Quota allocation for stocks that span multiple management zones: analysis with a vector autoregressive spatiotemporal model

Running title: VAST spatial allocation

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Abstract

Allocating quotas among stakeholders requires an agreed upon formula. If the stock unit spans multiple management jurisdictions, the formula may require updated biomass estimates of the stock's spatial distribution with respect to those jurisdictions. Data for calculating stock biomass often come from fishery-independent surveys. While stratified random sampling is a common design, strata boundaries may not always align with state or national jurisdictions, requiring post hoc stratification and imputation to calculate area-specific biomass. The vector autoregressive spatiotemporal (VAST) model was explored as a tool for calculating fish biomass within subareas of a defined stock unit for three different stocks jointly managed by the United States and Canada on Georges Bank in the Northwest Atlantic Ocean. VAST estimated proportions of stock biomass in each nation's waters were compared with an existing allocation algorithm that utilizes a loess smooth through the average design-based swept area biomass from three fishery-independent surveys. The ability of VAST to impute biomass when no tows occur in a subarea of a survey stratum was demonstrated, as well as the relatively smoother biomass trend compared with design-based estimates, which may be desirable if the intent is to avoid large inter-annual swings in allocated quota.

1. Introduction

Allocating quotas among stakeholders is a management challenge, requiring a transparent management process and buy-in from stakeholders. An agreed-upon formula that considers factors such as total landings, capital investment and years fished for a specified reference period (Anderson and Holliday, 2007) can provide the basis for achieving that transparency. If the managed stock spans multiple management jurisdictions (adjacent states or provinces within a nation, or multiple nations with an international boundary that intersects the stock unit), then recent estimates of spatial distribution of the stock with respect to those jurisdictions could be a component of the allocation formula that is regularly updated.

Globally, it is estimated there are 344 marine fish species whose stock boundaries span the territorial waters of multiple nations and the high seas in between (Teh and Sumaila, 2015). These include transboundary stocks, defined as fish that cross from the boundary of one exclusive economic zone (EEZ) into the EEZs of one or more coastal countries; and highly migratory stocks, such as tunas (Thunnus spp.) and billfish (Istiophoridae, Xiphiidae), that are managed through multinational regional fisheries management organisations, such as the International Commission for the Conservation of Atlantic Tunas (ICCAT). There are also examples of inland multijurisdictional cooperation: The Great Lakes Fishery Commission between the United States of America (USA) and Canada; The Lake Victoria Fisheries Organization, which facilitates between Kenya, Tanzania and Uganda; and the Mekong River Commission, which includes Cambodia, Lao PDR, Thailand and Vietnam as full signatories (Lynch et al., 2016).

In the Northwest Atlantic Ocean, species of groundfish range along the coasts of the USA and Canada, with individual stock boundaries that bridge the jurisdiction of one or more states (coastal waters), federal waters, extending beyond coastal out to the EEZ, and transboundary waters where the EEZ of the USA and Canada meet (the Hague Line), officially delimited by the International Court of Justice in the Hague, The Netherlands (International Court of Justice, 1984).

On Georges Bank (Figure 1), three species are jointly managed by the USA and Canada through a scientific body that performs assessments, the Transboundary Resource Assessment Committee (TRAC). The species are: Atlantic cod (Gadus morhua L.), haddock (Melanogrammus aeglefinus (L.)) and yellowtail flounder (Limanda ferruginea (Storer)). The existing quota allocation formula incorporates historical utilization (1967–1994 total landings by country) and proportion of biomass in each country's waters from a smoothed average of three federal bottom trawl surveys. The latter are updated annually by incorporating data from the latest survey (e.g. 2017) and dropping data from the earliest survey used in the previous year (e.g. 1984) so that a 33-year window is maintained (Barrett & Brooks, 2018). While this allocation formula is simple, transparent and well documented (Murawski & Gavaris, 2004), it requires post-stratification of two of the surveys to accommodate the Hague line and management unit borders for two of the stocks (Figure 2). These management boundaries were established several decades after the USA survey strata were standardised. This post-stratification occurs at a finer spatial scale and occasionally results in low or no sampling occurring in the substrata due to the random allocation of tows at the spatial scale of the original survey strata (although procedures have been put in place since the autumn 2018 survey to ensure sampling in these substrata). Results of the allocation procedure may be sensitive to gaps in survey sampling (substrata where no tows occurred) or very low sampling (substrata with one to two tows), and the terminal year estimate of the loess smoothing algorithm (Cleveland, 1979) applied to the survey average proportion.

Recent development of a vector autoregressive spatiotemporal (VAST) model (Thorson & Barnett, 2017) provides a tool to estimate biomass in defined spatial areas, and could be useful in quota allocation (Thorson, 2019). In the Northwest Atlantic Ocean, VAST has been used to standardise indices for the northern shrimp (Pandalus borealis Krøyer) assessment (Cao et al., 2017); to combine data from multiple fishery-independent surveys to predict density estimates for cusk (Brosme brosme (Ascanius)) for use in habitat suitability indices (Runnebaum et al., 2018), as well as to predict hotspots of cusk bycatch in the American lobster (Homarus americanus Milne-Edwards) fishery (Runnebaum et al., 2020); to test the incorporation of environmental covariates in a length-structured assessment of the American lobster (Hodgdon et al., 2020); and to examine distribution shifts for cod (Guan et al., 2017) and summer flounder (Paralichthys dentatus (L.)) in the region (Perretti & Thorson, 2019).

For this application, the ability of VAST to estimate spatial autocorrelation could improve the estimates of biomass at unsampled locations near stock boundaries or in post hoc substrata, and previous research has noted greater precision of indices compared with design-based estimators (Thorson et al., 2015). Estimates of biomass were derived using VAST, focusing on three stock units that are co-managed by the TRAC (Figure 2): eastern Georges Bank (EGB) Atlantic cod (hereafter referred to as cod) and haddock; and GB yellowtail flounder (hereafter referred to as yellowtail). The primary objective was to demonstrate the use of VAST for estimating area-specific biomass and proportion of resource within each nation's jurisdiction. The ability of VAST to overcome the identified limitations and sensitivities to the current allocation method for these stocks is shown. Resource distribution and biomass results from the current allocation method are compared with the results from VAST applied to the same data.

2. Methods

2.1. Data

Data from two fishery-independent survey programmes that sampled on both sides of the Hague line were used in this analysis. The Northeast Fisheries Science Center (NEFSC) has conducted spring and autumn bottom trawl surveys on the continental shelf of the Northeast United States since 1968 and 1963, respectively. Data from 1985 to 2017 were used in this analysis (to align with the 33-year moving window), with spring and autumn treated as two separate surveys (Barrett & Brooks, 2018). The survey employs a stratified random design. Strata are defined primarily by depth and latitude. Several gear and vessel changes have occurred over the course of the survey (Miller at al., 2010; Johnston & Sosebee, 2014) and conversion factors to account for these changes were applied as necessary.

Fisheries and Oceans Canada has conducted a spring bottom trawl survey on GB since 1986, with full coverage of strata beginning in 1987. Data from 1987 to 2017 were used in this analysis (Barrett & Brooks, 2018). The survey employs a stratified random design. Strata are defined primarily by depth, as well as the location of the international boundary and geographic regions on the bank. Two vessels have been used over the course of the survey, but no conversions are necessary as they are considered identical (Benoît, 2006; Stone & Gross, 2012).

2.2. Background

Details of the current TRAC quota allocation method can be found in Murawski and Gavaris (2004). Briefly, design-based indices of swept area biomass (mt) are calculated for all three surveys, for the country-specific area on each side of the Hague Line. Since the NEFSC survey strata are split by both the Hague Line and the boundary of the EGB region (Figure 2), there are years when no tows occurred within these modified strata due to the random allocation of tows within the original strata. These cases have historically used either undocumented imputation to fill strata with no tows, or they were assumed to be zero. For this application, no imputation was performed, and strata biomass was assumed to be zero if no tows occurred there. The proportion of biomass of each species within each country's waters was calculated from the estimated biomass on each side of the Hague Line. A combined survey proportion for each country is calculated as the simple average of the proportions from the three surveys for haddock and yellowtail, while for cod the Canadian and NEFSC spring proportions were averaged first, and this was averaged with the autumn NEFSC proportions. A loess smooth (span = 0.3) was then applied to the country-specific proportion to remove unpredictable fluctuation and sampling variation from the time series. To determine quota allocation estimates for the current year, the result of the smoother (i.e. the current year estimate of proportion of a given stock in each country's water) was weighted by 90% and the fraction of historic utilisation weighted by 10% to determine the overall fraction of quota that was allocated to each country. This overall fraction was then multiplied by the quota for the whole stock area (based on results from annual stock assessments) to obtain country-specific quota amounts.

VAST is an open source (https://github.com/James-Thorson-NOAA/VAST) package in the R statistical environment (R Core Team, 2019). To facilitate comparisons with the current TRAC approach, all three survey data sets were combined to produce a single index, with an uncertainty estimate, for each stock, with each of the three surveys treated as a vessel effect with overdispersion (Grüss et al., 2017; Thorson, 2019, section 4.1). This differs from a recent VAST study (Thorson et al., 2020) that modelled seasonal variation in spatial distribution of yellowtail. It was noted that, while this previous work combined all three of the same surveys into one model, the final output was separate indices of relative abundance or biomass for each season (or survey), and thus was not suitable for the current objective of a single index, with an uncertainty estimate, for each stock. Given the low number of tows east/west of the Hague Line in some years, and to better inform points near the EGB boundary, species-specific spatial domains were based on the larger stock unit defined by USA management for cod and haddock rather than the smaller management unit agreed to for the TRAC. The USA and TRAC stock definition are identical for yellowtail. From these stock-specific spatial domains, the predicted biomass was estimated, and the proportion of biomass was calculated east/west of the Hague Line for either

EGB (cod, haddock) or GB (yellowtail). As VAST is by definition a smoother, a loess was not applied to the calculated biomass proportion (as is done for the current allocation method).

2.3. VAST model

Details and equations of the VAST model have been published elsewhere (Thorson et al., 2015; Thorson & Barnett, 2017; Thorson, 2019). Briefly, VAST is a spatiotemporal delta generalised linear mixed model. The default delta model includes a logit-linked linear predictor for encounter probability, and a log-linked linear predictor for expected catch rate, given a positive encounter. There is also an option for a Poisson link model, which has a log-link for encounter probability. The default error distribution for positive catch rates is the gamma. There is also an option for a lognormal error distribution. The footnote in Table 1 shows the combinations of encounter probability link functions and observed error distributions examined for each of the three stocks. Altogether, there are 15 major decisions that must be made by users of VAST (Thorson, 2019). The decisions made in the present analysis are summarised in Table 2. Another decision that must be made is the number of prediction locations, i.e. knots. The recommendation of 1000 knots for index standardisation (Thorson, 2019) was used.

Model convergence was checked by ensuring that the Hessian of the likelihood function was positive definite, and that the absolute value of the final gradient of parameters was less than 0.0001. The Akaike Information Criterion, or AIC (Burnham & Anderson, 2002), was used to select the best model run for each stock. Additionally, standard diagnostic outputs from VAST (e.g. Q-Q plot) were examined to ensure that there was no strong evidence of misspecification.

2.4. Comparison with the current TRAC method

The VAST estimates of biomass, with 95% confidence intervals, were compared with the design-based swept area estimates used in the TRAC allocation. Comparisons were plotted for east/west of the Hague Line for EGB cod and haddock, and GB yellowtail. Proportion of total biomass east/west of the Hague Line was also calculated. Qualitative differences in biomass trend and quantitative differences in biomass proportion were summarised; the TRAC allocation is ad hoc and does not produce estimates of uncertainty so precision cannot be compared.

VAST performance was evaluated for cases where the current TRAC allocation method has known limitations and sensitivities. As noted in above, there are a number of years in which there has been zero, or only one to two, tows on either side of the Hague Line in the thin strata along the edge of the bank, i.e. strata 17–18 and 21–22 (Figure 1). For the current TRAC allocation method, biomass in these strata was assumed to be zero if no tows occurred. Thus, it was of interest to compare VAST estimates of biomass for these strata. This was done using the Georges Bank spring haddock data (1968–2015) that come with VAST to facilitate replication by other investigators. Default delta-model settings were used with 1000 knots.

In addition to testing the performance of VAST when no tows occurred in a stratum, VAST was evaluated to determine if estimates of annual biomass are sensitive to new years of data as the 33-year window moves forward, as this is a known sensitivity for the current allocation method. This was done by comparing the estimated biomass trends and proportion of biomass trends east/west of the Hague Line for two consecutive time series: 1985–2017 and 1986–2018. This analysis was limited to one stock (cod). In particular, the behavior of terminal year estimates from VAST were compared to determine if they are less sensitive than those from the loess smoother used in the current approach. A Poisson link model was used with 1000 knots.

2.5. Software

NEFSC strata must be specified as a named list of area codes in VAST. Strata coordinates were contained in the northwest_atlantic_grid that comes with VAST. As it does not contain the split EGB strata (Figure 2), it was recalculated for this study using ArcGIS Desktop 10.7 (ESRI, Inc., Redlands, California, USA). The NEFSC survey strata were projected into a customised North America Albers Equal Area Conic projection to maximise accuracy in later area calculations. Another new feature class was created in the same projection consisting of 3.7 × 3.7 km (2 × 2 nmi) gridded polygons using the fishnet tool. A geometric intersection of these two feature classes produced the final feature class. The centre longitude and latitude (in decimal degrees) as well as the area (in km^2) of each individual polygon were then calculated. The attribute table was outputted as a text file for reading into R.

R version 3.6.0 and VAST version 2.1.0 were used in this analysis. VAST uses Template Model Builder (Kristensen et al., 2016) to estimate fixed effects while integrating through random effects, and the R-INLA package (Illian et al., 2012) to model spatial variation. Versions of these packages used in this analysis were 1.17.15 and 18.07.12, respectively.

3. Results

Diagnostics (Supporting Information) suggested no obvious misspecification for any model run. AIC indicated that a Poisson link for encounter probability was the best for all three stocks (Table 1). In terms of error distribution, gamma was best for cod and haddock, while the lognormal was better for yellowtail. It is also worth noting that for cod, the ΔAIC between run 2 and run 1 was 0.65, indicating essentially no difference in the link function used for encounter probability.

All four runs estimated similar trends for each of the stocks with only minor differences in biomass, although there were slightly higher biomass estimates with the lognormal error distribution (runs 3 and 4) for haddock (Figure 3). The coefficient of variation (CV) suggests reasonably precise biomass estimates (Figure 3): CVs for cod were less than 0.35; while CVs for haddock and yellowtail were, with the exception of 1986, less than 0.3. For cod and haddock, run 1, with a gamma error distribution and logit link had the lowest CV, while Run 4 (lognormal error distribution with Poisson link) almost always had the highest CV.

3.1. Comparison with current TRAC method

VAST estimates of biomass, with 95% confidence intervals, were compared with the TRAC allocation swept area estimates in Figure 4. VAST proportions of biomass in USA waters (i.e., west of the Hague Line) were also compared with TRAC estimates of resource proportion, as well as the loess smooth for the latter. In general, the trend of population biomass on each side of the Hague Line was similar for the two methods, but the estimates following the current TRAC allocation method showed strong annual variability (Figure 4, top and middle rows). The annual variability was similarly present in the TRAC estimates of average proportion of biomass per country (Figure 4, bottom row). These large annual swings in proportion would translate to large annual swings in quota allocation, if taken at face value. The loess smoothed proportion of biomass, which is the final step currently used for allocation, showed a more stable trend through time. Comparing the loess smoothed annual proportions with the VAST estimated proportions, there were differences in the direction of the trend for the first points in the time series (1985) for all three stocks, and for the last point in the time series (2017) for yellowtail. In any given year, the VAST estimated proportion in USA waters differed from the loess smoothed proportion between ± 0.0005 and ± 0.32, depending on the stock.

In each stratum area where no tows occurred, VAST predicted non-zero biomass. As these were narrow strata with very little fraction of the total stock area, the predicted biomasses were not very large, and ranged from 0.2 t to 2195 t (Table 3), with a trend towards higher biomass estimates in recent years due to the historic high biomass for haddock (Figure 4). VAST estimates for strata with no tows ranged from 0 to 72% of the total biomass estimated in those years. Similarly, in each stratum where only one to two tows occurred, VAST predicted biomass ranging from 0.3 t to 7935 t, as compared with 0 t to 20,964 t from the TRAC estimates, with the largest differences occurring in stratum 21 and 22 east of the Hague Line (Table 3).

The consecutive fits of VAST to 1985–2017 and 1986–2018 EGB cod data showed no sensitivity to the biomass estimate in 2017, as opposed to the consecutive fits with the TRAC method (Figure 5): in the loess for 1985–2017 the estimated trend “chases” the high biomass estimate in 2017; but when the loess is applied for 1986–2018, the smoothed estimate for 2017 is much lower. The VAST estimate of biomass in 2017 in both fits was stable because VAST uses spatial correlation across the spatial domain to inform estimates, whereas the TRAC method relies on stratum means with occasionally few or no tows in a given stratum. In addition, the loess smoother predicted values at the terminal year were unstable because that point was only informed by data from earlier years, and when additional data were added for later years these can influence estimates that had previously been endpoints.

4. Discussion

The primary objective of this study was to demonstrate the use of VAST to estimate the proportion of stock biomass in country-specific waters for multijurisdictional allocation of quotas. This was contrasted with the current approach that uses the stratified random sampling design to estimate average proportion of biomass in each management zone, to which a loess curve is then fit. An advantage of the VAST approach is that it provides an objective way to fill strata with no tows and inform strata with few tows based on tows in neighboring strata, which is important when strata are post-stratified to deal with allocation issues. Another advantage of VAST is that it smooths large inter-annual fluctuations that are potentially due to outlier tows or low sample size rather than real trends in the population. This was observed for USA cod biomass in 2005 and 2010, and Canadian yellowtail biomass in 2008 and 2009, and led to estimated biomass spikes in those years in the design-based method. Previous comparisons of

VAST versus design-based indices have also found that the latter exaggerated temporal variability (Cao et al., 2017). However, Hodgdon et al. (2020) found that model-based abundance indices were not intrinsically better than design-based indices and should be tested for each species individually, as has been done in this study.

Across the four model configurations defined by the link function (logit or Poisson) and assumed error distribution (gamma or lognormal), no observed error distribution was consistently best. The gamma was better for cod and haddock; while the lognormal was better for yellowtail. There were two extreme outlier tows for yellowtail, one in both 2008 and 2009 (Figure 4), and it was hypothesised that the lognormal error distribution provided a better fit due to its heavier tail compared to the gamma. Regarding the link function, AIC indicated that the Poisson link models were generally best, but in one case (cod) there was essentially no difference from the conventional delta-model. These findings support the recommendation of Thorson (2019) to compare the performance of conventional delta-models versus Poisson link models, and to explore multiple distributions.

The general trend in proportion of biomass was similar for the VAST estimate and the loess smoothed estimate. Although absolute differences of 0.0005–0.32 existed, there was no consistent trend in the direction of which country had more or less proportion estimated in a given year. The current TRAC method allocates quotas for the upcoming year based on the current year's estimate of resource distribution, implicitly assuming it will be similar. The application of a loess with a span of 0.3 provides some responsiveness, while removing fluctuations that may be due to sampling variation (Murawski & Gavaris, 2004). Given the relative similarity of trend between VAST and TRAC estimates of biomass proportion, the question is whether one method is more appropriate than the other. One advantage of the VAST approach was highlighted in model performance explorations, focusing on strata areas where no tows, or only one to two tows occurred. In all instances where no tows occurred, VAST estimated non-zero biomass; with the current TRAC approach, ad hoc imputation would be necessary to infer biomass. Thus, VAST provides a better way to fill a missing stratum than assuming it has zero biomass, and it is preferable to ad hoc imputation for transparency and reproducibility considerations. The performance of VAST for models such as this has been tested previously through simulation (Thorson et al., 2015; Grüss & Thorson, 2019; Grüss et al., 2019; Johnson et al., 2019; Brodie et al., 2020), and future simulation experiments exploring performance for the combined surveys method proposed here are recommended. Specifically, future work could explore the accuracy of VAST imputed biomass in these cases.

The USA proportion (Figure 4) suggests potentially significant differences in annual allocations between those from the current TRAC method and the VAST estimates. Confidence intervals are not available for the TRAC allocation method, so it is not possible to tell whether intervals for the two methods overlap, but there are several instances for each stock where the TRAC loess estimates are outside the 95% confidence interval for the VAST estimates: 1994 and 2015 for EGB cod; 1994, 1998, 2001, 2003, 2008, 2012 and 2014–2016 for EGB haddock; and 2003, 2006 and 2011 for GB yellowtail. Although these differences did not consistently favour one country, the country-specific quotas are obtained by multiplying proportion of country-specific biomasses by a total allowable quotas (based on results from a stock assessment of the total stock area); thus, in a given year the scale of total allowable quota could make the magnitudes of those differences in proportion financially significant. Moreover, it is not uncommon that available quota for one species can impact fishers' decisions about targeting and effort for other species, ultimately affecting individual vessel income. Thus, even seemingly minor differences can be important.

In the present study, the ability of VAST to calculate biomass within subareas of a defined stock unit for three stocks jointly managed by the USA and Canada on the Georges Bank was explored. A similar approach could be taken for other transboundary species. For example, quota for Pacific halibut (Hippoglossus stenolepis Schmidt) is shared between the USA and Canada based on regional biomass estimates (Cox et al., 2013). A review of the allocation suggested that a combined spatio-temporal smoothing applied to each year could help to retain spatial consistency in biomass across regulatory areas. Other examples include stocks in the Northeast Atlantic, such as Barents Sea cod, which has experienced a poleward displacement since the late 1980s (Gullestad et al., 2020).

VAST offers some advantages over currently applied methods to allocate quota in situations where there are multijurisdictional considerations. It overcomes sampling gaps, provides estimates of biomass with uncertainty bounds, and is less sensitive to outlier tows and sharp trend changes at the end of the time series. The cost of this more sophisticated method is potentially revisiting model selection as data are updated. Formal restratification, to address management boundaries that are defined after survey strata definitions and ensure proper tow allocation, would be another way to avoid sampling gaps. However, inevitable challenges such as weather delays and mechanical problems may be insurmountable in some years, leaving gaps in sampling despite best intentions to avoid such occurrences. Thus, a method such as VAST provides reliability against the unforeseen and unavoidable realities of field sampling.

Spatial boundaries help make making environmental issues more manageable (Lidskog et al., 2011). On the other hand, it is known that such boundaries are a political and management construct, which may not be aligned with, nor respected by, ecological and human components essential to commercial fishing (Song et al., 2017). Ecologically, boundary mismatches can create added pressure on fish stocks, resulting in overfishing (Song et al., 2017). Given changes in fish distribution worldwide, whether due to climate change or stock expansion, survey data should be used not only to set catch limits, but to re-examine catch shares (Fernandes and Fallon, 2020). This VAST analysis illustrates how temporal changes in spatial distributions can be modeled and incorporated into the allocation of stocks that span multiple management jurisdictions, thereby aiding in the conservation of fishery resources.

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Tables

Table 1. Akaike information criterion (AIC) for VAST model runs for each of the three stocks, with all models based on 77 parameters. Runs are sorted by AIC, and ΔAIC relative to the model with the lowest AIC is also shown.

Cod			Haddock			Yellowtail		
Run	AIC	ΔAIC	Run	AIC	ΔAIC	Run	AIC	ΔAIC
2	32062.13	0	2	46100.37	0	4	18159.15	0
1	32062.78	0.64	4	46151.88	51.50	2	18216.15	56.99
3	32132.00	69.87	1	46195.46	95.09	3	18250.13	90.97
4	32163.11	100.98	3	46275.89	175.52	1	18306.41	147.26

Note:

Run 1: gamma error distribution; logit link for encounter probability

Run 2: gamma error distribution; Poisson link for encounter probability

Run 3: lognormal error distribution; logit link for encounter probability

Run 4: lognormal error distribution; Poisson link for encounter probability

Table 2. Summary of 15 major decisions for VAST used in this analysis

#	Description	Decision
1	Spatial domain used when calculating derived quantities	Eastern Georges Bank[†] for cod[‡] and haddock[§] Georges Bank[†] for yellowtail flounder[¶]
2	Which categories (species/sizes) to include	Cod[‡], haddock‡ and yellowtail flounder[§]; each analyzed separately
3	Identify whether to analyze encounter, abundance, and/or biomass sampling data	Biomass
4	Including spatial and/or spatiotemporal variation	Both
5	Choosing the spatial smoother and resolution	Anisotropic Matérn correlation function
6	Choosing the number of spatial and spatiotemporal factors	On
7	Specifying temporal correlation on model components	Fixed effects
8	Including density covariates as a semi-parametric model	NA
9	Accounting for catchability covariates and confounding variables	NA
10	Treating area swept as a catchability covariate or offset	On
11	Including vessel effects as overdispersion	On
12	Choosing among distributions and link functions	Logit & Poisson for encounter probability link function Gamma & lognormal for observed error distribution
13	Derived quantities	Biomass index
14	Bias correction for derived quantities	On
15	Model selection	AIC

[†] See Figure2 for geographic boundaries

[‡] Gadus morhua

[§] Melanogrammus aeglefinus

[¶] Limanda ferruginea

Table 3. Haddock spring biomass (mt) in Northeast Fisheries Science Center strata 17–18 and 21–22, west (USA) and east (Canada = CAN) of the Hague Line, on eastern Georges Bank (Figure 2) using the Transboundary Resource Assessment Committee (TRAC) allocation method (left) and VAST (right). For the TRAC allocation method, "0" represents observed zeros, italics denotes one to two tows, and NA indicates that no tows occurred. One significant digit is shown for VAST to emphasize that the model did not estimate zero biomass in any substratum in any year. Only years that overlap for the Georges Bank spring haddock data that comes with VAST (1968–2015) and the data used in the analysis in the main body of the text (1985–2017) are shown

Table is shown on next page

	TRAC								VAST							
Year	USA 17	CAN 17	USA 18	CAN 18	USA 21	CAN 21	USA 22	CAN 22	USA 17	CAN 17	USA 18	CAN 18	USA 21	CAN 21	USA 22	CAN 22
1985	14	99	0	18	NA	3696	NA	54	8.1	124.3	3.3	46.0	121.4	1046.8	55.4	165.9
1986	0	21	0	0	0	1297	NA	0	4.8	119.3	1.5	32.1	35.6	947.8	10.4	165.7
1987	0	101	0	17	NA	63	NA	69	1.7	88.2	0.5	23.7	86.6	861.9	26.5	120.6
1988	0	13	NA	0	0	310	0	0	2.1	78.9	0.6	20.2	28.0	440.2	9.4	74.0
1989	28	146	NA	79	0	751	NA	256	10.9	236.0	4.0	79.5	70.2	616.5	25.2	161.1
1990	0	64	NA	NA	33	1305	NA	21	4.2	210.6	1.3	57.7	52.2	856.4	19.4	156.0
1991	NA	37	NA	0	0	28	NA	0	2.3	140.1	0.7	29.5	15.3	230.0	5.5	33.2
1992	NA	80	NA	0	NA	376	NA	0	0.7	74.5	0.2	17.3	10.5	242.2	4.1	45.1
1993	NA	439	NA	0	NA	387	NA	154	1.5	128.9	0.5	38.8	39.6	557.7	14.9	102.4
1994	11	1	0	NA	6	5644	NA	0	1.1	43.7	0.4	14.5	22.8	1739.5	7.3	277.6
1995	NA	60	0	NA	NA	3356	NA	888	1.1	56.2	0.3	14.1	82.2	2180.1	29.5	404.4
1996	NA	32	NA	0	NA	972	31	0	1.3	46.8	0.4	13.5	98.3	914.9	36.4	161.7
1997	10	28	0	11	45	1239	NA	74	3.2	100.6	1.3	32.4	82.3	995.4	28.1	185.7
1998	3	84	NA	5	282	227	0	108	1.9	125.3	0.8	38.9	96.3	797.2	38.1	154.2
1999	0	1598	NA	0	42	366	37	38	4.8	319.4	1.7	83.5	65.7	637.3	34.0	117.6
2000	0	220	0	NA	522	151	NA	55	1.8	153.5	0.6	41.2	185.0	1409.9	64.2	258.1
2001	NA	446	NA	0	1214	4339	NA	15	10.7	266.5	4.4	92.8	267.8	1400.4	94.3	313.5
2002	0	332	NA	16	0	896	93	77	11.5	281.5	4.4	93.6	171.1	1318.3	70.2	242.3
2003	2	77	NA	0	1123	NA	19	NA	4.7	454.5	1.8	116.2	161.8	1648.1	40.6	312.6
2004	NA	977	NA	75	NA	669	NA	2	116.4	811.6	44.3	261.2	518.8	1402.6	145.9	232.3
2005	680	948	0	NA	NA	3945	132	484	90.2	557.8	40.7	208.0	386.6	2641.1	155.9	613.1
2006	5	323	0	97	143	4140	NA	40	21.2	290.8	8.6	112.8	221.2	2006.8	89.3	444.9
2007	7	64	0	90	295	795	NA	123	7.0	515.8	3.0	148.1	294.7	2223.2	91.9	297.4

2008	2	135	NA	164	484	151	NA	204	5.0	185.1	1.8	62.3	230.2	784.7	113.6	140.1
2009	100	279	0	42	7452	7085	0	22	82.1	411.6	30.4	156.3	1186.6	3599.1	400.7	699.4
2010	105	96	0	168	1553	3379	41	125	47.9	382.1	19.5	147.1	616.6	2464.1	294.2	436.9
2011	19	978	0	179	415	3008	NA	843	36.9	711.4	13.9	248.8	405.0	3105.1	198.5	701.4
2012	17	2321	1	358	NA	4138	NA	115	31.0	1166.8	13.1	429.4	514.4	2352.5	226.2	414.3
2013	0	634	0	335	NA	20964	140	371	15.4	526.9	6.3	230.8	584.5	6623.6	221.2	1031.0
2014	151	2872	0	565	798	2737	NA	1401	113.6	1572.1	61.9	641.2	1308.3	6758.4	485.5	1454.5
2015	417	1071	67	858	NA	6472	NA	796	285.9	1988.0	150.4	914.2	2195.4	7934.6	903.0	1834.8

Figure captions

Figure 1. Northeast Fisheries Science Center (NEFSC) bottom trawl survey offshore strata, with Georges Bank (GB) strata 13–22 in black.

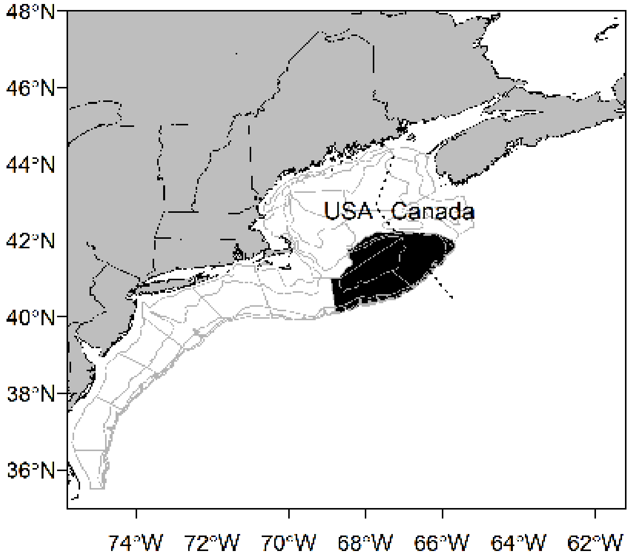
Figure 2. Detail of Northeast Fisheries Science Center (NEFSC) strata 13–21 used by the Transboundary Resource Assessment Committee (TRAC) for the assessment of Georges Bank (GB) yellowtail flounder (upper); detail of NEFSC strata 16–22 used by the TRAC for the assessment of eastern Georges Bank (EGB) Atlantic cod and haddock (middle). Fisheries and Oceans Canada bottom trawl survey strata 5Z1–5Z4 overlaid on the NEFSC strata for comparison (lower). The Hague Line separating USA and Canada jurisdictions is shown as a dotted line in all plots.

Figure 3. Biomass (mt) and coefficient of variation (CV) for the four VAST model runs for each stock. Run 1: gamma error distribution; logit link for encounter probability. Run 2: gamma error distribution; Poisson link for encounter probability. Run 3: lognormal error distribution; logit link for encounter probability. Run 4: lognormal error distribution; Poisson link for encounter probability

Figure 4. Comparison of Transboundary Resource Assessment Committee (TRAC) allocation method swept area biomass (solid line) and VAST estimates of biomass (dashed line) for USA (upper) and Canada (middle). Shaded region is the 95% confidence interval for the VAST index. Lower panel shows the proportion USA for TRAC (solid line) and VAST estimates (dashed). Blue line is the loess smooth for the TRAC proportion USA. Shaded region is the 95% confidence interval for the proportion USA computed from the VAST index.

Figure 5. Comparison of the proportion USA for Transboundary Resource Assessment Committee (TRAC) and VAST estimates of eastern Georges Bank (EGB) cod biomass. TRAC proportion USA is shown for 1985–2018, with loess fits for 1985–2017 and 1986–2018. VAST estimates of proportion USA are shown for 1985–2017 and 1986–2018. A Poisson link model

was used for both VAST runs. Proportion USA for VAST 1985–2017 is the same as that shown in Figure 3.



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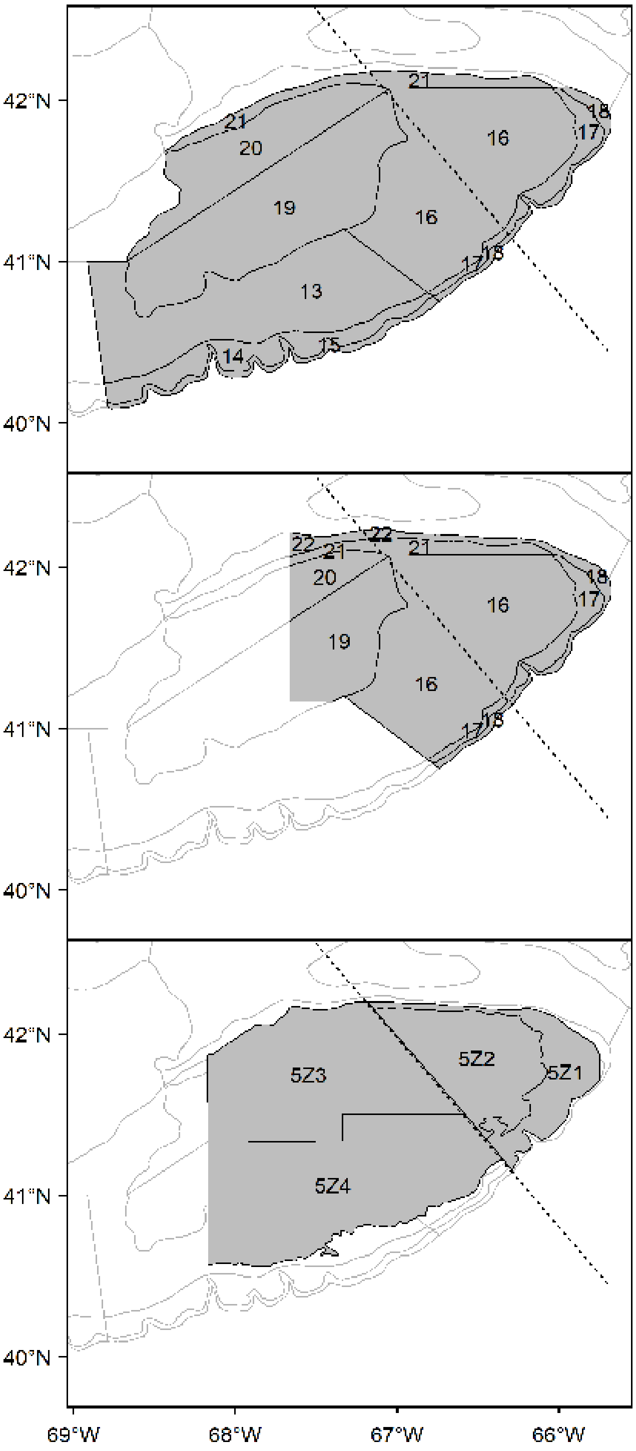

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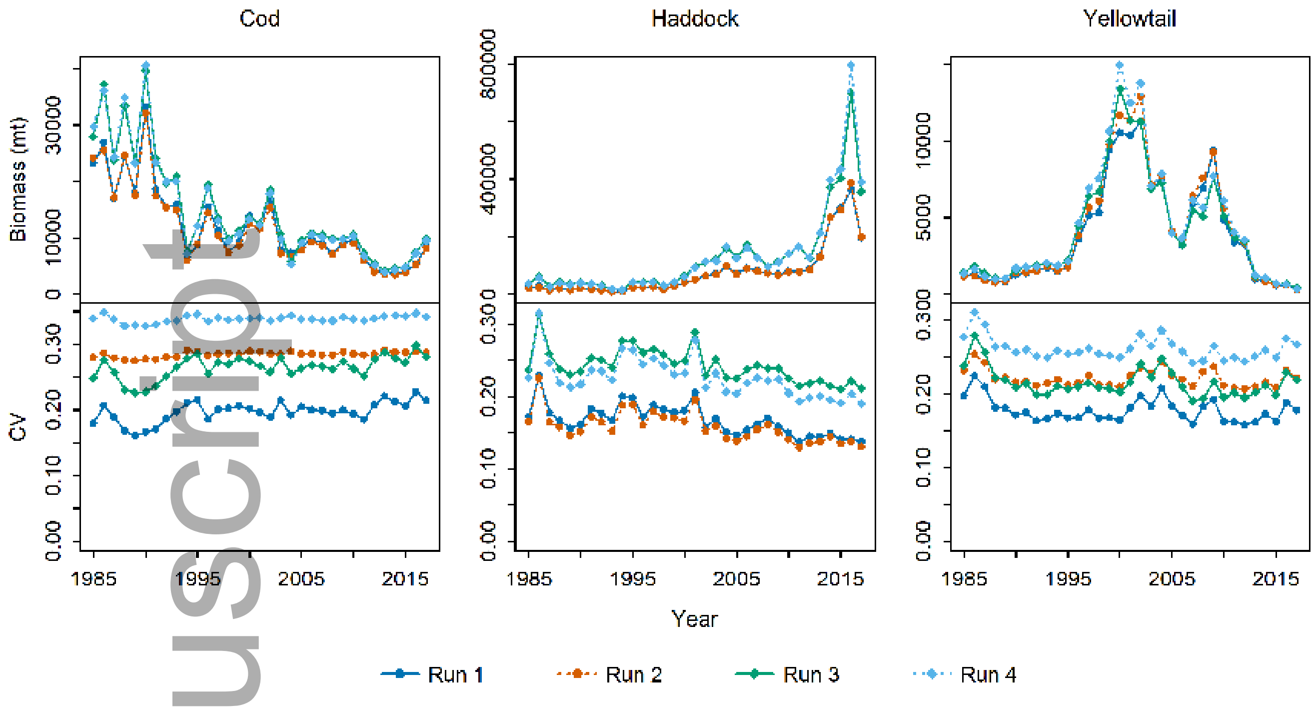

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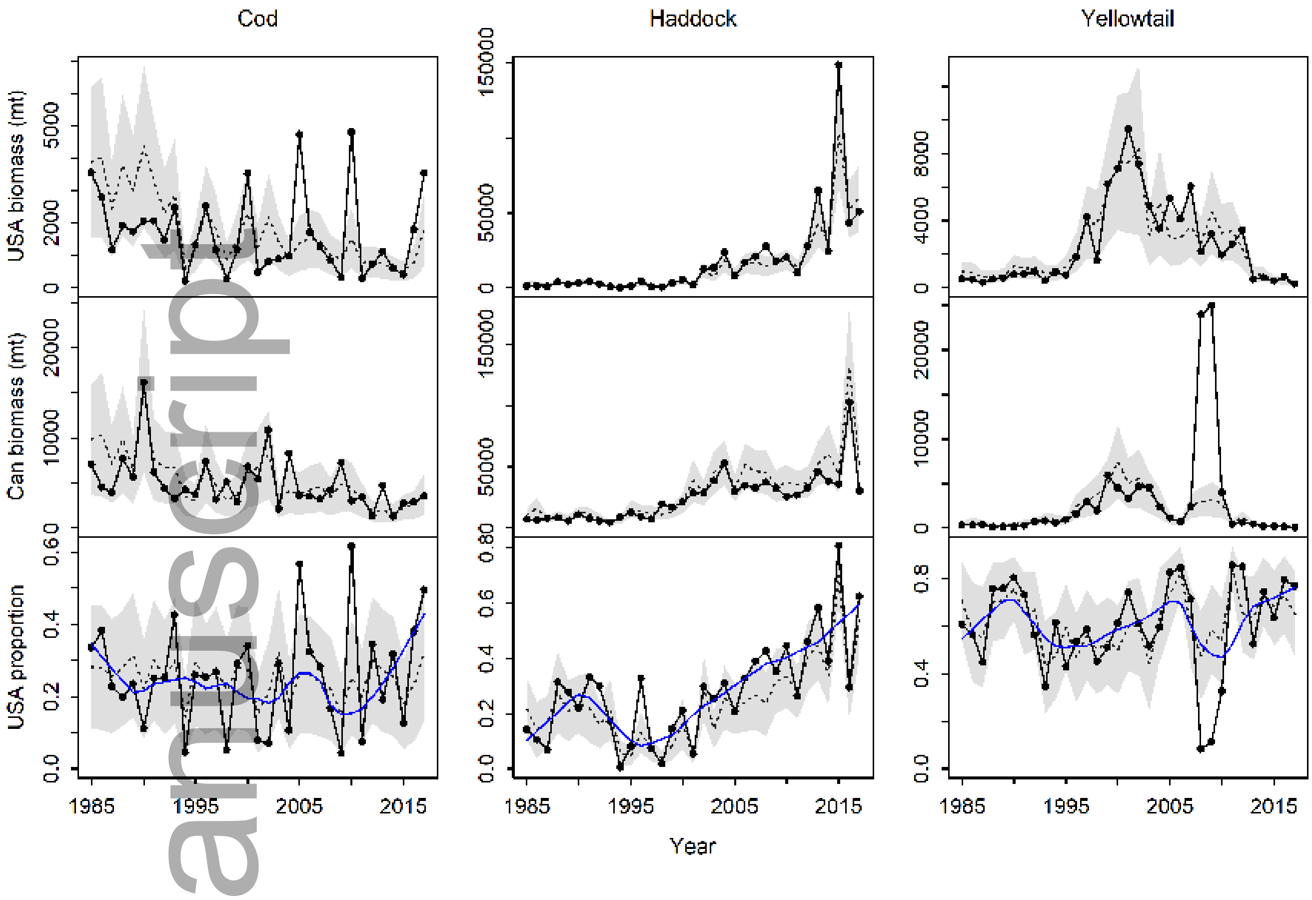

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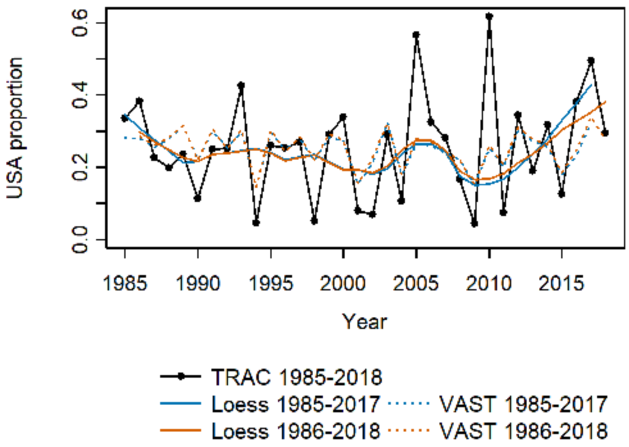

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