7-27-2022

Age Based Assessment in the Sea Scallop Placopecten magellanicus: A Pilot Study - Final Report

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Recommended Citation
Mann, R. L., Rudders, D., Roman, S., Southworth, M., & Clark, K. R. (2022) Age Based Assessment in the Sea Scallop Placopecten magellanicus: A Pilot Study - Final Report. Marine Resource Report No. 2022-02. Virginia Institute of Marine Science, William & Mary. https://doi.org/10.25773/vacb-7505

Final Report

Age Based Assessment in the Sea Scallop *Placopecten magellanicus*: A Pilot Study

Award Number: NA18NMF4540014
VIMS Marine Resource Report No. 2022-02

Submitted to:

National Marine Fisheries Service
Northeast Fisheries Science Center
Cooperative Research Program
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July 28, 2022

VIRGINIA INSTITUTE OF MARINE SCIENCE
MARINE ADVISORY PROGRAM

Project Background

If the current sea scallop fishery is well managed with a Catch At Size Analysis (CASA) length structured model, then why bother with an age based assessment? The success of the CASA based approach, in conjunction with management measures, is demonstrated by the development of the scallop fishery over the past two decades to its current status as the one of the most valuable fisheries on the Atlantic coast of the United States (NOAA, 2021). But, even the best length-based model can be improved by the addition of age data. An age-based model calibrates a length-based model, including a description as to whether or not the age-length relationship is constant across time and space throughout the exploited range of the fishery. It also improves description of recruitment in species where age estimation for small/young individuals is difficult, and description of mortality where age estimation of large/old individuals is difficult (both are the current case for sea scallops). The project described here also improves on the current status quo for age estimation in that it allows the use of a full range of sizes collected individuals, rather than just larger individuals, in age estimation, and is not compromised where external shell signatures, the current base for scallop age estimation, are eroded and difficult to read. In short, an age-based assessment would provide tools to the scallop assessment that are currently limited in certain aspects.

If an age-based approach is so good why has it not already been implemented for scallops? Scallops present some unusual challenges in age estimation. Age estimation in bivalve molluscs has received considerable attention in the past two decades for ecological studies, fisheries management, and because long lived bivalves have proven to be useful tools in studies of long-term climate and environmental change (Richardson, 2001). Bivalve shells contain a complete archive of the life history of the individual animal, from recruitment of the larva to the benthos, through a mixture of daily, tidal, spawning, seasonal, and annual signatures to the growing edge on the post recruit to benthic form. Shells are produced in sequential layers by the mantle, with the youngest layer always being on the inside shell surface. The youngest layer is exposed at the growing edge, and the junctions between these overlapping layers appear as exposed signatures not unlike shingles on the side of a house. “Reading” this history is typically a matter of sectioning the individual valves and examining the periodicity of the recorded signatures (Richardson, 2001). Scallops, unfortunately, produce very little in the way of internal signatures and thus age estimation has forced focus on the external signatures, and these external signatures can easily be compromised.

Age and growth in seas scallops has been examined in support of fishery management since at least the 1950s. Merrill et al. (1966) provide a description of “Annual Marks on the Shell and Ligament of Sea Scallop”. The contribution both validates annual external signatures and provides a comprehensive description of the architecture of the hinge ligament including periodic signatures that are clearly annual. Strangely, the value of the ligament in general age estimation appears to have enjoyed very little subsequent attention. Posgay and Merrill (1979) provide a data summary for growth of *Placopecten magellanicus* over its latitudinal and bathymetric range including 1953, 1956 through 1963, and 1965. While the NEFSC surveys continued to collect specimens in the 1980s and 1990s (post Posgay and Merrill, 1979), these collections received only modest examination in support of management, despite this being a period of major rebuilding in the fishery, changes in gear design (notably ring size), reduction in crew size, area closures, and even signals of ecosystem change (Munroe et al., 2016). The recent (post 2000) NEFSC scallop assessments have considered annual growth increments as part of the size structured population assessments (NEFSC, 2018). In addition, there have been a number of excellent contributions addressing latitudinal and bathymetric variation in growth at various locations from Canadian to mid-Atlantic waters (Harris and Stokesbury, 2006; Hart and Chute 2009a; Hart and Chute 2009b; Langton et al., 1987; Parsons et al., 1993).

Merrill et al. (1966) verified the formation of annual external rings on the valve surface. Not all rings are annual, thus the first challenge in developing an age and growth description is to identify rings that have consistent causal processes such as spawning or growth cessation or initiation. An excellent review of literature to date addressing rings as records of scallop growth can be found in Chute et al. (2012).

External growth rings have generally been assumed to be annual (spring) in accordance with the earlier report of Merrill et al. (1996) and Hart and Chute (2009a); however, recent efforts employing oxygen isotopes by Chute et al. (2012) note the relationship of rings to (usually fall) spawning (see also Krantz et al. (1984) and Tan et al. (1988). A collective consideration of the literature reviewed by Chute et al. (2012) suggests a north to south gradation in season of external ring formation. Indeed, examination of rings near the hinge demonstrates that they are often numerous and discrimination of the first annual ring is difficult. How then are we to use external rings in generation of age at length descriptors? The current approach adopted by both NEFSC scientists and VIMS has been to focus on larger scallops with distinct annual rings in the mid to latter years of growth, measure growth increments and employ a Ford-Walford plot to estimate K and L_∞ growth parameters and include a mixed model approach to account for the variation in individual growth. We have employed this approach to successfully describe age and growth in eighty archive populations from 1982 through 1999 along the complete latitudinal gradient examined by NEFSC surveys (Mann and Rudders, 2019). The requirement for larger scallops with more easily defined rings has resulted in no data being generated from collections at stations where small(er) scallops were abundant and where external rings were either present in very large numbers (suggesting disturbance lines) or eroded. Thus, a significant proportion of 1977-2000 archive collections (from which our 1982-1999 samples originate) contribute nothing to the overall goal. In general, this limitation is countered by the availability of large numbers of shells for examination, but in focused problems, such as the abundance of “stunted” or “Peter Pan” scallops in the Nantucket Lightship South Deep scallop area management simulator (SAMS) area, such impediments can largely exclude collection of much relevant data.

An alternative method for ageing bivalves includes sectioning of either the entire shell or the hinge region, and polishing the exposed surface to emphasize internal signatures to identify external growth rings as the shell is formed (review in Richardson, 2001). Such methods have been developed and routinely used in surf clam age and growth estimation for stock assessment purposes at NEFSC. They have also been used extensively in studies of very long-lived species, such as the ocean quahog *Arctica islandica*, in climate change and fisheries related studies (Harding et al., 2008; Butler et al., 2013; Marchitto et al., 2000; Wannamaker et al., 2009; Wannamaker et al. 2011; Pace et al. 2017). Importantly, internal signature counts allow examination where external rings may be less identifiable as a result of shell erosion and biofouling. The Mann laboratory at VIMS has worked on aspects of surf clam and ocean quahog age determination since 2005, including development of image analysis-based approaches to discriminating growth signatures of varying intensity (methods in Harding et al., 2008; Pace et al. 2017, Hemeon et al 2021). VIMS has examined sections of scallop shell both from the hinge to the growing edge along the main axis of growth, and through the “wings” of the hinge that exhibit complex external signatures. Surprisingly, in neither case do we observe any strong signatures that can be related to annual grow patterns (Mann and Rudders, 2019).

Merrill et al. (1966) describe the presence of annual signatures in the ligaments and resilia of scallops. As part of our efforts to develop accurate methods to age scallops, ageing of the ligaments and resilia has been conducted at VIMS (Mann and Rudders, 2019). Preparation of the ligaments and resilia is both relatively simple and inexpensive. Figures 1 through 3 illustrate parts of the hinge, resilia and ligament structure. There are distinct, well preserved (in archive) signatures that are related to annual growth cessations, and are present in both valves.

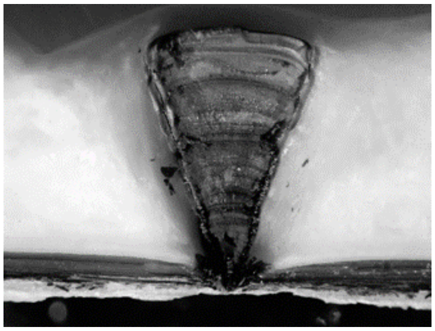


Figure 1. Banding pattern on the inner valve resilia surface of *Placopecten magellanicus* after removal of the ligament.

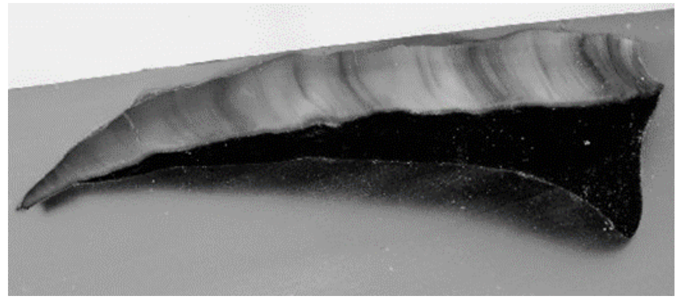


Figure 2. Embedded polished section through resilia (light upper portion) and ligament (dark lower portion) of *Placopecten magellanicus* illustrating internal growth signatures.

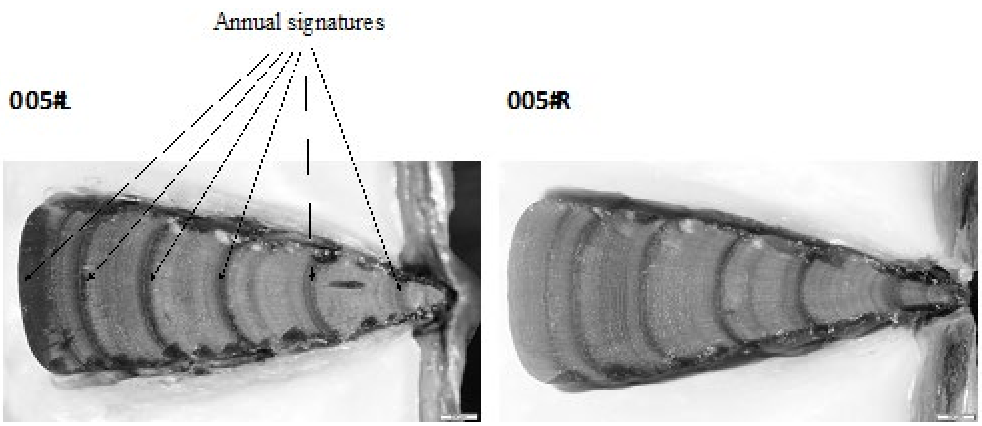


Figure 3. Resilia from left (L) and right (R) valve hinge structures of one scallop indicating annual growth signatures – both valves provide information.

We have prepared specimens as in Figure 1 and 3 from scallops collected from the NEFSC and VIMS scallop dredge surveys. The method can equally be applied to previously frozen samples. We have also successfully employed the same approach to estimate age in the Antarctic scallop *Adamussium colbecki*, a species that has been notoriously difficult to age because of its very thinly calcified shells (Cronin et al., 2020).

We argue that scallop age can be estimated with accuracy and consistency and at modest cost in large numbers of individuals of differing size and status with respect to external signatures or other structures. Mann and Rudders (2019) provided an overview of the different ageing techniques assessed by VIMS and which methods were determined to be the best approaches to continue ageing scallops collected from the VIMS resource assessment surveys. The challenge is to create (minimally) age at length (anatomically length is dimension parallel to the hinge, the maximum distance from hinge (umbo) to the growing edge is height; however, the hinge to growing edge measure is commonly termed length in scallop management so we use the term length for this text) relationships for each year of collection, and (preferably) to provide age at length relationships for both years and location (region) of collection. It is also important to explain several terms: “signature” include both external rings and internal (to the shell structure) markings that are the result of variation in growth rate whereas “rings” refers only to external signatures resulting from junctions at overlapping layers of shell production. We examined the utility of external rings, internal signatures, signatures in sectioned ligaments, ligament scars, and verification of estimates with stable isotopes.

For this project, we continued collecting sea scallop shells during the VIMS scallop resource surveys from the Mid-Atlantic and Georges Bank areas for ageing. This was done in support of developing paired data sets based on length for the current CASA approach and age for the pilot comparison. Again, the development of an age-based pilot assessment is predicated on the premise that scallop age can be estimated with accuracy and consistency in a large number of scallops. Several objectives were addressed for this project with respect to the development of an age dataset for use in an pilot assessment:

- Age length keys by year and resource area were generated and assessed for accuracy;
- External ring signature age data were compared to resilia age data to determine the utility of both age methods for future use; and
- von Bertalanffy growth models were developed by resource area and Scallop Area Management Simulator (SAMS) Area.

Methods

Shell Collection

Scallops shells were collected during the VIMS Mid-Atlantic Bight (MAB) and Georges Bank (GB) surveys included in this report from 2016-2019. In 2016 and 2017 scallop shells were collected at one station in the south, west, east, north, and center of each survey. In 2018 and 2019 at the majority of survey stations, up to fifteen scallop shells were collected at every fifth station on all surveys for ageing purposes. For select stations in the Elephant Trunk and Hudson Canyon SAMS Areas in the MAB and in the Nantucket Light South Deep SAMS Area on GB, up to 30 shells were collected. This augmented sampling was completed for another VIMS RSA project where sampling intensity was increased to study the effects of density on scallop biology and sampling for this project was conducted during our annual surveys (Roman et al., 2021). Shells were selected to be representative of the length distribution at a given survey station to ensure collection of both smaller and larger individuals, and if there was no shell damage (i.e., broken shell, damaged margin of shell or deformed). Shells were collected in May of 2018 and 2019 from the Mid-Atlantic survey. On Georges Bank, shells were collected from Closed Area I and II in June of 2018 and 2019 and the Nantucket Lightship survey in July of 2018 and 2019 (Figure 4).

Shells were aged using the external ring method described in Hart and Chute (2009a), as well as by examining the resilia structure as described in Mann and Rudders (2019), beginning in 2018. The external ring method identifies annual rings on the outside of the scallop shell. External annual rings were identified to take measurements between consecutive rings for use in estimating growth parameters (K and L_∞) following Hart and Chute (2009a), and to estimate the age. This approach does not always ensure annual rings align with an estimated age, as earlier external rings are often difficult to identify due to degradation as a result of erosion over time, especially for larger animals (Chute et al., 2012; NEFSC, 2018). For smaller animals identifying early external rings is difficult due to the overall size of the animal as well as when an animal spawned. Also, external rings on the outer part of the shell can often be difficult to identify and there is no age 1 ring (Chute et al., 2012; NEFSC, 2018). This can result in a misspecification of age based on counting the number of annual rings identified, when assuming the number of annual rings equals the true age of an animal. For example, a scallop that had three external rings identified could be assumed to be age 3 even if the animal was 60 mm or 140 mm in length. The NEFSC (2018) identifies 65-70 mm as the average length for a 2.5 year old scallop. External ring age was estimated by summing up the number of annual rings identified. The resilia age method counted the number of bands observed in the structure and age was assigned based on the number of bands identified (Mann and Rudders, 2019). A subset of shells was added to the archived collection housed at VIMS.

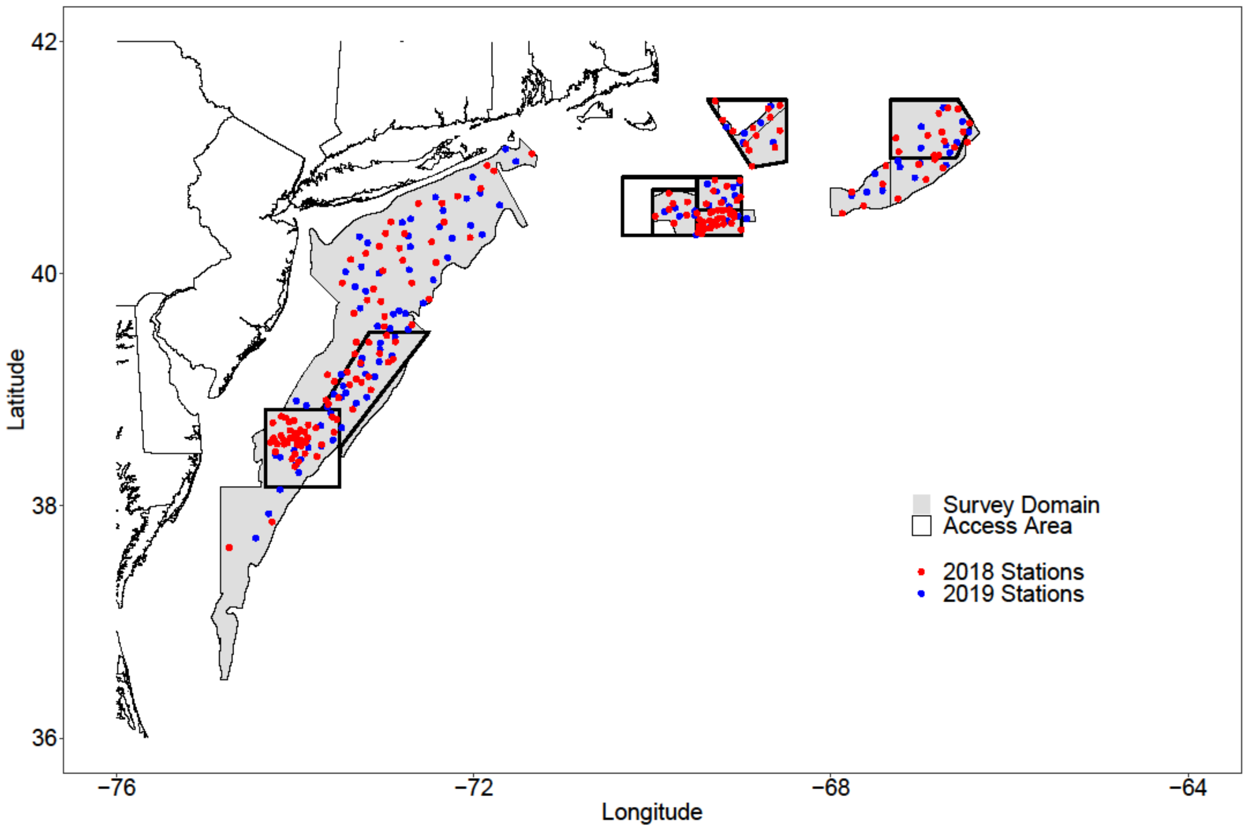


Figure 4. Station locations where scallops were collected for ageing in 2018 and 2019 during VIMS scallop dredge surveys.

Data Analysis

Age Length Keys

Age length keys (ALK) were created by year for 2018 and 2019 and survey area (MAB and GB) with the external ring and resilia datasets following the methods described in Ogle (2016). ALKs were generated with the FSA package in R version 4.1.2 (Ogle, 2016; R, 2021; Ogle et al., 2022). Scallops were binned into five mm length bins for consistency with the stock assessment (NEFSC, 2018). Observed ALKs were generated using only data from aged scallops for both the external ring and resilia datasets. Since several length bins were not represented in the observed aged scallops and sample sizes were small for several length bins, ALKs were also generated with a multinomial logistic regression model for the external ring dataset only for the entire length distribution of scallops observed in either the external or resilia dataset (Gerritsen et al., 2006; Ogle et al., 2022). Modelled ALKs fit age at length data for all length intervals observed in the population and allow for the predicted proportion of shellfish at age to be affected by data from other length bins and ages. The mulitnom function in the nnet R package was used to model length at age and predicted ALKs were generated from the model predictions (Venables and Ripley, 2002; Ogle et al. 2022).

Both observed and predicted ALKs were assessed for bias by visual inspection of ALKs with respect to the current understanding of scallop growth and age, with a particular focus on younger ages (1-4). The assumption for scallop size-at-age for ages 1-4 is: age 1=25mm, age 2=50 mm, age 3=75 mm ,and age 4=100 mm. Bias was defined as if the estimated age was over or underestimated over any portion of the length range (Ogle, 2016). The length distribution of scallops selected for aging with the external ring method was compared to the length distribution of all scallops sampled on the surveys to determine if a representative sample of all sizes classes was being aged. The resilia ALKs were compared to the external ring ALKs to assess relative performance of this age method.

External vs Resilia Age Comparison

Scallops aged with both the external ring signature method and the resilia method were compared to assess the accuracy, precision, and bias of both methods. Age data were aggregated across years and resource areas. The definition of bias is the same as for the ALKs. Accuracy was defined as if the estimated age was equal to the true age, with the assumption that the external ring signature age is the true age (Ogle, 2016). Precision was defined as the repeatability of two different paired age methods to generate similar ages for individual scallops (Olge, 2016). The difference between the resilia minus the external paired age data for individual scallops was estimated using the ageBias function in the FSA R package (Campana et al., 1995; Ogle, 2016; Ogle et al., 2022). This function tests for significant differences between age pairs with a Evans and Hoenig symmetry test (Evans and Hoenig, 1998). Statistical significance was equal to $\alpha < 0.5$. Paired age data were plotted by age with the mean external ring age estimate and range of the difference. Marginal histograms for the external ring age and the difference between the resilia and external ring samples were plotted along with sample sizes. The plotAB function from the FSA R package was also used to create an age bias plot comparing mean age with 95% confidence intervals by age (Campana et al., 1995, Ogle et al., 2022). Finally, a generalized additive model (GAM) was used to estimate the difference between the two datasets as a function of mean age with the mgcv R package (Ogle, 2016; Wood, 2017). The response variable was the difference between the resilia and external age and the predictor variable was the mean age. The mean predicted age difference over the length range of scallops aged was plotted with 95% confidence intervals. A marginal histogram of the difference between age types was also included. The measure of precision between the two datasets was determined with the agePrecision function in the FSA R package (Olge, 2016; Ogle et al., 2022). The function provides the percent agreement for all paired ages with perfect agreement, the average coefficient of variation (CV) of ages within scallops, and the average standard deviation (SD) of ages within a scallop across all scallops. A histogram of the difference was also plotted.

von Bertalanffy Growth Models

von Bertalanffy growth models were developed for both the external ring and resilia datasets by resource area separately. von Bertalanffy growth models with the external ring data followed methods described by Hart and Chute (2009a) and used a mixed effect generalized linear model with scallop as a random effect to account for repeated measures taken on each animal. Mean growth parameters (L_∞ and K) were estimated using a random intercept model (L_∞ only) due to sample size (Hart, personal communication). Scallops with only two annual external ring signatures were removed. One deviation from the Hart and Chute (2009a) approach was to retain scallops < 40 mm. This was done to include scallops in the Nantucket Light South Deep SAMS Area that have exhibited slow growth and as such may have been excluded based on the 40 mm length threshold used by Hart and Chute (2009a) (NEFSC, 2018). The effect of additional predictor variables on L_∞ was also estimated via GLMMs. Additional predictors considered were SAMS Area, average depth, latitude, and year. Models with additional predictor variables were developed with forward selection and the preferred model was selected based on Bayesian information criteria (BIC). Predicted growth curves were plotted for the preferred models with additional predictor variables by resource area.

von Bertalanffy growth models were also estimated with the resilia dataset by resource area to compare to the traditional external ring growth parameter estimates. The non-linear traditional von Bertalanffy model was used initially to estimate growth parameters with the nls and vbStarts R functions from the stats and FSA packages, respectively. Based on the mixed effect model results of Hart and Chute (2009a) indicating growth estimates were more accurate, two additional von Bertalanffy models were developed that accounted for scallop shells collected at a given station being similar in length and potentially age. Two different approaches were explored to model the dataset. The nlme function in the nlme R package (Pinheiro et al., 2021) treated station as the random effect and the clus.vb.fit function in the fishmethods R package (Nelson, 2018) estimated growth parameters with bootstrapping by station. L_∞ and K parameter estimates from the external ring von Bertalanffy models were used as starting values for the nlme function and 0 was the starting value for the t0. Alternative starting values were also used to evaluate model convergence to a global minimum and the impact on parameter estimates (McCullough, 2008).

Results

Shell Collection

Table 1 provides the number of scallop shells aged by year, area, and age method. Due to the limited number of shells collected in 2016 and 2017, these years were not included in any analysis. Table 2 provides the number of shells aged by resource area and age method for 2018 and 2019 used in all analyses.

Table 1. Number of shells aged by year, area, and method (external ring signature or resilia) from 2016-2019.

Year	Area	Age Method	Number
2016	GB	External	29
2016	MAB	External	42
2017	GB	External	123
2017	MAB	External	93
2018	GB	External	235
2018	GB	Resilia	143
2018	MAB	External	374
2018	MAB	Resilia	138
2019	GB	External	715
2019	GB	Resilia	840
2019	MAB	External	1,032
2019	MAB	Resilia	1,143

Table 2. Number of shells aged in 2018 and 2019 by resource area and age method.

Year	Area	Age Method	
		External	Resilia
2018	GB	235	143
	MAB	374	138
2019	GB	715	840
	MAB	1,032	1,143
Total			2,761

Age Length Keys

External ring dataset ALKs by resource area and year are provided in Tables 3 and 4. Bubble plots of the external ring ALKs are provided in Figures 5 and 6. Based on the proportion of scallops in each length bin at age for both the MAB and GB in 2018 and 2019, there appears to be a misspecification of age for larger scallops. For the MAB in 2018, age 2 scallops range in length from 90 to 140 mm. The same problem is apparent in 2019 for ages 2 through 4, although the problem is more pronounced for ages 3 and 4 across the length range of scallops aged. For the GB ALKs, in both 2018 and 2019, the same problem persists for ages 2,3, and 4. In 2019, scallops across the majority of length range, excluding the largest size class (>160 mm), have a similar proportion of scallops aged as age 5. There are also several missing ages for both resource areas. In the MAB in 2019 there are no age 8 scallops, and for GB in 2019 there are no age 12 or 13 scallops. In 2018 for both areas there are less age classes than in 2019. There are no age 1 scallops in the external ring dataset, which is to be expected since age 1 external rings are not visible (NEFSC, 2018).

The modelled external ring ALKs are provided in Tables 5-8 and bubble plots are in Figures 7 and 8. Scallops in the sampled population ranged from 10 to 195 mm in length across both resource areas. While the modelled ALKs estimated the proportion at age for missing length bins for both resource areas, similar problems for ageing of younger scallops was detected. Age 2 scallops in the MAB ranged from 10 to 145 mm in 2018 and 2019. For GB, age problems were evident for age 2 through age 3 scallops in 2018 and up to age 5 scallops in 2019. For older scallops, the modelled ALK appeared to align better with expectation with respect to size at age.

Resilia bubble plots for the ALKs are in Figures 9 and 10. A comparison of external ring and resilia ALKs are in Figures 11 and 12. The resilia dataset was able to assign scallops as age 1 for the smallest length bins, but the length range of age 1 scallops across both resource areas was large. The largest age 1 scallop 115 mm and lengths ranged from 10 to 115 mm. For larger size scallops, the ALKs assigned older ages for larger scallops across the length range compared to the external ring ALKs for ages 2-5, with the exception of the GB 2019 ALK. Although there was still a large range of sizes that were assigned ages 3-5 for the GB dataset.

Age samples for the majority of smaller size classes (< 80 mm) are missing for both the MAB and GB resource areas in both years for the external ring dataset (Table 9). If one of the goals of the project is to age smaller size classes of scallops, there should be an increased effort in retaining smaller sizes for ageing. Only resilia aged scallops were determined to be age 1, and these scallops ranged in length from 43-131 mm.

Table 3. External ring dataset age length keys for the Mid-Atlantic resource area for 2018 and 2019.

2018								
	Age							
Length Bin	2	3	4	5	6	7	8	9
90	1	0	0	0	0	-	-	-
95	1	0	0	0	0	-	-	-
100	0.78	0.22	0	0	0	-	-	-
105	0.69	0.28	0.03	0	0	-	-	-
110	0.50	0.50	0	0	0	-	-	-
115	0.69	0.25	0.05	0	0	-	-	-
120	0.59	0.29	0.11	0.01	0	-	-	-
125	0.38	0.38	0.20	0.04	0	-	-	-
130	0.32	0.43	0.14	0.11	0	-	-	-
135	0.15	0.15	0.31	0.23	0.15	-	-	-
140	0.14	0	0.43	0.14	0.29	-	-	-
145	0	0	1	0	0	-	-	-
150	0	0	0.5	0.5	0	-	-	-

2019								
	Age							
Length Bin	2	3	4	5	6	7	8	9
80	0	0.50	0.50	0	0	0	0	0
85	0.71	0.29	0	0	0	0	0	0
90	0.62	0.31	0.08	0	0	0	0	0
95	0.47	0.27	0.23	0.03	0	0	0	0
100	0.60	0.14	0.26	0	0	0	0	0
105	0.50	0.21	0.29	0	0	0	0	0
110	0.33	0.24	0.39	0.04	0	0	0	0
115	0.22	0.26	0.50	0.02	0	0	0	0
120	0.08	0.28	0.59	0.04	0.01	0	0	0
125	0.02	0.22	0.65	0.10	0.01	0	0	0
130	0	0.14	0.62	0.18	0.06	0	0	0
135	0	0.12	0.59	0.10	0.15	0.03	0	0
140	0	0.03	0.42	0.44	0.06	0.06	0	0
145	0	0	0.22	0.33	0.22	0.11	0.11	0.11
150	0	0	0	0	1	0	0	0

Table 4. External ring dataset age length keys for the Georges Bank resource area for 2018 and 2019.

	2018												
	Age												
Length Bin	2	3	4	5	6	7	8	9	10	11	12	13	14
75	0	1	0	0	0	0	0	-	-	-	-	-	-
80	0.50	0.50	0	0	0	0	0	-	-	-	-	-	-
85	0	1	0	0	0	0	0	-	-	-	-	-	-
90	0.50	0.33	0.17	0	0	0	0	-	-	-	-	-	-
95	0.44	0.44	0.11	0	0	0	0	-	-	-	-	-	-
100	0.32	0.37	0.32	0	0	0	0	-	-	-	-	-	-
105	0.30	0.45	0.20	0.05	0	0	0	-	-	-	-	-	-
110	0.24	0.47	0.24	0.06	0	0	0	-	-	-	-	-	-
115	0.21	0.63	0.16	0	0	0	0	-	-	-	-	-	-
120	0.09	0.48	0.30	0.04	0.04	0.04	0	-	-	-	-	-	-
125	0.05	0.32	0.32	0.26	0.05	0	0	-	-	-	-	-	-
130	0.11	0.39	0.33	0.06	0.06	0.06	0	-	-	-	-	-	-
135	0.16	0.37	0.11	0.26	0.11	0	0	-	-	-	-	-	-
140	0	0.35	0.25	0.1	0.1	0.15	0.05	-	-	-	-	-	-
145	0	0.18	0.36	0.09	0.09	0.18	0.09	-	-	-	-	-	-
150	0	0	0	0.33	0	0.67	0	-	-	-	-	-	-
155	0	0	0	0	1	0	0	-	-	-	-	-	-
160	0	0	0	0	1	0	0	-	-	-	-	-	-
	2019												
	Age												
Length Bin	2	3	4	5	6	7	8	9	10	11	12	13	14
70	0	0.50	0	0.50	0	0	0	0	0	0	-	-	0
75	0	0	0.14	0.86	0	0	0	0	0	0	-	-	0
80	0	0.21	0.05	0.74	0	0	0	0	0	0	-	-	0
85	0.05	0.24	0.24	0.47	0	0	0	0	0	0	-	-	0
90	0.05	0.19	0.32	0.43	0	0	0	0	0	0	-	-	0
95	0.05	0.23	0.33	0.38	0	0	0	0	0	0	-	-	0
100	0.06	0.17	0.31	0.39	0.08	0	0	0	0	0	-	-	0
105	0.12	0.22	0.43	0.19	0.03	0	0	0	0	0	-	-	0
110	0.17	0.14	0.29	0.34	0.06	0	0	0	0	0	-	-	0
115	0.13	0.15	0.20	0.42	0.10	0	0	0	0	0	-	-	0
120	0.13	0.20	0.17	0.33	0.16	0.02	0	0	0	0	-	-	0
125	0.05	0.29	0.20	0.27	0.20	0	0	0	0	0	-	-	0
130	0	0.05	0.13	0.48	0.23	0.04	0.05	0	0.02	0	-	-	0
135	0	0.07	0.13	0.40	0.29	0.07	0.04	0	0	0	-	-	0
140	0	0	0.04	0.46	0.39	0.04	0.06	0	0	0.02	-	-	0
145	0	0	0.03	0.21	0.48	0.10	0.07	0	0.07	0	-	-	0.03
150	0	0	0	0.27	0.40	0.20	0.07	0.07	0	0	-	-	0
155	0	0	0	0.25	0	0.25	0.25	0.25	0	0	-	-	0
160	0	0	0	0	0	0	0.50	0	0.5	0	-	-	0
165	0	0	0	0	0	0.50	0	0	0.5	0	-	-	0

Figure 5. Bubble plots of the external ring age length keys for the Mid-Atlantic resource area by year.

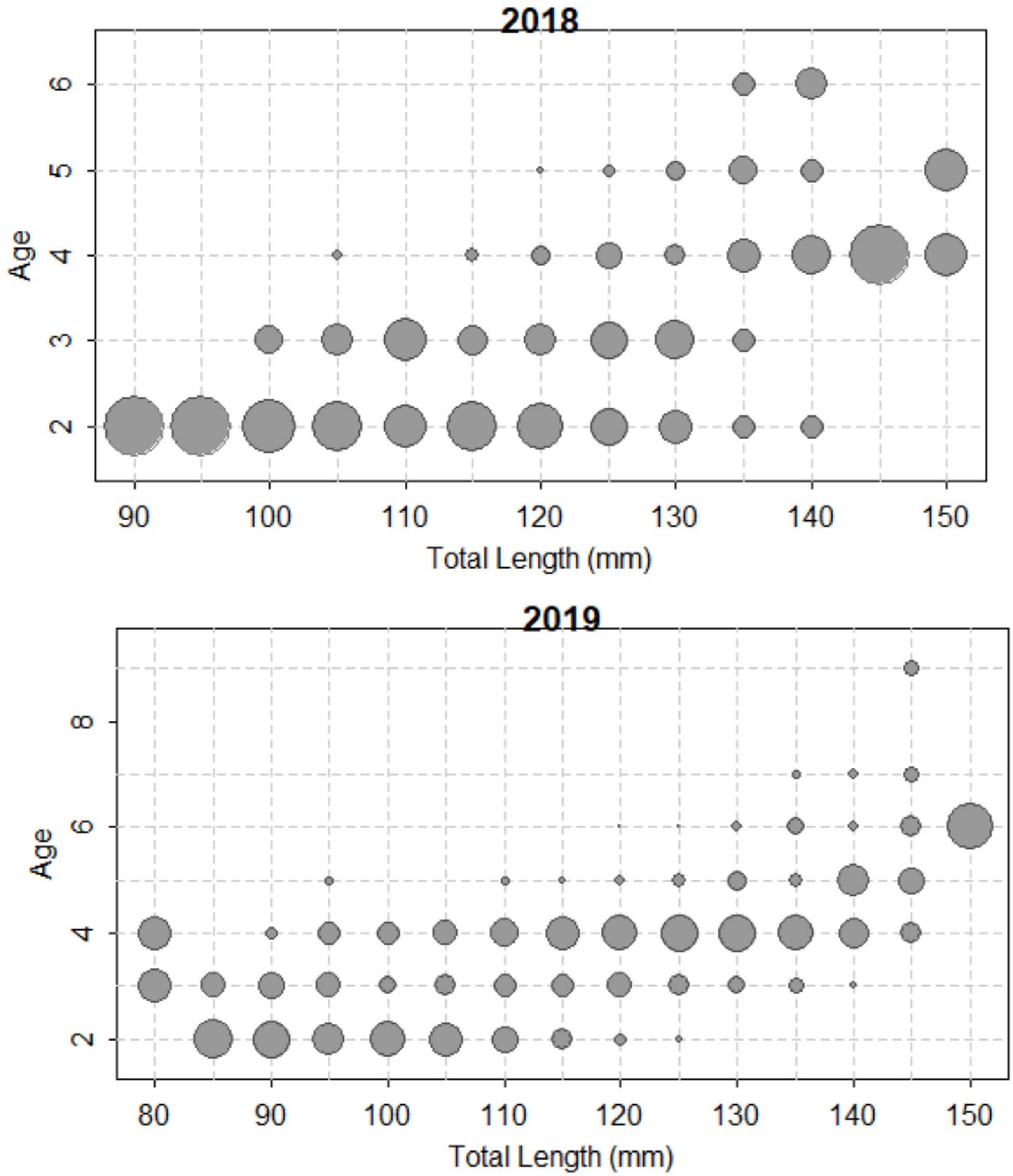


Figure 6. Bubble plots of the external ring age length keys for the Georges Bank resource area by year.

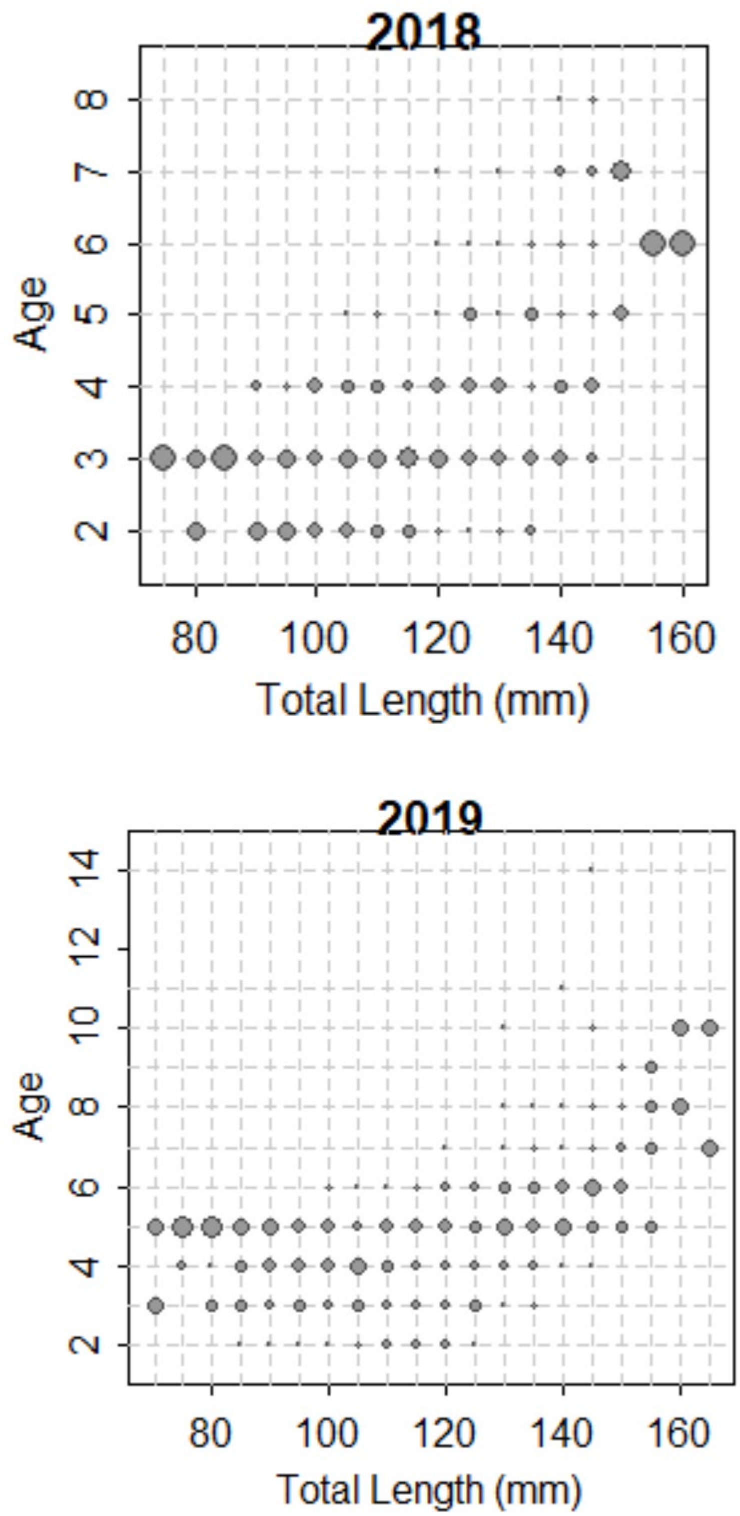


Table 5. Modelled external ring age length keys for the Mid-Atlantic resource area for 2018.

2018								
	Age							
Length Bin	2	3	4	5	6	7	8	9
10	0.99	0	0	0	0	-	-	-
15	0.98	0	0	0	0	-	-	-
20	0.98	0	0	0	0	-	-	-
25	0.98	0	0	0	0	-	-	-
30	0.97	0	0	0	0	-	-	-
35	0.97	0	0	0	0	-	-	-
40	0.96	0	0	0	0	-	-	-
45	0.95	0	0	0	0	-	-	-
50	0.95	0	0	0	0	-	-	-
55	0.94	0.1	0	0	0	-	-	-
60	0.93	0.1	0	0	0	-	-	-
65	0.91	0.1	0	0	0	-	-	-
70	0.90	0.1	0	0	0	-	-	-
75	0.88	0.1	0	0	0	-	-	-
80	0.86	0.1	0	0	0	-	-	-
85	0.84	0.2	0.0	0	0	-	-	-
90	0.81	0.2	0.0	0	0	-	-	-
95	0.78	0.2	0.0	0	0	-	-	-
100	0.75	0.2	0.01	0	0	-	-	-
105	0.72	0.3	0.01	0	0	-	-	-
110	0.67	0.3	0.02	0	0	-	-	-
115	0.62	0.3	0.05	0.01	0	-	-	-
120	0.54	0.4	0.09	0.01	0	-	-	-
125	0.45	0.3	0.17	0.04	0.01	-	-	-
130	0.33	0.3	0.27	0.09	0.02	-	-	-
135	0.20	0.2	0.36	0.17	0.05	-	-	-
140	0.10	0.1	0.40	0.27	0.10	-	-	-
145	0.04	0.1	0.37	0.37	0.16	-	-	-
150	0.02	0	0.30	0.44	0.22	-	-	-
155	0.01	0	0.23	0.48	0.28	-	-	-
160	0	0	0.16	0.49	0.34	-	-	-
165	0	0	0.11	0.49	0.40	-	-	-
170	0	0	0.07	0.47	0.45	-	-	-
175	0	0	0.05	0.45	0.50	-	-	-
180	0	0	0.03	0.42	0.55	-	-	-
185	0	0	0.02	0.38	0.60	-	-	-
190	0	0	0.01	0.35	0.64	-	-	-
195	0	0	0.01	0.31	0.68	-	-	-

Table 6 Modelled external ring age length keys for the Mid-Atlantic resource area for 2019.

2019								
	Age							
Length Bin	2	3	4	5	6	7	8	9
10	1	0	0	0	0	0	-	0
15	1	0	0	0	0	0	-	0
20	1	0	0	0	0	0	-	0
25	1	0	0	0	0	0	-	0
30	1	0	0	0	0	0	-	0
35	1	0	0	0	0	0	-	0
40	1	0	0	0	0	0	-	0
45	1	0	0	0	0	0	-	0
50	0.99	0.01	0	0	0	0	-	0
55	0.99	0.01	0	0	0	0	-	0
60	0.99	0.01	0	0	0	0	-	0
65	0.98	0.02	0	0	0	0	-	0
70	0.96	0.03	0.01	0	0	0	-	0
75	0.94	0.05	0.01	0	0	0	-	0
80	0.91	0.07	0.02	0	0	0	-	0
85	0.86	0.10	0.04	0	0	0	-	0
90	0.78	0.14	0.08	0	0	0	-	0
95	0.68	0.19	0.14	0	0	0	-	0
100	0.55	0.23	0.22	0	0	0	-	0
105	0.41	0.27	0.32	0.01	0	0	-	0
110	0.28	0.28	0.43	0.02	0	0	-	0
115	0.17	0.27	0.53	0.03	0	0	-	0
120	0.10	0.24	0.60	0.06	0.01	0	-	0
125	0.05	0.20	0.63	0.10	0.02	0	-	0
130	0.03	0.15	0.62	0.16	0.04	0	-	0
135	0.01	0.11	0.55	0.23	0.09	0.02	-	0
140	0	0.06	0.42	0.28	0.17	0.05	-	0.01
145	0	0.03	0.25	0.27	0.26	0.14	-	0.04
150	0	0.01	0.10	0.18	0.29	0.28	-	0.14
155	0	0	0.03	0.09	0.21	0.38	-	0.29
160	0	0	0.01	0.03	0.12	0.38	-	0.47
165	0	0	0	0.01	0.05	0.31	-	0.62
170	0	0	0	0	0.02	0.23	-	0.74
175	0	0	0	0	0.01	0.16	-	0.83
180	0	0	0	0	0	0.11	-	0.89
185	0	0	0	0	0	0.07	-	0.93
190	0	0	0	0	0	0.04	-	0.96
195	0	0	0	0	0	0.03	-	0.97

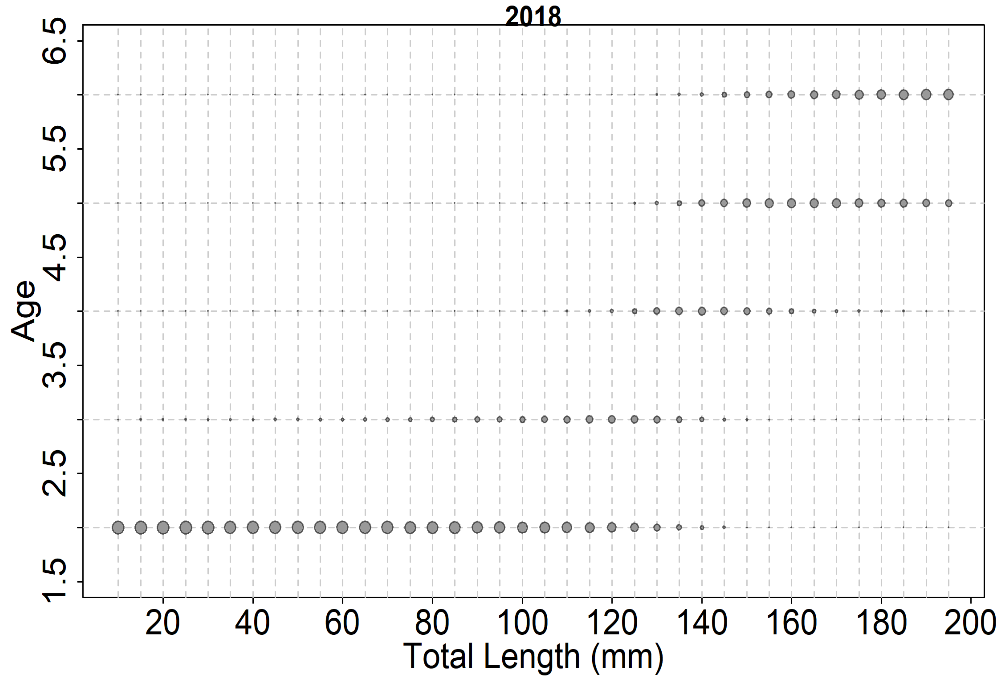
Table 7. Modelled external ring age length keys for the Georges Bank resource area for 2018.

	2018												
	Age												
Length Bin	2	3	4	5	6	7	8	9	10	11	12	13	14
10	0.76	0.2	0.0	0	0	0	0	-	-	-	-	-	-
15	0.73	0.3	0.0	0	0	0	0	-	-	-	-	-	-
20	0.71	0.3	0.0	0	0	0	0	-	-	-	-	-	-
25	0.69	0.3	0.0	0	0	0	0	-	-	-	-	-	-
30	0.67	0.3	0.0	0	0	0	0	-	-	-	-	-	-
35	0.64	0.3	0.0	0	0	0	0	-	-	-	-	-	-
40	0.62	0.4	0.0	0	0	0	0	-	-	-	-	-	-
45	0.59	0.4	0.0	0	0	0	0	-	-	-	-	-	-
50	0.56	0.4	0.0	0	0	0	0	-	-	-	-	-	-
55	0.53	0.4	0.0	0	0	0	0	-	-	-	-	-	-
60	0.50	0.4	0.0	0	0	0	0	-	-	-	-	-	-
65	0.48	0.5	0.1	0	0	0	0	-	-	-	-	-	-
70	0.45	0.5	0.1	0	0	0	0	-	-	-	-	-	-
75	0.42	0.5	0.1	0	0	0	0	-	-	-	-	-	-
80	0.38	0.5	0.1	0	0	0	0	-	-	-	-	-	-
85	0.35	0.5	0.1	0.01	0	0	0	-	-	-	-	-	-
90	0.32	0.5	0.1	0.01	0	0	0	-	-	-	-	-	-
95	0.30	0.5	0.2	0.01	0	0	0	-	-	-	-	-	-
100	0.27	0.5	0.2	0.02	0	0	0	-	-	-	-	-	-
105	0.24	0.5	0.2	0.03	0	0	0	-	-	-	-	-	-
110	0.21	0.5	0.2	0.04	0	0	0	-	-	-	-	-	-
115	0.18	0.5	0.2	0.06	0.01	0	0	-	-	-	-	-	-
120	0.16	0.5	0.3	0.08	0.01	0.01	0	-	-	-	-	-	-
125	0.13	0.4	0.3	0.10	0.03	0.02	0	-	-	-	-	-	-
130	0.10	0.4	0.3	0.13	0.05	0.04	0.01	-	-	-	-	-	-
135	0.08	0.3	0.3	0.16	0.09	0.07	0.01	-	-	-	-	-	-
140	0.05	0.2	0.2	0.17	0.14	0.12	0.03	-	-	-	-	-	-
145	0.03	0.2	0.2	0.17	0.21	0.18	0.04	-	-	-	-	-	-
150	0.02	0.1	0.1	0.15	0.28	0.24	0.06	-	-	-	-	-	-
155	0.01	0.1	0.1	0.12	0.34	0.29	0.09	-	-	-	-	-	-
160	0	0	0.1	0.09	0.38	0.33	0.11	-	-	-	-	-	-
165	0	0	0	0.07	0.41	0.35	0.13	-	-	-	-	-	-
170	0	0	0	0.04	0.42	0.37	0.15	-	-	-	-	-	-
175	0	0	0	0.03	0.42	0.37	0.17	-	-	-	-	-	-
180	0	0	0	0.02	0.42	0.37	0.18	-	-	-	-	-	-
185	0	0	0	0.01	0.41	0.37	0.20	-	-	-	-	-	-
190	0	0	0	0.01	0.40	0.37	0.22	-	-	-	-	-	-
195	0	0	0	0.01	0.39	0.36	0.24	-	-	-	-	-	-

Table 8. Modelled external ring age length keys for the Georges Bank resource area for 2019.

	2019												
	Age												
Length Bin	2	3	4	5	6	7	8	9	10	11	12	13	14
10	0.06	0.34	0.42	0.18	0	0	0	0	0	0	0	-	-
15	0.06	0.33	0.41	0.19	0	0	0	0	0	0	0	-	-
20	0.07	0.33	0.41	0.20	0	0	0	0	0	0	0	-	-
25	0.07	0.32	0.40	0.21	0	0	0	0	0	0	0	-	-
30	0.07	0.31	0.39	0.23	0	0	0	0	0	0	0	-	-
35	0.07	0.30	0.39	0.24	0	0	0	0	0	0	0	-	-
40	0.07	0.30	0.38	0.25	0	0	0	0	0	0	0	-	-
45	0.07	0.29	0.37	0.27	0	0	0	0	0	0	0	-	-
50	0.07	0.28	0.37	0.28	0	0	0	0	0	0	0	-	-
55	0.07	0.27	0.36	0.29	0.0	0	0	0	0	0	0	-	-
60	0.08	0.26	0.35	0.31	0.0	0	0	0	0	0	0	-	-
65	0.08	0.26	0.34	0.32	0.0	0	0	0	0	0	0	-	-
70	0.08	0.25	0.33	0.34	0.0	0	0	0	0	0	0	-	-
75	0.08	0.24	0.32	0.36	0.0	0	0	0	0	0	0	-	-
80	0.08	0.23	0.31	0.37	0.0	0	0	0	0	0	0	-	-
85	0.08	0.22	0.31	0.39	0.0	0	0	0	0	0	0	-	-
90	0.08	0.21	0.29	0.40	0.0	0	0	0	0	0	0	-	-
95	0.08	0.20	0.28	0.42	0.0	0	0	0	0	0	0	-	-
100	0.08	0.19	0.27	0.43	0.0	0	0	0	0	0	0	-	-
105	0.08	0.18	0.26	0.44	0.0	0	0	0	0	0	0	-	-
110	0.08	0.17	0.24	0.45	0.1	0	0	0	0	0	0	-	-
115	0.07	0.16	0.23	0.45	0.1	0	0	0	0	0	0	-	-
120	0.07	0.14	0.21	0.44	0.1	0.01	0	0	0	0	0	-	-
125	0.06	0.13	0.19	0.42	0.2	0.01	0.01	0	0	0	0	-	-
130	0.06	0.11	0.16	0.39	0.2	0.02	0.02	0	0	0	0	-	-
135	0.05	0.09	0.13	0.34	0.3	0.04	0.03	0	0	0	0	-	-
140	0.04	0.06	0.10	0.27	0.4	0.07	0.06	0.01	0.01	0	0	-	-
145	0.03	0.04	0.07	0.20	0.4	0.11	0.09	0.01	0.03	0.01	0.01	-	-
150	0.02	0.03	0.04	0.13	0.4	0.16	0.13	0.03	0.07	0.01	0.01	-	-
155	0.01	0.01	0.02	0.07	0.3	0.18	0.16	0.06	0.14	0.01	0.01	-	-
160	0	0.01	0.01	0.03	0.2	0.19	0.17	0.09	0.25	0.01	0.01	-	-
165	0	0	0	0.01	0.1	0.17	0.15	0.12	0.38	0.01	0.01	-	-
170	0	0	0	0.01	0.1	0.13	0.12	0.15	0.51	0	0.01	-	-
175	0	0	0	0	0	0.09	0.09	0.17	0.61	0	0.01	-	-
180	0	0	0	0	0	0.06	0.06	0.17	0.69	0	0.01	-	-
185	0	0	0	0	0	0.04	0.04	0.17	0.74	0	0	-	-
190	0	0	0	0	0	0.02	0.02	0.16	0.78	0	0	-	-
195	0	0	0	0	0	0.01	0.01	0.16	0.81	0	0	-	-

Figure 6. Bubble plots of the modelled external ring age length keys for the Mid-Atlantic resource area by year.



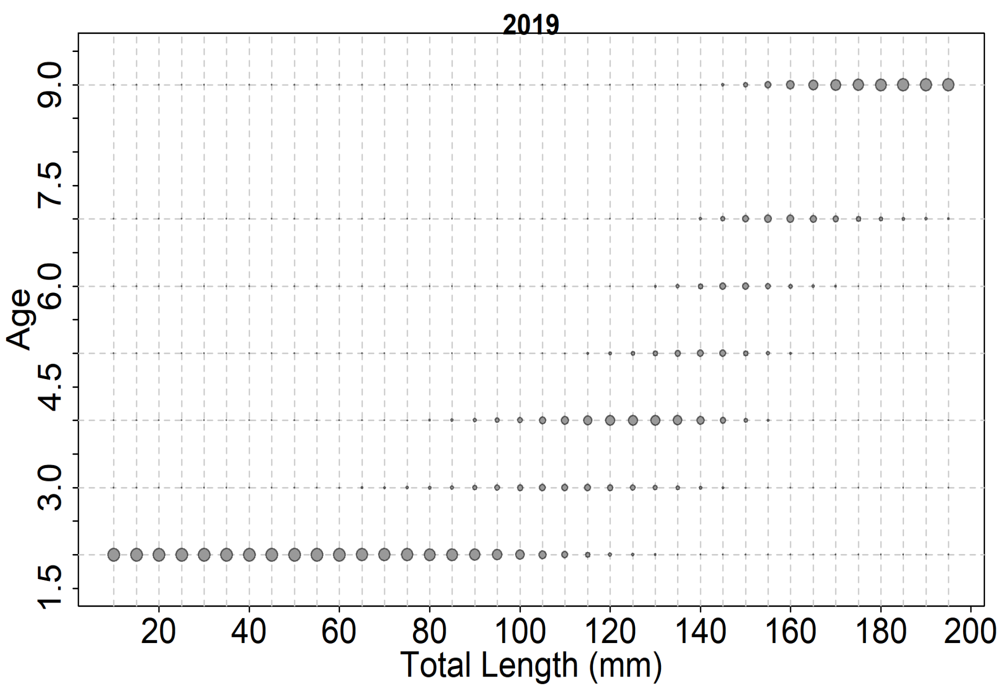
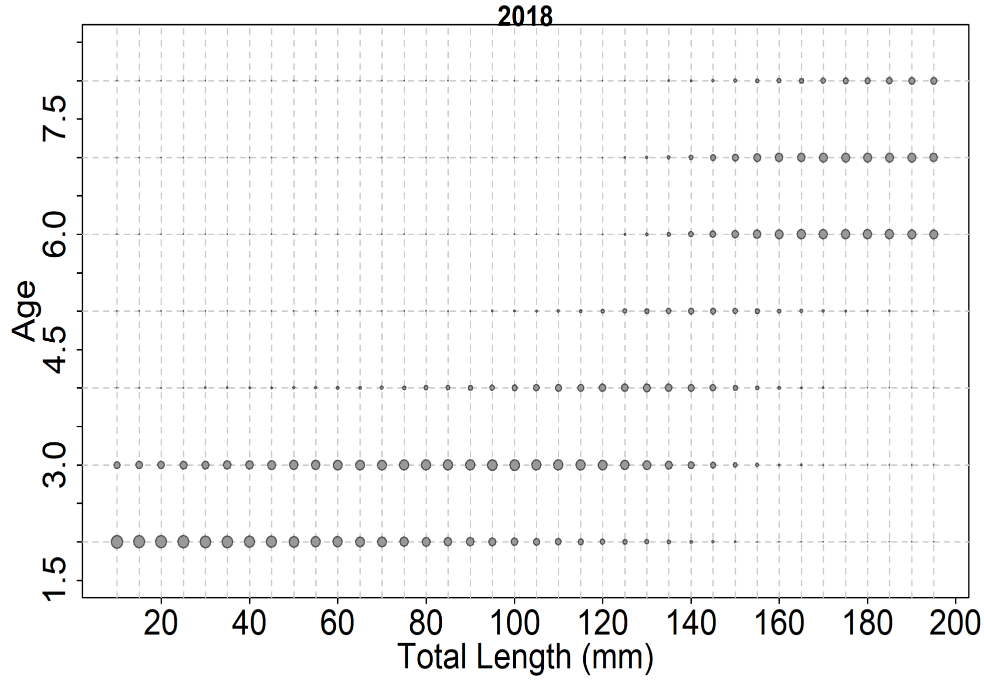


Figure 7. Bubble plots of the modelled external ring age length keys for the Georges Bank resource area by year.



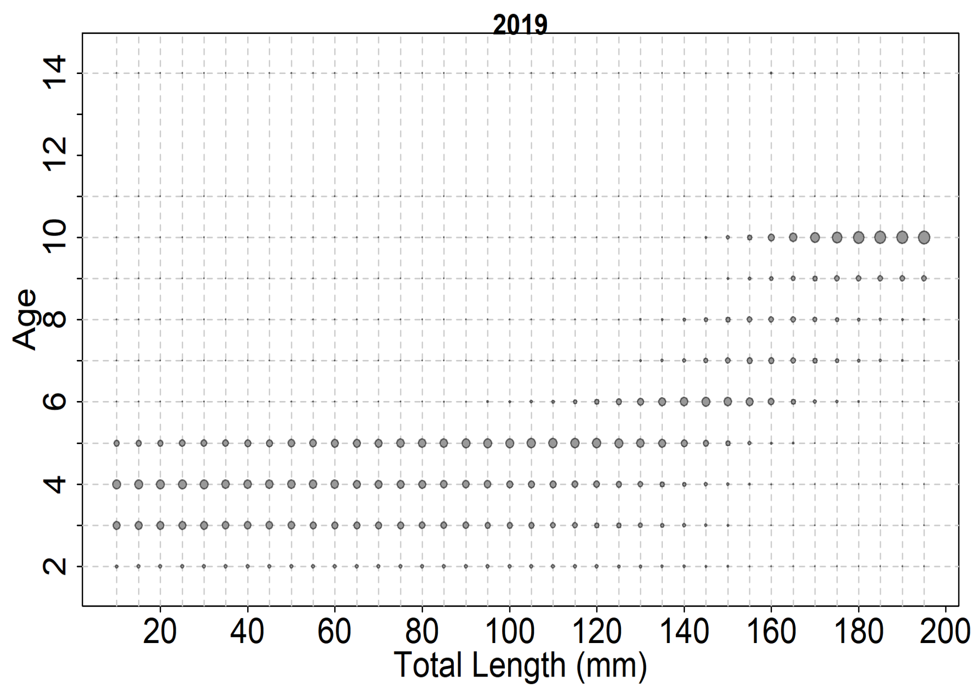


Figure 9. Bubble plots of the resilia age length keys for the Mid-Atlantic resource area by year.

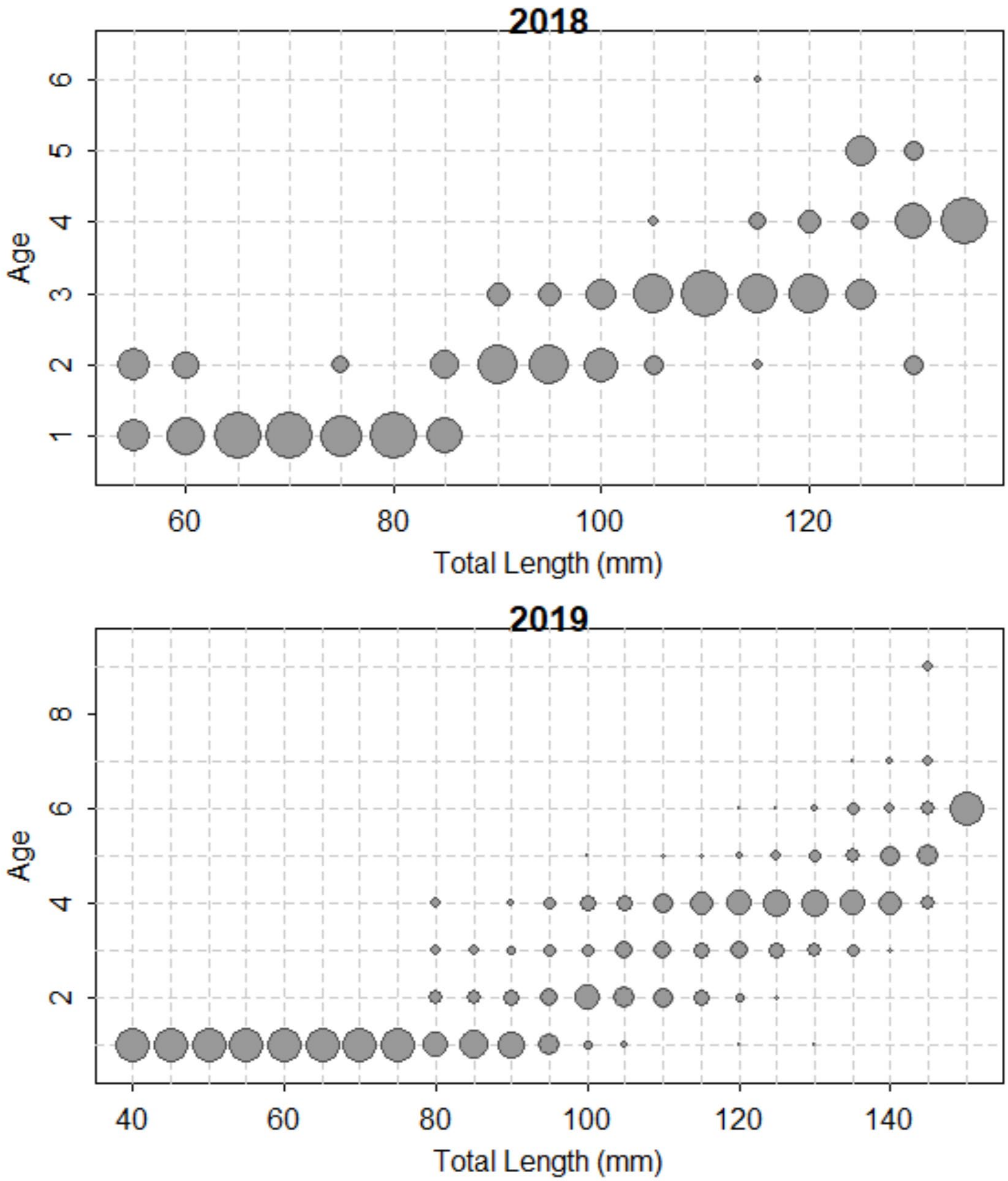


Figure 10. Bubble plots of the resilia age length keys for the Georges Bank resource area by year.

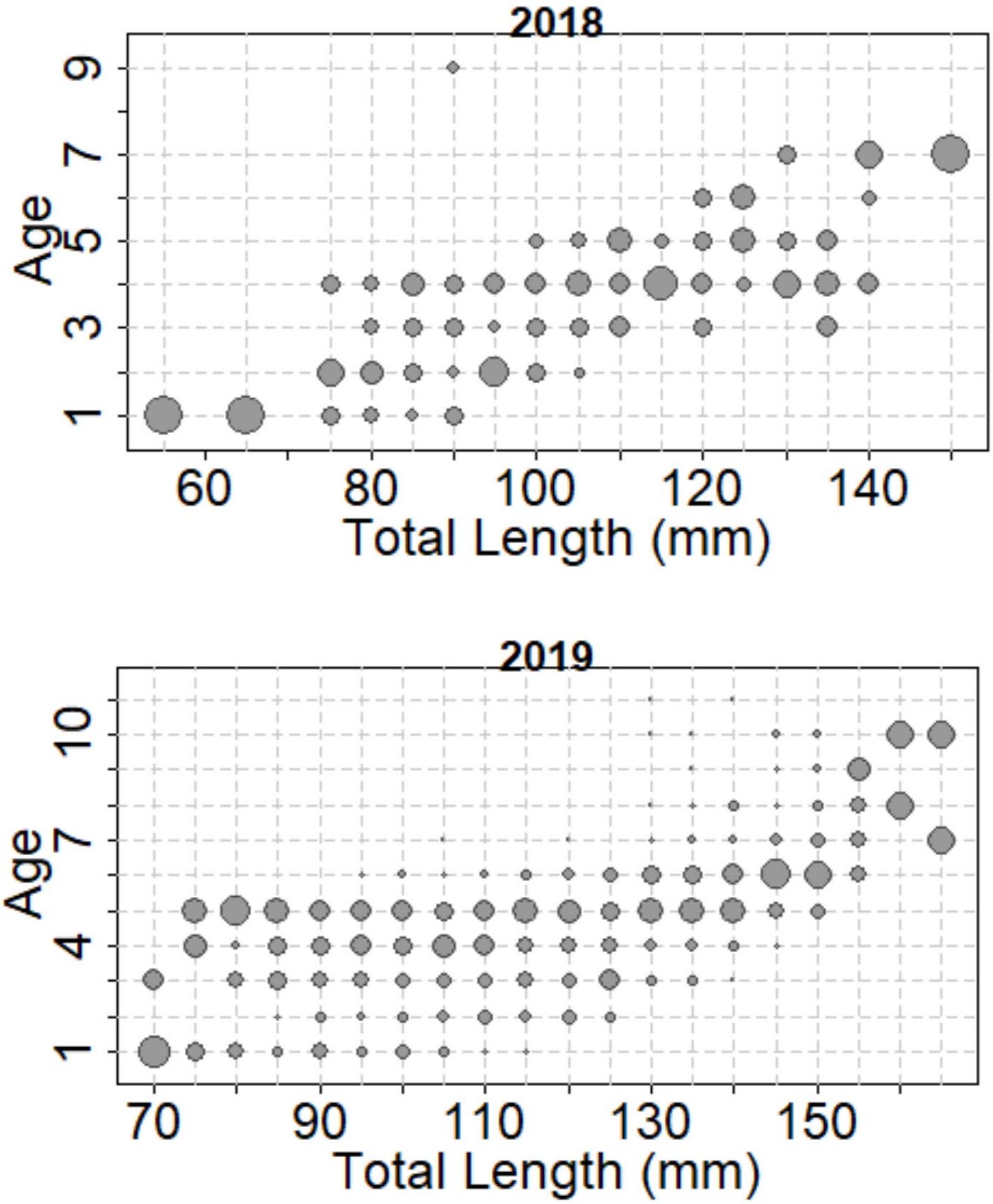
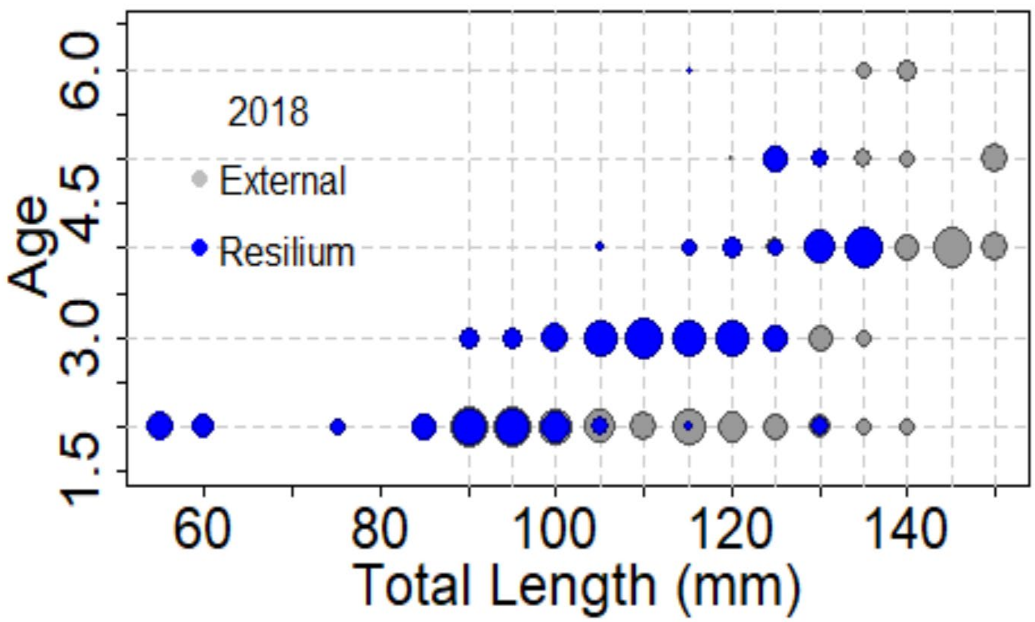


Figure 11. Bubble plots of the external ring (gray) and resilia (blue) age length keys for the Mid-Atlantic resource area by year.



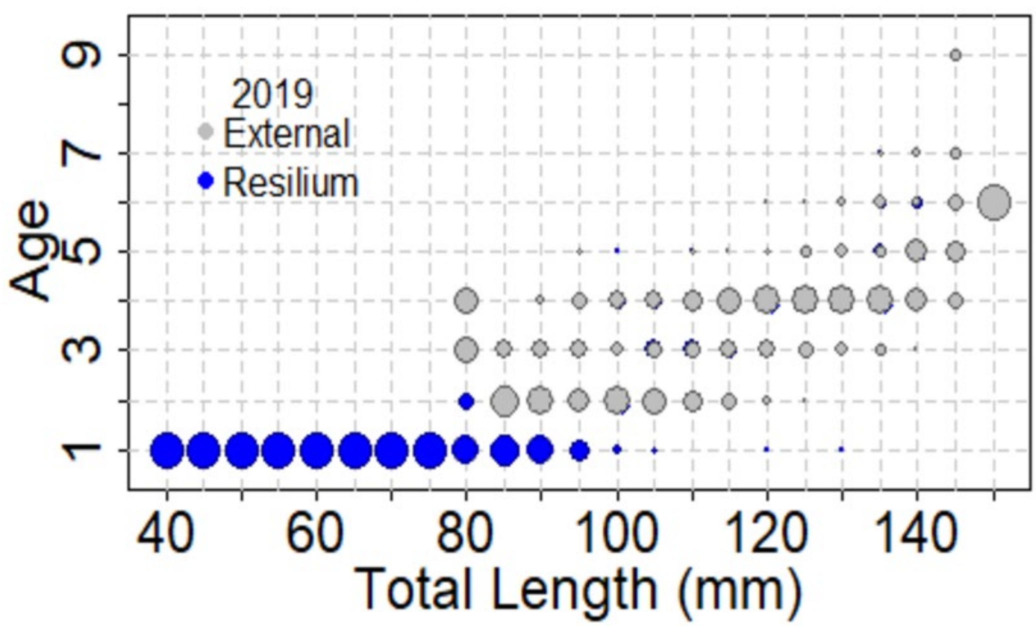
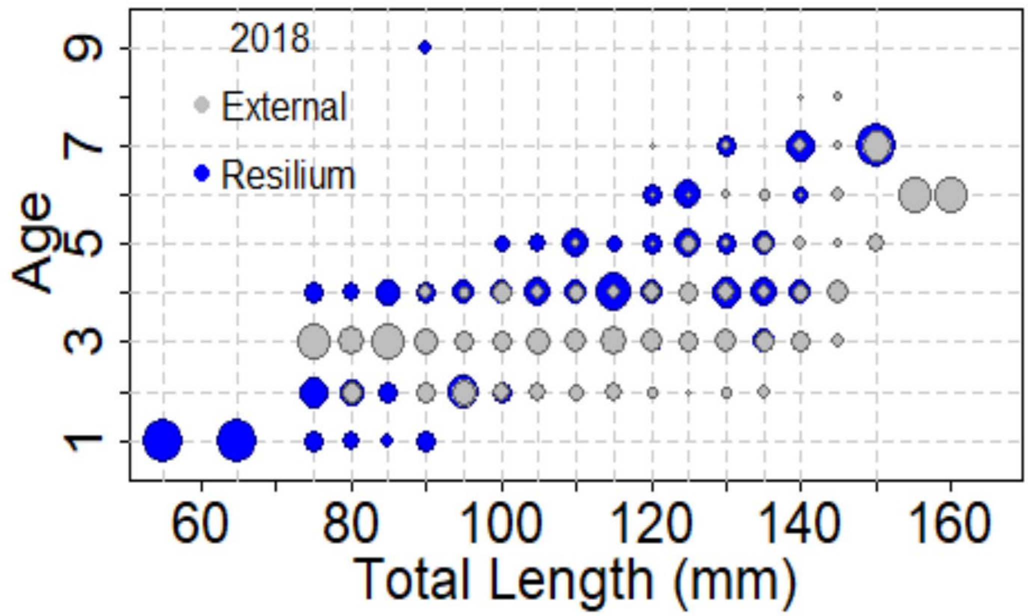


Figure 12. Bubble plots of the external ring (gray) and resilia (blue) age length keys for the Georges Bank resource area by year.



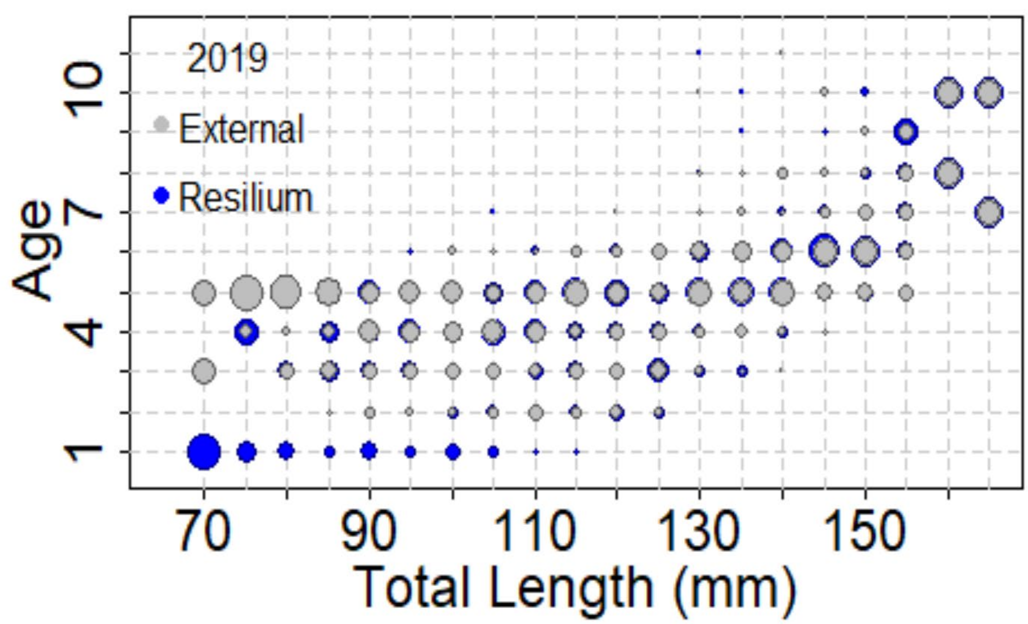


Table 9. Number of scallops at length in the aged external ring samples and all scallops sampled (expanded number at length) by year and resource area for 2018 and 2019. Length is 5 mm bins.

2018								2019							
MAB				GB				MAB				GB			
Aged		All Scallops		Aged		All Scallops		Aged		All Scallops		Aged		All Scallops	
Length	Number	Length	Number	Length	Number	Length	Number	Length	Number	Length	Number	Length	Number	Length	Number
		15	3			5	1			10	1			10	20
		20	19			15	2			15	8			15	223
		25	89			20	15			20	23			20	1,119
		30	254			25	81			25	167			25	2,086
		35	686			30	377			30	481			30	4,067
		40	929			35	604			35	925			35	7,553
		45	1,173			40	778			40	1,026			40	10,008
		50	1,112			45	997			45	1,064			45	7,109
		55	1,324			50	1,204			50	781			50	3,691
		60	1,408			55	2,618			55	679			55	1,053
		65	1,667			60	8,215			60	611			60	620
		70	2,214			65	17,877			65	667			65	1,928
		75	2,942			70	24,282			70	698	70	2	70	7,732
		80	3,768	75	2	75	26,453			75	1,079	75	14	75	16,649
		85	5,691	80	3	80	23,749			80	1,744	80	15	80	24,666
90	3	90	9,718	85	6	85	21,036			85	2,364	85	37	85	27,452
95	1	95	15,637	90	6	90	18,933	90	3	90	2,900	90	35	90	23,120
100	9	100	21,928	95	9	95	18,123	95	1	95	3,879	95	61	95	18,249
105	29	105	25,060	100	17	100	16,473	100	9	100	6,052	100	53	100	14,670
110	46	110	21,326	105	22	105	11,802	105	29	105	9,034	105	54	105	11,469
115	95	115	12,560	110	34	110	8,604	110	46	110	11,315	110	63	110	8,482
120	83	120	5,339	115	20	115	6,209	115	95	115	11,945	115	64	115	6,946
125	45	125	2,228	120	21	120	5,313	120	83	120	9,275	120	61	120	5,965
130	37	130	785	125	21	125	4,511	125	45	125	5,448	125	46	125	5,015
135	13	135	458	130	17	130	3,331	130	37	130	2,540	130	54	130	3,743
140	7	140	156	135	19	135	1,822	135	13	135	1,020	135	49	135	2,338
145	3	145	37	140	19	140	940	140	7	140	304	140	49	140	1,134
150	2	150	5	145	12	145	400	145	3	145	82	145	33	145	510
155	1	155	11	150	4	150	113	150	2	150	36	150	16	150	156
		170	1	155	2	155	60	155	1	155	6	155	5	155	41
				160	1	160	9			170	1	160	2	160	18
						165	1							165	1
						180	1							195	1

External vs Resilia Age Comparison

There were 1,847 scallops with paired external ring resilia age data included in the analysis. A total of 405 scallops were aged only with the resilia method, and data for these scallops were not retained for the age comparison. This was a result of scallop shells with damage or abrasions on the top value making external rings difficult to identify. While damage to the top value makes the external ring age method impossible to use, the resilia can still be extracted from the shell for ageing. Results from the age bias analysis detected accuracy and bias challenges with the resilia age method, when assuming the external age was the true age for age 2 and 3 scallops. The resilia age was significantly different from the external ring data for age 2 and 3 scallops (Figures 13-15). There were no differences between both age methods for scallops older than age 4, although for the predicted GAM age at length confidence intervals for older ages was wider relative to younger ages. Both age methods had relatively high precision. The percent agreement between age methods was 88%, with an average SD of ages within a scallop across all scallops of 0.09, and an average CV of ages within scallops of 2.67.

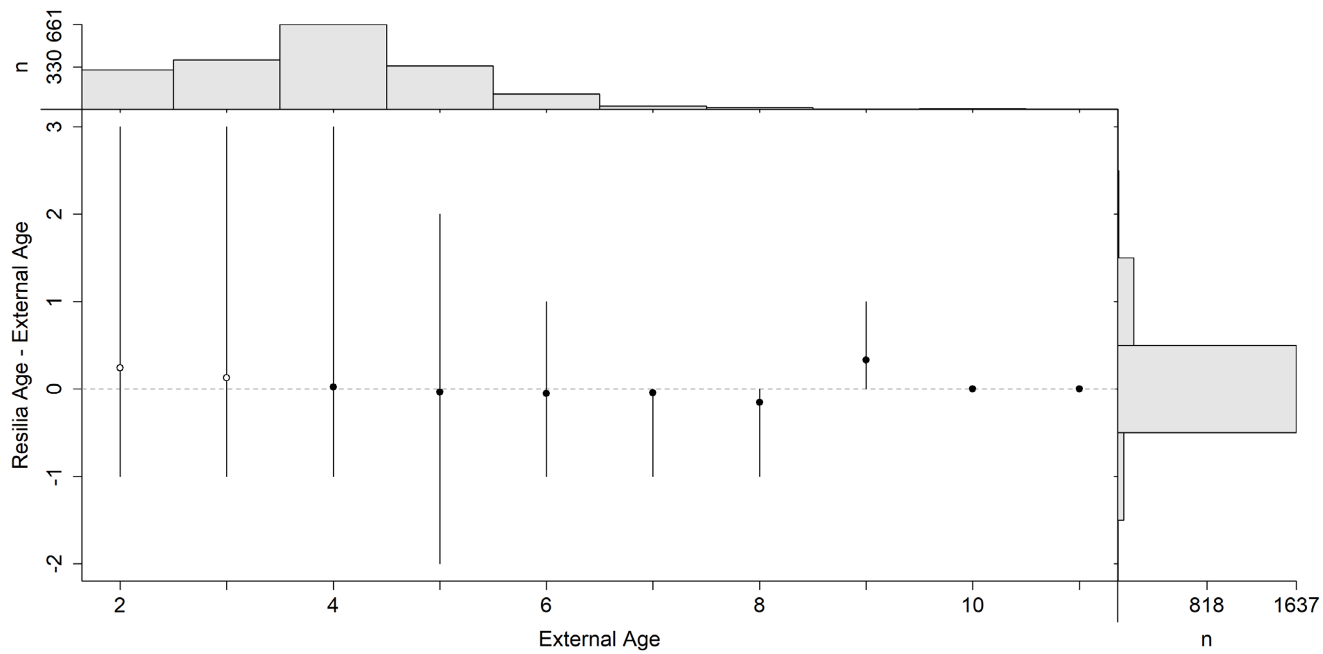


Figure 13. Paired resilia external ring age data plotted by age with the mean external ring age estimate and range of the difference. The x axis is the external ring age and the y axis is the difference between the resilia age minus the external ring age. Marginal histograms for the external ring age (top histogram) and the difference between the resilia and external ring samples (right histogram) were plotted along with sample sizes. If the mean age circle is empty there was a significant difference between the two age methods for a given age. If the mean age circle is filled with black, there was no significant difference between ages for both age methods.

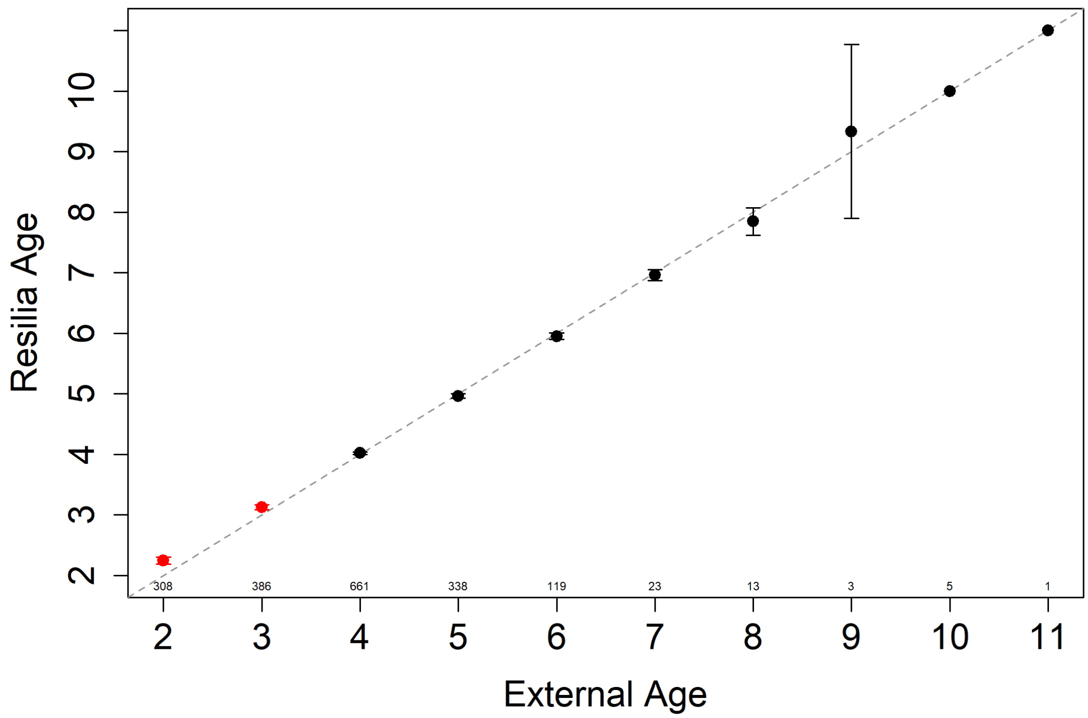


Figure 14. Age bias plot with external ring age on the x axis and resilia age on the y axis. Mean age with 95% confidence intervals are plotted, along with a 1:1 line. Red symbols and confidence intervals indicate significant differences between age methods. Black symbols and confidence intervals indicate no significant difference between age methods. Sample sizes for each age are provided above the x axis labels.

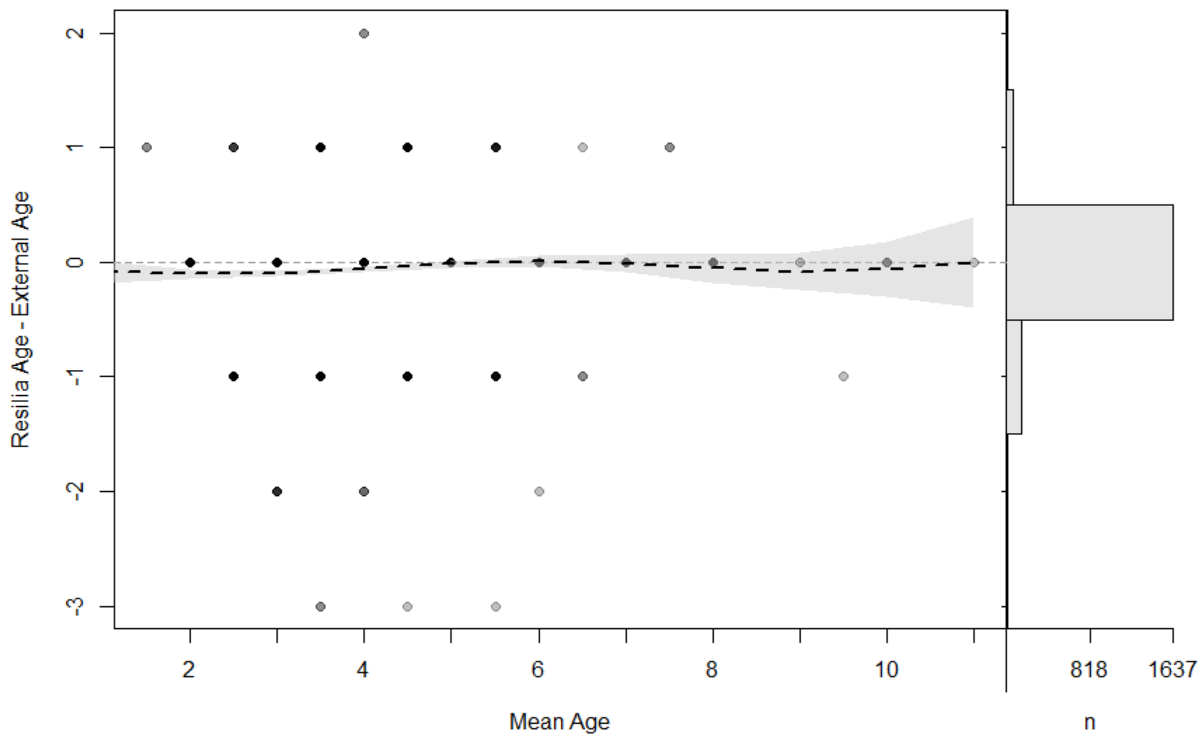


Figure 15. The difference between the resilia and external ring age estimates for each predicted mean age from the generalized additive model. The dashed gray horizontal line equals 0 and indicates no difference between age methods for each mean age. The dashed black line and gray polygon are the mean and 95% confidence intervals for the predicted mean difference in age estimates, respectively. The marginal histogram (right) is the difference between the resilia and external ring age estimates, along with sample sizes.

von Bertalanffy Growth Models

Ford-Walford plots by resource area for the original external ring dataset are provided in Figure 16. Slopes were similar between years within each resource area. The GB resource area had a lower intercept compared to the MAB resource area as a result of the NL South Deep SAMS Area scallops. External ring growth parameter estimated by resource area are provided in Table 10. The MAB L_∞ and K estimates from this study of 132 and 0.56 are comparable to the results from Hart and Chute (2009a) of 0.5 (K) and 133.3 (L_∞). For our GB results, our K estimate of 0.45 was similar to the Hart and Chute value of 0.42, although our L_∞ value of 127 was lower that the 143.9 Hart and Chute (2009a) value.

von Bertalanffy models for the MAB resource unit with additional predictor variables indicated average depth, SAMS Area, and latitude had significant effects on L_∞ (Table 11). A likelihood ratio test indicated mab_7 was preferred over mab_6 (p-value=0.02). Parameters estimates for mad_7 are provided in Table 12. Predicted growth curves are provided in Figure 17 based on mab_7 parameter estimates. Scallops in shallower nearshore SAMS Areas, specially the NYB and NYB_Nearshore SAMS Areas, exhibited faster growth compared to scallops located in deeper offshore SAMS Areas (HCS SAMS Area).

Results for the GB resource area differed from the MAB results in terms of which predictor variables effected L_∞. SAMS Area and latitude had significant impacts on L_∞, while other predictors were not included in the preferred model (Table 13). Parameters estimates are provided in Table 14 and predicted growth curves are in Figure 18. The NLS_West and NLS_South_Deep SAMS Areas had the lowest and similar growth curves. The NLS_North and CAI_Access SAMS Areas were also comparable and had the largest growth for a given shell height compared to all other SAMS Areas.

Results for the resilia growth dataset varied by resource area. For the MAB resource area, all three methods produced similar mean K and L_∞ estimates (Table 15). K estimates for the resilia dataset were 0.46 and 0.51, and similar to the external ring estimate of 0.56 as well as Hart and Chute's (2009a) estimate. For L_∞, all resilia estimates were greater (135-137) compared to the external ring value of 132 and the Hart and Chute (2009a) value of 133. For the GB models only the nlme model produced semi-reliable values; the von Bertalanffy model did not converge and the clus.vb.fit estimates were deemed unreliable (Table 15). The nlme values for both parameters differed from the external ring values and the Hart and Chute (2009a) values. The K estimate of 0.27 was lower and the L_∞ was greater at 140 compared to 127. Alternative starting values for the nlme models did not affect parameters estimates.

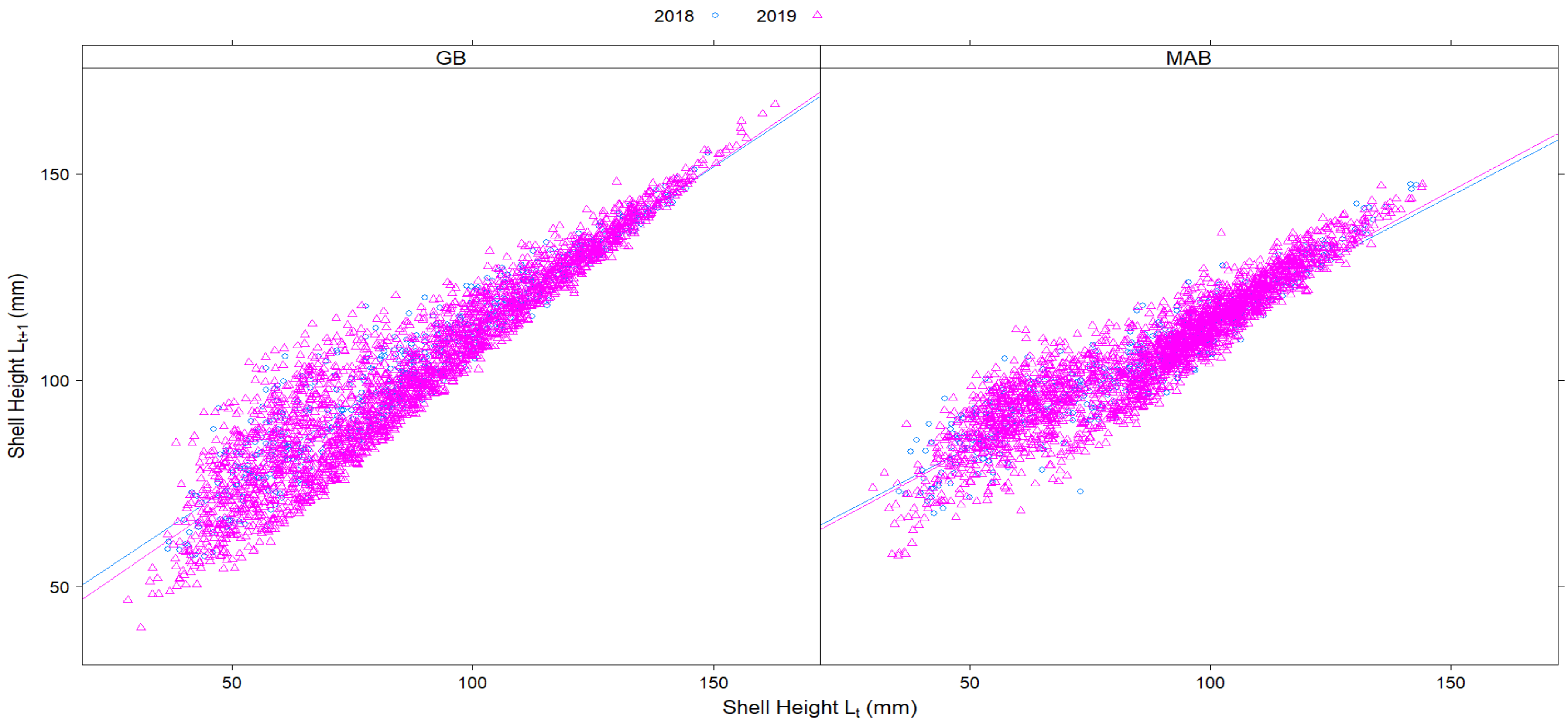


Figure 16. Ford-Walford plots for the original external ring dataset by resource area and year.

Table 10. von Bertalanffy mean L_∞ and K estimates by resource area. The standard deviation for each parameter estimate as well as the number of shells and number of intervals measured are also provided.

Area	$\bar{K}$	$\bar{L}_\infty$	σ_k	$\sigma_{L\infty}$	Number of Shells	Number of Intervals
MAB	0.56	132.02	0.006	0.53	1,606	2,880
GB	0.45	127.05	0.005	0.84	1,155	3,092

Table 11. von Bertalanffy growth models developed for the MAB resource unit with additional predictor variables. The number of parameters, BIC, and ∆BIC are also provided. The preferred model is in bold.

Model	Predictors	K	BIC	∆BIC
mab_6	Ring 1 +Avg Depth + SAMS Area	12	17,473.90	-
mab_7	**Ring 1 +Avg Depth + SAMS Area + Latitude**	**13**	**17,476.76**	**2.85**
mab_8	Ring 1 +Avg Depth + SAMS Area + Latitude + Year	14	17,478.47	4.57
mab_2	Ring 1 +Avg Depth	5	17,480.79	6.89
mab_11	Ring 1 +Avg Depth + Latitude	6	17,488.54	14.64
mab_10	Ring 1 +Avg Depth + Year	6	17,488.61	14.71
mab_9	Ring 1 +Avg Depth + Year + Latitude	7	17,496.23	22.33
mab_1	Ring 1 + Avg Depth	4	17,534.81	60.90
mab_3	Ring 1 + Latitude	5	17,538.62	64.72
mab_5	Ring 1 + Year	5	17,542.39	68.49
mab_15	Ring 1 + Year + Latitude	6	17,545.21	71.30
mab_4	Ring 1 + SAMS Area	11	17,548.50	74.59
mab_13	Ring 1 + SAMS Area + Year	12	17,552.18	78.28
mab_12	Ring 1 + SAMS Area + Latitude	12	17,556.38	82.48
mab_14	Ring 1 + SAMS Area + Latitude + Year	13	17,560.10	86.20

Table 12. Parameter estimates for the preferred MAB von Bertalanffy growth model (mab_7).

Predictor	Estimate	Std. Error	P-value
Intercept	131.10	29.22	<0.01
Ring 1	0.57	0.00	<0.01
Avg Depth	-0.36	0.04	<0.01
DMV	0.41	2.88	0.88
ET_Flex	-3.16	2.21	0.16
ET_Open	-0.75	2.31	0.74
HCS	0.31	1.98	0.87
LI	0.29	1.53	0.84
NYB_Inshore	-2.21	3.46	0.52
NYB	1.38	1.84	0.45
Latitude	-1.60	0.71	0.02

Figure 17. Predicted growth curves for the MAB resource area by SAMS Area from the preferred mad_7 von Bertalanffy growth model.

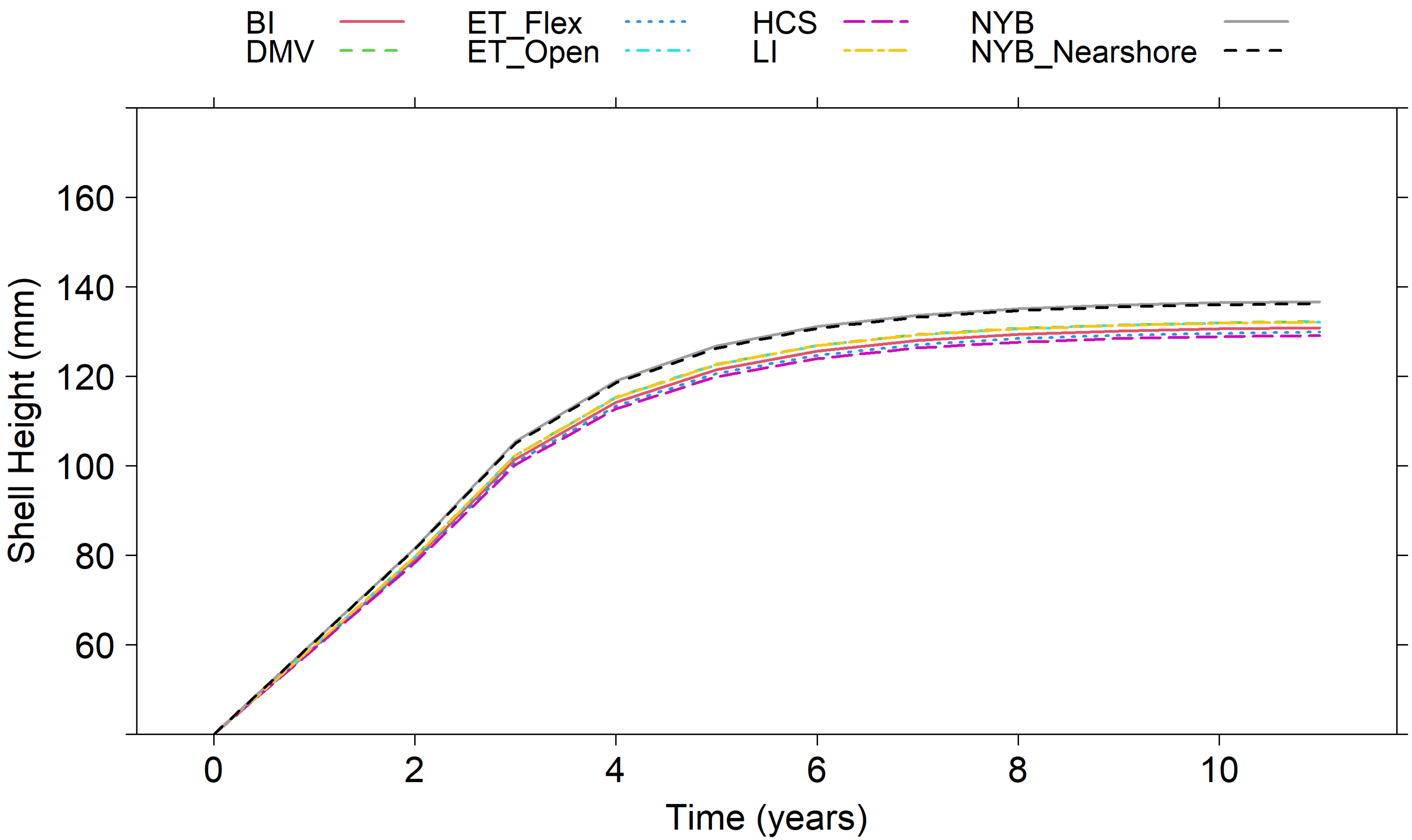


Table 13. von Bertalanffy growth models developed for the GB resource unit with additional predictor variables. The number of parameters, BIC, and ΔBIC are also provided. The preferred model is in bold.

Model	Predictors	K	BIC	ΔBIC
gb_12	**Ring 1 + SAMS Area + Latitude**	**13**	**18,828.98**	-
gb_7	Ring 1 +Avg Depth + SAMS Area + Latitude	14	18,833.53	4.55
gb_14	Ring 1 + SAMS Area + Latitude + Year	14	18,836.85	7.87
gb_8	Ring 1 +Avg Depth + SAMS Area + Latitude + Year	15	18,841.57	12.58
gb_4	Ring 1 + SAMS Area	12	18,946.35	117.36
gb_13	Ring 1 + SAMS Area + Year	13	18,947.81	118.83
gb_6	Ring 1 +Avg Depth + SAMS Area	13	18,951.22	122.23
gb_11	Ring 1 +Avg Depth + Latitude	6	18,964.29	135.30
gb_3	Ring 1 + Latitude	5	18,970.75	141.77
gb_9	Ring 1 +Avg Depth + Year + Latitude	7	18,972.18	143.19
gb_15	Ring 1 + Year + Latitude	6	18,978.56	149.58
gb_1	Ring 1 + Avg Depth	4	19,132.68	303.70
gb_5	Ring 1 + Year	5	19,134.49	305.51
gb_2	Ring 1 +Avg Depth	5	19,135.60	306.62
gb_10	Ring 1 +Avg Depth + Year	6	19,139.96	310.98

Table 14. Parameter estimates for the preferred GB von Bertalanffy growth model (gb_12).

Predictor	Estimate	Std. Error	P-value
Intercept	-1,094.27	99.10	<0.01
Ring 1	0.64	0.00	<0.01
CAI_Sliver	-11.79	1.57	<0.01
CAII_Access	-7.17	1.43	<0.01
CAII_Ext	-5.20	1.57	<0.01
NLS_North	11.14	1.82	<0.01
NLS_South_Deep	5.97	2.02	<0.01
NLS_EXT	10.23	3.85	<0.01
NLS_West	4.34	2.03	0.03
SF	5.09	1.83	<0.01
Latitude	27.95	2.41	<0.01

Figure 18. Predicted growth curves for the GB resource area by SAMS Area from the preferred gb_12 von Bertalanffy growth model.

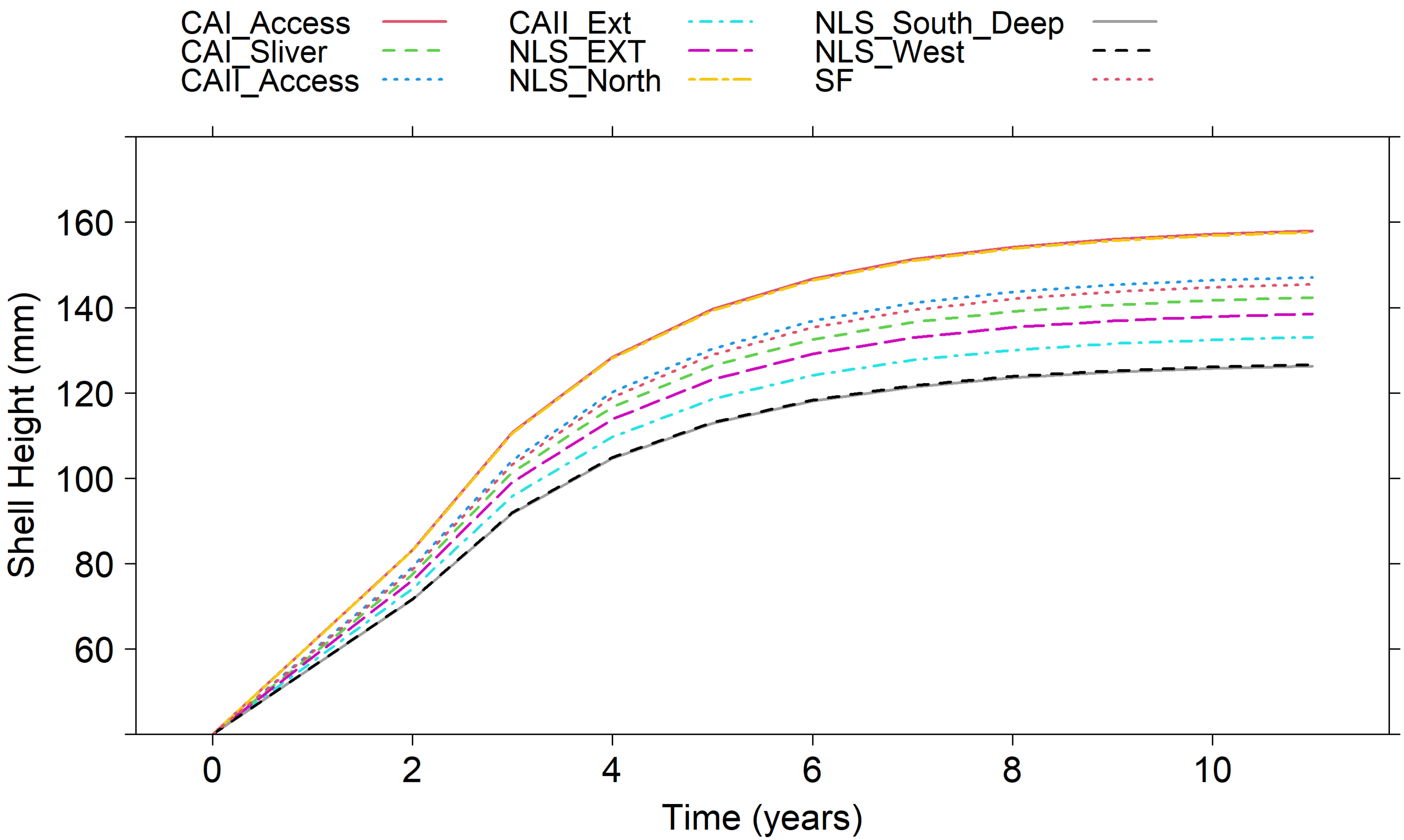


Table 15. Resilia dataset von Bertalanffy mean growth parameter estimates by resource area and modelling approach. The standard error for L_∞ and K as well as the number of shells included in the analysis are also provided.

Area	Method	$\overline{K}$	$\overline{L}_\infty$	$\overline{t0}$	SE_k	SE_{L_∞}	Number of Shells
MAB	traditional	0.46	136.52	-0.99	0.04	2.09	1,281
	clus.vb.fit	0.51	135.09	-1.07	0.08	3.68	
	nlme	0.46	137.48	-1.07	2.05	0.04	
GB	traditional	Model did not converge					983
	clus.vb.fit	0.03	587.94	-9.95	0.004	531.3	
	nlme	0.27	140.73	-2.7	3.51	0.03	

Outreach

Presentations

American Fisheries Society Annual Meeting Atlantic City NJ, August 2018. M. Chase Long, Roger Mann, David Rudders, Sally Roman, Antonia Chute, K. Cronin, and S. Walker S. Growth rate measurement in scallops: revisiting Merrill after 50 years on the library shelf.

New England fishery management Council Sea Scallop RSA Share Day virtual May 2019. Roger Mann, David Rudders, Sally Roman, Theresa Redmond, Chase Long, Sarit Tukey, Sara Thomas, Erin Mohr, Melissa Southworth, Kaitlyn Clark, and Larry Jacobson. Age-based assessment in the sea scallop, a pilot study.

5TH International Pectinid Workshop Santiago de Compostela Spain April 2019. David Rudders, Theresa Redmond, M. Chase Long, Sara G. Thomas, Sally A. Roman, and Roger Mann. Age and growth rate measurement in scallops from the mid-Atlantic: a comparison of shell signatures, hinge resilia and isotope based methods.

National Shellfishes Association Annual Meeting New Orleans, LA March 2019. Theresa Redmond, M. Chase Long, Sara Thomas, Sally Roman, David Rudders, and Roger Mann. Age and growth rate measurement in scallops from the mid-Atlantic: a comparison of shell signatures, hinge resilia and isotope based methods.

Peer publications include:

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Cronin K.E., S.E. Walker, R. Mann; A.S. Chute, M.C. Long; S.S. Bowser (2020). Growth and longevity of the Antarctic scallop *Adamussium colbecki,* an ecosystem engineer, under annual and multi-annual sea ice. Antarctic Science. 32 (6) 466-475. https://doi.org/10.1017/S0954102020000322].

Discussion

Several problems were identified with the ALKS for both resource areas, years, and ageing methods. There were problems with age misspecification, especially for larger scallops, and across a large length range. This problem is present for ages 2-5 for the external ring dataset, where scallops ranging in length from 75-140 mm were identified as age 2 scallops in the 2018 MAB ALK. This problem continued for ages 3 and 4 in the 2019 MAB ALK as well as in both of the GB ALKs. While the resilia dataset ALKs appeared to more accurately assign ages to scallops, scallops across a wide length range were assigned to younger age groups, so the problem with age misspecification is occurring in both datasets. Smaller scallops (< 80 mm) from both resource areas were not aged using the external ring approach. This lack of age data for smaller scallops should be investigated as one of the objectives of this project was to provide age data across the length distribution of scallops in the population. The resilia dataset did include smaller scallops ranging in length from 40-80 mm. Smaller scallops were captured in the resource surveys. These scallops were either not retained for shell samples, were discarded for external age determination during the ageing process because the rings were indistinct, or were only able to be aged with the resilia method. A discussion regarding a minimum length for scallops that can be aged along with the best ageing method for this size class would be beneficial. The resource surveys captured small scallops ranging in length from 5-65 mm that were not in the external ring aged samples. Understanding that the smallest scallops <40 mm are not fully retained by the survey gear and that small scallops are difficult to age could help guide the conservation regarding a minimum size and age method to consider for ageing scallops. There were also ages not included in the ALKs, this could be addressed by examining the method scallop shells are selected and collected for ageing. Shells collected come from a subset of scallops selected to be representative of the length distribution at a given station assuming these also represent the age distribution in the resource. Additional samples may need to be collected in the future, especially for larger size classes when possible, to safeguard against missing age classes. This action would be dependent on the size structure of the population at the time of sampling. One benefit of the resilia method is that age 1 scallops can be identified. This benefit should be considered when discussing the merits of each age method. Overall, both ageing methods should be reexamined to determine where the errors with ageing scallop shells for younger ages/sizes is occurring.

The modelled ALKS appeared to provide more accurate ALKs with respect to larger scallops and ages. These ALKs suffer from the same problems for younger ages/sizes (ages 2-5), depending on resource area, as a result of the underlying external ring data used in the modelling efforts. Once problems with the age methods are resolved, modelled ALKs accuracy should improve. A discussion regarding whether to use observed or modelled ALKs should also be considered.

There was general agreement between the two ageing methods with respect to age assignment. Significant differences between the resilia and external ring methods were observed only for age 2 and 3 scallops. There was also a high degree of precision between the two approaches. The difference between the two methods for age 2 and 3 scallops should be investigated. Differences or similarities between the approaches may vary after reexamining both age methods. Currently, either method could be used to estimate growth parameters for the MAB resource area. The K and L_∞ parameter estimates for the MAB resource area were similar between the external interval approach and the three resilia models developed. There was also agreement between the parameter estimates from this study and those presented by Hart and Chute (2009a). The resilia dataset did not perform as well for the GB resource area. Only one model (the nlme model) converged with an L_∞ parameter estimate that was realistic compared to Hart and Chute (2009a) or the external ring method. The K estimate from this model is considered unrealistically low. The fishmethods model estimates were highly unrealistic and the traditional von Bertalanffy model did not converge. Further investigation into the performance of the resilia model approach for the GB resource area should be completed.

von Bertalanffy growth parameters for both resource areas were comparable to the Hart and Chute (2009a) values. The GB L_∞ value was lower compared to Hart and Chute (2009a) and indicates that the asymptotic length in 2018 and 2019 was lower than in earlier years. This difference may stem from having a smaller sample size than what was used in Hart and Chute (2009a) as well as only using two years of data to estimate growth parameters. Additionally, water temperatures on Georges Bank have marginally increased in the period between the studies – a change that would be expected to increase K but decrease the L_∞ value.

Growth curves estimated when including the effects of other predictor variables indicated SAMS Area, latitude, and depth impacted growth. This result is consistent with Hart and Chute (2009a) with respect to depth and latitude. SAMS Area was also found to impact scallop growth. This result should be considered when forward projections for setting catch advice are completed. A reduced L_∞ value has been used in forward projections for the NL South Deep SAMS Area and the NL West SAMS Area in recent years to account for reduced growth.

The pilot dataset generated for this report in its current iteration needs to be reassessed before further work can be completed toward a pilot age-based assessment. Scallops aged in 2018 and 2019 remaining in the VIMS archive should be reexamined using both methods. Data collected from the 2020 and 2021 resource surveys should also be analyzed to determine if ageing issues are persistent across years. ALKs for 2020 and 2021 for both age methods should be generated at a minimum. Other options that could be explored are investigating back-calculating length-at-age (Ogle, 2016) and using von Bertalanffy growth parameters to estimate length-at-age (Ogle and Iserman, 2017).

The project budget and compensation are provided in Appendix A.

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