STANDARDIZED CPUE INDICES FOR CANADIAN BLUEFIN TUNA FISHERIES: 1984-2016

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SUMMARY

Standardized indices of Atlantic bluefin tuna abundance were developed for the Canadian rod and reel, tended line and harpoon fisheries in the Atlantic Ocean and Gulf of St. Lawrence. The size composition of the catch indicates that smaller fish, more characteristic of the Atlantic fishery, are occurring in the Gulf of St Lawrence in increasingly greater numbers. The size composition within areas has changed to the point where they are now very similar. Recent trends in relative abundance are similar between areas but differ in the early part of the series. A model of the combined Canadian Atlantic and Gulf data that encompasses the potential redistribution of the stock is provided.

RÉSUMÉ

Des indices standardisés de l'abondance du thon rouge de l'Atlantique ont été mis au point pour les pêcheries canadiennes de canne et de moulinet, de ligne surveillée et de harpon dans l'océan Atlantique et le golfe du Saint-Laurent. La composition par taille des prises indique que des poissons de plus petite taille, plus caractéristiques de la pêcherie de l'Atlantique, sont de plus en plus nombreux dans le golfe du Saint-Laurent. La composition par taille dans les zones a changé au point qu'ils sont désormais très similaires. Les tendances récentes de l'abondance relative sont semblables d'une région à l'autre, mais diffèrent au début de la série. Il est fourni un modèle des données combinées de l'Atlantique canadien et du golfe qui englobe la redistribution potentielle du stock.

RESUMEN

Se desarrollaron índices de abundancia estandarizados para el atún rojo de las pesquerías canadienses de caña y carrete, barrilete y arpón en el océano Atlántico y golfo de San Lorenzo. La composición por tallas de la captura indica que hay un número cada vez mayor de peces más pequeños, más característicos de la pesquería del Atlántico, en el golfo de San Lorenzo. La composición por tallas dentro de las zonas ha cambiado hasta el punto de que ahora son muy similares. Las tendencias recientes en la abundancia relativa son similares en las diferentes zonas, pero difieren en la primera fase de la serie. Se proporciona un modelo de datos canadienses combinados para el Atlántico y el golfo que abarca la redistribución potencial del stock.

KEYWORDS

Catch Rates, size Composition, bluefin tuna, rod and reel

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1. Description of the data source

Directed Bluefin tuna rod and reel, harpoon and tended line fisheries occur both along Canada's Atlantic coast and in the Gulf of St. Lawrence. Each area supports an index of relative abundance with the former being identified as the southwestern Nova Scotia (SWNS) index and the latter as the southern Gulf of St. Lawrence index (sGSL). The SWNS time series spans the years 1988 to 2015 while the longer sGSL series begins in 1984 and is continuous to 2016. A directed Bluefin tuna rod and reel fishery also occurs in coastal Newfoundland waters however the catch is too small on which to base an index of relative abundance.

1.1. Description of the fishery and target species (see SCRS\2015\047)

The Canadian commercial Bluefin tuna fisheries target Bluefin tuna migrating into Canadian waters between the months of July and November. Bluefin have been observed outside of these main fishing months to the extent that in the present day there are sightings by other fisheries as late as January and as early as April.

Prior to 1994, the Atlantic fishery occurred between Georges and Browns banks in a region known as the Hell Hole, at the entrance of the Bay of Fundy off Grand Manan Island and to a lesser degree near the entrance to the Strait of Canso (SCRS\2015\047). In the Gulf of St. Lawrence, most of the fishing occurred at the eastern end of the Northumberland Strait and neighbouring St. Georges Bay and at the western and eastern ends of Prince Edward Island. Since 1994, the spatial distribution of the Atlantic and Gulf fisheries has become more widespread.

The SWNS fishery generally takes place between the months of August and October, though in recent years the effort has been delayed until October (SCRS\2015\047). This fishery continues to be dominated by rod and reel catches, with smaller contributions by tended line and harpoon. The Scotia-Fundy (SF) home fleet accounts for 80% of the catches in SWNS, due to decreased activity by ex-sector fleets.

Similarly, fishing in the Gulf of St. Lawrence mainly occurs from August to October, with more effort deferred to the later months. The catches are made almost exclusively by rod and reel gear, with the home fleets of New Brunswick, Nova Scotia, Quebec and Prince Edward Island (GNB, GNS, PQ and PEI) responsible for ~95% of the trips.

Historically, the data from NAFO areas 4V and 4W (**Figure 1**) have not been included in the SWNS index. In the 1990s, fishing in this area spanned the months of August through October. More recently, the season has shifted to September through November. This shift follows the transition from a competitive to an individual quota management system. 4VW is fished almost entirely by rod and reel gear, though some harpoon catches appear in recent years. The 4VW area is fished by a variety of fleets, with the GNS fleet becoming predominant in the last two years.

1.2. Size, age range and condition of the fish that the index applies to

As indicated in SCRS\2015\047, the median round weight of Bluefin tuna landed in the Southwest Nova Scotia fishery has been increasing throughout the 2000s (**Figure 2, Figure 3**). The 2013 to 2015 estimates of 250 kgs are well above the long term series mean of 172 kgs. The corresponding figures for the Gulf of St. Lawrence fishery are showing the opposite trend.

The round weight of catch in the southern Gulf of St. Lawrence fishery averaged 350 kgs from 1981 to 2014 and began to decline below this average in 2001. By 2009 a significant fraction of Bluefin less than 200 kgs is observed (SCRS\2015\047). The fraction of small Bluefin has increased to the extent that the mean catch weight has declined from a 15 year high of 349 kgs in 2008 to a low of 246 kgs in 2016 (**Figure 2, Figure 3**) with the majority of the catch (93%) below 350 kgs. Evidence from stock origin analyses (SCRS\2015\041) suggests an increasing fraction of Bluefin in the Gulf of St. Lawrence is from the eastern stock and that these fish are among the smaller fish in the catch.

Given that the size range of the Bluefin tuna landed in the two fisheries is similar the corresponding age ranges are as well. The maximum and minimum age observed in the SWNS fishery was 21 and 6 in 2014 and in the sGSL fishery it was 26 and 7 in 2014.

1.3. Changes in the fishery that might affect catch rates

The fisheries gradually transitioned from tended line to the rod and reel gear type. Consideration for a possible effect on catch rates because of this change is accommodated in the model.

2. Methods

2.1. Data Exclusions and Rationale

The SWNS index was limited to catches made by tended line, rod and reel and harpoon and excluded catches made by the trap net fishery in St. Margaret's Bay. Geographically, the data were limited to NAFO areas 4X, 4V, 4W, 5Y and 5Z (**Figure 1**) but for modeling purposes adjacent areas with sparse data were combined with data rich areas to form 2 areas, 4X and 4W. Only trips from mid-July to the end of the first week in November were included.

The sGSL index was based on catches by rod and reel and tended line with a distinction made between trolling and chumming activities within the rod and reel gear type. Only trips from mid-July to the end of the first week in November were included. Trips were confined to NAFO area 4T which is essentially defined by a box with coordinates 68°W to 60°W longitude, and 46°N to 50°N latitude (**Figure 1**). Only the PEI, GNS, GNB and PQ fleets had sufficient effort in area 4T to justify their inclusion. Finally, any fishing district with fewer than 20 observations was excluded.

The index based on the combined sGSL and SWNS fishery data was limited to the rod and reel, tended line and harpoon gears. Only trips from mid-July to the end of the first week in November were included. The only other adjustment that was required was to aggregate the SWNS fishery data to the same level as the sGSL data. Thus total catch and effort per trip and gear type was summed over gear, Julian day, NAFO area and fleet.

2.2. Management Regulations

The mandatory submission of logbooks was instituted in 1996 and provided detailed information on all trips targeting Bluefin tuna in Canadian waters, including trips with no catch. Prior to 1996, this information was submitted on a voluntary basis.

In 2004 the southwest Nova Scotia fleet transitioned from a competitive fishery to an Individual Transferrable Quota (ITQ) system. In the southern Gulf of St. Lawrence, the PEI fleet adopted an ITQ-like system in 2011. Fishing in 4W is subject to the same management measures as SWNS, except in 4Wd where the fishery continues to operate in a competitive manner. Historical catches in 4V are subject to the same rules as the sGSL fleets.

2.3. Dataset used in the Analysis

2.3.1. The effort and catch variables

In both the SWNS and sGSL indices, hours fished have been used as the measure of effort (Paul et al. 2010), while catch was the number, not the weight, of Bluefin tuna caught. Both effort and catch were aggregated to the trip level for the SWNS index; however, in the Gulf of St. Lawrence trips are only a day long and the catch is limited to one fish for most of the time series therefore catch and effort were aggregated by combining all trips by the same fleet, using the same gear on the same day. This level of aggregation was also applied to the SWNS data prior to combining it with the sGSL data for use in a combined index.

2.4. Model Standardization and Diagnostics

The Gulf and SWNS data were each fit with general additive mixed effect models (Wood 2011, Zuur et al. 2014). Models were compared using analysis of deviance and AIC. Comparisons of models with the same covariates but different random structures, required fitting with REML while comparisons of models with the same variance structure but a different set of covariates and smoothers required fitting by ML. Model fits were tested for over dispersion. Sources of over dispersion considered were missing covariates, missing interaction terms, outliers, non linear patterns and variation larger than what the Poisson distribution allows. Heterogeneity of variances was tested by applying a regression model or GAM to the residuals as a function of each of the covariates. The justification for using effort as an offset was tested by adding log(Effort) as a covariate to the model and determining if the estimated coefficient was close to 1.

sGULF Index

The best fitting model for the sGSL data is defined as follows:

$$BFT_{ij} \sim NB(\mu_{ij}, \theta)$$

$$E(BFT_{ij}) = \mu_{ij}, \qquad V(BFT_{ij}) = \mu_{ij} + \frac{\mu_{ij}^2}{\theta}$$

$$\log(\mu_{ij}) = \eta_{ij}$$

$$\eta_{ij} = \beta_1 + \beta_2 fYear_{ij} + \beta_3 fFleet_{ij} + \beta_4 fGear_{ij} + f(Effort_{ij}) + f(Jday_{ij}) + a_i$$

$$a_i \sim N(0, \sigma^2)$$

BFT_{ij} is the j[th] observation from the i[th] gear-fleet combination. a_i is a random intercept that allows for random variation by gear-fleet combination and models the correlation between all observations with the same gear and fleet. $fYear_{ij}$ is a categorical variable for the fixed year effect (1984-2016), $fFleet_{ij}$ is a categorical variable for the fixed fleet effect (Nova Scotia Gulf fleet, New Brunswick Gulf fleet, Prince Edward Island fleet and Quebec fleet), $fGear_{ij}$ is a categorical variable for the fixed gear effect (angling with chumming, angling with trolling, tended line and mixed tended line/angling), $f(Effort_{ij})$ is a smoother for fishing effort hours and $f(Jday_{ij})$ is a smoother for day of the year.

The correlation between the catch data for two observations from the same gear-fleet is quantified by the expression:

$$Intraclass\ correlation = \frac{\sigma_a^2}{\sigma_a^2 + \sigma_\epsilon^2}$$

SWNS Index

The best fitting model for the SWNS data is defined as follows:

$$BFT_{ij} \sim NB(\mu_{ij}, \theta)$$

$$E(BFT_{ij}) = \mu_{ij}, \qquad V(BFT_{ij}) = \mu_{ij} + \frac{\mu_{ij}^2}{\theta}$$

$$\log(\mu_{ij}) = \eta_{ij}$$

$$\eta_{ij} = \beta_1 + \beta_2 fYear_{ij} + \beta_3 fFleet_{ij} + \beta_4 fGear_{ij} + \beta_5 fArea_{ij} + \beta_6 fOT_{ij} + f(Effort_{ij}){:}\,fGear_{ij} + f(Jday_{ij}){:}\,fGear_{ij} + a_i$$

$$a_i \sim N(0, \sigma^2)$$

BFT_{ij} is the j[th] observation from the i[th] area-week-of-the-year-gear (AWG) combination. a_i is a random intercept that allows for random variation by AWG combination and models the correlation between all observations with the same gear in the same area and week of the year. $fYear_{ij}$ is a categorical variable for the fixed year effect (1989-2015), $fFleet_{ij}$ is a categorical variable for the fixed fleet effect (Gulf Nova Scotia, Gulf New Brunswick, Prince Edward Island, Scotia-Fundy, Newfoundland, Quebec and Undesignated), $fGear_{ij}$ is a categorical variable for the fixed gear effect (harpoon, angling with trolling and tended line), $fArea_{ij}$ is a fixed area effect (NAFO divisions 4X and 4W), fOT_{ij} is a fixed effect indicating when a trip landed other tunas (Yellowfin, Bigeye and Albacore) and distinguishes between Bluefin tuna targeted trips (True, False), $f(Effort_{ij}){:}\,fGear_{ij}$ is a smoother for fishing effort hours by gear type and $f(Jday_{ij}){:}\,fGear_{ij}$ is a smoother for day of the year by gear type.

Combined Index

The best fitting model for the Combined data is defined as follows:

$$BFT_{ij} \sim NB(\mu_{ij}, \theta)$$

$$E(BFT_{ij}) = \mu_{ij}, \qquad V(BFT_{ij}) = \mu_{ij} + \frac{\mu_{ij}^2}{\theta}$$

$$\log(\mu_{ij}) = \eta_{ij}$$

$$\eta_{ij} = \beta_1 + \beta_2 fYear_{ij} + \beta_3 fFleet_{ij} + \beta_4 fGear_{ij} + \beta_5 fArea_{ij} + \beta_6 fOT_{ij} + f(Effort_{ij}){:}\, fGear_{ij} + f(Jday_{ij}){:}\, fArea_{ij} + a_i$$

$$a_i \sim N(0, \sigma^2)$$

BFT_{ij} is the j^{th} observation from the i^{th} area-week-of-the-year-gear (AWG) combination. a_i is a random intercept that allows for random variation by AWG combination and models the correlation between all observations with the same gear in the same area and week of the year. $fYear_{ij}$ is a categorical variable for the fixed year effect (1984-2015), $fFleet_{ij}$ is a categorical variable for the fixed fleet effect (Gulf Nova Scotia, Gulf New Brunswick, Prince Edward Island, Scotia-Fundy, Newfoundland, Quebec and Undesignated), $fGear_{ij}$ is a categorical variable for the fixed gear effect (harpoon, angling and tended line), $fArea_{ij}$ is a fixed area effect (NAFO divisions 4X, 4W and 4T), fOT_{ij} is a fixed effect indicating when a trip landed other tunas (Yellowfin, Bigeye and Albacore) and distinguishes between Bluefin tuna targeted trips (True, False), $f(Effort_{ij}){:}\, fGear_{ij}$ is a smoother for fishing effort hours by gear type and $f(Jday_{ij}){:}\, fArea_{ij}$ is a smoother for day of the year by area.

3. Results

3.1. sGSL index

The best fitting model incorporated the Year effect as a categorical variable and is contrasted with a model in which Year is included as a smoothed term (Table 4**, Figure 4**). Population level estimates of the Bluefin tuna catch per hour of effort and the associated standard error of estimation are provided in **Table 1**. Neither model was overdispersed with values of 1.035 and 1.091 for the Year as a smoother and Year as a factor models, respectively. Both the analysis of deviance and AIC tests favoured the model with Year as a factor. Though a model with a random effect had lower deviance, the intraclass correlation was only 0.0136 and 0.0123 for the Year as a factor and Year as a smoother models, respectively. The θ parameter of the negative binomial distribution was estimated to be 1.912 and 2.226 for the models with Year as smoother and as a factor, respectively.

Both models have similar looking diagnostic plots (**Figure 5, 6 and 7)** with no evidence of patterns in the residuals based on fits of the residuals to each of the covariates.

Trends in catch (**Figure 4**) estimated by the two models both indicate low relative abundance from 1984 to the early 1990s. A gradual increase in relative abundance begins in 1996 and is followed by a more rapid increase from 2008 to 2011. Thereafter, the relative abundance remains fairly constant.

3.2. SWNS index

Final models fit with the Year effect as a categorical variable or as a smoother were very similar according to analysis of deviance test with the Year as a factor model having significantly lower deviance residuals and a lower AIC (70342.19 vs 69801.32) (**Table 5, Figure 8**). Population level estimates of the Bluefin tuna catch per hour of effort and the associated standard error of estimation are provided in **Table 2**. Neither model was overdispersed with values of 1.01 and 1.0 for the Year as a smoother and Year as a factor models, respectively.

The intraclass correlation was high for both models at 0.1893 (smooth) and 0.1886 (factor) and the θ parameter of the negative binomial distribution was estimated to be 1.891 (smooth) and 2.014 (factor).

Both models had similar looking diagnostic plots (**Figure 9, 10 and 11**) with no strong signs of patterns in the residuals. GAM and GLM fits of the residuals to each of the covariates were not significant.

The estimated trends in catch (**Figure 8**) for the two models indicated a decline in relative abundance from 1988 to 1996 and then a gradual increase to the series high in 2009/2010. Thereafter the relative abundance declined very gradually until 2015.

3.3. Combined index

The combined sGSL and SWNS data produced a single index of abundance for the Canadian Bluefin tuna fisheries data whose trends were consistent with those observed in each single index (**Table 6, Figure 12**). Population level estimates of the Bluefin tuna catch per hour of effort and the associated standard error of estimation are provided in **Table 3.** Again, two of the best fitting models involved Year as a smoother or Year as a factor with the later having a lower AIC (69379.27 versus 68924.30) and significantly smaller deviance residuals. The θ parameter of the negative binomial distribution was estimated to be 0.941 and 0.977 and the resulting fits indicated no overdisperion with values of 1.06 and 1.04 for the models with Year as smoother and as a factor, respectively.

The diagnostic plots are provided in **Figure 13, 14 and 15** and do not indicate any strong residual patterns or signs of heterogeneity.

4. Summary

Catches of Bluefin tuna in the Canadian EEZ using rod and reel, harpoon and tended line were modeled using negative binomial general additive mixed effect models. These models were not overdispersed and did not exhibit strong patterns in the residuals. Separate indices of relative abundance were estimated for the southern Gulf of St. Lawrence and southwest Nova Scotia fisheries as well as for the combined data. Trends in relative abundance for the sGSL and SWNS fisheries were generally very similar. Evidence from the catch composition indicates that the index ages are now very similar whereas prior to the early to mid 2000s the SWNS index was based on much younger fish. In the 2012 assessment the SWNS index ages were 8 to 14 and the sGSL was 13 to 16. By the 2014 assessment, these were adjusted to 5 to 16 for SWNS and 8 to 16 for sGSL. The observed age range for 2014 was 6 to 21 for SWNS and 7 to 26 for SWNS. The changing age composition of the catch in the two areas can be dealt with by estimating an index of relative abundance for both areas combined since the minimum age for the combined data has remained stable at about age 6 or 7 and the maximum is fixed by the plus group at 16.

Each of the three trends in relative abundance shows an increase from the mid 1990s and reaches a plateau by 2009/2010. They differ with respect to the magnitude of relative abundance at the beginning and end of the time series. The relative abundance estimated for SWNS at the beginning of the series is similar to what it was in 2015 whereas for both the combined and sGSL series the current estimates are about 3x higher. These differences between the SWNS and sGSL series could be a function of the changing age composition which may be resolved by fitting a model to the combined data.

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Table 1. Population estimates of Bluefin tuna catch per hour of effort and associated standard error of estimation and coefficient of variation for the sGSL fishery. Fit1, SE1 and CV1 were derived from a GAMM with Year as a smoother while Fit2, SE2 and CV2 were derived from an identical model but with Year as a categorical covariate.

Year	**FIT1**	**SE1**	**CV1**	**FIT2**	**SE2**	**CV2**	**N**
1984	0.353	0.037	0.105	0.338	0.036	0.107	436
1985	0.221	0.021	0.095	0.160	0.021	0.131	268
1986	0.151	0.017	0.113	0.110	0.021	0.191	290
1987	0.125	0.016	0.128	0.128	0.045	0.352	94
1988	0.130	0.016	0.123	0.176	0.040	0.227	153
1989	0.164	0.018	0.110	0.378	0.067	0.177	140
1990	0.229	0.023	0.100	0.075	0.017	0.227	205
1991	0.310	0.030	0.097	0.285	0.057	0.200	175
1992	0.360	0.032	0.089	0.475	0.062	0.131	211
1993	0.337	0.027	0.080	0.351	0.038	0.108	293
1994	0.261	0.019	0.073	0.120	0.015	0.125	400
1995	0.183	0.013	0.071	0.349	0.031	0.089	350
1996	0.132	0.009	0.068	0.067	0.007	0.104	615
1997	0.109	0.008	0.073	0.068	0.007	0.103	580
1998	0.110	0.008	0.073	0.126	0.012	0.095	472
1999	0.133	0.009	0.068	0.193	0.017	0.088	587
2000	0.176	0.011	0.062	0.167	0.015	0.090	480
2001	0.232	0.015	0.065	0.141	0.013	0.092	539
2002	0.284	0.019	0.067	0.229	0.020	0.087	621
2003	0.315	0.022	0.070	0.281	0.025	0.089	587
2004	0.330	0.023	0.070	0.495	0.046	0.093	309
2005	0.350	0.024	0.069	0.329	0.026	0.079	604
2006	0.401	0.027	0.067	0.318	0.026	0.082	592
2007	0.508	0.033	0.065	0.733	0.066	0.090	246
2008	0.690	0.043	0.062	0.482	0.038	0.079	444
2009	0.947	0.058	0.061	0.836	0.079	0.094	172
2010	1.228	0.071	0.058	2.373	0.328	0.138	41
2011	1.445	0.075	0.052	1.434	0.097	0.068	418
2012	1.541	0.077	0.050	1.771	0.117	0.066	383
2013	1.535	0.078	0.051	1.524	0.100	0.066	410
2014	1.489	0.073	0.049	1.409	0.091	0.065	476
2015	1.446	0.070	0.048	1.170	0.071	0.061	633
2016	1.416	0.085	0.060	1.715	0.110	0.064	443

Table 2. Population estimates of Bluefin tuna catch per hour of effort and associated standard error of estimation and coefficient of variation for the SWNS fishery. Fit1, SE1 and CV1 were derived from a GAMM with Year as a smoother while Fit2, SE2 and CV2 were derived from an identical model but with Year as a categorical covariate.

Year	**FIT1**	**SE1**	**CV1**	**FIT2**	**SE2**	**CV2**	**N**
1988	1.601	0.331	0.207	1.525	0.314	0.206	135
1989	0.977	0.196	0.201	1.403	0.283	0.202	266
1990	0.670	0.134	0.200	0.746	0.148	0.198	2026
1991	0.556	0.112	0.201	0.672	0.133	0.198	1335
1992	0.547	0.110	0.201	0.715	0.142	0.199	1543
1993	0.573	0.115	0.201	0.447	0.090	0.201	599
1994	0.573	0.115	0.201	0.770	0.154	0.200	868
1995	0.522	0.104	0.199	1.052	0.212	0.202	480
1996	0.453	0.090	0.199	0.465	0.091	0.196	2791
1997	0.413	0.082	0.199	0.365	0.071	0.195	4164
1998	0.425	0.084	0.198	0.470	0.091	0.194	5009
1999	0.496	0.098	0.198	0.746	0.145	0.194	2758
2000	0.617	0.122	0.198	0.387	0.076	0.196	2114
2001	0.759	0.151	0.199	0.940	0.183	0.195	1658
2002	0.881	0.176	0.200	1.145	0.232	0.203	1426
2003	0.972	0.194	0.200	1.218	0.249	0.204	689
2004	1.057	0.210	0.199	1.043	0.205	0.197	1068
2005	1.168	0.232	0.199	1.159	0.226	0.195	1415
2006	1.314	0.261	0.199	1.635	0.319	0.195	1504
2007	1.466	0.291	0.198	1.405	0.276	0.196	1013
2008	1.577	0.314	0.199	1.486	0.292	0.197	1085
2009	1.619	0.323	0.200	1.820	0.363	0.199	402
2010	1.600	0.319	0.199	1.955	0.393	0.201	345
2011	1.549	0.309	0.199	1.517	0.304	0.200	352
2012	1.489	0.298	0.200	1.487	0.298	0.200	415
2013	1.428	0.285	0.200	1.497	0.300	0.200	452
2014	1.367	0.273	0.200	1.352	0.275	0.203	337
2015	1.306	0.268	0.205	1.375	0.278	0.202	411

Table 3. Population estimates of Bluefin tuna catch per hour of effort and associated standard error of estimation and coefficient of variation for the combined sGSL and SWNS fishery. Fit1, SE1 and CV1 were derived from a GAMM with Year as a smoother while Fit2, SE2 and CV2 were derived from an identical model but with Year as a categorical covariate.

Year	FIT1	SE1	CV1	FIT2	SE2	CV2	N
1984	0.266	0.061	0.229	0.372	0.086	0.231	436
1985	0.316	0.069	0.218	0.201	0.050	0.249	268
1986	0.349	0.076	0.218	0.117	0.033	0.282	290
1987	0.338	0.074	0.219	0.144	0.060	0.417	94
1988	0.287	0.062	0.216	0.391	0.091	0.233	226
1989	0.225	0.048	0.213	0.421	0.095	0.226	277
1990	0.177	0.037	0.209	0.151	0.033	0.219	733
1991	0.152	0.032	0.211	0.140	0.030	0.214	743
1992	0.146	0.031	0.212	0.152	0.033	0.217	700
1993	0.154	0.032	0.208	0.153	0.034	0.222	609
1994	0.167	0.035	0.210	0.137	0.030	0.219	749
1995	0.179	0.038	0.212	0.310	0.067	0.216	611
1996	0.185	0.039	0.211	0.178	0.038	0.213	1323
1997	0.190	0.040	0.211	0.151	0.032	0.212	1676
1998	0.201	0.042	0.209	0.224	0.048	0.214	1484
1999	0.228	0.048	0.211	0.334	0.071	0.213	1212
2000	0.278	0.059	0.212	0.209	0.045	0.215	1208
2001	0.355	0.075	0.211	0.323	0.069	0.214	1157
2002	0.449	0.095	0.212	0.482	0.105	0.218	855
2003	0.542	0.114	0.210	0.618	0.135	0.218	779
2004	0.619	0.130	0.210	0.708	0.153	0.216	741
2005	0.680	0.143	0.210	0.643	0.137	0.213	1030
2006	0.742	0.156	0.210	0.823	0.176	0.214	1015
2007	0.823	0.173	0.210	0.811	0.175	0.216	622
2008	0.928	0.195	0.210	0.717	0.154	0.215	834
2009	1.041	0.219	0.210	1.274	0.278	0.218	361
2010	1.131	0.238	0.210	1.487	0.329	0.221	238
2011	1.174	0.247	0.210	1.204	0.260	0.216	610
2012	1.173	0.247	0.211	1.342	0.289	0.215	620
2013	1.154	0.243	0.211	1.096	0.236	0.215	697
2014	1.142	0.241	0.211	1.104	0.238	0.216	693
2015	1.150	0.243	0.211	1.015	0.218	0.215	866
2016	1.172	0.252	0.215	1.517	0.333	0.220	443

Table 4. Wald tests of the significance of each parametric and smooth term in the sGSL model with Year as a smoother (A) and Year as a factor (B). Interpretation is analogous to a type III ANOVA, rather than a sequential type I ANOVA.

A)

```
Family: Negative Binomial(1.912)
Link function: log

Formula:
BFT_c ~ s(Effort) + s(Year) + s(Jday, k = 12) + HMA_f + Gear +
    s(FG, bs = "re", by = dum)

Parametric Terms:
      df Chi.sq  p-value
HMA_f  3  6.541   0.0881
Gear   3 32.061 5.08e-07

Approximate significance of smooth terms:
            edf Ref.df  Chi.sq  p-value
s(Effort) 8.828  8.992 5347.98  < 2e-16
s(Year)   8.848  8.992 2168.82  < 2e-16
s(Jday)   7.060  8.444  355.40  < 2e-16
s(FG):dum 6.771  9.000   40.24 1.48e-07
```

B)

```
Family: Negative Binomial(2.226)
Link function: log

Formula:
BFT_c ~ s(Effort) + Year_f + s(Jday, k = 12) + HMA_f + Gear +
    s(FG, bs = "re", by = dum)

Parametric Terms:
       df  Chi.sq  p-value
Year_f 32 2769.69  < 2e-16
HMA_f   3   10.12   0.0176
Gear    3   24.01 2.49e-05

Approximate significance of smooth terms:
            edf Ref.df  Chi.sq  p-value
s(Effort) 8.831  8.992 5575.43  < 2e-16
s(Jday)   6.718  8.100  335.44  < 2e-16
s(FG):dum 6.727  9.000   40.17 1.45e-07
```

Table 5. Wald tests of the significance of each parametric and smooth term in the SWNS model with Year as a smoother (A) and Year as a factor (B). Interpretation is analogous to a type III ANOVA, rather than a sequential type I ANOVA.

A)

```
Family: Negative Binomial(1.891)
Link function: log

Formula:
BFT_c ~ s(Effort, by = Gear) + s(Year) + s(Jday, k = 12, by = Gear) +
    HMA_f + NAFO + OT + s(NWG, bs = "re", by = dum)

Parametric Terms:
      df  Chi.sq p-value
HMA_f  6 1776.31  <2e-16
NAFO   1   82.33  <2e-16
OT     1  177.59  <2e-16

Approximate significance of smooth terms:
                    edf Ref.df   Chi.sq  p-value
s(Effort):Gear54  8.873  8.994  825.377  < 2e-16
s(Effort):Gear60  8.871  8.992 2007.538  < 2e-16
s(Effort):Gear81  8.351  8.873   83.623 2.92e-14
s(Year)           8.782  8.985 2133.800  < 2e-16
s(Jday):Gear54    2.871  3.445    4.705   0.2741
s(Jday):Gear60    9.111 10.211   44.949 1.83e-06
s(Jday):Gear81    1.001  1.002    2.736   0.0984
s(NWG):dum       69.967 88.000 1147.432  < 2e-16
```

B)

```
Family: Negative Binomial(2.014)
Link function: log

Formula:
BFT_c ~ s(Effort, by = Gear) + Year_f + s(Jday, k = 12, by = Gear) +
    HMA_f + NAFO + OT + s(NWG, bs = "re", by = dum)

Parametric Terms:
       df  Chi.sq p-value
Year_f 27 2664.51  <2e-16
HMA_f   6 1393.97  <2e-16
NAFO    1   84.76  <2e-16
OT      1  181.67  <2e-16

Approximate significance of smooth terms:
                    edf Ref.df   Chi.sq  p-value
s(Effort):Gear54  8.865  8.993  678.711  < 2e-16
s(Effort):Gear60  8.870  8.992 2018.057  < 2e-16
s(Effort):Gear81  8.334  8.867   79.104 2.50e-13
s(Jday):Gear54    2.044  2.390    1.709   0.4536
s(Jday):Gear60    8.875 10.054   35.970 6.63e-05
s(Jday):Gear81    1.021  1.029    2.968   0.0898
s(NWG):dum       70.459 88.000 1169.635  < 2e-16
```

Table 6. Wald tests of the significance of each parametric and smooth term in the combined SWNS and sGSL analysis with Year as a smoother (A) and Year as a factor (B). Interpretation is analogous to a type III ANOVA, rather than a sequential type I ANOVA.

```
A)
Family: Negative Binomial(0.941)
Link function: log

Formula:
BFT_c ~ s(Effort, by = Gear) + s(Year) + s(Jday, k = 12, by = Nafo_f) +
    HMA_f + Nafo_f + OT + s(NWG, bs = "re", by = dum)

Parametric Terms:
       df Chi.sq  p-value
HMA_f   6 803.50  < 2e-16
Nafo_f  2 341.93  < 2e-16
OT      1  41.53 1.16e-10

Approximate significance of smooth terms:
                     edf  Ref.df  Chi.sq  p-value
s(Effort):Gear54   7.706   8.007 2184.94  < 2e-16
s(Effort):Gear60   8.790   8.987 4528.38  < 2e-16
s(Effort):Gear81   3.919   4.490  146.25  < 2e-16
s(Year)            8.727   8.974 3137.38  < 2e-16
s(Jday):Nafo_f4T   3.085   3.597   37.72 1.16e-07
s(Jday):Nafo_f4W   2.590   2.926   15.60  0.00104
s(Jday):Nafo_f4X   6.561   7.665   55.35 3.08e-09
s(NWG):dum        81.842 115.000  553.73  < 2e-16

B)
Family: Negative Binomial(0.977)
Link function: log

Formula:
BFT_c ~ s(Effort, by = Gear) + Year_f + s(Jday, k = 12, by = Nafo_f) +
    HMA_f + Nafo_f + OT + s(NWG, bs = "re", by = dum)

Parametric Terms:
       df  Chi.sq p-value
Year_f 32 3679.47 < 2e-16
HMA_f   6  729.04 < 2e-16
Nafo_f  2  326.60 < 2e-16
OT      1   52.37 4.6e-13

Approximate significance of smooth terms:
                     edf  Ref.df  Chi.sq  p-value
s(Effort):Gear54   7.726   8.017 2119.72  < 2e-16
s(Effort):Gear60   8.789   8.987 4604.34  < 2e-16
s(Effort):Gear81   4.024   4.583  134.90  < 2e-16
s(Jday):Nafo_f4T   3.321   3.900   37.65 1.25e-07
s(Jday):Nafo_f4W   2.250   2.528   13.24  0.00213
s(Jday):Nafo_f4X   6.968   8.110   52.94 1.36e-08
s(NWG):dum        82.415 115.000  546.17  < 2e-16
```

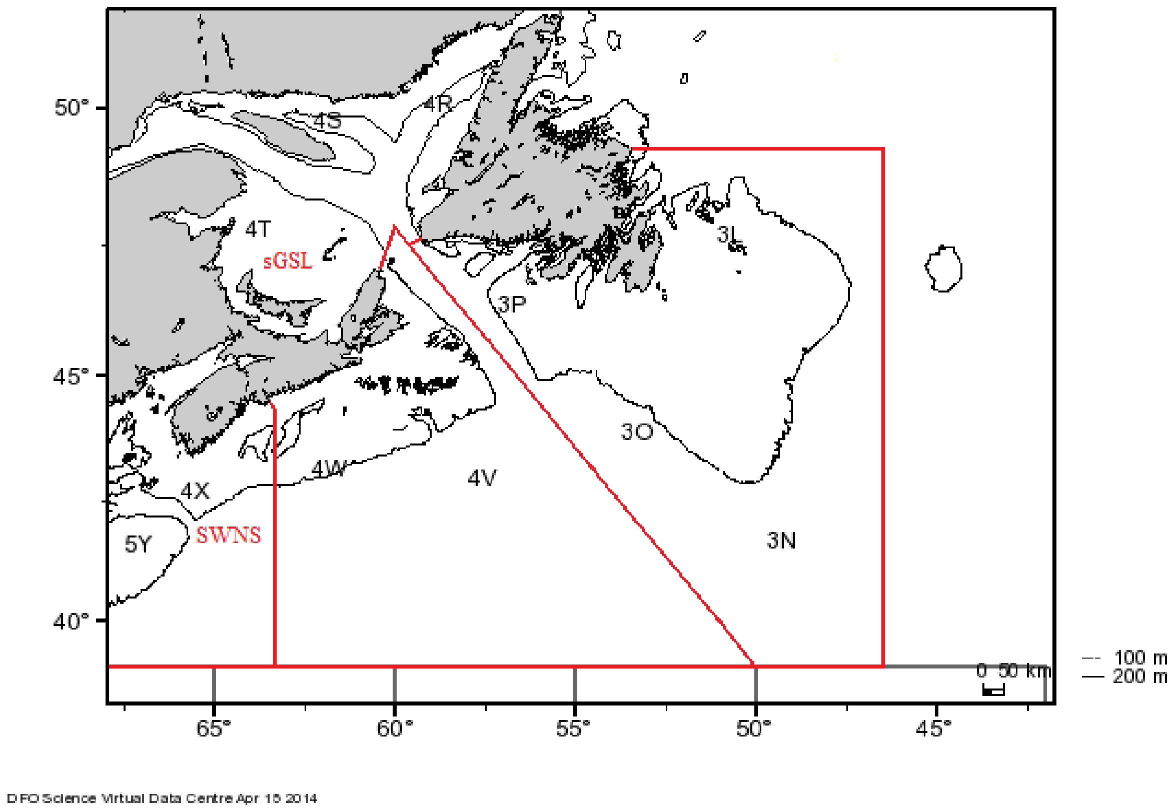

Figure 1. Map delimiting major NAFO areas within the Canadian EEZ.

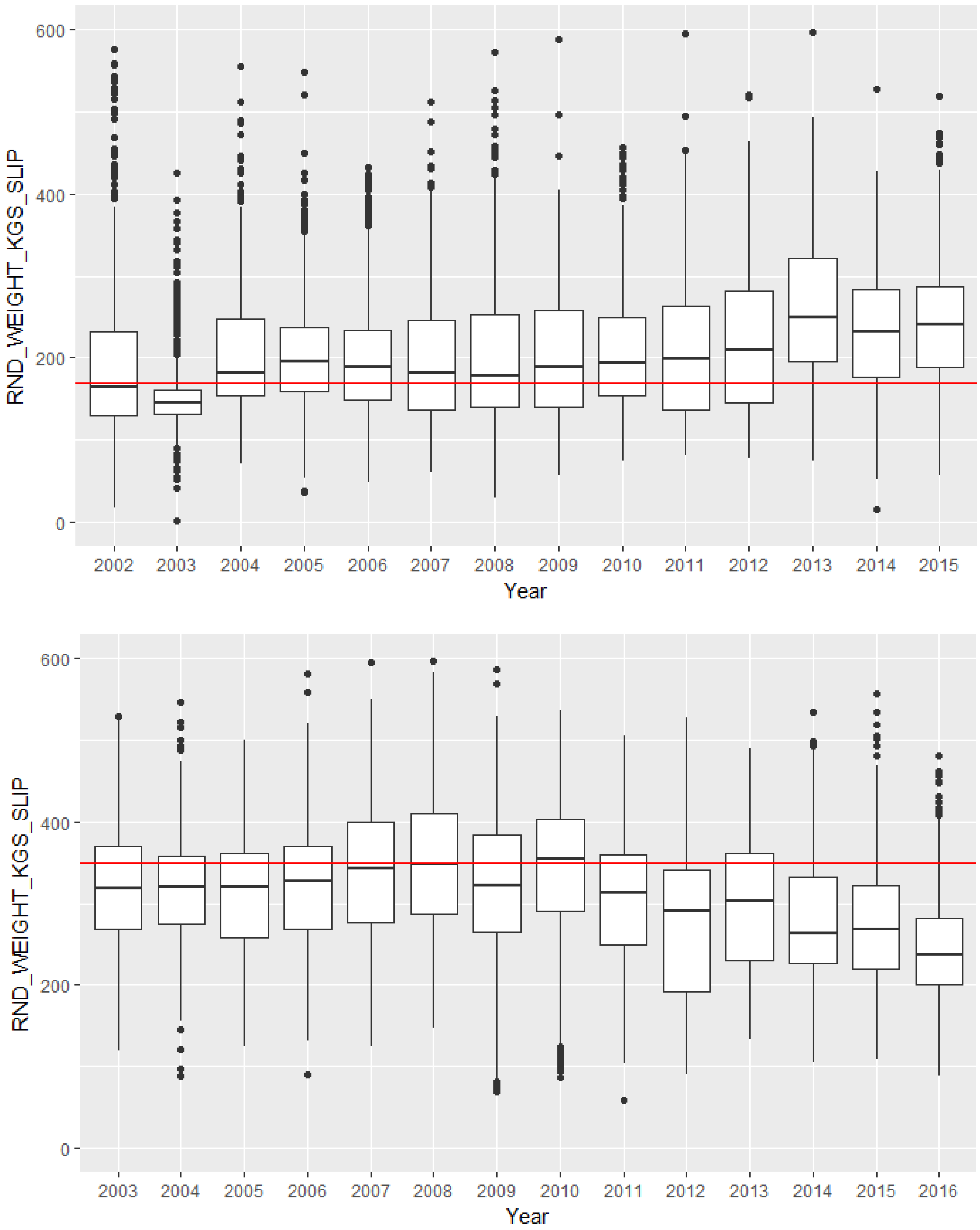

Figure 2. Round weight (kg) of recent Bluefin tuna landed in the Southwest Nova Scotia (top) and Gulf of St. Lawrence (bottom) fisheries. Red lines indicate series mean for the longer catch time series and are 175 kgs for SWNS and 350 kgs for the sGSL.

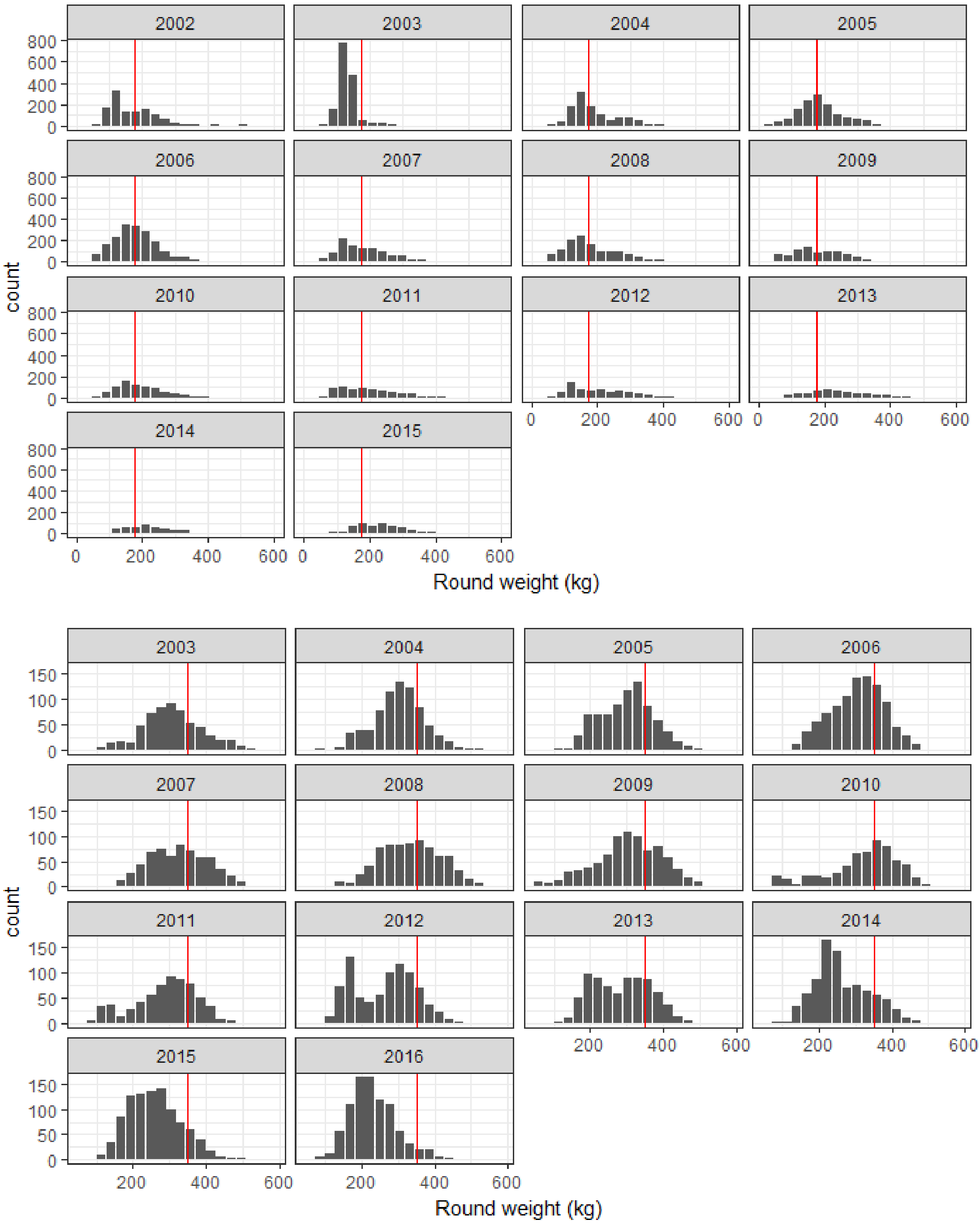

Figure 3. Catch composition for the SWNS fishery (top) from 2002 to 2015 and for the sGSL fishery (bottom) from 2003 to 2016. The vertical line marks the long term series mean of 175 kgs and 350 kgs for the SWNS and sGSL fisheries, respectively.

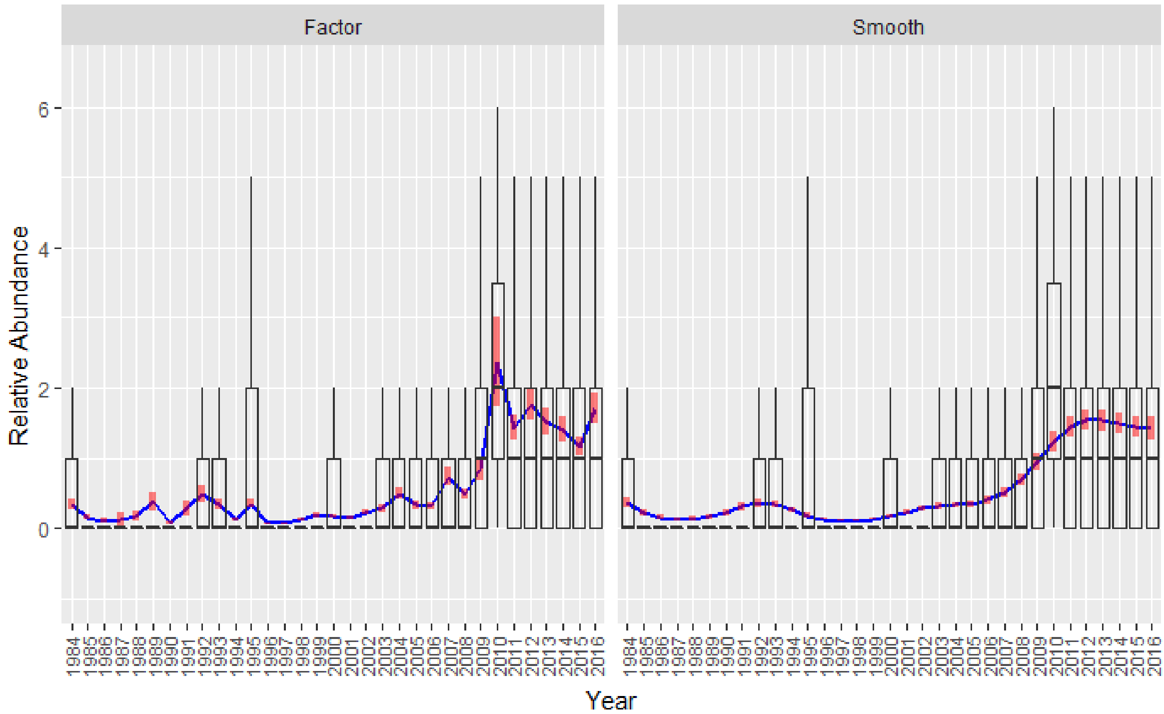

Figure 4. Two relative indices of Bluefin tuna abundance based on landings data from the sGSL fisheries. These population level predictions were derived from two identical models except with respect to the Year effect. The estimates shown in the left panel are from a model with Year as a factor while in the right panel Year is a smoother. The bars centered on each estimate represent 95% confidence intervals and the box and whisker plot is based on the observed response. See text for details.

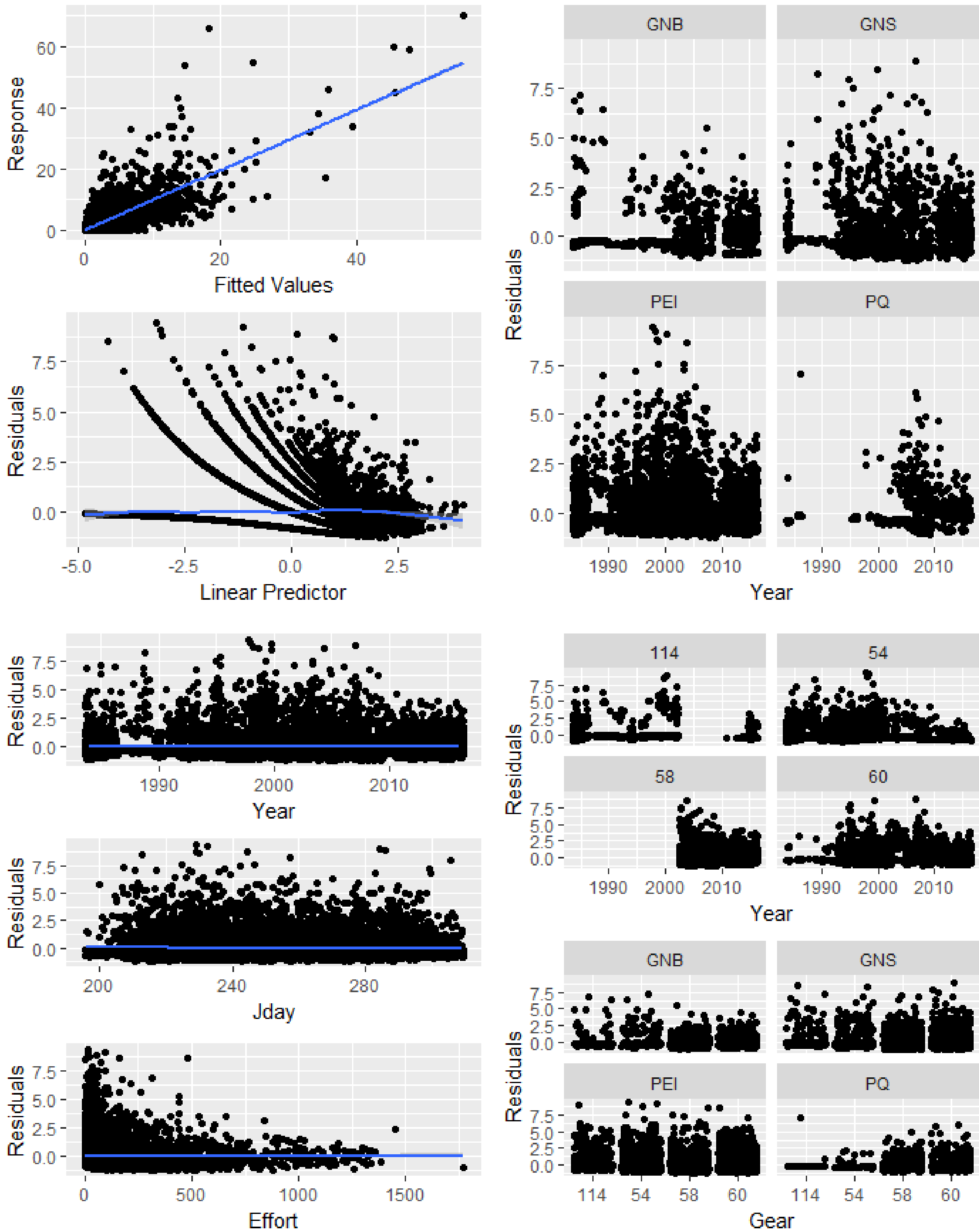

Figure 5. Diagnostic plots for the sGSL index model with Year as a smoother. Pearson residuals are shown relative to the covariates in the model and the linear predictor. Fitted values are the marginal expected values of the response.

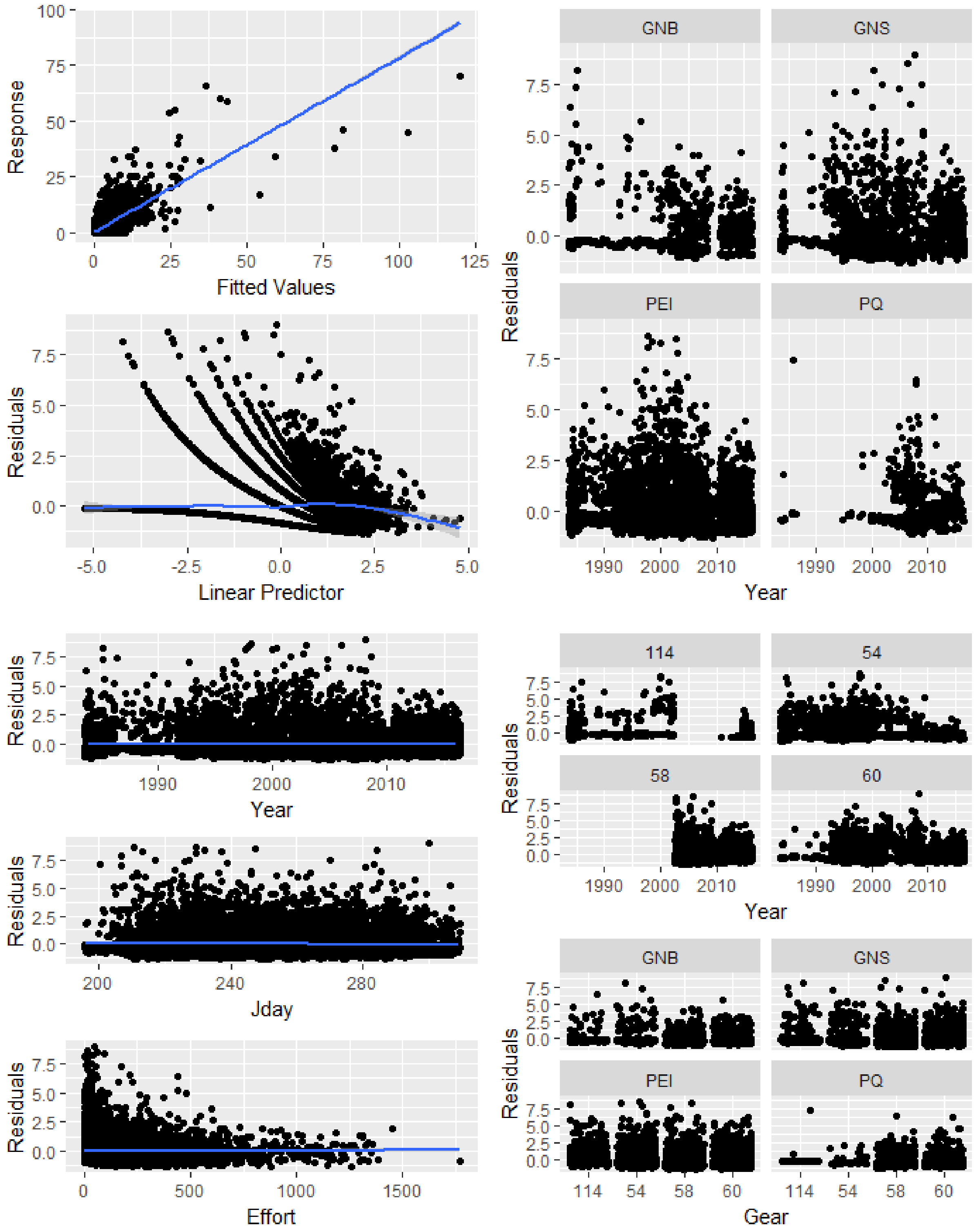

Figure 6. Diagnostic plots for the sGSL index model with Year as a factor. Pearson residuals are shown relative to the covariates in the model and the linear predictor. Fitted values are the marginal expected values of the response.

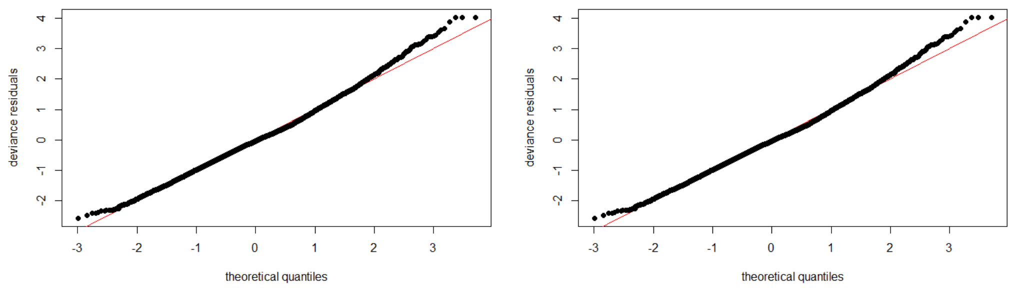

Figure 7. sGSL index deviance residuals versus the theoretical quantiles of the negative binomial distributions fit with the model including Year as a smoother (left) and as a factor (right).

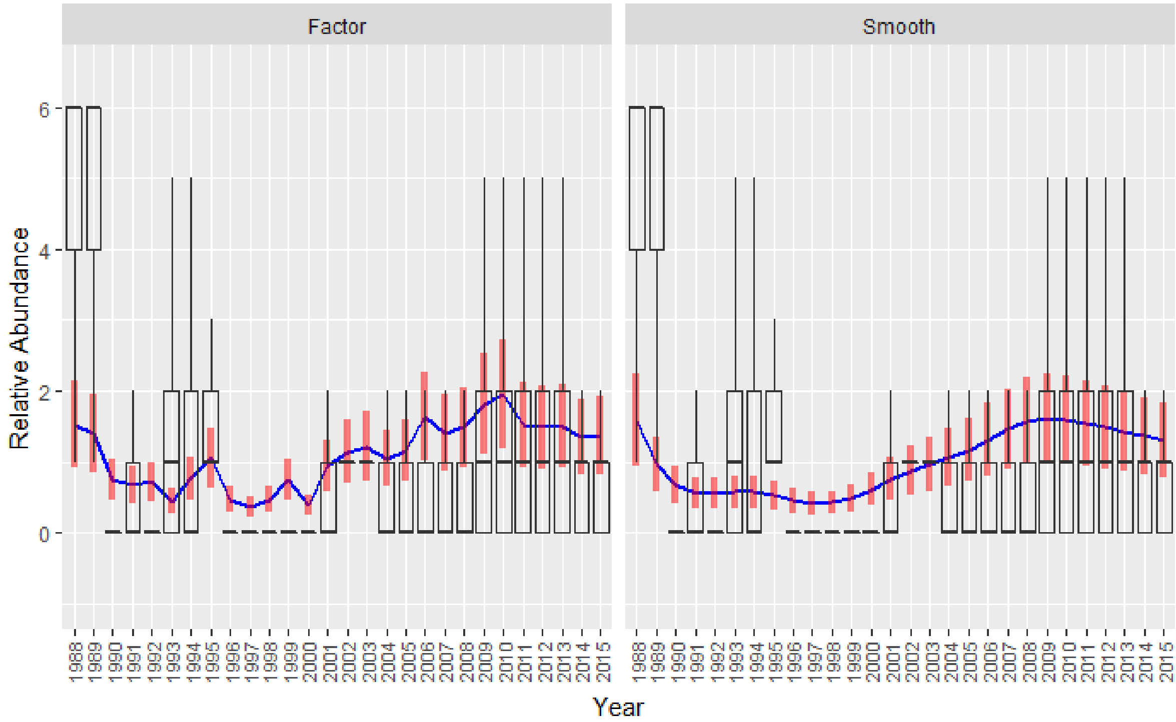

Figure 8. Two relative indices of Bluefin tuna abundance based on landings data from the SWNS fishery. These population level predictions were derived from two identical models except with respect to the Year effect. The estimates shown in the left panel are from a model with Year as a factor while on the right Year is a smoother. The bars centered on each estimate represent 95% confidence intervals and the box and whisker plot is based on the observed response. See text for details.

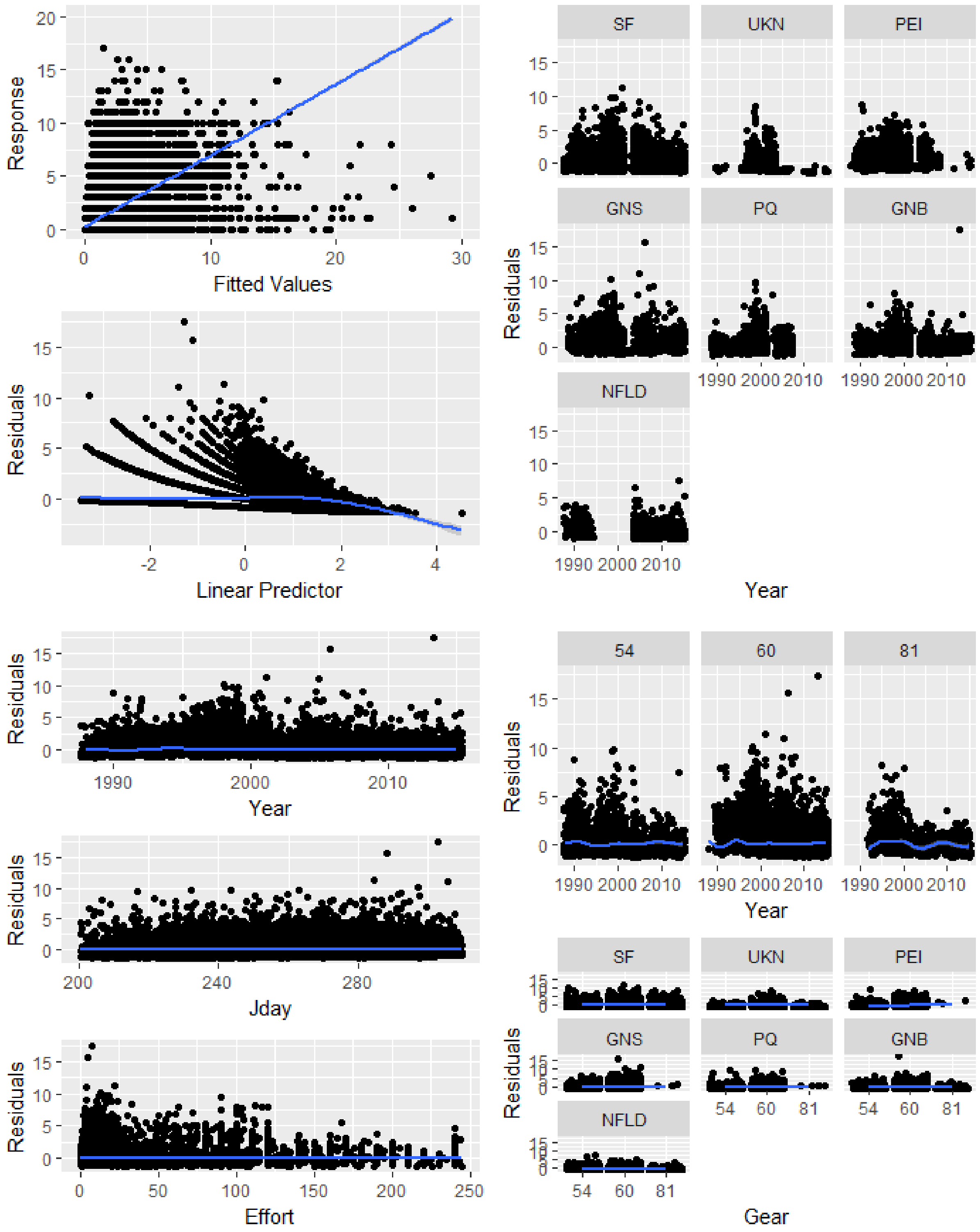

Figure 9. Diagnostic plots for the SWNS index model with Year as a smoother. Pearson residuals are shown relative to the covariates in the model and the linear predictor. Fitted values are the marginal expected values of the response.

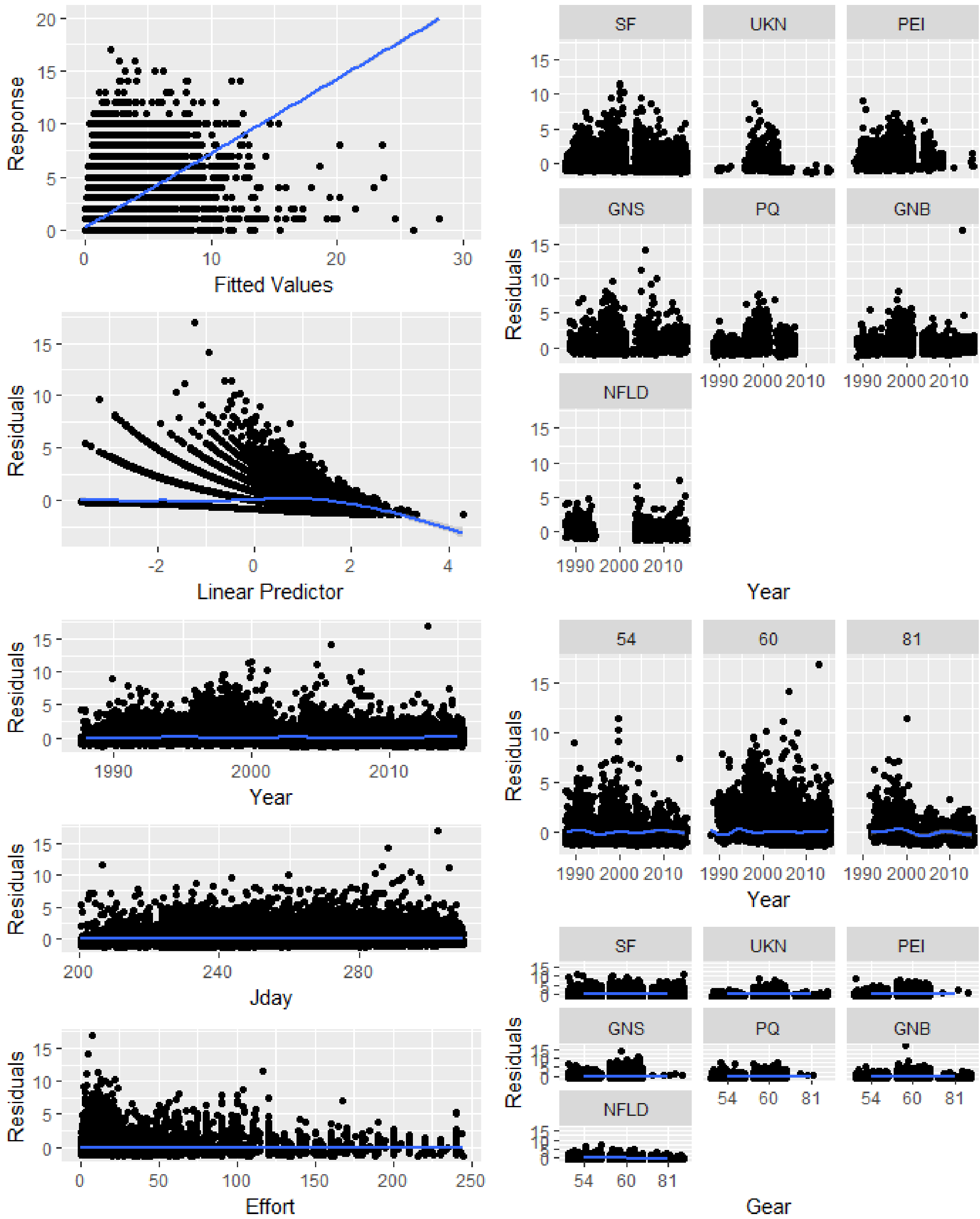

Figure 10. Diagnostic plots for the SWNS index model with Year as a factor. Pearson residuals are shown relative to the covariates in the model and the linear predictor. Fitted values are the marginal expected values of the response.

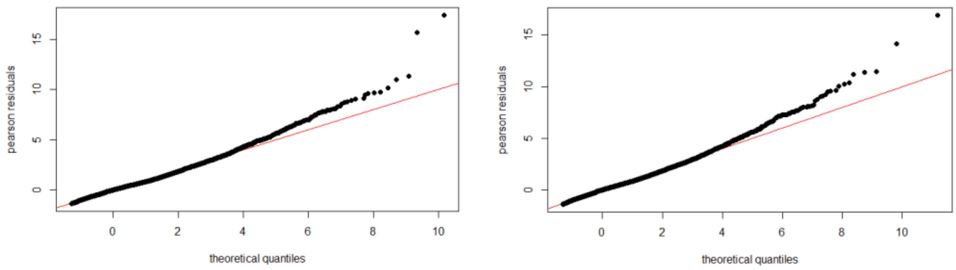

Figure 11. SWNS index deviance residuals versus the theoretical quantiles of the negative binomial distributions fit with the model including Year as a smoother (left) and as a factor (right).

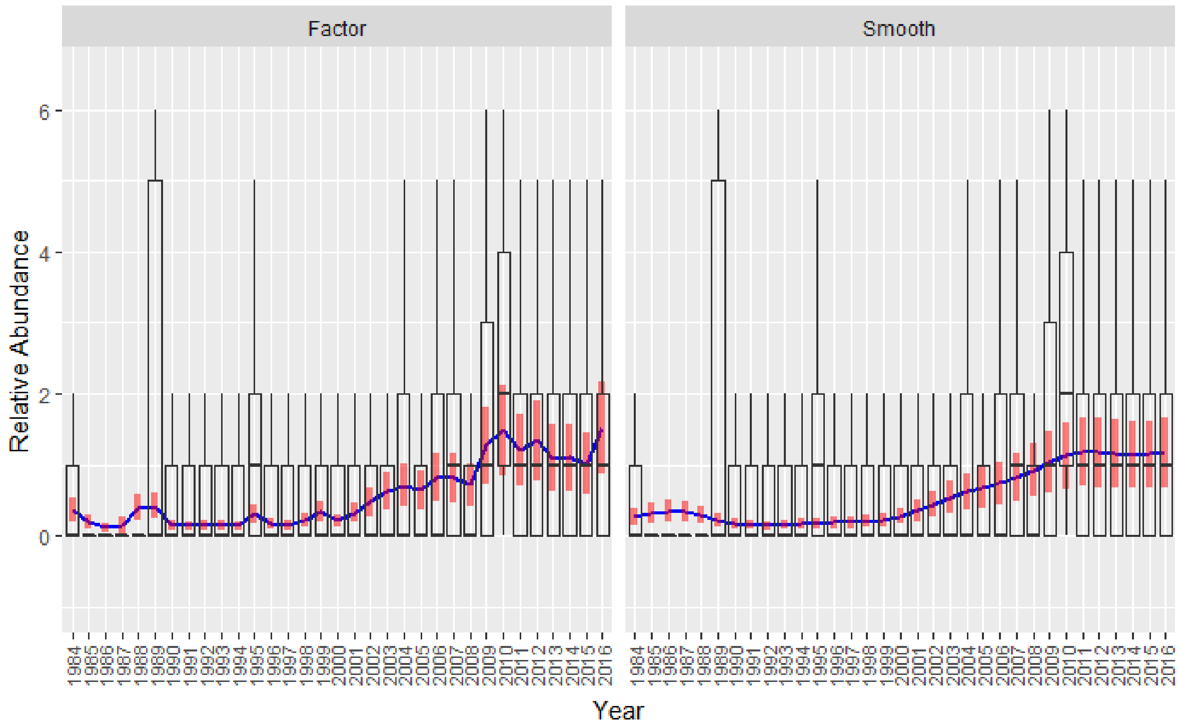

Figure 12. Two relative indices of Bluefin tuna abundance based on landings data from the combined SWNS and sGSL fisheries. These population level predictions were derived from two identical models except with respect to the Year effect. The estimates shown in the left panel are from a model with Year as a factor while on the right Year is a smoother. The bars centered on each estimate represent 95% confidence intervals and the box and whisker plot is based on the observed response. See text for details.

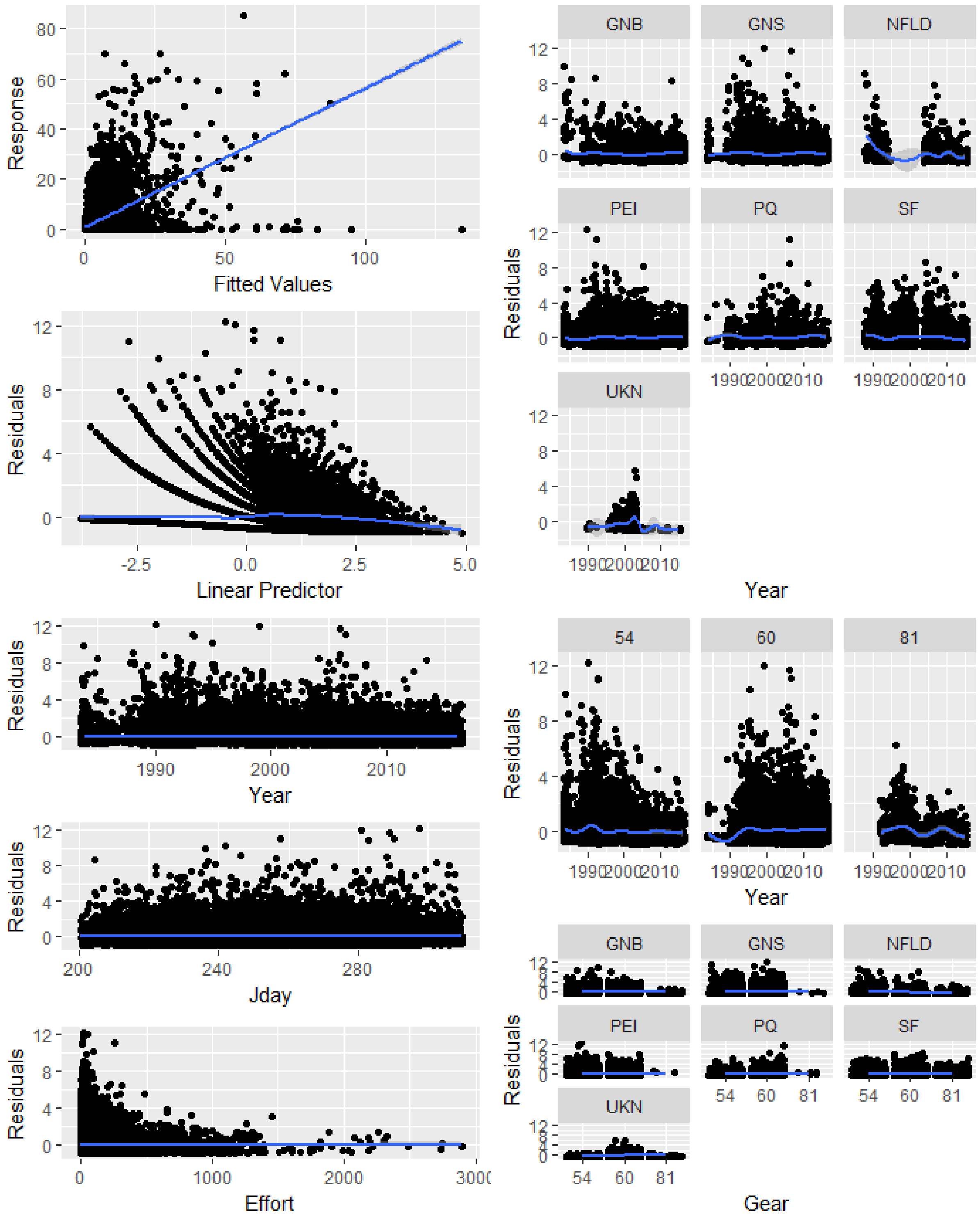

Figure 13. Diagnostic plots for the Combined index model with Year as a smoother. Pearson residuals are shown relative to the covariates in the model and the linear predictor. Fitted values are the marginal expected values of the response.

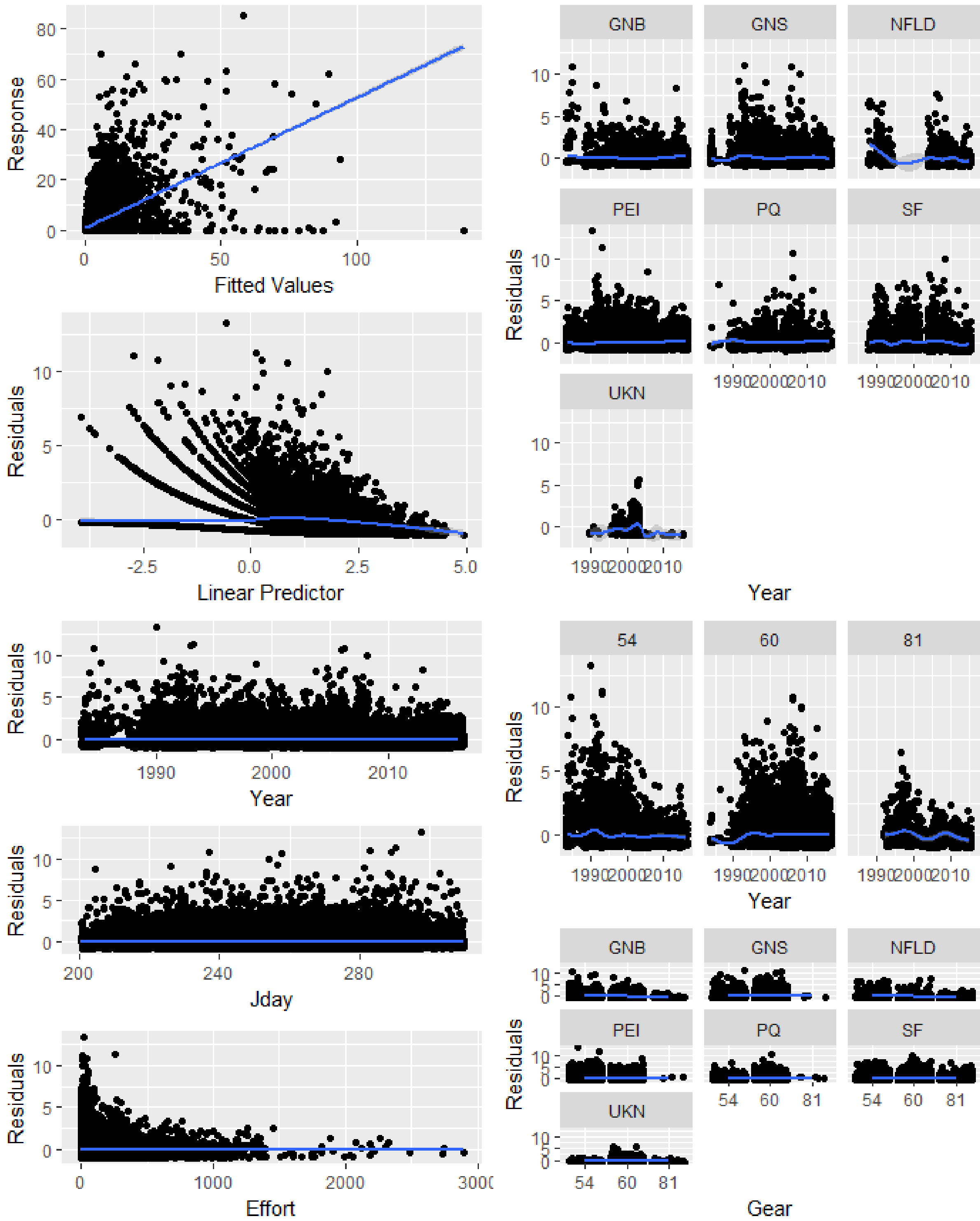

Figure 14. Diagnostic plots for the Combined index model with Year as a factor. Pearson residuals are shown relative to the covariates in the model and the linear predictor. Fitted values are the marginal expected values of the response.

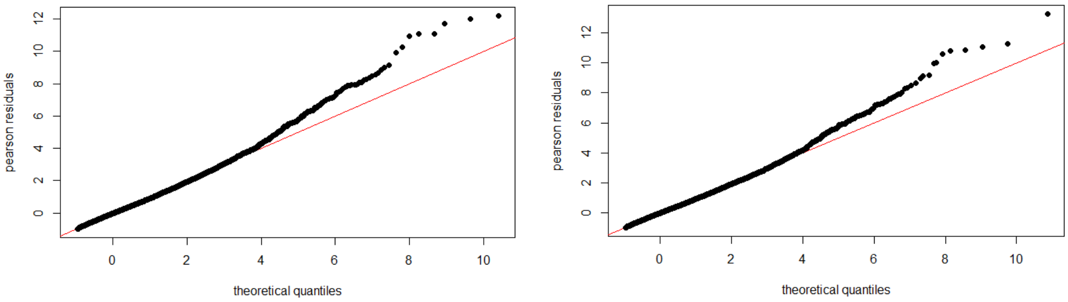

Figure 15. Combined index Pearson residuals versus the theoretical quantiles of the negative binomial distributions fit with the model including Year as a smoother (left) and as a factor (right).