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A RELATIVE INDEX OF ATLANTIC SWORDFISH ABUNDANCE BASED ON CANADIAN PELAGIC LONGLINE DATA (2002 TO 2016)

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SUMMARY

A relative index of North Atlantic swordfish abundance was developed for the period 2002 to 2016 using set level data and from 1962 to 2016 using trip level data. The standardizations were based on the number of Swordfish caught and involved fitting general additive mixed effects models that controlled for the effect of hooks, bait, Julian day, month, shark and tuna caught, area and vessel. The area specific index indicates a decline in relative abundance to levels comparable with the years prior to the institution of a rebuilding plan in 1999.

RÉSUMÉ

Un indice relatif de l'abondance de l'espadon de l'Atlantique Nord a été mis au point pour la période allant de 2002 à 2016 au moyen de données par opération couvrant la période de 1962 à 2016 utilisant des données par sortie. Les standardisations reposaient sur le nombre d'espadons capturés et impliquaient l'ajustement aux modèles additifs généralisés d'effets mixtes qui tenaient compte de l'effet dû aux hameçons, à l'appât, au jour julien, au mois, aux prises de requins et de thonidés, à la zone et au navire. L'indice spécifique à la zone indique une baisse de l'abondance relative, se situant ainsi aux niveaux comparables aux années antérieures à l'entrée en vigueur du programme de rétablissement en 1999.

RESUMEN

Se elaboró un índice de abundancia relativa para el pez espada del Atlántico norte para el periodo 2002 a 2016 utilizando los datos de lances desde 1962 a 2016 utilizando datos de mareas. Las estandarizaciones se basaron en el número de peces espada capturados e incluyeron el ajuste de modelos de efectos mixtos aditivos generalizados que controlan el efecto de anzuelos, cebo, día juliano, mes, tiburón y atún capturado, zona y buque. El índice específico de la zona indica una disminución en la abundancia relativa hasta niveles comparables con los años anteriores al establecimiento del plan de recuperación en 1999.

KEYWORDS

Catch/effort, Swordfish, pelagic fisheries, mixed effects

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1. Introduction

The Canadian pelagic longline fishery landings data is available from that fisheries inception in 1962 and, except for the period from 1971 to 1978 when fear of mercury contaminated fish stopped exports, is continuous to the most recent year of fishing, 2016. To maintain the continuity of this series, the more recent data is aggregated to the trip level and analyses are restricted to the original set of variables. From 2002 to the present, set level information is available allowing the development of a second index based on more detailed information. Indices developed from both the trip and set level swordfish catch data are presented here.

2. Description of the Fishery

Annual Swordfish landings of the Canadian pelagic longline fleet ranged from 898 to 2,234 mt between 1988 and 2016, with 39 to 77 actively fishing vessels. In 2016, ~44 pelagic longline vessels landed 1,504.5 mt of Swordfish, reaching the levels of catch last seen by the longline fleet in 2005 (**Figure 1**). In contrast, the harpoon fishery involved 34 active licenses and landed 85.2 mt of Swordfish in 2016, the lowest annual catch for this fleet since 2002 (**Figure 1**). Representatives from the harpoon industry have attributed low catch to fewer Swordfish basking on the surface, reducing the chance of an encounter with a harpoon vessel. This change in behavior has been attributed to increasing water temperatures, allowing the Swordfish to recover quickly from deep dives and/or removing the need to enter the surface layer altogether. Historically, for stock assessment purposes, the Canadian Swordfish catch per unit effort (CPUE) index has been based exclusively on the longline fishery, as a harpoon-based CPUE can be often influenced by weather.

The Canadian longline fishery operates in waters from Georges Bank to the Flemish Cap (**Figure 2**), with highest Swordfish catches along the edge of the Scotian Shelf and Emerald Basin. The fleet's fishing distribution has been shifting both northward and more inshore in most months since 2000 (**Figure 3**). As indicated in Andrushchenko et al. (2014), there has been fewer longline trips going east of the Grand Banks since 2006 and this is still generally true. This shift has been attributed to unfavorable water conditions, high cost of fuel and abundance of catch along the Scotian Shelf. Since 2010, there has been a surge of activity in Emerald Basin that was attributed to a decrease in shark encounters, an abundance of Swordfish in this area and proximity to ports (pers. communication, industry representatives, May 2013). In a given year, fishing activity can begin as early as May, staying south of the Scotian Shelf and along the edge of the Gulf Stream. As the season progresses, the fleet moves north from Georges Bank and along the Scotian Shelf towards the Grand Banks. The fishing season generally finishes by mid-November, though December catches have been reported periodically.

Throughout the history of the pelagic longline fishery, the fishing patterns/behaviour of the fleet has been affected by changes in management regulations. Log submission for Canadian fisheries became mandatory in 1994, suggesting that records prior to this may provide an incomplete account of fleet activity. Some assurance that the absence of logbooks was largely random is provided in **Figure 4** which shows similar temporal patterns in fishing just before and after the implementation of mandatory reporting. Additional shifts in management structure came in the form of time closures and trip limits for Swordfish-directed fishing between 1999 and 2001. Finally, the traditional competitive structure of the fishery was changed to an Individual Transferable Quota (ITQ) system in 2002. This change appears to restore the temporal pattern in fishing observed prior to 1994. From 1994 until 2001 the fishery was subject to a declining TAC **(Figure 1)** as well as further trip and area restrictions that resulted in an incremental decline in the length of the season (Andrushchenko et al. 2015).

Prior to the implementation of ITQ management, longline vessels targeted other tunas in the spring and fall, generally filling their annual Swordfish quota during the summer months. Under the current ITQ system, the Swordfish season extends from May until November with longline vessels being able to either direct for Swordfish or to target other tunas while catching Swordfish as bycatch. Due to current quota levels, Canadian longline fishermen have reported primarily using Swordfish quota for bycatch to target other tunas.

3. Environmental Considerations

The description of environmental considerations has not been updated since the 2013 Swordfish assessment. The most recent description can be found in Andrushchenko et al. 2014.

4. Methods

4.1 Data

Catch and effort data for the Canadian Swordfish longline fishery were obtained from mandatory logbook submissions made to the Department of Fisheries and Oceans beginning in 1994; submissions prior to 1994 were entirely voluntary. The logbook database provides information about each species caught, such as total weight[2], number of fish caught, type and size of hook used, type of bait, surface temperature and effort (number of hooks) for each set.

The set level data allows for added flexibility in modeling the Swordfish catch data and, given that there is now 15 years of it available, a time series of relative abundance was created from it. However, in order to preserve the longer time series based on trip level data, the set level data were aggregated to trip level and a separate time series of relative abundance was estimated. In both cases the catches by the harpoon fleet were excluded. Prior to its use, the set level detail was quality control to correct obvious errors and delete nonsensical records.

Tally sheets obtained from the Dockside Monitoring program provide individual fish weights for approximately 90% of the landed Swordfish catch. The sampling program has been in place since 1999 and provides individual round weights, which were used to generate lower jaw fork lengths (LJFL) using Turner (1978) conversion factors. These lengths were used to show time trends in the catch composition of both the pelagic longline and harpoon gear types.

4.1.1Standardized Age-aggregated CPUE (1962 – 2016)

The Canadian standardized index contains historic logbook records from the Canadian longline Swordfish fishery from 1963-1970 and 1979-2012. Data is also available for 1962 but has been excluded in past assessments due to the low number of trips (11); however it was included in the current standardized index. High Canadian catch rates in the initial years of the 1962-1970 series were validated with paper log records and interviews[3]. Data was not available between 1971 and 1978 because fish were not landed in Canada due to export restrictions on mercury contaminated fish. The data for the early time series (pre-2003) were available on a trip-level, so the recent years (2003-2012) were also aggregated to trip level.

4.1.2 Standardized Age-aggregated CPUE (2002 – 2016)

The set level data on which this index is based was all obtained while the fishery was consistently managed under an ITQ system adopted in 2002.

4.2 Variables

The current protocols for filtering and aggregating the data and constructing factors used in the standardization are described.

4.2.1. Gear filter

Canadian pelagic longline vessels can use longline, tended line and harpoon gear concurrently on a given trip, but the resulting sets are all recorded as ‘longline’ in the log system. This is thought to have a confounding effect on CPUE (Paul and Neilson 2010a), and was addressed in Hanke et al. (2012) by excluding suspected harpoon and tended line sets based on effort, weight of Swordfish and presence of other species. Sets with fewer than 300 hooks were considered a mixture of gears (likely tended line and harpoon), while those with equal to or greater than 300 hooks were strictly longline. Sets with only one hook were considered harpoon, unless more than one species was identified or the total weight for the set exceeded the maximum known weight of a single fish (537 kg). This filter was applied to the set-level. It should be noted that the effect of the harpoon filter on 1988-2001 data would exclude 3 trips, but it was not applied.

This filter could only be applied to the set level data from 2002 to 2016. The earlier trip level data was left as is.

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[2] Weight and number from logs are values estimated by the fisherman. Accurate weight and number data come from dockside monitor records and are available on trip-level only.
[3] It was recommended during the 2009 stock assessment that these high values be checked

4.2.2. Targeting, bait and species effects

As the fishery evolved from targeting exclusively Swordfish to a mixed fishery targeting Swordfish and other tunas, a variable had to be introduced into the model that would control for an effect due to targeting. Historically, this was achieved by only considering trips where the weight of the Swordfish exceeded the weight of the other species (Paul and Neilson 2007). Following a review of other potential targeting variables (bait type and sea surface temperature), Paul and Neilson (2010b) recommended continued use of the traditional weight-based targeting, citing poor data availability for the other factors and lack of data for the earlier part of the series (1988 – 1993). However, a weight-based targeting variable involving Swordfish is strongly correlated with both catch in numbers and in weight and its inclusion may remove time trends in the catch rate which should be attributed to the year effect (Maunder and Punt 2004). Consequently, other variables were also considered in the present analysis such as bait type. The availability of sharks and tunas at a given time and place was assumed to reflect on gear saturation and/or targeting effects, so separate covariates for the fraction of sharks and tunas by weight per set or trip were included in the fitted model.

The bait type on a given set was grouped into one of four categories: fish only (alewife, herring, mackerel and silver hake), a mixture of squid with one or more pelagic fish species, squid only and unknown bait composition. The fleet generally targets Swordfish using pelagic fish species and tunas using squid. The bait type for a trip was the most frequent type used.

The total number of unique fish species caught per set and per trip was included in the fitted model.

4.2.3. Area effect

Each set was identified to a NAFO statistical unit area and frequently included set coordinates as well. The historical data had a coarser resolution but given the scale of the domain this was not considered to be problematic. Where coordinates were absent, these were assigned using the centroid of the fishing occurring with the same NAFO unit area and in a few cases the centroid of the NAFO unit polygon. The coordinates assigned to the trips, which could span several of NAFO unit areas, where the average of the set coordinates.

4.2.4. Management effect

The years of the time series can be linked to the changes in the fishery described above but this information could not be included in the model because it was confounded with the year effect. However, this variable was found to be useful for detecting residual patterns associated with the changes in management. The phases of the fishery are as follows: Phase 1, 1962:1970 (unrestricted fishing); Phase 2, 1979:1993 (post export restrictions on mercury contaminated fish, introduction of quotas); Phase 3, 1994:1998 (mandatory logbook submissions); Phase 4, 1999:2001 (trip and area restrictions) and Phase 5, 2002:2012 (switch from fleet quota to individual transferable quotas).

4.3 Standardized Age-aggregated CPUE Indices

4.3.1 Model Standardization and Diagnostics

The set and trip level data were each fit with general additive mixed effect models (Wood 2011, Zuur et al. 2014). The model selection process followed the method of Diggle et al. (2002) and began by specifying a model where the fixed component had all explanatory variables and as many interactions as possible so that the optimal structure of the random component could be found. 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. After selecting the optimal random component the optimal fixed structure was determined using ML estimation and a stepwise backwards and forwards search for the model with the lowest AIC (Venables and Ripley 2002). The final model was estimated using REML to generate unbiased estimates of the parameters. 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.

2002-2016 Index

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

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

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

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

$$\eta_{ij} = \beta_1 + \beta_2 fYear_{ij} + \beta_3 Species_{ij} + \beta_4 Hooks_{ij} + \beta_5 fBait_{ij} + f(Jday_{ij}) + f(Tuna_{ij}) + f(Shark_{ij}) + f(Latitude{:}Longitude_{ij}) + a_i$$

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

SWO_{ij} is the j[th] observation from the i[th] vessel. a_i is a random intercept that allows for random variation by vessel and models the correlation between all observations from the same vessel. $fYear_{ij}$ is a categorical variable for the fixed year effect (2002-2016), $Species_{ij}$ is a continuous variable for the fixed effect of the number of unique species caught (1 to 8), $Hooks_{ij}$ is a continuous variable for the number of hooks per set (300 to 2300), $fBait_{ij}$ is a categorical variable for the fixed effect of bait (pelagic fish, squid, squid-fish mix and unknown), $f(Jday_{ij})$ is a smoother for day of the year (113 to 345), $f(Tuna_{ij})$ is a smoother for the effect of targeting other tunas (0 to 1), $f(Shark_{ij})$ is a smoother for the effect of catching sharks (0 to 0.98) and $f(Latitude{:}Longitude_{ij})$ is a two dimensional smoother for the spatial effect (37.45 to 50.48 north latitude and 38.5 to 66.97 west longitude).

1962-2016 Index

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

$$SWO_j \sim NB(\mu_j, \theta)$$

$$E(SWO_j) = \mu_j, \qquad V(SWO_j) = \mu_j + \frac{\mu_j^2}{\theta}$$

$$\log(\mu_j) = \eta_j$$

$$\eta_j = \beta_1 + \beta_2 fYear_j + \beta_3 Species_j + \beta_4 Hooks_j + \beta_5 fBait_j + f(Month_j) + f(Tuna_j) + f(Shark_j) + f(Latitude{:}Longitude_j)$$

SWO_j is the j[th] observation. $fYear_{ij}$ is a categorical variable for the fixed year effect (1962-2016), $Species_j$ is a continuous variable for the fixed effect of the number of unique species caught (1 to 11), $Hooks_j$ is a continuous variable for the number of hooks per trip (150 to 34725), $fBait_j$ is a categorical variable for the fixed effect of bait (pelagic fish, squid, squid-fish mix and unknown), $f(Month_j)$ is a smoother for month of the year (3 to 12), $f(Tuna_j)$ and $f(Shark_{ij})$ are smoothers for the effect of targeting other tunas and the effect of catching sharks (0 to 1), and $f(Latitude{:}Longitude_{ij})$ is a two dimensional smoother for the spatial effect (34 to 50.8 north latitude and 38 to 74 west longitude).

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

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

The year effects were represented by their population level estimates and were extracted from the model by setting hooks, month and day of year to their median value, latitude and longitude to their mean value, species and bait to their modal value and tuna and sharks to 5 or 10% (Maunder and Punt 2004). These choices also reflect the levels most likely associated with Swordfish directed fishing over the entire time series.

1962-2016 Index refit following Swordfish Meeting

During the 2017 Swordfish data preparatory meeting in Madrid (April 3-7) a review of the alternative indices provided for the 1962 to 2016 data resulted in the Group selecting the model where the year effect was included as a factor rather than a smoother. A smoother was thought to eliminate pulses in abundance that are not consistent with a smoothly varying trend. Furthermore, it was requested that Swordfish abundance not be modeled as a smooth function of month and that the effort be incorporated as an offset. Also, as a result of model validation the Species factor was dropped, the functional form of the Tuna and Shark covariates were constrained to 3 knots and the distributional form of the model was changed to a Tweedie.

$$SWO_j \sim Tw\left(\mu_j, a\mu_j^p\right)$$

$$\log\left(\mu_j\right) = \eta_j$$

$$\eta_j = \beta_1 + \beta_2 fYear_j + LogHooks_j + \beta_3 fBait_j + \beta_4 fMonth_j + f\left(Tuna_j, k = 3\right) + f\left(Shark_j, k = 3\right) + f\left(Latitude{:}Longitude_j, bs = "sos"\right)$$

The Tweedie is an exponential family distribution with variance given by the mean to the power *p* and dispersion a function of *a*. Choice of *p* was restricted to variance function powers between 1 and 2 and *a* was fixed at 1. Ultimately, a *p* = 1.745 resulting in a dispersion of 1.001 was the basis for the final model. Values of p between 1 and 2 describe a class of mixed compound Poisson–gamma distributions which have positive mass at zero and are continuous otherwise. Definitions for the factors are as given above.

5. Results and Discussion

5.1 Catch characteristics

The Swordfish catch of the Canadian pelagic longline fishery has an average lower jaw fork length (LJFL) of 180.8 cm (**Figure 5**) while the harpoon fleet has averaged 204.5 cm over the same period (199 to 2016). The mean annual length of the catch by the longline fleet is less variable than that of the harpoon fleet and has been increasing since 2011. **Figure 6** shows that since 2011the fraction of the catch less than 180.8 cm has been increasing. By 2016, the distribution is distinctly bimodal. Harpoon catches are also becoming less common during this period.

5.2 Indices

5.2.1 Standardized Age-Aggregated CPUE (2002-2016)

A test of the marginal sum of squares for the parametric and smooth terms in the final set level models (year as a smooth vs parametric tem) for Swordfish catch in numbers is given in **Table 1**. All terms in both final models were highly significant and both models explain between 60.5 and 60.8% of the deviance. The models were not over dispersed with dispersion estimated to be 1.05 and 1.06 for the year as smoother and year as factor models, respectively. The intra class correlation for two observations from the same vessel was small at about 4%. The θ parameter of the negative binomial distribution was estimated to be 4.197 and 4.244 for the models with Year as smoother and as a factor, respectively.

Population level estimates of the Swordfish catch per thousand hooks and the associated standard error of estimation are provided in

Table 4.

Both models have similar looking diagnostic plots (**Figure 7** and **Figure 8)** with no evidence of strong patterns in the residuals based on fits of the residuals to each of the covariates.

Trends in catch (**Figure 9**) estimated by the two models both indicate a series low in relative abundance for 2016 and series peak in 2010.

Figure 10**Figure 10** indicates a high degree of similarity between the trends estimated by the two models except for the 2010 value.

5.2.2 Standardized Age-Aggregated CPUE (1962-2016)

A test of the marginal sum of squares for the parametric and smooth terms in the final trip level models (year as a smooth vs parametric tem) for Swordfish catch in numbers is given in **Table 2.** All terms in both final models were highly significant and both models explain between 70.5 and 72.4% of the deviance. The models were not over dispersed with dispersion estimated to be 1.099 and 1.066 for the year as smoother and year as factor models, respectively. The θ parameter of the negative binomial distribution was estimated to be 3.197 and 3.432 for the models with Year as smoother and as a factor, respectively.

Estimates of the Swordfish catch for the median number of hooks per trip (8,365) and the associated standard error of estimation are provided in **Table 5**.

Both models have similar looking diagnostic plots (**Figure 11 and Figure 12**) with no evidence of strong patterns in the residuals based on fits of the residuals to each of the covariates except with the hook variable which also exhibits some heterogeneity. The problem appears to be associated with the large hook values for which there is an overestimation of the number of Swordfish caught and is resolved by introducing hooks as a smoother (not shown).

Trends in catch (**Figure 13**) estimated by the two models both indicate a series low in relative abundance for 2016 comparable to that estimated for 1968 and 1996. **Figure 14** indicates a high degree of similarity between the trends estimated by the two models with some exceptions. When year is a smoother, catch during the mercury ban can be estimated.

5.2.3 Updated Standardized Age-Aggregated CPUE (1962– 2016)

The significance of the marginal sum of squares for the parametric and smooth terms in the updated trip level model for Swordfish catch in numbers is given in **Table 3.** All terms were highly significant and explained 57.7% of the deviance. On the basis of the AIC the updated model fit was not better than the year as a factor model above (76859.76 versus 76847.77). The equivalent model based on a negative binomial distribution had a lower AIC (75609.45) but was moderately overdispersed compared to the model based on a Tweedie distribution.

Estimates of the Swordfish catch for the median number of hooks per trip (8,365) and the associated standard error of estimation are provided in **Table 6.** The diagnostic plots for the updated model **(Figure 15)** show no evidence of strong patterns in the residuals based on fits of the residuals to each of the covariates except with the hook variable which also exhibits some heterogeneity. The problem appears to be associated with the large hook values for which there is an overestimation of the number of Swordfish caught.

Trends in catch (**Figure 16** and **Figure 17**) for the updated model compared to the year as factor model above are similar. Between 1962 and 1985, the updated model provides lower estimated year effects and from 1986 to 1998 the year effects are similar, thereafter the update model provides larger estimates than the previous model.

6. Conclusions and Recommendations

1. The trends in relative abundance from set level and trip level data are similar and indicate a decline since 2010 to a level comparable to that in 1996.

2. A general additive mixed effects model with year as a smoother fits the data as well as a GAM with year as a factor and provides estimates of relative abundance for years when there was no fishing.

3. The size composition of the catch has been shifting towards shorter, presumably younger fish as the relative abundance has declined.

4. It is important to determine if the trends in relative abundance are a function of changes in the abundance of important prey species and/or fluctuations in oceanographic conditions.

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Table 1. Model fits to the 2002 to 2016 set level data. Wald tests of the significance of each parametric and smooth term in 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. Marginal sum of squares are for each term in the final model test the effect of adding each with all other terms already in the model.

A)

Family: Negative Binomial(4.197); Link function: log

Formula:

SWO_COUNT ~ NUM_OF_HOOKS + s(YEAR) + s(JDAY, k = 12) + SPECIES_COUNT + fBAIT2 + s(TUNASc) + s(SHARKc) + s(LATITUDE2, LONGITUDE2, bs = "sos") + s(VR_NUMBER, bs = "re", by = dum)

Parametric Terms:

	df	Chi.sq	p-value
NUM_OF_HOOKS	1	505.5	<2e-16
SPECIES_COUNT	1	188.1	<2e-16
fBAIT2	3	167.6	<2e-16

Approximate significance of smooth terms:

	edf	Ref.df	Chi.sq	p-value
s(YEAR)	8.198	8.819	648.3	<2e-16
s(JDAY)	9.662	10.488	674.4	<2e-16
s(TUNASc)	8.237	8.830	3701.7	<2e-16
s(SHARKc)	8.670	8.966	2659.9	<2e-16
s(LATITUDE2,LONGITUDE2)	44.391	49.000	10934.4	<2e-16
s(VR_NUMBER):dum	95.499	117.000	1039.8	<2e-16

B)

Family: Negative Binomial(4.244); Link function: log

Formula:

SWO_COUNT ~ NUM_OF_HOOKS + fYEAR + s(JDAY, k = 12) + SPECIES_COUNT + fBAIT2 + s(TUNASc) + s(SHARKc) + s(LATITUDE2, LONGITUDE2, bs = "sos") + s(VR_NUMBER, bs = "re", by = dum)

Parametric Terms:

	df	Chi.sq	p-value
NUM_OF_HOOKS	1	504.1	<2e-16
fYEAR	14	806.0	<2e-16
SPECIES_COUNT	1	168.7	<2e-16
fBAIT2	3	169.4	<2e-16

Approximate significance of smooth terms:

	edf	Ref.df	Chi.sq	p-value
s(JDAY)	9.543	10.407	685.9	<2e-16
s(TUNASc)	8.261	8.840	3742.8	<2e-16
s(SHARKc)	8.670	8.966	2663.1	<2e-16
s(LATITUDE2,LONGITUDE2)	44.188	49.000	11008.0	<2e-16
s(VR_NUMBER):dum	95.393	117.000	1036.0	<2e-16

Table 2. Model fits to the 1962 to 2016 trip level data. Wald tests of the significance of each parametric and smooth term in 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. Marginal sum of squares are for each term in the final model test the effect of adding each with all other terms already in the model.

A)

Family: Negative Binomial(3.197)

Link function: log

Formula:

```
SWO_COUNT ~ NUM_OF_HOOKS + s(YEAR) + s(MONTH, k = 6) + SPECIES_COUNT +
    fBAIT2 + s(TUNASc) + s(SHARKc) + s(LATITUDE2, LONGITUDE2,
    bs = "sos")
```

Parametric Terms:

	df	Chi.sq	p-value
NUM_OF_HOOKS	1	4466.59	< 2e-16
SPECIES_COUNT	1	33.19	8.37e-09
fBAIT2	3	85.33	< 2e-16

Approximate significance of smooth terms:

	edf	Ref.df	Chi.sq	p-value
s(YEAR)	8.929	8.998	780.5	<2e-16
s(MONTH)	4.655	4.941	242.0	<2e-16
s(TUNASc)	8.350	8.881	3228.2	<2e-16
s(SHARKc)	8.618	8.953	1532.8	<2e-16
s(LATITUDE2,LONGITUDE2)	41.761	49.000	1242.0	<2e-16

B)

Family: Negative Binomial(3.432)

Link function: log

Formula:

```
SWO_COUNT ~ NUM_OF_HOOKS + fYEAR + s(MONTH, k = 6) + SPECIES_COUNT +
    fBAIT2 + s(TUNASc) + s(SHARKc) + s(LATITUDE2, LONGITUDE2,
    bs = "sos")
```

Parametric Terms:

	df	Chi.sq	p-value
NUM_OF_HOOKS	1	4704.748	< 2e-16
fYEAR	46	1408.912	< 2e-16
SPECIES_COUNT	1	8.293	0.00398
fBAIT2	3	69.044	6.84e-15

Approximate significance of smooth terms:

	edf	Ref.df	Chi.sq	p-value
s(MONTH)	4.731	4.964	267.2	<2e-16
s(TUNASc)	8.397	8.897	3350.1	<2e-16
s(SHARKc)	8.598	8.948	1528.3	<2e-16

s(LATITUDE2,LONGITUDE2) 41.593 49.000 1303.3 <2e-16

Table 3. Model fits to the 1962 to 2016 trip level data. Wald tests of the significance of each parametric and smooth term from a model with a Tweedie distribution. Interpretation is analogous to a type III ANOVA, rather than a sequential type I ANOVA. Marginal sum of squares are for each term in the final model test the effect of adding each with all other terms already in the model.

Family: Tweedie(1.745)

Link function: log

Formula:

SWO_COUNT ~ offset(LogEffort) + fYEAR + fMONTH + fBAIT2 + s(TUNASc,
k = 3) + s(SHARKc, k = 3) + s(LATITUDE2, LONGITUDE2, bs = "sos")

Parametric Terms:

	df	F	p-value
fYEAR	46	36.05	< 2e-16
fMONTH	9	38.61	< 2e-16
fBAIT2	3	18.08	1.09e-11

Approximate significance of smooth terms:

	edf	Ref.df	F	p-value
s(TUNASc)	1.998	2.000	1430.63	<2e-16
s(SHARKc)	1.998	2.000	992.56	<2e-16
s(LATITUDE2,LONGITUDE2)	39.745	49.000	23.92	<2e-16

Table 4. Population estimates of number of Swordfish caught, standard error of the mean and CV for models with year as a smoother (FIT1) and for year as a factor (FIT2). Estimates were based on the median number of hooks per set (1,000), modal bait used (fish), median Julian day (227), modal species count (1), fraction of tuna, by weight in catch of 10%, fraction of sharks by weight in catch of 10% and mean coordinates of 42.7 N latitude, 61.92 west longitude. Fit was based on set level data.

YEAR	**FIT1**	**SE1**	**CV1**	**FIT2**	**SE2**	**CV2**	**N**
2002	8.842	0.429	0.049	9.147	0.444	0.049	1272
2003	8.101	0.380	0.047	8.220	0.394	0.048	1347
2004	8.361	0.388	0.046	8.466	0.403	0.048	1420
2005	8.977	0.419	0.047	9.500	0.453	0.048	1515
2006	9.124	0.428	0.047	9.122	0.436	0.048	1477
2007	9.414	0.448	0.048	9.660	0.473	0.049	1288
2008	10.379	0.499	0.048	11.118	0.551	0.050	1080
2009	11.172	0.536	0.048	10.652	0.527	0.049	1011
2010	11.052	0.528	0.048	12.629	0.628	0.050	921
2011	10.586	0.501	0.047	10.284	0.497	0.048	1241
2012	10.223	0.485	0.047	10.345	0.502	0.049	1316
2013	9.741	0.464	0.048	10.920	0.538	0.049	1186
2014	8.954	0.418	0.047	8.324	0.394	0.047	1565
2015	7.907	0.367	0.046	8.606	0.407	0.047	1742
2016	6.783	0.321	0.047	6.775	0.320	0.047	1689

Table 5. Population estimates of number of Swordfish caught, standard error of the mean and CV for models with year as a smoother (FIT1) and for year as a factor (FIT2). Estimates were based on the median number of hooks per trip (8,365), modal bait used (fish), median Month (8), modal species count (5), fraction of tuna, by weight in catch of 5%, fraction of sharks by weight in catch of 5% and mean coordinates of 42.19 N latitude, 61.82 west longitude. Fit was based on trip level data.

YEAR	FIT1	SE1	CV1	FIT2	SE2	CV2	N
1962	112.832	8.516	0.075	69.456	12.422	0.179	11
1963	85.863	5.581	0.065	137.930	10.938	0.079	94
1964	66.555	3.829	0.058	60.035	3.956	0.066	251
1965	53.705	2.876	0.054	40.808	2.702	0.066	195
1966	45.959	2.405	0.052	42.042	2.611	0.062	199
1967	42.087	2.212	0.053	59.648	3.720	0.062	211
1968	41.110	2.201	0.054	39.972	2.432	0.061	290
1969	42.264	2.333	0.055	38.873	2.428	0.062	267
1970	44.895	2.584	0.058	48.981	3.287	0.067	185
1971	48.503	2.934	0.060	NA	NA	NA	0
1972	52.852	3.371	0.064	NA	NA	NA	0
1973	57.710	3.880	0.067	NA	NA	NA	0
1974	62.734	4.421	0.070	NA	NA	NA	0
1975	67.451	4.931	0.073	NA	NA	NA	0
1976	71.266	5.322	0.075	NA	NA	NA	0
1977	73.511	5.496	0.075	NA	NA	NA	0
1978	73.548	5.374	0.073	NA	NA	NA	0
1979	70.910	4.933	0.070	75.355	7.613	0.101	39
1980	65.686	4.263	0.065	65.405	5.223	0.080	75
1981	59.241	3.608	0.061	62.764	6.508	0.104	36
1982	53.329	3.165	0.059	52.371	5.596	0.107	34
1983	49.193	2.962	0.060	43.970	5.011	0.114	29
1984	47.371	2.933	0.062	45.117	4.844	0.107	33
1985	47.856	3.009	0.063	50.394	5.388	0.107	34
1986	50.207	3.148	0.063	72.761	8.102	0.111	30
1987	53.513	3.308	0.062	53.962	5.661	0.105	35
1988	56.399	3.424	0.061	53.789	5.583	0.104	36
1989	57.393	3.398	0.059	45.811	4.409	0.096	44
1990	55.642	3.161	0.057	67.334	6.379	0.095	45
1991	51.455	2.740	0.053	46.838	3.320	0.071	115
1992	46.105	2.266	0.049	55.500	3.909	0.070	117
1993	41.080	1.875	0.046	45.571	2.703	0.059	218
1994	37.461	1.635	0.044	34.908	1.660	0.048	427
1995	35.800	1.542	0.043	40.872	1.996	0.049	404
1996	36.291	1.568	0.043	25.748	1.334	0.052	330
1997	38.914	1.693	0.044	38.344	2.043	0.053	272
1998	43.413	1.909	0.044	49.602	2.760	0.056	210
1999	49.124	2.197	0.045	61.627	3.534	0.057	202
2000	54.881	2.502	0.046	45.656	2.745	0.060	186
2001	59.271	2.738	0.046	50.651	2.843	0.056	234
2002	61.288	2.840	0.046	74.163	4.607	0.062	216
2003	60.908	2.818	0.046	60.762	3.575	0.059	206
2004	59.067	2.740	0.046	52.003	2.970	0.057	267
2005	57.094	2.673	0.047	64.585	3.642	0.056	278
2006	56.125	2.656	0.047	55.261	3.076	0.056	294
2007	56.811	2.705	0.048	54.933	3.289	0.060	224
2008	59.251	2.835	0.048	65.866	4.120	0.063	177
2009	62.936	3.041	0.048	60.141	3.800	0.063	170
2010	66.703	3.275	0.049	83.001	5.159	0.062	176
2011	68.923	3.426	0.050	62.361	3.831	0.061	184
2012	68.131	3.377	0.050	67.267	4.070	0.061	201
2013	63.861	3.110	0.049	62.732	3.839	0.061	186
2014	56.961	2.743	0.048	53.044	3.126	0.059	206
2015	49.038	2.430	0.050	55.083	3.238	0.059	222
2016	41.519	2.231	0.054	41.803	2.437	0.058	212

Table 6. Population estimates of number of Swordfish caught, standard error of the mean and CV for the updated model. Estimates were based on the median number of hooks per trip (8,365), modal bait used (fish), median Month (8), fraction of tuna, by weight in catch of 5%, fraction of sharks by weight in catch of 5% and mean coordinates of 42.19 N latitude, 61.82 west longitude. Fit was based on trip level data.

YEAR	FIT	SE	CV	N
1962	109.27	20.24	0.19	11
1963	201.92	14.38	0.07	94
1964	79.73	4.63	0.06	251
1965	55.55	3.20	0.06	195
1966	58.74	3.16	0.05	199
1967	78.04	4.02	0.05	211
1968	54.03	2.61	0.05	290
1969	51.12	2.57	0.05	267
1970	65.66	3.57	0.05	185
1971	NA	NA	NA	0
1972	NA	NA	NA	0
1973	NA	NA	NA	0
1974	NA	NA	NA	0
1975	NA	NA	NA	0
1976	NA	NA	NA	0
1977	NA	NA	NA	0
1978	NA	NA	NA	0
1979	94.62	8.99	0.10	39
1980	81.66	6.00	0.07	75
1981	85.02	8.30	0.10	36
1982	66.70	6.97	0.10	34
1983	57.93	6.29	0.11	29
1984	57.23	6.04	0.11	33
1985	67.85	7.01	0.10	34
1986	112.51	11.92	0.11	30
1987	80.25	8.11	0.10	35
1988	77.46	7.81	0.10	36
1989	73.07	6.87	0.09	44
1990	105.10	9.33	0.09	45
1991	70.71	4.59	0.06	115
1992	83.75	5.37	0.06	117
1993	70.63	3.61	0.05	218
1994	51.84	2.21	0.04	427
1995	64.40	2.81	0.04	404
1996	39.37	1.91	0.05	330
1997	56.10	2.78	0.05	272
1998	78.32	4.03	0.05	210
1999	104.47	5.35	0.05	202
2000	77.58	4.24	0.05	186
2001	89.67	4.56	0.05	234
2002	134.23	7.57	0.06	216
2003	94.73	5.17	0.05	206
2004	88.85	4.68	0.05	267
2005	106.22	5.43	0.05	278
2006	92.80	4.76	0.05	294
2007	86.94	4.87	0.06	224
2008	110.49	6.44	0.06	177
2009	96.25	5.74	0.06	170
2010	137.25	8.01	0.06	176
2011	100.51	5.71	0.06	184
2012	108.48	6.06	0.06	201
2013	105.22	6.03	0.06	186
2014	84.92	4.63	0.05	206
2015	88.35	4.77	0.05	222
2016	65.27	3.57	0.05	212

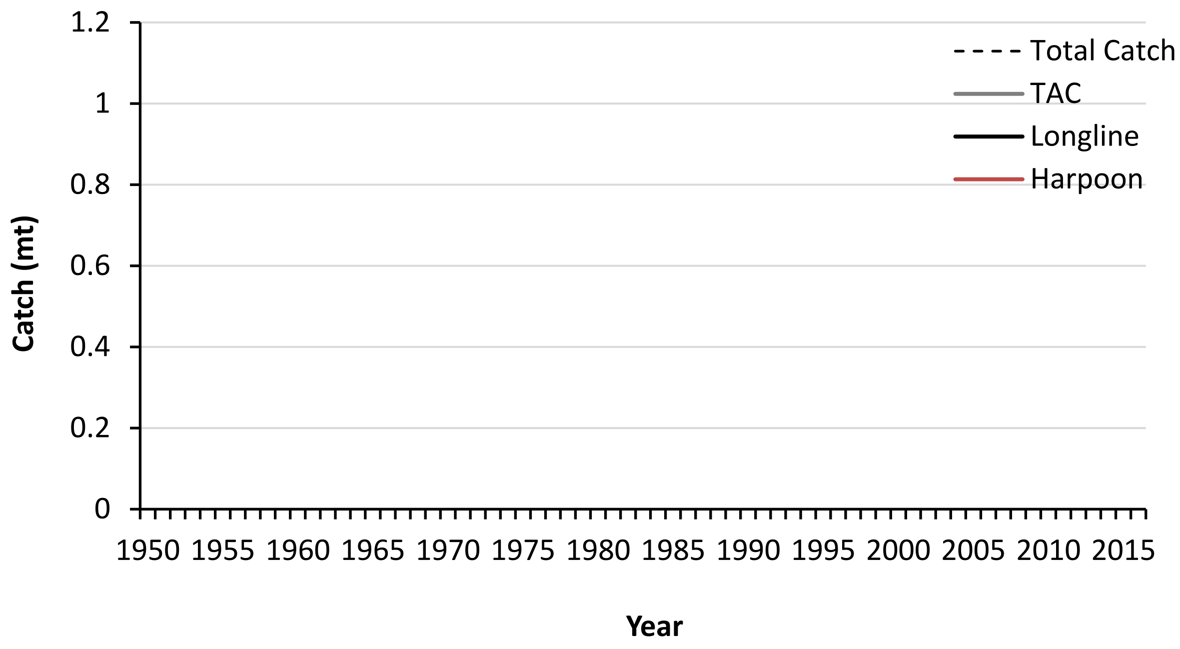

Figure 1. Total annual historic landings (metric tonnes) of North Atlantic Swordfish caught in Canadian waters by longline (solid black) , harpoon (solid red) and all gears (harpoon and longline; dashed black). The grey line represents the total TAC allocated to Canada by ICCAT which can be exceeded due to transfers from other CPCs. The weight of dead discards is not included in the totals.

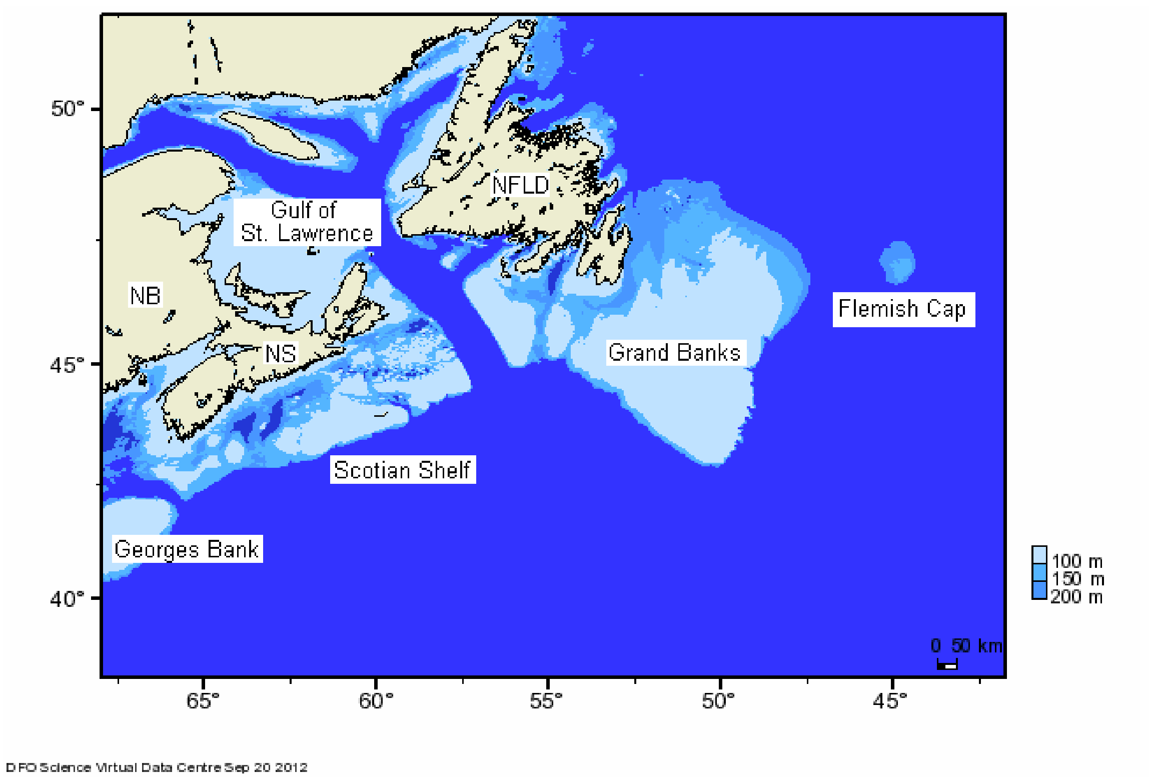

Figure 2. Map of key geographic locations off the Canadian Atlantic coast associated with the Canadian pelagic long line fishery. No long line fishing occurs within the Gulf of St. Lawrence.

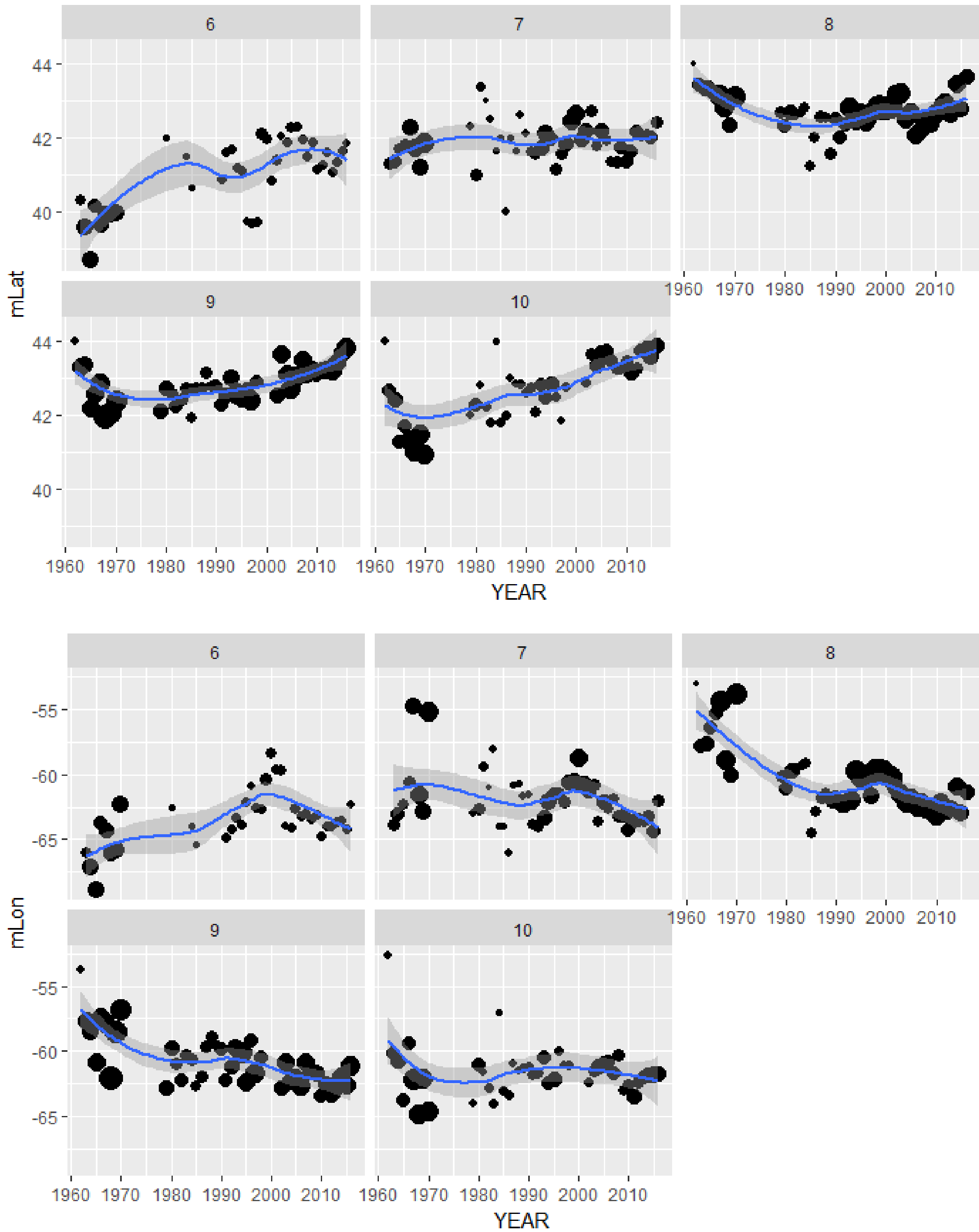

Figure 3. Long term trends in the distribution of the Canadian pelagic longline fishery by month from 1962 to 2016. Each point is the mean latitude (top plot) or longitude (bottom) for a given year where point size expands with total number of swordfish caught.

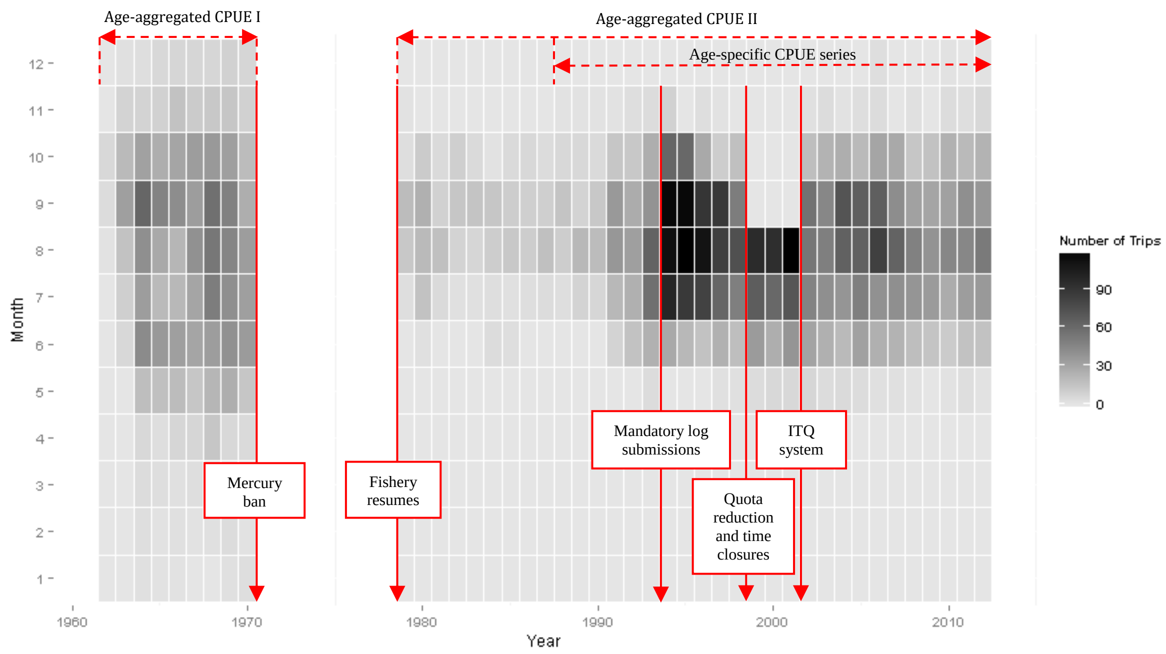

Figure 4. Number of reported trips made in a given month by the Canadian pelagic longline fishery between 1962 and 2012. Solid lines identify years in which changes in fishing opportunity and introduction of management actions occurred. Dotted lines indicate span of current ASPIC and VPA series.(Source: Andrushchenko et al. 2014)

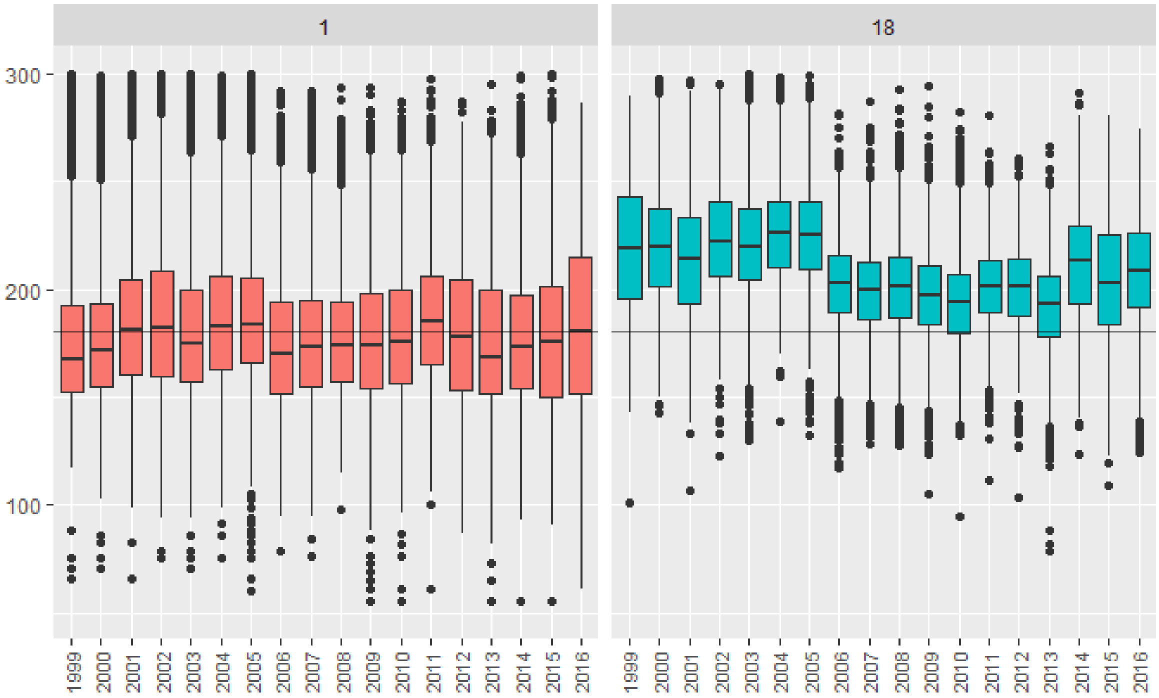

Figure 5. Box and whisker plots for Swordfish Lower Jaw Fork Length (LJFL, cm) caught in the Canadian pelagic long line fishery between 1999 and 2016 (left) and by the Canadian harpoon fishery (right). The black line indicates the mean LJFL for the long line series (180.8 cm).

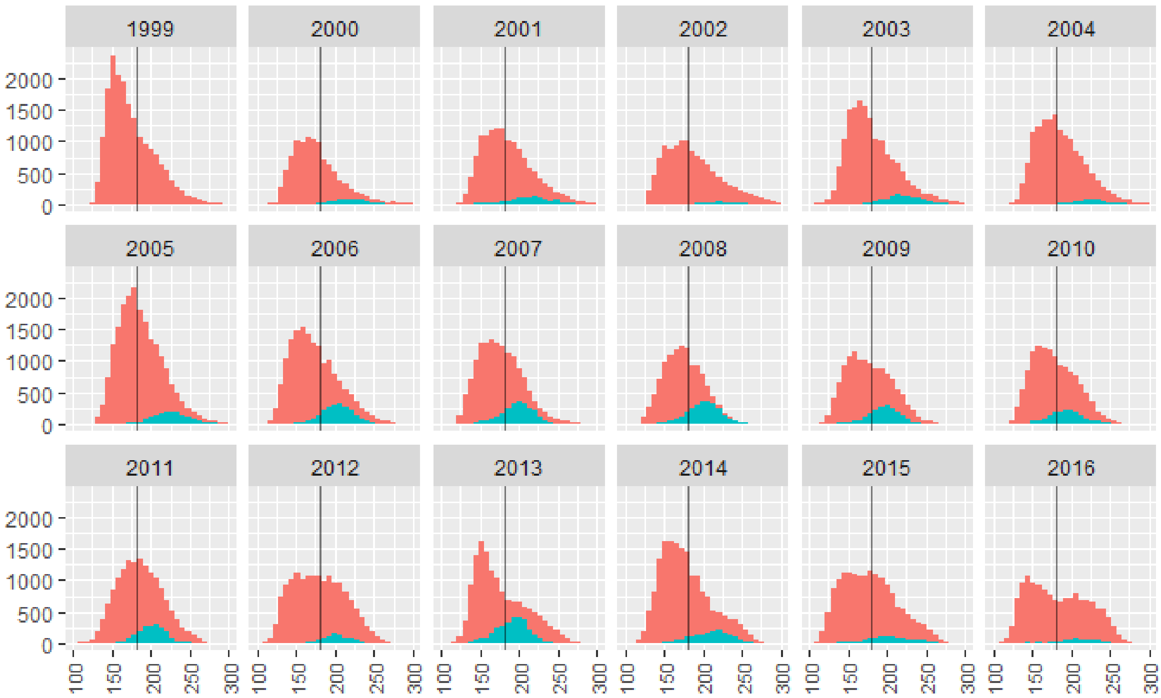

Figure 6. Swordfish Lower Jaw Fork Length (LJFL, cm) length frequencies for fish caught in the Canadian pelagic long line fishery between 1999 and 2016 (red) and by the Canadian harpoon fishery (blue). The black line indicates the mean LJFL for the long line series (180.8 cm).

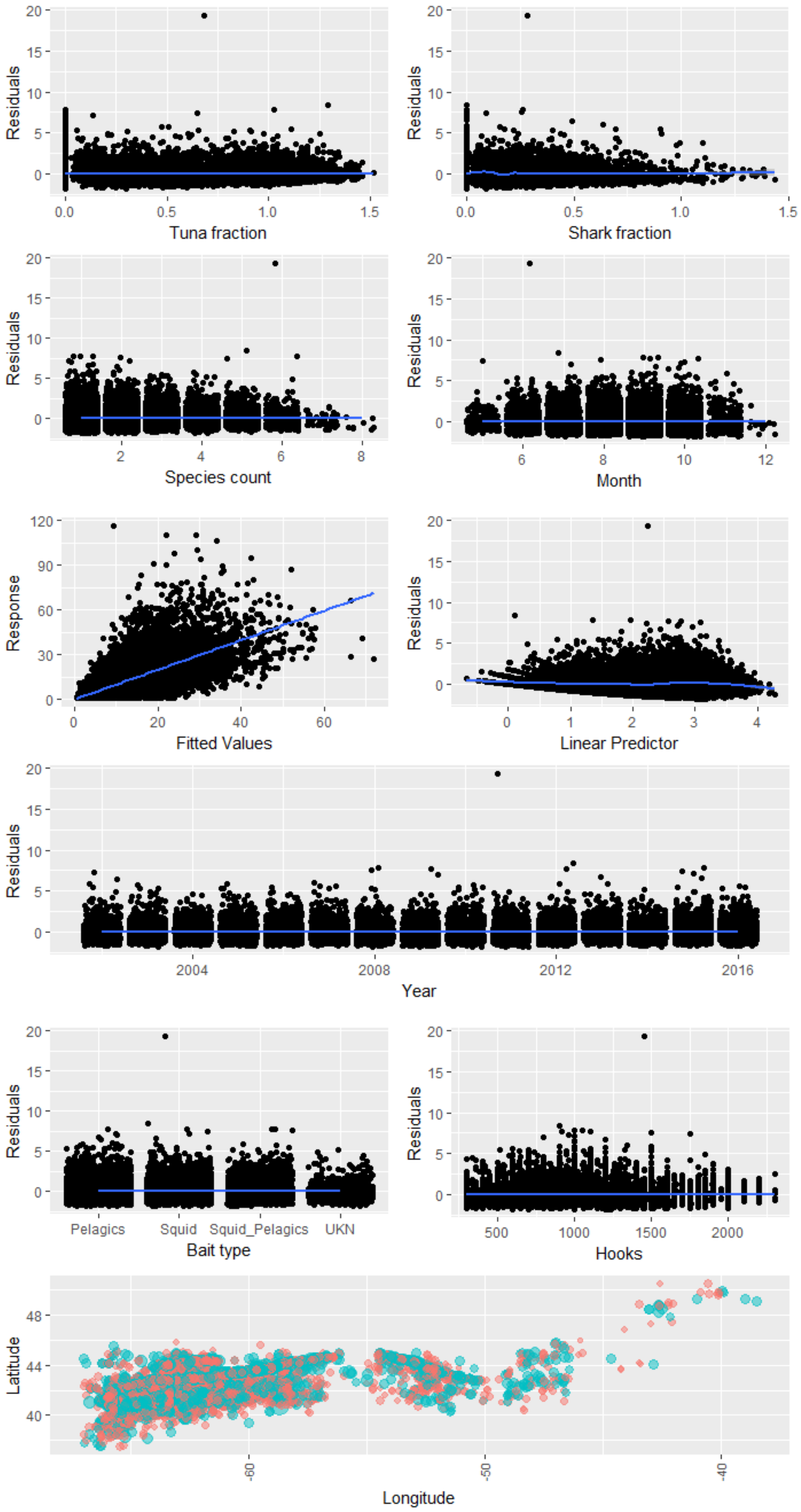

Figure 7. Diagnostic plots for a model fit to the 2002 to 2016 set level data with Year fit as a smoother. Pearson residuals are shown relative to the covariates in the model and the linear predictor. Fitted values are the marginal expected values of the response.

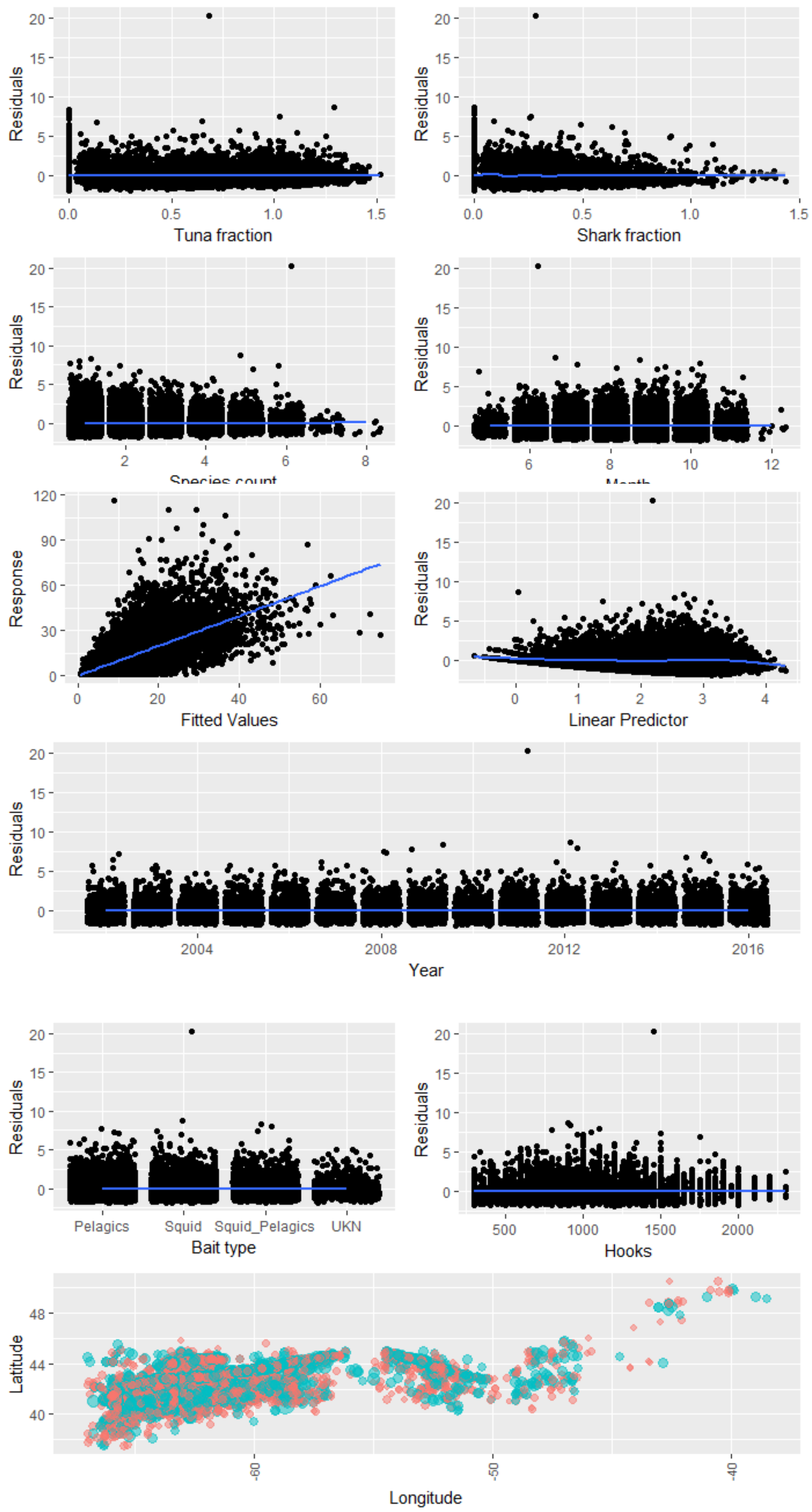

Figure 8. Diagnostic plots for a model fit to the 2002 to 2016 set level data with Year fit as a factor. Pearson residuals are shown relative to the covariates in the model and the linear predictor. Fitted values are the marginal expected values of the response.

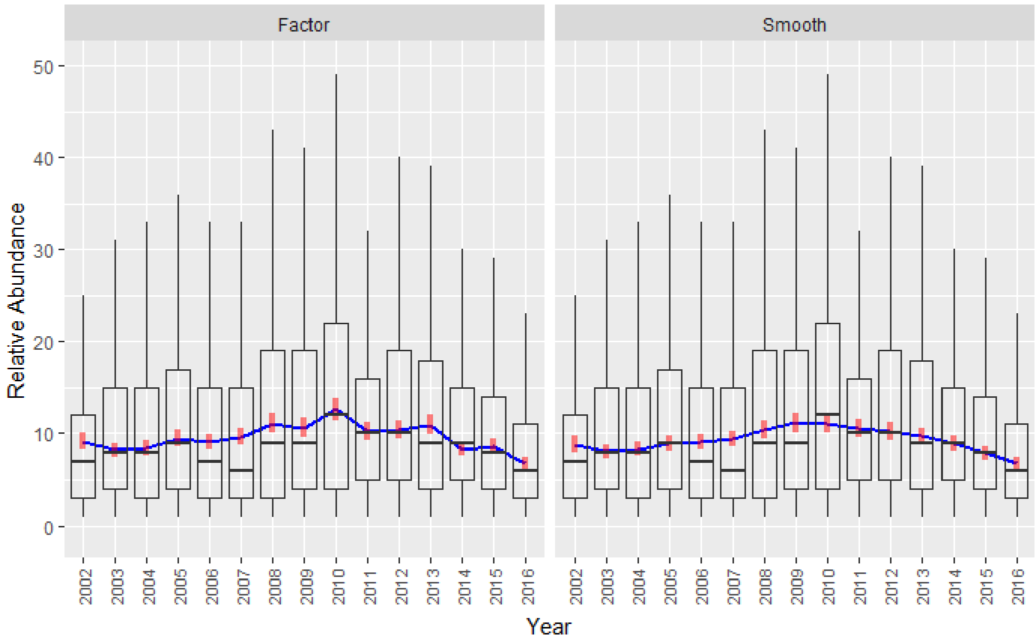

Figure 9. Two relative indices of Swordfish abundance based on the 2002 to 2016 set level data from the Canadian pelagic long line fishery. These population level predictions were derived from two identical models except with respect to the Year effect. The estimates shown in the left panel are from a model with Year as a factor while 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.

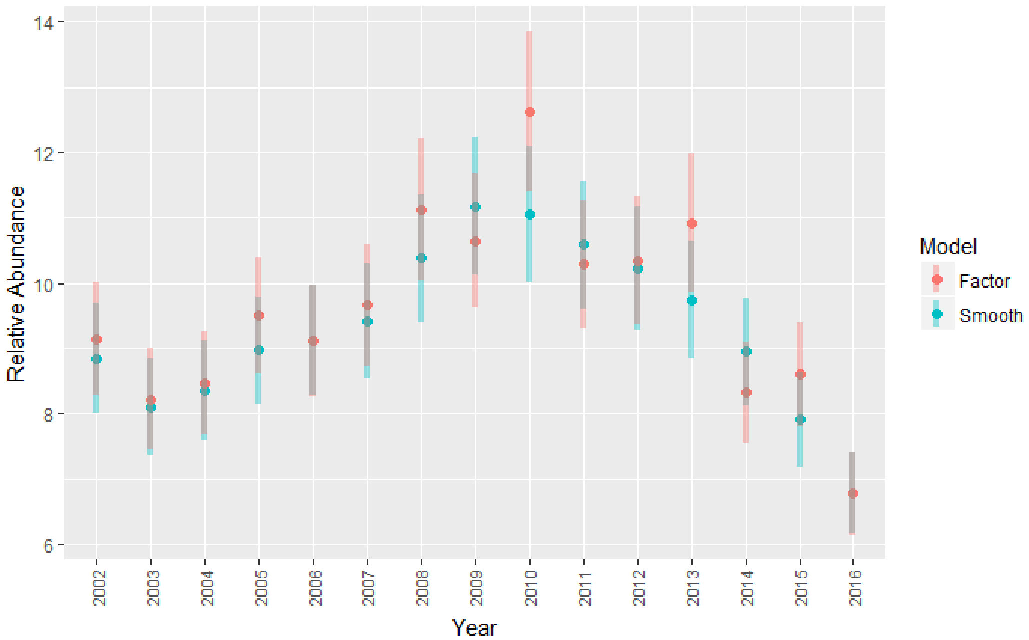

Figure 10. A comparison of two relative indices of Swordfish abundance based on the 2002 to 2016 set level data from the Canadian pelagic long line fishery. These population level predictions were derived from two identical models except with respect to the Year effect.

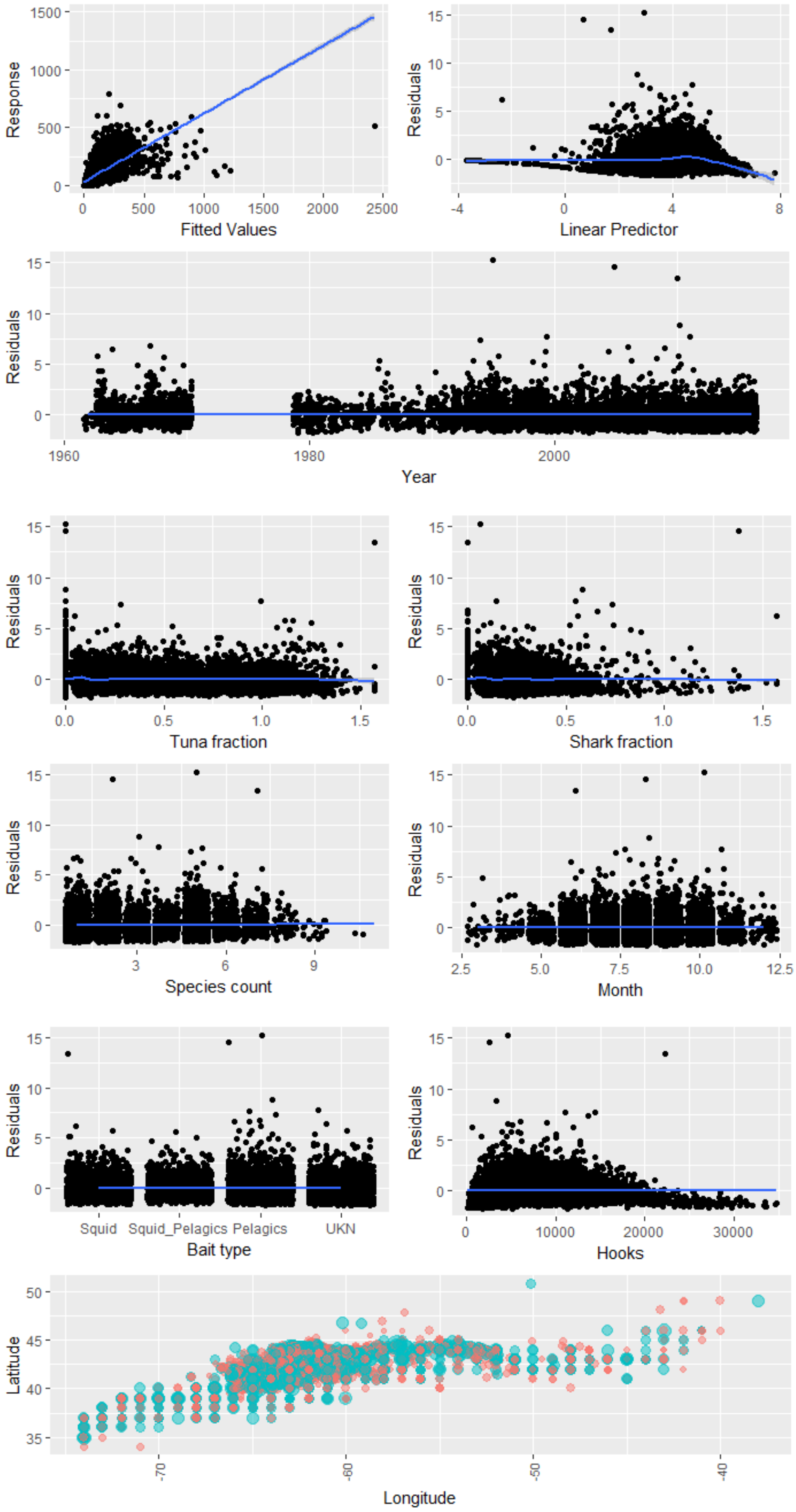

Figure 11. Diagnostic plots for a model fit to the 1962 to 2016 trip level data with Year fit as a smoother. Pearson residuals are shown relative to the covariates in the model and the linear predictor. Fitted values are the marginal expected values of the response.

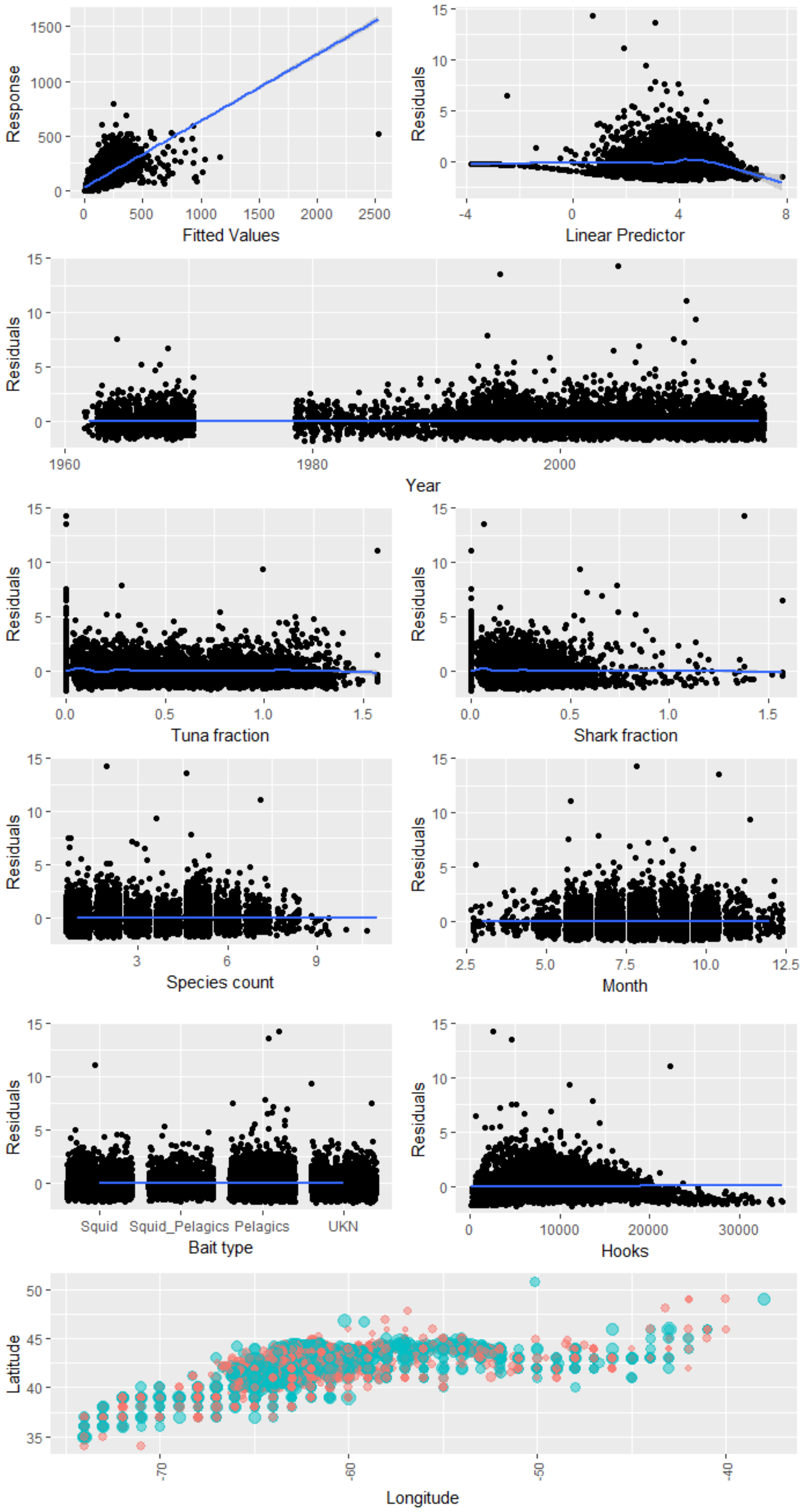

Figure 12. Diagnostic plots for a model fit to the 1962 to 2016 trip level data with Year fit as a factor. Pearson residuals are shown relative to the covariates in the model and the linear predictor. Fitted values are the marginal expected values of the response.

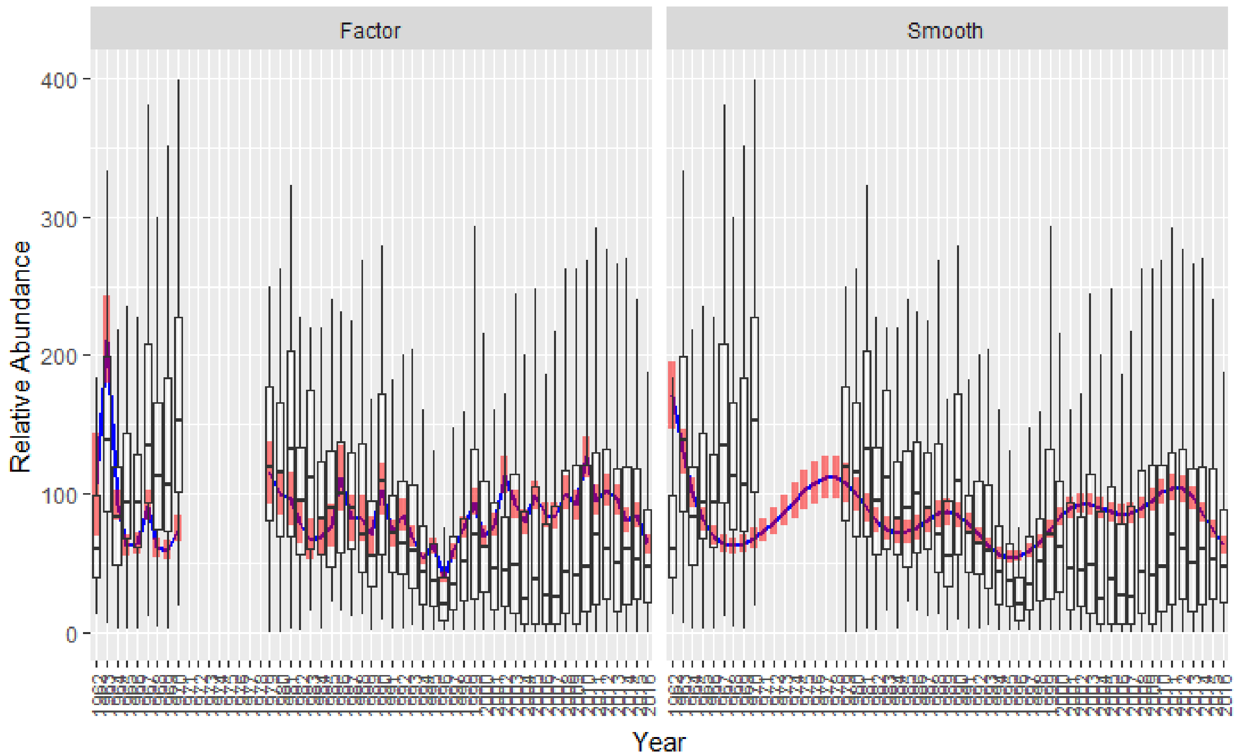

Figure 13. Two relative indices of Swordfish abundance based on the 1962 to 2016 trip level data from the Canadian pelagic long line fishery. These population level predictions were derived from two identical models except with respect to the Year effect. The estimates shown in the left panel are from a model with Year as a factor while 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.

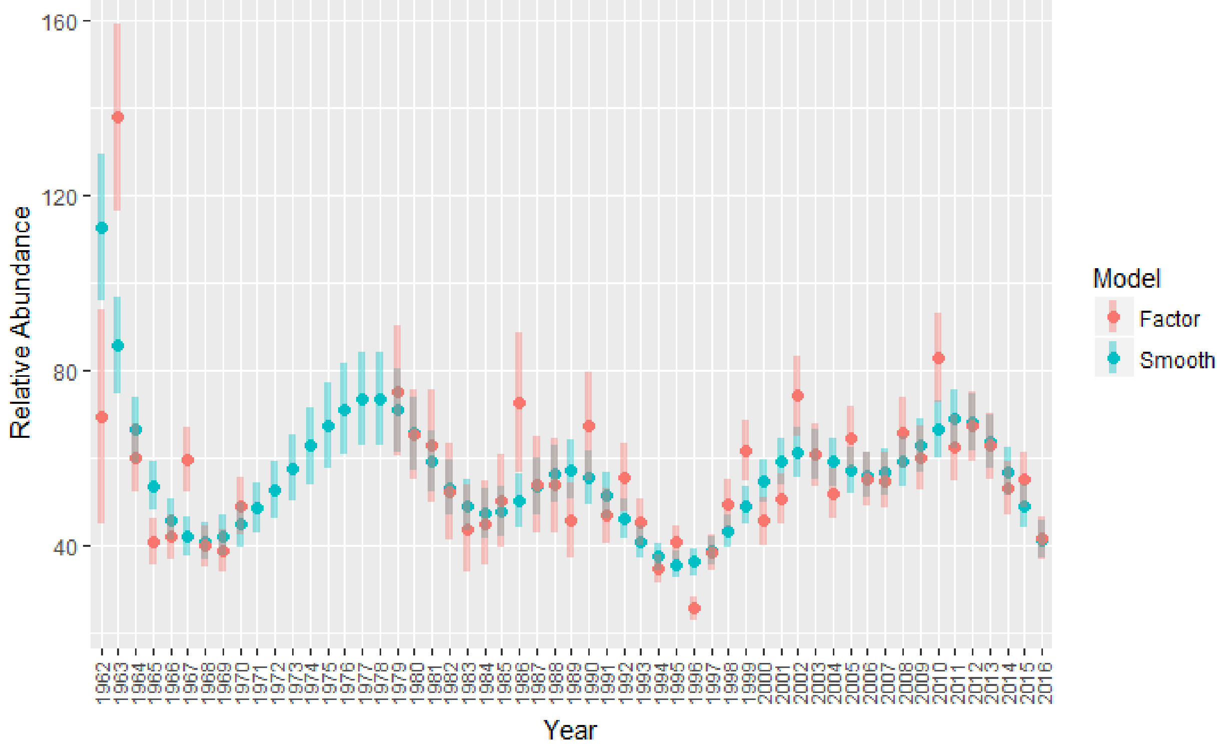

Figure 14. A comparison of two relative indices of Swordfish abundance based on the 1962 to 2016 trip level data from the Canadian pelagic long line fishery. These population level predictions were derived from two identical models except with respect to the Year effect.

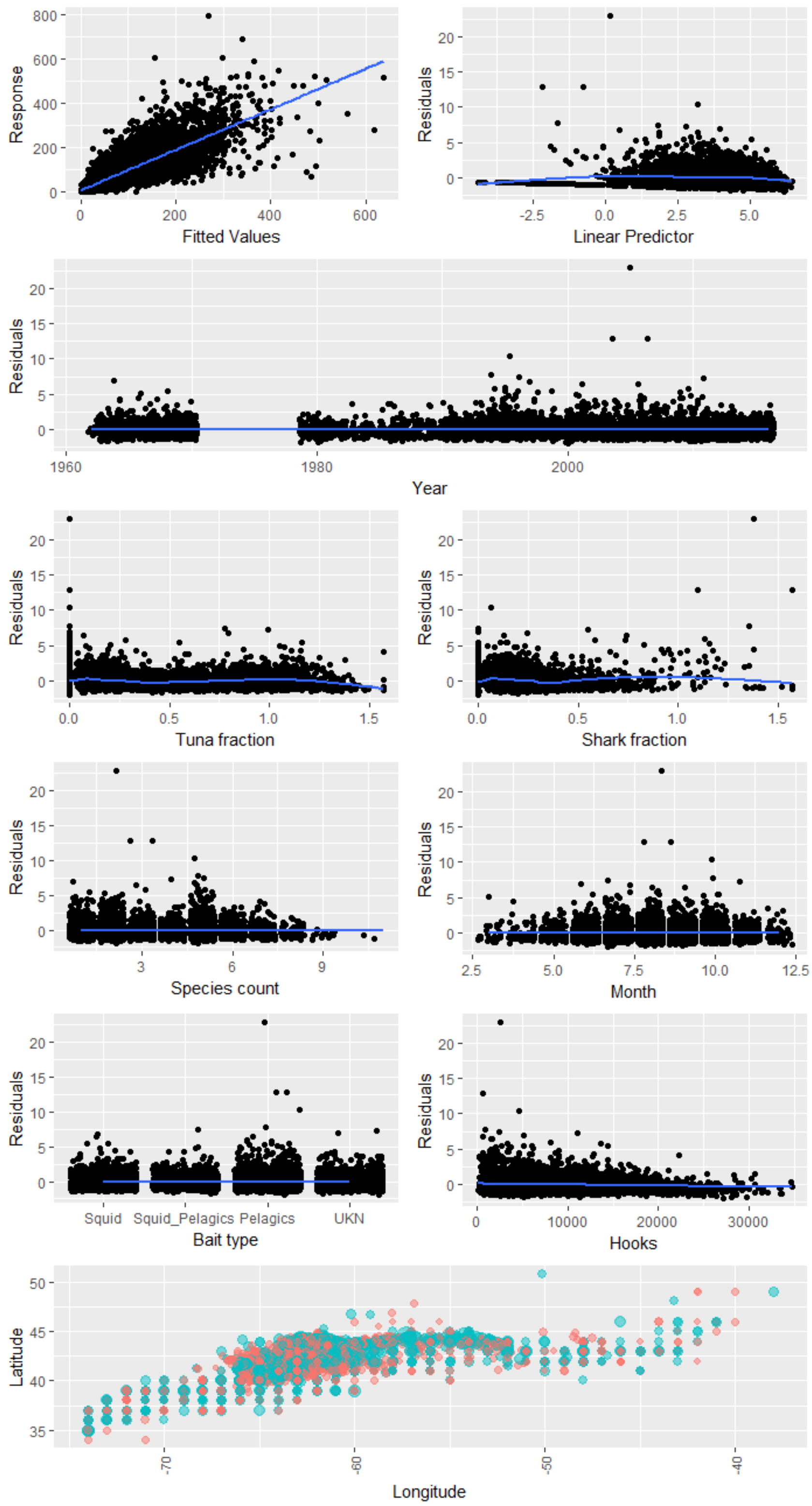

Figure 15. Diagnostic plots for the updated model fit to the 1962 to 2016 trip level data. Year and month are fit as a factors and hooks are an offset. Pearson residuals are shown relative to the covariates both in and out of the model. Fitted values are the marginal expected values of the response.

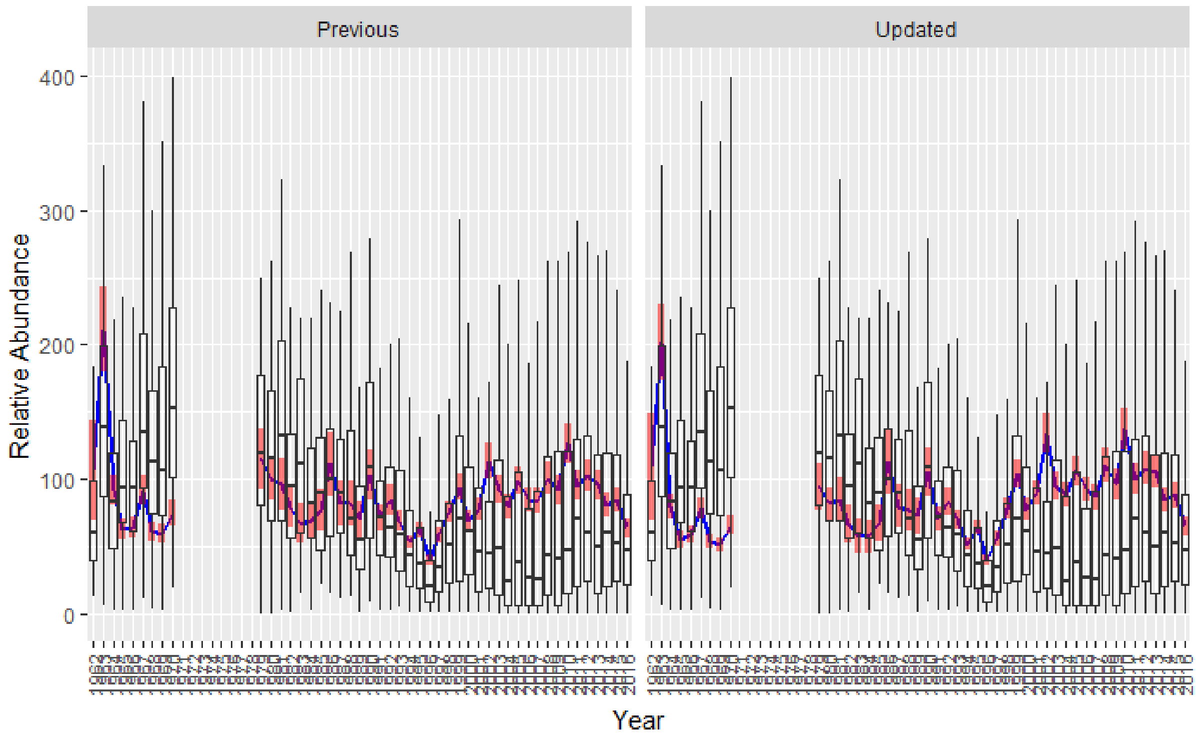

Figure 16. Two relative indices of Swordfish abundance based on the 1962 to 2016 trip level data from the Canadian pelagic long line fishery. The population level predictions for the "Updated" model are based on a Tweedie distribution whereas "Previous" refers to the "Factor" model from **Figure 13**. 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.

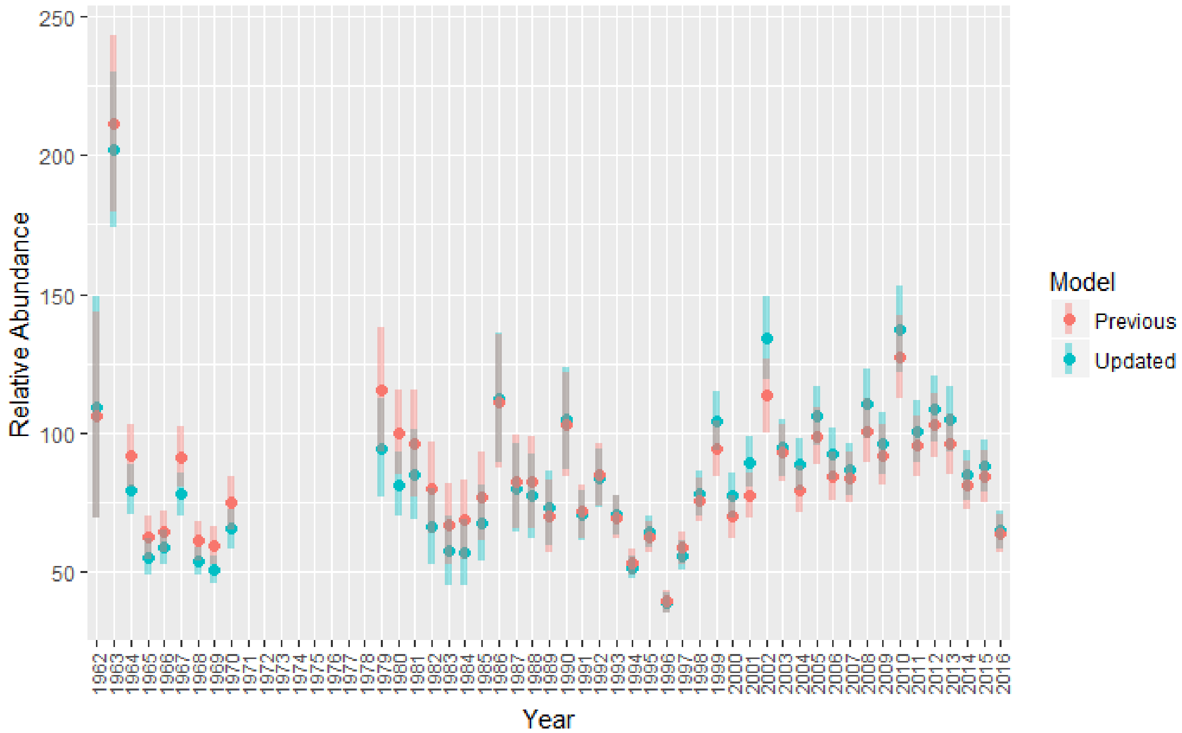

Figure 17. A comparison of two relative indices of Swordfish abundance based on the 1962 to 2016 trip level data from the Canadian pelagic long line fishery. The population level predictions for the "Updated" model are based on a Tweedie distribution whereas "Previous" refers to the "Factor" model from **Figure 13**.