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# A proposed, tested, and applied adjustment to account for bias in growth parameter estimates due to selectivity

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## ABSTRACT

Growth information is important for stock assessments because it gives an indication of spawning stock biomass in the form of weight or fecundity, which is an important indicator of stock status, as well as being important if fitting to length composition data. Sampling for growth characteristics should include all ages and sizes in the population, but data are often only available from fishery-dependent sampling, which can lead to biased estimates of true underlying population growth parameters because of selectivity, which includes both gear selectivity and availability. Two stock assessments with the potential for biased growth because of dome-shaped selectivity and lack of fishery-independent age data are the Gulf and Atlantic menhaden assessments. The objectives of our study were (1) to develop and test a method to estimate unbiased growth parameters regardless of the selectivity of the gear used to sample ages and lengths and (2) to apply the proposed method to fit unbiased population growth parameters for Gulf and Atlantic menhaden. We propose a method to adjust for the bias in the growth curve parameters and account for missing samples at smaller and larger lengths. The proposed method was tested on simulated data and applied to data for Gulf and Atlantic menhaden. Use of the adjustments was robust and resulted in reduced bias in the growth parameter estimates with accuracy being affected by both sample size and variability in mean length at age. Increasing the sample sizes increased the accuracy of the adjustments (i.e., as the coefficient of variation (CV) for length at age increased, the accuracy of the estimates decreased). For Gulf menhaden, the parameters estimated for the unadjusted growth curve were  $L_\infty = 240.8$ ,  $k = 0.38$ ,  $t_0 = -1.14$ , and CV of length at age = 0.06 (assumed constant) with a total sample size of 366,710 from 1977 to 2011. For Atlantic menhaden, the parameters estimated for the unadjusted growth curve were  $L_\infty = 350.9$ ,  $k = 0.32$ ,  $t_0 = -0.83$ , and CV of length at age = 0.12 (assumed constant) with a total sample size of 480,668 from 1955 to 2011. The adjustment for a maximum length of capture had a large impact on the overall growth parameters for both species, while the adjustment for a minimum length of capture had less impact. Bias in the growth curve parameter estimates can be reduced by using the method outlined to account for selectivity.

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## 1. Introduction

Selectivity is important in stock assessments as it defines what ages or lengths are being represented by an index or harvested from a fishery (Quinn and Deriso, 1999). The concept of selectivity includes a combination of fishery targeting, capture by the gear, size limits, and spatial distribution of the fish population by age and size (Quinn and Deriso, 1999; Sampson and Scott, 2011). Selectivity can also have an impact on the estimates of model parameters used to describe life history characteristics for a stock assessment because often samples come from fishery-dependent sampling.

Ideally, information on growth for assessment models comes from fishery-independent and -dependent sampling and includes all ages and sizes in the population. However, in reality, often the only age samples available are those from the fishery-dependent sampling. If the fishery selects for only certain size classes, then estimates of growth can be biased (Ricker, 1969).

Growth information, such as the parameters of the von Bertalanffy growth curve, is important for stock assessments because it is important when fitting to length composition data and is generally used to give an indication of spawning stock biomass in the form of weight or fecundity, which is an important stock status indicator for harvested species (von Bertalanffy, 1957; Restrepo et al., 1998). For some stock assessments, parameter  $k$  or the size-at-age information from the growth curve is used to derive other important life history characteristics (Williams and Shertzer, 2003; Charnov et al., 2012). While estimates of growth curve parameters have

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been adjusted because of minimum length limits (McGarvey and Fowler, 2002) and selectivity (Troynikov, 1999; Taylor et al., 2005; Troynikov and Koopman, 2009), growth curve parameter estimates are generally unadjusted for maximum length limits or dome-shaped selectivity and few studies have tested proposed methods with simulated data. Gwinn et al. (2010) explored the bias in the methods that account for dome-shaped selectivity including fixing  $L_\infty$ . However, when good data are unavailable to provide an estimate of  $L_\infty$ , fixing it is inappropriate. Alternately, one could use the variance observed in fully selected age classes to assume a variance at non-fully selected ages to provide information about the approximate scale of the  $L_\infty$  value. Two stock assessments with the potential for biased growth because of dome-shaped selectivity and lack of fishery-independent age data are assessments for Gulf menhaden *Brevoortia patronus* and Atlantic menhaden *B. tyrannus*.

Both Gulf menhaden and Atlantic menhaden are ubiquitous filter-feeding clupeid species (Ahrenholz, 1991). Gulf menhaden occur in the northern Gulf of Mexico from Florida to Mexico, and Atlantic menhaden are found along the U.S. Atlantic coast from Florida to Maine and into Canada. Both species are schooling, forage fish that are harvested by large, industrial purse-seine fisheries. Gulf menhaden move towards the centre of the species range, off

the coast of Louisiana, as they age (Ahrenholz, 1981). Atlantic menhaden migrate north in spring from the spawning grounds off North Carolina through summer and stratify by size and age with older and larger individuals migrating the farthest north (Nicholson, 1971, 1978; Ahrenholz, 1991). Both species exhibit spatial heterogeneity in size and age, and as such, spatial heterogeneity in age occurs on the fishing grounds, which may be responsible for overall dome-shaped selectivity in the fishery (Sampson and Scott, 2011).

The commercial purse-seine fishery is the largest fishery by volume in the Gulf of Mexico and the second largest (along with Atlantic menhaden) in the United States (NOAA, 2012). Currently, there are four processing plants on the Gulf coast, and one plant on the Atlantic coast. Biological samples are collected from vessels at dockside at each of the plants. The 10-fish samples are obtained from the top of a vessel's fish hold (Smith, 1991). Fork length and weight are measured for each specimen sampled, and a scale sample is taken for later age estimation. All scales are sent to the National Marine Fisheries Service (NMFS) Beaufort Laboratory for processing. Scales are used for age estimation because menhaden are short-lived, menhaden otoliths are small and fragile, and the effort needed to process enough otoliths for such a large fishery

**Table 1**

Run specifications, parameter estimates, and likelihood for runs completed to adjust the growth curve for Gulf menhaden with a minimum adjustment, maximum adjustment, and a minimum and maximum adjustment simultaneously. NA means that the minimum or maximum was not applied. A – indicates a run that did not converge.

Minimum	Maximum	$L_\infty$	k	$t_0$	CV	Likelihood
100	NA	242.92	0.36	-1.25	0.06	653.09
105	NA	242.97	0.36	-1.26	0.06	650.13
110	NA	243.14	0.36	-1.27	0.06	646.41
115	NA	243.63	0.35	-1.30	0.06	641.37
120	NA	242.97	0.36	-1.28	0.06	636.36
125	NA	240.55	0.38	-1.17	0.06	630.00
130	NA	240.61	0.38	-1.20	0.05	621.63
135	NA	241.23	0.37	-1.26	0.05	612.59
140	NA	242.21	0.36	-1.34	0.05	601.87
145	NA	243.45	0.35	-1.45	0.05	586.78
150	NA	244.53	0.34	-1.53	0.05	568.67
NA	200	–	–	–	–	–
NA	205	–	–	–	–	–
NA	210	–	–	–	–	–
NA	215	–	–	–	–	–
NA	220	314.59	0.20	-1.73	0.07	547.74
NA	225	283.50	0.25	-1.57	0.07	591.00
NA	230	265.94	0.29	-1.44	0.07	624.25
NA	235	253.86	0.32	-1.32	0.07	644.36
NA	240	246.31	0.35	-1.22	0.07	653.93
NA	245	243.17	0.37	-1.17	0.06	660.39
NA	250	242.67	0.37	-1.17	0.06	665.79
100	200	–	–	–	–	–
105	205	–	–	–	–	–
110	210	–	–	–	–	–
115	215	–	–	–	–	–
120	220	–	–	–	–	–
125	225	266.75	0.27	-1.63	0.06	556.14
130	230	257.25	0.30	-1.58	0.06	580.07
135	235	248.18	0.33	-1.45	0.05	590.28
140	240	243.24	0.35	-1.37	0.05	588.23
145	245	242.95	0.35	-1.44	0.05	579.04
150	250	245.21	0.33	-1.56	0.05	566.28
150	200	–	–	–	–	–
145	205	–	–	–	–	–
140	210	–	–	–	–	–
135	215	–	–	–	–	–
130	220	282.69	0.23	-1.86	0.06	506.33
125	225	266.75	0.27	-1.63	0.06	556.14
120	230	264.44	0.27	-1.68	0.06	593.97
115	235	254.70	0.31	-1.52	0.06	618.29
110	240	246.95	0.34	-1.34	0.06	632.47
105	245	244.29	0.35	-1.28	0.06	642.35
100	250	244.30	0.35	-1.28	0.06	650.60

was extensive. Over 750,000 menhaden have been measured and aged since the sampling program's inception in 1955. These data are then used for the Gulf and Atlantic menhaden stock assessments to provide the observed commercial fishery age compositions, landings, and weights of the fishery and population by age. Additionally, the length data are used to estimate growth curve parameters and mean lengths at age, which are used to provide fecundity. Estimates of fecundity at age are determined from mean length at age, and population fecundity is the metric of spawning stock biomass that is used to determine stock status.

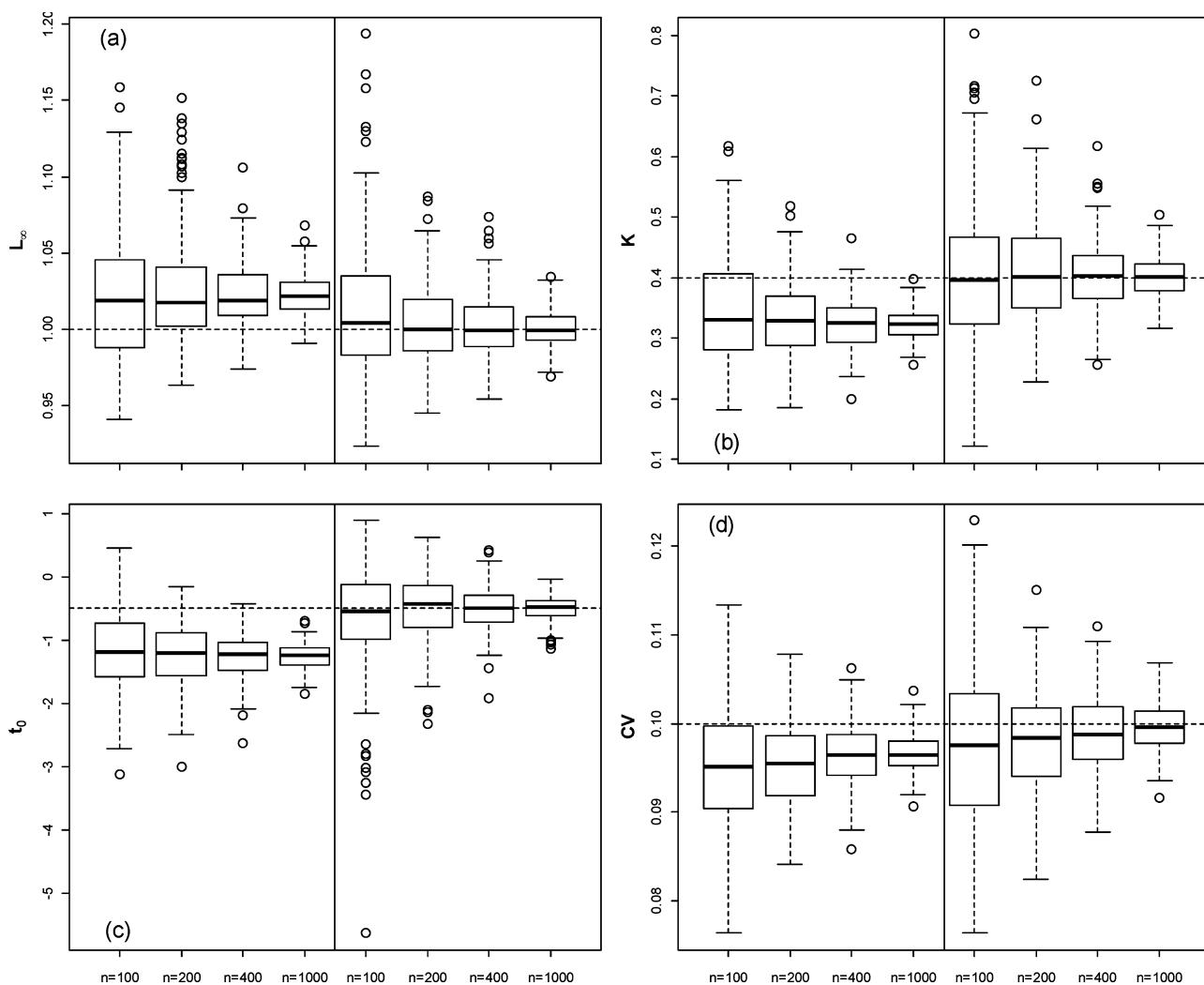
The only fishery-independent data available on adult abundance for the Gulf menhaden stock assessment are data collected by the Louisiana Department of Wildlife and Fisheries (LDWF), while comparable information for the Atlantic menhaden population is unavailable. The fishery-independent data for Gulf menhaden consist of survey data from experimental gill nets, which are fished year-round, but most frequently in April through September (the same months that the fishery operates). Each gill net consists of multiple panels with different mesh sizes. Length is measured for the first 30 menhaden captured in each gill net panel; no scales are collected for age estimates. Comparisons of the length compositions from the gill net survey to the length compositions of the commercial fishery revealed that both larger and smaller fish were sampled by the survey as compared to the fishery. This led to increased concerns regarding the growth function used in the Gulf menhaden stock assessment.

The objectives of our study were (1) to develop and test a method to estimate unbiased growth parameters regardless of the selectivity of the gear used to sample ages and lengths and (2) to apply the proposed method to fit unbiased population growth parameters for Gulf and Atlantic menhaden. First, we propose a method to account for missing samples at smaller and larger specimen lengths in order to reduce the bias in the estimates of growth curve parameters. Second, we test the proposed method on simulated data. Third, we present the data available to determine the functional form of the selectivity function for the Gulf menhaden commercial fishery as compared to the LDWF gill net survey data. Finally, we apply the proposed and tested method to the Gulf and Atlantic menhaden data.

**Table 2**

Run specifications, parameter estimates, and likelihood for runs completed to adjust the growth curve for Atlantic menhaden with a minimum adjustment, maximum adjustment, and a minimum and maximum adjustment simultaneously. NA means that the minimum or maximum was not applied.

Minimum	Maximum	$L_{\infty}$	$k$	$t_0$	CV	Likelihood
100	NA	351.23	0.32	-0.85	0.12	2066.31
110	NA	351.70	0.31	-0.89	0.11	2025.94
120	NA	352.83	0.31	-0.95	0.11	1972.15
130	NA	353.31	0.31	-1.00	0.11	1913.06
140	NA	352.31	0.31	-1.01	0.10	1853.58
150	NA	351.27	0.31	-1.01	0.10	1792.89
160	NA	350.96	0.31	-1.06	0.10	1734.52
170	NA	349.55	0.32	-1.06	0.10	1679.99
180	NA	348.70	0.32	-1.10	0.09	1619.16
190	NA	348.60	0.31	-1.22	0.09	1551.71
200	NA	349.79	0.30	-1.46	0.09	1482.44
NA	360	434.69	0.20	-1.16	0.13	2044.36
NA	370	395.32	0.24	-1.04	0.13	2072.80
NA	380	374.08	0.27	-0.95	0.13	2082.62
NA	390	363.52	0.29	-0.90	0.12	2088.07
100	350	489.57	0.16	-1.30	0.13	1960.11
125	360	414.28	0.21	-1.29	0.12	1896.76
150	370	377.01	0.26	-1.22	0.11	1776.88
175	380	359.14	0.29	-1.22	0.10	1642.44
200	390	353.29	0.29	-1.55	0.09	1478.09
200	350	398.17	0.20	-2.00	0.09	1398.78
175	360	393.52	0.22	-1.56	0.10	1612.60
150	370	377.01	0.26	-1.22	0.11	1776.88
125	380	369.67	0.27	-1.09	0.11	1931.42
100	390	362.11	0.29	-0.92	0.12	2058.07



**Fig. 1.** Boxplots of the estimates of  $L_\infty$ ,  $k$ ,  $t_0$ , and  $CV$  (panels a, b, c, and d, respectively) for both the unadjusted (left side of each panel) fit to the data and the fit to the data with an adjustment (right side of each panel) for the minimum size. Each boxplot reflects a range of samples sizes including 100, 200, 400, and 1000 individuals sampled evenly across age classes. Dashed lines represent the true value for each parameter.

and maximum, only those length values between the minimum and maximum are used in likelihood calculations and each value of length is assigned in the data file as contributing to either the minimum or maximum part of the likelihood function.

The von Bertalanffy curve (von Bertalanffy, 1957) was used to model growth whereby the asymptotic length,  $L_\infty$ , the rate at which growth approaches asymptotic length,  $k$ , and the theoretical time at zero length,  $t_0$ :

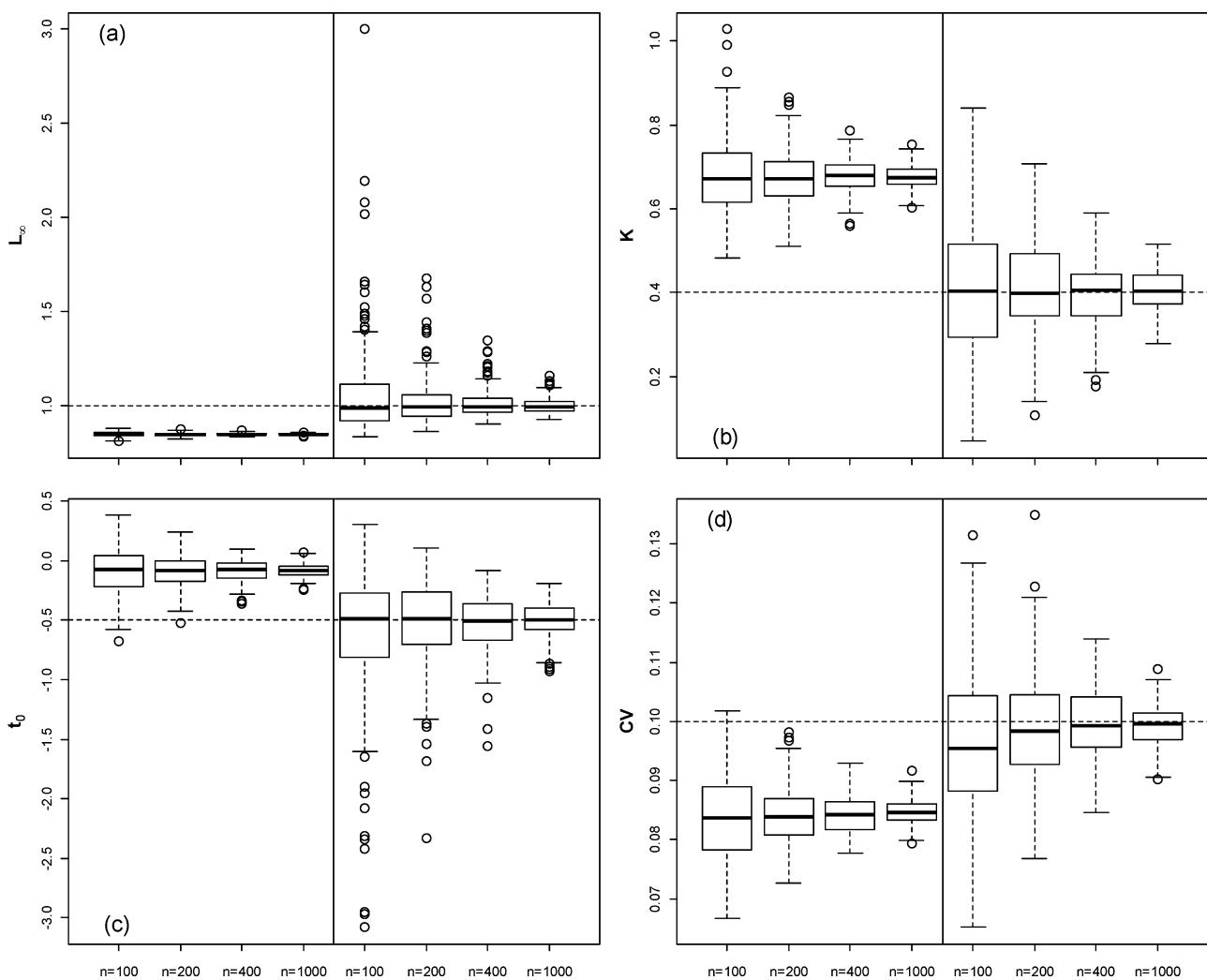
$$L_a = L_\infty \times (1 - \exp(-k(a - t_0)))$$

are parameters estimated by minimizing the negative log-likelihood across all length and age measurement pairs using the ADMB software (Fournier et al., 2012). We tested the method with the assumption that the CV describing the variability in the age-at-length data was constant. However, an additional two options are available in the code and include estimating standard deviation,  $\sigma$ , and estimating variance,  $\sigma^2$ , proportional to the mean. Finally, for each age and length pair in the data set, we created specifications for which part of the likelihood function a given age contributes to and is based on selectivity.

We tested the proposed method with simulated growth data mimicking menhaden-like growth under several scenarios. The true underlying growth curve was specified as  $L_\infty = 1.0$ ,  $k = 0.4$ ,

$t_0 = -0.5$ . The simulated data included eight age classes where lengths at each age were assumed to be normally distributed with a CV of 0.10. Overall sample sizes of 100, 200, 400, and 1000 individual fish were drawn evenly from each of the age classes and were used to test for the effects of reduced overall sample sizes. The CV of length was assumed constant across age classes. To explore the effects of variability on the overall results, we tested CV values of 0.05, 0.10, 0.15, and 0.20, while holding the sample sizes constant at 400.

The simulated data were generated using the R statistical software. More specifically, the random normal deviate function (rnorm) was used to generate the simulated data as described above. To simulate dome-shaped selectivity, a minimum size cutoff was set at 0.6, and a maximum size cutoff was set at 0.9. Data below and above the minimum and maximum size cutoffs, respectively, were dropped in various combinations for fitting of the growth curve using the ADMB optimization software, thus mimicking observed length and age data from different types of selectivity. We explored the effect of uneven sample sizes across age classes using the multinomial sample function in R by mimicking an exponential decay of 0.4 and 1.8 in proportions with increasing age while still maintaining the overall sample sizes listed above. The value of 1.8 matches estimates of total mortality rate seen in Gulf



**Fig. 2.** Boxplots of the estimates of  $L_\infty$ ,  $k$ ,  $t_0$ , and  $CV$  (panels a, b, c, and d, respectively) for both the unadjusted (left side of each panel) fit to the data and the fit to the data with an adjustment (right side of each panel) for the maximum size. Each boxplot reflects a range of samples sizes including 100, 200, 400, and 1000 individuals sampled evenly across age classes. Dashed lines represent the true value for each parameter.

menhaden samples and 0.4 was chosen as an intermediate value. Additional values for the von Bertalanffy growth parameters were tested, but had no effect on the overall outcomes. Thus, those results are not presented. Finally, each set of simulations was run 200 times.

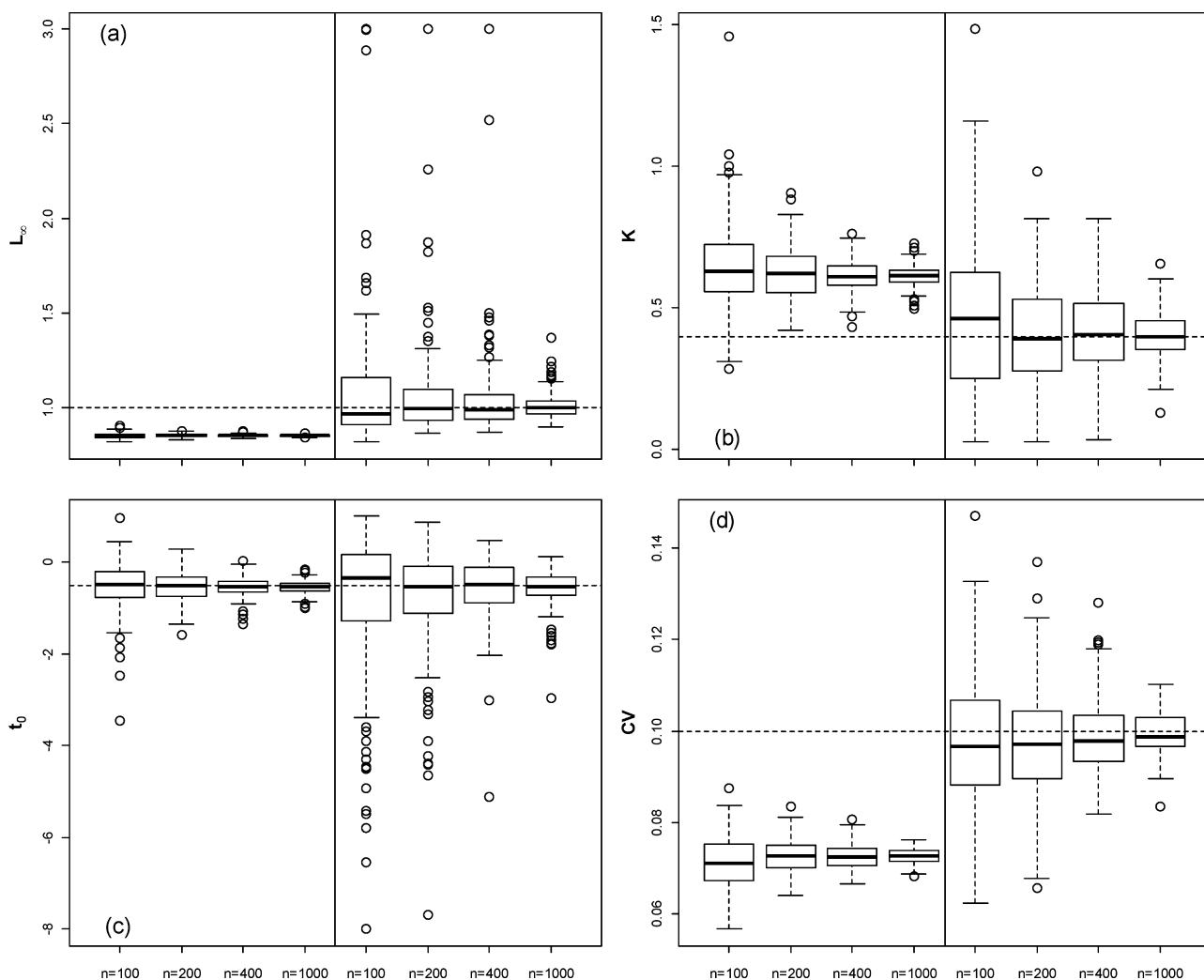
Data from each of the simulations were fitted under three different scenarios and estimates for the von Bertalanffy growth parameters and variability were obtained. First, data were removed below the minimum size cutoff, which reflects a flat-topped or logistic selectivity curve. The data were then used to estimate growth curve parameters with and without an adjustment for the minimum. Second, data were removed above the maximum size cutoff, which reflects selectivity with a negative logistic function. Growth curve parameters were estimated with and without an adjustment for a maximum size limit. Finally, data were removed below the minimum size cutoff and above the maximum size cutoff, which reflects dome-shaped selectivity. Growth curve parameters were then estimated with and without an adjustment for both the minimum and maximum size limits. We explored how well each of these scenarios estimated the growth parameters and variability by comparing the true underlying growth parameters and variability to the estimated parameters with and without the appropriate adjustments.

## 2.2. Application to menhaden

Length composition data from the Gulf commercial fishery were compared against LDWF gill net survey length composition data using plots of the probability density function of each data source. Length compositions from the LDWF gill net survey were plotted as probability density functions by mesh size. Louisiana collects data for each panel of the experimental gill net, which has five mesh sizes of 2, 2.5, 3, 3.5, and 4 inch stretched mesh.

Data used to estimate growth curves parameters for the Gulf and Atlantic menhaden stock assessments come from the commercial fishery databases. Gulf menhaden data are from 1977 to 2011, while Atlantic menhaden data are from 1955 to 2011. Those data were displayed in standard graphs of length (mm fork length [nose of fish to fork in caudal fin]; FL) versus age for each species and the coefficient of variation ( $CV$ ) of each age was estimated. The age data used for each specimen accounted for the month of capture, and thus each age was a fractional number based on an assumed spawning date of January 1.

We applied the adjustments to estimate population growth parameters for the Gulf and Atlantic menhaden stock assessments. As evidenced by the density plots of length, catches from the LDWF gill net survey display a wider range of lengths than for the Gulf



**Fig. 3.** Boxplots of the estimates of  $L_\infty$ ,  $k$ ,  $t_0$ , and  $CV$  (panels a, b, c, and d, respectively) for both the unadjusted (left side of each panel) fit to the data and the fit to the data with an adjustment (right side of each panel) for both the minimum and maximum sizes. Each boxplot reflects a range of samples sizes including 100, 200, 400, and 1000 individuals sampled evenly across age classes. Dashed lines represent the true value for each parameter.

menhaden commercial fishery (Fig. 8 upper panel). As noted, Gulf and Atlantic menhaden exhibit heterogeneity in size distribution throughout their range. Our results are evidence of a minimum and maximum size of capture or dome-shaped selectivity. However, we do not know the exact values of the minimum and maximum sizes, so we tested a range of values for both species. For each menhaden data set, growth curve parameters were estimated with no adjustment, with an adjustment for minimum size, with an adjustment for maximum size, and with an adjustment for both the minimum and maximum sizes. Each menhaden age and length pair was weighted, as done in each assessment, by the catch in numbers by year, season, and fishing area. A constant  $CV$  for the distribution of length at age was assumed for both species.

For Gulf menhaden, we fitted the growth function with minimum size specified as 100–150 mm FL in increments of 5 mm (number of runs = 11) and maximums specified as 200–250 mm FL in increments of 5 mm (number of runs = 11; Table 1). Then, we fitted combinations of minimum and maximum adjustments simultaneously by incrementally increasing both the minimum and maximum sizes simultaneously (e.g., 100 and 200 or 115 and 215 for minimum and maximum, respectively; number of runs = 11), which kept the window of unadjusted lengths constant. We also fitted adjustments simultaneously by expanding the window of

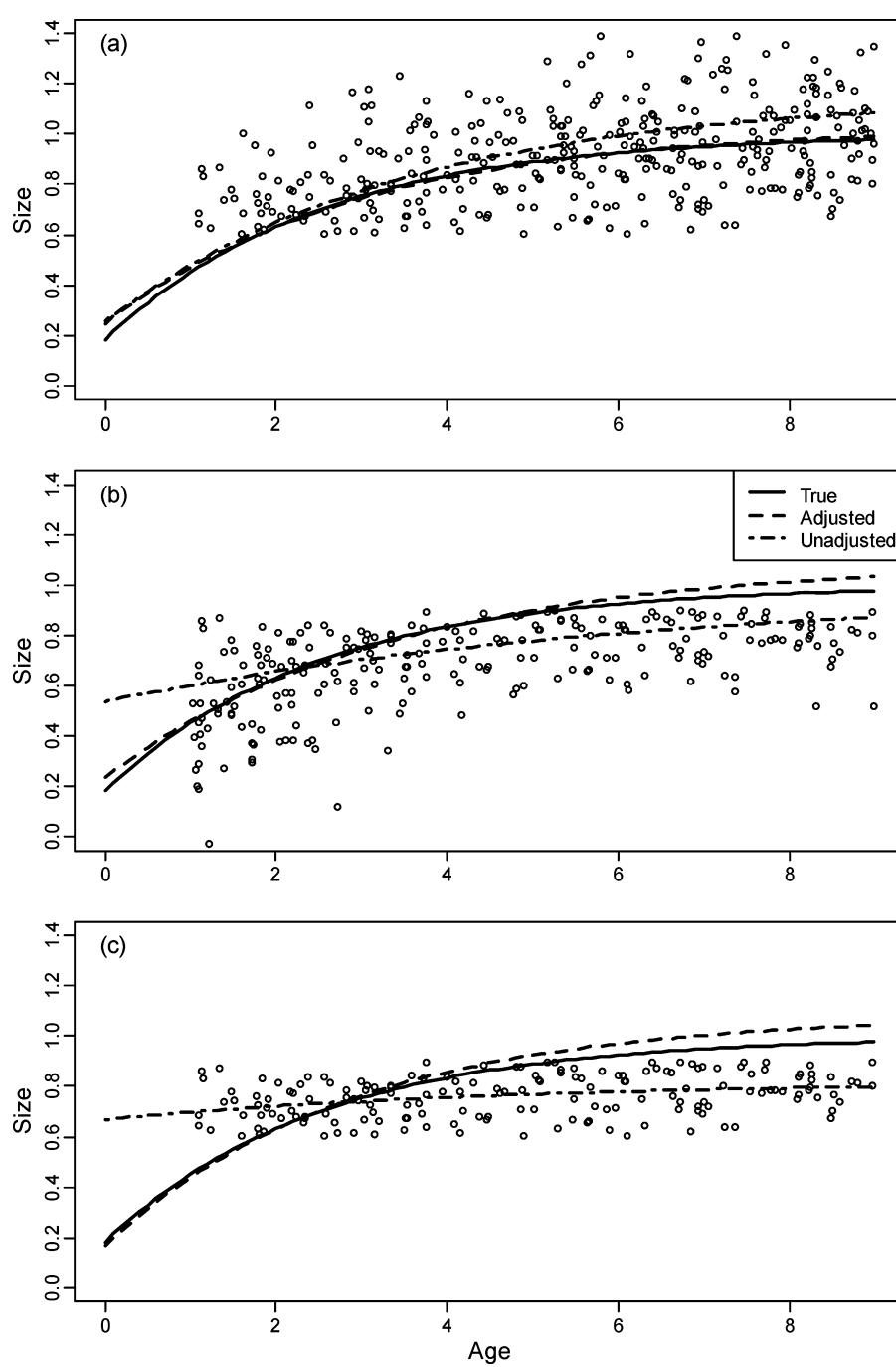
unadjusted lengths (e.g., 150 and 200 or 100 and 250 for minimum and maximum, respectively; number of runs = 11). Age-0 and -1 individuals contributed to the likelihood for the minimum, and age-2+ individuals contributed to the likelihood for the maximum (Table 1).

For Atlantic menhaden, we fitted the growth function with minimum size specified as 100–200 mm FL in increments of 10 mm (number of runs = 11), maximum size specified as 360–390 mm FL in increments of 10 mm (number of runs = 4; Table 2). Then, we fitted combinations of minimum and maximum adjustments simultaneously by incrementally increasing both the minimum and maximum sizes simultaneously. We also fitted adjustments simultaneously by expanding the window of unadjusted lengths. Age-0 to -2 individuals contributed to the likelihood for the minimum, and age-3+ individuals contributed to the likelihood for the maximum.

### 3. Results

#### 3.1. Proposed method and testing

For the simulated data, use of the adjustments was robust and resulted in reduced bias in the growth parameter estimates with accuracy being affected by sample size and variability in length

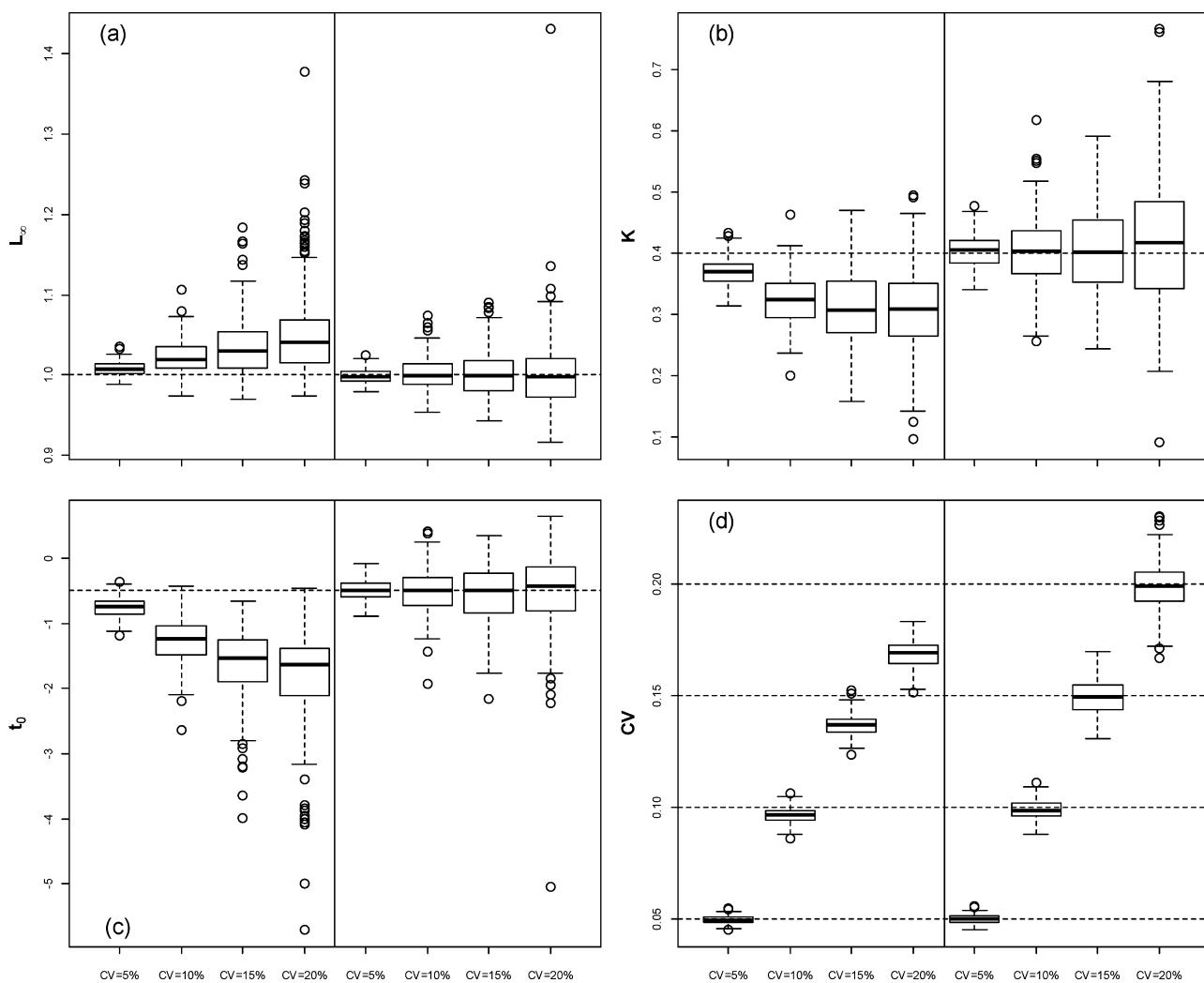


**Fig. 4.** Example plots of the data with the true underlying growth curve and the unadjusted and adjusted fits to the data. Panel a is an example with data removed below 0.6, and data fit without an adjustment and with an adjustment for the minimum size. Panel b is an example with data removed above 0.9, and data fit without an adjustment and with an adjustment for the maximum size. Panel c is an example with data removed below 0.6 and above 0.9, and data fit without an adjustment and with an adjustment for both the minimum and maximum sizes.

at age. Regardless of sample size, use of the proposed adjustments for the minimum, maximum, and both the minimum and maximum simultaneously resulted in reduced bias for the growth parameter and variability estimates (Figs. 1–3). Increasing the sample sizes increased the accuracy of the adjustments for all scenarios (Figs. 1–3). Adjustments improved fits to the simulated data over the fits observed with the unadjusted growth curves (Fig. 4). Use of an adjustment led to less biased results across all CVs evaluated (Figs. 5–7). However, as the CV increased the accuracy of the estimates decreased (Figs. 5–7). Adjusting for a maximum size resulted in the largest reduction in bias, especially for

estimates of  $k$ . The bias and accuracy of the estimation of the growth parameters were unaffected by uneven sample sizes across age classes. As a consequence, we do not present any further results related to this topic. Also, not shown here, but tested were various levels of minimum and maximum size limits. The results of this testing followed basic statistical principles in that increased sample size and decreased variance resulted in more accurate results.

Ultimately, all the simulation scenarios tested indicated that the minimum and maximum size limit adjustments resulted in unbiased estimates of  $L_\infty$ ,  $k$ , and  $t_0$ . Variance in the estimates followed



**Fig. 5.** Boxplots of the estimates of  $L_\infty$ ,  $k$ ,  $t_0$ , and  $CV$  (panels a, b, c, and d, respectively) for both the unadjusted (left side of each panel) fit to the data and the fit to the data with an adjustment (right side of each panel) for the minimum size. Each boxplot reflects a range of true variability in the length data including CVs of 0.05, 0.10, 0.15, and 0.20 with a constant sample size of 400. Dashed lines represent the true value for each parameter.

expected patterns of increase with decreasing sample sizes. Estimates of  $CV$  from some of the simulation tests suggested a slight bias as sample sizes decreased.

### 3.2. Application to menhaden

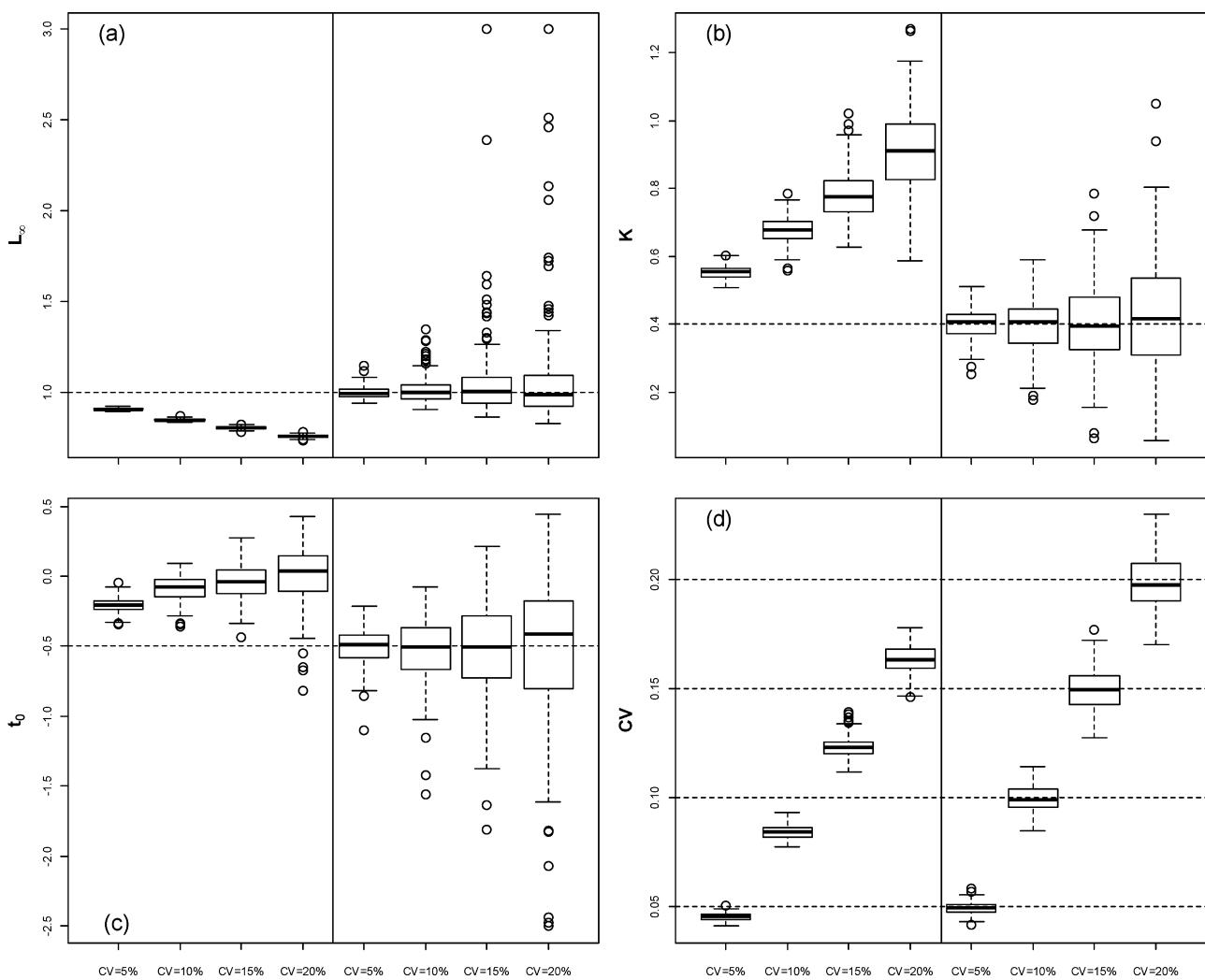
The LDWF gill net survey captured a wider range of sizes of Gulf menhaden than the commercial fishery (Fig. 8). Specifically, the LDWF survey captured both smaller and larger individuals than the fishery. The length distributions of the LDWF survey suggested representative age classes. However, the apparent age classes were determined to be size-specific selection of fish by mesh size (Fig. 8).

The commercial fishery age-length data exhibited reduced variability in length with increasing age for both Gulf and Atlantic menhaden (Fig. 9). The decreased variability was evident in a decreased  $CV$  from age-0 to age-6 of 0.16, 0.09, 0.06, 0.04, 0.05, 0.05, and 0.03, respectively, for Gulf menhaden ( $n = 366,710$ ). The decreased variability was also apparent for Atlantic menhaden, which had a decreased  $CV$  from age-0 to age-10 of 0.18, 0.17, 0.15, 0.10, 0.07, 0.05, 0.05, 0.04, 0.04, 0.04, and 0.04, respectively ( $n = 480,668$ ).

Based on commercial samples for Gulf menhaden, the parameters estimated for the unadjusted growth curve were  $L_\infty = 240.8$ ,  $k = 0.38$ ,  $t_0 = -1.14$ , and  $CV = 0.06$  ( $n = 366,710$ ; Fig. 10). All 11 runs

with adjustments for the minimum converged, and resulted in slightly higher estimates of  $L_\infty$  and slightly lower estimates of  $k$  and  $t_0$  (Table 1). With a maximum adjustment, only runs with a maximum of 220 mm or greater converged. As the maximum size specified increased, the estimates for the growth parameters moved closer to the estimates from the unadjusted fit. The largest difference in  $L_\infty$  was for the maximum value specified at the length of the largest specimens collected (see Fig. 9 for example). When adjusting for both the minimum and maximum simultaneously, the size cutoff chosen for the maximum had more impact on convergence and exhibited the same pattern of the estimates for the growth parameters, moving closer to the estimates from the unadjusted fit as the maximum size was increased.

Based on commercial samples for Atlantic menhaden, the parameters estimated for the unadjusted growth curve were  $L_\infty = 350.9$ ,  $k = 0.32$ ,  $t_0 = -0.83$ , and  $CV = 0.12$  ( $n = 480,668$ ; Fig. 11). All 11 runs with adjustments for the minimum converged, and resulted in essentially equivalent estimates of  $L_\infty$ ,  $k$ , and  $t_0$  as the unadjusted run (Table 2). With a maximum adjustment, only runs with a maximum of 360 mm or greater converged. As the maximum size specified increased, the estimates for the growth parameters moved closer to the estimates from the unadjusted fit. The largest difference in  $L_\infty$  was for the maximum value specified at the length of the largest specimens collected (see Fig. 9 for example). When



**Fig. 6.** Boxplots of the estimates of  $L_\infty$ ,  $k$ ,  $t_0$ , and  $CV$  (panels a, b, c, and d, respectively) for both the unadjusted (left side of each panel) fit to the data and the fit to the data with an adjustment (right side of each panel) for the maximum size. Each boxplot reflects a range of true variability in the length data including CVs of 0.05, 0.10, 0.15, and 0.20 with a constant sample size of 400. Dashed lines represent the true value for each parameter.

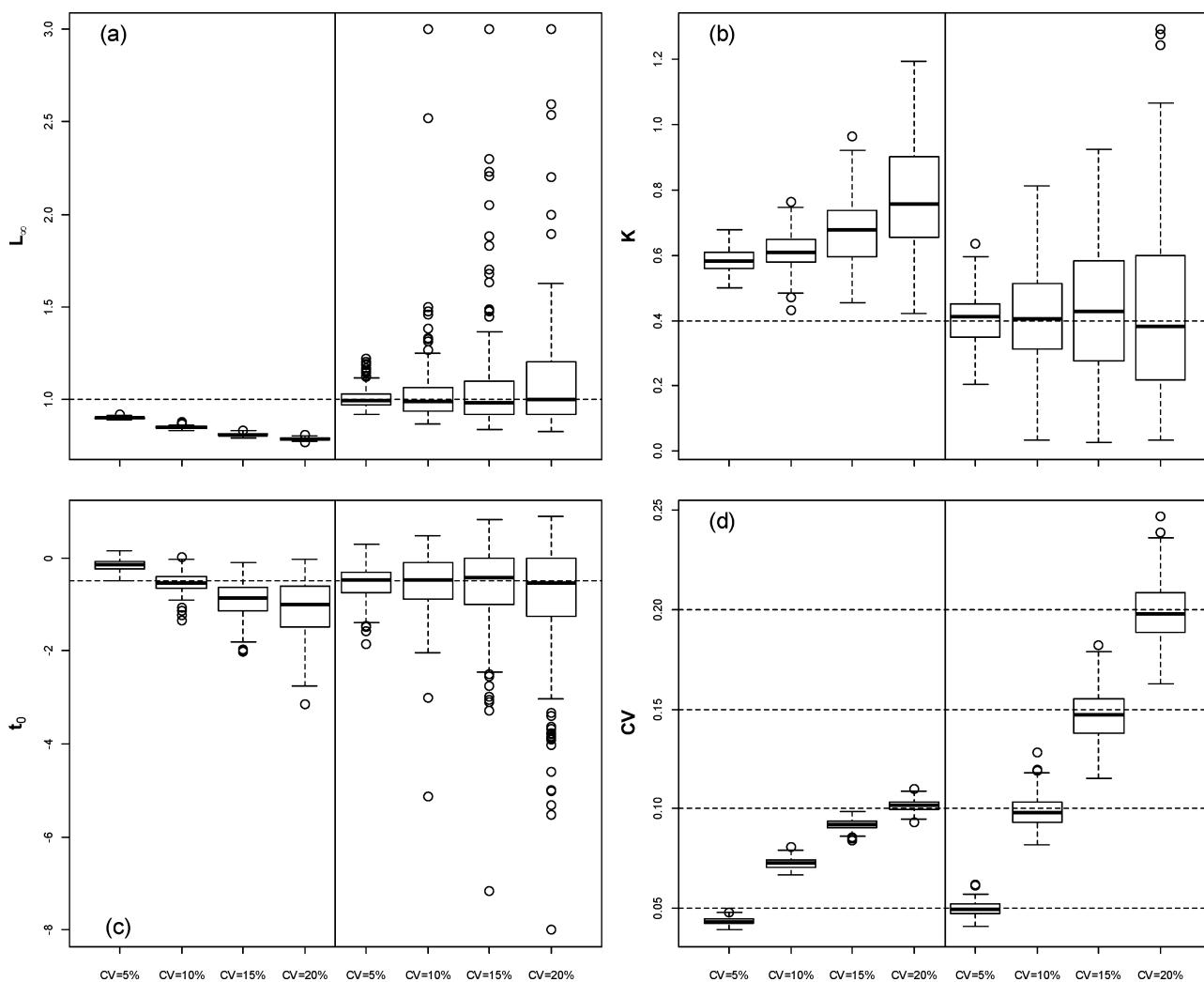
adjusting for both the minimum and maximum simultaneously, the size cutoff chosen for the maximum had more impact on convergence and exhibited the same pattern of the estimates for the growth parameters, moving closer to the estimates from the unadjusted fit as the maximum size was increased.

#### 4. Discussion

Bias in growth curve parameters can be reduced by using the method outlined to account for minimum size limits, maximum size limits, and selectivity of a gear. When McGarvey and Fowler (2002) proposed the method to adjust for a minimum size limit, they tested their results against data collected from a fishery-independent data source. However, fishery-independent data are often unavailable, so we wanted to look at the performance of the method using simulated data. In addition, we proposed an adjustment for a maximum size cutoff or dome-shaped selectivity and also proposed use of both the minimum and maximum adjustments simultaneously. Under all sample size scenarios and across a range of variability, the bias was reduced in the growth curve parameter estimates, which can have significant impacts on a stock assessment. For example, reducing bias in the growth curve parameter estimates will reduce bias in spawning stock biomass, fecundity, weight, and any other growth function-derived quantities

in assessment models. Overall, the implications of biased growth parameters on stock assessments and the resulting stock status could be substantial. Thus, stock assessment scientists should carefully consider the selectivity under which the data were collected to estimate growth.

Accuracy of the growth curve parameter estimates can be improved with increased sample sizes, which is expected according to the central limit theorem, and with lower variability around mean length at age. Here, we assumed that sample sizes were distributed evenly across age classes; we tested for uneven samples across age classes but found no differences in bias or accuracy with reduced samples at older age classes. Our lowest sample size was 100, which would have resulted in approximately 12 samples per age class; this demonstrates the ability of our method to perform even at sample sizes that are generally much below what is typical for fishery-dependent data sources. Accuracy was also less for scenarios with lower variability about mean length at age. This demonstrates the importance of correctly interpreting the age of individuals such that the true variability in length is evident (which would be smaller than with ageing error) and therefore would result in the most accurate estimates of the growth curve parameters. As scientists and data providers examine the data that will be used for estimates of growth curves in stock assessments, they should acknowledge the uncertainty in the variability in length and



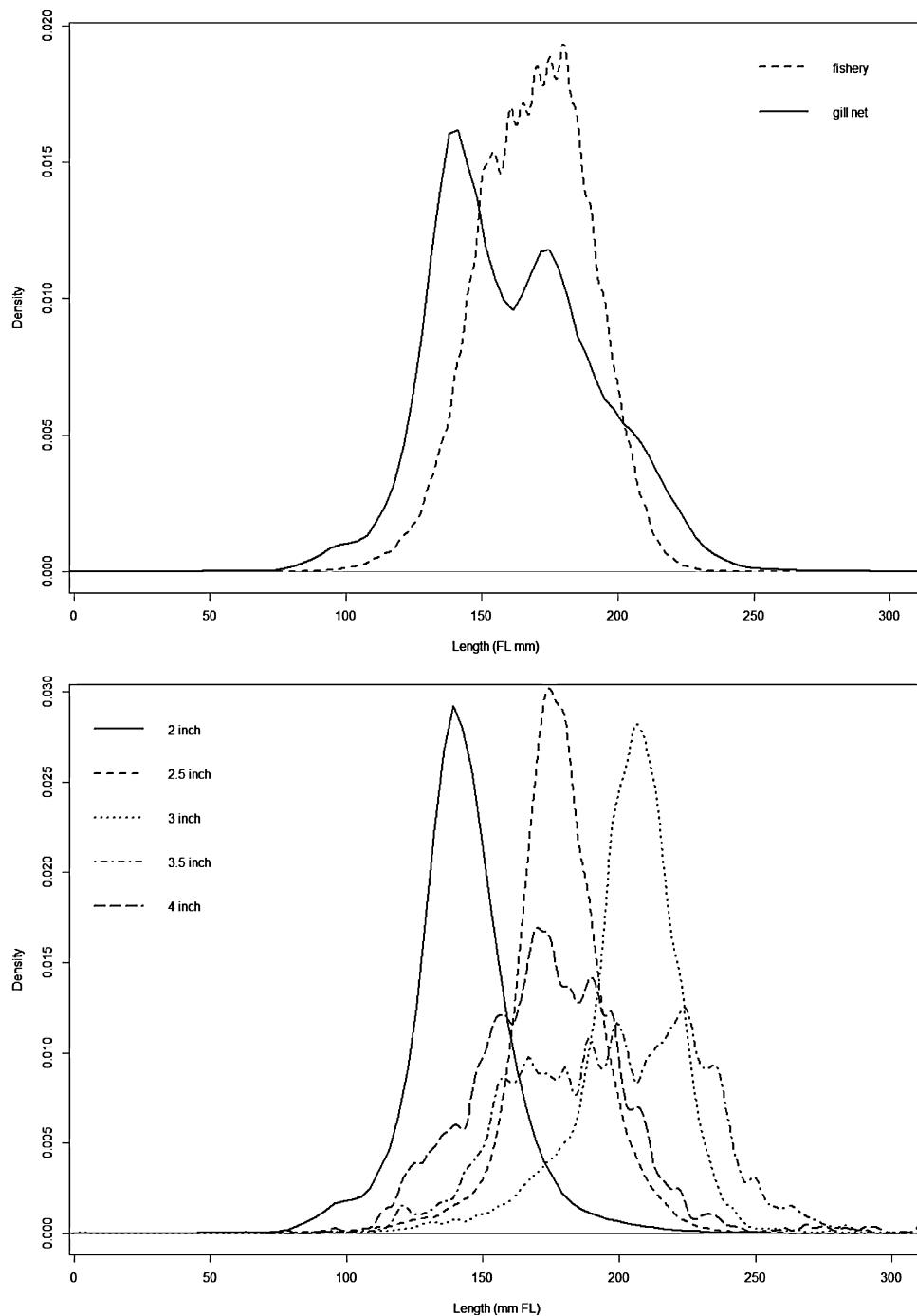
**Fig. 7.** Boxplots of the estimates of  $L_\infty$ ,  $k$ ,  $t_0$ , and  $CV$  (panels a, b, c, and d, respectively) for both the unadjusted (left side of each panel) fit to the data and the fit to the data with an adjustment (right side of each panel) for both the minimum and maximum sizes. Each boxplot reflects a range of true variability in the length data including CVs of 0.05, 0.10, 0.15, and 0.20 with a constant sample size of 400. Dashed lines represent the true value for each parameter.

the potential effects on the accuracy of their estimates of growth curve parameters for the assessment and the resulting stock status.

Bias in growth due to selectivity has been considered in the past, but has often been considered along with size-selective mortality and variation in individual growth (Ricker, 1969; Taylor et al., 2005). Some applications assume known gear selectivity, retention, and availability (Troynikov and Koopman, 2009) or are able to use tagging data to help estimate values of vulnerability (Taylor et al., 2005). However, unlike other studies, we explored the effects of dome-shaped selectivity on estimation of growth parameters. Bayesian methods and estimation of growth parameters within integrated analysis have been applied but have generally not been tested with simulated data (Troynikov, 1999; Troynikov and Koopman, 2009), except see Taylor et al. (2005). When growth is estimated from paired age-length data within a fully integrated stock assessment model, the influence of selectivity on the growth parameters is potentially accounted for. We tested the proposed method with simulated data outside of an assessment model to ensure that the growth parameter estimates were not confounded with other parameter estimates. Some assessments do not use integrated analysis (e.g. virtual population analysis, VPA) and if selectivity is not accounted for in those assessments bias could result when using length compositions converted into ages, for example. The proposed method could be included as an additional

term in the likelihood function of an integrated analysis, but further analyses would be required to explore how that likelihood component should be weighted in the overall likelihood and if all parameters in the analysis remained identifiable.

The functional form of the Gulf menhaden commercial fishery selectivity is likely dome-shaped. A broader range of lengths was sampled with fishery-independent gears than were sampled in the fishery. In addition, spatial heterogeneity in size and age occurs across the fishing grounds, which can lead to dome-shaped selectivity when effort is not homogeneous across the fishing grounds (Sampson and Scott, 2011). In previous assessments of Gulf menhaden, the selectivity for the fishery has always been assumed logistic or flat-topped (Vaughan et al., 2007), and growth has been based on growth parameters estimated from fishery-dependent sampling. The resulting assessment likely had biased growth parameter estimates and biased mean length at age estimates. Biased mean length at age would have been used to provide mean weight at age values as well as mean fecundity at age values. Thus, spawning stock biomass, which is in units of fecundity, would also be biased. The assessment likely had a negatively biased indicator of stock status. The magnitude of the bias on the stock assessment would be contingent upon the magnitude of the bias on the growth parameters. For Gulf menhaden, when correcting for both a minimum and maximum size cutoff, up to a 40 mm



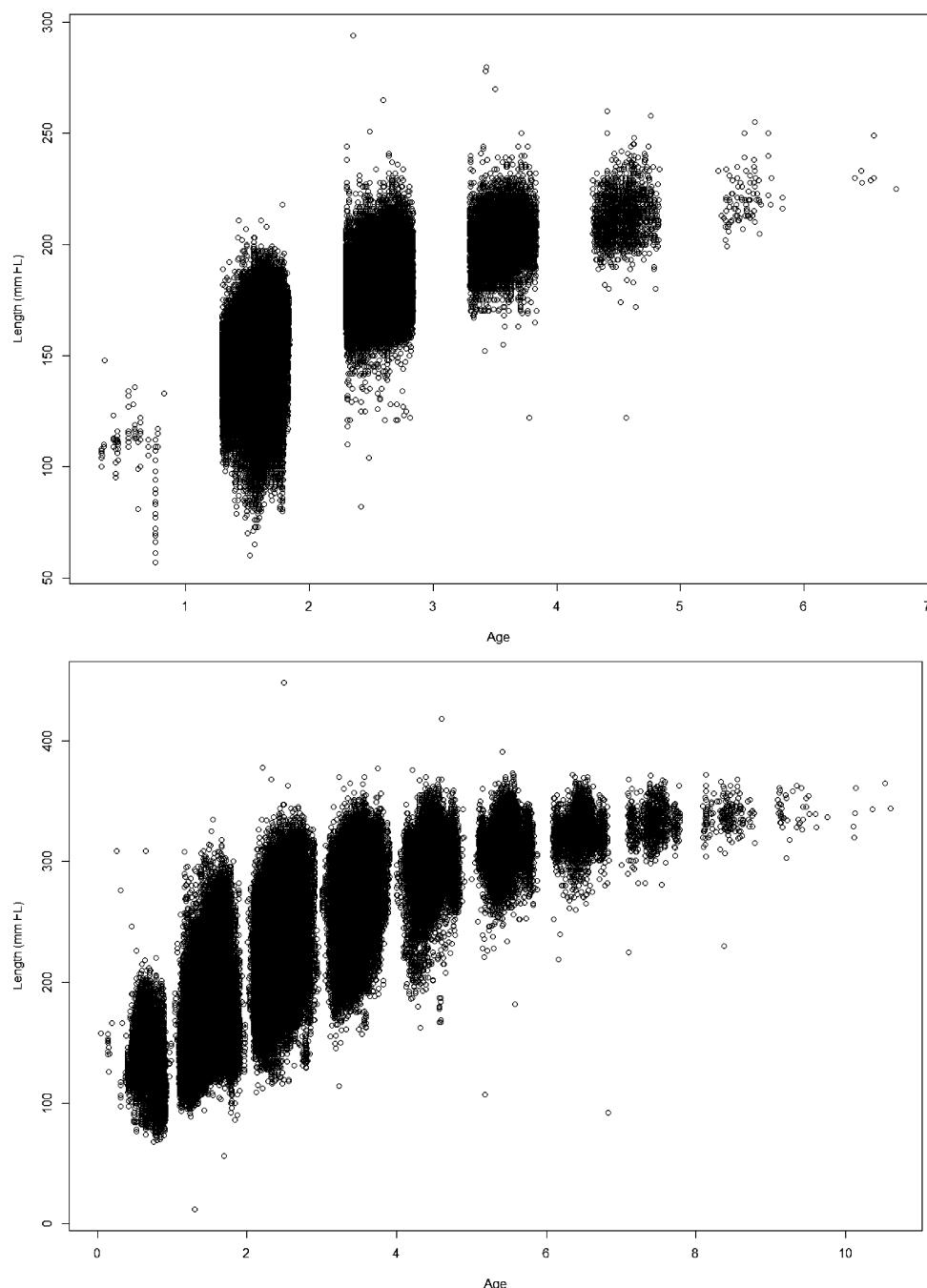
**Fig. 8.** Probability density functions of the commercial fishery ( $n = 254,420$ ) and LA gill net survey ( $n = 93,483$ ) length compositions for the years 1986–2011 (upper panel). Length is in mm fork length. Probability density functions of the LA gill net survey length samples by mesh size (lower panel).

difference in  $L_\infty$  could result. This size of a bias likely has substantial impacts on the stock assessment and could cause bias in fecundity, weight, other growth function-derived quantities, and spawning stock biomass and the resulting stock status.

Two hypotheses have been proposed for the existence of dome-shaped selectivity in the commercial fishery in the Gulf of Mexico. First, the fishery may target the largest schools, which presumably consist of the most abundant age classes available, ages-1 and -2, because menhaden school by size and therefore age. Thus, the smaller schools likely consist of age-3 and older individuals and are not harvested as often. One avenue of future research to address the

relevance of this hypothesis would be to sample smaller schools on the fishing grounds. Second, larger fish move offshore or outside of the range of the fishery. The question becomes what is the true nature of age and length in the population? This hypothesis could be addressed by sampling beyond the normal fishing grounds. Support for both of these hypotheses from field studies would bolster our evidence that the Gulf menhaden commercial fishery exhibits dome-shaped selectivity.

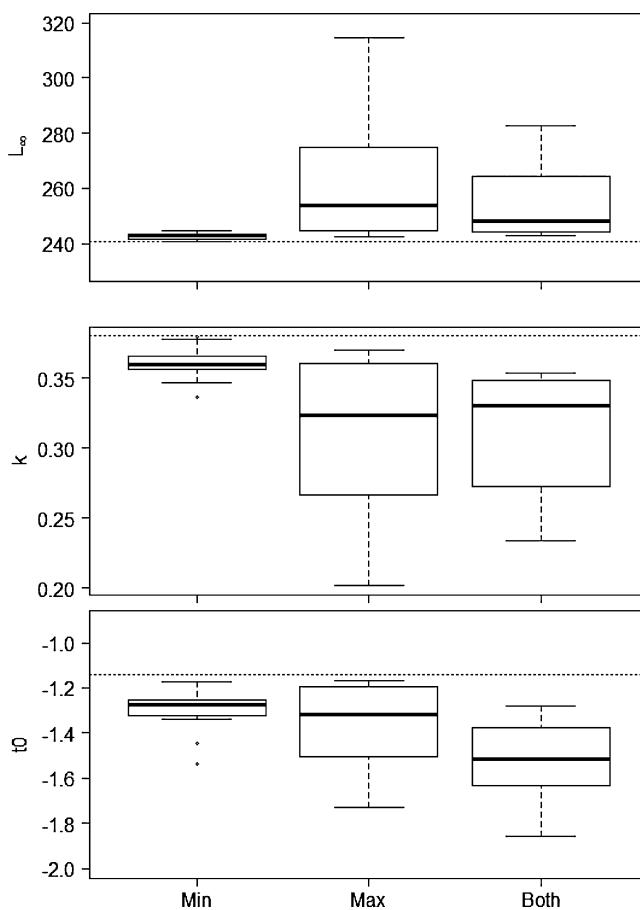
The functional form of selectivity for the Atlantic menhaden commercial fishery is more difficult to discern. The population undergoes annual migrations whereby the largest and oldest fish



**Fig. 9.** Length (mm FL) versus age for the commercial fishery for the years 1977–2011 for Gulf menhaden (upper panel;  $n = 366,710$ ) and for the years 1955–2011 for Atlantic menhaden (lower panel;  $n = 480,668$ ). Each age is offset from the full age by the month of capture.

migrate farthest north. Moreover, the fishery is limited spatially such that fishing is mostly centred around Virginia and on smaller and younger fish. Therefore, spatial heterogeneity in size and age occurs, which can lead to dome-shaped selectivity (Sampson and Scott, 2011). Other fishery-independent and -dependent data are unavailable. Thus, additional corroborative evidence is lacking to indicate any specific type of selectivity. However, given the appearance of the growth data (Fig. 2 lower panel), there appears to be a size beyond which fish are no longer captured by the commercial fishery. Fish larger than that particular size have been documented in the literature (Smith and O'Bier, 1996). Given this information, it is likely that dome-shaped selectivity is present in the commercial fishery on the Atlantic coast. In past assessments of Atlantic

menhaden, selectivity for the commercial fishery has been treated as logistic or flat-topped (SEDAR 20, 2010), and growth was based on growth parameters estimated from the fishery-dependent sampling. The resulting assessment also may have had biased growth parameter estimates and biased mean length at age estimates. Biased mean length at age would have been used to provide mean weight and fecundity at age values. Thus, spawning stock biomass, which is in units of fecundity, would also be biased. The assessment for Atlantic menhaden may have had a negatively biased indicator of stock status, although the magnitude of the bias is unknown. For Atlantic menhaden, when correcting for both a minimum and maximum size cutoff, up to a 130 mm difference in  $L_\infty$  could result. This size of a bias likely has substantial

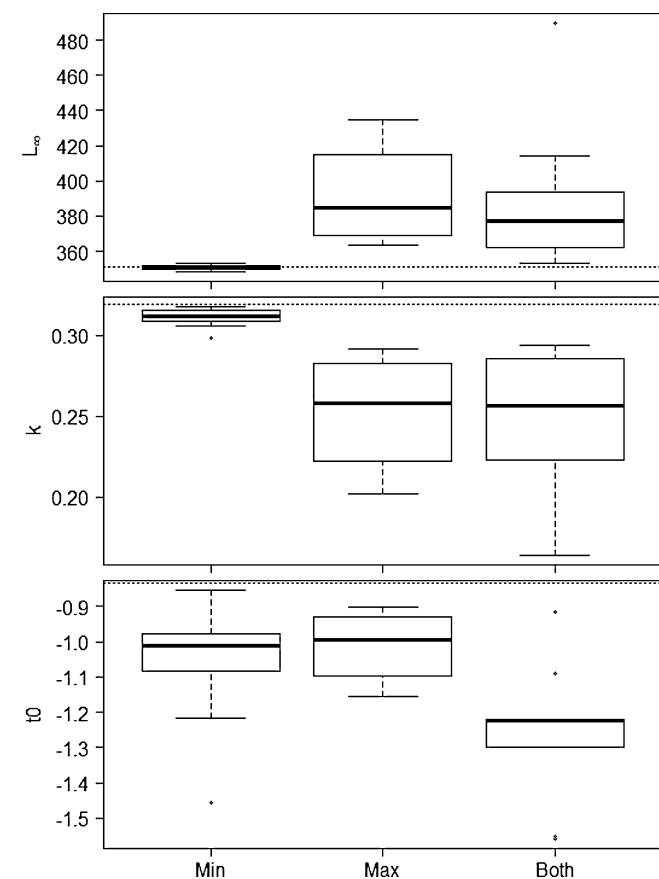


**Fig. 10.** Boxplots of  $L_{\infty}$ ,  $k$ , and  $t_0$  estimated using no adjustments (dashed line on each panel) and with using adjustments for a minimum, maximum, and both a minimum and maximum simultaneously for Gulf menhaden during 1977–2011 ( $n = 366,710$ ).

impacts on the stock assessment and could cause bias in fecundity, weight, other growth function-derived quantities, and spawning stock biomass and the resulting stock status.

Our recommendations for applying our method based on the simulations and the application to data for Gulf and Atlantic menhaden are: (1) to include as much of the data as possible in the analyses, (2) retain as many age classes as possible, and (3) set the maximum length cutoff at a value at or above the maximum length of specimens captured. These recommendations should help ensure unbiased parameter estimates, and avoid some model fitting and convergence issues that may yield invalid estimates. However, choice of a size cutoff may not be straightforward and depending upon the choice, parameter estimates could differ. Considerable uncertainty could surround the parameter estimates. Thus, testing numerous minima and maxima and acknowledging their uncertainty in the stock assessment is recommended.

The results from this study are reliant on the assumption that the variability in lengths with age is correctly specified and that the form of the growth curve is correctly specified. Our assumptions of constant CV with age and a von Bertalanffy growth curve were used to both simulate the data and to estimate the growth parameters with the proposed adjustments. If the variance or standard deviation in lengths across age increases, but a constant CV is specified in the model adjustment or vice versa, then bias could result in the estimates of the growth parameters. If the growth curve functional form is different, then bias could result in the estimates of the growth parameters. These topics were not addressed in this paper, but are a future topic for research.



**Fig. 11.** Boxplots of  $L_{\infty}$ ,  $k$ , and  $t_0$  estimated using no adjustments (dashed line on each panel) and with using adjustments for a minimum, maximum, and both a minimum and maximum simultaneously for Atlantic menhaden during 1955–2011 ( $n = 480,668$ ).

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