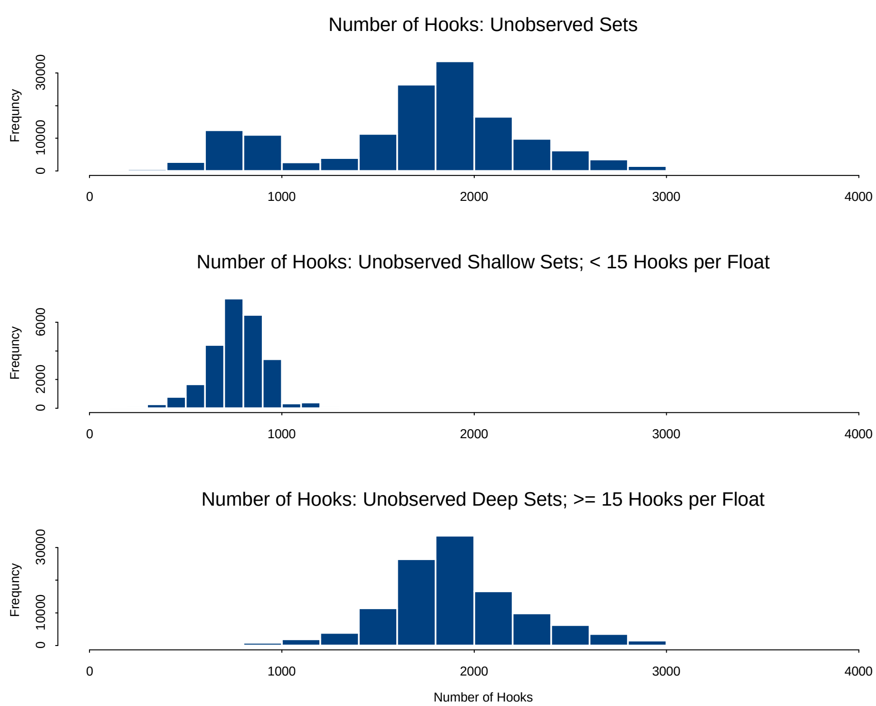


Figure 7-A. Hooks per Float: Observed Sets.

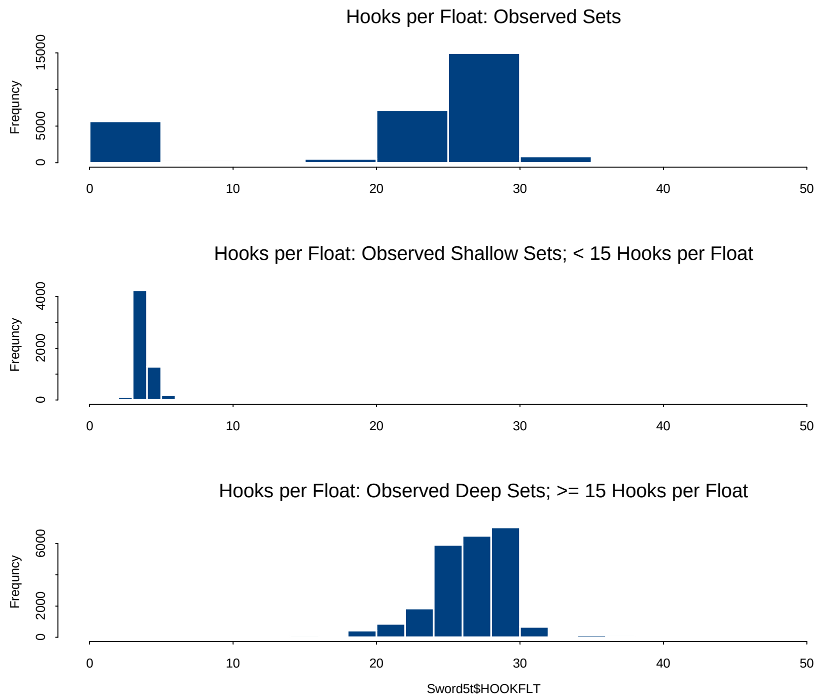


Figure 7-B. Hooks per Float: Unobserved Sets.

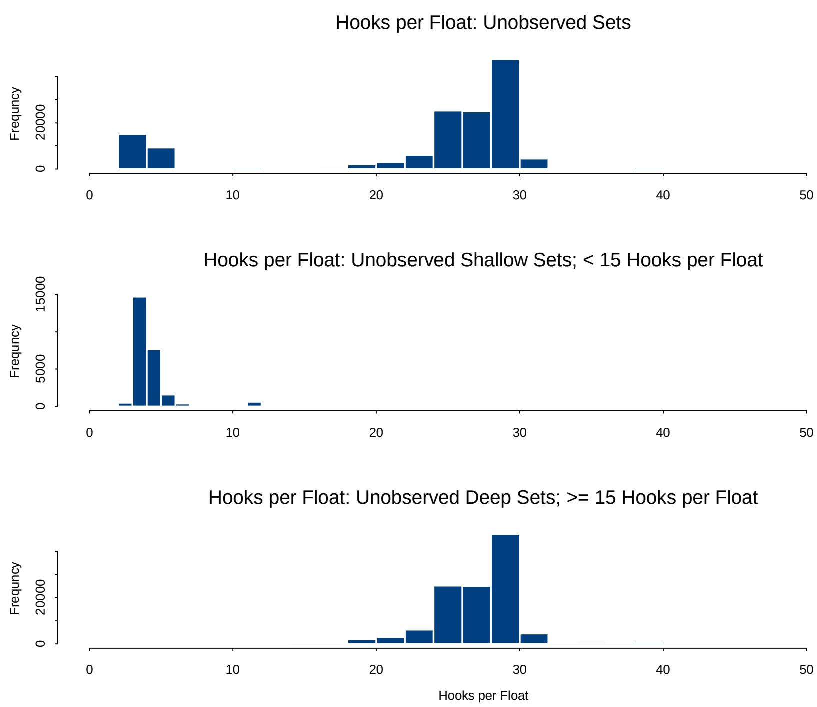


Figure 8-A. Sea Surface Temperature: Observed Sets.

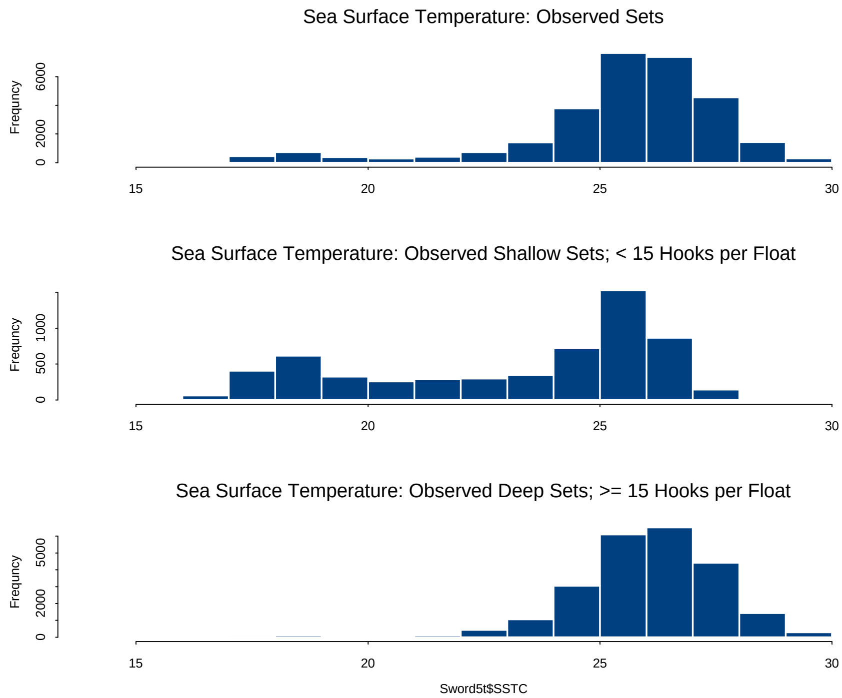


Figure 8-B. Sea Surface Temperature: Unobserved Sets.

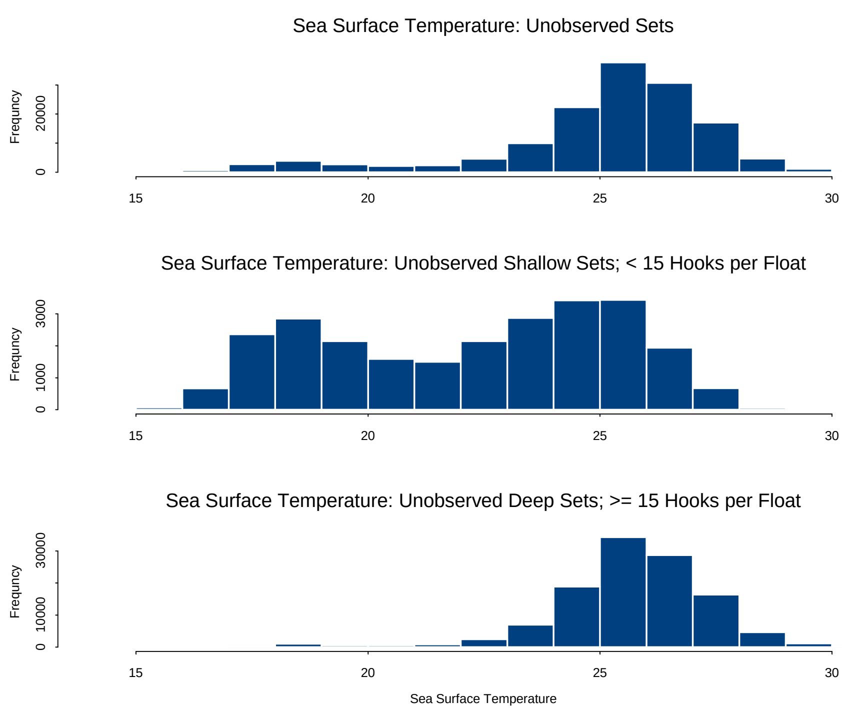


Figure 9-A. Vessel Length: Observed Sets.

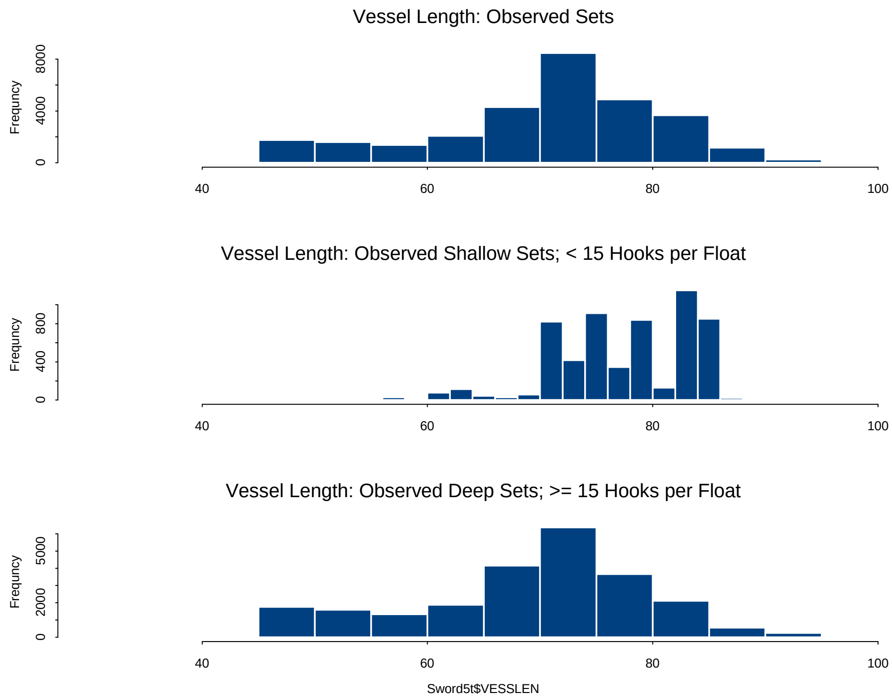
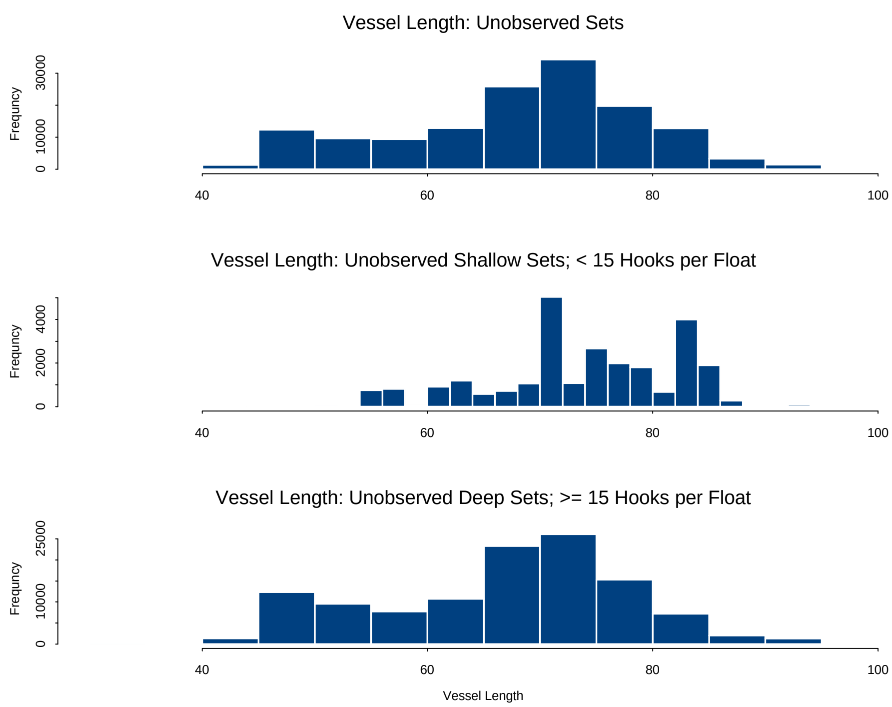


Figure 9-B. Vessel Length: Unobserved Sets.



Appendix B – Smoother Traces by Predictor

Figure 1. GAM Fit to Observed Sets (Shallow and Deep Combined).

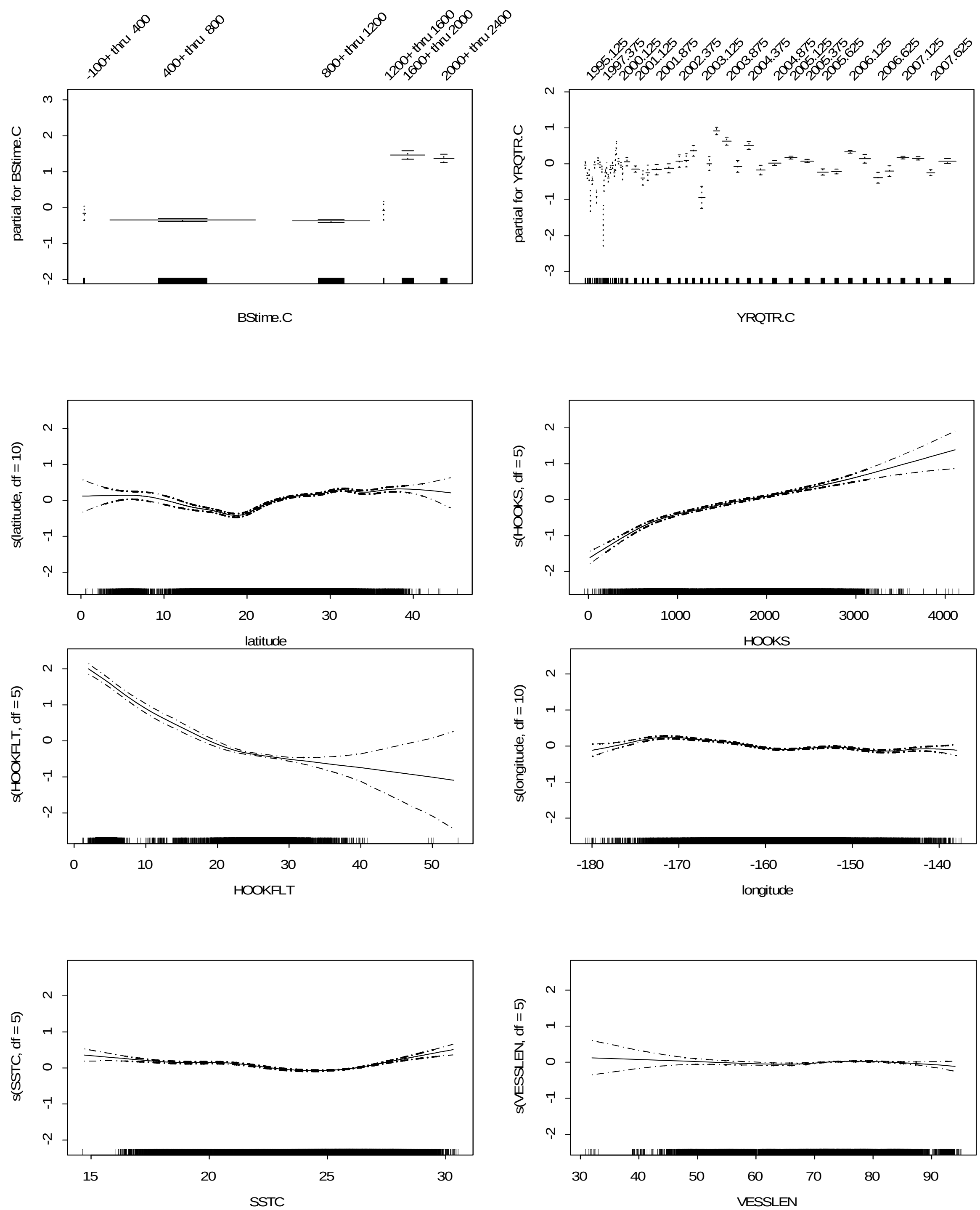


Figure 2. GAM Fit to Observed Shallow Sets.

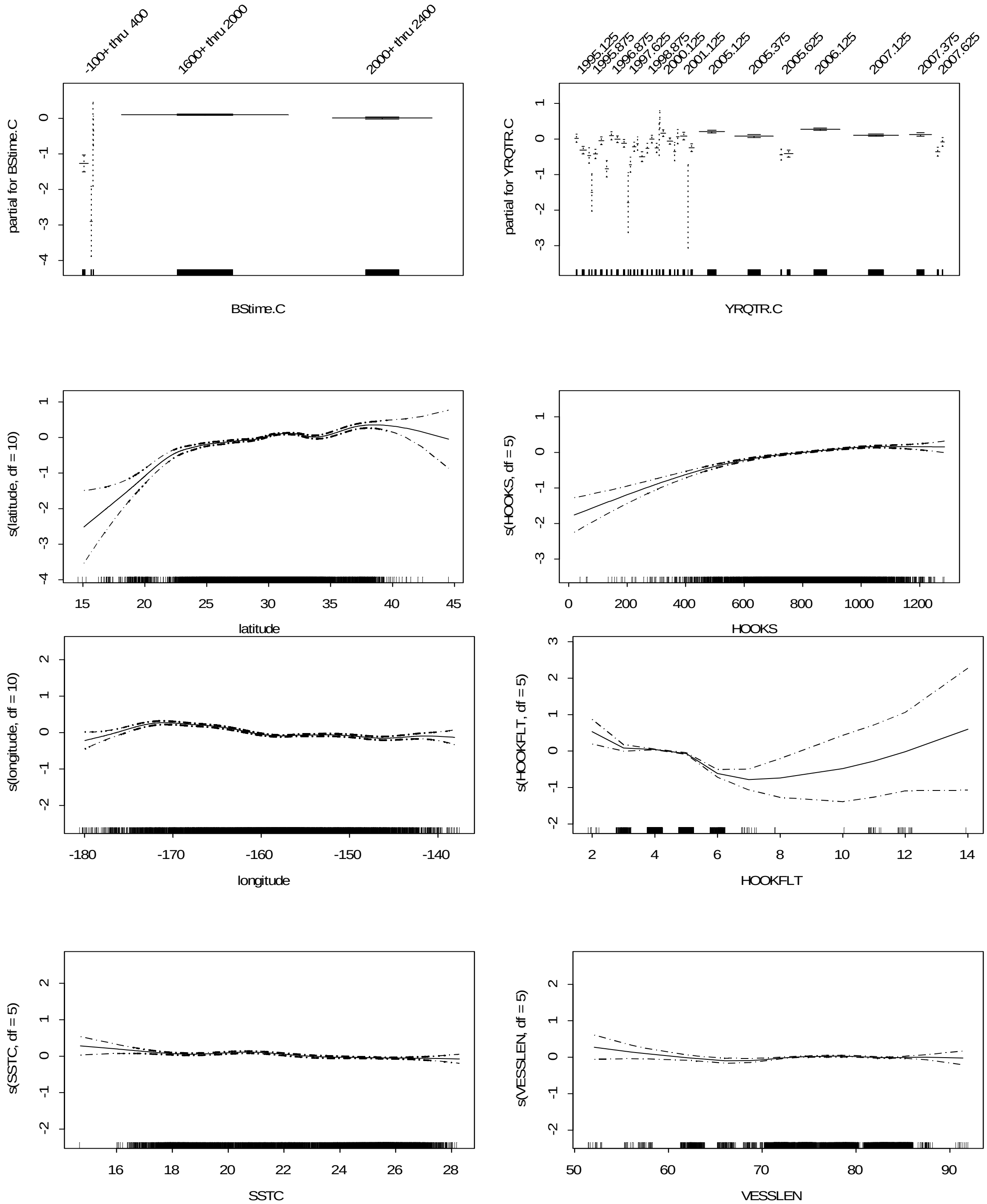
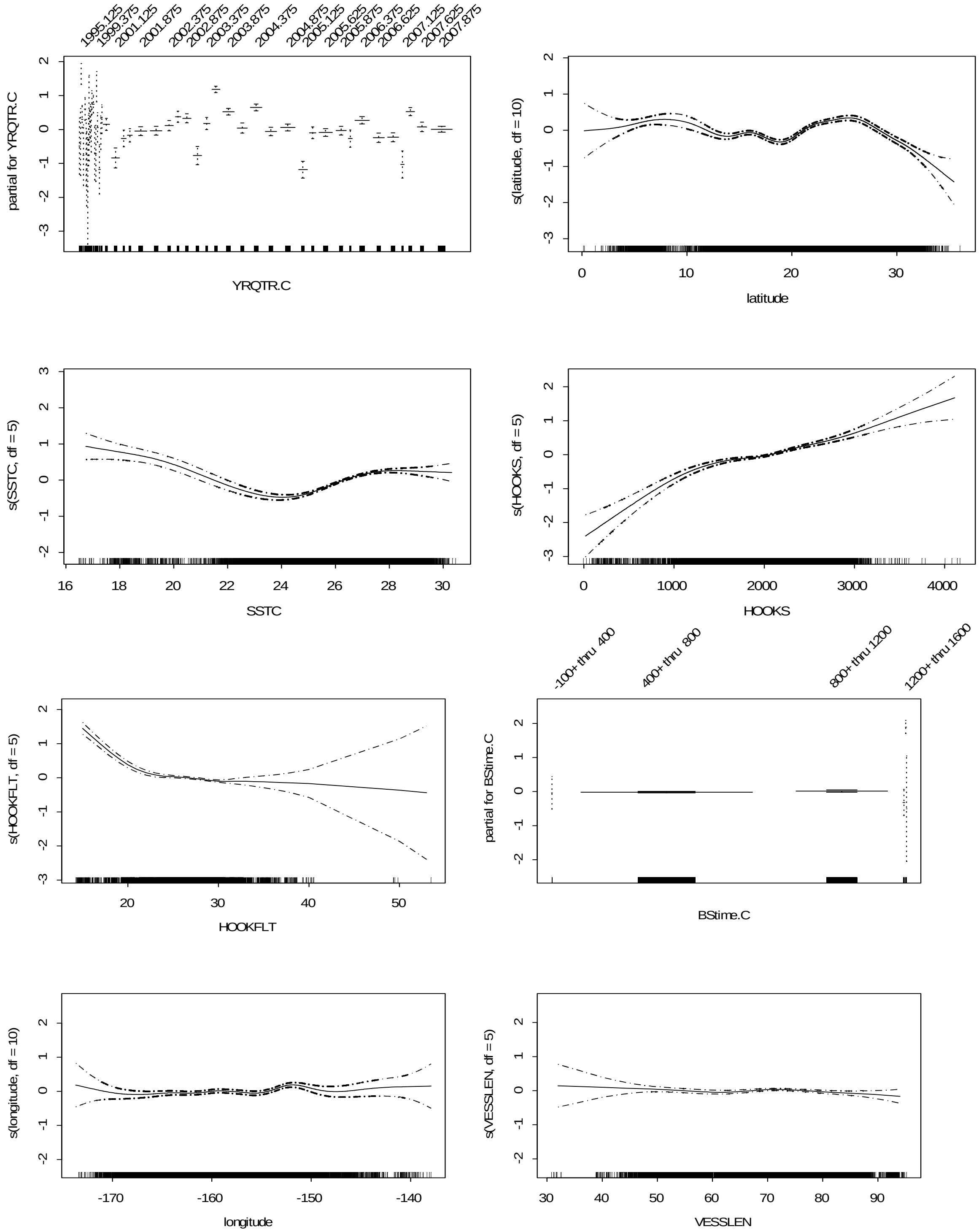
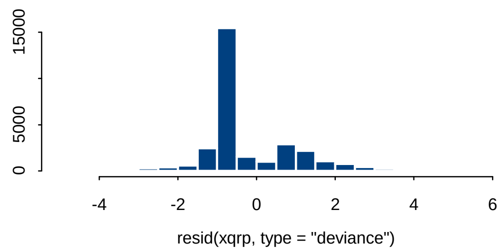


Figure 3. GAM Fit to Observed Deep Sets.



Appendix C –Deviance Residuals

Figure 1-A. GAM Fit to Observed Sets (Shallow and Deep Combined).



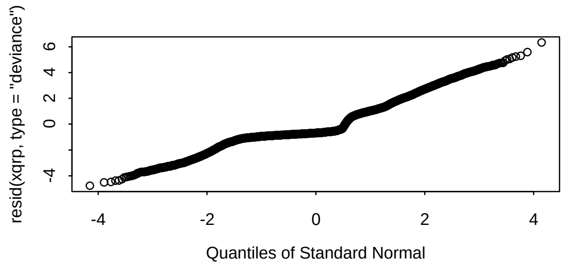
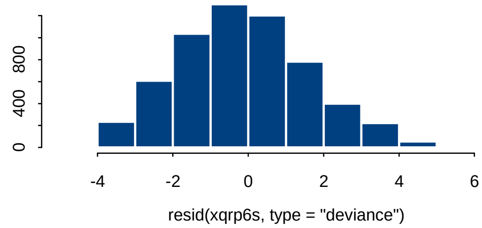


Figure 1-B. GAM Fit to Observed Shallow Sets.



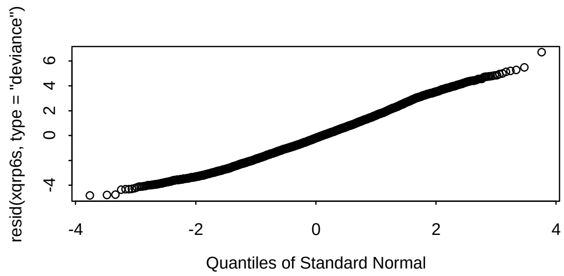
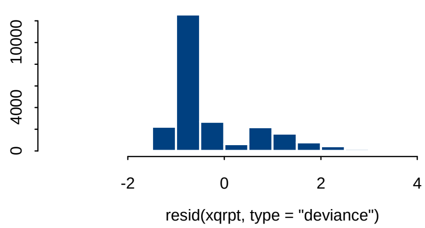


Figure 1-C. GAM Fit to Observed Deep Sets.



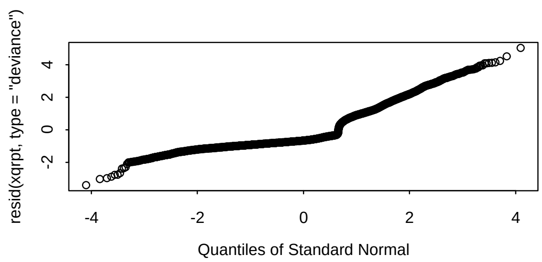


Figure 2. GAM Fit to Observed Sets (Shallow and Deep Combined).

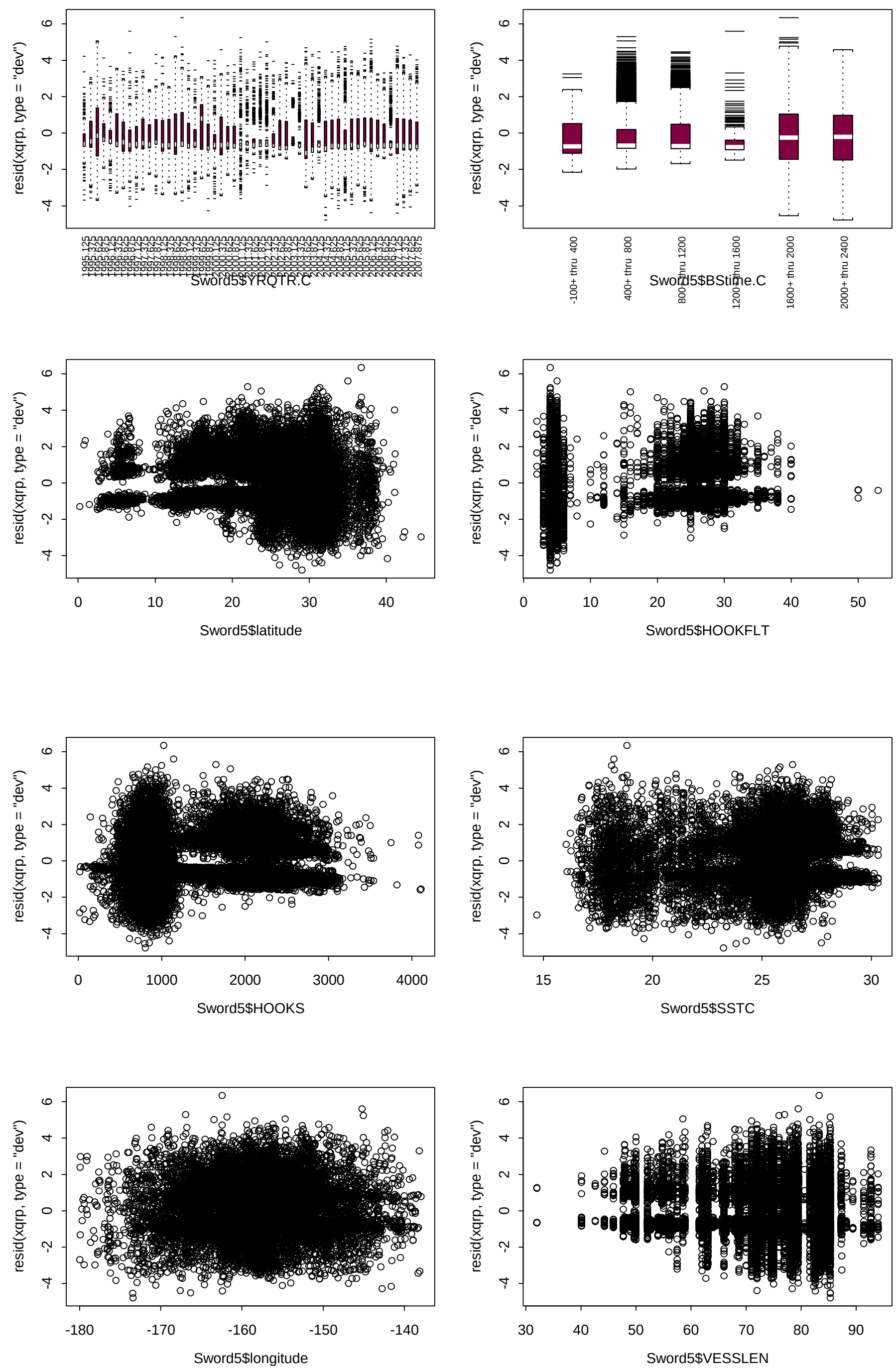


Figure 3. GAM Fit to Observed Shallow Sets.

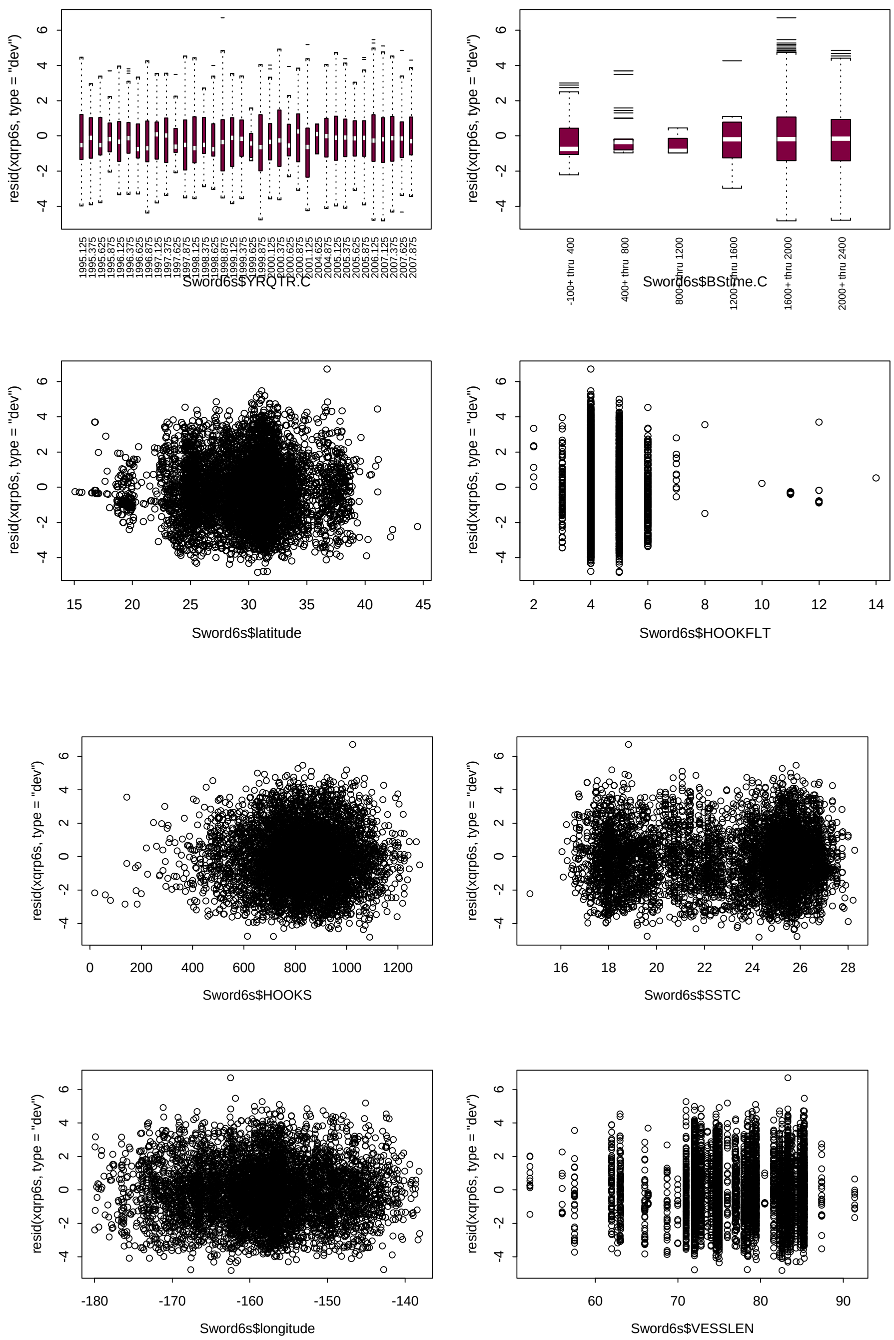


Figure 4. GAM Fit to Observed Deep Sets.