Analysis of trends in alewife and blueback herring relative abundance: Report to the NMFS River Herring Status Review Team

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May 2013

Methods

Trends in the relative abundance of alewife and blueback herring were assessed for each species range-wide, as well as for each proposed species-specific stock complex (stock structure section of listing determination). For alewife, proposed stock complexes included Canada, Northern New England, Southern New England and the Mid-Atlantic. For blueback herring, proposed stock complexes included Canada, Northern New England, Southern New England, Mid-Atlantic and Southern. The boundaries for Southern New England and Mid-Atlantic stocks differed for each species.

Range-wide data

Relative abundance indices from multiple fishery-independent survey time series were considered as possible data inputs for the range-wide analysis. These time series included the NOAA Northeast Fisheries Science Center (NEFSC) spring, fall, and winter bottom trawl surveys as well as the NEFSC shrimp survey. For alewife, two additional time series were available: Canada's Department of Fish and Oceans (DFO) summer research vessel (RV) survey of the Scotian Shelf and Bay of Fundy (1970-present), and DFO's Georges Bank RV survey (1987-present, conducted during February and March).

For the NEFSC spring and fall bottom trawl surveys, inshore (8-27 m) and offshore (27-366 m) strata have been most consistently sampled by the RVs *Albatross IV* and *Delaware II* since the fall of 1975 and spring of 1976. Prior to these time periods, either only a portion of the survey area was sampled or a different vessel and gear were used to sample the inshore strata (Azarovitz 1981). Accordingly, seasonal alewife and blueback herring relative abundance indices were derived from these trawl surveys using both inshore and offshore strata for 1976-2012 in the spring (Figure 1) and 1975-2011 in the fall (Figure 2). Additional relative abundance indices were derived using only offshore strata for 1968-2012 in the spring (Figure 3) and 1967-2011 in the fall (Figure 4, from 1963-1967 the fall survey did not extend south of Hudson Canyon). These time series were developed following the same methodology used in the 2012 Atlantic States Marine Fisheries Commission (ASMFC) river herring stock assessment (ASMFC 2012).

Through 2008, standard bottom trawl tows were conducted for 30 minutes at 6.5 km/hour (3.5 knots) with the *Albatross IV* as the primary survey research vessel (Despres-Patanjo et al. 1988). However, vessel, door and net changes did occur during this time, resulting in the need for conversion factors to adjust survey catches for some species. Conversion factors were not available for net and door changes, but a vessel conversion factor for alewife was available to account for years where the RV *Delaware II* was used. A vessel conversion factor of 0.58 was applied to alewife weight-per-tow indices. Alewife number-per-tow indices did not require a conversion factor (Byrne and Forrester 1991).

In 2009, the survey changed primary research vessels from the *Albatross IV* to the *Henry B. Bigelow*. Due to the deeper draft of the *Bigelow*, the two shallowest series of inshore strata (8-18m depths) are no longer sampled. Concurrent with the change in fishing vessel, substantial changes to the characteristics of the sampling protocol and trawl gear were made, including tow speed, net type and tow duration (NEFSC 2007). Calibration experiments, comprising paired standardized tows of the two fishing vessels, were conducted to measure the relative catchability between the two vessel-gear combinations and develop calibration factors to convert *Bigelow* survey catches to *Albatross* equivalents (Miller et al. 2010). Species-specific calibration coefficients were estimated for both catch numbers and weights using the method of Miller et al. (2010) (Table 1). The calibration factors were combined across seasons due to low within-season sample sizes from the 2008 calibration studies (less than 30 tows with positive catches by one or both vessels).

Bottom trawl catches of river herring tend to be higher during the daytime due to diel migration patterns (Loesch et al. 1982; Stone and Jessop 1992). Accordingly, only daytime tows were used to compute relative abundance and biomass indices. In addition, the calibration factors used to convert *Bigelow* catches to *Albatross* equivalents were estimated using only catches from daytime tows. Daytime tows, defined as those tows between sunrise and sunset, were determined for each survey station based on sampling date, location, and solar zenith angle using the method of Jacobson et al. (2011). Although there is a clear general relationship between solar zenith and time of day, tows carried out at the same time but at different geographic locations may have substantially different irradiance levels that could influence survey catchability (NEFSC 2011). Preliminary analyses (Lisa Hendrickson, NMFS – *unpublished data*) confirmed that river herring catches were generally greater during daylight hours compared to nighttime hours.

In addition to the NEFSC spring and fall trawl surveys, the NEFSC winter and shrimp surveys were considered for inclusion in the analysis. For the winter survey (February), the sampling area extended from Cape Hatteras NC through the southern flank of Georges Bank, but did not include the remaining portion of Georges Bank or the Gulf of Maine. With the arrival of the RV *Bigelow* in late 2007, the NEFSC winter survey was merged with the NEFSC spring survey and discontinued. Alewife and blueback herring indices of relative abundance were developed for the winter survey from 1992-2007 using daytime tows from all sampled inshore and offshore strata (Figure 5). The shrimp survey is conducted during the summer (July / August) in the western Gulf of Maine during daylight hours. Relative abundance indices were derived for alewife and blueback herring from 1983-2011 using all strata that were consistently sampled across the survey time series (Figure 6).

Stratified mean indices of relative abundance of alewife from Canada's summer RV survey and the Georges Bank RV survey were provided by Heath Stone of Canada's DFO (Figure 7). In these surveys, alewife is the predominant species captured; however, there are likely some blueback herring included in the alewife indices because catches are not always separated by river herring species (Heath Stone, pers. comm.). Furthermore, some Georges Bank strata were not sampled in all years of the survey due to inclement weather and vessel mechanical problems (Stone and Gross 2012).

Due to the restricted spatial coverage of the winter, shrimp and Canadian Georges Bank surveys, these surveys were not used in the final range-wide analyses. Accordingly, relative abundance (number-per-tow) from the NEFSC spring and fall surveys were used in the range-wide models for blueback herring, and number-per-tow from the NEFSC spring survey, NEFSC fall survey, and the Canadian summer survey were used in the range-wide models for alewife.

Data from 1976 through the present were incorporated into the trend analysis. This time series permitted the inclusion of the spring and fall surveys' inshore strata. In addition, with this time series, the required assumption of stationarity in the population growth rate was reasonable. Prior to 1976, fishing intensity was much greater due to the presence of distant water fleets on the U.S. east coast.

Years with zero catches were treated as missing data. For alewife, there were not any years with zero catches in the spring, fall and Scotian shelf surveys. Zero catches of blueback herring occurred in the fall survey in 1988, 1990, 1992 and 1998.

Stock-specific data

Stock-specific time series of alewife and blueback herring relative abundance were obtained from the ASMFC and Canada's DFO. Available time series varied among stocks and included run counts, as well as young-of-year (YOY), juvenile and adult surveys that occurred solely within the bays or sounds of the stock of interest (alewife: Table 2, blueback herring: Table 3). All available datasets were included in the stock-specific analyses, with the exception of run counts from the St. Croix and Union Rivers. These datasets were excluded due to the artificial impacts of management activities on run sizes. The closure of the Woodland Dam and Great Falls fishways in the St. Croix River prevented the upstream passage of alewives to spawning habitat. In contrast, fluctuations in Union River run counts were likely impacted by lifting and stocking activities used to maintain a fishery above the Ellsworth Dam. In the southern Gulf of St. Lawrence trawl survey, all river herring were considered to be alewife because survey catches were not separated by river herring species (Luc Savoie (DFO), pers. comm.). No blueback herring abundance indices were available for the Canadian stock. Select strata were not used to estimate stock-specific indices from the NEFSC trawl surveys because mixing occurs on the continental shelf. Accordingly, any NEFSC trawl survey indices, even estimated using only particular strata, would likely include individuals from more than one stock.

Each available dataset in the stock-specific analyses represented a particular age or stage (spawners, YOY, etc) of fish. Consequently, each time series was transformed using a running sum over four years. The selection of four years for the running sum was based on the generation time of river herring. For age- and stage-specific data, a running sum transformation is recommended to obtain a time series that more closely approximates the total population (Holmes 2001). In order to compute the running sums for each dataset, missing data were imputed by computing the means of immediately adjacent years. For both species four years were imputed for the Monument river, and one year was imputed for the DC seine survey. For alewife, one year was also imputed for the Mattapoisett river, Nemasket river, and the southern Gulf of St. Lawrence trawl survey. For blueback herring, one year was also imputed for the Long Island Sound (LIS) trawl survey and Santee-Cooper catch-per-unit-effort (CPUE).

If possible data from 1976 through the present were incorporated into each stock-specific model, with the first running sum incorporating data from 1976 through 1979. However, for some stocks, observation time series began after 1976. In these cases, the first modeled year coincided with the first running sum of the earliest survey.

Model description

Multivariate Autoregressive State-Space models (MARSS) were developed using the MARSS package in R (Holmes et al. 2012a). This package fits linear MARSS models to time series data using a maximum likelihood framework based on the Kalman smoother and an Expectation Maximization algorithm (Holmes et al 2012b).

Each MARSS model is comprised of a process model and an observation model (Holmes and Ward 2010, Holmes et al. 2012b). The process model is represented as:

$$\boldsymbol{x}_t = \boldsymbol{B}\boldsymbol{x}_{t-1} + \boldsymbol{u} + \boldsymbol{w}_t; \quad \boldsymbol{w}_t \sim \text{MVN}(0, \boldsymbol{Q})$$

where x_t represents the unobserved state in log space in time t, B reflects the interactions between the state processes, u represents the mean population growth rate, w_t represents the process error in time t, and Q represents the process variance-covariance matrix. In both the range-wide and stock-specific analyses, we assumed that each species was represented by one unobserved state (one time series of x_t in the process model). The observation model is then represented as:

$$\boldsymbol{y}_t = \boldsymbol{Z}\boldsymbol{x}_t + \boldsymbol{a} + \boldsymbol{v}_t; \quad \boldsymbol{v}_t \sim \text{MVN}(0, \boldsymbol{R})$$

where y_t represents the observations in log space at time t, Z indicates which observation time series is observing which unobserved state, a is a scalar for each observation time series, v_t represents the observation error in time t, and R represents the observation variance-covariance matrix (Holmes and Ward 2010, Holmes et al. 2012b). If an unobserved state is represented by more than one observation time series, the parameter a scales each additional time series to the scale of the first observation time series. Furthermore, estimates of the unobserved state are also scaled to the first observation time series. Consequently, the MARSS model is used to quantify trends in the unobserved state, but cannot be used to quantify absolute abundance (Holmes and Ward 2010).

Estimated parameters include the mean population growth rate, process and observation error variance and covariance terms, the unobserved state in the first model year, and the scalars for all but one observation time series. For each model run, a Monte Carlo search was conducted for the optimal model parameter initial estimates in order to minimize the chance that the Expectation Maximization algorithm would terminate at a local maximum and not reach the true maximum likelihood estimates (Holmes and Ward 2010).

For each stock definition (range-wide or stock-specific), a sequence of runs were conducted that varied in the assumptions regarding the observation error correlation structure. Observation errors for each time series were initially assumed to be independent with equal variances (run a). This model run was the most parsimonious parameterization of observation error, adding only one estimated parameter to the model. In the second iteration, observation errors were assumed to be independent with unique variances (run b). A priori, it may be expected that observation errors from different fishery-independent surveys should be independent with unique variances; however, the run with independent and equal variances was included because data available for each stock may not contain sufficient information to permit estimation of a variance parameter for each observation time series. Observation errors were then assumed to be unconstrained with both unequal variances and unique correlation parameters for each observation time series (run c). While it may not be expected that indices from different surveys strongly covary, indices may be correlated due to temporal proximity in sampling times or spatial proximity of sampling locations. As a result of these proximities, surveys may be similarly impacted by river herring movement patterns or particular environmental signals. For analyses that were comprised of more than two time series, an additional run was conducted that allowed the covariance between the two observation time series with the greatest estimated covariance in the unconstrained iteration to be estimated; otherwise, the errors were assumed to be independent with unique variances (run d). A final run was conducted that assumed equal variance and covariance terms for each time series (run e). The final two runs were included because they permitted observation time series to covary, but were more parsimonious than the unconstrained model run (run c).

For each model set, the final model was selected using a variant of Akaike's Information Criteria specific for state-space models. This variant of AIC, AICbp, uses parametric bootstrapping to compute the small sample AIC corrector (Holmes and Ward 2010, Ward et al. 2010). Unlike the small sample size corrector in AICc, AICbp does not under-penalize complex MARSS models (Holmes et al. 2012a). At small numbers of bootstraps (1000 – 2000), the preferred model in some analyses varied with the number of bootstraps. As a consequence, the number of bootstraps was increased in 1000 increments until the same model was preferred in four consecutive iterations. Confidence intervals (95%) were constructed for each estimated parameter using parametric bootstrapping with 2000 bootstraps.

In some stock-specific model sets (ex: Southern New England alewife), some model runs did not converge. For each model that did not converge, the first modeled year was increased in order to minimize the extent of missing data and potentially achieve model convergence. However, in all instances, modifying the range of modeled years did not achieve convergence. For stocks where at least one model run did not converge, the run with the lowest AICbp from those that successfully converged was chosen as the preferred run.

Population projections and model analysis

For each stock definition, the estimated population growth rate and associated 95% confidence intervals were used to classify whether the stock's relative abundance was stable, increasing or decreasing. Relative abundance of a stock was considered to be significantly increasing or decreasing if the 95% confidence intervals of the population growth rate did not include zero. In contrast, if the 95% confidence intervals included zero, the population was considered to be stable because the increasing or decreasing trend in abundance was not significant.

Results

Range-wide Analyses

MARSS models for the range-wide analysis were fit to data from 1976 through 2012.

For the range-wide analyses, the model runs with the lowest AICbp values assumed independent observation errors with unequal variances (run b) for alewife, and independent observation errors with equal variances (run a) for blueback herring (Table 4). For both species, the preferred model run was robust to the number of bootstraps used to calculate AICbp. However, even with 5000 bootstraps, the AICbp values for three of the five models examined for alewife were within two units of the minimum AICbp value, indicating only a minimal increase in support for the preferred model. For blueback herring, approximately four units separated the two runs with the lowest AICbp values and 41 units separated the three runs with the lowest AICbp values, indicating greater differences in support for the models.

The estimated population growth rate and associated standard error was 0.032 ± 0.006 for alewife and 0.039 ± 0.040 for blueback herring (Table 5), with predicted abundance over the time series significantly increasing for alewife but not for blueback herring (alewife: Figure 8, blueback herring: Figure 9). For both species, substantial patterns in the residuals of the best model fit were not apparent (alewife: Figure 10, blueback herring: Figure 11). For alewife, the maximum likelihood estimate for process error equaled zero in all model runs, indicating that the data were not sufficient to estimate both process and observation error variances (Holmes and Ward 2010).

Most importantly, the significance of relative abundance trends for both species (i.e. the inclusion or exclusion of zero in the population growth rate 95% confidence intervals) was robust to assumptions regarding the observation error correlation structure (Table 6). This robustness was especially important given the small differences in support for the model runs as indicated by AICbp values. Across all model runs, the 95% confidence intervals for the estimated population growth rate did not contain zero for alewife but did contain zero for blueback herring (Table 6). Accordingly, the abundance of alewife range-wide significantly increased over time, but the increase in blueback herring abundance was not significant.

Stock-specific analyses

MARSS models for the alewife stock-specific analyses were fit to running sum data from 1983-2012 for the Southern New England stock, 1982-2012 for the Northern New England stock, and 1987-2012 for the Canadian stock. For the Mid-Atlantic stock, two time series of observations began before 1976; however, when the model was fit to data from 1976 through 2011, the model runs took too many iterations to converge. As a consequence, the models were fit to running sum data from 1983-2011 to reduce convergence time. In the first year of this time series (1983), four data sets were available.

In the stock-specific runs for alewife, the runs with the lowest AICbp assumed independent observation errors with unequal variances (run b) for the Mid-Atlantic and Southern New

England stocks, and independent observation errors with equal variances (run a) for the Northern New England stock (Table 7). The Canadian stock analysis only comprised one observation time series; therefore, assumptions about the observation error structure were not required. For Southern New England alewife, the unconstrained model (run c) did not converge over 20,000 iterations. As a consequence, a run estimating one covariance term and otherwise assuming independence among time series (run d) was not conducted. For the Northern New England stock, neither the run assuming independent observation errors with unequal variances (run b) nor the run with one estimated covariance term (run d) converged over 20,000 iterations.

For the Mid-Atlantic and Southern New England stocks, the preferred model initially changed as the number of bootstraps used to calculate AICbp was increased (Table 7). However, the preferred model became stable when at least 3000 bootstraps were conducted. With 6000 bootstraps used to calculate AICbp, approximately three units separated the two runs with the lowest AICbp values for the Mid-Atlantic stock and 14 units separated the three most preferred runs, indicating moderate support for the models with independent observation errors and either equal or unequal variances. For the Southern New England stock, 34 units separated the two runs with the lowest AICbp values, indicating strong support for the selected model run. For Northern New England alewife, the preferred model run was robust to the number of bootstraps used to calculate AICbp. With 5000 bootstraps, approximately 30 units separated the two runs with the lowest AICbp values, again indicating strong support for the selected model run.

The stock-specific estimated population growth rates were -0.021 for the Mid-Atlantic stock, 0.017 for Southern New England, 0.036 for Northern New England and 0.111 for the Canadian stock (Table 8). For the Mid-Atlantic, Southern New England and Northern New England stocks, the population growth rate 95% confidence intervals included zero across all model runs, indicating these stocks were not significantly increasing or decreasing in abundance (Table 10). However, across all model runs the growth rate 95% confidence intervals for the Canadian stock did not include zero, indicating that the abundance of this stock was significantly increasing. Importantly, the significance of relative abundance trends for all stocks was robust to assumptions regarding the observation error correlation structure. This robustness was especially critical for the Mid-Atlantic alewife stock, given the small difference in the AICbp values between model runs. Estimated alewife growth rates and 95% confidence intervals from the preferred models for both the range-wide and stock-specific analyses are illustrated in Figure 12.

The predicted unobserved population abundances depict the trends in the stock-specific growth rates (Figure 13). For stocks represented by more than one observation time series, patterns in many of the residuals from the best model fit were apparent (Figure 14). However, residual patterns were not entirely unexpected because many of the observation time series represented only one component of the stock (such as a particular river) and therefore would not be expected to depict the overall trends of the stock.

MARSS models for the blueback herring stock-specific analyses were fit to running sum data from 1979-2011 for the Southern and Mid-Atlantic stocks, 1983-2012 for the Southern New England stock, and 1995-2011 for the Northern New England stock. In the stock-specific runs for blueback herring, the runs with the lowest AICbp assumed independent observation errors with unequal variances (run b) for the Southern and Mid-Atlantic stocks, and independent observation errors with equal variances (run a) for Northern New England (Table 7). Southern New England blueback herring were only represented by one available time series, run counts from the Monument River; therefore, assumptions about the observation error structure were not required. For the Mid-Atlantic stock, the unconstrained model (run c) did not converge over 20,000 iterations. As a consequence, a run estimating one covariance term and otherwise assuming independence among time series (run d) was not conducted. For Northern New England blueback herring, only one model run converged; the run assuming independent observation errors with unequal variances (run b) as well as the unconstrained model (run c) did not converge successfully. As a consequence, AICbp was not calculated for the Northern New England stock. For both the Southern and Mid-Atlantic stocks, the preferred model run was robust to the number of bootstraps used to calculate AICbp. With 5000 bootstraps used to calculate AICbp, the two runs with the lowest AICbp values were separated by 15 units for the Southern stock and 340 units for the Mid-Atlantic stock, indicating strong support for the preferred model runs.

Estimated stock-specific population growth rates were 0.022 for the Southern stock, -0.048 for the Mid-Atlantic, -0.033 for Southern New England, and -0.076 for Northern New England (Table 9). Across all model runs, the growth rate 95% confidence intervals for the Mid-Atlantic stock did not include zero, indicating that the abundance of this stock was significantly decreasing (Table 10). For all other blueback herring stocks, the 95% confidence intervals of the estimated population growth rate included zero in all model runs, indicating that these stocks were not significantly increasing or decreasing in abundance. Importantly, the significance of relative abundance trends for all blueback herring stocks was again robust to assumptions regarding the observation error correlation structure. Estimated blueback herring growth rates and 95% confidence intervals from the preferred models for both the range-wide and stock-specific analyses are illustrated in Figure 15.

The predicted time series of population abundance for each stock is shown in Figure 16. Similar to alewife, blueback herring stocks that were represented by more than one observation time series showed strong patterns in the residuals from the best model fit (Figure 17). However, it should again be noted that residual patterns were not unexpected because many of the observation time series represented only one component of the stock.

Model assumptions and limitations

The available data for each analysis varied considerably among species and stocks. Some stocks such as Southern New England blueback herring had only one available data set; however, other stocks such as Southern New England alewife and Mid-Atlantic blueback herring had eight or more available time series. Within each analysis, all input time series must be weighted equally, regardless of the variability in the dataset. Furthermore, only the annual point estimates of relative abundance are inputs to the model; associated standard errors for the time series are not inputted.

However, some observation time series may be more representative of the stock of interest than other time series. For example, for Northern New England alewife, available datasets included run counts from five rivers and Maine’s juvenile alosine seine survey. Each time series of run counts represents the spawning population in one particular river, whereas the juvenile seine survey samples six Maine rivers including Merrymeeting Bay (ASMFC 2012). Accordingly, it is possible that the juvenile seine survey provides a better representation of Northern New England alewife than the run counts from any particular river because the seine survey samples multiple populations. Likewise, for Southern New England alewife, available datasets included the Long Island Sound (LIS) trawl survey, New York juvenile seine survey, and run counts from six rivers. The LIS trawl survey samples Long Island Sound from New London to Greenwich Connecticut with stations in both Connecticut and New York state waters, including the mouths of several rivers including the Thames, Connecticut, Housatonic, East and Quinnipiac (ASMFC 2012, CTDEP 2011). The NY juvenile seine survey samples the Hudson River estuary (ASMFC 2012), and run counts are specific to particular rivers. As a consequence, the LIS trawl survey may be more representative of the Southern New England alewife stock because it samples not only a greater proportion of the stock, but also samples LIS where mixing of river-specific populations likely occurs.

One source of uncertainty arose from the method used to select the preferred model for each stock definition. When initially calculating the bootstrapped AIC, the number of bootstraps was increased until the estimated AICbp converged to a single value. However for many stock-specific runs, AICbp estimates did not converge to a single value as the number of bootstraps was increased (e.g. the unconstrained model run for Mid-Atlantic alewife). Furthermore, the length of time required to complete these bootstraps (some runs took over two weeks) prohibited increasing the number of bootstraps until convergence was achieved. Consequently, the preferred model was chosen when one model run had the lowest AICbp estimate for four consecutive iterations. This approach to selecting a preferred model is not as robust as achieving convergence in the AICbp estimate. However, because significance of abundance trends did not vary across model runs for any species or stock definition, this uncertainty in model selection is minimized.

The MARSS model assumes density-independent growth (Holmes 2001, Holmes and Ward 2010). For river herring, density-independence is likely a reasonable assumption because many individual river populations are classified as depleted (ASMFC 2012), indicating that their abundance is well below historical levels and presumably their carrying capacity.

The MARSS model also estimates a time-invariant population growth rate. This parameterization requires the assumption that the growth rate of the stock has not changed systematically (i.e. other than random variation) over the time series incorporated into the model. However, it is possible that total mortality (either through changes in fishing or natural mortality), recruitment, and therefore stock-specific growth rates have exhibited systematic trends due to several factors including changes in fishing pressure, predator biomass or environmental conditions. Furthermore, when assessing the risk of extinction in the foreseeable future, we must assume that this population growth rate does not change and is representative of future conditions, including fishing or environmental conditions.

The estimated stock-specific growth rates are dependent on the time series incorporated into the model. If relative abundance indices for a particular stock exhibited different temporal trends over different portions of the time series, the choice of years would impact the resulting population growth rate estimate. The years included in the analyses presented here were selected a priori by the status review team. Years were selected to maximize the length of the time series incorporated into the model while minimizing the possibility that stock-specific growth rates changed systematically over the time series. Consequently, the status review team chose to incorporate data from 1976 through the present (with running sums therefore beginning in 1979 to incorporate data from 1976 through 1979) because prior to 1976, fishing intensity was much greater due to the presence of distant water fleets on the U.S. east coast.

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Table 1: Coefficients and associated standard errors used to convert RV *Bigelow* catches of alewife and blueback herring to RV *Albatross IV* equivalents for the 2009-2011 NEFSC bottom trawl surveys.

	Number		Biomass	
Species	**Coefficient**	**SE**	**Coefficient**	**SE**
Alewife	1.05	0.16	0.72	0.11
Blueback herring	0.87	0.17	1.59	0.45

Table 2: Datasets available for each stock of alewife.

Survey	**Stock**	**Type**	**First year**	**Last year**
Gulf of St Lawrence Trawl Survey	CAN	Trawl	1984	2012
Albemarle Sound Gill Net Survey	MATL	Adult Index	1991	2011
Albemarle Sound Seine Survey	MATL	YOY	1972	2011
DC Seine Survey	MATL	YOY	2000	2011
MD Juvenile Seine Survey	MATL	YOY	1959	2011
NJ Juvenile Seine Survey	MATL	YOY	1980	2011
VIMS Trawl Survey	MATL	YOY	1979	2011
Androscoggin	NNE	Run Counts	1981	2012
Cochecho	NNE	Run Counts	1992	2011
Damariscotta	NNE	Run Counts	1987	2012
Exeter	NNE	Run Counts	1992	2011
Lamprey	NNE	Run Counts	1992	2011
ME Juvenile Seine Survey	NNE	YOY	1979	2011
St.Croix	NNE	Run Counts	1983	2012
Union	NNE	Min Pop Size	1981	2011
Gilbert-Stuart	SNE	Run Counts	1981	2012
Greenville	SNE	Run Counts	1996	2012
LIS Trawl Survey	SNE	Trawl	1984	2011
Mattapoisett	SNE	Run Counts	1988	2012
Monument	SNE	Run Counts	1980	2012
Nemasket	SNE	Run Counts	1996	2011
Nonquit	SNE	Run Counts	1999	2012
NY Juvenile Seine Survey	SNE	YOY	1980	2011

Table 3: Datasets available for each stock of blueback herring.

Survey	Stock	Type	First year	Last year
Albemarle Sound Gill Net Survey	MATL	Adult Index	1991	2011
Albemarle Sound Seine Survey	MATL	YOY	1972	2011
Chowan	MATL	Run Counts	1972	2009
CT Juvenile Seine Survey	MATL	YOY	1979	2011
DC Seine Survey	MATL	YOY	2000	2011
Holyoke	MATL	Run Counts	1967	2012
LIS Trawl Survey	MATL	Trawl	1984	2011
MD Juvenile Seine Survey	MATL	YOY	1959	2011
NJ Juvenile Seine Survey	MATL	YOY	1980	2011
NY Juvenile Seine Survey	MATL	YOY	1980	2011
VIMS Seine Survey	MATL	YOY	1989	2011
VIMS Trawl Survey	MATL	YOY	1979	2011
ME Juvenile Seine Survey	NNE	YOY	1992	2011
Oyster	NNE	Run Counts	1992	2011
Monument River	SNE	Run Counts	1980	2012
Santee-Cooper-Cpue	SOU	CPUE	1969	2010
Santee-Cooper-MinPop	SOU	Min Pop Size	1990	2011

Table 4: Bootstrapped AIC values (AIC_{bp}) with increasing number of bootstraps for each range-wide model run. The preferred model run (lowest AIC) for each set of bootstraps is highlighted in grey.

				AICbp		
Species	**Run**	**1000**	**2000**	**3000**	**4000**	**5000**
Alewife	Independent with equal variances	237.917	237.525	237.483	237.780	237.574
	Independent with unequal variances	237.502	237.372	237.091	237.657	237.078
	Unconstrained	241.423	241.084	241.004	241.188	240.971
	Unequal variances with one covariance term	296.495	299.170	301.927	299.130	301.753
	Equal variance and covariance	238.329	238.693	238.737	238.885	238.804
Blueback	Independent with equal variances	314.239	312.239	312.032	310.914	312.380
	Independent with unequal variances	314.470	315.744	314.232	316.579	316.278
	Unconstrained	339.355	345.274	349.891	350.125	353.454
	Equal variance and covariance	368.918	358.072	360.662	369.591	363.518

Table 5: Species-specific parameter estimates (± one standard error) from the range-wide models with the lowest bootstrapped AIC (highlighted in grey in Table 4).

Species	Surveys	Population growth rate (u)	Process variance (Q)	Initial population size (x_0)	Survey scalars (a)
Alewife	NEFSC fall	0.032 ± 0.006	0 ± 0.002	0.144 ± 0.173	0
	NEFSC spring				1.396 ± 0.152
	Canadian Scot. Shelf				-0.752 ± 0.177
Blueback herring	NEFSC fall	0.039 ± 0.040	0.044 ± 0.043	-2.300 ± 0.537	0
	NEFSC spring				2.961 ± 0.278

Species	Surveys	Observation error variance-covariance matrix (R)		
Alewife	NEFSC fall	0.612 ± 0.140	0	0
	NEFSC spring	0	0.274 ± 0.062	0
	Canadian Scot. Shelf	0	0	0.524 ± 0.124
Blueback herring	NEFSC fall	1.337 ± 0.244	0	
	NEFSC spring	0	1.337 ± 0.244	

Table 6: Population growth rate maximum likelihood estimates (ML.Est), associated standard errors (Std.Err) and lower and upper 95% confidence intervals (low.CI, up.CI) for each range-wide model run. The preferred model run (lowest AIC) for each species is highlighted in grey.

Species	Run	ML.Est	Std.Err	low.CI	up.CI
Alewife	Independent with equal variances	0.034	0.006	0.022	0.046
	Independent with unequal variances	0.032	0.006	0.020	0.043
	Unconstrained	0.030	0.005	0.020	0.041
	Unequal variances with one covariance term	0.035	0.013	0.009	0.062
	Equal variance and covariance	0.034	0.005	0.023	0.045
Blueback herring	Independent with equal variances	0.039	0.040	-0.040	0.119
	Independent with unequal variances	0.022	0.036	-0.047	0.093
	Unconstrained	0.026	0.045	-0.063	0.112
	Equal variance and covariance	0.040	0.052	-0.064	0.144

Table 7: Bootstrapped AIC values (AIC_{bp}) with increasing number of bootstraps for each stock-specific model run. The preferred model run (lowest AIC) for each set of bootstraps is highlighted in grey.

			AICbp					
Species	**Stock**	**Run**	**1000**	**2000**	**3000**	**4000**	**5000**	**6000**
Alewife	Mid Atlantic	Independent with equal variances	477.040	471.706	469.102	476.961	471.807	472.868
		Independent with unequal variances	482.205	480.416	465.454	468.981	468.720	469.928
		Unconstrained	4234.350	1275.288	1489.449	47766.304	2233.856	6145.626
		Unequal variances with one covariance term	461.045	481.074	481.234	476.879	475.260	483.663
		Equal variance and covariance	501.567	513.984	502.153	507.941	494.866	493.558
	Southern New England	Independent with equal variances	497.077	476.127	467.887	465.428	467.839	482.994
		Independent with unequal variances	481.113	498.261	434.288	460.782	457.915	448.977
		Equal variance and covariance	472.779	486.868	513.939	546.983	527.073	505.417
	Northern New England	Independent with equal variances	424.863	429.286	440.036	426.244	429.491	NA
		Unconstrained	485.830	520.333	506.292	503.433	497.480	NA
		Equal variance and covariance	468.218	449.073	470.420	464.310	459.264	NA
	Canadian		NA	NA	NA	NA	NA	NA
Blueback herring	Southern	Independent with equal variances	150.094	153.657	157.181	158.798	158.237	NA
		Independent with unequal variances	86.548	92.175	94.796	84.218	83.798	NA
		Unconstrained	87.826	102.816	110.829	114.696	98.834	NA
		Equal variance and covariance	129.292	157.733	151.529	153.090	155.810	NA
	Mid Atlantic	Independent with equal variances	1029.963	1029.691	1029.727	1029.784	1029.999	NA
		Independent with unequal variances	689.017	689.274	689.476	689.479	689.733	NA
		Equal variance and covariance	1314.250	1292.775	1308.842	1318.290	1317.697	NA
	Southern New England		NA	NA	NA	NA	NA	NA
	Northern New England		NA	NA	NA	NA	NA	NA

Table 8: Species-specific parameter estimates (± one standard error) from the stock-specific alewife models with the lowest bootstrapped AIC (highlighted in grey in Table 7).

Stock	Surveys	Population growth rate (u)	Process variance (Q)	Initial population size (x_0)	Survey scalars (a)
Mid Atlantic	Albermarle Sound IGNS	-0.021 ± 0.036	0.034 ± 0.019	1.956 ± 0.302	0
	Albermarle Sound Seine				-1.773 ± 0.265
	DC Seine				-3.409 ± 0.314
	MD Juvenile Seine				-0.214 ± 0.225
	NJ Juvenile Seine				-1.070 ± 0.250
	VIMS Trawl				-0.932 ± 0.177
Southern New England	Gilbert-Stuart	0.017 ± 0.028	0.019 ± 0.011	11.872 ± 0.272	0
	Greenville				-4.486 ± 0.181
	LIS Trawl				-11.104 ± 0.108
	Mattapoisett				-0.813 ± 0.207
	Monument				1.022 ± 0.133
	Nemasket				2.282 ± 0.109
	Nonquit				0.064 ± 0.132
	NY Juvenile Seine				-11.393 ± 0.141
Northern New England	Androscoggin	0.036 ± 0.038	0.036 ± 0.027	11.225 ± 0.436	0
	Cochecho				-0.615 ± 0.204
	Damariscotta				1.475 ± 0.184
	Exeter				-4.975 ± 0.207
	Lamprey				-0.503 ± 0.204
	ME Juvenile Seine				-7.057 ± 0.171
Canada	Southern Gulf of St Lawrence	0.111 ± 0.031	0.025 ± 0.006	2.405 ± 0.159	0

Stock	Surveys	Observation error variance-covariance matrix (R)							
Mid Atlantic	Albermarle Sound IGNS	0.585 ± 0.189	0	0	0	0	0		
	Albermarle Sound Seine	0	1.048 ± 0.272	0	0	0	0		
	DC Seine	0	0	0.630 ± 0.279	0	0	0		
	MD Juvenile Seine	0	0	0	0.572 ± 0.151	0	0		
	NJ Juvenile Seine	0	0	0	0	0.900 ± 0.234	0		
	VIMS Trawl	0	0	0	0	0	0.024 ± 0.016		
Southern New England	Gilbert-Stuart	0.287 ± 0.078	0	0	0	0	0	0	0
	Greenville	0	0.311 ± 0.114	0	0	0	0	0	0
	LIS Trawl	0	0	0.042 ± 0.015	0	0	0	0	0
	Mattapoisett	0	0	0	0.702 ± 0.21	0	0	0	0
	Monument	0	0	0	0	0.222 ± 0.061	0	0	0
	Nemasket	0	0	0	0	0	0.011 ± 0.008	0	0
	Nonquit	0	0	0	0	0	0	0.073 ± 0.032	0
	NY Juvenile Seine	0	0	0	0	0	0	0	0.289 ± 0.078
Northern New England	Androscoggin	0.406 ± 0.055	0	0	0	0	0		
	Cochecho	0	0.406 ± 0.055	0	0	0	0		
	Damariscotta	0	0	0.406 ± 0.055	0	0	0		
	Exeter	0	0	0	0.406 ± 0.055	0	0		
	Lamprey	0	0	0	0	0.406 ± 0.055	0		
	ME Juvenile Seine	0	0	0	0	0	0.406 ± 0.055		
Canada	Southern Gulf of St Lawrence	2.213E-05 ± 1.258E-07							

Table 9: Species-specific parameter estimates (± one standard error) from the stock-specific blueback herring models with the lowest bootstrapped AIC (highlighted in grey in Table 7).

Stock	Surveys	Population growth rate (u)	Process variance (Q)	Initial population size (x_0)	Survey scalars (a)
Southern	Santee-Cooper CPUE	0.022 ± 0.041	0.057 ± 0.018	5.317 ± 0.248	0
	Santee-Cooper MinPop				9.239 ± 0.124
Mid Atlantic	Albermarle Sound IGNS	-0.048 ± 0.003	0.000 ± 0.001	3.904 ± 0.093	0
	Albermarle Sound Seine				-1.908 ± 0.161
	Chowan				14.398 ± 0.193
	CT Juvenile Seine				0.467 ± 0.072
	DC Seine				-0.557 ± 0.175
	Holyoke				8.533 ± 0.460
	LIS Trawl				-3.271 ± 0.104
	MD Juvenile Seine				-1.644 ± 0.333
	NJ Juvenile Seine				0.590 ± 0.080
	NY Juvenile Seine				1.388 ± 0.085
	VIMS Seine				-2.149 ± 0.105
	VIMS Trawl				-2.596 ± 0.147
Southern New England	Monument River	-0.033 ± 0.035	0.036 ± 0.009	12.352 ± 0.195	0
Northern New England	ME Juvenile Seine	-0.076 ± 0.058	0.038 ± 0.043	4.545 ± 0.396	0
	Oyster				7.837 ± 0.213

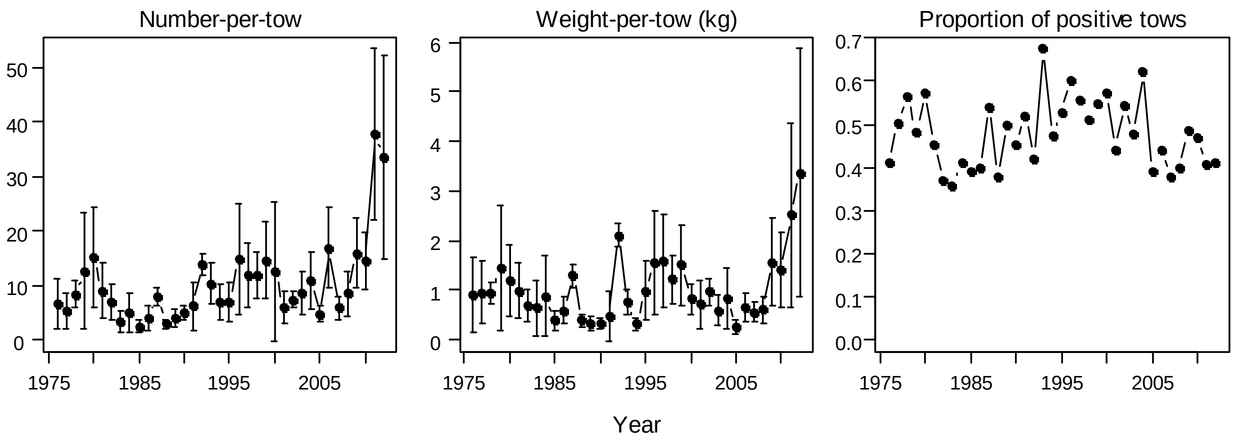
Stock	Surveys	Observation error variance-covariance matrix (R)											
Southern	Santee-Cooper CPUE	0 ± 0.007	0										
	Santee-Cooper MinPop	0	0.291 ± 0.094										
Mid Atlantic	Albermarle Sound IGNS	0.060 ± 0.019	0	0	0	0	0	0	0	0	0	0	0
	Albermarle Sound Seine	0	0.767 ± 0.190	0	0	0	0	0	0	0	0	0	0
	Chowan	0	0	1.068 ± 0.267	0	0	0	0	0	0	0	0	0
	CT Juvenile Seine	0	0	0	0.054 ± 0.014	0	0	0	0	0	0	0	0
	DC Seine	0	0	0	0	0.245 ± 0.106	0	0	0	0	0	0	0
	Holyoke	0	0	0	0	0	6.800 ± 1.669	0	0	0	0	0	0
	LIS Trawl	0	0	0	0	0	0	0.190 ± 0.056	0	0	0	0	0
	MD Juvenile Seine	0	0	0	0	0	0	0	3.605 ± 0.876	0	0	0	0
	NJ Juvenile Seine	0	0	0	0	0	0	0	0	0.091 ± 0.024	0	0	0
	NY Juvenile Seine	0	0	0	0	0	0	0	0	0	0.116 ± 0.030	0	0
	VIMS Seine	0	0	0	0	0	0	0	0	0	0	0.147 ± 0.046	0
	VIMS Trawl	0	0	0	0	0	0	0	0	0	0	0	0.534 ± 0.140
Southern New England	Monument River	7.114E-06 ± 8.069E-09											
Northern New England	ME Juvenile Seine	0.373 ± 0.103	0										
	Oyster	0	0.373 ± 0.103										

Table 10: Population growth rate maximum likelihood estimates (ML.Est), associated standard errors (Std.Err) and lower and upper 95% confidence intervals (low.CI, up.CI) for each stock-specific model run. The preferred model run (lowest AIC) for each stock is highlighted in grey.

Species	Stock	Run	ML.Est	Std.Err	low.CI	up.CI
Alewife	Mid Atlantic	Independent with equal variances	0.004	0.034	-0.061	0.073
		Independent with unequal variances	-0.021	0.036	-0.092	0.048
		Unconstrained	-0.013	0.029	-0.071	0.044
		Unequal variances with one covariance term	-0.021	0.035	-0.088	0.054
		Equal variance and covariance	-0.004	0.046	-0.092	0.088
	Southern New England	Independent with equal variances	0.008	0.032	-0.052	0.072
		Independent with unequal variances	0.017	0.028	-0.038	0.071
		Equal variance and covariance	0.005	0.032	-0.057	0.069
	Northern New England	Independent with equal variances	0.036	0.038	-0.041	0.109
		Unconstrained	0.038	0.036	-0.034	0.108
		Equal variance and covariance	0.036	0.041	-0.048	0.114
	Canada	Independent with equal variances	0.111	0.031	0.050	0.170
Blueback herring	Southern	Independent with equal variances	-0.004	0.047	-0.091	0.091
		Independent with unequal variances	0.022	0.041	-0.058	0.102
		Unconstrained	0.024	0.042	-0.058	0.103
		Equal variance and covariance	-0.001	0.046	-0.091	0.092
	Mid Atlantic	Independent with equal variances	-0.070	0.008	-0.085	-0.055
		Independent with unequal variances	-0.048	0.003	-0.054	-0.042
		Equal variance and covariance	-0.072	0.013	-0.097	-0.046
	Southern New England	Independent with equal variances	-0.033	0.035	-0.101	0.036
	Northern New England	Independent with equal variances	-0.076	0.058	-0.185	0.041

Figure 1: Stratified mean number-per-tow, stratified mean weight (kg)-per-tow, and the proportion of positive tows for alewife (a) and blueback herring (b) from the NEFSC spring bottom trawl survey, including both inshore and offshore strata. Error bars correspond to two standard errors.

a)



b)

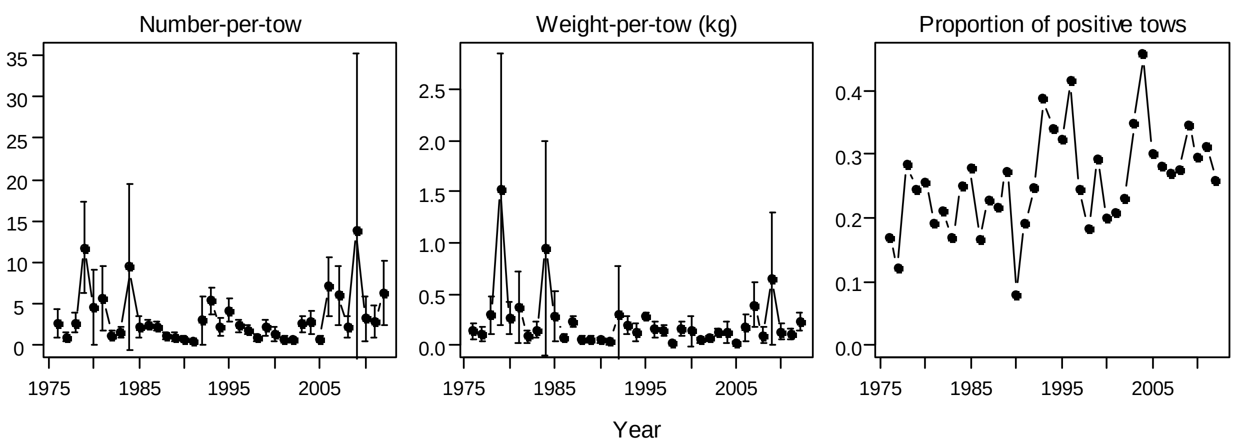
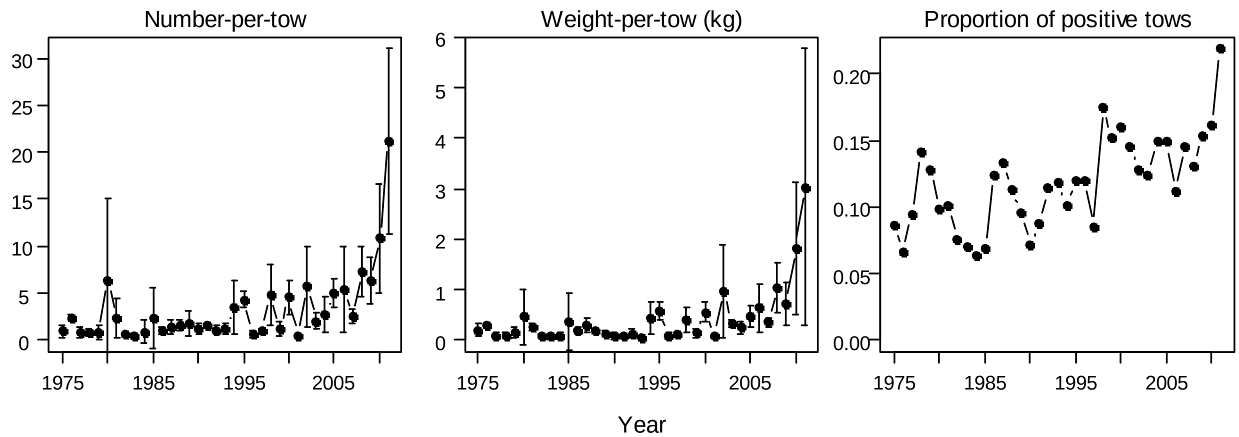


Figure 2: Stratified mean number-per-tow, stratified mean weight (kg)-per-tow, and the proportion of positive tows for alewife (a) and blueback herring (b) from the NEFSC fall bottom trawl survey, including both inshore and offshore strata. Error bars correspond to two standard errors.

a)



b)

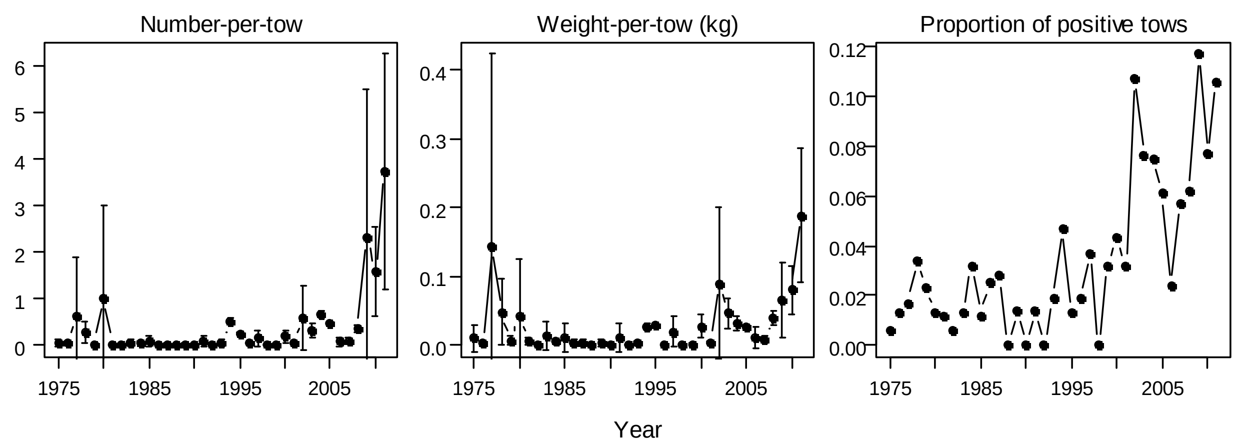
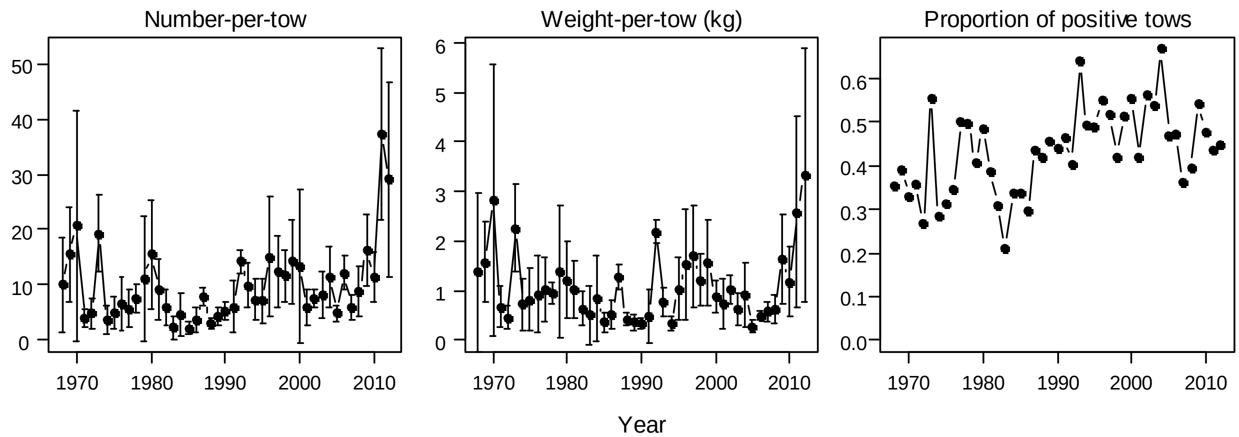


Figure 3: Stratified mean number-per-tow, stratified mean weight (kg)-per-tow, and the proportion of positive tows for alewife (a) and blueback herring (b) from the NEFSC spring bottom trawl survey, including both offshore strata only. Error bars correspond to two standard errors.

a)



b)

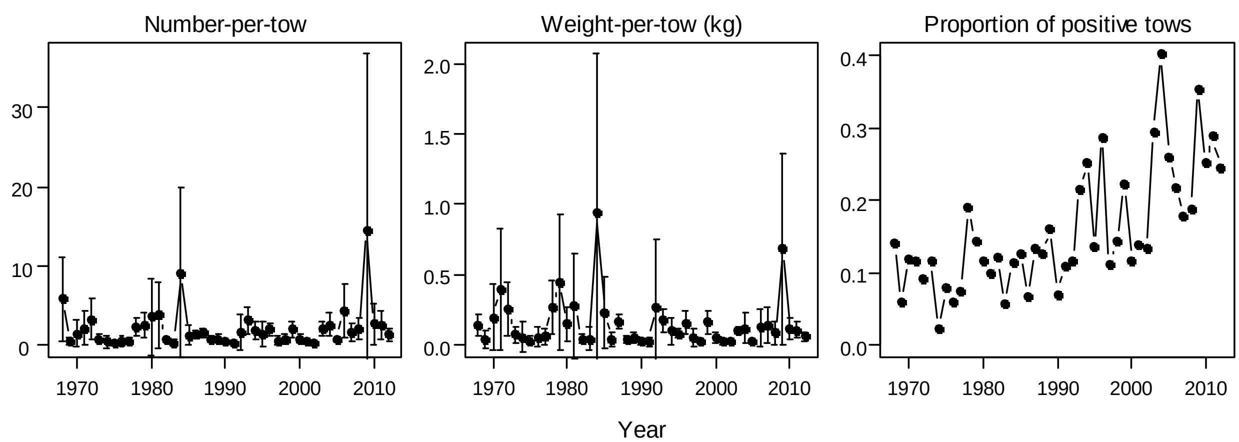
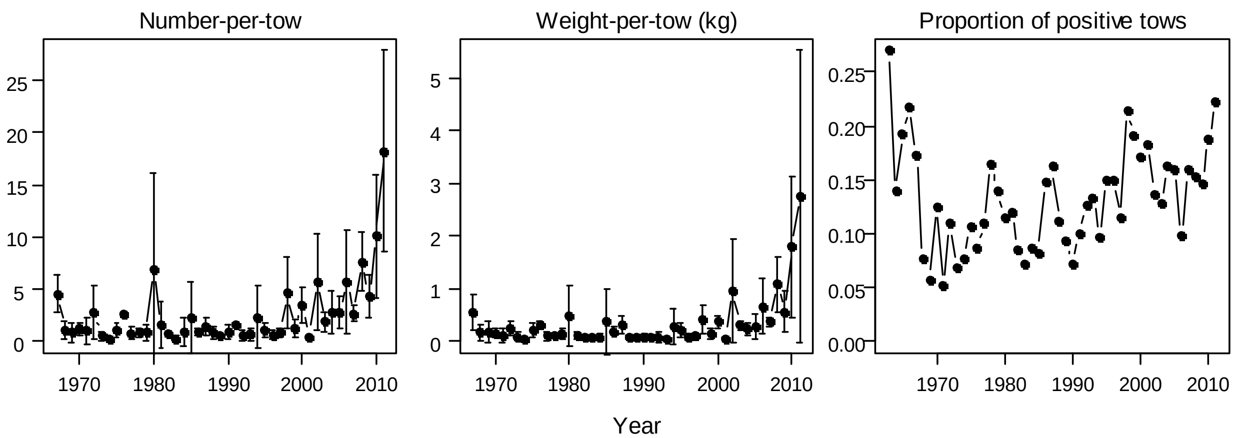


Figure 4: Stratified mean number-per-tow, stratified mean weight (kg)-per-tow, and the proportion of positive tows for alewife (a) and blueback herring (b) from the NEFSC fall bottom trawl survey, including both offshore strata only. Error bars correspond to two standard errors.

a)



b)

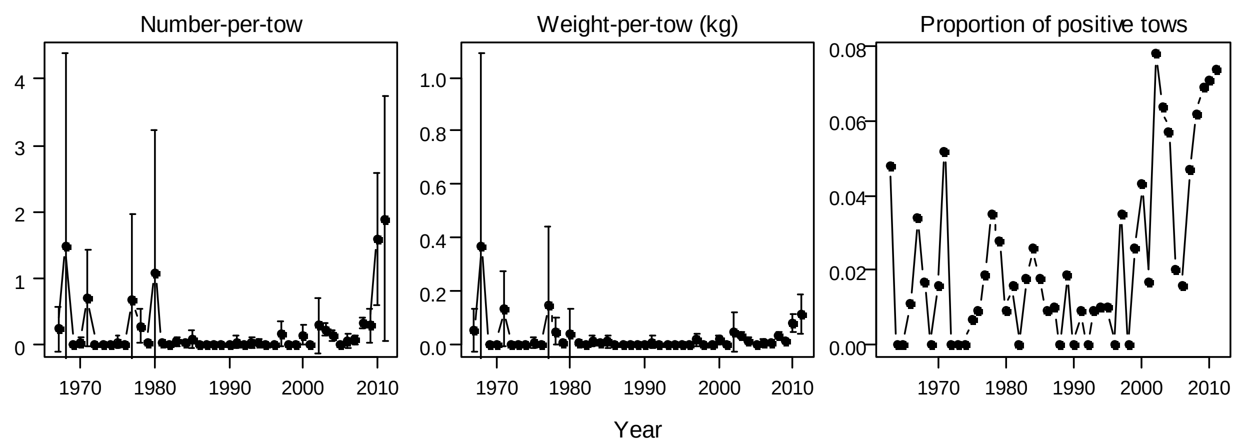
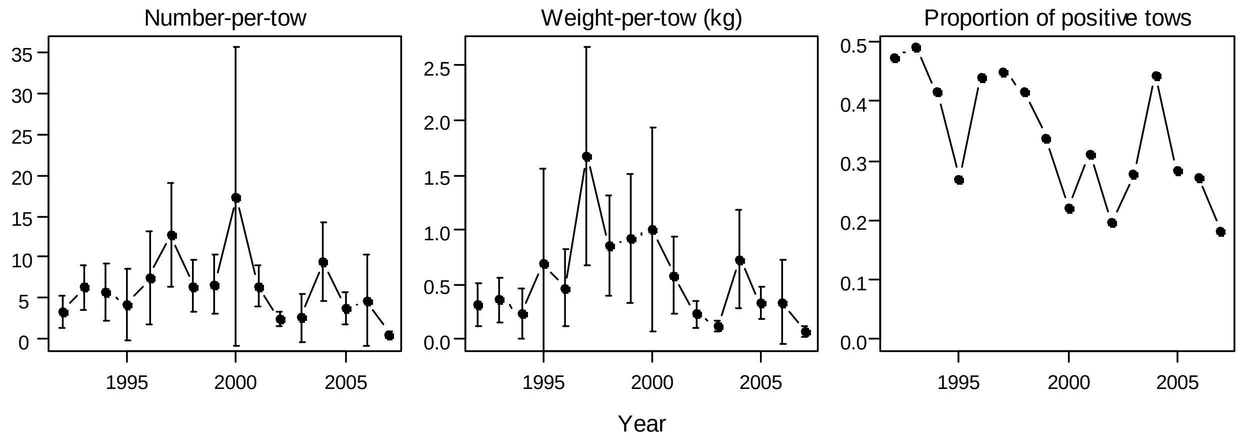


Figure 5: Stratified mean number-per-tow, stratified mean weight (kg)-per-tow, and the proportion of positive tows for alewife (a) and blueback herring (b) from the NEFSC winter bottom trawl survey. Error bars correspond to two standard errors.

a)



b)

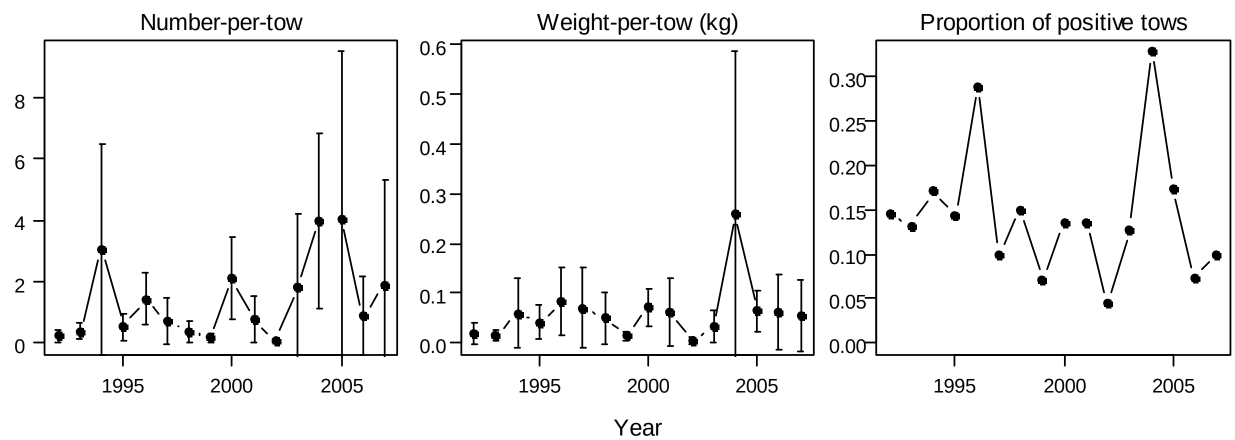
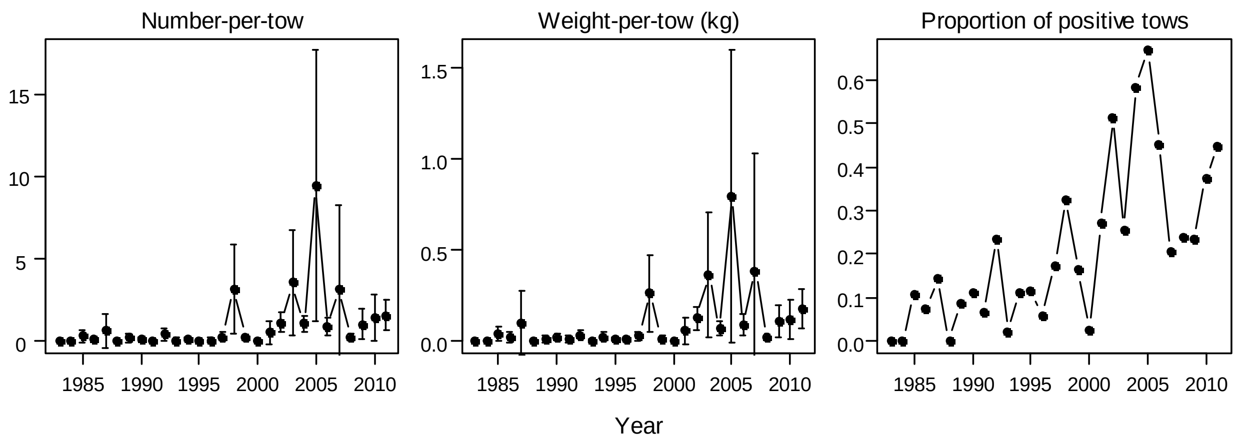


Figure 6: Stratified mean number-per-tow, stratified mean weight (kg)-per-tow, and the proportion of positive tows for alewife (a) and blueback herring (b) from the NEFSC shrimp trawl survey. Error bars correspond to two standard errors.

a)



b)

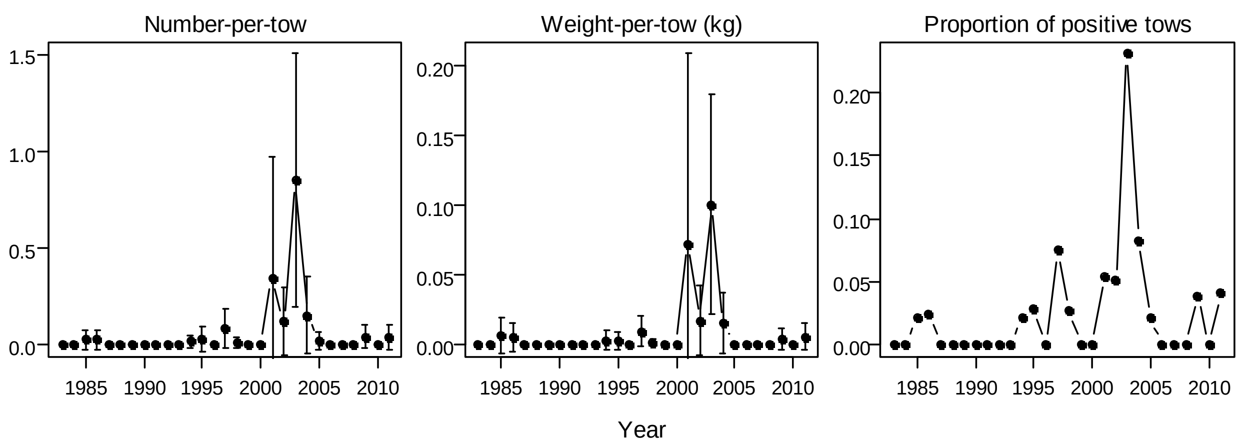
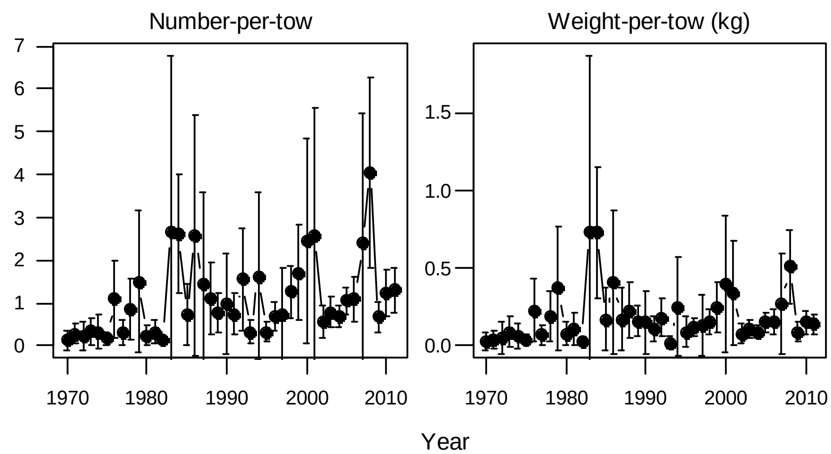


Figure 7: Stratified mean number-per-tow of alewife from Canada's Department of Fish and Oceans' Scotian Shelf summer research vessel survey (a) and Georges Bank research vessel survey (b). Error bars correspond to two standard errors.

a)



b)

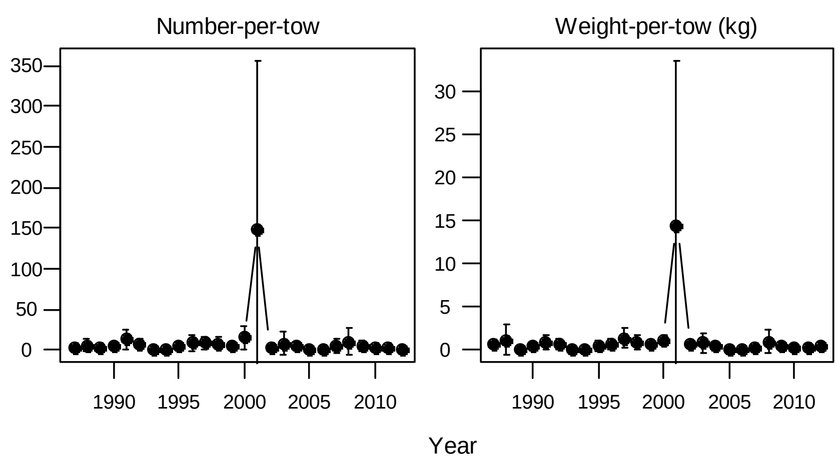


Figure 8: Observed (points) and predicted (solid line) abundance from the preferred range-wide model for alewife. Since this model incorporated more than one observation time series, each additional time series was scaled to the first observation time series with the scaling parameter, a.

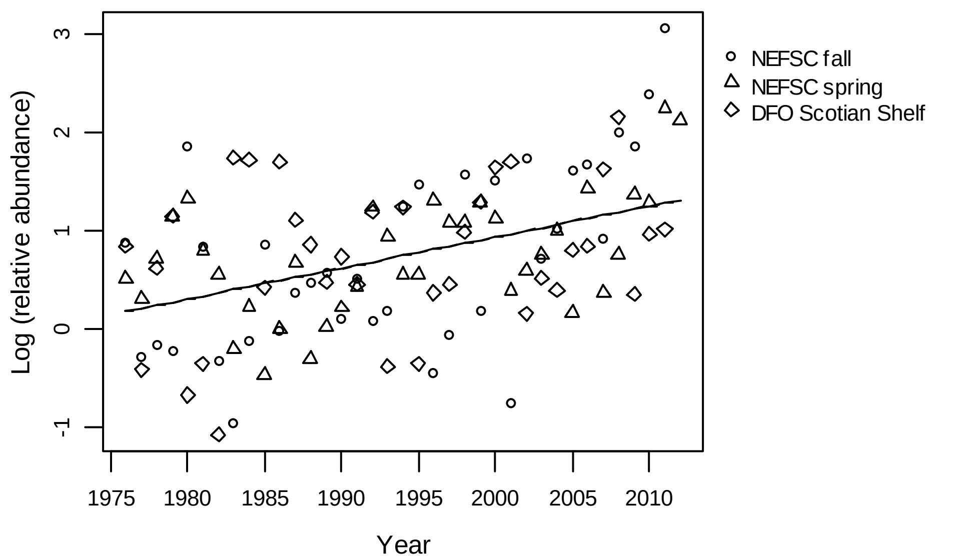


Figure 9: Observed (points) and predicted (solid line) abundance from the preferred range-wide model for blueback herring. The dashed lines represent the 95% confidence intervals. Since this model incorporated more than one observation time series, each additional time series was scaled to the first observation time series with the scaling parameter, a.

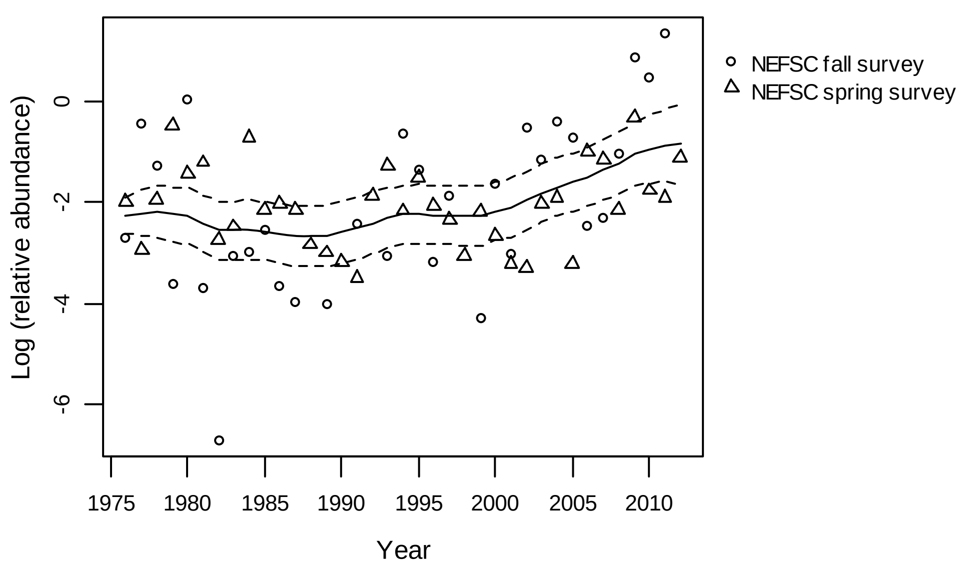


Figure 10: Residuals for each observation time series from the preferred range-wide model for alewife.

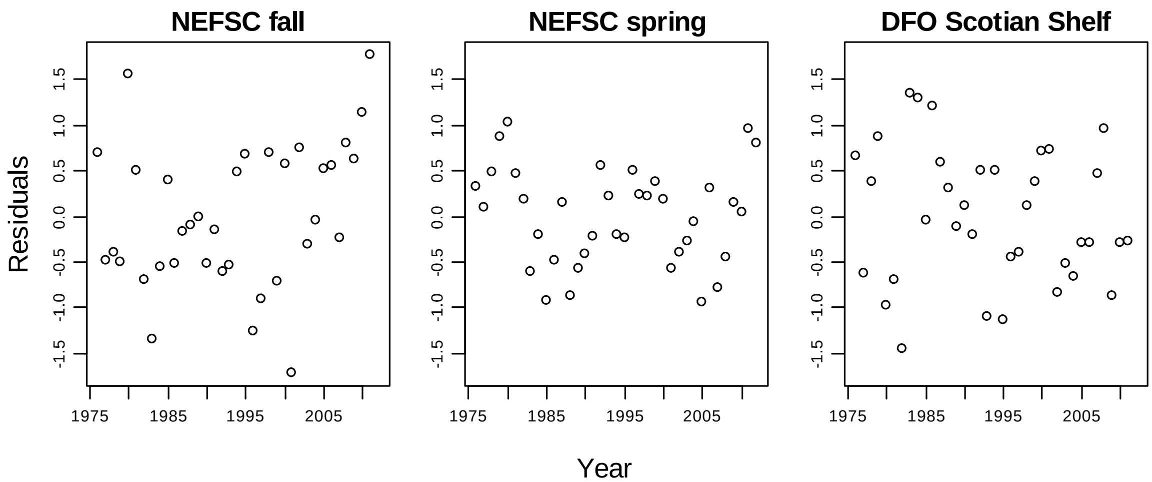


Figure 11: Residuals for each observation time series from the preferred range-wide model for blueback herring.

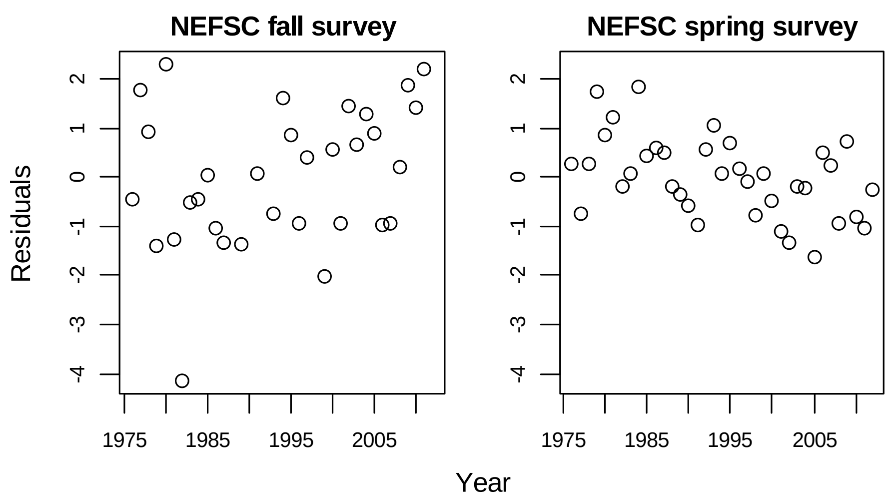


Figure 12: Estimated population growth rate and associated 95% confidence intervals from the preferred model for each alewife stock.

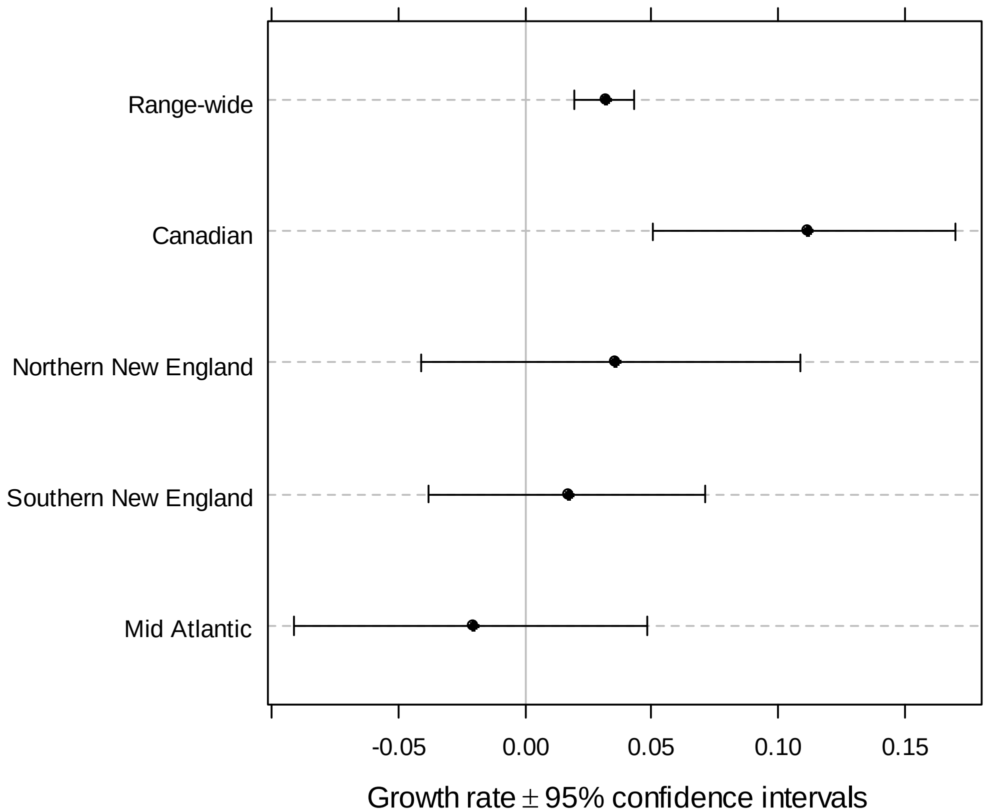
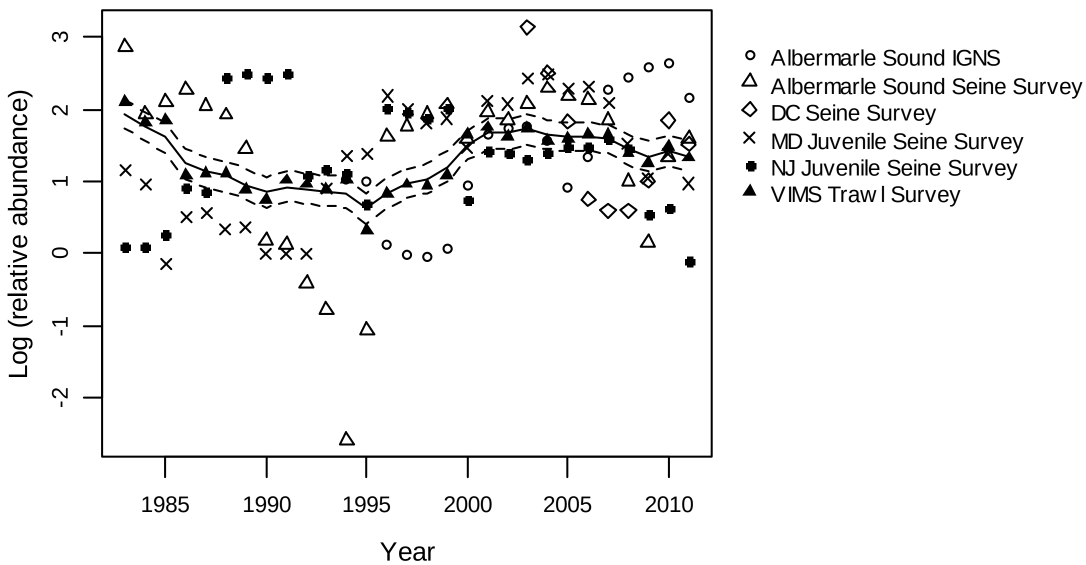
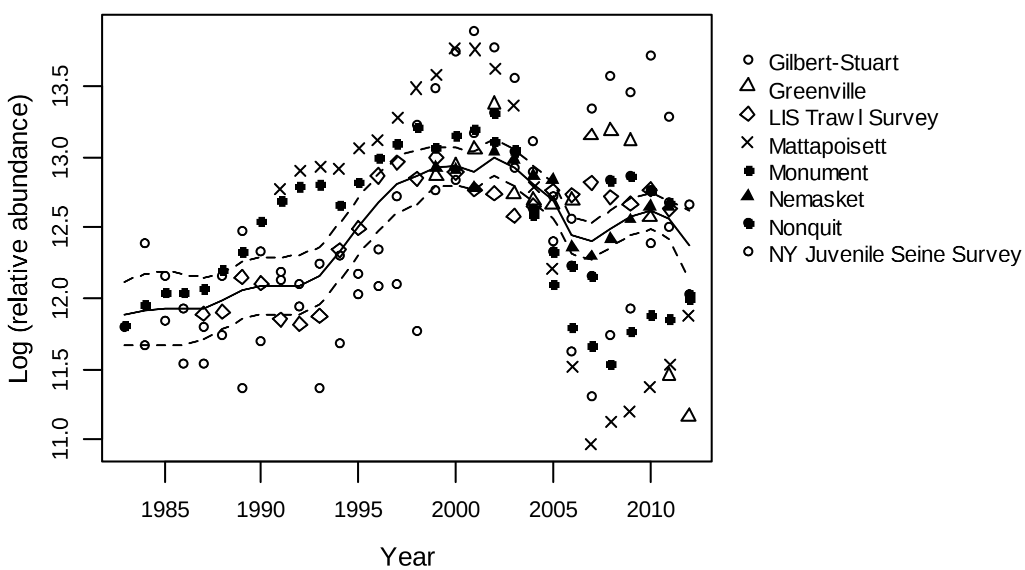


Figure 13: Observed and predicted abundance from the preferred model for each alewife stock: a) Mid-Atlantic, b) Southern New England, c) Northern New England and d) Canada. For stocks with more than one observation time series, each additional time series is scaled to the first observation time series with the scaling parameter, a.

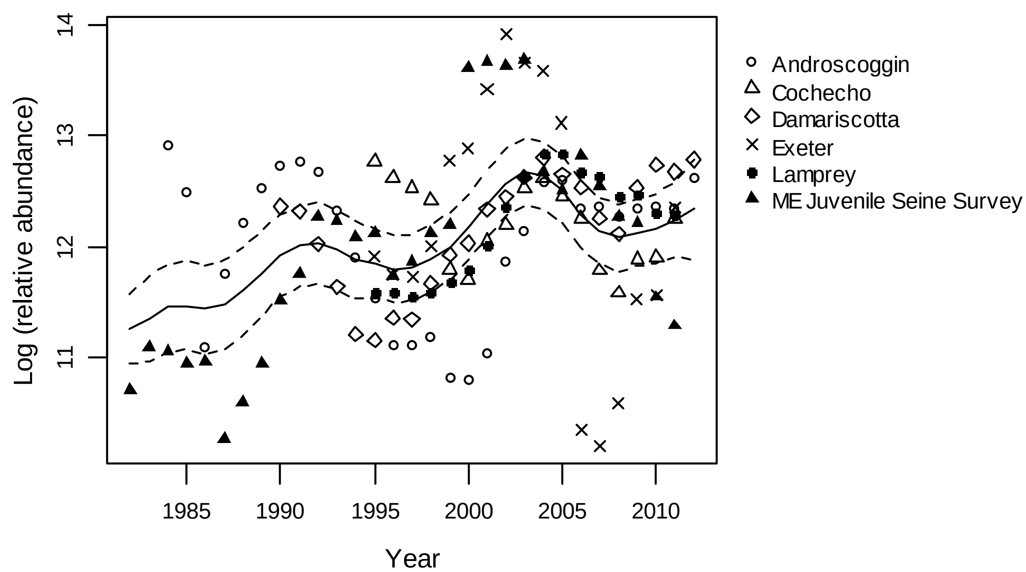
a)



b)



c)


Log (relative abundance)
14
13
12
11
1985
1990
1995
2000
2005
2010
Year
Androscoggin
Cochecho
Damariscotta
Exeter
Lamprey
ME Juvenile Seine Survey

d)

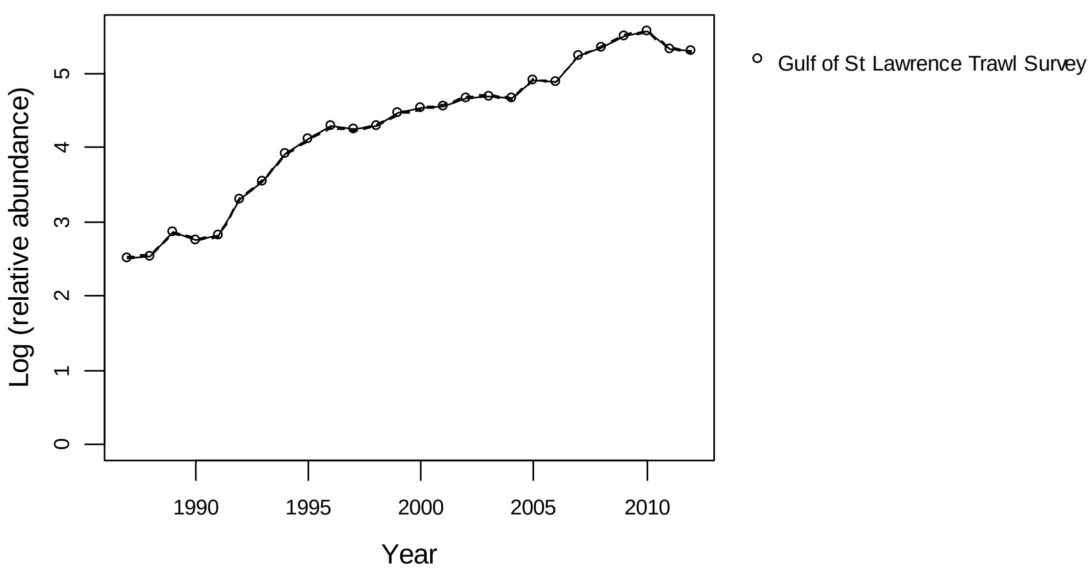
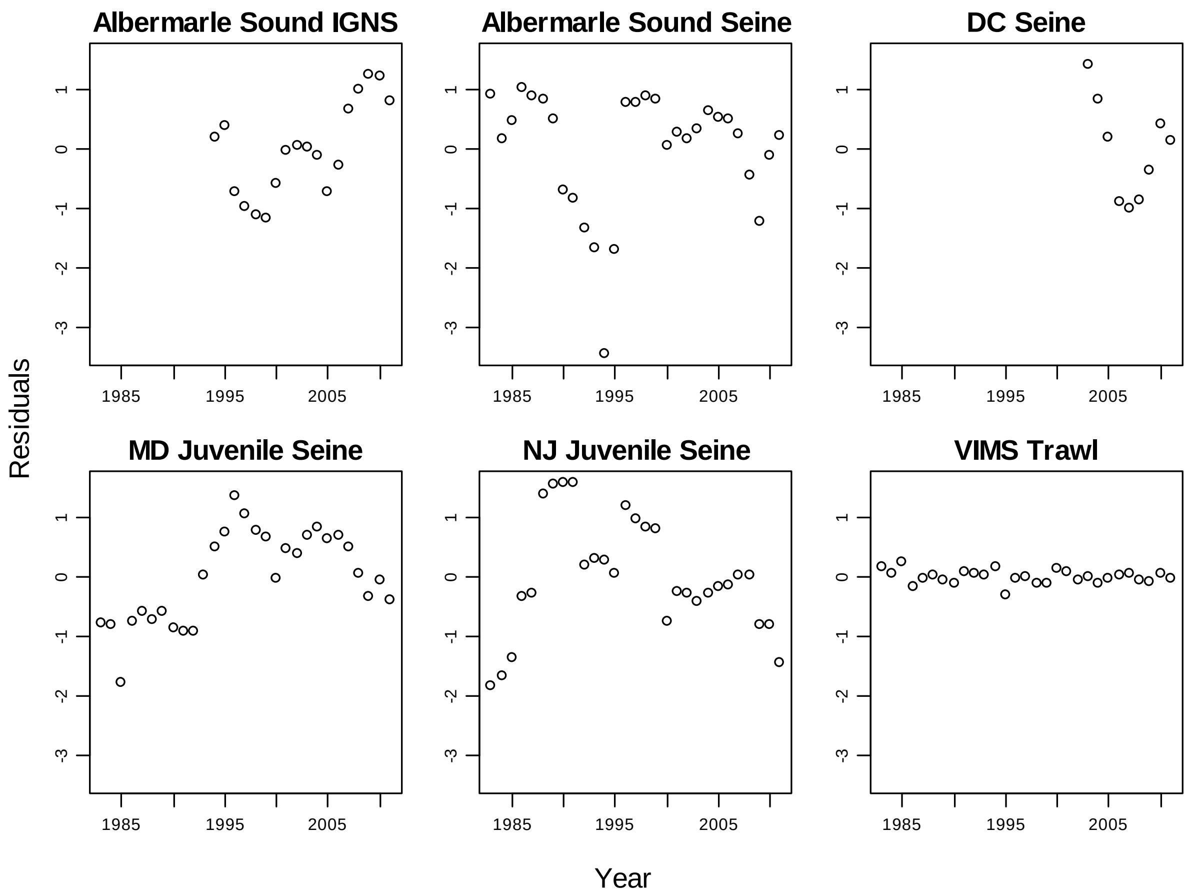
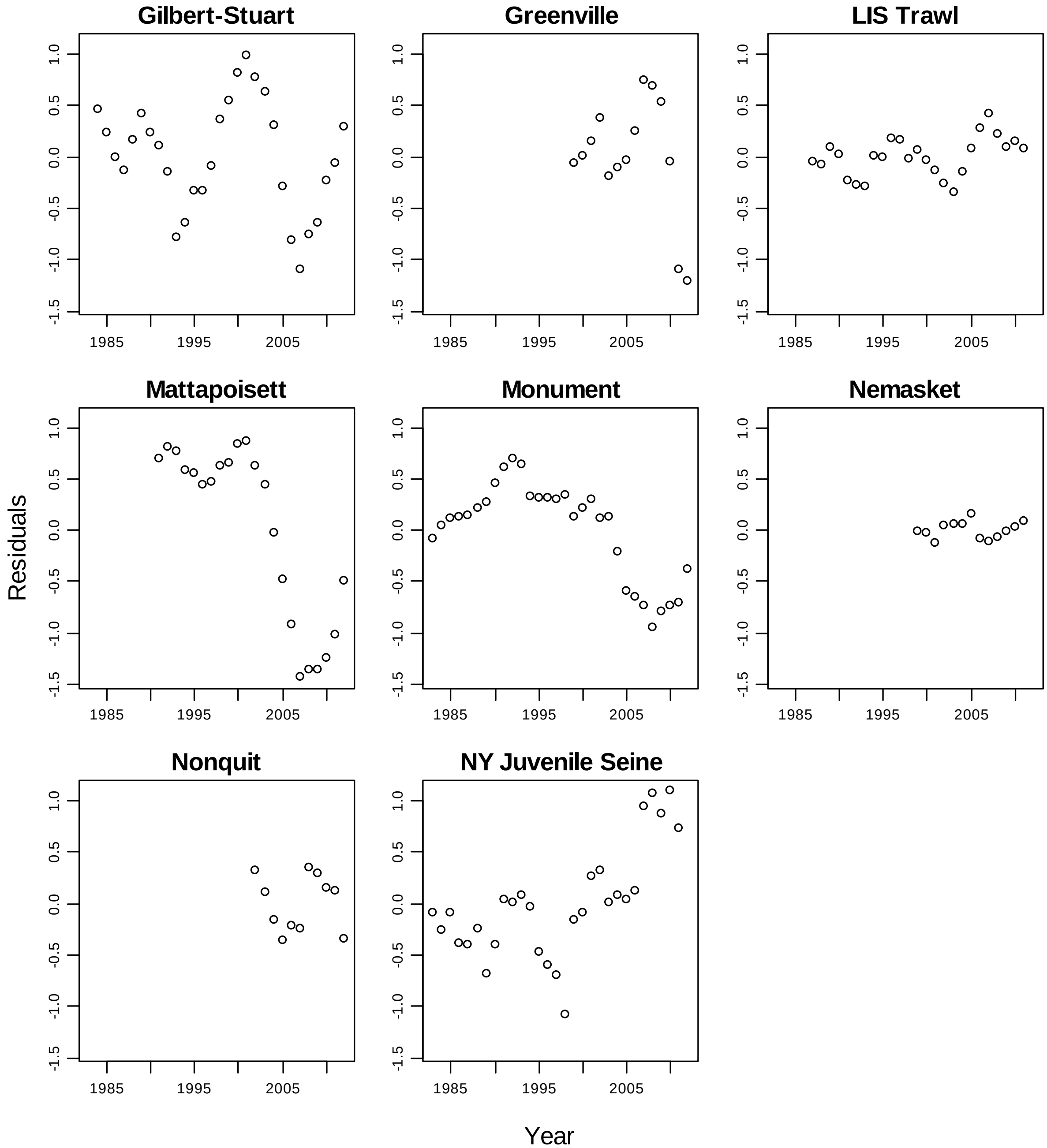

Log (relative abundance)
0
1
2
3
4
5
1990
1995
2000
2005
2010
Year
Gulf of St Lawrence Trawl Survey

Figure 14: Residuals for each observation time series from the preferred model for each alewife stock: a) Mid-Atlantic, b) Southern New England, c) Northern New England and d) Canada.

a)

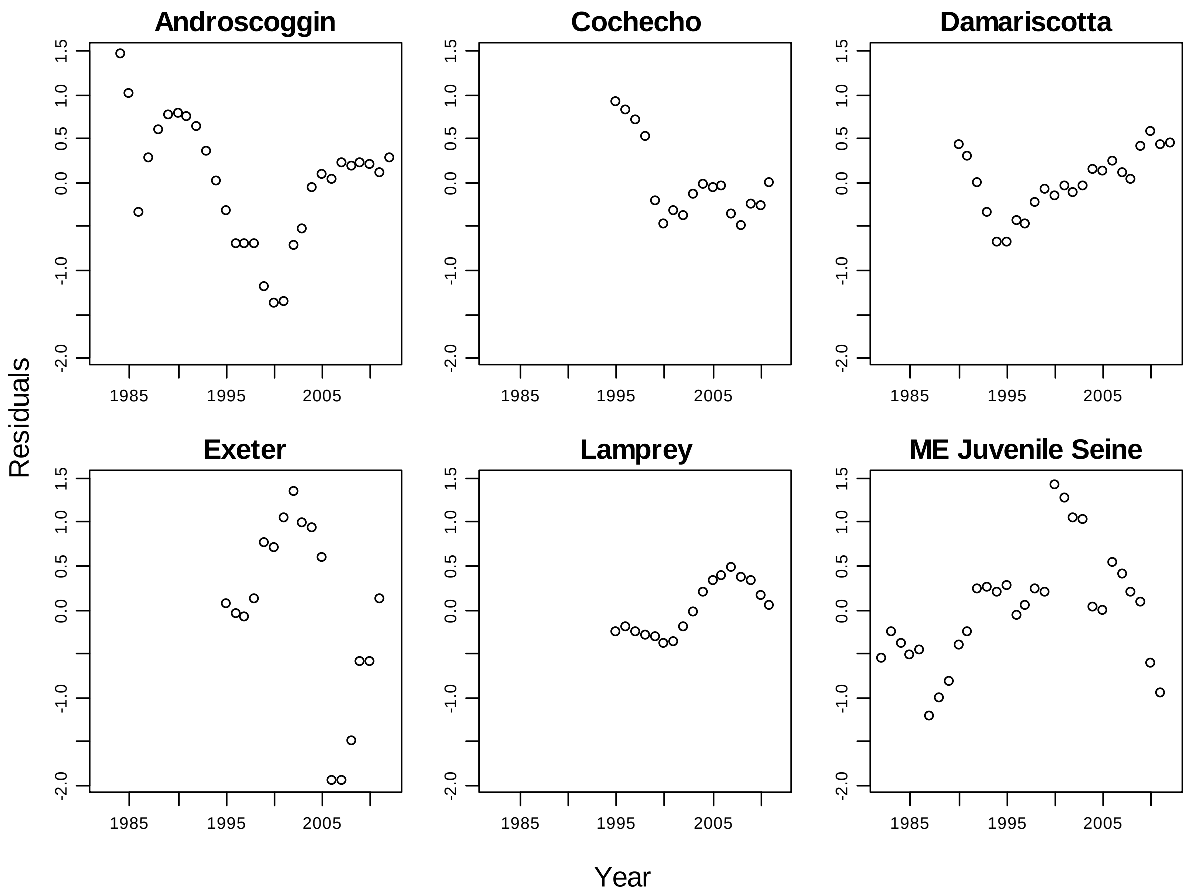


b)



Gilbert-Stuart
Greenville
LIS Trawl
Mattapoisett
Monument
Nemasket
Nonquit
NY Juvenile Seine
Residuals
Year
1.0
0.5
0.0
-0.5
-1.0
-1.5
1985
1995
2005

c)


Androscoggin
Cochecho
Damariscotta
Exeter
Lamprey
ME Juvenile Seine
Residuals
Year
1985
1995
2005
1.5
1.0
0.5
0.0
-1.0
-2.0

d)

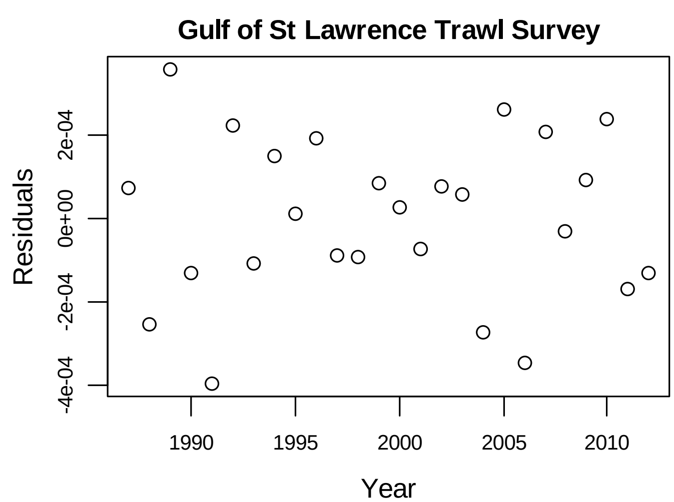

Gulf of St Lawrence Trawl Survey
Residuals
Year
2e-04
0e+00
-2e-04
-4e-04
1990
1995
2000
2005
2010

Figure 15: Estimated population growth rate and associated 95% confidence intervals from the preferred model for each blueback herring stock.

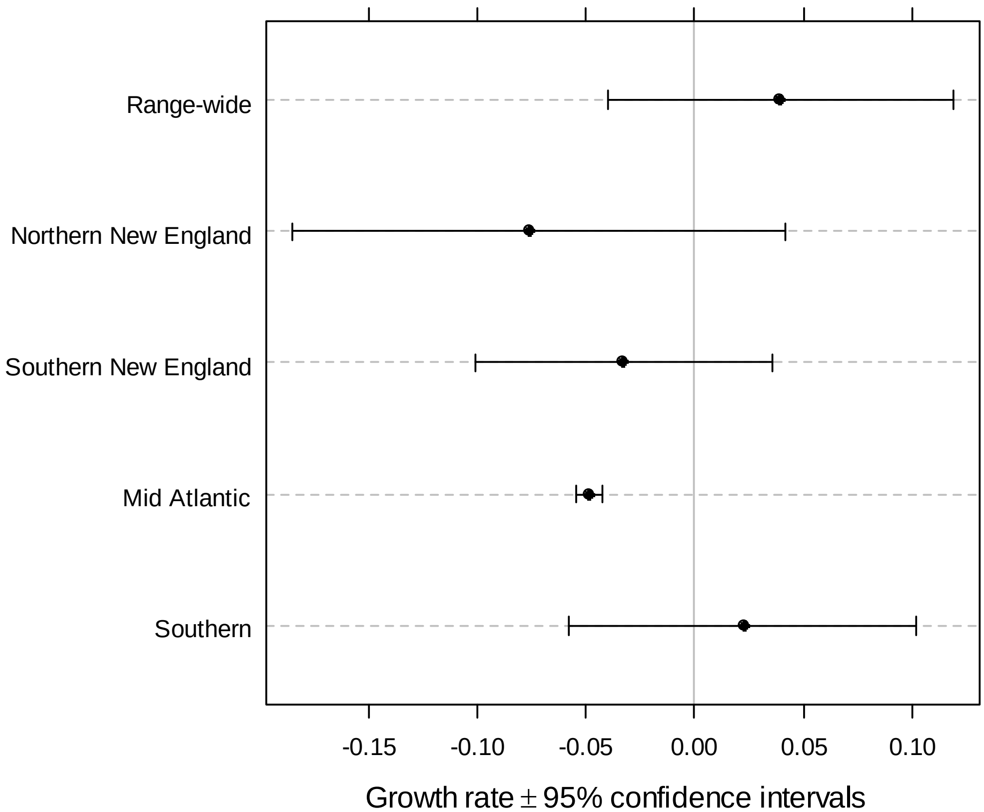
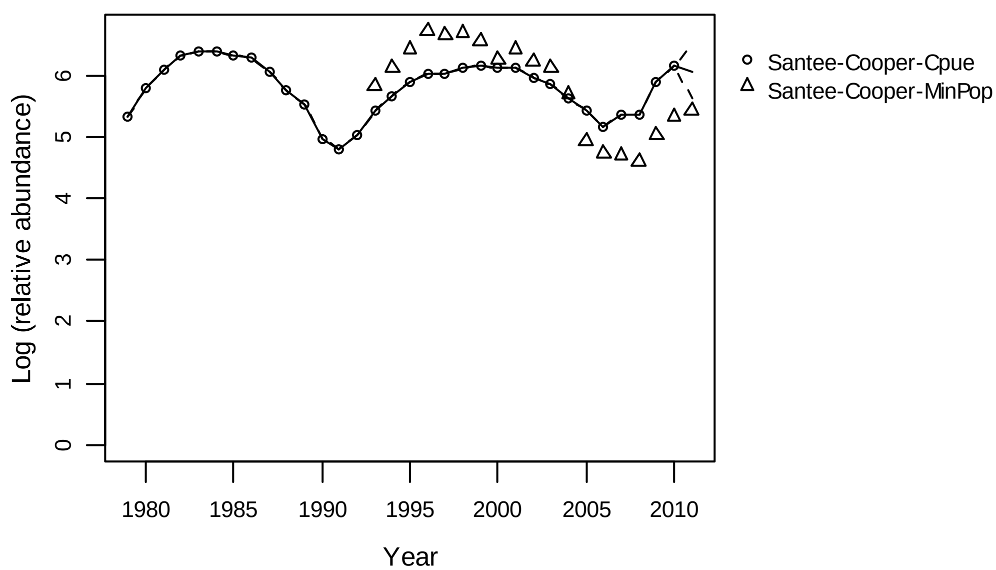
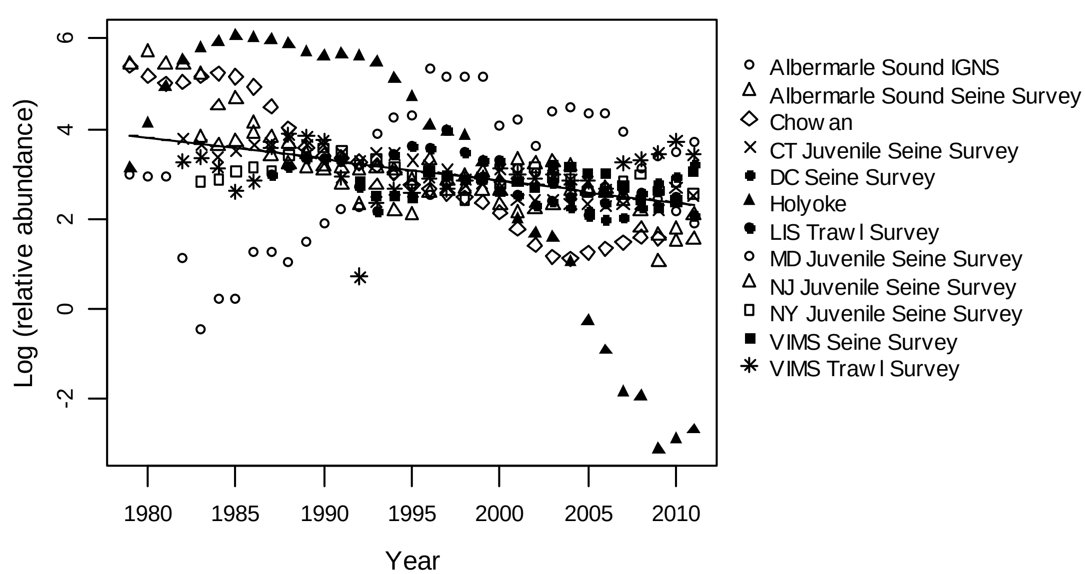


Figure 16: Observed and predicted abundance from the preferred model for each blueback herring stock: a) Southern, b) Mid-Atlantic, c) Southern New England and d) Northern New England. For stocks with more than one observation time series, each additional time series is scaled to the first observation time series with the scaling parameter, a.

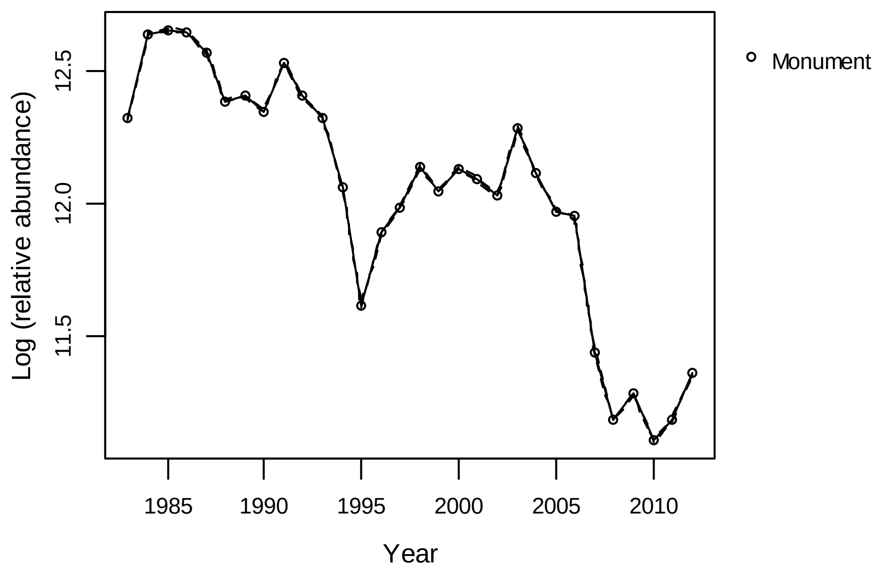
a)



b)



c)


Monument
Log (relative abundance)
12.5
12.0
11.5
1985
1990
1995
2000
2005
2010
Year

d)

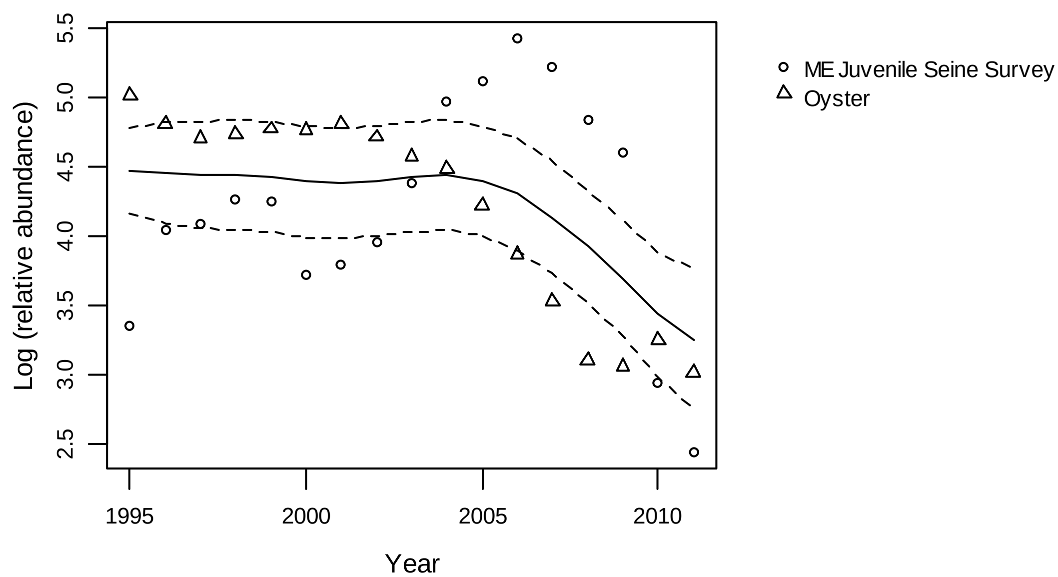
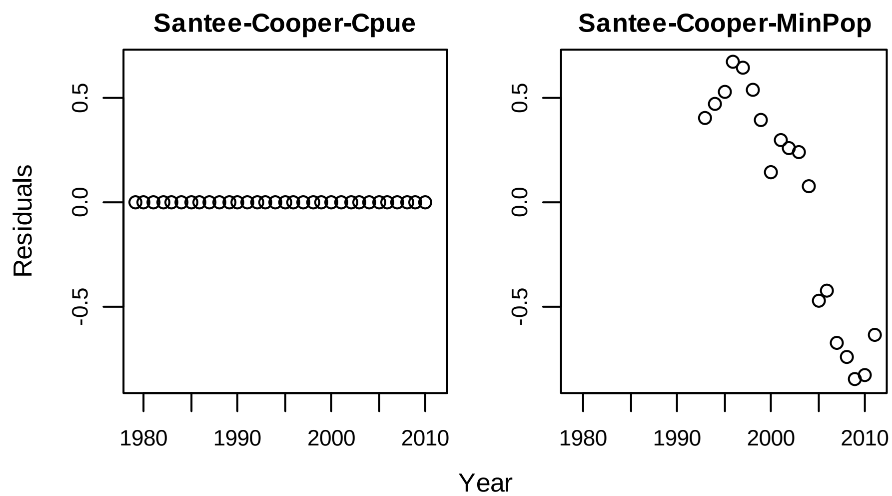
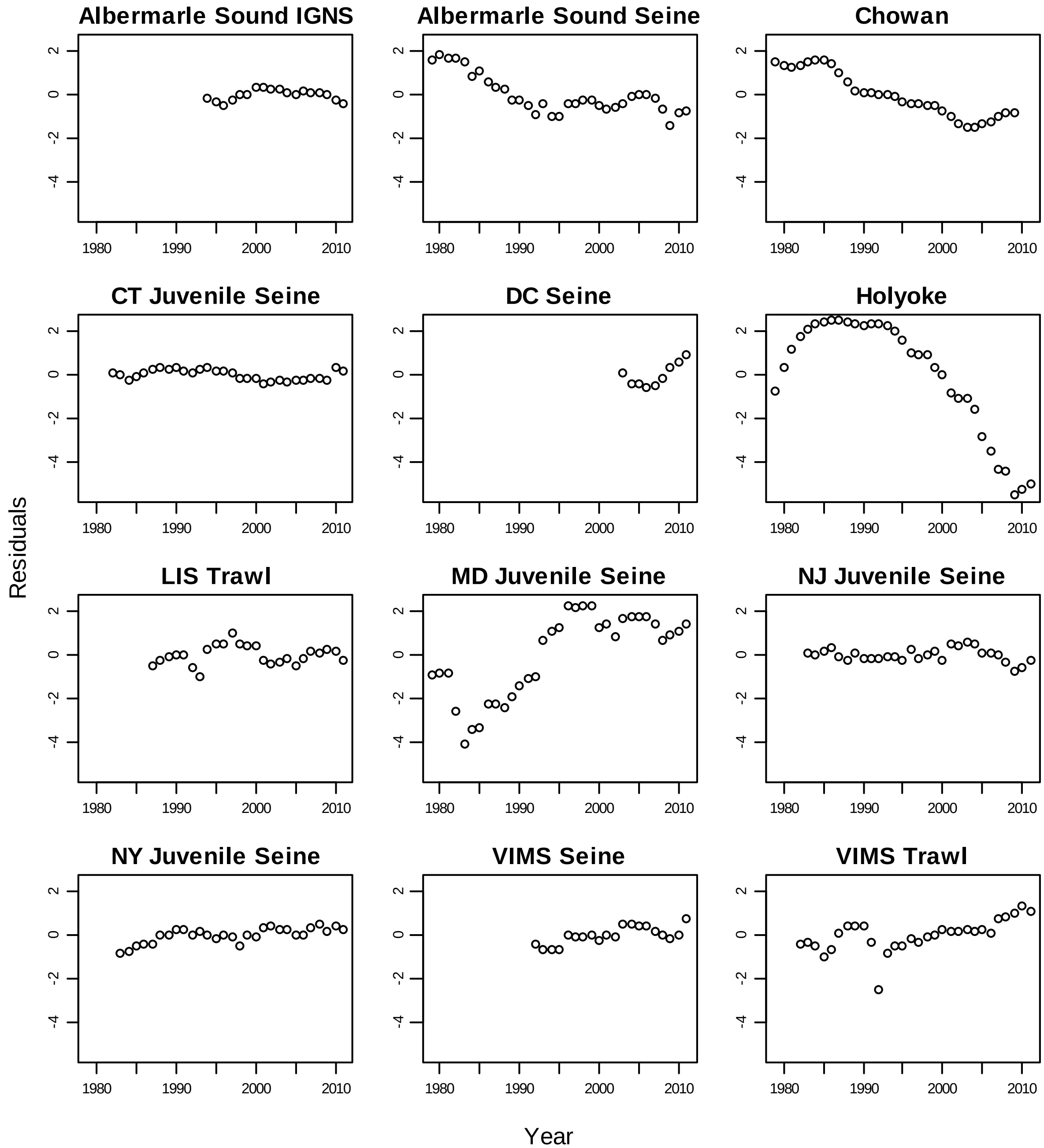

ME Juvenile Seine Survey
Oyster
Log (relative abundance)
5.5
5.0
4.5
4.0
3.5
3.0
2.5
1995
2000
2005
2010
Year

Figure 17: Residuals for each observation time series from the preferred model for each blueback herring stock: a) Southern, b) Mid-Atlantic, c) Southern New England and d) Northern New England.

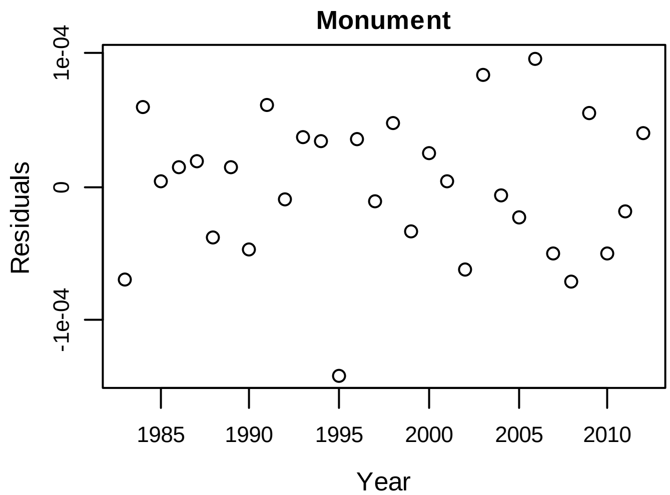
a)



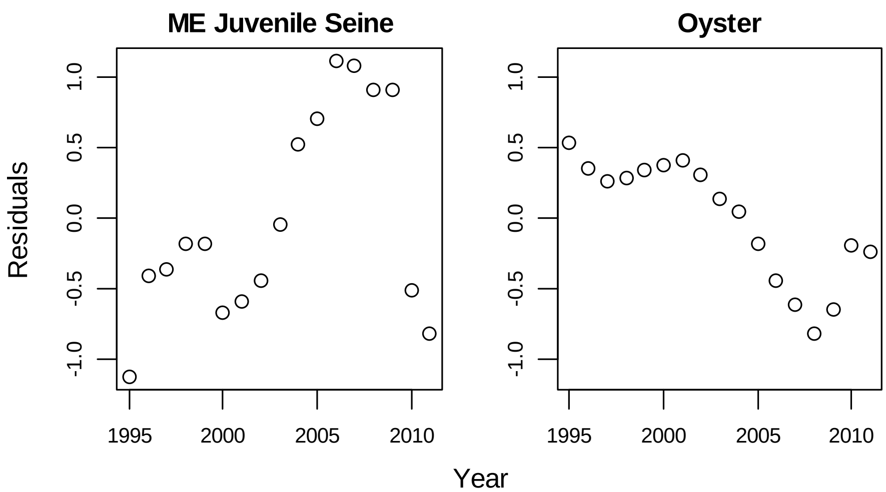
b)


Albermarle Sound IGNS
Albermarle Sound Seine
Chowan
CT Juvenile Seine
DC Seine
Holyoke
LIS Trawl
MD Juvenile Seine
NJ Juvenile Seine
NY Juvenile Seine
VIMS Seine
VIMS Trawl
Residuals
Year
2
0
-2
-4
1980
1990
2000
2010

c)


Monument
1e-04
0
-1e-04
Residuals
1985
1990
1995
2000
2005
2010
Year

d)


ME Juvenile Seine
Oyster
1.0
0.5
0.0
-0.5
-1.0
Residuals
1995
2000
2005
2010
Year