DEVELOPMENT OF A WESTERN LARGE (>177 cm) ATLANTIC BLUEFIN TUNA INDEX OF ABUNDANCE BASED ON CANADIAN AND U.S. ROD AND REEL FISHERIES DATA

A. Hansell[1,2], A. Hanke[3], S. Becker[2], S. Cadrin[4], M. Lauretta[5], J. Walter[5], W. Golet[2], L. Kerr[2]

SUMMARY

United States (U.S.) and Canadian indices of abundance were removed from the last western Atlantic bluefin tuna virtual population analysis (VPA) stock assessment because of conflicting trends. It is hypothesized that conflicting trends result from spatial shifts rather than stock abundance. Consolidating data between the two regions should produce an annual signal that is proportional to stock abundance while less sensitive to changes in stock distribution over time. Here we use two separate statistical frameworks to combine U.S. and Canadian data into a single index of abundance. Both model frameworks converge, agree with fishermen perceptions and indicate that abundance in the northwest Atlantic is increasing. Results are a proof of concept; however, more work is needed to reconcile differences between U.S. and Canadian data before a combined index can be recommended for use in the stock assessment.

RÉSUMÉ

Les indices d'abondance des États-Unis et du Canada ont été retirés de la dernière évaluation du stock de thon rouge de l'Atlantique Ouest utilisant l'analyse de population virtuelle (VPA) en raison de tendances contradictoires. On suppose que les tendances contradictoires résultent de déplacements spatiaux plutôt que de l'abondance du stock. La consolidation des données entre les deux régions devrait produire un signal annuel qui est proportionnel à l'abondance du stock tout en étant moins sensible aux changements dans la distribution du stock au fil du temps. Deux cadres statistiques distincts ont été utilisés pour combiner les données américaines et canadiennes en un seul indice d'abondance. Les deux cadres de modélisation convergent, correspondent aux perceptions des pêcheurs et indiquent que l'abondance dans l'Atlantique Nord-Ouest est en augmentation. Les résultats constituent une preuve de concept ; toutefois, d'autres travaux sont nécessaires pour concilier les différences entre les données américaines et canadiennes avant de pouvoir recommander l'utilisation d'un indice combiné dans l'évaluation du stock

RESUMEN

Los índices de abundancia de Estados Unidos y Canadá se eliminaron de la última evaluación de stock de análisis de población virtual (VPA) del atún rojo del Atlántico occidental a causa de tendencias contradictorias. Se ha planteado la hipótesis de que las tendencias contradictorias son resultado de cambios espaciales más que de la abundancia del stock. Consolidar los datos entre las dos regiones debería producir una señal anual que es proporcional a la abundancia del stock, aunque menos sensible a cambios en la distribución del stock a lo largo del tiempo. Aquí se usan dos marcos estadísticos separados para combinar los datos estadounidenses y canadienses en un único índice de abundancia. Ambos marcos de trabajo convergen, están de acuerdo con las percepciones de los pescadores e indican que la abundancia en el Atlántico noroccidental está aumentando. Los resultados son una demostración conceptual, sin embargo, es necesario más trabajo para reconciliar las diferencias entre los datos estadounidenses y canadienses antes de que pueda recomendarse un índice combinado para su uso en la evaluación del stock.

KEYWORDS

Atlantic bluefin tuna, catch per unit effort, index of abundance, VAST, hierarchical index

[1] Massachusetts Division of Marine Fisheries, New Bedford MA, USA; Email: Alexander.Hansell@Mass.gov
[2] Gulf of Maine Research Institute, Portland ME, USA
[3] Fisheries and Oceans Canada, St. Andrews Biological Station, St. Andrews, Canada
[4] University of Massachusetts Dartmouth School for Maine Science and Technology, New Bedford MA, USA
[5] National Marine Fisheries Service Southeast Fisheries Science Center, Miami, USA

1. Background

The western Atlantic bluefin tuna (*Thunnus thynnus,* BFT) stock assessment is conducted using two age structured models (i.e., Stock Synthesis and virtual population analysis, VPA). Both assessment models are fit to fleet-specific catch-per-unit-effort (CPUE) indices assumed to be directly proportional to abundance. A limitation of fleet-specific indices is that they are local and only reflect abundance where fishermen fish. Over the last three decades, CPUE from the U.S. and Canadian fleets targeting large (> 177 cm) BFT have exhibited periods of conflicting trends (**Figure 1 & 2**). It is hypothesized that changes in CPUE between U.S. and Canadian indices could result from changing spatial distribution due to oceanographic conditions and not from changes in stock abundance (Hansell et al. 2020)

The 2020 ICCAT stock assessment of western BFT recommended resolving conflicting trends in the CPUE indices of U.S. and Canadian rod and reel fleets (ICCAT 2020). The assessment group explored several approaches to treat these conflicting indices, including: i) allowing for time-varying catchability for western Atlantic indices, ii) *a priori* adjusting indices to account for a relationship with the Atlantic Multidecadal Oscillation (AMO), iii) several alternative approaches to index weighting, and iv) removal of the conflicting indices (ICCAT 2020). Ultimately, the AMO was used in Stock Synthesis to reconcile conflicting trends between assessment models fit to the U.S. and Canadian indices of abundance. However, the group decided to remove the U.S. and Canadian rod and reel indices from the VPA because they indicated opposing trends and were believed to be the indices most sensitive to the hypothesis of shifting spatial distribution of fish (ICCAT 2020).

We explored two alternative methods for combining U.S. and Canadian rod and reel data into a single representative index of abundance. This builds on previous joint index work (Hanke et al. 2016) and incorporates stakeholder feedback derived from a series of virtual meetings. We anticipate that this work will help reconcile conflicting CPUE trends, provide a framework for reincorporating U.S. and Canadian catch rates into the western BFT stock assessment (i.e., VPA), and potentially provide a reliable index of abundance for a candidate management procedure.

2. Methodology

2.1. Stakeholder Meetings

A series of five joint U.S.-Canada fishery dependent data meetings were held in 2020-2021 (December 21, January 11, January 21, January 28, March 4). Early meetings focused on reviewing the U.S. and Canadian data that informs indices of abundance for large (>177 cm) BFT. Meetings included visualization of data and group discussion of data quality, challenges, and potential improvements to U.S. and Canadian indices as well as the feasibility of a joint index of abundance. For more detail about these meetings see: Hanke (2021) and Hansell et al. (2021).

2.2. Exploration of Joint U.S. and Canadian Large Fish Index

Data on large (>177 cm) BFT was available from three separate fisheries: 1) U.S. recreational fishery; 2) Southwest Nova Scotia commercial fishery; and 3) Gulf of St. Lawrence commercial fishery. For the U.S. fishery, catch rates were obtained from the Large Pelagics Survey (Salz et al. 2007, Foster et al. 2008), which is an intercept survey used to estimate catch and effort. For Canadian fisheries, catch data were obtained from logbooks. For additional details on U.S. and Canadian data sources see: Hanke (2021) and Hansell et al. (2021).
Two alternative approaches were explored for combining U.S. and Canadian catch rate data. The first approach uses a vector-autoregressive spatiotemporal delta-generalized linear mixed model (VAST, Thorson et al. 2015), and the second uses a hierarchical approach (Conn 2010). VAST requires raw data, while the hierarchical model uses the year effects and coefficients of variation estimated from individual standardization models. VAST is a flexible framework that is designed to estimate spatial variation in density while accounting for habitat associations. VAST allows users to analyze data from multiple sampling gears and designs (Grüss and Thorson, 2019;Thorson et al. 2019). The hierarchical model allows for multiple, noisy indices with the goal of estimating a single time series of relative abundance (Conn 2010).

2.2.1. VAST

VAST was applied to BFT catch data from the U.S. and Canada (Thorson et al. 2015). The spatial domain for the model was defined from Massachusetts, U.S. to Nova Scotia, Canada and all models were fit using a 2-D grid approach (**Figure 3**). The 2-D grid approach evenly spaces knots throughout the spatial domain and is recommended for fisheries dependent data (Thorson, 2019). Alternative model configurations explored the sensitivity of model results to the numbers of knots (e.g., 100, 200, 300, 400). Fisheries data were aggregated at the trip level and analyses focused on trips that targeted BFT from July to October and spent less than 24 hours fishing (**Figure 4**; **Table 1**). VAST separates catch into two components: 1) the probability of a positive catch, and 2) the positive catch rate. In this study, the probability of a positive catch was estimated using a logit-linked linear predictor while several different distributions were explored for the distribution of positive catch (Poisson, negative binomial, log-normal, and gamma).

Probability of positive catch:

$$logit(P_{1,i}) = \beta_1(t_i) + \omega_1(s_i) + \varepsilon_1(s_{i,}t_i) + \delta_1(v_i) + \sum_{k_1=1}^{n_{k_1}} \lambda_1(k_1)Q(i,k_1)$$

Positive catch rate:

$$(P_{2,i}) = \beta_2(t_i) + \omega_2(s_i) + \varepsilon_2(s_{i,}t_i) + \delta_2(v_i) + \sum_{k_2=1}^{n_{k_2}} \lambda_2(k_2)Q(i,k_2)$$

where $\beta(t_i)$ is the intercept for each year (fixed effect), $\omega(s_i)$ is a time-invariant spatial autocorrelated variation for knot s, and $\varepsilon(s_{i,}t_i)$ is a time-varying spatial-temporal autocorrelated variation for knot *s* and in year *t*, $\delta(v_i)$ is the random variation in catchability for the *v* vessel, $Q(i,k)$ are the fixed effects for catchability, and subscripts are for the model component (1: presence/absence, 2: non-zero density) and observation *i*.

Besides the catchability covariates, the estimated values of the fixed and random effects are used to predict local density ($d(s,t)$) for knot *s* and year *t*. The index of abundance ($B(t)$) is calculated as the sum of the density of each knot using an area weighted approach:

$$d(s,t) = logit^{-1}\left(\beta_1(t_i) + \omega_1(s_i) + \varepsilon_1(s_{i,}t_i)\right) \times exp\left(\beta_2(t_i) + \omega_2(s_i) + \varepsilon_2(s_{i,}t_i)\right)$$

$$B(t) = \sum_{s=1}^{n_s} (a(s) \times d(s,t))$$

where $B(t)$ is the area re-weighted density in year *t* throughout the specific domain, which in this study is Massachusetts, U.S. to Nova Scotia, Canada, and $a(s)$ is the areas of knot *s*.

Four alternative effort statistics (hours, lines, hours * lines, and time at sea) were tested for deriving CPUE. Covariates necessary to account for changes in catchability (month, country) and density (SST, Chlorophyll, ocean depth) were explored. Collinearity of covariates was examined using generalized variance-inflation factor (GVIF) scores. Any covariate with a score greater than three was removed, and the GVIFs were recalculated (Zuur, et al. 2012). Regardless of significance, year was kept in all models, because the primary objective was to detect relative abundance trends over time (Maunder and Punt 2004). Akaike Information Criterion (AIC) scores were used to determine the best-fitting model. If AIC scores were within two units of one another, the most parsimonious model was selected (Zuur et al. 2007).

2.2.2. Hierarchical Index

A hierarchical approach was used to estimate a single index of abundance from the U.S. rod and reel (>177cm), Southwest Nova Scotia and the Gulf of St. Lawrence indices (Hansell et al. 2021; Hanke 2021). The framework assumes that each index is subjected to both process and observation error (Conn, 2010). The hierarchical model can be expressed as:

$$Log(U_{it}) \sim Normal(v_t + x_i, (\sigma_{it}^p)^2 + (\sigma_{it}^s)^2)$$

where U_{it} is the index at time t, v_t is the log of a scaled abundance time series in which annual changes reflect changes in abundance at the population level, x_i is the log of catchability, σ^P is the standard deviation associated with process error, and σ^s is the standard deviation associated with observation error. The subscripts t and i correspond to a given year and index. Prior distributions are required for $[v_t]$, $[x_i]$, and $[\sigma^P]$. The same priors were used as in Conn (2010); a lognormal prior was used for $[v_t]$ and $[x_i]$, while a uniform prior was chosen for $[\sigma^P]$. Given the choice of priors the posterior distribution is:

$$[x, v, \sigma^P | U, \sigma^s] \propto [U | x, v, \sigma^P, \sigma^s [x][v][\sigma^p]$$

given standardized indices and their estimates of observation error, the equation above can then be sampled using Markov chain Monte Carlo (MCMC). The model was built in RStudio using the program 'rjags' (Plummer, 2019). Four MCMC chains were run with a burn-in period of 5,000 samples, the chains were thinned every 50th step, and in total collected 50,000 samples.

3. Results

Scientists and stakeholders from the working group highlighted that when using raw data it would be most appropriate to combine U.S. and Southwest Nova Scotia fisheries data to create a joint index because of these fleets' close proximity. Many fishermen stated that abundance of BFT is currently at an all-time high.

3.1. VAST

The selected model configuration used 200 knots. The model failed to converge when discrete distributions (e.g., Poisson, Negative binomial) were used for the positive catch component. Thus, CPUE was used as the response variable and calculated as catch/fishing hours. The optimal model used a logit link for the probability of catch and a gamma distribution for the positive catch component. For all parameters in the optimal model, maximum likelihood estimates were near zero and did not hit parameter boundaries (**Figure 5**). A country*year effect was significant and showed patterns between U.S. and Canadian data (**Figure 6**). Model selection indicated that country and month influenced catchability and sea surface temperature influenced density (**Table 2**). Predicted density and year effect trends indicate that relative abundance is increasing (**Figure 7 & 8**).

3.2. Hierarchical Index

The hierarchical model converged and passed all routine diagnostic checks (**Table 3 & 4; Figure 9**). Residual patterns suggest the model did a good job of fitting to the indices after 1993; however, earlier in the time series the model struggled to fit to the Gulf of St. Lawrence index (**Figure 10**). Process error was estimated to be lowest for the Southwest Nova Scotia index (**Figure 11**). Overall, the hierarchical model suggests that relative abundance has been increasing throughout the entire time series (**Figure 12**).

4. Discussion

The motivation for an index of abundance that combines U.S. and Canadian fishery data is to try to account for spatial shifts that are hypothesized to be driving conflicting trends between indices. Conflicting trends between indices currently prevent U.S. and Canadian indices from being included into the western Atlantic Bluefin VPA. Targeting strategies between the two regions are similar, so consolidating data to produce a joint index should produce an annual signal that is proportional to stock abundance while less sensitive to changes in stock distribution over time. The two joint indices presented here agree with stakeholder perceptions and show an increasing trend in relative abundance for large (>177 cm) BFT (**Figure 13**). The hierarchical index covers a longer time period, while the VAST model provides a fine scale estimate of spatial temporal changes in relative abundance. Both frameworks are robust to spatial changes and provide an index of abundance that can be directly incorporated into future stock assessments.

Several concerns were raised during the workshop regarding the feasibility of combining U.S and Canadian data: 1) the US fishery is open access and uses a survey to estimate catch and effort, while the Canadian fishery is closed access and uses a logbook system to report all BFT captures; 2) participation in the U.S. fishery has increased in recent years (see Hansell et al. 2021 for description); and 3) there is no spatial overlap between the fisheries. The two model frameworks presented here try to address the major concerns discussed during working group meetings. The hierarchical model uses the year effect and coefficients of variation from each index standardization, which allows individual standardization methods to account for issues in each fishery and prevents the need to reconcile differences in data collection between the regions. VAST can derive a combined index from fundamentally different datasets (Grüss and Thorson, 2019).

Despite these advancements, the working group felt more work is needed before either approach is recommended for use in the western BFT stock assessment. We recommend continued development of a joint VAST index with future iterations focusing on: 1) different statistical distributions for U.S. and Canadian catch rates; 2) estimate location data for trips missing latitude and longitude; 3) investigate other potential drivers of BFT density (e.g., prey); 4) adapt the model to estimate effective area and range shifts.

5. Conclusions

Here we presented two alternative statistical frameworks to estimate a joint index between U.S. and Canadian fishery data. The two models have different structures but were able to account for concerns expressed by stakeholders. However, more work is needed before either approach can be recommended for inclusion in the western BFT stock assessment. Future work should focus on continued model development within VAST because this framework provides a robust tool for combing data, estimating relative abundance and range shifts.

6. Acknowledgements

We thank everyone who participated in the meeting. Funding for this project was provided by the U.S. NOAA Bluefin Tuna Research Program (NA19NMF4720096). The scientific results and conclusions, as well as any views or opinions expressed herein, are those of the authors and do not necessarily reflect those of their institutions.

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Table 1. Data filters applied to U.S. and Southwest Nova Scotia, Canada fishing trips. Percentages represent the percent of data after each associated data filter.

Filter	USA	Canada
Raw	100 % (n = 15464)	100 % (n = 45714)
Year (1996 – 2019)	64.2 %	79.1 %
Month (7 – 10)	59.9 %	77.0 %
Location	54.0 %	30.7 %
Hours (0.1 – 24)	52.1 %	20.7 %
Outliers	49.8 % (n = 7694)	20.4 % (n = 9307)

Table 2. Model selection for VAST.

Variables	AIC	Change in AIC	Max Gradient
Year	15787.4	9942.622	< 0.0001
Year + Month	6093.29	248.487	< 0.0001
Year + Month + Country	5866.55	21.75	< 0.0001
Year + Month + Country + sst	5844.8	0	< 0.0001
Year + Month + Country + sst + depth	5845.76	0.963	< 0.0001

Table 3. Year effect estimates used in the hierarchical analysis. GSL = Gulf of St. Lawrence, Canada; SWNS = Southwest Nova Scotia, Canada; and LPS = Large Pelagics Survey, U.S.

Year	GSL	SWNS	LPS
1988	0.21770099		
1989	0.19872163		
1990	0.10258058		
1991	0.11259915		
1992	0.44609766		
1993	0.61068339		0.74623359
1994	0.24881643		0.93958872
1995	0.92340112		1.18577454
1996	0.15218633	0.65492085	1.30533312
1997	0.16919065	0.47040912	1.10690966
1998	0.28183231	0.57859904	1.169413
1999	0.4419668	0.70122206	1.16524173
2000	0.41141893	0.41091055	1.05704704
2001	0.36837876	0.511226	1.22367347
2002	0.5909154	0.6250785	1.21907438
2003	0.64186234	0.88300676	0.91928285
2004	1.14074971	0.90309736	0.8367964
2005	1.05082749	0.88757856	0.87281653
2006	0.98970931	1.26387277	0.74890682
2007	1.61328257	0.96938365	0.7518422
2008	1.14080959	0.91486529	0.72335447
2009	1.55903631	1.62933758	0.76549447
2010	2.19047038	1.5854841	0.97472898
2011	1.64623762	1.23538928	0.99621761
2012	1.96894125	1.26917818	0.97005013
2013	1.85917856	0.97804515	0.83750461
2014	1.88331649	1.1687934	0.88210081
2015	1.58857947	1.07644145	1.01347694
2016	1.95188229	1.10719298	1.05671403
2017	1.73833456	1.40504147	1.16867051
2018	1.89661887	1.2611264	1.17560183
2019	1.86367307	1.50979948	1.18815155

Table 4. Coefficients of variation used in the hierarchical analysis. GSL = Gulf of St. Lawrence, Canada; SWNS = Southwest Nova Scotia, Canada; and LPS = Large Pelagics Survey, U.S.

Year	GSL	SWNS	LPS
1988	0.26782556		
1989	0.28993062		
1990	0.24091566		
1991	0.32191158		
1992	0.17135049		
1993	0.15568943		0.18595519
1994	0.15989604		0.1595121
1995	0.1257941		0.12261339
1996	0.13151279	0.24329227	0.10766859
1997	0.13415534	0.25656046	0.12713704
1998	0.13055127	0.25712945	0.12036621
1999	0.12523055	0.26624372	0.12150659
2000	0.12129884	0.26754146	0.13676542
2001	0.12447651	0.25083402	0.12214726
2002	0.12081797	0.20778883	0.11504266
2003	0.11921149	0.21371112	0.15658212
2004	0.11809154	0.20096247	0.17898419
2005	0.11781008	0.20576681	0.16952587
2006	0.11645369	0.20152046	0.2255705
2007	0.12060552	0.20090283	0.20701036
2008	0.12029908	0.2003085	0.21315713
2009	0.12044673	0.20018698	0.19550004
2010	0.12657809	0.20309551	0.14644323
2011	0.12301761	0.20277003	0.14281088
2012	0.1228747	0.20779524	0.14640292
2013	0.12345733	0.20524916	0.17224712
2014	0.12106795	0.21610567	0.16361718
2015	0.12078742	0.20827077	0.13836886
2016	0.12231196	0.21854529	0.13242996
2017	0.12224365	0.21066294	0.11900134
2018	0.1218787	0.20957437	0.11851859
2019	0.12030386	0.21242657	0.11696596

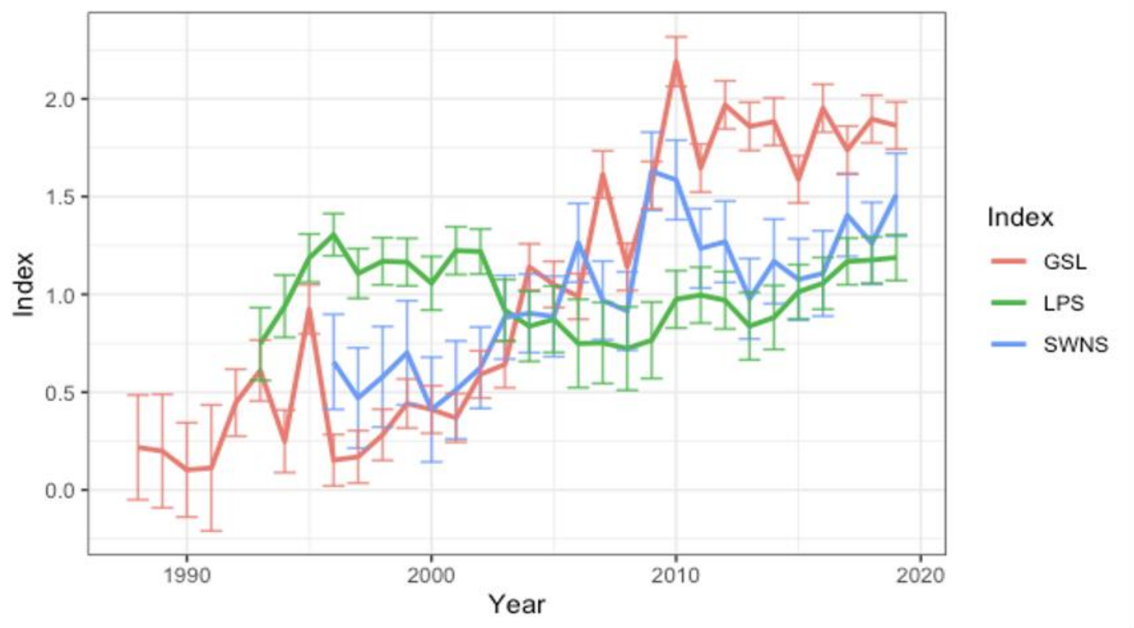

Figure 1. Standardized indices of abundance for large BFT (>177 cm) from the Gulf of St. Lawrence, Canada (GSL), Southwest Nova Scotia, Canada (SWNS) and Large Pelagics Survey, U.S. (LPS).

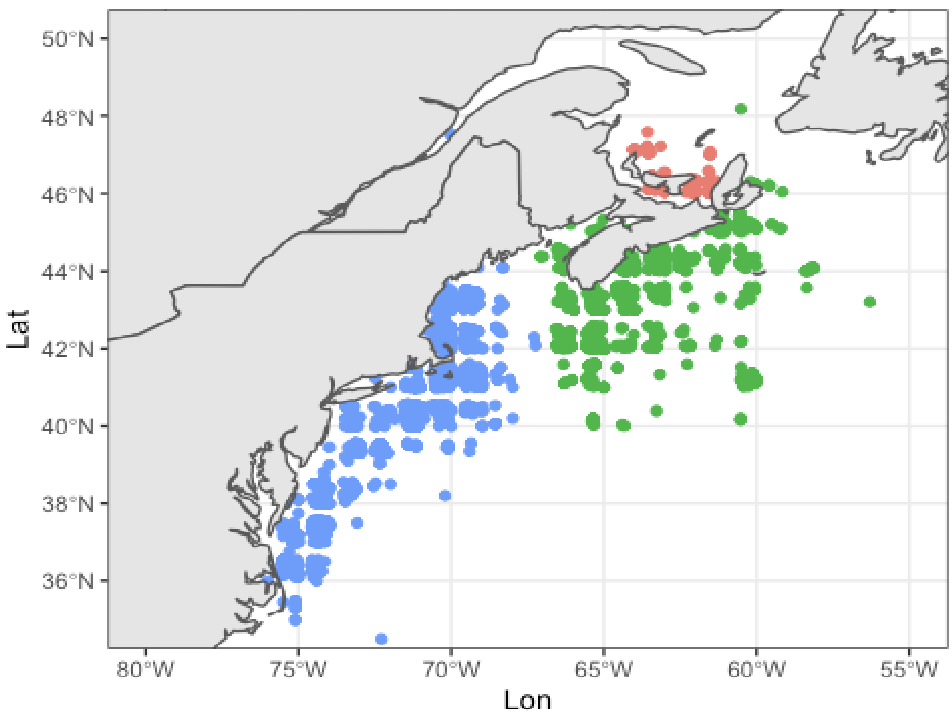

Figure 2. Spatial distribution of fishing trips aggregated at 1x1 grid targeting large (> 177 cm) BFT. Red is the Gulf of St. Lawrence, Canada (GSL), green is Southwest Nova Scotia, Canada (SWNS) and blue is Large Pelagics Survey, U.S. (LPS).

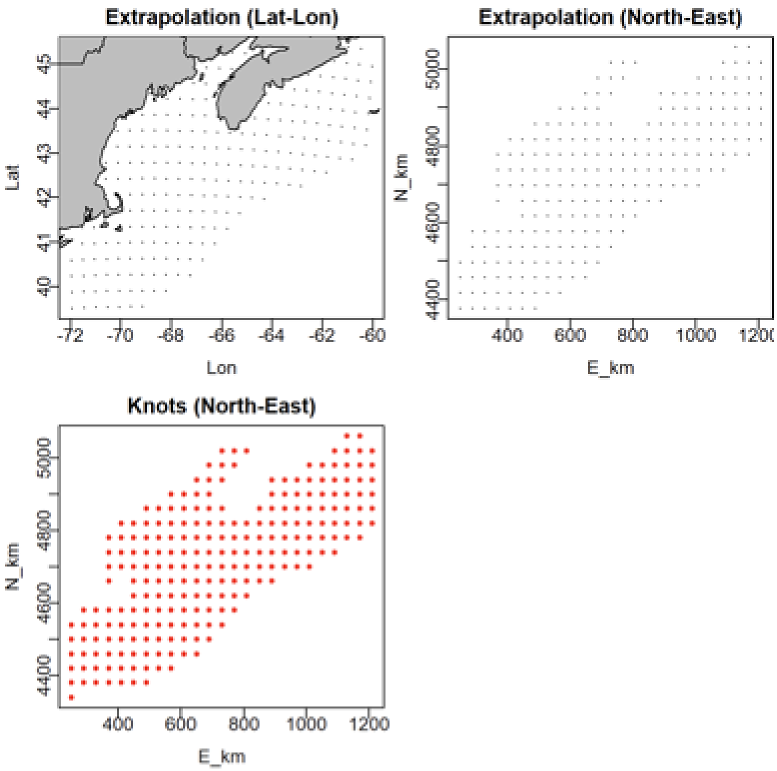

Figure 3. Spatial domain and knots used in VAST to estimate a joint index of abundance for U.S. and Canadian fisheries.

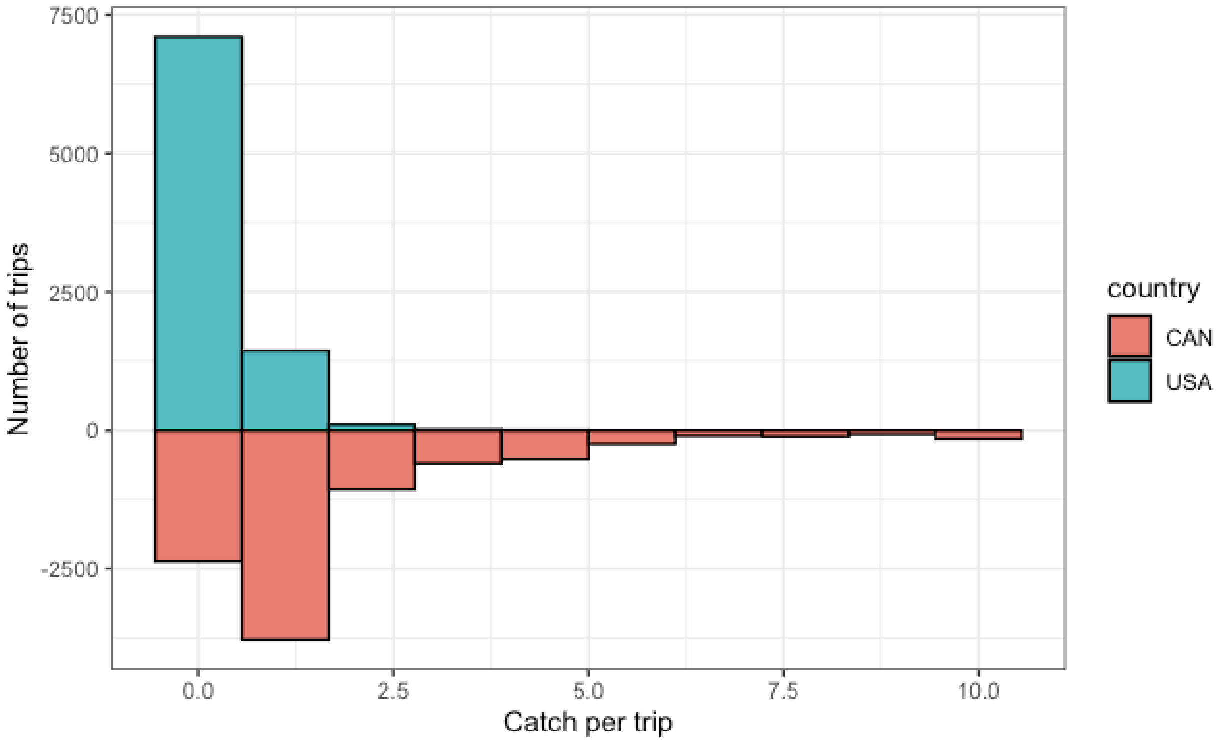

Figure 4. Catch distribution for data used in VAST joint index of abundance.

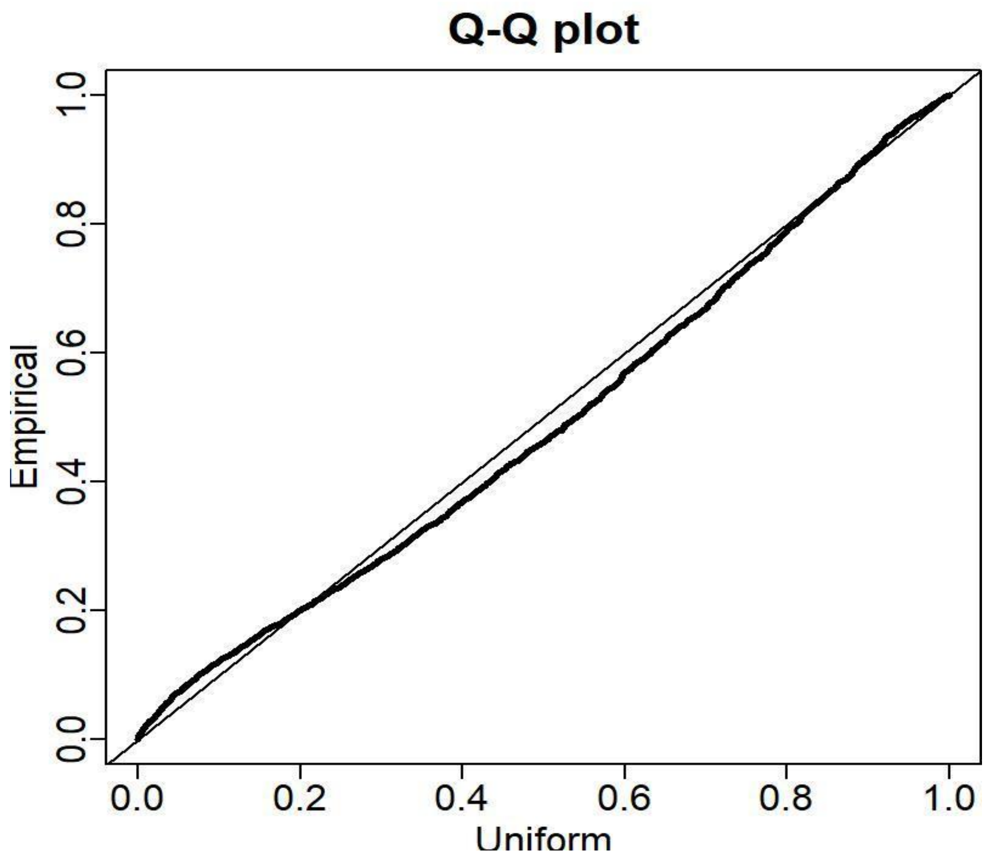

Figure 5. Q-Q plot for VAST model used to estimate a joint index of abundance for large BFT (> 177 cm).

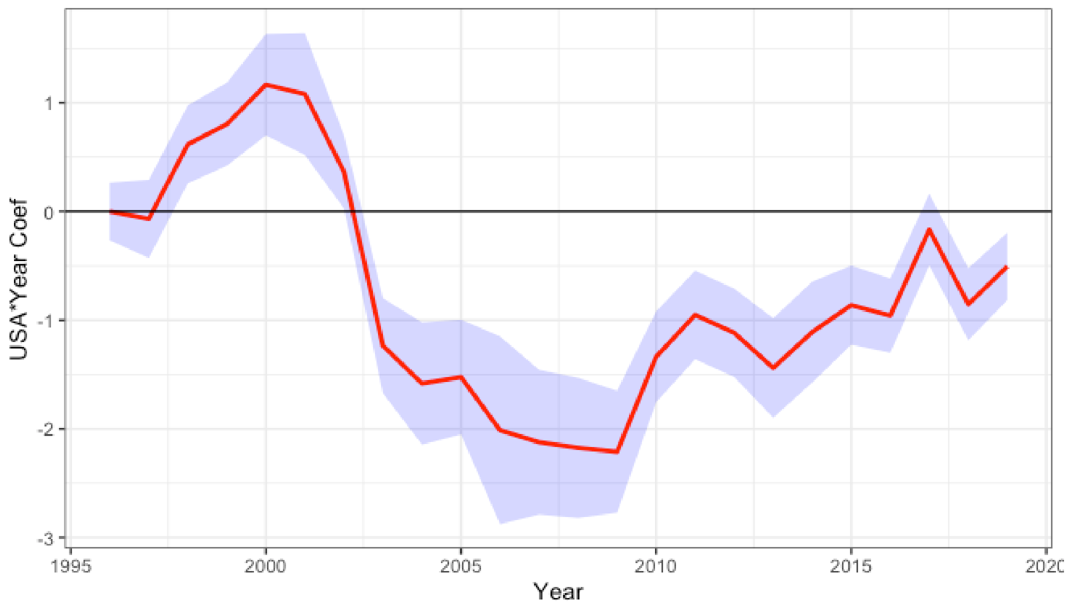

Figure 6. Year*flag interaction coefficients for the VAST model, noting that Canada is modeled as a baseline of 0, so U.S. coefficients are offsets from Canada.

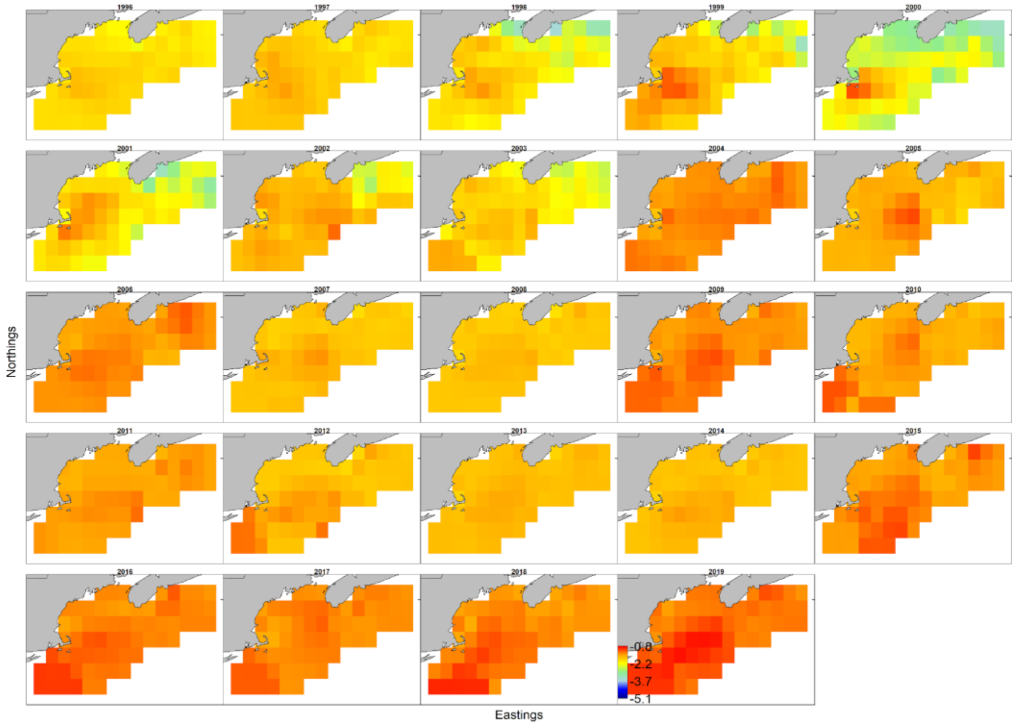

Figure 7. VAST predicted density from 1996 to 2019 for large (> 177 cm) BFT.

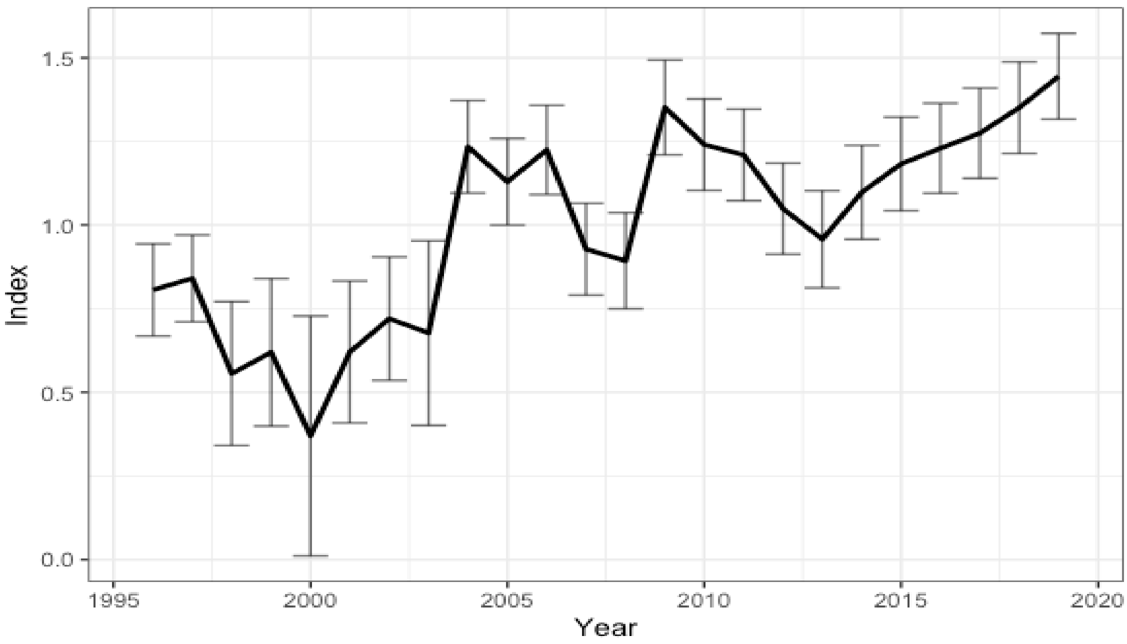

Figure 8. VAST index of relative abundance for large BFT(> 177 cm). Error bars are +/- one standard deviation.

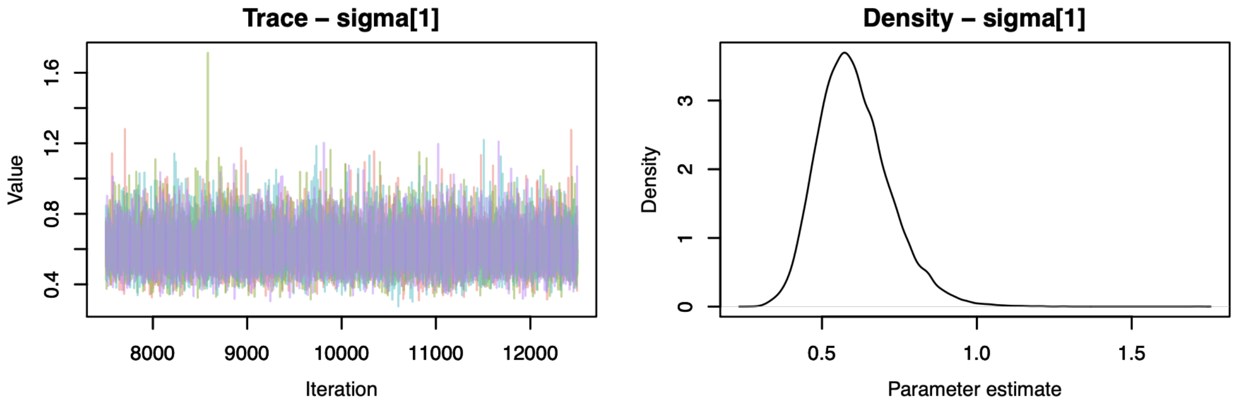

Figure 9. Trace plot for process error estimated by the hierarchical model for the Gulf of St. Lawrence index. Trace plots for all other parameters indicated similar level of convergence.

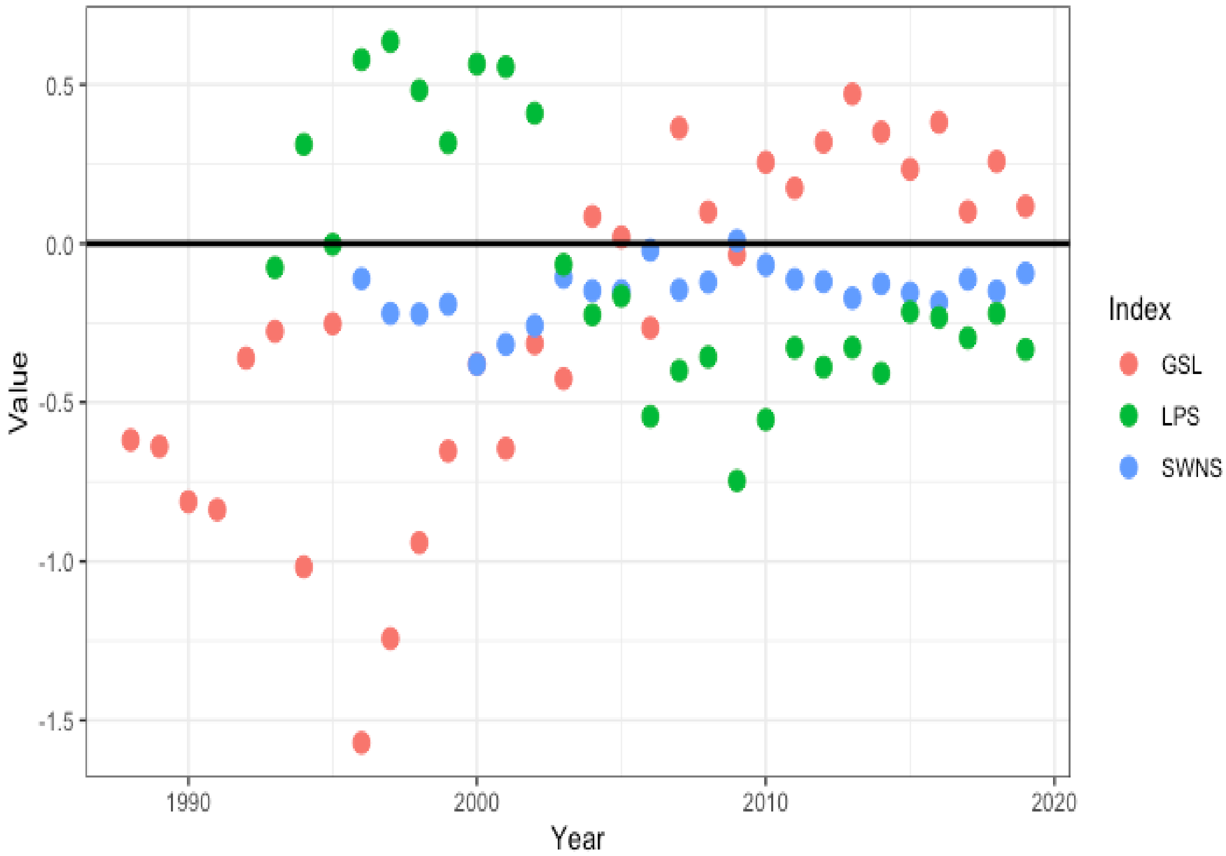

Figure 10. Residual plot for hierarchical model fit to standardized indices of abundance. GSL = Gulf of St. Lawrence, Canada; SWNS = Southwest Nova Scotia, Canada; and LPS = Large Pelagics Survey, U.S.

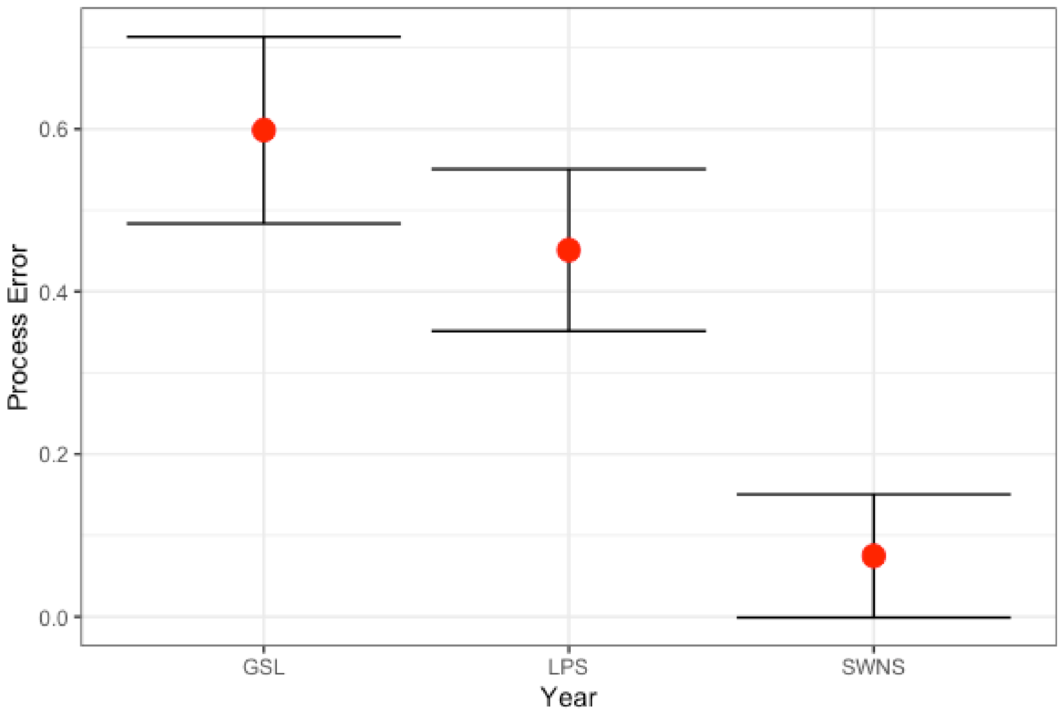

Figure 11. Process errors associated with each index of abundance used in the hierarchical index. GSL = Gulf of St. Lawrence, Canada; SWNS = Southwest Nova Scotia, Canada; and LPS = Large Pelagics Survey, U.S.

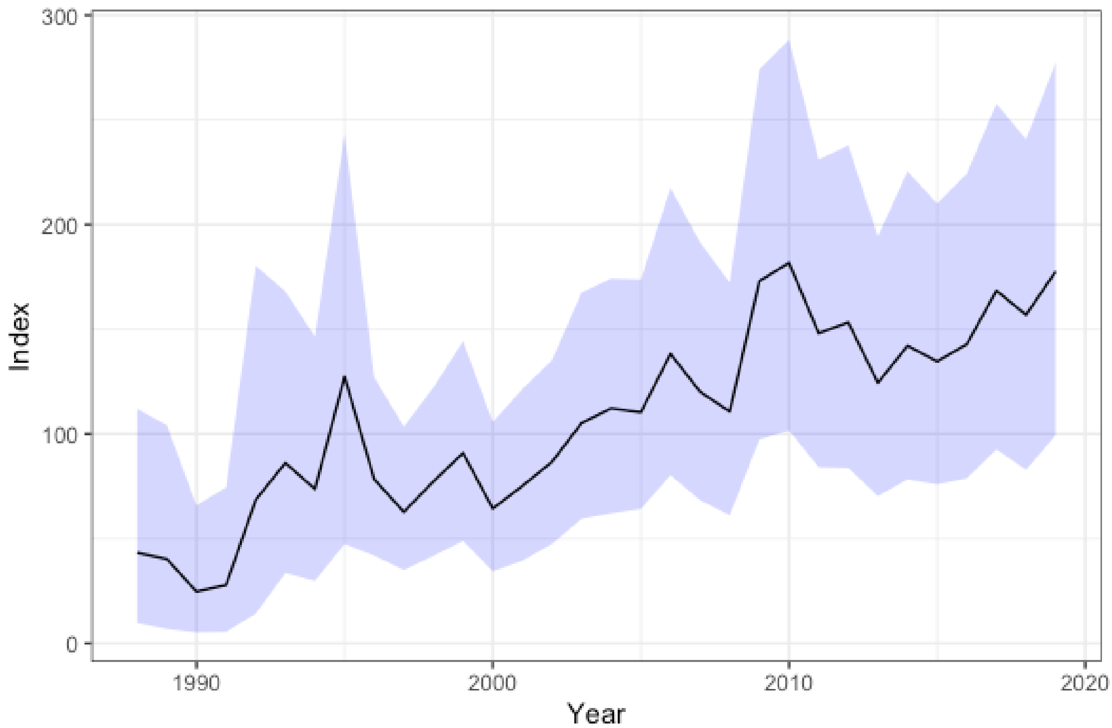

Figure 12. Hierarchical index of relative abundance for large (> 177 cm) BFT. Shaded area represents the 95 % credible intervals.

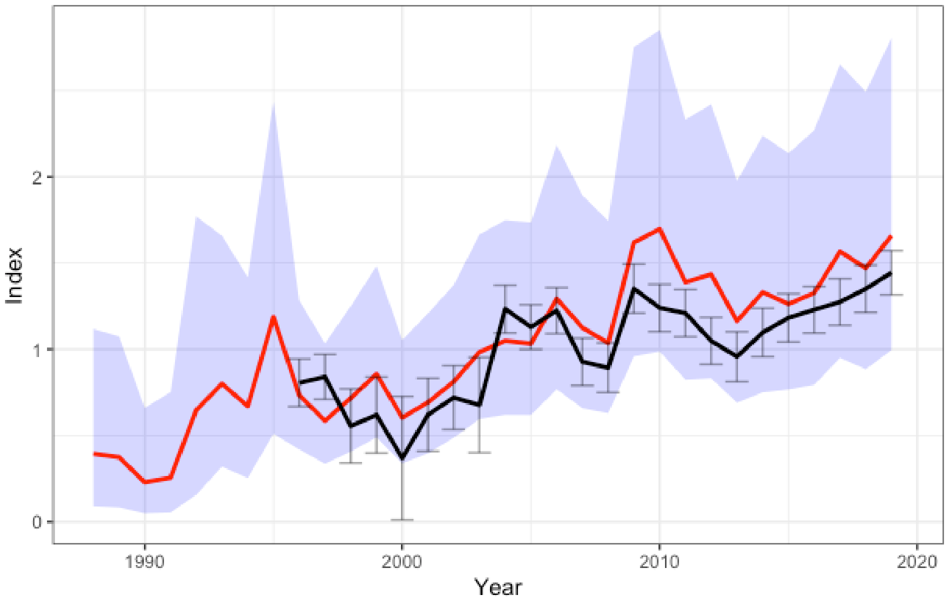

Figure 13. VAST and hierarchical index of abundance for large (> 177 cm) BFT.