

(Appendix B3)

APPENDIX III: Methodology for estimation of growth from shell rings

Shells were collected on the 2001-2006 NEFSC surveys. At about half the valid tows in the survey, scallops were chosen randomly (averaging about 6 per station) to be used for the growth analysis. The scallops were scrubbed with a wire brush, shucked, and both valves were frozen and transported back to shore for later analysis. After the shells were thawed and cleaned, rings on the top valve of each shell that represented annuli were marked with a pencil. On some shells, one or more “shock marks” were evident. These were distinguishable from annuli by their irregular nature and because a point of injury was usually evident in the form of a crack or deformation of the shell. After the shells were marked, the distance in millimeters from the umbo to each of the ring marks was measured with calipers. Since the first ring is often very small and difficult to discern, the data only include the measurements to the second ring and above. Growth increments were calculated as the distance between the rings (in mm). The partial increment from the last ring to the edge of the shell was not used in the analysis.

Growth matrices were calculated by binning the growth ring shell heights into 5 mm classes (e.g., 40-44 mm shell height), and labeling the bins 1, 2, . . . , n , where the last bin represents a plus group. The ij th entry of the matrix represents the fraction of scallops that started in bin i that grew in a year’s time to bin j . Growth matrices based on the shell increments for Georges Bank and the Mid-Atlantic are given in Table App3-1.

To estimate growth parameters from the increment data, we used the growth increment form of the Von Bertalaffy equation:

$$\Delta L = (L_{\infty} - L)[1 - \exp(-K\Delta t)], \quad (1)$$

where L is the starting length, ΔL is the growth increment that occurred over time Δt , and L_{∞} and K are the two growth parameters to be estimated. Equation (1) predicts that a plot of the increments (ΔL) vs. starting length (L) will be a straight line with slope $m = -[1 - \exp(-K\Delta t)]$, x -intercept L_{∞} and y -intercept $b = -mL_{\infty}$. Thus, one could estimate K and L_{∞} from a plot of increment vs. starting length, with

$$K = -\frac{1}{\Delta t} \ln(1 + m) \quad (2)$$

and

$$L_\infty = -b/m \quad (3)$$

L_∞ and K may vary considerably among individuals in real populations. If this is the case, the naive estimation using equations (2) and (3) that ignores this variability can be seriously biased (Sainsbury 1980). We will derive here approximately unbiased estimates of L_∞ and K when these parameters have individual variability.

The growth increment of the i th individual, ΔL_i depends on a fixed effect (the starting length L) and random effects depending on the individual:

$$\Delta L_i = (m + m_i)L + (b + b_i) + \epsilon, \quad (4)$$

where m and b are the mean slope and intercept (averaging over all individuals), m_i and b_i are deviations from the mean slope and intercept for the i th individual, ϵ is a random independent error, and $E(\epsilon) = E(m_i) = E(b_i) = 0$. Note that the slope and intercept obtained from a simple linear regression of ΔL_i vs. L will not necessarily be the same as m and b .

The parameters associated with the i th individual can be calculated as:

$$K_i = -\ln(1 + m + m_i) \quad (5)$$

and

$$L_{\infty,i} = -(b + b_i)/(m + m_i). \quad (6)$$

We define $K = E(K_i)$, i.e., the mean of the individual K_i s in the population. We have

$$K = E(K_i) = E(-\ln(1+m+m_i)) \geq -\ln(E(1+m+m_i)) = -\ln(1+m). \quad (7)$$

Thus, estimating $E(K_i)$ as $-\ln(1+m)$ using the mean slope only will result in an estimate that is biased low.

Approximating $\ln(1 + m + m_i)$ by a second order Taylor polynomial,

$$\ln(1 + m + m_i) \simeq \ln(1 + m) + \frac{1}{1 + m}m_i - \frac{1}{2(1 + m)^2}m_i^2. \quad (8)$$

Taking expectations in the above equation gives:

$$K = -E(\ln(1 + m + m_i)) \simeq -\ln(1 + m) + \frac{\text{Var}(m_i)}{2(1 + m)^2} \quad (9)$$

An approximately unbiased estimate of $L_\infty = E(L_{\infty,i})$ can be computed similarly:

$$E(L_{\infty,i}) = -E\left(\frac{b + b_i}{m + m_i}\right) \simeq -\frac{b}{m} - \frac{1}{m^2}\left[\frac{b}{m}\text{Var}(m_i) - \text{Cov}(b_i, m_i)\right] \quad (10)$$

Approximate formulas for the standard errors of K and L_∞ , σ_K and σ_{L_∞} , are

$$\sigma_K \simeq \frac{\sigma_m}{(1 + m)} \quad (11)$$

and

$$\sigma_{L_\infty}^2 \simeq L_\infty^2 \left(\frac{\sigma_b^2}{b^2} + \frac{\sigma_m^2}{m^2} - \frac{2\sigma_b\sigma_m\rho(b, m)}{bm} \right) \quad (12)$$

where σ_b and σ_m are the standard errors of b and m respectively, and $\rho(b, m)$ is the correlation coefficient of b with m (see e.g., Rice 1987).

All analysis were conducted using the statistical program *R* (v2.3.1), using the mixed-effects (Pineiro and Bates 2000) package *lme4*. The above techniques require shells to have at least two increments, in order to estimate the two parameters $L_{\infty,i}$ and K_i . The increments included in the analysis included all shells collected at random stations with at least two growth increments.

Numerical simulations

As a verification technique of the above formulas, increments were simulated using the statistical program *R*, assuming L_∞ and K are gamma random variables, with means 140 and 0.5, respectively, and a specified CV. 1000 animals were simulated, with each contributing 4 increments. The simulated growth increments were subject to a 10% CV. Naive and mixed-effects estimates were made for various CVs (Fig App3-1). As expected, growth variability caused fairly considerable biases in the naive estimates, with K underestimated and L_∞ overestimated (Sainsbury 1980). Mixed-effect estimates were always within 3% of the true values.

Results

In Georges Bank, 15685 increments were measured from 3656 shells (Fig App3-2). In the Mid-Atlantic, 5706 increments were measured from 2098 shells (Fig App3-2). Parameter estimates, with standard errors, are given in

the table below, together with some previous estimates. Comparison of the new mean growth curve with previous curves indicate that the new Georges Bank parameters give similar growth to that of Serchuk et al. (1979) until about 120 mm, and then predict slower mean growth (Fig A3-4). The new Mid-Atlantic curve predicts somewhat faster growth for small scallops (< 80 mm), but slower growth at larger sizes, with a considerably smaller asymptotic size. Further analysis, demonstrating that growth depends on such factors as depth and closure status, will be detailed in a forthcoming publication (Hart and Chute in prep.).

Growth Parameter Estimates

Source	L_{∞}	sd	K	sd
Georges Bank				
New	146.5	0.3	0.375	0.002
Harris and Stokesbury (2006)	140.0	2.1	0.51	0.04
Harris and Stokesbury (2006)	148.6	4.0	0.36	0.04
Harris and Stokesbury (2006)	121.1	6.2	0.27	0.09
Thouzeau et al. (1991)	144.87		0.2814	
Serchuk et al. (1979)	152.46		0.3374	
Posgay (1979)	143.6		0.37	
Merrill et al. (1966)	143.3		0.2324	
Merrill et al. (1966)	145.1		0.2258	
Mid-Atlantic				
New	131.6	0.4	0.495	0.004
Serchuk et al. (1979)	151.84		0.2997	

Table App3-1. Growth matrices for (a) Georges Bank and (b) Mid-Atlantic, derived from shell growth increments.

(a)

	42	47	52	57	62	67	72	77	82	87	92	97	102	107	112	117	122	127	132	137	142	147	
42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
57	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
62	0.06	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
67	0.2	0.06	0.03	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
72	0.31	0.16	0.07	0.04	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
77	0.3	0.3	0.14	0.13	0.09	0.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
82	0.11	0.3	0.25	0.15	0.17	0.16	0.05	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
87	0.02	0.14	0.29	0.19	0.22	0.29	0.18	0.08	0.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0
92	0	0.03	0.16	0.24	0.21	0.26	0.3	0.18	0.11	0.06	0.01	0	0	0	0	0	0	0	0	0	0	0	0
97	0	0	0.05	0.18	0.18	0.12	0.27	0.3	0.23	0.2	0.07	0.01	0	0	0	0	0	0	0	0	0	0	0
102	0	0	0	0.06	0.1	0.11	0.15	0.25	0.26	0.29	0.23	0.11	0.01	0	0	0	0	0	0	0	0	0	0
107	0	0	0	0	0.02	0.04	0.04	0.11	0.25	0.26	0.31	0.29	0.15	0.02	0	0	0	0	0	0	0	0	0
112	0	0	0	0	0	0	0.01	0.05	0.09	0.13	0.25	0.31	0.29	0.19	0.02	0	0	0	0	0	0	0	0
117	0	0	0	0	0	0	0	0.01	0.01	0.05	0.12	0.2	0.29	0.34	0.22	0.03	0	0	0	0	0	0	0
122	0	0	0	0	0	0	0	0	0	0	0.02	0.07	0.21	0.28	0.37	0.34	0.04	0	0	0	0	0	0
127	0	0	0	0	0	0	0	0	0	0	0	0.02	0.05	0.13	0.29	0.38	0.44	0.05	0	0	0	0	0
132	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0.03	0.09	0.2	0.4	0.55	0.07	0	0	0	0
137	0	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0.05	0.11	0.32	0.67	0.12	0	0	0	0
142	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0.08	0.23	0.67	0.19	0	0	0	0
147	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.03	0.21	0.81	1	0	0

(b)

	42	47	52	57	62	67	72	77	82	87	92	97	102	107	112	117	122	127	132			
42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
57	0.014	0.005	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
62	0.089	0.024	0.003	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
67	0.183	0.043	0.047	0.015	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
72	0.307	0.134	0.097	0.072	0.046	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
77	0.239	0.262	0.13	0.135	0.114	0.068	0.031	0	0	0	0	0	0	0	0	0	0	0	0	0		
82	0.133	0.348	0.258	0.15	0.193	0.143	0.07	0.038	0.002	0	0	0	0	0	0	0	0	0	0	0		
87	0.034	0.152	0.296	0.272	0.196	0.233	0.191	0.137	0.054	0.002	0	0	0	0	0	0	0	0	0	0		
92	0	0.027	0.139	0.249	0.216	0.267	0.312	0.261	0.144	0.083	0.007	0	0	0	0	0	0	0	0	0		
97	0	0.005	0.028	0.069	0.176	0.196	0.219	0.269	0.311	0.206	0.103	0.007	0	0	0	0	0	0	0	0		
102	0	0	0.003	0.039	0.046	0.09	0.152	0.202	0.302	0.315	0.267	0.193	0.007	0	0	0	0	0	0	0		
107	0	0	0	0	0.013	0.003	0.025	0.081	0.146	0.282	0.337	0.315	0.22	0.017	0	0	0	0	0	0		
112	0	0	0	0	0	0	0	0.013	0.041	0.098	0.235	0.289	0.374	0.292	0.036	0	0	0	0	0		
117	0	0	0	0	0	0	0	0	0	0.013	0.048	0.16	0.241	0.407	0.331	0.022	0	0	0	0		
122	0	0	0	0	0	0	0	0	0	0	0.005	0.033	0.143	0.234	0.435	0.455	0.037	0	0	0	0	
127	0	0	0	0	0	0	0	0	0	0	0	0.002	0.016	0.039	0.173	0.404	0.511	0.089	0	0	0	0
132	0	0	0	0	0	0	0	0	0	0	0	0	0	0.011	0.025	0.118	0.452	0.911	1	0	0	0

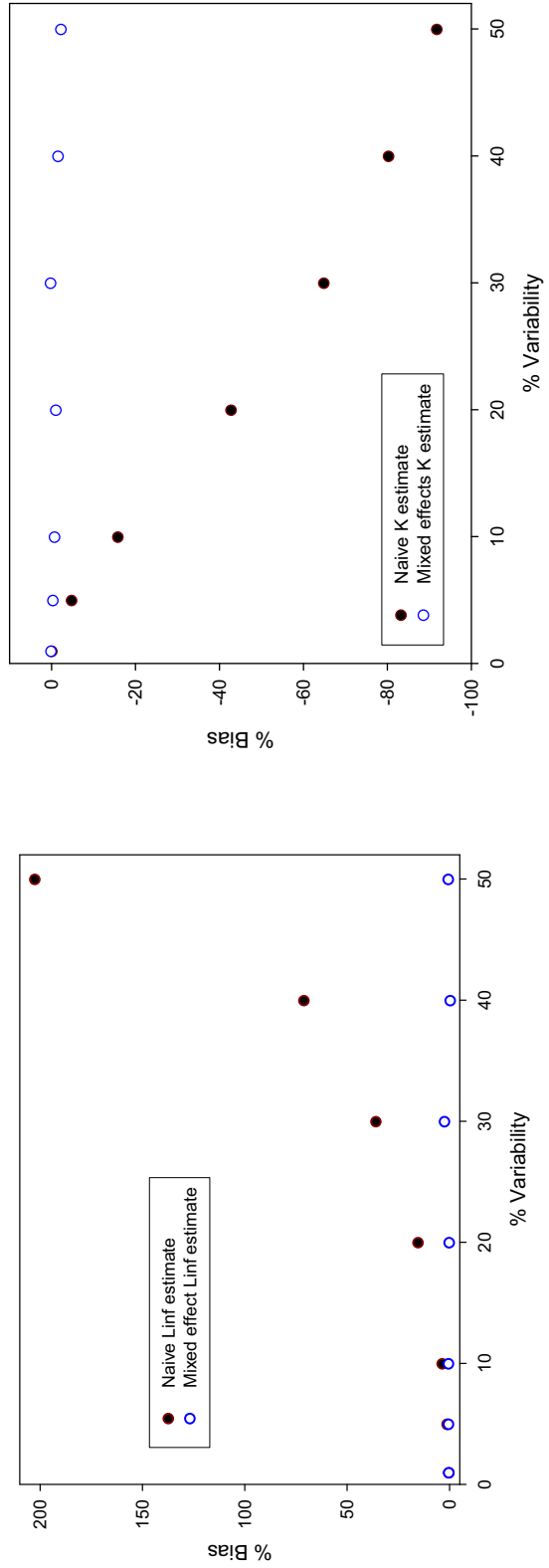


Fig App3-1. Percentage bias in simulated data for naive and mixed-effect estimates of growth parameters, where both growth parameters are assumed to vary.

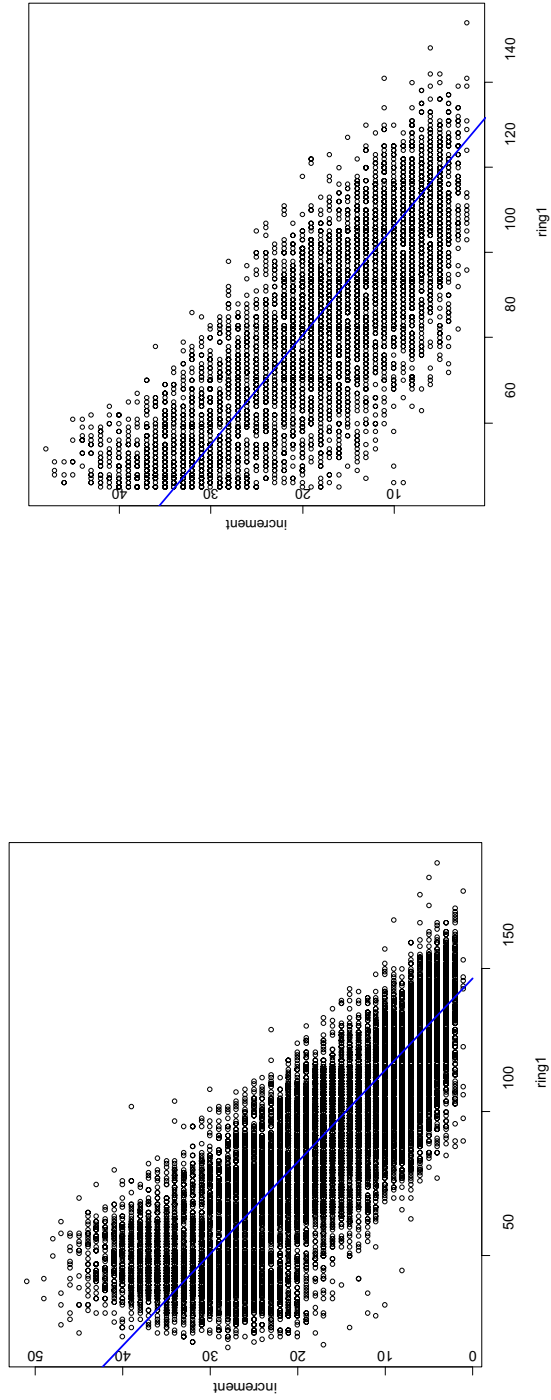


Fig App3-2. Georges Bank (left) and Mid-Atlantic (right) growth increments with mixed-effect regression lines.

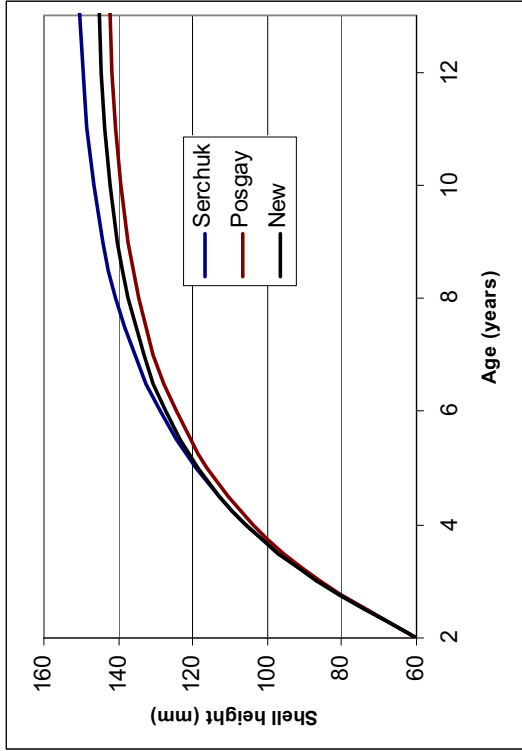
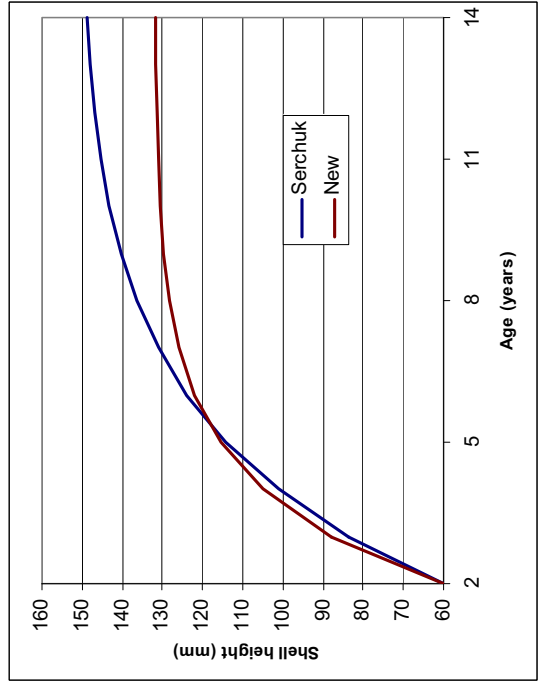


Fig App3-3. Comparison of the new growth curves (left is those for Georges Bank and right are the two for the Mid-Atlantic) with those of Serchuk et al. (1979) and Posgay (1979), for a scallop starting (at age 2) at 60 mm.