Appendix B7: Shell height-meat weight relationships from NEFSC survey data.

Dan Hennen and Dvora Hart, Northeast Fisheries Science Center, Woods Hole, MA.

New shell height and meat weight data were collected during 2007 – 2009 annual NMFS sea scallop surveys. This appendix updates shell height-meat weight relationships using these data.

Methods

Sea scallops (averaging about 6 per station) were collected for shell height-meat weight analysis at roughly half of all stations during 2001-2009 (717 stations in the Mid-Atlantic, 812 stations on Georges Bank). The scallops were measured to the nearest millimeter, carefully shucked, excess water was removed from the meat, and the meat was weighed to the nearest gram. Samples were collected in 2003, but there was partial data loss, so these data will not be used. During 2001-2009, whole and gonad weights were also recorded, but these data will not be presented here. The sampling protocol was altered slightly in 2009 to begin to account for seasonal shifts in scallop size. Since the data in 2009 were not collected at the same time of year as the data from earlier surveys, 2009 will generally be excluded from this analysis, though it is included in comparisons between years to illustrate the potential effects of shifts in the timing of the survey.

Preliminary analysis indicated a residual pattern for scallops with shell heights less than 70 mm. The small weights of these scallops (1-3 g) combined with the fact that meat weight could only be measured to the nearest gram resulted substantial measurement error. For this reason, the analysis was restricted to scallops that are at least 70 mm shell height. Scallops less than this height are below commercial size and have relatively little influence on CASA model calculations.

A generalized linear mixed model with a log link was used to predict meat weight using shell height, depth, density, latitude, and subarea (a finer scale regional division within each broad region). The GLM used a "quasi" likelihood with a log link, appropriate for data with "constant CV" error (McCullagh and Nelder 1989). This method avoids log-transforming the response variable (meat weight) which can lead to biased estimates when the results are back-transformed. The best model was chosen by AIC (Burnham and Anderson, 2002). The grouping variable for the random effects was a unique code formed by combination of survey station number and the year in which the survey took place. Survey stations were chosen randomly within NEFSC survey strata and generally in proportion to the size of the stratum. Survey stations numbers are assigned sequentially so that a survey station number in one year does not have any particular relationship to the same station number in the next year. Thus, a grouping variable based on a combination of survey station number and year incorporates random variation in the data that is due to both time (year) and fine scale spatial differences (station number).

Several analyses using simplified versions of the best model were employed to explore the effects of year, subarea, and fishing regulations.

All data analysis was conducted using the R statistical program (v2.9.2).

Results

In general, using mixed models appears to be very important in terms of AIC (Table 1). Accounting for the random effects of time and space measured as survey year and location absorbs much of the variation in the data.

Mid-Atlantic
The following model had the lowest AIC value (Table 1).

$$W = e^{\left(\alpha + a(St) + \beta \ln(H) + \gamma ln(D) + \rho(\ln(L) * \ln(D))\right) + \epsilon} \quad (1)$$

Where *W* was meat weight (g), and St was the year-station grouping variable for the random effects. The random effects were always modeled as an intercept and sometimes as a slope coefficient. The fixed effects were: shell height (*H)* in mm, depth (*D*) in m, and an interaction between shell height and depth (*H**D*). A total of 4181 observations were sampled from 717 stations were used in the analysis (Figure 1). Parameters (Table 1) were well estimated with no evidence of residual patterns (Table 2, Figure 2-4). The estimates presented here were similar to most previous estimates (Table 3). Compared to the estimates used in previous assessments, with the exception of Lai and Helser (2004) (Figure 5), the new estimates predicted slightly heavier meats at small shell heights, but lighter meats at very large shell heights, though the differences were small. The relationship that includes a depth effect indicated that sea scallops have heavier meats at shallower depths (Figure 6).

Meat weights varied by year, with the heaviest meats during 2004 (Table 4, Figure 7). Meats were generally heavier in 2009 when the survey was conducted earlier in the year. Meat weights by subarea were less variable, though "New York Bight" did produce heavier meats at the larger shell heights, and particularly at deeper depths (60 and 70 m) than the other areas (Table 5, Figures 8-10). In general samples taken from the Mid-Atlantic tend to be from water shallower than 70 m (Figure 11).

Georges Bank

The following model had the lowest AIC value (Table 1).

$$W = e^{(\alpha + a(St) + \beta ln(H) + \gamma ln(D) + \delta ln(lat) + \theta(sub) + b(L_{St})) + \epsilon} \quad (2)$$

Where *W* was meat weight (g), and survey station (St) was the grouping for the random effects. The random effects were modeled as an intercept (*a*), and as a slope parameter (*b*) for shell height (*H*). The fixed effects were in mm*,* *D* in m, latitude (*lat*) in decimal degrees, and subarea (*sub*) based on area management boundaries. Based on 6145 scallops from 812 stations, model fits appeared good with little or no residual pattern (Figures 12-15). Parameters were reasonably precise (Tables 1 and 2). They predict slightly heavier meat weights at small shell heights, and slightly lighter meat weights at large shell heights, than the model used in the previous assessment (Table 3, Figure 16). Meat weights were heavier at shallower depths (Figure 17).

Scallop shell height-meat weight relationships were generally consistent over time, although recent years (2007 and 2008) had heavier meats for large shell heights (Table 4, Figure 18). The 2009 survey which was conducted earlier in the year than previous surveys, collected meats that tended to be heavier at small shell heights, but did not otherwise differ from meats collected in other years. Results were dependent on subareas with "South East Part" and

“Closed Area 1” producing larger meats and “South Channel” and “Northern Edge and Peak” tending to produce lighter meats at all shell heights at the shallower depths (50 and 60 m) (Table 5, Figures 19 - 20). At 90 m depth, the heaviest meats were found in Northern Light Ship area at all shell heights and South East Channel produced some of the smallest meats at all shell heights. It should be noted however that samples from Northern Light Ship area were all taken from waters less than 90 m deep so the heavy weights found by the model fit could be an artifact of sampling (Figure 21). Areas that were closed to fishing tended to have larger meats (Figure 23).

Literature Cited

Burnham and Anderson 2002. Model Selection and Multimodel Inference A Practical Information-Theoretic Approach. 2nd. Ed. Springer.

Haynes EB. 1966. Length-weight relationship of the sea scallop *Placopecten magellanicus* (Gmelin). Res Bull Int Comm Northw Atl Fish. 3:32-48.

Lai HL, Helser T. 2004. Linear mixed-effects models for weight-length relationships. Fish Res. 70:377-387.

McCullagh and Nelder 1989. Generalized Linear Models 2nd. Ed. Chapman and Hall. New York.

NEFSC. 2001. 32nd Northeast Regional Stock Assessment Workshop (32nd SAW). Stock Assessment Review Committee (SARC) consensus summary of assessments. NEFSC Ref Doc. 01-05; 289 p.

NEFSC. 2007. 45th Northeast Regional Stock Assessment Workshop (45th SAW): 45th SAW assessment report. US Dep Commer, Northeast Fish Sci Cent Ref Doc 07-16; 370 p.

Serchuk FM, Rak RS. 1983. Biological characteristics of offshore Gulf of Maine scallop populations: size distributions, shell height-meat weight relationships and relative fecundity patterns. NMFS Woods Hole Lab Ref Doc. 83-07; 42 p.

Appendix B7-Table 1. Model building results. The models with minimum AIC values are indicated by bold font. Random effects are shown as parameters inside parentheses. All random effects were grouped by year_station and each model included a random intercept represented by the 1 inside parentheses. Fixed effects are shown to the right of the ~ symbol which separates the response variable from the predictors. Interaction terms are represented as factor1 * factor2. The best model tested without random effects for each region is included for comparison.

Formula	AIC	BIC	logLik	deviance
Georges Bank				
meat_weight ~ height + depth + lat + subarea + (height + 1 | year_station)	6636	6723	-3305	6610
meat_weight ~ height + depth + subarea + (height + 1 | year_station)	6694	6774	-3335	6670
meat_weight ~ height + depth + subarea + height * depth + (height + 1 | year_station)	6696	6783	-3335	6670
meat_weight ~ height + subarea + height * depth + (height + 1 | year_station)	6696	6783	-3335	6670
meat_weight ~ height + depth + lat + (height + 1 | year_station)	6707	6761	-3346	6691
meat_weight ~ height + depth + density + lat + (height + 1 | year_station)	6708	6769	-3345	6690
meat_weight ~ height + depth + lat + height * depth + (height + 1 | year_station)	6709	6770	-3346	6691
meat_weight ~ height + depth + lat + (1 | year_station)	6761	6801	-3374	6749
meat_weight ~ height + depth + subarea + (1 | year_station)	6761	6828	-3370	6741
meat_weight ~ height + depth + density + lat + (1 | year_station)	6762	6809	-3374	6748
meat_weight ~ height + depth + (height + 1 | year_station)	6786	6833	-3386	6772
meat_weight ~ height + depth + density + (height + 1 | year_station)	6788	6841	-3386	6772
meat_weight ~ depth + height * depth + (height + 1 | year_station)	6788	6842	-3386	6772
meat_weight ~ height + height * depth + (height + 1 | year_station)	6788	6842	-3386	6772
meat_weight ~ height + density + height * depth + (height + 1 | year_station)	6790	6850	-3386	6772
meat_weight ~ height + depth + density + height * depth + (height + 1 | year_station)	6790	6850	-3386	6772
meat_weight ~ height + depth + (1 | year_station)	6839	6873	-3414	6829
meat_weight ~ height + depth + density + (1 | year_station)	6840	6881	-3414	6828
meat_weight ~ depth + height * depth + (1 | year_station)	6841	6881	-3414	6829
meat_weight ~ height + height * depth + (1 | year_station)	6841	6881	-3414	6829
meat_weight ~ height + lat + (height + 1 | year_station)	6988	7035	-3487	6974
meat_weight ~ height + (height + 1 | year_station)	7040	7081	-3514	7028
meat_weight ~ height + lat + (1 | year_station)	7041	7075	-3515	7031
meat_weight ~ height + density + (height + 1 | year_station)	7042	7090	-3514	7028
meat_weight ~ height + (1 | year_station)	7093	7120	-3542	7085
meat_weight ~ height + density + (1 | year_station)	7095	7128	-3542	7085
meat_weight ~ depth + (height + 1 | year_station)	9074	9115	-4531	9062
meat_weight ~ depth + (1 | year_station)	29295	29322	-14643	29287
meat_weight ~ height + depth + height * depth + lat + subarea	42747		-6107	376871

Mid-Atlantic Bight				
*meat_weight ~ depth + height * depth + (1 | year_station)*	3626	3664	-1807	3614
meat_weight ~ height + height * depth + (1 | year_station)	3626	3664	-1807	3614
meat_weight ~ height + depth + density + height * depth + (height + 1 | year_station)	3629	3686	-1806	3611
meat_weight ~ height + density + height * depth + (height + 1 | year_station)	3629	3686	-1806	3611
meat_weight ~ height + height * depth + (height + 1 | year_station)	3630	3681	-1807	3614
meat_weight ~ depth + height * depth + (height + 1 | year_station)	3630	3681	-1807	3614
meat_weight ~ height + depth + lat + height * depth + (height + 1 | year_station)	3631	3688	-1807	3613
meat_weight ~ height + depth + subarea + height * depth + (height + 1 | year_station)	3632	3708	-1804	3608
meat_weight ~ height + subarea + height * depth + (height + 1 | year_station)	3632	3708	-1804	3608
meat_weight ~ height + depth + density + (1 | year_station)	3634	3672	-1811	3622
meat_weight ~ height + depth + (1 | year_station)	3635	3667	-1813	3625
meat_weight ~ height + depth + subarea + (1 | year_station)	3636	3693	-1809	3618
meat_weight ~ height + depth + density + lat + (1 | year_station)	3636	3681	-1811	3622
meat_weight ~ height + depth + density + (height + 1 | year_station)	3637	3687	-1810	3621
meat_weight ~ height + depth + lat + (1 | year_station)	3637	3675	-1812	3625
meat_weight ~ height + depth + (height + 1 | year_station)	3638	3682	-1812	3624
meat_weight ~ height + depth + subarea + (height + 1 | year_station)	3638	3708	-1808	3616
meat_weight ~ height + depth + density + lat + (height + 1 | year_station)	3638	3696	-1810	3620
meat_weight ~ height + depth + lat + (height + 1 | year_station)	3639	3690	-1812	3623
meat_weight ~ height + depth + lat + subarea + (height + 1 | year_station)	3640	3716	-1808	3616
meat_weight ~ height + lat + (1 | year_station)	3838	3870	-1914	3828
meat_weight ~ height + lat + (height + 1 | year_station)	3841	3886	-1914	3827
meat_weight ~ height + (1 | year_station)	3848	3873	-1920	3840
meat_weight ~ height + density + (1 | year_station)	3848	3880	-1919	3838
meat_weight ~ height + (height + 1 | year_station)	3851	3889	-1919	3839
meat_weight ~ height + density + (height + 1 | year_station)	3851	3895	-1918	3837
meat_weight ~ depth + (height + 1 | year_station)	5644	5682	-2816	5632
meat_weight ~ depth + (1 | year_station)	15340	15365	-7666	15332
meat_weight ~ height + depth	26144		-8715	126965

Appendix B7-Table 2. The standard errors for the parameter estimates in Table 1. The parameters estimated are: the intercept (α), the shell height coefficient (β), the depth coefficient (γ), the latitude coefficient (δ), and (ρ) the shell height by depth interaction in MAB, and the subarea coefficient in GBK.

	α	β	γ	δ	ρ	resid.
Mid-Atlantic Bight						
NEFSC (2007)	0.150	0.050				
NEFSC (2007) with Depth effect	0.390	0.050	0.080			
NEFSC (2010)	0.024	0.096				3.61[a]
NEFSC (2010) with Depth effect	0.021	0.093	0.104			3.61[a]
NEFSC (2010) with Depth effect and interaction	0.021	0.095	0.106		0.472	3.61[a]
Georges Bank						
NEFSC (2007)	0.270	0.060				
NEFSC (2007) with Depth effect	0.170	0.050	0.050			
NEFSC (2010)	0.034	0.090				4.57[a]
NEFSC (2010) with Depth and Latitude effect	0.028	0.102	0.131			4.46[a]
NEFSC (2010) with Depth, Latitude and subarea effect	0.061	0.104	0.129	3.286	0.098[b]	4.46[a]

a - these are standard deviations

b - averaged across all subarea levels

Appendix B7-Table 3. Current shell height/meat weight parameters, compared with those from other studies. The parameters estimated are: the intercept (α), the shell height coefficient (β), the depth coefficient (γ), the latitude coefficient (δ), and (ρ) the shell height by depth interaction in MAB, and the average subarea coefficient in GBK.

	α	β	γ	δ	ρ
Mid-Atlantic Bight					
Haynes (1966)	-11.09	3.04			
Serchuk and Rak (1983)	-12.16	3.25			
NEFSC (2001)	-12.25	3.26			
Lai and Helser (2004)	-12.34	3.28			
NEFSC (2007)	-12.01	3.22			
NEFSC (2007) with Depth effect	-9.18	3.18	-0.65		
NEFSC (2010)	-10.80	2.97			
NEFSC (2010) with Depth effect	-8.94	2.94	-0.43		
NEFSC (2010) with Depth effect and interaction	-16.88	4.64	1.57	-	-0.43
Georges Bank					
Haynes (1966)	-10.84	2.95			
Serchuk and Rak (1983)	-11.77	3.17			
NEFSC (2001)	-11.60	3.12			
Lai and Helser (2004)	-11.44	3.07			
NEFSC (2007)	-10.70	2.94			
NEFSC (2007) with Depth effect	-8.62	2.95	-0.51		
NEFSC (2010)	-10.25	2.85			
NEFSC (2010) with Depth effect	-8.05	2.84	-0.51		
NEFSC (2010) with Depth, Latitude and subarea effect	14.380	2.826	-0.529	5.980	0.051[b]

b - averaged across all subarea levels

Appendix B7-Table 4. Current shell height/meat weight parameters, compared across years. The parameters estimated are: the intercept (α), the shell height coefficient (β), the depth coefficient (γ). The numbers of stations used in each year are also shown.

	α	β	γ	$n_{(stations)}$
Mid-Atlantic Bight[b]				
2001	-10.40	2.97	-0.1007	69
2002	-8.54	2.86	-0.4601	54
2003[a]				
2004	-9.70	2.98	-0.2592	124
2005	-8.60	3.12	-0.7516	130
2006	-8.75	3.05	-0.6331	111
2007	-8.83	2.77	-0.2365	120
2008	-8.03	2.80	-0.4744	109
2009	-8.44	2.75	-0.303	101
Georges Bank[b]				
2001	-7.7695	2.8203	-0.5614	52
2002	-7.3727	2.72	-0.5394	90
2003[a]				
2004	-7.9818	2.7536	-0.4313	154
2005	-8.3563	2.8691	-0.477	137
2006	-7.0069	2.728	-0.6328	135
2007	-7.6659	2.9681	-0.7194	155
2008	-9.247	2.9165	-0.3091	89
2009	-7.1515	2.5507	-0.3874	110

a - estimates using 2003 survey data were excluded from the model

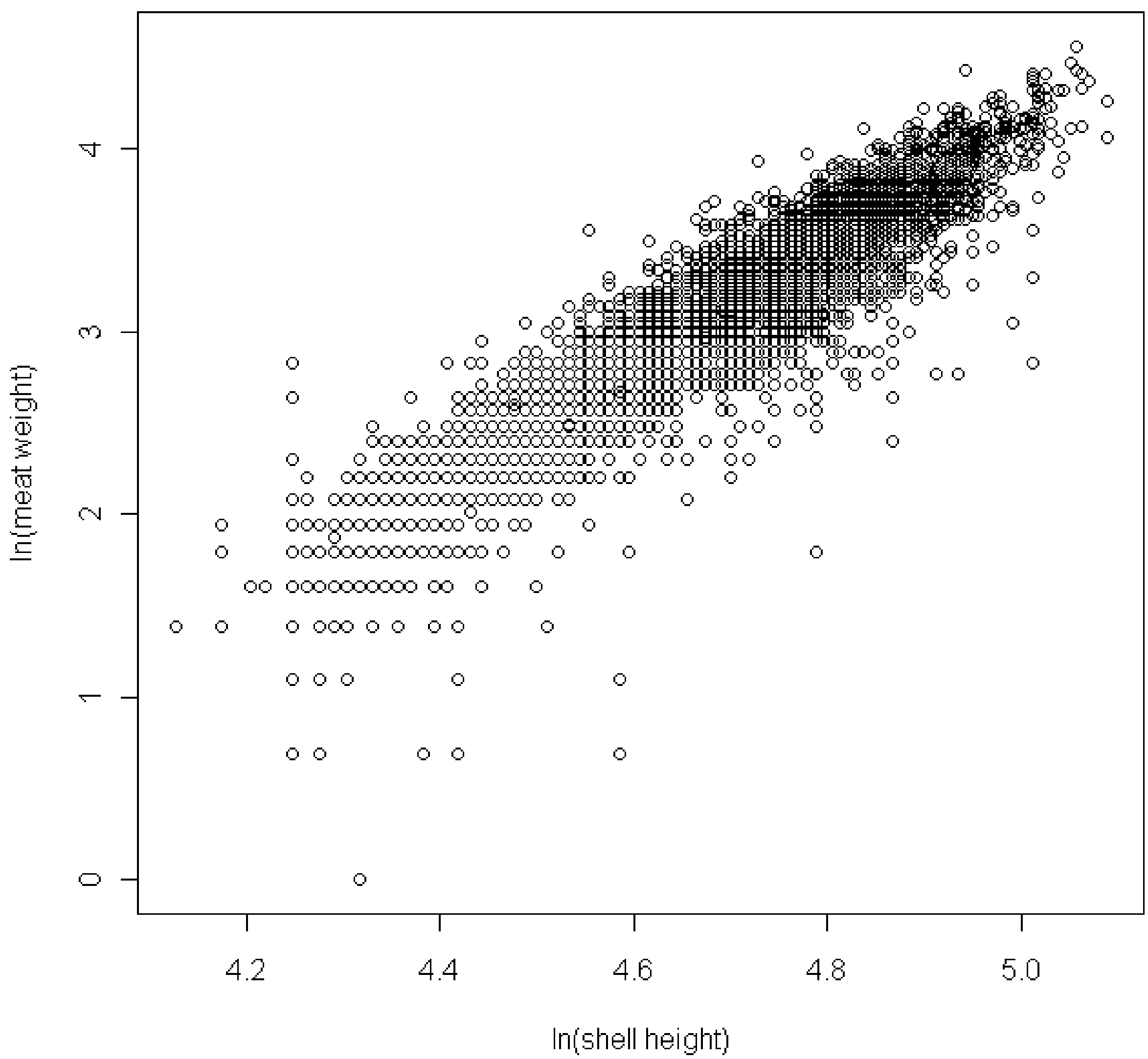
b - model = meat_weight ~ height + depth + (1 | year_station)

Appendix B7-Table 5. Current shell height/meat weight parameters, compared across subareas within each region. The parameters estimated are: the intercept (α), the shell height coefficient (β), the depth coefficient (γ). The numbers of stations used in each year are also shown.

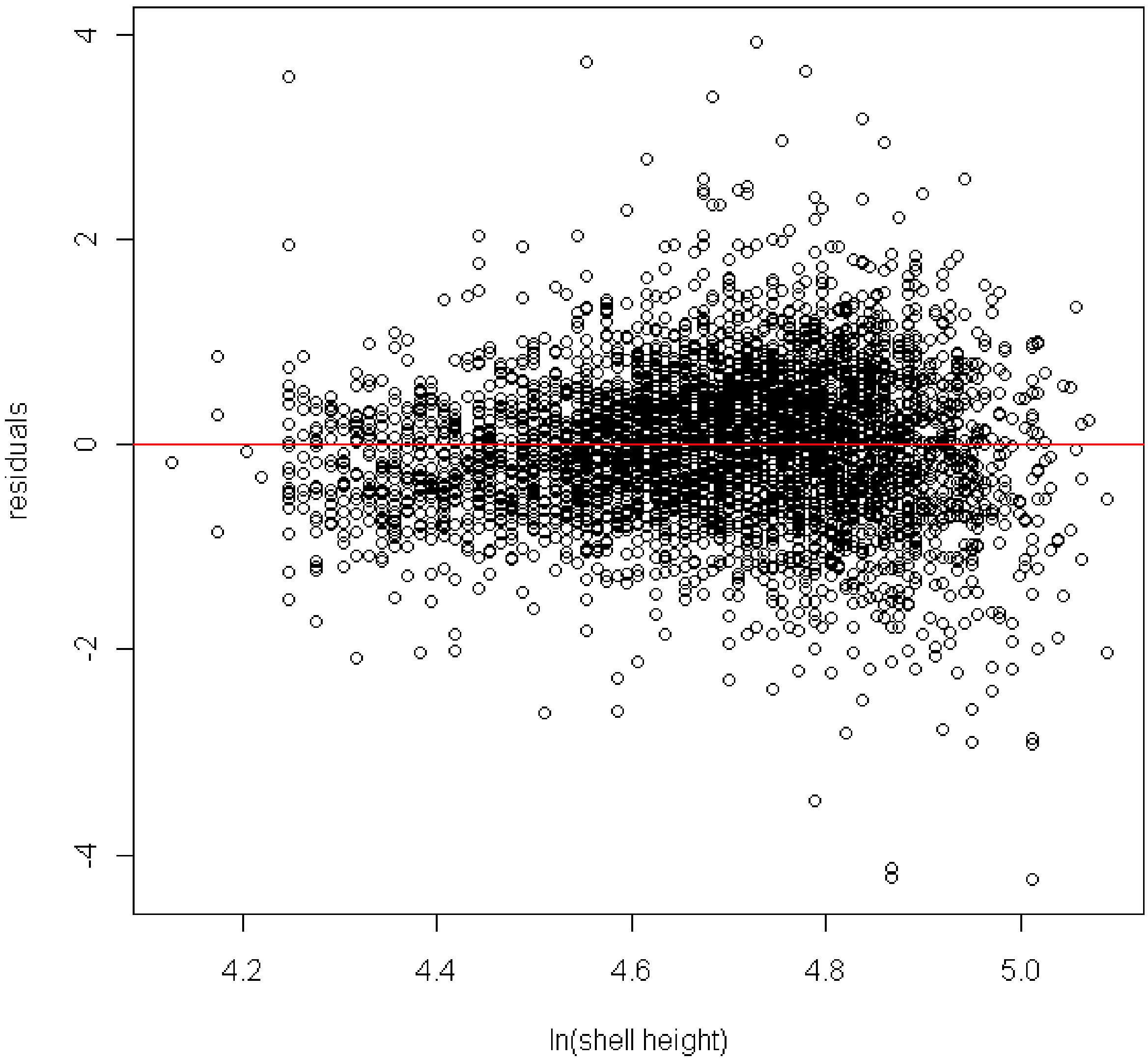
	α	β	γ	$n_{(stations)}$
Mid-Atlantic Bight[a]				
DMV-VB	-8.0407	2.8249	-0.5194	125
ET	-7.0358	2.9036	-0.861	194
HC	-7.305	2.9066	-0.7863	139
LI	-9.7815	2.9439	-0.224	150
NYB	10.3701	3.0698	-0.213	109
Georges Bank[b]				
CL-1	-6.3757	2.7999	-0.8405	148
CL-2	-8.7026	2.8338	-0.3354	205
NEP	-7.9355	2.8325	-0.5477	152
NLS	-8.1709	2.6454	-0.2298	92
Sch	-9.5245	2.9359	-0.2808	146
SEP	-4.3756	2.6291	-1.1166	69

a - model = meat_weight ~ height + depth + (1 | year_station)

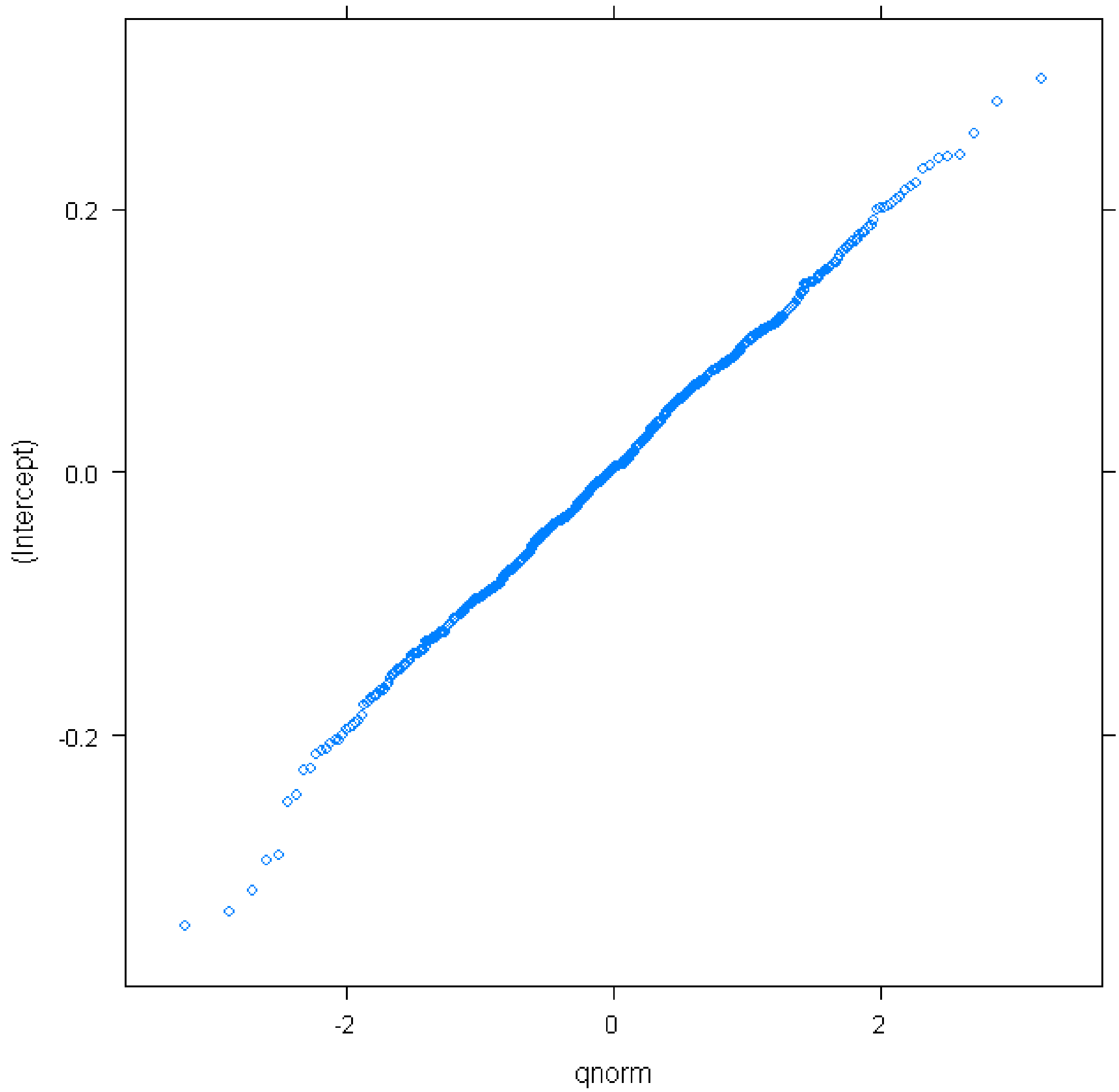
b - model = meat_weight ~ height + depth + (height + 1 | year_station)



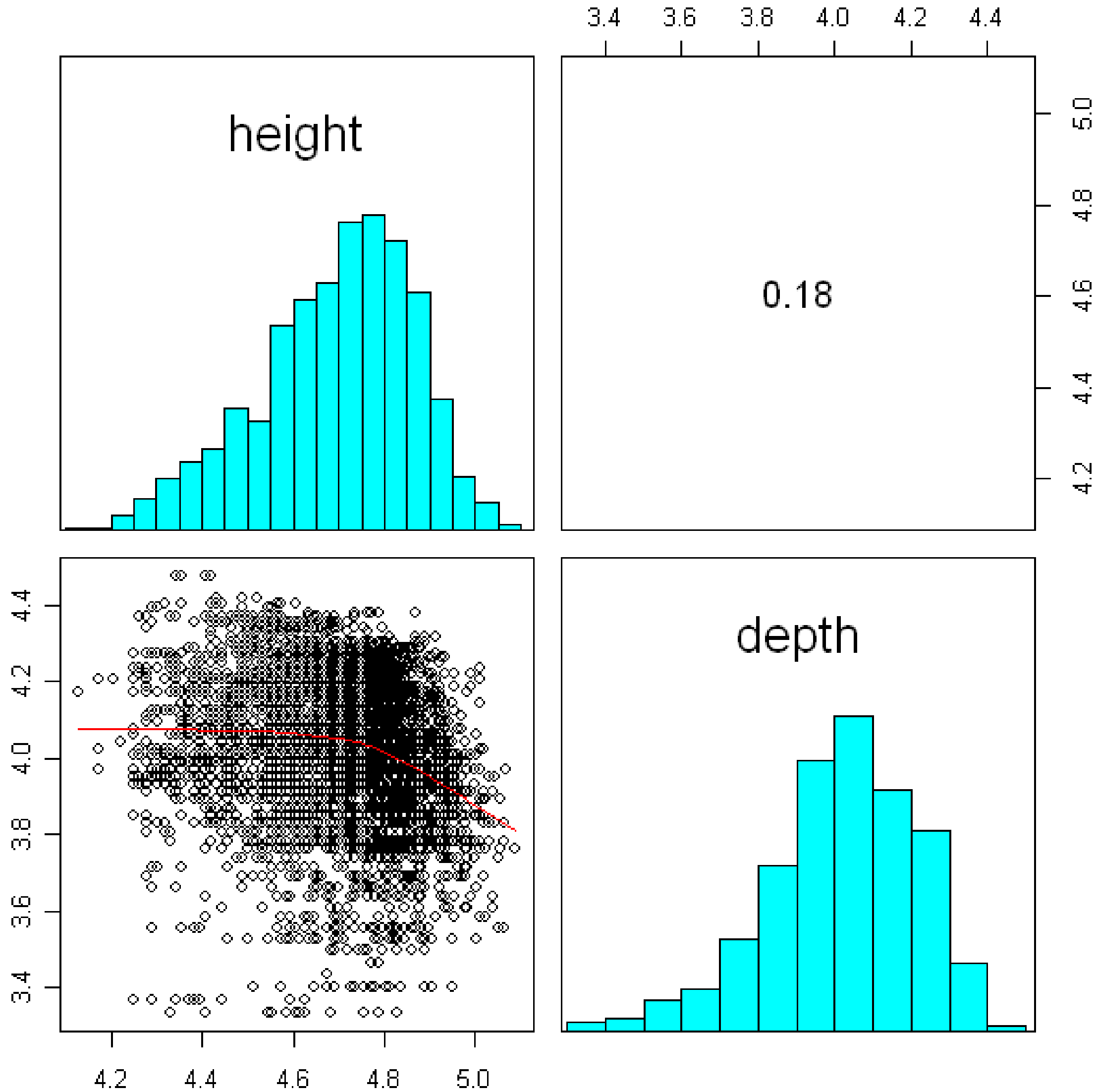
Appendix B7-Figure 1. Mid-Atlantic shell height/meat weight data



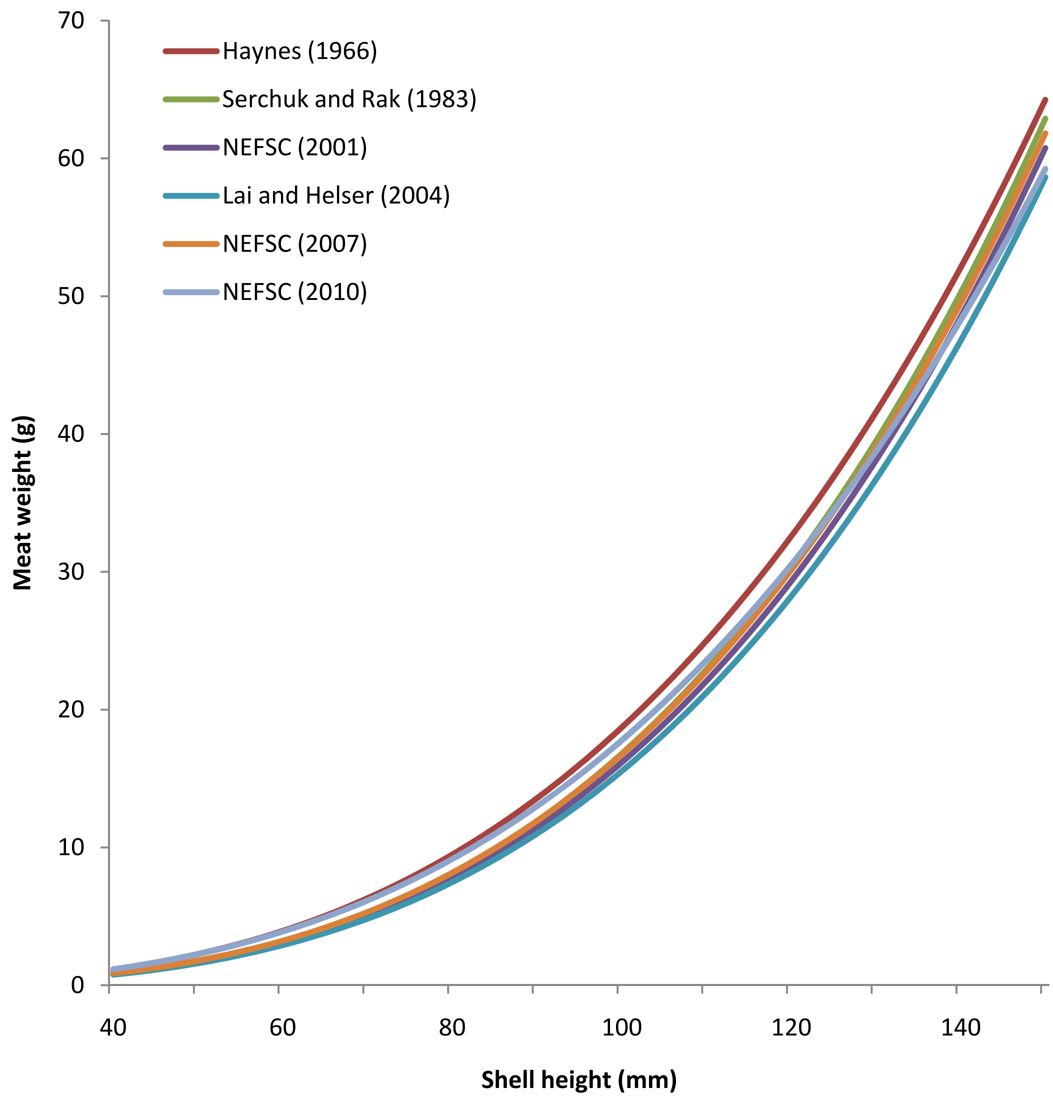
Appendix B7-Figure 2. Residual plot of Mid-Atlantic shell height/meat weight data



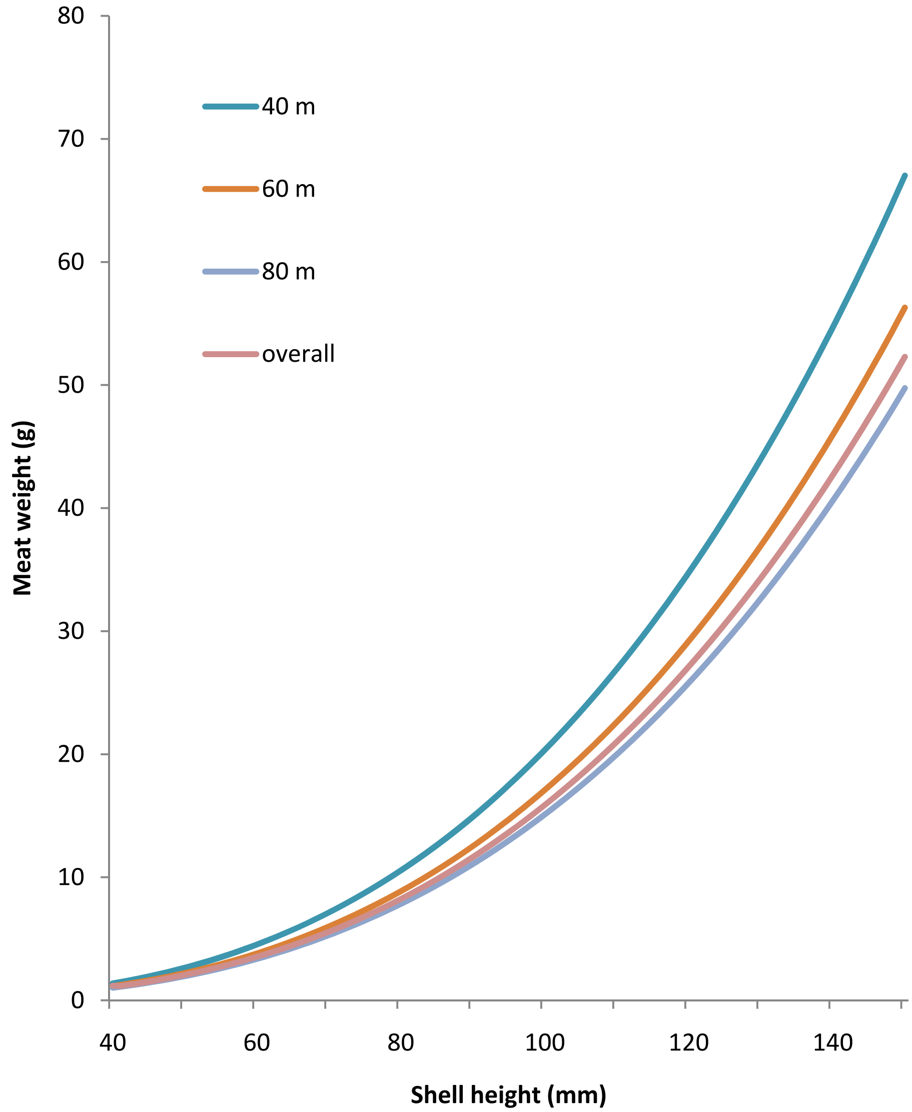
Appendix B7-Figure 3. Normality plot of the BLUPs (Best Linear Unbiased Predictions of the random effects) from the best model (Eq. 1) for the Mid-Atlantic Bight. The only random effect is an intercept, grouped by station (where station is a unique identifier that incorporates spatial – survey station, and temporal – year, variability).



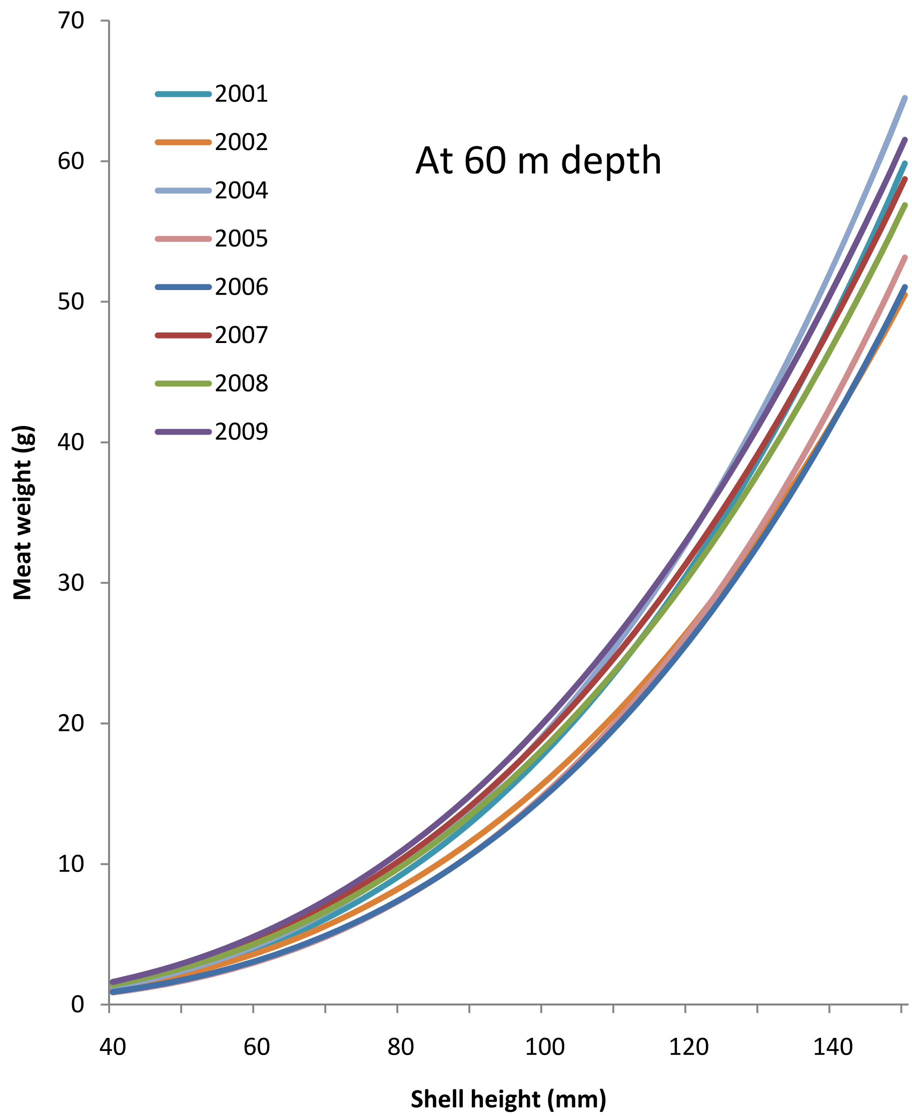
Appendix B7-Figure 4. The correlation plot of the fixed effects from the best model (Eq. 1) for the Mid-Atlantic Bight. The values of the correlation coefficients for each comparison are shown in the upper diagonal. The main diagonal shows the frequency histogram of each effect and the scatter plot in the lower diagonal includes a smooth curve meant only to aid visual interpretation.



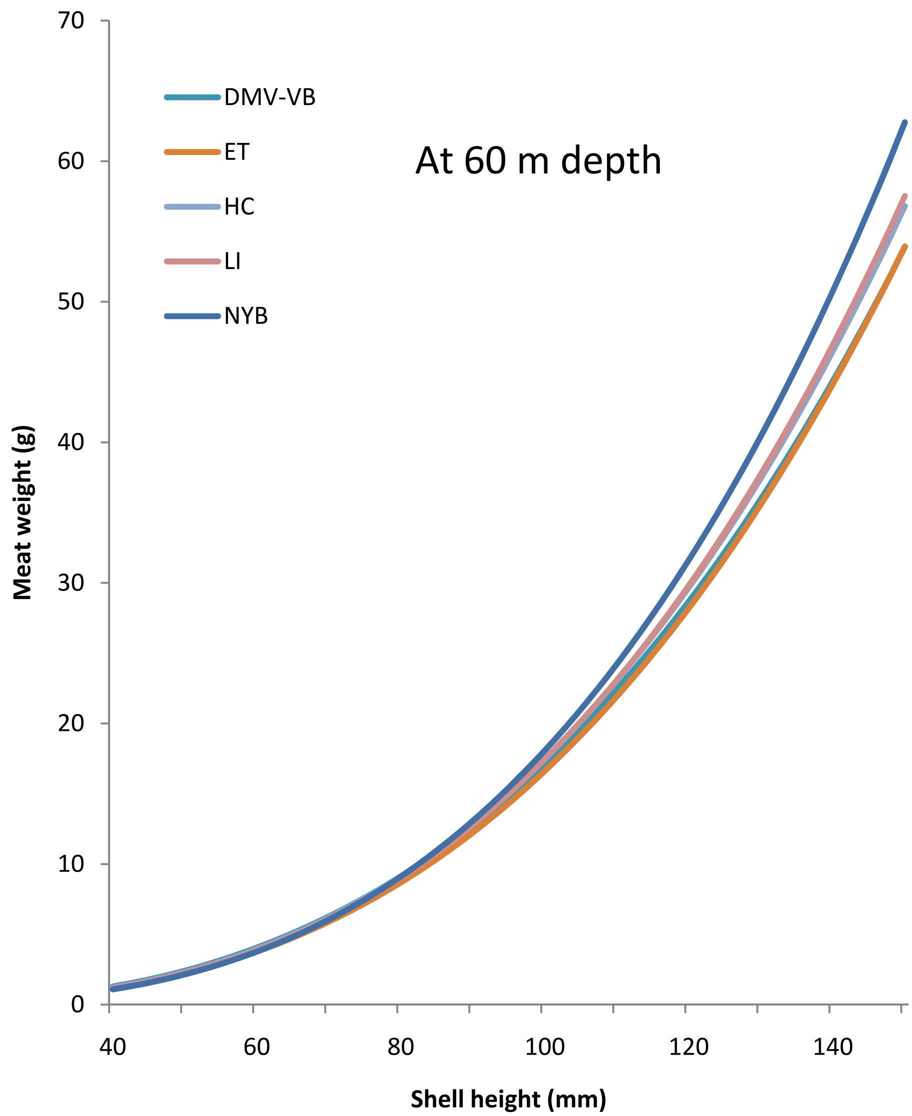
Appendix B7-Figure 5. Comparison of historical shell height/meat weight parameter estimates in the Mid-Atlantic (directly comparable models only, i.e. of the form $\boldsymbol{W = e^{(\alpha+a(St)+\beta)+\epsilon}}$).



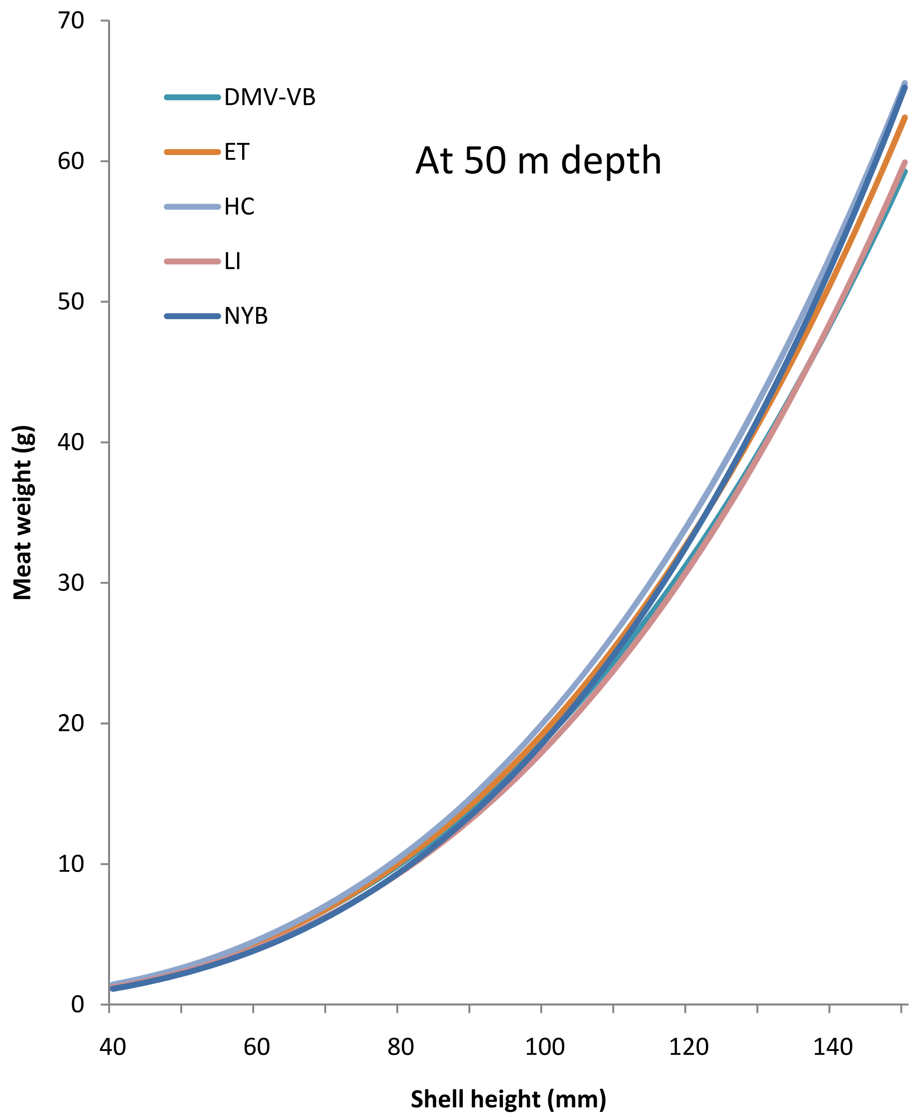
Appendix B7-Figure 6. Shell height/meat weight relationships at relationships 40, 60, 80 m depth, and overall in the Mid-Atlantic
($\boldsymbol{W = e^{(\alpha + a(St) + \beta \ln(L) + \gamma ln(D)) + \epsilon}}$).



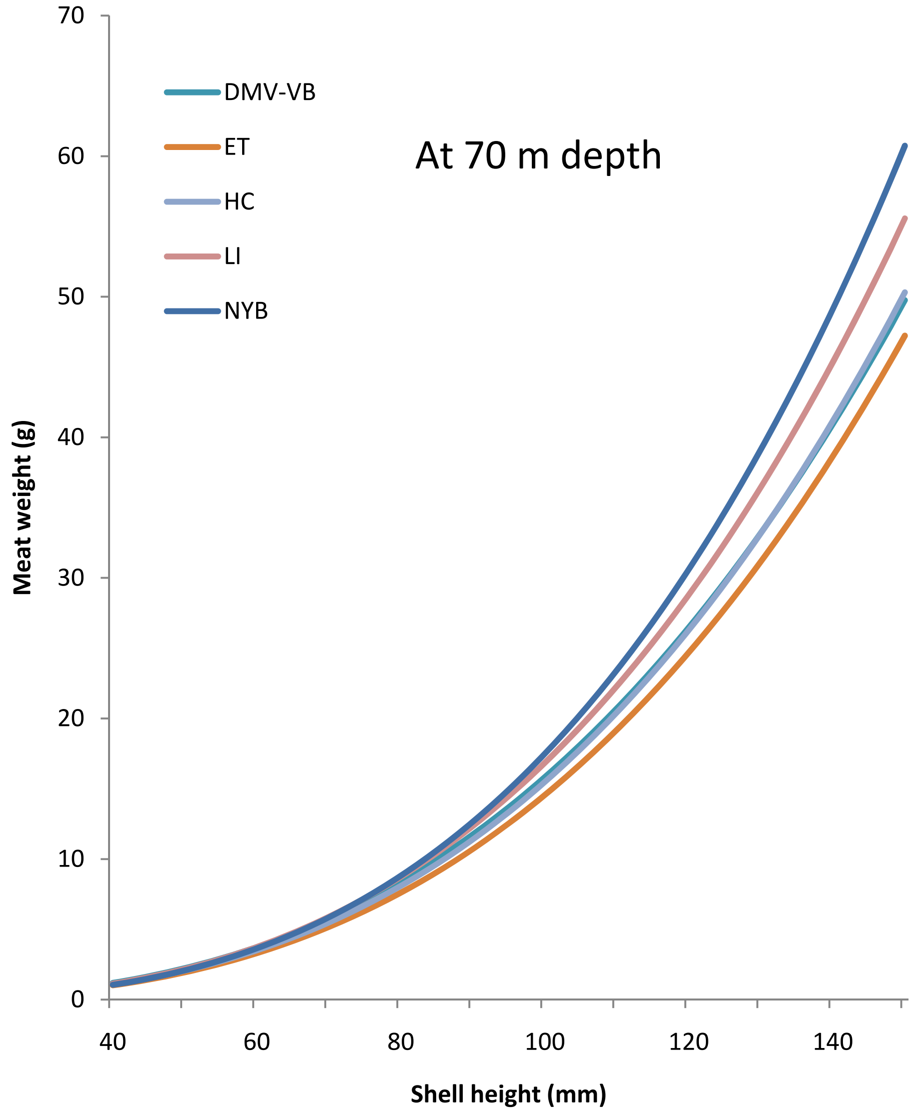
Appendix B7-Figure 7. Shell height/meat weight relationships for each survey year at 60 m depth in the Mid-Atlantic Bight ($\boldsymbol{W = e^{(\alpha + a(St) + \beta \ln(L) + \gamma ln(D)) + \epsilon}}$).



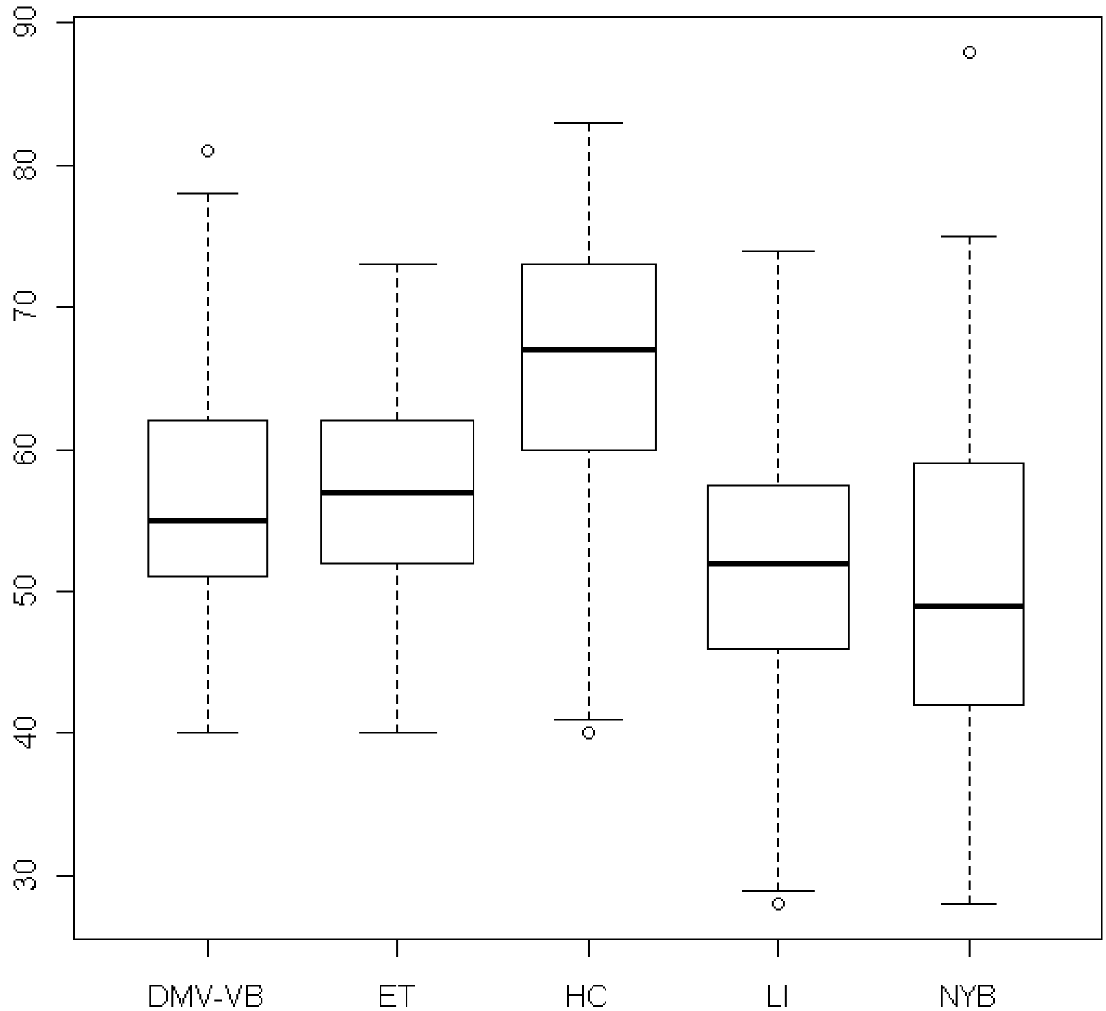
Appendix B7-Figure 8. Shell height/meat weight relationships for each subarea at 60 m depth in the Mid-Atlantic Bight ($\boldsymbol{W} = \boldsymbol{e}^{(\boldsymbol{\alpha}+\boldsymbol{a}(\boldsymbol{St})+\boldsymbol{\beta}\ln(\boldsymbol{L})+\boldsymbol{\gamma} \boldsymbol{ln}(\boldsymbol{D}))+\boldsymbol{\epsilon}}$).



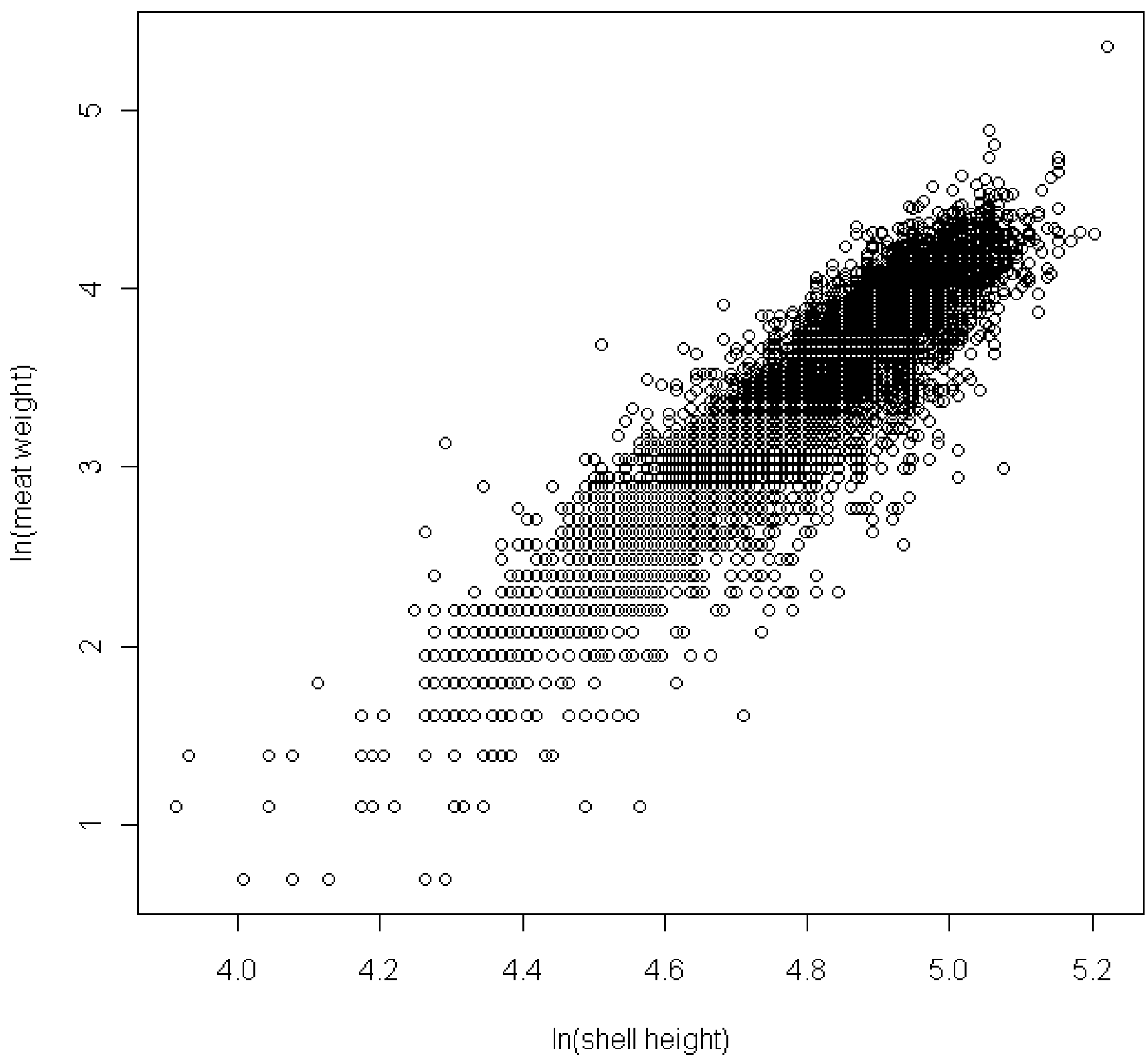
Appendix B7-Figure 9. Shell height/meat weight relationships for each subarea at 50 m depth in the Mid-Atlantic Bight ($\boldsymbol{W} = \boldsymbol{e}^{(\alpha+a(St)+\beta\ln(L)+\gamma ln(D))+\epsilon}$).



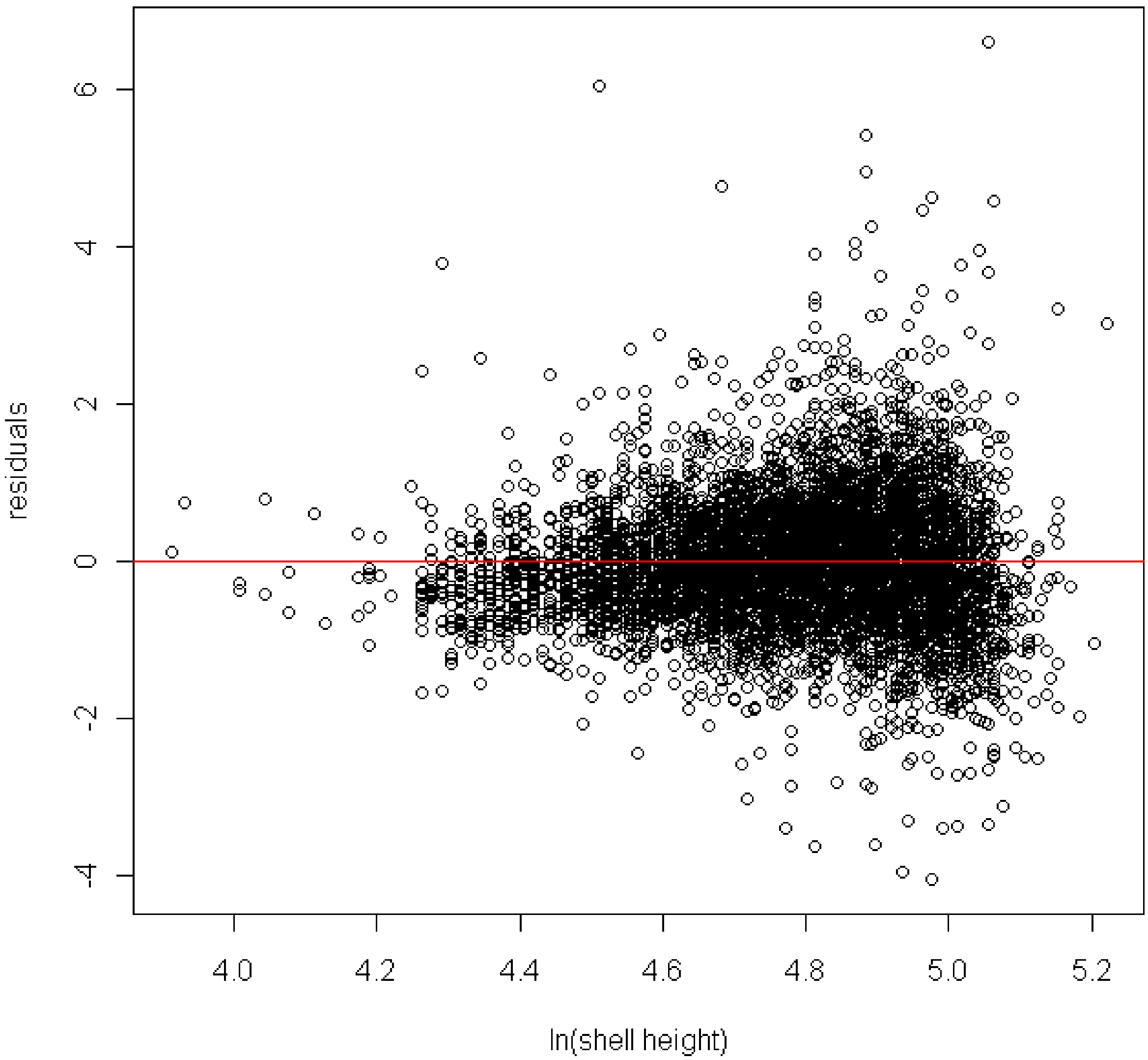
Appendix B7-Figure 10. Shell height/meat weight relationships for each subarea at 70 m depth in the Mid-Atlantic Bight ($\boldsymbol{W = e^{(\alpha + a(St) + \beta \ln(L) + \gamma ln(D)) + \epsilon}}$).



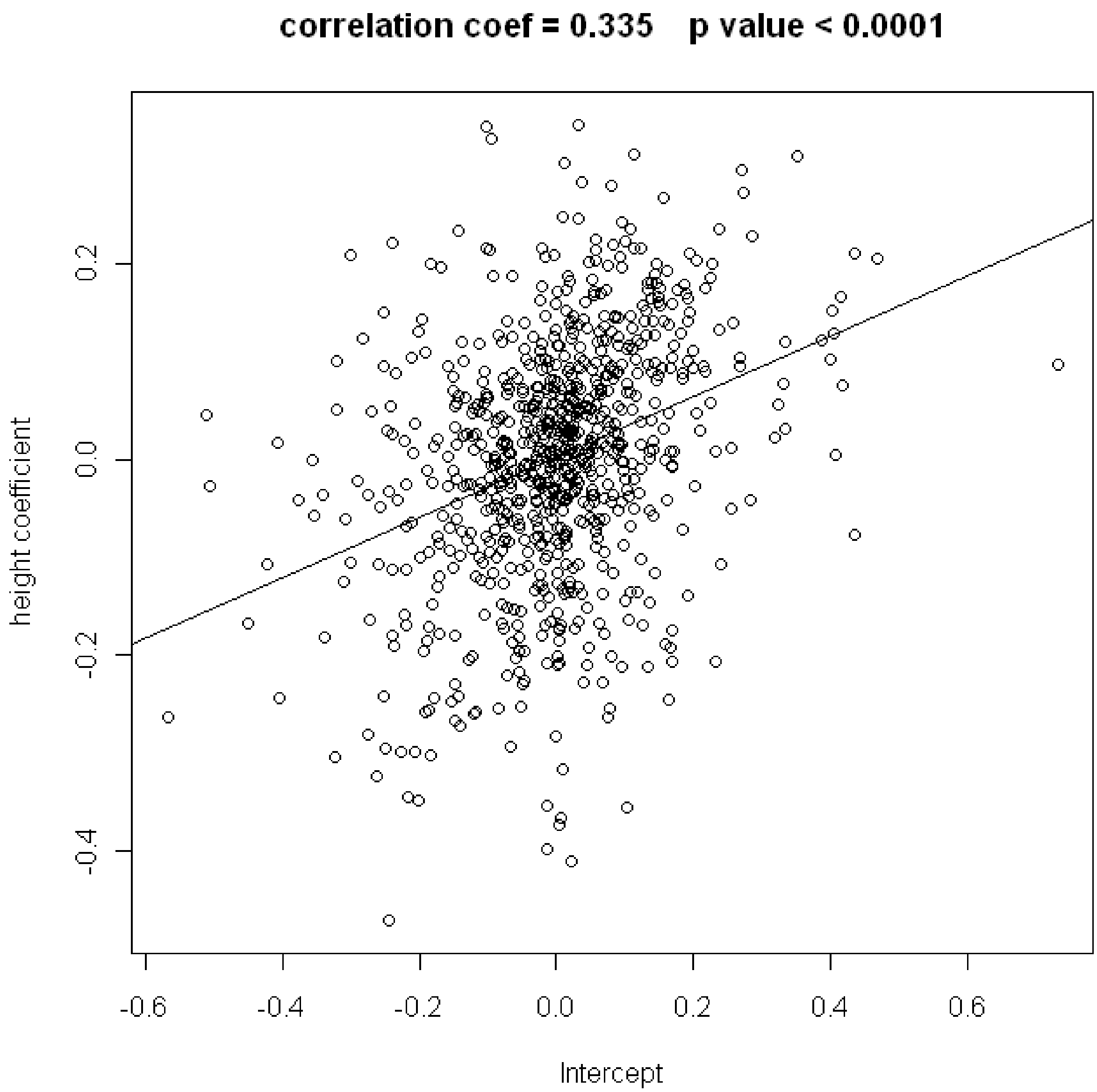
Appendix B7-Figure 11. Box plots of the depths of samples taken from each of the subareas in the Mid-Atlantic Bight.



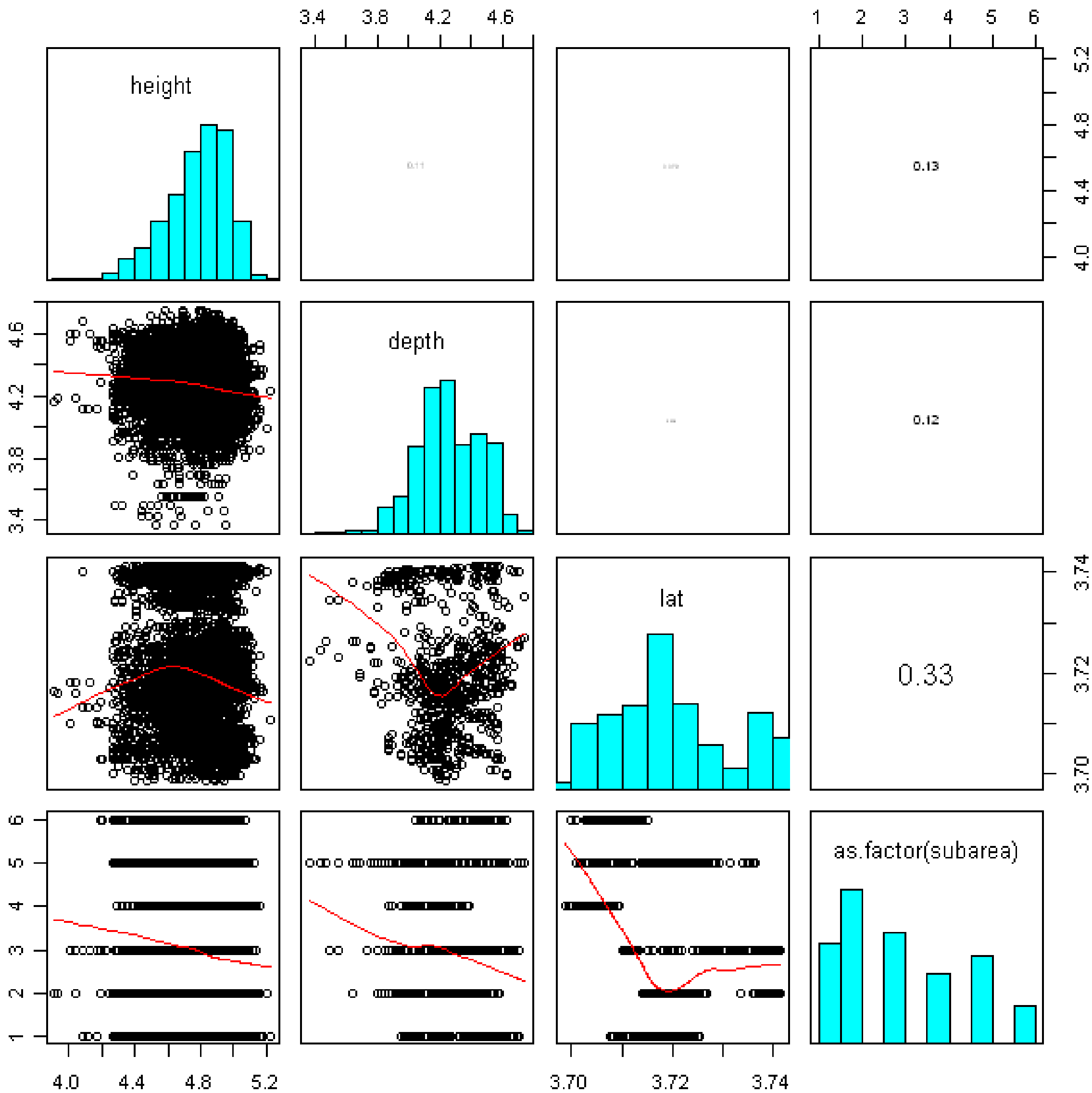
Appendix B7-Figure 12. Georges Bank shell height/meat weight data.



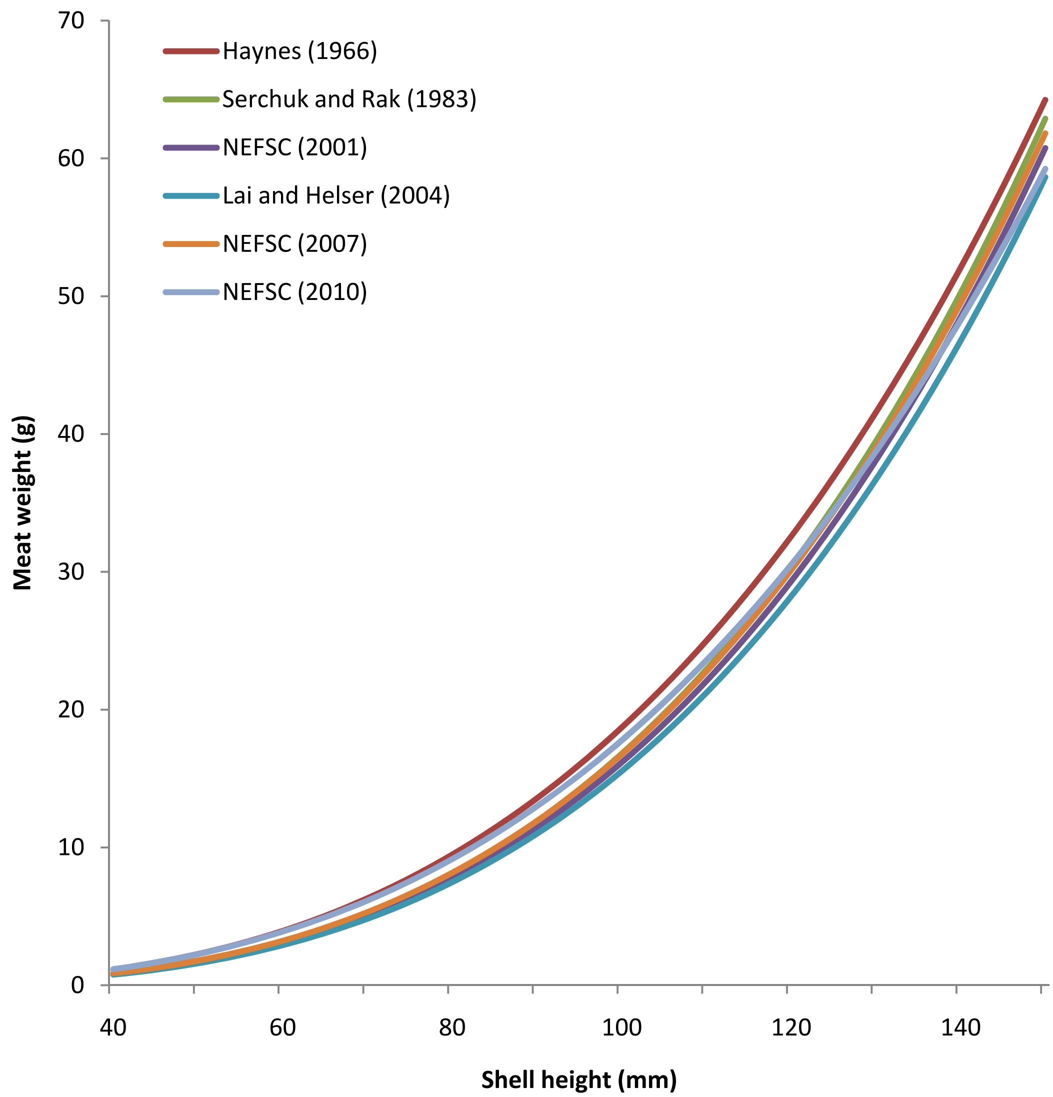
Appendix B7-Figure 13. Residual plot of Georges Bank shell height/meat weight data.



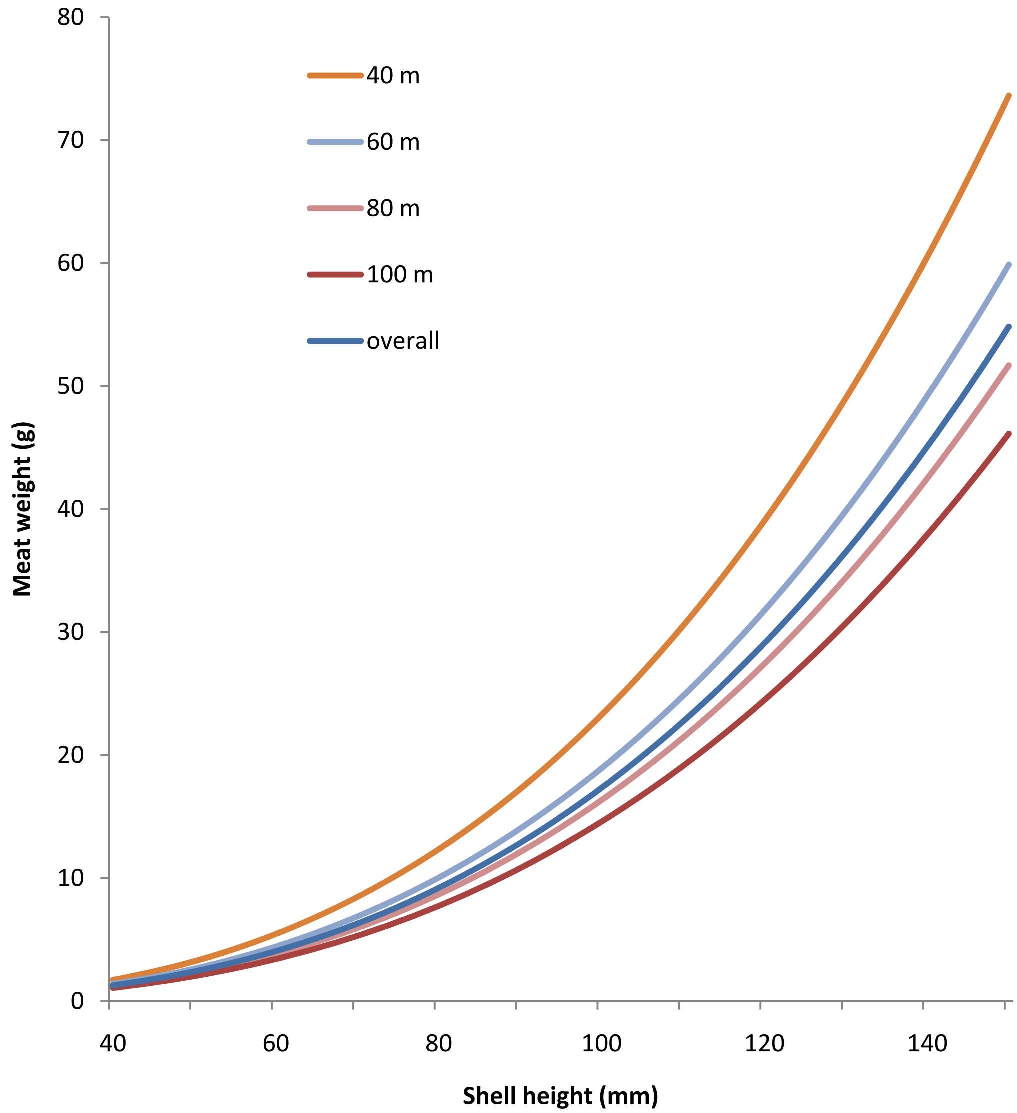
Appendix B7-Figure 14. The correlation between BLUPs (Best Linear Unbiased Predictions of random effects) from the best model (2) for Georges Bank. These are a random slope coefficient (on shell height) and a random intercept, both grouped by station (where station is a unique identifier that incorporates spatial – survey station, and temporal – year, variability).



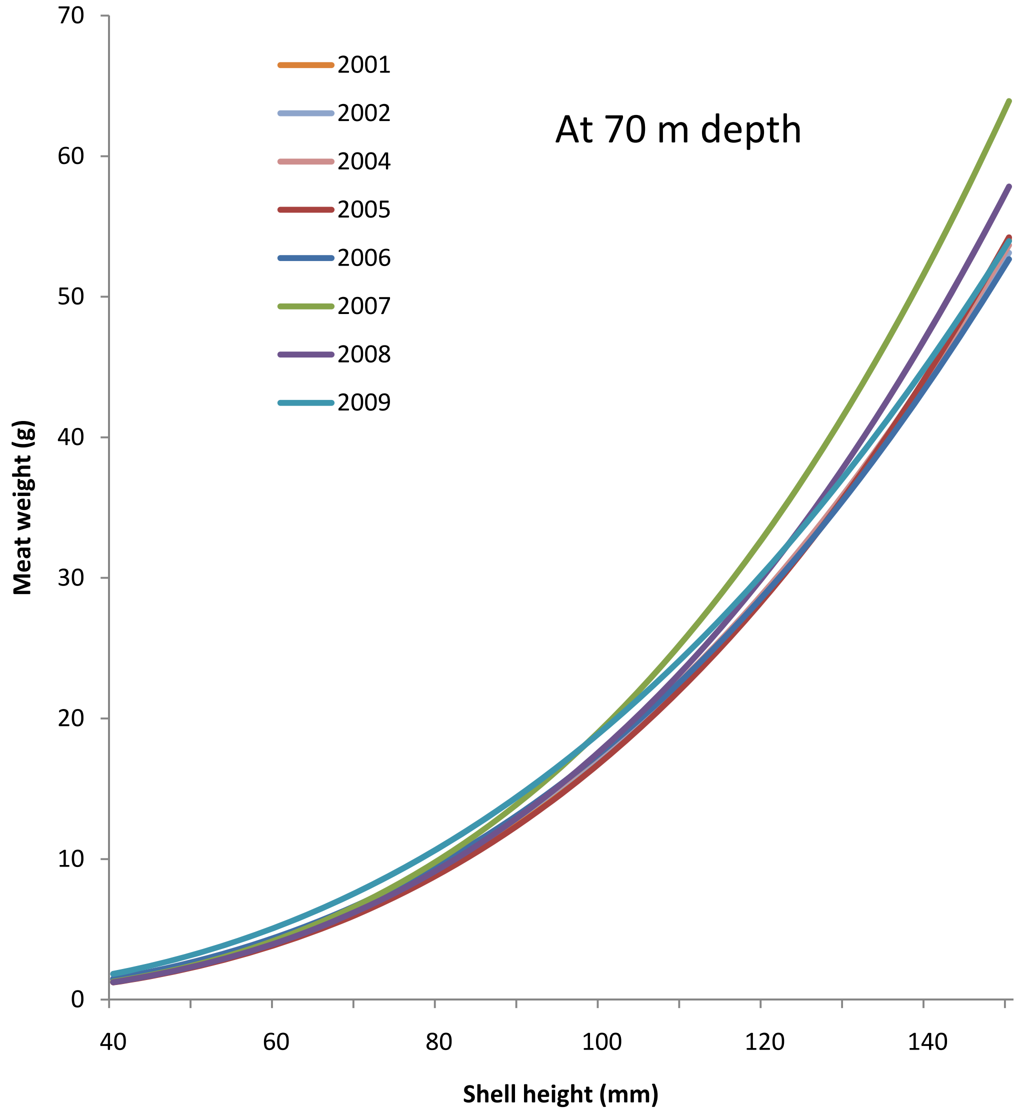
Appendix B7-Figure 15. Correlation of Fixed effects from the best model (2) for Georges Bank. The values of the correlation coefficients for each comparison are shown in the upper diagonal and the text font is scaled relative to the significance of the correlation. The main diagonal shows the frequency histogram of each effect and the scatter plots in the lower diagonal include a smooth line meant only to aid visual inspection.



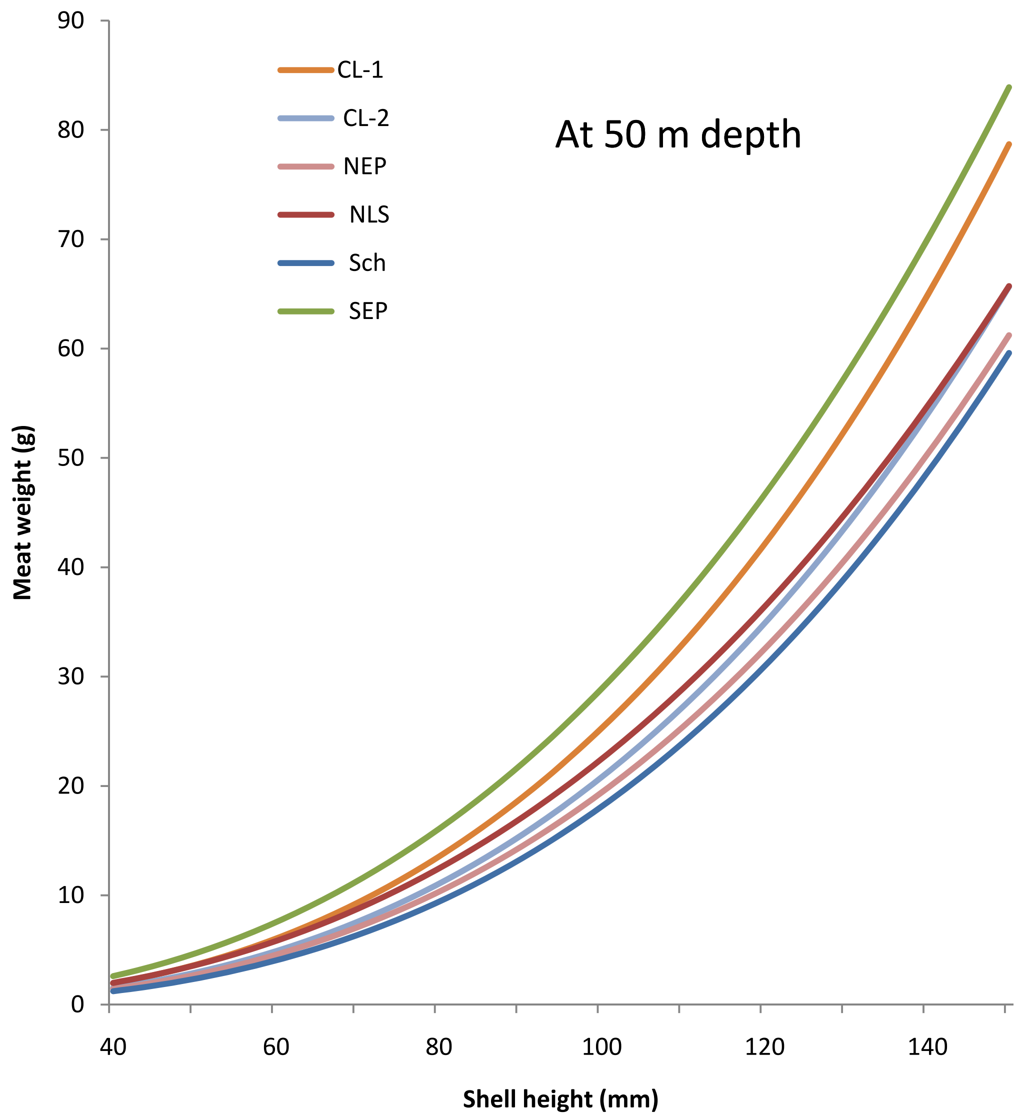
Appendix B7-Figure 16. Comparison of shell height/meat weight parameter estimates in the Georges Bank (directly comparable models only, i.e. of the form $= \boldsymbol{e}^{(\alpha+a(St)+\beta)+\epsilon}$).



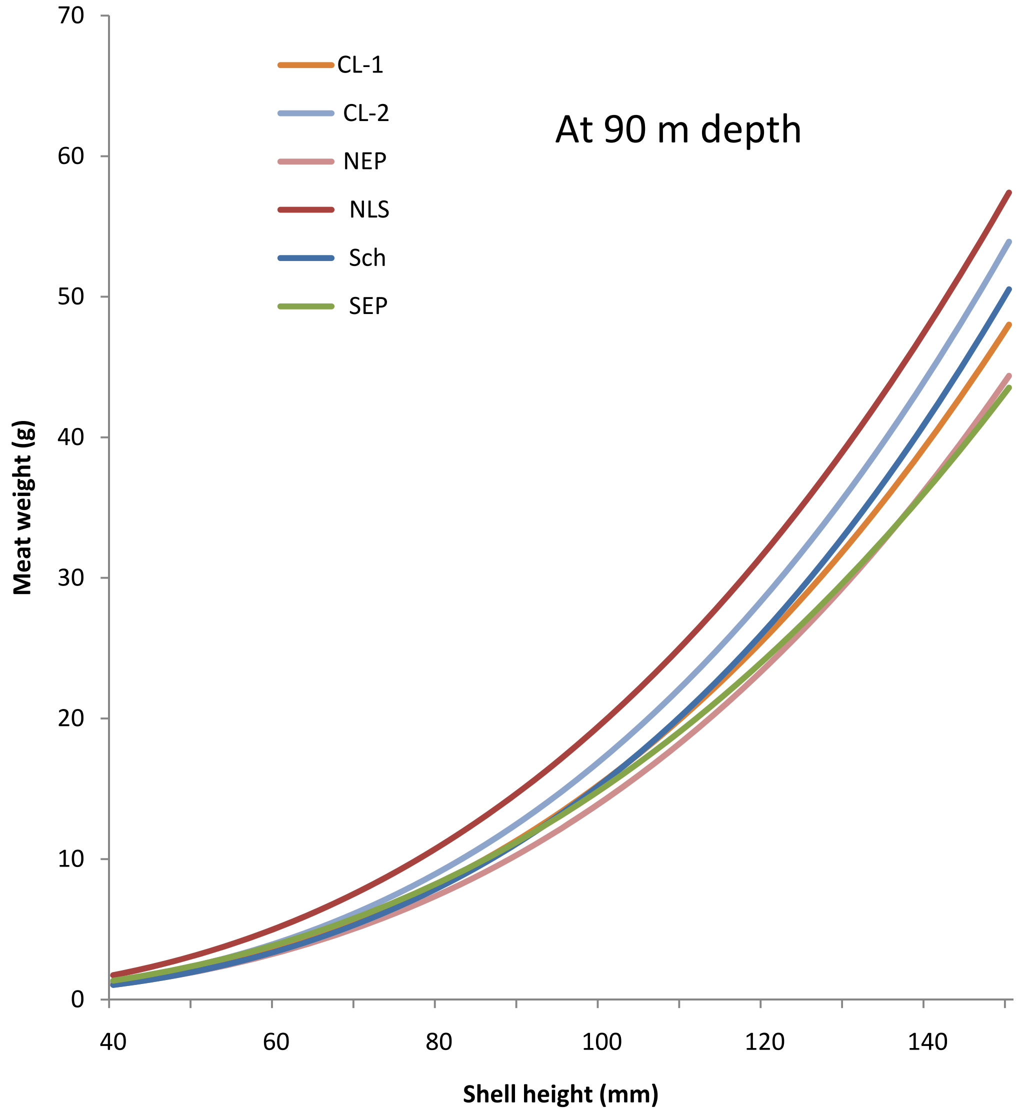
Appendix B7-Figure 17. Shell height/meat weight relationships at relationships 40, 60, 80, 100 m depth, and overall in Georges Bank ($\boldsymbol{W = e^{(\alpha + a(St) + \beta \ln(L) + \gamma ln(D) + b(L_{St})) + \epsilon}}$).



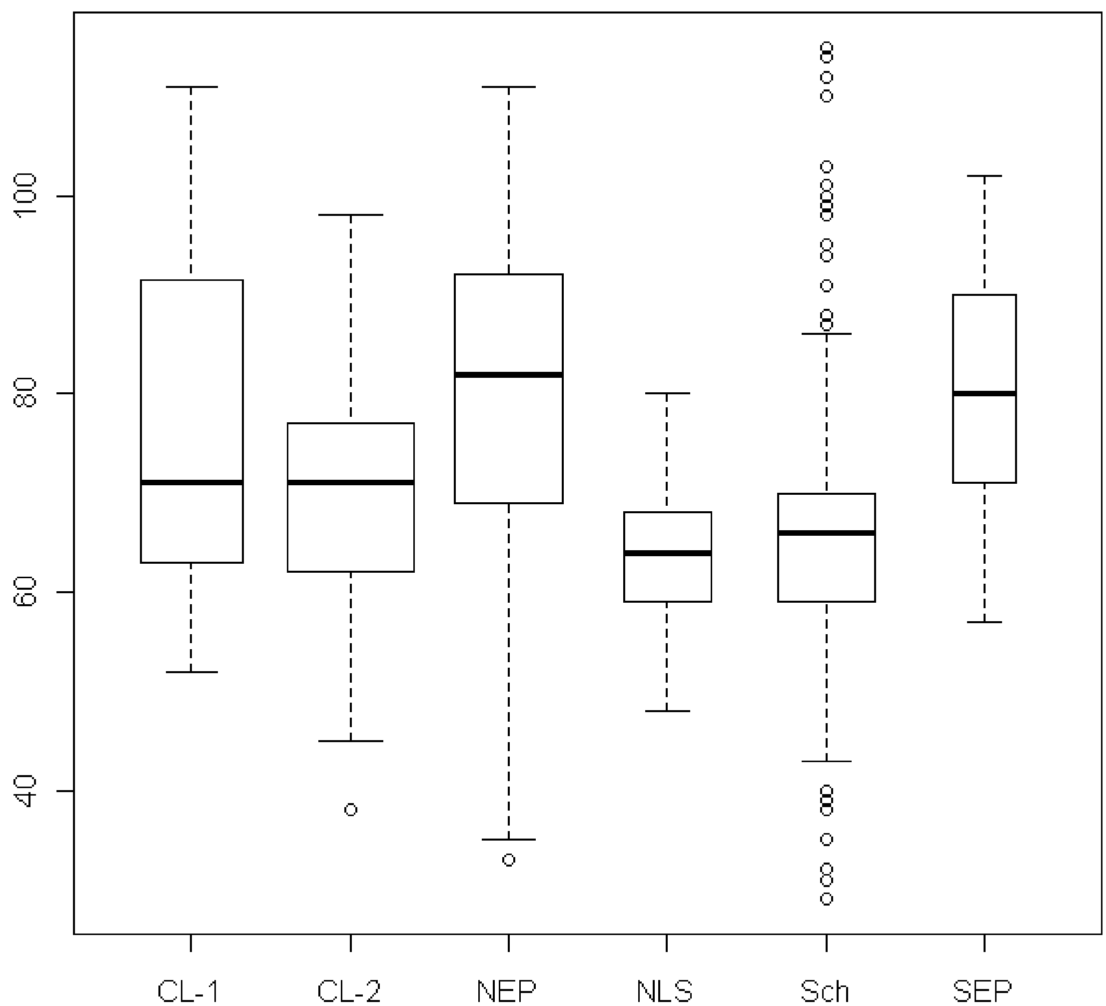
Appendix B7-Figure 18. Shell height/meat weight relationships for each survey year at 70 m depth on Georges Bank ($\boldsymbol{W = e^{(\alpha + a(St) + \beta \ln(L) + \gamma ln(D) + b(L_{St})) + \epsilon}}$).



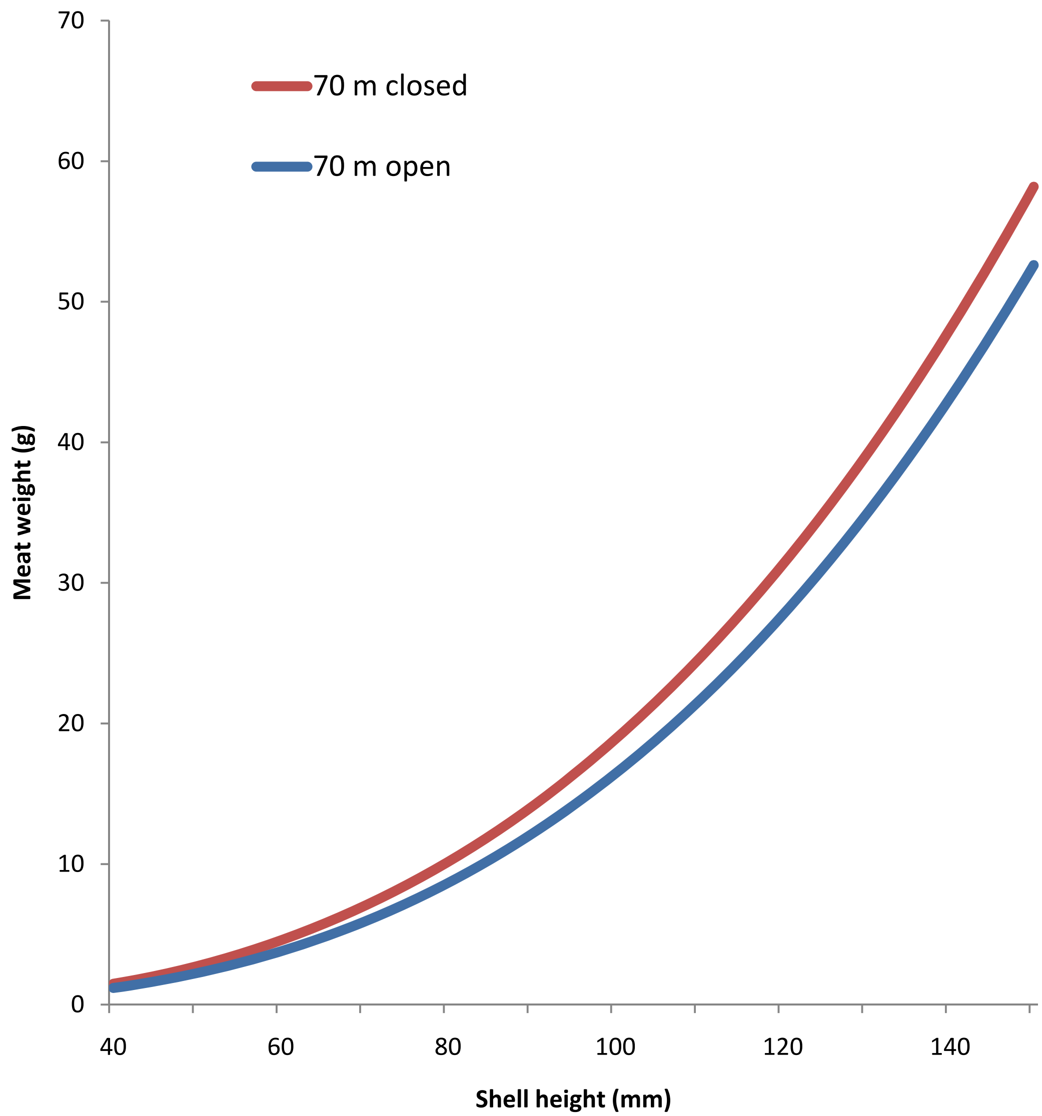
Appendix B7-Figure 19. Shell height/meat weight relationships for each survey year at 50 m depth on Georges Bank ($\boldsymbol{W} = \boldsymbol{e}^{(\alpha + a(St) + \beta \ln(L) + \gamma ln(D) + b(L_{St})) + \epsilon}$).



Appendix B7-Figure 20. Shell height/meat weight relationships for each survey year at 90 m depth on Georges Bank ($\boldsymbol{W} = \boldsymbol{e}^{(\alpha + a(St) + \beta \ln(L) + \gamma ln(D) + b(L_{St})) + \epsilon}$).



Appendix B7-Figure 21. Box plots of the depths of samples taken from each of the subareas on Georges Bank.



Appendix B7--Figure 22. Shell height/meat weight relationships at relationships for open and closed to fishing areas at 60 m depth on Georges Bank ($W = e^{(\alpha + a(St) + \beta \ln(L) + \gamma ln(D) + b(L_{St})) + \epsilon}$).