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Standardized catch rates of shortfin mako shark in the U.S. West Coast drift gillnet fishery[1]

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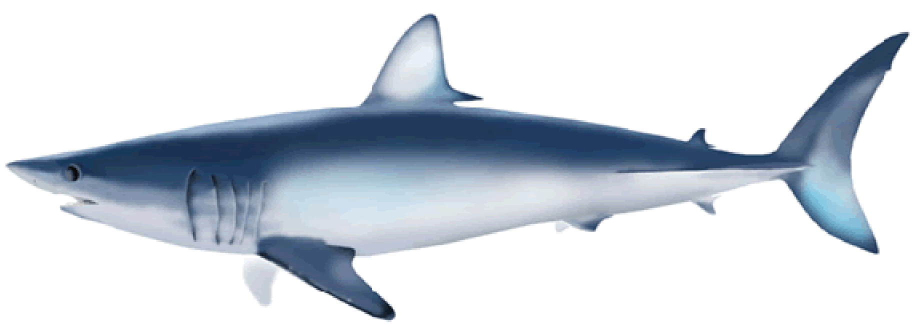

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ABSTRACT

A US west coast large-mesh drift gillnet fleet (DGN) has been through a series of regulations to manage the catch and bycatch since California started managing the fishery in 1980. The increasing regulatory pressure and limitations to areas available for fishing have led to dramatic changes to the DGN fleet resulting in a 90% reduction in the number of DGN vessels in 2011 from the peak in 1985. The objectives of this paper were to evaluate factors affecting shortfin mako shark catch in the DGN fishery and to develop standardized catch per unit effort (CPUE) indices using set-by-set logbook data. The data set were examined, filtered, and divided into strata based on available factors in the logbook for the use of developing CPUE indices. We used a delta approach to model the annual CPUE index because there were a large number of sets with zero mako catch. We further used a step-wise regression procedure to determine the set of spatial, temporal, fishing and oceanographic factors and interactions that explained the observed variability. Two time periods (before and after implementation of a 2001 closure of the Pacific Leatherback Conservation Area) were analyzed to reflect the change in management. The resulting abundance indices were relatively flat during 1985-2000 and 2001-2012. We note that the catchabilities for both indices were likely to be non-constant because of the increasing number of time-area closures as well as the unknown consequences of other management measures such as pingers and net extenders. Given current limited participation along with the limited spatial extent of the fleet, the representativeness of these data as a proxy for shortfin mako shark stock abundance in the North Pacific is questionable.

INTRODUCTION

Fishermen in the nearshore small-mesh gillnet fishery off the California coast targeting coastal species, including California barracuda, white seabass, and California halibut, observed that they occasionally caught pelagic sharks in their nets (Hanan *et al.* 1993). Based on these observations, a large-mesh drift gillnet fleet (DGN) fishing further offshore was developed in the late 1970's in the Southern California Bight (SCB) and originally targeted pelagic sharks. However, by the mid-1980s, the DGN fishery switched to primarily targeting swordfish due to higher economic returns (Bedford 1987, Holts 1988) and that switch in targeting was aided by the elimination of regulations requiring a fixed ratio (1:1) of shark to swordfish landings in 1985.

A series of regulations were soon imposed on this DGN fishery to manage the catch and bycatch of this fishery (Table 1). For example, regulations included a minimum fourteen inch mesh size to prevent the take of smaller sized fish since 1982, and requirements for pingers and six-fathom net extenders to reduce marine mammal interactions since 1997. However, the primary regulations have been time-area closures. In 1982, the EEZ off of California within 200 nautical miles (nmi) was closed from February 1st to April 30th. Then in 1986, regulatory measures were enacted under California state law to implement three major management changes: fishermen were only allowed to target thresher sharks in May, as DGN effort was not permitted within 75 nmi of the CA coast from June 1st to August 14th, and the area within 25 nmi off the CA coast was off limits from December 15th to January 31st. The 75 nmi closure was expanded in 1990 by extending the closure from May 1st to August 14th and is sometimes referred to as the thresher shark closure, since its intent was to eliminate the direct targeting of thresher shark by the DGN fleet in time and area combinations of conservation concern. The last major time and area closures were established in 2001 when DGN fishermen were prohibited from fishing within a 160,000 square nmi quadrant called the Pacific Leatherback Conservation Area (PLCA) from August 15th to November 15th. Similarly, an area in the SCB was designated as a loggerhead turtle closure to protect the species during El Niño seasons when oceanic conditions increase the chances of their occurrence inside the West Coast EEZ.

Increasing regulatory pressure and limitations to areas available for fishing have led to dramatic changes to the DGN fleet (Urbisci *et al.* in review). The number of DGN vessels peaked in the 1980's at over 200, but have dwindled to less than 20 presently (Figure 1). Location of the present fishing effort is constrained to mostly occurring in the SCB south of 34°N latitude (Figure 2). Urbisci *et al.* (in review) showed that although the thresher shark area closure had a significant effect on shortfin mako catch rates, the other areas closure did not. The authors argued that the combined effects of regulation and spatial/temporal limitation along with other factors were responsible for the dramatic loss of fishing vessels. Current limited participation along with the limited spatial extent of the fleet makes the usefulness of this catch per unit effort (CPUE) data as a proxy of shortfin mako shark stock abundance questionable (Urbisci *et al.* in review).

The objectives of this paper are to evaluate factors affecting shortfin mako shark catch from DGN fishery and to develop standardized CPUE indices for changes in fishery practices. We make recommendations for how useful this information is as a reliable measure of shortfin mako relative population abundance.

MATERIALS AND METHODS

Data used

Set-by-set logbook data were used in the shortfin mako CPUE analyses. The logbook program was initially established in 1980 (Huppert and Odemar 1986). Logbook reporting by boat captains have generally been assumed to be good since California started managing the fishery in 1980 (Miller et al. 1983, Beeson and Hanan 1991) and reporting has been mandatory since the fishery became federally-managed in 2004. The logbooks recorded information on the fishing operations of each set deployed including, fishing time, fishing location, target species, catch by species (retained and discarded), vessel identifiers, set identifiers, gear type (set net or drift gillnet), water depth, length of net, mesh size, and soak hour.

Preliminary examination of the data set indicated that two stages of filtering were required before the data could be used for developing abundance indices. The number of sets in the data after each filtering stage is summarized in Table 2. The two filtering stages are:

1. Identifying large-mesh driftnet sets

The original data set did not specifically identify sets of the large-mesh drift gillnet fishery. Therefore, the logbook observations were filtered to select large-mesh drift gillnet sets where mesh size is ≥ 14 inch (large-mesh) and gear type is defined as "drift gillnet". To prevent incorrectly rejecting true large-mesh drift gillnet sets due to the missing mesh size information, sets with target species as "Swordfish or shark" were selected and assumed to be the drift gillnet fishery.

2. Identifying abnormal fishing operations

The majority of fishing operations (the length of net and soak hours) for the DGN fleet used nets with lengths around 1,000 fathoms and soak times within a day. Abnormal fishing operations could result from nets being left in the water without retrieval, and experimental trips using shorter nets and/or soak times. Sets with abnormal fishing operations were identified and removed in the second filtering stage because it is inappropriate to use the data from these abnormal fishing operations.

Abnormal sets were identified based on fishery knowledge and statistical outlier analyses using 2 times interquartile range. As a result, sets that used soak times below 3 hours or above 18 hours and net lengths below 700 fathoms or above 1,200 fathoms were eliminated (Figure 3).

The logbook data were divided into strata based on available factors. Season was categorized into either quarter (Q1: Jan-Mar, Q2: Apr-Jun, Q3: Jul-Sep, Q4: Oct-Dec) or bi-month (Jan-Feb, Mar-Apr, May-Jun, Jul-Aug, Sep-Oct, Nov-Dec). The choice of quarter or bi-month is based on the extent of deviance explained in the model. Each region is assumed to have homogeneous shortfin mako shark density in accordance with the distribution of CPUE (number of shortfin mako sharks per set) (Figure 2). Regions were defined as Region 1: <= 35 °N latitude, Region 2: >35 & <=40 °N and Region 3: > 40 °N, where 35 °N is at the southern boundary of Pacific Leatherback Conservation Area (PLCA) closure. Other factors included water depth (6 blocks: <500 m, 500-1,000m, 1,000-1,500m, 1,500-2,000m, 2,000-2,500m, >2,500m), net length (3 blocks: <1,400 m, 1,400-1,600m, >1,600m), mesh size (3 blocks: 36-43cm, 43-50cm, >50cm) and soak time (3 blocks: <8hrs, 8-13hrs, >13hrs).

Model methods and model selection

A delta approach (Lo *et al.* 1992, Stefánsson 1996) was used to model the annual index of relative abundance (CPUE) because there were a large number of sets with zero mako catch (Figure 4). Catch was defined as the sum of all kept and released shortfin makos and effort was defined as number of sets according to the data strata.

The delta approach models the proportion of positive observations using a binomial error assumption and the catch rate of positive observations using the best fitting of several different error distributions (gamma, log-normal etc.) as separate models. The standardized index is the product of these two model-estimated components. The estimated proportion of successful sets per stratum is assumed to be the result of *r* positive sets of a total *n* number of sets, and each one is an independent Bernoulli-type realization. The estimated proportion is a linear function of fixed effects and interactions. The logit function was used as a link between linear factor components and binomial errors. For positive observations, which were defined as at least one shortfin mako shark caught, the estimated positive CPUE rate was assumed to follow a log-normal error distribution (lnCPUE-nominal) of a linear function of fixed factors and interactions. The final estimate of the annual abundance index was the product of the back transformed marginal year effects (Searle 1980), corrected for the log bias in the log-normal back transformation. The variance estimates were obtained by jackknifing the data using the function delGLM() (delta_glm_1-7-2 for R, provided by Alec MacCall, SWSFC - Santa Cruz, CA).

A step-wise regression procedure was used to determine the set of fishing and oceanographic factors and interactions that significantly explained the observed variability. The Chi-square distribution was used to test the statistical significance of the difference in deviance between two consecutive models (McCullagh and Nelder 1989). Deviance analysis tables presented include the deviance for the proportion of positive observations (i.e. positive sets/total sets), and the deviance for the positive catch rates. Final selection of explanatory factors was conditional on (1) the relative percentage of deviance explained by adding the factor in evaluation (factors that explained more than 2% were selected) for both model components; and (2) significance of the Chi-square test for both model components; and (3) the type III test of significance within the final specified model.

RESULTS AND DISCUSSION

We excluded data during 1981-1984, when the fishery was in the development phase and effort was increasing due to a rapidly increasing number of active vessels (Figure 1). Catchability (proportionality constant between an index of abundance and population size) of the DGN fleet has likely changed substantially during this early period because of rapidly changing regulations: minimum mesh size changed from 8 to 14 inch in 1982, increasing number of permits in 1984, and shark-swordfish quota before 1985 (Table 1). After 1985, there were two major time-area closure events, the shark conservation closure since 1986 and leatherback conservation closure since 2001. These major time-area closures have resulted in changes in catchability for shortfin mako shark by redistributing DGN fishermen away from certain times or fishing grounds (Figure 2) (Urbisci *et al.* in review). We therefore separated the logbook data into two time periods (before and after the 2001 leatherback conservation closure) to reflect the change in management. Within each time period (1985-2000 and 2001-2012), we included spatial, temporal and fishing factors to explain changes in the CPUE.

Most factors investigated were found to be significant in both positive CPUE and proportion of positive set models ($p<0.01$) (Table 2). The exceptions were region, water depth, and soak time for 2001-2012. Bimonth explained more model deviance than quarter in all the model components. We therefore chose bimonth as our seasonal factor. Among these significant factors, factors such as year, bimonth, region, or water depth explained more than 2% of model deviance in both model components for the first series (1985-2000) and year and bimonth for the second series (2001-2012). Interaction among factors (Bimonth * region, Bimonth * water depth, or region * water depth) were neither significant nor explained more than 2% of model deviance for both model components. The final model used to estimate CPUE in both proportion positive and positive catch rate included year, bimonth, region, and water depth as main factors for 1985-2000 and year and bimonth as main factors for 2001-2012.

Model diagnostics indicated reasonable performance of the log-normal and binominal models for both time series (Figure 5). Residuals of the log-normal (positive catch) model were slightly skewed, but do not indicate severe departures from model assumptions.

Catch rates are higher in shallower water depths around 500-1,500m than deeper depths (Figure 6). This could be due to the time-area closures within certain distances from the coast, which is indicated by a significant interaction term between depth and season. However, this interaction did not explain much of model deviance compared to other main factors. The fishery is predominantly in region 1 (Figure 6). Catch rates are high during July and August and low during February, March and April for both series (Figure 2 and 7), which could be due to the fishery closure from February 1- April 30 since 1982. Fishery activities move south of 35°N after the leatherback area closure in 2001 during August 15- November 15, with higher catch rates and less effort than before the closure. The more recent time-area closures appear to shift the effort and areas of high catch rates southward.

The resulting abundance indices were relatively flat during 1985-2000 and 2001-2012 (Figure 8). Estimated CV's are higher and more stable during 1985-2000 (~14-18%) than 2001-2012 (~7-14%). Use of a statistical model, as well as filtering the data to remove abnormal trips improved the model fit (results not shown). However, we note that the catchabilities for both indices were likely to be non-constant because of the increasing number of time-area closures as well as the unknown consequences of other management measures such as pingers and net extenders.

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Table 1. Key regulation changes of the large-mesh and offshore drift gillnet fleet (DGN) fishery. Table taken from Urbisci *et al.* (in review).

Year	Management Changes
1980	Non-transferable limited entry program, allows fishermen to retain swordfish, creates the logbook program, and establishes 6,000 ft as the maximum DGN length. Minimum mesh size of 8 inches.
1982	Moratorium on the issuance of new permits and establishes that each vessel can land no more swordfish than shark by weight per month from May 1 to September 15 (50-50 quota). The fishery closes from February 1 – April 30 within 200 nmi and around portions of the Channel Islands. Minimum mesh size of 14 inches.
1985	The shark-swordfish quota is removed from regulations.
1986	Thresher shark fishing season is reduced to 30 days in May, fishing is prohibited within 75 nmi off the coast of CA from June 1 - August 14, and from December 15 – January 31 the fishery is closed within 25 nmi of the CA coast.
1990	The 75 nmi thresher closure is extended from May 1 – August 14. The Fisheries Observer Program is established.
1994	California caps new entrants to the fishery and only allows permits to be transferred.
1997	Vessels are required to use acoustic pingers and to place the float line at least 36 ft below the surface water.
2001	The DGN fishery is closed to protect the leatherback sea turtles from August 15 – November 15, covering an area north of Pt. Sur, including the offshore waters to Pt. Conception, and extending north to 45°N. A second turtle closure is implemented in the area south of Pt. Conception and is designed to protect the loggerhead sea turtles only during forecasted or occurring El Niño events from June 1 – August 31.
2002	The permit holders are required to purchase a permit every year to remain in the fishery, but are not required to land every year.
2004	Establishment of federal fishery management plan for highly migratory species.

Table 2. Number of sets at each stage of filtering where logbook observations were filtered for large-mesh drift gillnet sets at stage 1 (DGN fishery) and were further filtering based on fishery knowledge and statistical outlier analyses using 2 times interquartile range at stage 2.

	No. of sets from the logbook	No. of sets after filtering stage 1	No. of sets after filtering stage 2
1985	34339	9622	9275
1986	33582	10405	10074
1987	27015	8281	8081
1988	20960	5760	5607
1989	17582	5631	5503
1990	16128	4166	4073
1991	15719	4292	4244
1992	13460	3746	3638
1993	15130	5124	5001
1994	9027	4127	4044
1995	7518	3415	3357
1996	7214	3166	3098
1997	7681	2678	2623
1998	6740	2652	2589
1999	7144	2390	2330
2000	6023	1195	1145
2001	5268	1414	1344
2002	5535	1430	1332
2003	4950	1180	1153
2004	4728	925	892
2005	3590	828	799
2006	3833	1401	1361
2007	3803	1216	1171
2008	3438	989	933
2009	2619	629	590
2010	2674	401	378
2011	2732	403	383
2012	359	344	307

Table 3. Deviance analysis table of explanatory variables in the delta-lognormal model for shortfin mako catch rates (in number per set) caught by U.S. west coast large-mesh drift gillnet fleet (DGN) fishery. Percentages of change deviance refer to the % deviance explained by the each model from the null model, and p values indicate the 5% Chi-square probability between consecutive model and null model. Highlighting indicates factors used in the final model.

Years 1985-2000

Model factors	DF_ Deviance	Deviance	% Change deviance	AIC	Adjust R-square	Pr(>F)
Positive catch rate						
Intercept	25383	13972.3		56885.4		
Year	25368	13564.3	2.9	56163.1	0.03	<0.0001
BiMonth	25378	13365.7	4.3	55768.7	0.04	<0.0001
Quarter	25380	13404.0	4.1	55837.3	0.04	<0.0001
Region	25381	13595.4	2.7	56195.2	0.03	<0.0001
Depth	13552	6872.4	50.8	29277.8	0.05	<0.0001
Net Length	11805	6373.6	54.4	26236.7	0.00	<0.0001
Mesh size	23966	12671.2	9.3	52750.5	0.03	<0.0001
Soak hrs	24300	13367.6	4.3	54449.5	0.00	<0.0001
Proportion positives						
Intercept	2621	7029.8		10003.8		
Year	2606	6523.9	7.2	9527.9	0.07	<0.0001
BiMonth	2617	6766.7	3.7	9748.7	0.04	<0.0001
Quarter	2618	6785.3	3.5	9765.3	0.03	<0.0001
Region	2619	6852.8	2.5	9830.8	0.02	<0.0001
Depth	2616	6060.2	13.8	9044.2	0.14	<0.0001
Net Length	2619	6968.6	0.9	9946.6	0.01	<0.0001
Mesh size	2619	6911.8	1.7	9889.8	0.02	<0.0001
Soak hrs	2619	7016.5	0.2	9994.5	0.00	0.001305

Years 2001-2012

Model factors	DF_ Deviance	Deviance	% Change deviance	AIC	Adjust R-square	Pr(>F)
Positive catch rate						
Intercept	3968	2216.3		8954.9		
Year	3957	2091.1	5.6	8746.1	0.05	<0.0001
BiMonth	3963	2157.1	2.7	8857.5	0.03	<0.0001
Quarter	3965	2175.0	1.9	8886.3	0.02	<0.0001
Region	3966	2212.2	0.2	8951.5	0.00	0.02457
Depth	2611	1469.1	33.7	5929.8	0.00	0.1271
Net Length	2886	1640.0	26.0	6570.9	0.01	<0.0001
Mesh size	3796	2102.8	5.1	8542.1	0.01	<0.0001
Soak hrs	3723	2103.0	5.1	8450.7	0.00	0.101
Proportion positives						
Intercept	960	2046.6		3045.6		
Year	949	1909.4	6.7	2930.5	0.06	<0.0001
BiMonth	956	1836.8	10.3	2843.9	0.10	<0.0001
Quarter	957	1938.8	5.3	2943.9	0.05	<0.0001
Region	959	2024.1	1.1	3025.1	0.01	<0.0001
Depth	955	2018.6	1.4	3027.7	0.01	<0.0001
Net Length	958	2025.0	1.1	3028.1	0.01	<0.0001
Mesh size	958	2021.5	1.2	3024.5	0.01	<0.0001
Soak hrs	958	2043.4	0.2	3046.4	0.00	0.2008

Table 4. Estimated CPUE and CV by jackknifing the data.

Separated standardized CPUE series

Year	CPUE (no./set) 1985-2000	Jackknife CV	CPUE (no./set) 2001-2012	Jackknife CV
1985	0.280	0.183		
1986	0.368	0.178		
1987	0.470	0.168		
1988	0.390	0.175		
1989	0.499	0.166		
1990	1.032	0.141		
1991	0.674	0.155		
1992	0.740	0.154		
1993	0.539	0.160		
1994	0.380	0.174		
1995	0.556	0.167		
1996	0.705	0.159		
1997	0.911	0.147		
1998	0.553	0.160		
1999	0.383	0.177		
2000	0.683	0.177		
2001			0.680	0.081
2002			1.445	0.076
2003			1.861	0.068
2004			0.947	0.083
2005			0.809	0.093
2006			1.111	0.073
2007			0.935	0.081
2008			0.748	0.085
2009			0.968	0.094
2010			0.587	0.136
2011			0.472	0.151
2012			0.820	0.128

One standardized CPUE series

Year	CPUE (no./set)	Jackknife CV
1985	0.251	0.150
1986	0.338	0.146
1987	0.429	0.139
1988	0.349	0.145
1989	0.454	0.138
1990	0.948	0.120
1991	0.618	0.130
1992	0.682	0.130
1993	0.503	0.133
1994	0.356	0.144
1995	0.510	0.139
1996	0.651	0.133
1997	0.860	0.124
1998	0.520	0.134
1999	0.349	0.148
2000	0.624	0.151
2001	0.331	0.163
2002	0.758	0.145
2003	0.917	0.134
2004	0.502	0.152
2005	0.359	0.168
2006	0.546	0.144
2007	0.541	0.148
2008	0.397	0.158
2009	0.679	0.158
2010	0.369	0.209
2011	0.280	0.208
2012	0.533	0.180

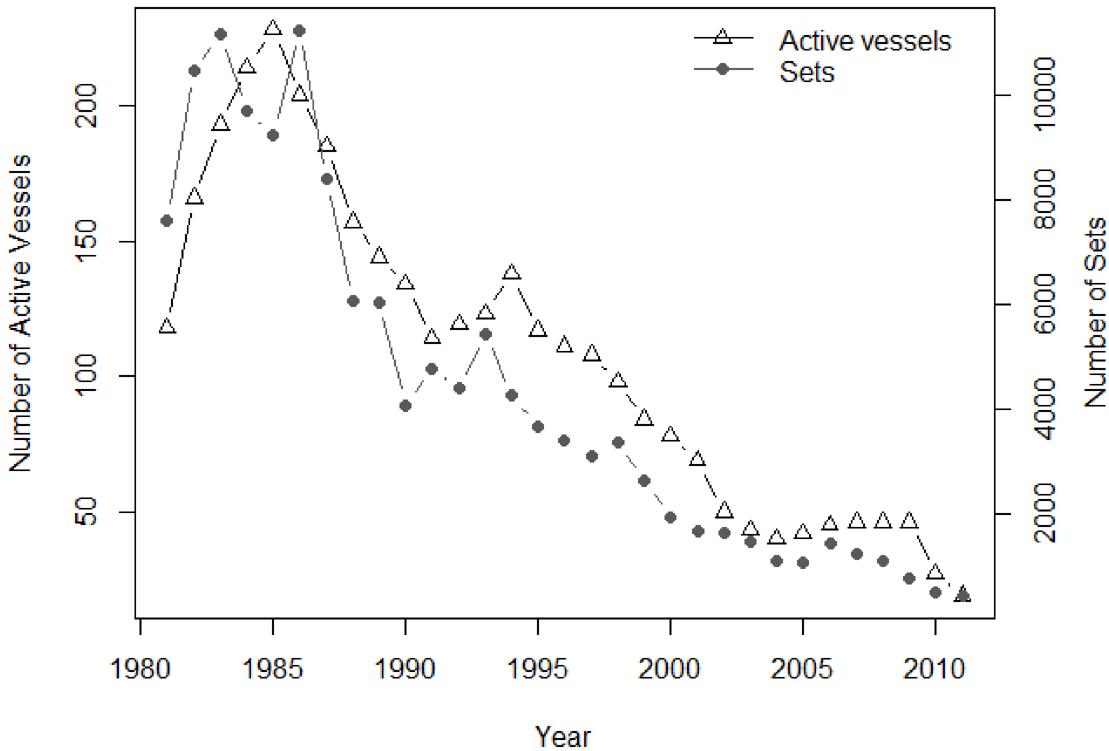

Figure 1. The number of large-mesh drift gillnet fleet (DGN) vessels operating by year (left scale) and total number of sets fished per year (right scale). (Data from the Biological Opinion on the continued management of the drift gillnet fishery under the Fishery Management Plan for U.S. West Coast Fisheries for Highly Migratory Species 2013 for set information from 1990 – 2011 and active DGN vessels; data from Holts et al. 1998 for set information from 1981-1989). Figure taken from Urbisci *et al.* (in review).

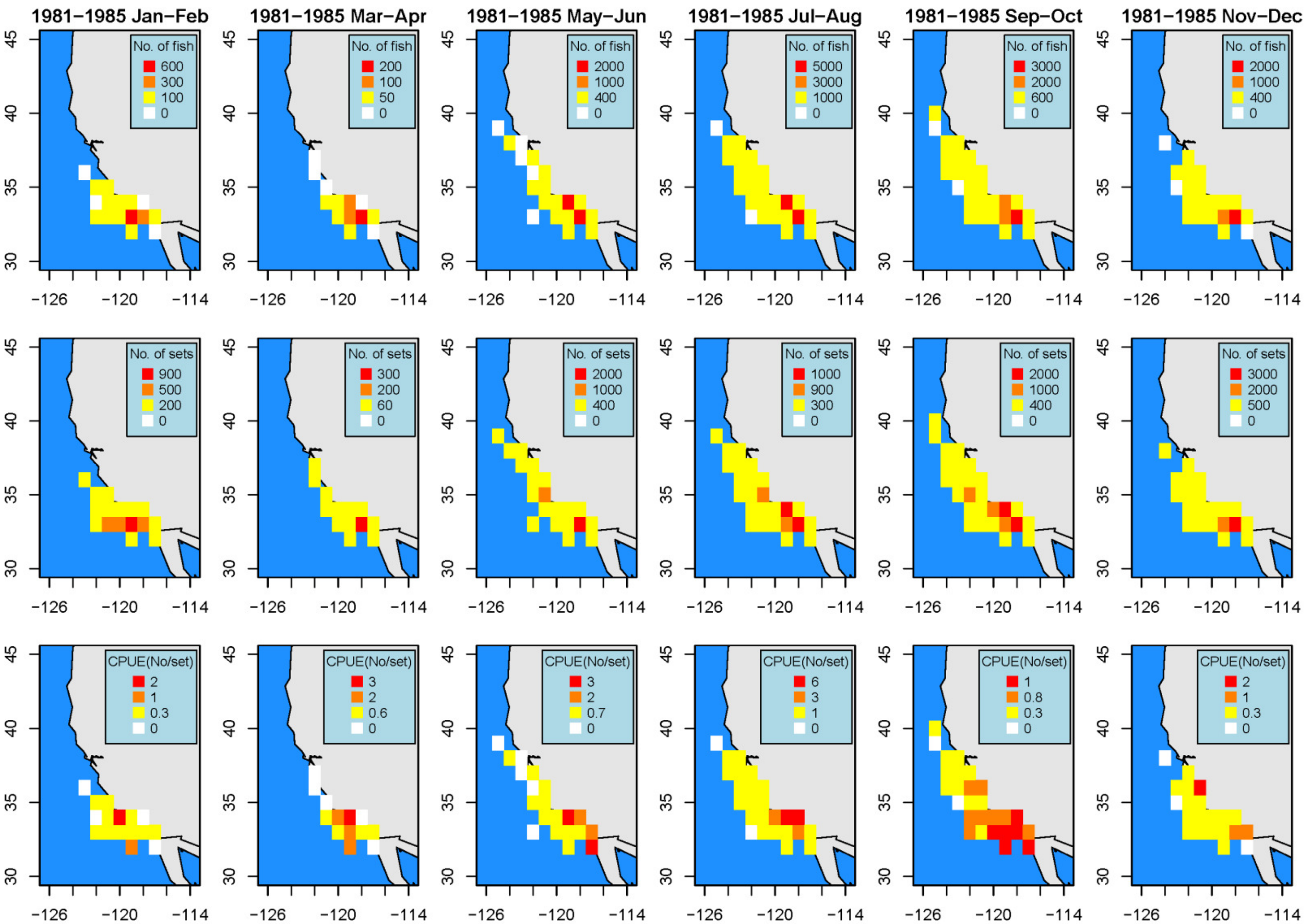

Figure 2-1. Distribution of shortfin mako sharks catch (first row), effort (second row), and shorkfin mako CPUE (third row) caught by large-mesh and offshore drift gillnet fleet (DGN) fishery in the period representing pre- shark seasonal area closure (1981-1985). Effort is given in 1x1 degree block. Effort is limited to extent of CDFW block coding system, so effort further offshore is excluded.

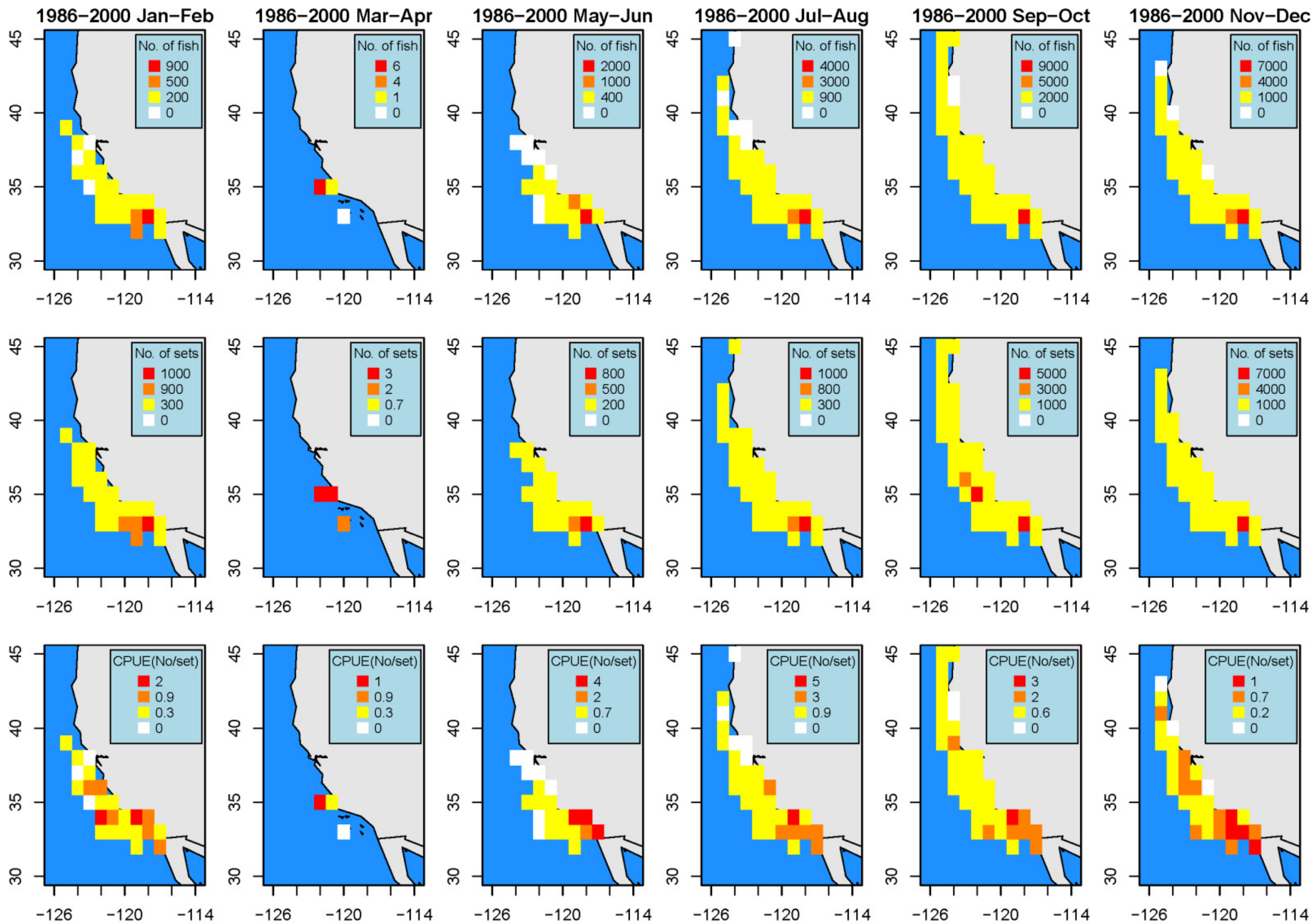

Figure 2-2. Distribution of shortfin mako shark catch (first row), effort (second row), and CPUE (third row) caught by the DGN fishery in the post-shark seasonal area closure period (1986-2000). Effort is given in 1x1 degree block. Effort is limited to extent of CDFW block coding system, so effort further offshore is excluded.

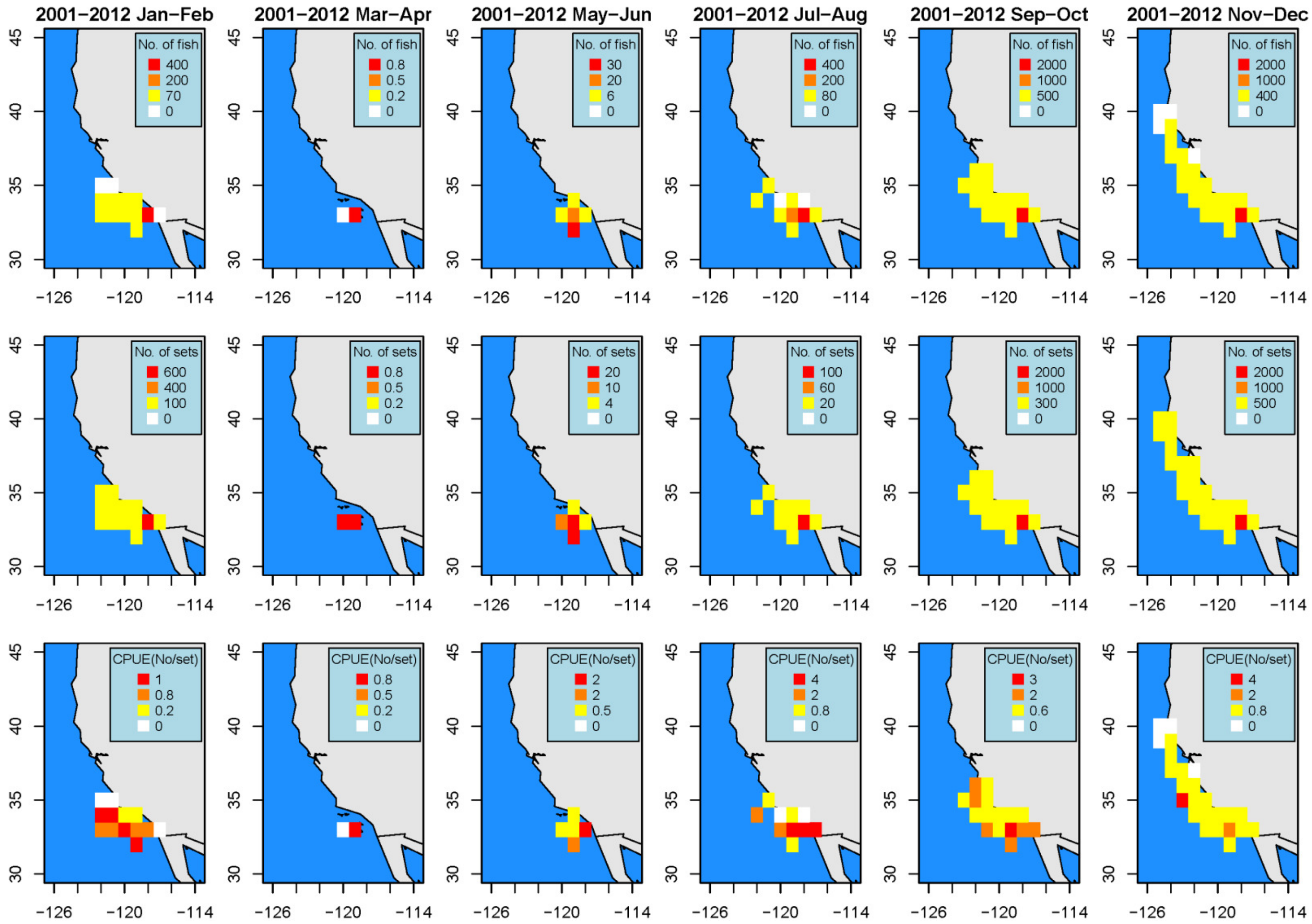

Figure 2-3. Distribution of shortfin mako shark catch (first row), effort (second row), and CPUE (third row) caught by the DGN fishery in the post PLCA closure period (2001-2010). Effort is given in 1x1 degree block. Effort is limited to extent of CDFW block coding system, so effort further offshore is excluded.

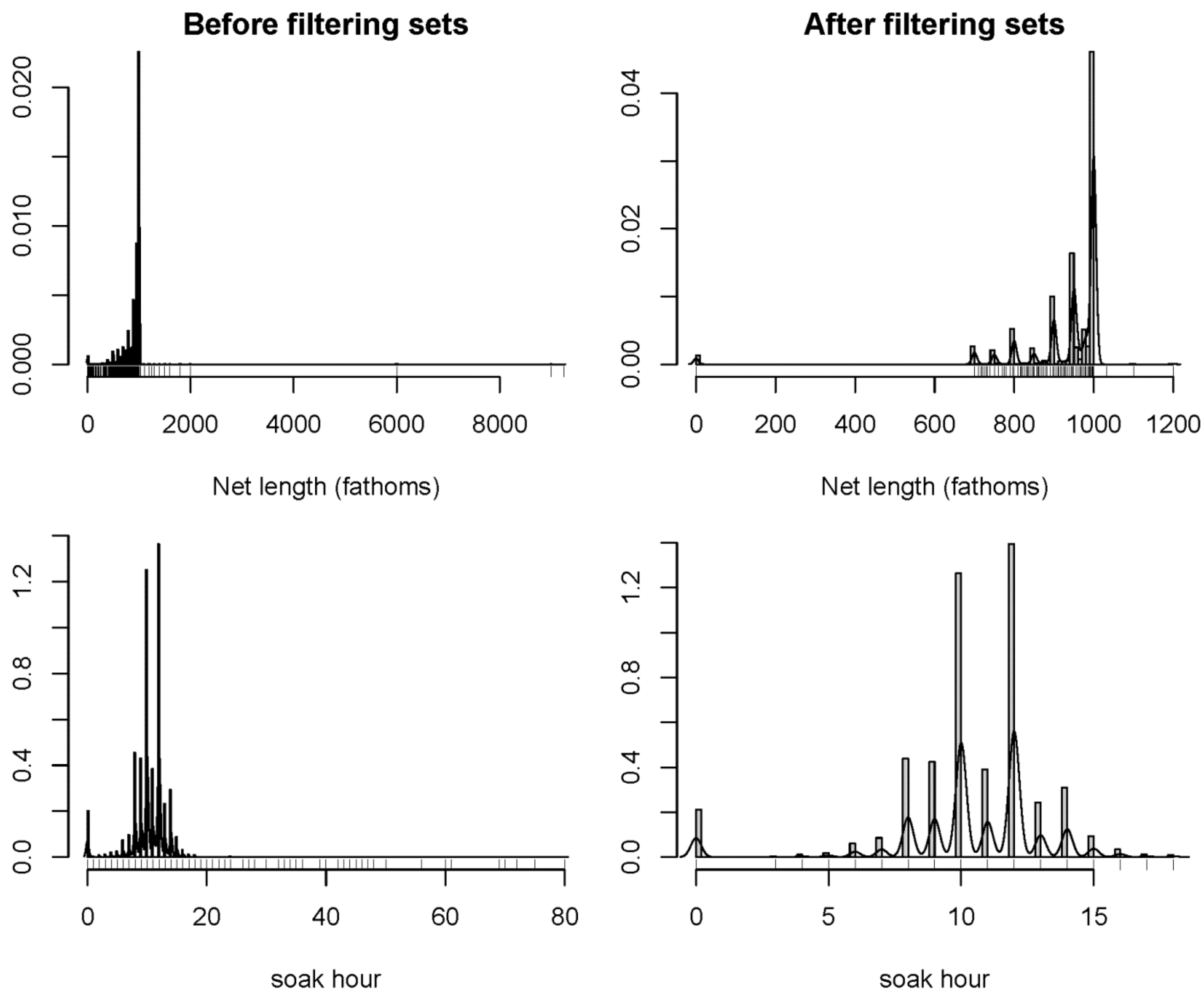

Figure 3. Histograms of fishing operations (first row: net length; second row: soak hour) for the datasets including (left panel) and excluding (right panel) abnormal fishing operations (left panel) for shortfin mako sharks caught by large-mesh drift gillnet fleet (DGN) fishery.

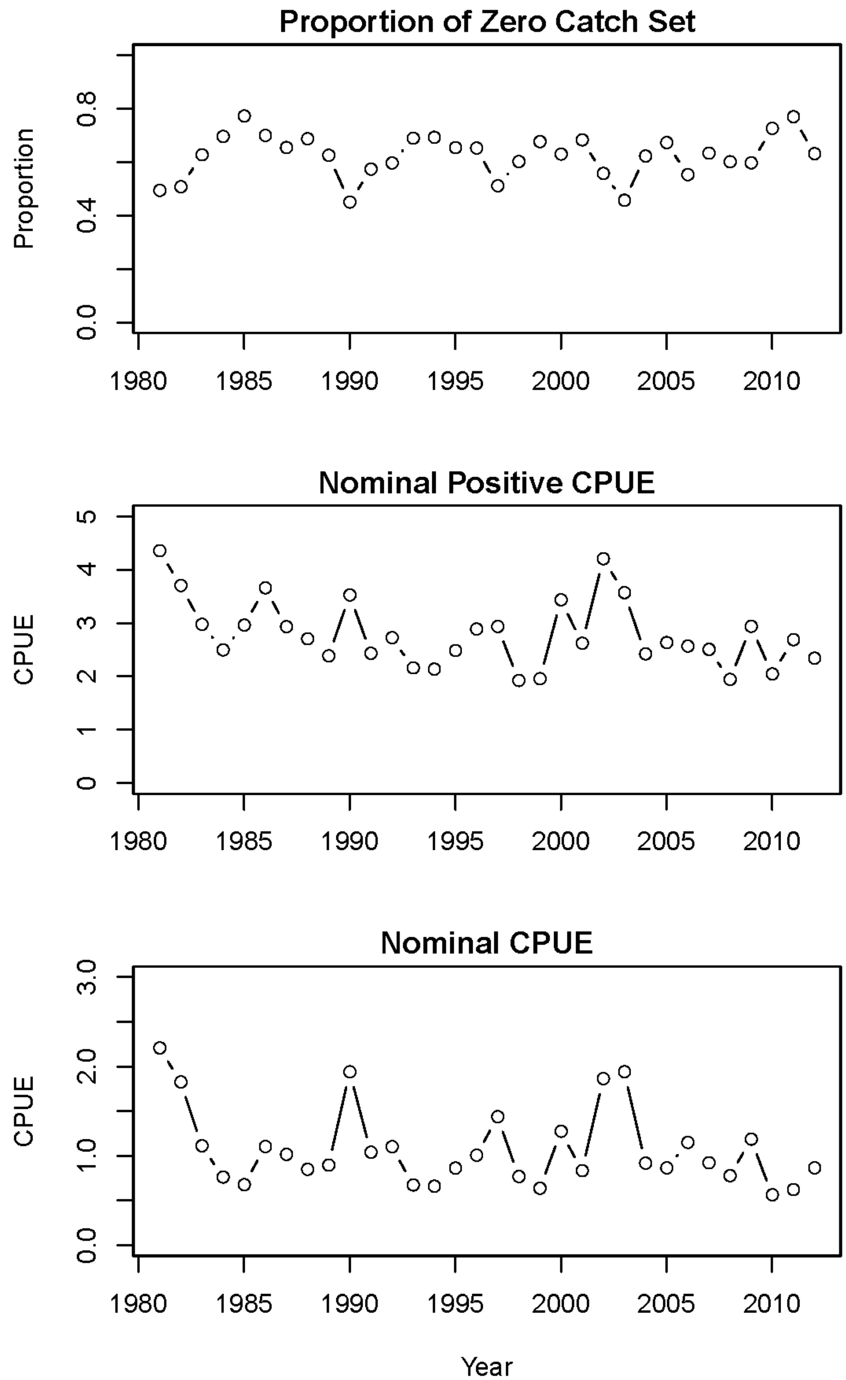

Figure 4. Proportion of zero-catch set (top panel), nominal positive CPUE (middle panel), and nominal CPUE (bottom panel) for shortfin mako sharks caught by large-mesh drift gillnet fleet (DGN) fishery.

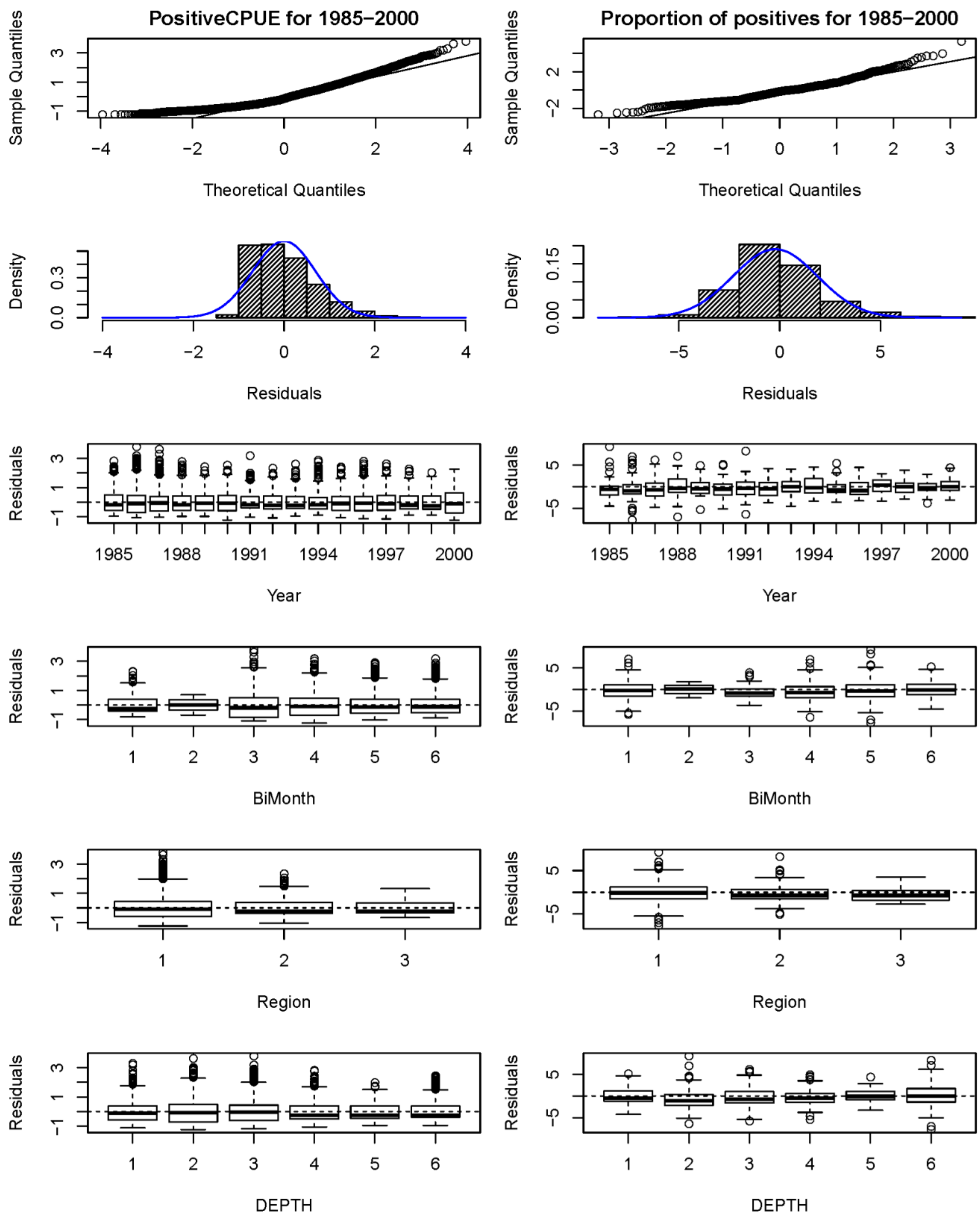

Figure 5-1. Residual diagnostic plots: residuals of the lognormal assumed error distribution for the positive sets (left panel) and Chi-square residuals of the binomial assumed error distribution for the proportion of positive sets (right panel) for shortfin mako sharks caught by DGN fishery for the standardized abundance index during 1985-2000.

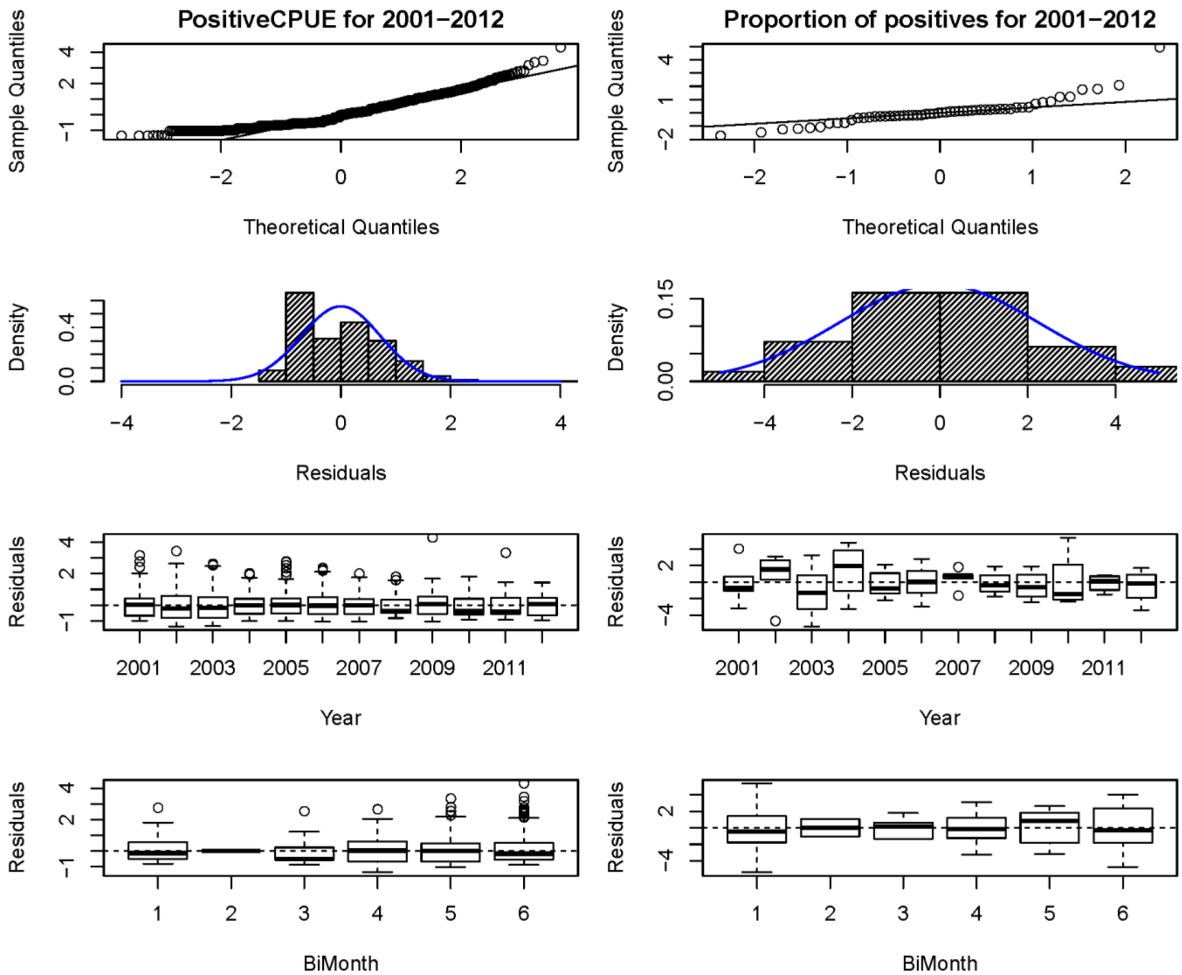

Figure 5-2. Residual diagnostic plots: residuals of the lognormal assumed error distribution for the positive sets (left panel) and Chi-square residuals of the binomial assumed error distribution for the proportion of positive sets (right panel) for shortfin mako sharks caught by DGN fishery for the standardized abundance index during 2001-2012.

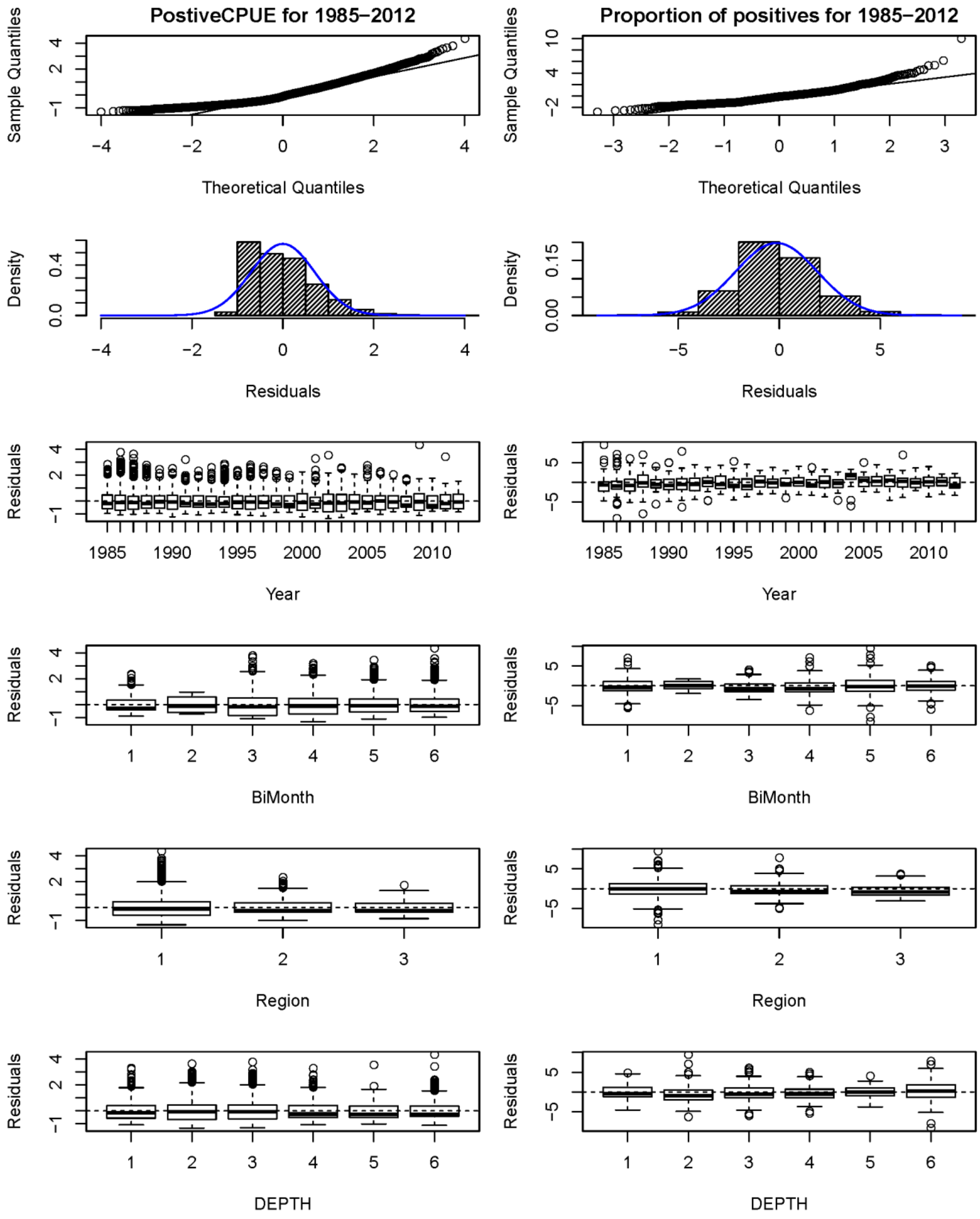

Figure 5-3. Residual diagnostic plots: residuals of the lognormal assumed error distribution for the positive sets (left panel) and Chi-square residuals of the binomial assumed error distribution for the proportion of positive sets (right panel) for shortfin mako sharks caught by DGN fishery for the standardized abundance index during 1985-2012.

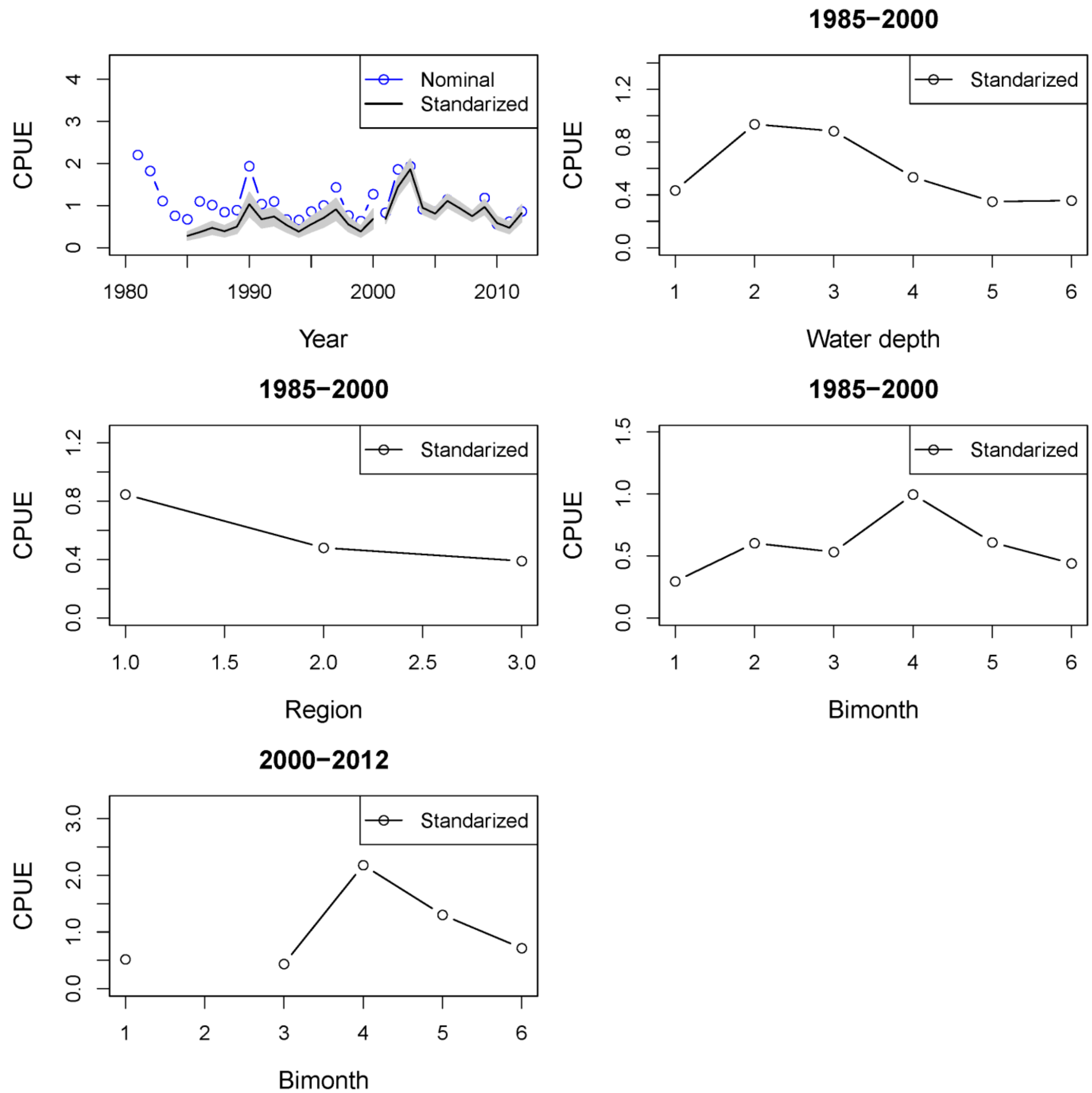

Figure 6-1. Standardized abundance indices extracted from each factor when time series data were divided for shortfin mako sharks caught by DGN fishery for 1985-2012, where the shaded area indicate the associated 95% CI.

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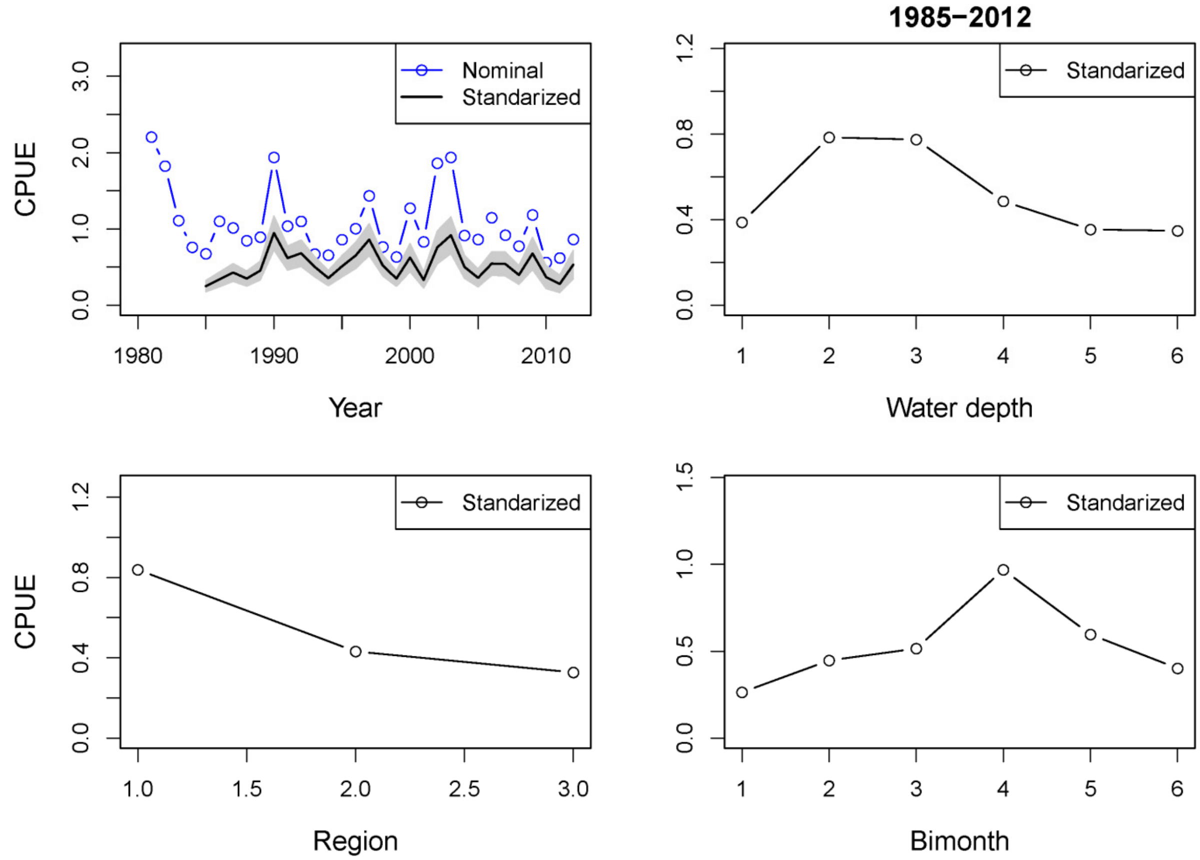

Figure 6-2. Standardized abundance indices extracted from each factor when time series data were treated as one time series for shortfin mako sharks caught by DGN fishery for 1985-2012, where the shaded area indicate the associated 95% CI.