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Age and growth of giant stargazer, *Kathetostoma giganteum*, from the west coast of the South Island (STA 7)

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EXECUTIVE SUMMARY

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This paper presents the results of the first study of age and growth of giant stargazer in STA 7, funded by the Ministry of Fisheries under research project MOF2002-01A Objective 1 "Age and growth of giant stargazers". The specific objective of the project was to determine the age of giant stargazer in STA 7 by reading otoliths collected during west coast South Island trawl surveys by RV *Kaharoa*, 1992–2000; to estimate population growth and mortality parameters for giant stargazer in STA 7; and to compare the age and growth of giant stargazer in STA 7 with the age and growth of giant stargazer in STA 3 and 5.

A total of 1887 otoliths collected during the trawl survey series were prepared and read. Precision of readings within reader was high (index of average percentage error = 2.47% and mean coefficient of variation = 3.50%). Precision between readers was lower (index of average percentage error = 8.73% and mean coefficient of variation = 12.35%), which is thought to reflect how difficult giant stargazer otoliths are to interpret, rather than any systematic bias; there is no evidence of systematic bias in any direction within or between readers. The interpretation protocol remains unvalidated, therefore it is unclear whether the age estimates derived are accurate or not.

A groomed dataset derived from 1784 otoliths (over 94% of all otoliths prepared and read) was produced for west coast fish ("final WCSI dataset"). This dataset was merged with existing datasets from the east and south coasts of the South Island to produce a combined age-length dataset for giant stargazer from around the South Island ("combined ECSI, SCSI, and WCSI dataset"), derived from 4247 otoliths.

Estimated scaled length frequency distributions were produced for each sex for each survey in the WCSI trawl survey series. The sex and survey-specific subsets of age-length data in the final WCSI dataset were converted to age-length keys, which were then applied to each estimated scaled length frequency to yield estimated scaled age frequency distributions. Bootstrapped c.v.s were produced for each length and age class from 300 resamples of the data. The profiles of the estimated length and age frequency distributions for each sex and survey suggest that the recruitment of young fish into the WCSI population has continued over the course of the trawl survey series. From this, and from the reasonably similar numbers of larger, mature fish that seem to be present in the survey catch from survey to survey, we conclude that the age structure of the WCSI population, as indexed by the survey catch, has remained reasonably stable over time, despite a doubling of the commercial catch during the trawl survey series.

Total mortality estimates were calculated using the Chapman-Robson estimator of total mortality. Chapman-Robson estimates were calculated for each sex for each survey from the corresponding estimated scaled age frequency distributions, assuming six different ages at full recruitment (3–8 years inclusive). Analytical and bootstrapped 95% confidence intervals were produced for each estimate. We suggest that reasonable estimates for each sex are the averaged estimates for each sex across the five surveys assuming age at full recruitment is 5 or 6: i.e. 0.33, 0.27, and 0.30 for males, females, and all fish when the age at full recruitment is assumed to be 5, and 0.40, 0.32, and 0.35 for males, females, and all fish when the age at full recruitment is assumed to be 6. The range in estimates for each sex for each survey for assumed ages at full recruitment greater than 4 suggests that STA 7 has

not reached a state of exploited equilibrium. Tracking the movement of successful year-classes over time may allow a better estimate of Z to be obtained and should be considered by a future study.

Growth was quantified by fitting additive and multiplicative von Bertalanffy models to the two age-length datasets. Von Bertalanffy models assuming a single set of common parameters, separate parameters by sex, and by survey and sex, were fitted to the final WCSI dataset; models assuming separate parameters by area and sex were fitted to the combined ECSI, SCSI, and WCSI dataset. From these results, growth appears to vary by sex, and by survey within sex, for WCSI fish, and by area within sex for fish around the South Island. Estimates for L_∞ and k from the fit of the additive model assuming separate parameters by sex to the final WCSI dataset are 71.91 and 0.1442 for all males, and 81.16 and 0.1443 for all females. Estimates from the fit of the corresponding multiplicative model are 73.52 and 0.1335 for all males, and 85.91 and 0.1208 for all females.

Likelihood ratio tests were used to compare competing von Bertalanffy growth models. The test results suggest that the apparent differences in growth by sex and by survey and sex for WCSI fish and by area within sex for South Island fish generally are statistically significant. Plots of the approximate joint 95% confidence regions for L_∞ and k conditioning on t_0 suggest that the differences in growth by sex for WCSI fish, and by area within sex for South Island fish, are biologically as well as statistically significant, whereas the differences by survey within sex for WCSI fish are not. We hypothesise that giant stargazer around the South Island form more than one biological stock with different biological properties.

Pairwise comparisons of individual parameter estimates between groups suggest that although male and female WCSI fish appear to grow at similar rates, females appear to be larger on average than males following maturity. Furthermore, WCSI fish appear to be slower growing, but larger on average at maturity, than fish of the same sex from other areas around the South Island. The apparently slower growth but larger mean maximum size of WCSI fish compared to fish of the same sex from around the South Island may result from the strong negative correlation of parameters L_∞ and k in the von Bertalanffy model. Refitting the models using a more stable parameterisation of the von Bertalanffy model to weighted length-at-age data may be useful.

Finally, although diagnostic residual plots suggest that the fits of all models to the data were acceptable, we prefer the fit of the multiplicative models. This is because we think funnelling present in the plots of residuals against fitted values for the additive models is reduced in the corresponding plots for the multiplicative models. We suggest that future modelling of giant stargazer growth use the multiplicative rather than the additive model, although alternative error structures should continue to be investigated. Developing a quantitative stock assessment model is the logical next step in research for this species; doing so requires properly addressing some of the basic scientific issues and questions raised in this paper, in particular validating the otolith interpretation protocol.

1. INTRODUCTION

Giant stargazer, *Kathetostoma giganteum*, are distributed widely throughout New Zealand waters. They are found on muddy or sandy substrates to depths exceeding 500 m, but are most common inshore, in waters between 50 and 300 m in depth (Anderson et al. 1998).

Since the introduction of the Quota Management System (QMS), giant stargazer in the New Zealand Exclusive Economic Zone (EEZ) have been managed as eight fishstocks (Figure 1), each with an annual Total Allowable Commercial Catch (TACC). Since the 1986–87 fishing year, total annual commercial landings have fluctuated between 2000 and 4150 t, and average about 3000 t per annum (Table 1). Total annual landings in fishstock STA 7 off the west coast of the South Island (WCSI), have accounted for 20–35% of total annual landings.

During the 1990–91 fishing year, the TACC in STA 7 was increased from 528 to 700 t under the conditions of the Adaptive Management Programme (AMP). The TACC in STA 7 has been exceeded every fishing year since, with total annual landings ranging from 715 t (1993–94 fishing year) to 1440 t (2000–01 fishing year), and averaging over 900 t.

Several age and growth studies on giant stargazer around the South Island have been carried out (Sutton 1999, Sutton unpublished data, Manning unpublished data). These studies focused on STA 3 on the east coast of the South Island (ECSI), and STA 5 on the south coast of the South Island (SCSI), however. To date, there have been no age and growth studies on giant stargazer in STA 7, hence the basic productivity of STA 7 not well known, and whether the current TACC over-catch can be sustained is unknown.

This paper presents the results of the first study of age and growth of giant stargazer in STA 7, funded by the Ministry of Fisheries under research project MOF2002-01A Objective 1 "Age and growth of giant stargazers". The overall objective of the project was to investigate the age and growth of giant stargazer in STA 7 and present information on the productivity and demography of the stock necessary for its sustainable management. The specific objective of the project was to determine the age of giant stargazer in STA 7 by reading otoliths collected during west coast South Island trawl surveys by RV *Kaharoa*, 1992–2000; to estimate population growth and mortality parameters for giant stargazer in STA 7; and to compare the age and growth of giant stargazer in STA 7 with the age and growth of giant stargazer in STA 3 and 5.

2. METHODS

2.1 Treatment of Tasman and Golden Bays

Fishstock STA 7 includes the WCSI and Tasman and Golden Bays (Figure 1). Documentation of the WCSI trawl survey series (see Table 2) treat fish caught in Tasman and Golden Bays separately from fish caught on the open west coast. Because very few otoliths were collected from Tasman and Golden Bays during the five WCSI trawl surveys 1992–2000 (less than 4% of all otoliths collected), we have not treated giant stargazer caught in Tasman and Golden Bays separately from those caught on the open west coast.

2.2 Otolith terminology

Otolith terminology follows the glossary for otolith studies produced by Kalish et al. (1995).

2.3 Otolith collection, preparation, and reading

Giant stargazer sagittal otoliths and length-frequency data were collected during randomised trawl surveys conducted by RV *Kaharoa* off the WCSI during March–April each year in 1992 (KAH9204), 1994 (KAH9404), 1995 (KAH9504), 1997 (KAH9701), and 2000 (KAH0004). The same two-stage, stratified, sampling design, sampling gear, and otolith collection methods were used throughout the trawl survey series; interested readers are referred to the trawl survey series documentation (see Table 2).

A stratified, "fixed allocation" (Davies et al. 2003) sampling protocol was used to collect otoliths from the catch at each station in each survey. Up to five otoliths per sex per centimetre size class were collected non-randomly from random length-frequency samples from the catch. Fish length measured to the nearest centimetre below total length and sex were recorded for all fish from which otoliths were collected. Otoliths were cleaned and stored dry in paper envelopes immediately following collection. A whole otolith showing orientation and major features appears in Figure 2.

All giant stargazer otoliths collected during the five WCSI trawl surveys were retrieved from the Ministry of Fisheries otolith collection, and all corresponding data extracted from research database "age" (Mackay & George 2000). All giant stargazer catch and length, station, stratum definition and area records for each survey were extracted from research database "trawl" (Mackay 2000). The giant stargazer catch and number of length frequency records and otoliths collected in each survey are given in Table 2.

A total of 1887 otoliths (n_{male} = 877 otoliths, n_{female} = 1002 otoliths, and $n_{unsexed}$ = 8 otoliths) collected during the five WCSI surveys were prepared and read using the methods of Sutton (1999). The otoliths were baked in an oven for 4 minutes at 285 °C, and then embedded in layers in Araldite K142 clear epoxy resin. Once the resin blocks had cured, the otoliths were sectioned transversely through the nucleus using a revolving diamond-edged saw. The cut surface of each resin block was polished with P1200 carborundum paper.

The otoliths were read under reflected light using a Wild M400 binocular microscope at x 25 magnification. A thin layer of paraffin oil was applied to the cut surface of each block before reading to improve the clarity of the sections. All otoliths exhibited alternating light and dark regions under reflected light. Following Sutton (1999), we assumed that these light and dark regions were opaque and translucent zones formed annually, and that a single light (opaque) zone and a single dark (translucent) zone corresponded to a single year's growth (annulus).

The number of fully formed translucent zones present, a five-point "readability" score (Table 3), and a three-point "marginal state" score (Table 4) were recorded for each otolith. All otoliths were read "blind" (i.e., the corresponding length and sex of each fish was unknown to the reader) although the approximate date of capture could be deduced as the WCSI surveys were all run at about the same time each year. Following Sutton (1999), the first fully formed translucent zone present in each otolith, the so-called "six-month" zone, was *not* counted, but accounted for when counts were converted to estimated ages (see section 2.5). A protocol set of giant stargazer otoliths held by NIWA was re-read before the otoliths in this study were read.

2.4 Otolith reading precision

Otolith reading precision was quantified by carrying out a "between" and "within" reader test, as recommended by Campana et al. (1995). A sample of 250 otoliths was randomly selected from the set of 1887 prepared otoliths, read by a second reader, and then re-read by the first reader. The second reader also re-read the protocol set of giant stargazer otoliths before starting his set of readings. Both sets of readings were compared with the first reader's initial set of results. The Index of Average Percentage Error (IAPE, Beamish & Fournier 1981) and mean coefficient of variation (mean c.v., Chang 1982) were calculated for each test using the statistical programming language "R" (Ihaka & Gentleman 1996), a dialect of the "S" language (Becker et al. 1988). Where X_{ij} is the ith count of the jth otolith, R is the number of times each otolith is read, and N is the number of otoliths read or re-read,

$$\text{IAPE} = 100 \times \frac{1}{N} \sum_{j=1}^{N} \left[\frac{1}{R} \sum_{i=1}^{R} \frac{|X_{ij} - X_j|}{X_j} \right] \quad (1)$$

and

$$\text{mean c.v.} = 100 \times \frac{1}{N} \sum_{j=1}^{N} \left[\frac{\sqrt{\sum_{i=1}^{R} \frac{(X_{ij} - X_j)^2}{R-1}}}{X_j} \right] \quad (2)$$

2.5 Converting translucent zone counts to age estimates

To convert translucent zone counts to age estimates, we treated estimated fish age, $\hat{a}$, as the sum of three time components. The estimated age of the ith fish, $\hat{a}_i$, is

$$\hat{a}_i = t_{i,1} + t_{i,2} + t_{i,3} \quad (3)$$

where $t_{i,1}$ is the elapsed time from spawning to the end of the first translucent zone present *after* the "six-month" zone for the ith fish (following Sutton (1999), the "six-month" zone is not counted), $t_{i,2}$

is the elapsed time from the end of the first translucent zone present following the "six-month" zone to the end of the outermost fully formed translucent zone for the *i*th fish, and $t_{i,3}$ is the elapsed time from the end of the outermost fully formed translucent zone to the date when the *i*th fish was captured. Hence,

$$\begin{aligned} t_{i,1} &= t_{i,\text{ end first translucent zone after "six-month" zone}} - t_{i,\text{ spawning date}} \\ t_{i,2} &= (n_i + w) - 1 \\ t_{i,3} &= t_{i,\text{ capture}} - t_{i,\text{ end last translucent zone}} \end{aligned} \qquad (4)$$

where n_i is the total number of translucent zones present after the "six-month" zone for fish *i*, and *w* is an edge interpretation correction after Francis et al. (1992) applied to n_i: $w = 1$ if the recorded margin state = "wide" *and* fish *i* was collected *after* the date when translucent zones are assumed to be fully formed, $w = -1$ if the recorded margin state = "narrow" *and* fish *i* was collected *before* the date when translucent zones are assumed to be fully formed, otherwise $w = 0$. Because all five surveys were run over the same March–April period, *w* always takes the value 0 in our study. Hence $t_{i,2} = (n_i + w) - 1$ simplifies to $t_{i,2} = n_i - 1$.

Because of our present inability to precisely estimate spawning and translucent zone completion dates for individual giant stargazer, these dates were generalised for all fish. We followed previous studies and assumed an arbitrary spawning date of 1 July based on the annual reproductive cycle and winter spawning season of giant stargazer (Annala et al. 2003), and assumed a date of 1 November for completion of all translucent zones. We used the matching trawl station start date as the capture date for each fish. Decimalised years were used for all time components. Thus, the estimated age for a fish captured on 1 April where a count of "3" was obtained from the prepared otolith, is $\hat{a} = t_1 + t_2 + t_3 = 1.33 + 3 + 0.42 = 3.75$ years (see Figure 3).

2.6 Data processing

Once all otoliths had been read, and translucent zone counts converted to estimated ages, the data were processed as follows.

2.6.1 Data grooming

A total of 83 "outlier" cases were identified in the data and re-examined. These were fish deemed to be unusually "old" (over 16 years), or following a visual inspection of the length-at-age data, unusually large or small at a given age. All outlier otoliths were re-read by the first reader and compared with his initial results using the following procedure.

- The database and otolith packet records for each outlier case were cross-checked for transcription errors.
- Where the re-reading differed by 2 years or less, the initial result was deemed to be the correct interpretation of that otolith, and the otolith was removed from the subset of outlier cases.
- Where the re-reading differed by more than 2 years, that otolith was read for a third time by the first reader, and all three readings compared. If the third reading differed from the first

reading by 2 years or less, the first reading was deemed to be the correct interpretation of the otolith, and the otolith was removed from the subset of outlier cases.

- If the first and third readings differed by more than 2 years, and the second and third readings differed by less than 2 years, the second reading was deemed to be the correct interpretation of that otolith, and replaced the first reading. There were no cases where the first and third readings differed by 2 years or more, and the second and third readings also differed by 2 years or more.

Of the 83 outlier cases, 60 were removed from the set of outlier cases unaltered. Of the remaining 23 cases, 21 were deemed to have an initial reading that was a misinterpretation of the otolith and was replaced. Two cases were deemed to be transcription errors, one of which could be corrected, the other was dropped from the dataset. Finally, all remaining cases in the dataset where the initial readability score was greater than 4 (93 cases), all remaining unsexed fish were either the recorded length or count and hence estimated age was null (1 case), and all remaining unsexed fish (8 cases) were dropped from the dataset.

2.6.2 The final WCSI dataset

The dataset used in all subsequent analyses consisted of the groomed initial set of readings and corresponding estimated ages produced by the first reader, numbering 1784 cases. We refer to this dataset as the "final WCSI dataset" elsewhere in this paper. The final WCSI dataset is summarised in Table 5.

2.6.3 The combined ECSI, SCSI, and WCSI dataset

The final WCSI dataset was merged with existing age-length datasets for giant stargazer from the ECSI (Manning, unpublished data) and SCSI (Sutton 1999) to produce a combined age-length dataset for giant stargazer from around the South Island. The ECSI dataset was derived from otoliths collected aboard RV *Kaharoa* during five randomised trawl surveys of the ECSI, 1997–2000 (Manning, unpublished data). The SCSI dataset was derived from otoliths collected aboard RV *Tangaroa* during six randomised trawl surveys of the SCSI, 1992–2000 (Sutton, unpublished data). We refer to the merged ECSI, SCSI, and WCSI datasets as the "combined ECSI, SCSI, and WCSI dataset" elsewhere in this paper. The combined ECSI, SCSI, and WCSI dataset is summarised in Table 6.

The same two-stage, stratified sampling design and otolith collection methods were used in all surveys, hence the estimated numbers-at-length and at-age, and consequently the growth estimates derived, are assumed to be comparable across the surveys across the areas. Although the design of the ECSI survey was changed during the 1996 calendar year from a winter to a summer survey, the ECSI dataset includes data derived from otoliths collected during the summer series only (calendar years 1997–2000).

Different sampling gear was used in each trawl survey series, however. The ECSI trawl survey series used an inshore trawl net with a 28 mm (inside-mesh) codend towed at 3.0 knots by RV *Kaharoa* (Beentjes & Stevenson 2001); the SCSI trawl survey series used a hoki trawl with a 60 mm (inside-mesh) codend towed at 3.5 knots by RV *Tangaroa* (O'Driscoll & Bagley 2001); and the WCSI trawl survey series used an inshore trawl net with a 60 mm inside-mesh (74 mm knot-to-knot) codend towed at 3.0 knots by RV *Kaharoa* (Stevenson & Hanchet 2000).

2.7 Estimating length and frequency distributions of WCSI fish using "Catch-at-age"

"Catch-at-age" is a library of S-plus functions developed by NIWA (Bull & Dunn 2002) that computes biomass estimates and scaled length frequency distributions by sex and by stratum for trawl survey catch and length frequency data using the calculations in Bull & Gilbert (2001) and Francis (1989). If passed a set of age-length data, Catch-at-age constructs an age-length key, which is then applied to the estimated scaled length frequency distributions to compute estimated scaled age-frequency distributions (Bull & Gilbert 2001). Catch-at-age computes the coefficient of variation (c.v.) for each length and age class and the overall Mean-Weighted c.v. using a bootstrapping routine: fish length records are resampled within each landing, landings are resampled within each stratum, and the age-length data are resampled, all with replacement. The bootstrap length and age-frequency distributions are computed for each resample, and the c.v.s for each length and age class computed from the bootstrap distributions.

Catch-at-age was used to calculate estimated scaled length-frequency distributions for each sex for each survey in the final WCSI dataset. The sex and survey-specific subsets of length-at-age data in the final WCSI dataset were passed to Catch-at-age, converted to age-length keys, and then applied to the estimated length distributions to calculate estimated age frequency distributions for each sex for each survey. Bootstrapped c.v.s were produced for each age class by Catch-at-age from 300 resamples of the data. Following the documentation of the WCSI trawl survey series, we included only catches and length frequency records from stations where the recorded gear performance score was 2 or better in our calculations (see Mackay (2000) for the definition of gear performance).

2.8 Estimating total mortality of WCSI fish

We calculated $\hat{Z}$, the Chapman-Robson estimator of total mortality (Chapman & Robson 1960), for each sex from each survey from the estimated age-frequency distribution for each sex from each survey using the "R" language, and assuming six different ages at full recruitment, 3 to 8 years inclusive. Analytical and bootstrapped 95% confidence intervals were calculated for each estimate using the methods below.

2.8.1 The Chapman-Robson estimator of total mortality

The Chapman-Robson estimator of total mortality is

$$\hat{Z} = -\log_e \hat{s} \qquad (5)$$

where $\hat{s}$, the estimated survival rate, is

$$\hat{s} = \frac{\sum_{i=1}^{N} y_i}{N + \sum_{i=1}^{N} y_i - 1} \qquad (6)$$

where y_i is the true age of the ith fish in terms of years after recruitment, and N is the total size of the recruited population. The number of individuals that survive to exactly age y is unknown, so the approximations

$$N = \sum_{x=0}^{k} N_x \tag{7}$$

and

$$\sum_{i=1}^{N} y_i = \sum_{x=1}^{k} x N_x \tag{8}$$

were used, where N_x is the number of individuals in the population or catch between age x and age $x+1$, and k is the number of age groups in the recruited population minus one (Jensen 1985). The Chapman-Robson estimator assumes that the population sampled has a stable age structure, i.e., that recruitment and mortality are constant, that fish greater than the age at full recruitment are equally vulnerable to sampling, and that there are no age-estimation errors (Ricker 1975).

2.8.2 An analytical confidence interval for the Chapman-Robson estimator

The estimated variance of $\hat{Z}$, $\hat{V}(\hat{Z})$, is (Jensen 1985)

$$\hat{V}(\hat{Z}) = \frac{\hat{V}(\hat{s})}{\hat{s}^2} \tag{9}$$

where $V(\hat{s})$, the estimated variance of $\hat{s}$, is (Chapman & Robson 1960)

$$\hat{V}(\hat{s}) = \frac{\hat{s}(1-\hat{s})^2}{N} \tag{10}$$

Thus a $100(1-\alpha)$ % confidence interval for $\hat{Z}$ is approximately

$$\hat{Z} \pm (Z_{(1-(\alpha/2))}) \times \sqrt{\hat{V}(\hat{Z})}) \tag{11}$$

where $Z_{(1-(\alpha/2))}$ is the $(1-(\alpha/2))$ th quantile of the standard normal distribution.

2.8.3 Bootstrapping confidence intervals for the Chapman-Robson estimator

We calculated bootstrapped 95% confidence intervals around each estimate, firstly by calculating $\hat{Z}$ for each assumed age at full recruitment for each of the 300 resampled age distributions produced by Catch-at-age when calculating bootstrapped c.v.s for each age class for each sex, then by taking the 2.5th and 97.5th percentiles of the bootstrapped distributions of $\hat{Z}$ produced as a result.

2.9 Fitting different von Bertalanffy growth models to the final WCSI and combined ECSI, SCSI, and WCSI datasets and comparing the fit of these models.

We used the "R" language and maximum likelihood methods to fit different von Bertalanffy growth models to the final WCSI and combined ECSI, SCSI, and WCSI datasets and to compare the fit of these models. Likelihood methods for the von Bertalanffy growth model were given by Kimura

(1980), compared with competing methods by Cerrato (1990), and discussed by Quinn II & Deriso (1999) among others. We review those aspects of theory pertinent to our analysis, specifically the derivation of the maximum likelihood estimates and the likelihood ratio test for comparing von Bertalanffy curves. We loosely follow the notation of both Kimura (1980) and Quinn II & Deriso (1999).

2.9.1 The von Bertalanffy growth model assuming additive or multiplicative normal errors

For age-length data collected from some group of fish, the von Bertalanffy of the mean length, L_j, of the jth fish at age t_j is (Bertalanffy 1938)

$$L_j = L_\infty\left[1-e^{-k(t_j-t_0)}\right] \tag{12}$$

where L_∞ is the mean asymptotic maximum length, where k is a rate parameter indicating how quickly L_∞ is approached (the "Brody rate parameter", Quinn II & Deriso (1999)), and where t_0 is the time, or age, at which mean length equals zero.

Fitting the von Bertalanffy curve to age-length data and estimating parameters L_∞, k, and t_0 requires assumptions to be made about the error structure of the data. Assuming that variation in length-at-age is *constant* as a function of age, the "additive" error model, the data are modelled by

$$\begin{aligned} L_j &= L_\infty\left[1-e^{-k(t_j-t_0)}\right]+\varepsilon_j \\ &= \mu_a(L_\infty,k,t_0)+\varepsilon_j \end{aligned} \tag{13}$$

where ε_j is an independent normally distributed random variable, with mean $\mu = 0$, and variance σ^2. Assuming that variation in length-at-age *increases* as a function of age, the "multiplicative" error model, the data are modelled by

$$L_j = L_\infty\left[1-e^{-k(t_j-t_0)}\right]e^{\varepsilon_j} \tag{14}$$

where ε_j is an independent normally distributed random variable, with mean $\mu = 0$, and variance σ^2. Taking the natural logarithm of this equation yields

$$\begin{aligned} \ln L_j &= \ln L_\infty + \ln\left[1-e^{-k(t_j-t_0)}\right]+\varepsilon_j \\ &= \left(\ln L_\infty + \ln\left[1-e^{-k(t_j-t_0)}\right]\right)+\varepsilon_j \\ &= \mu_m(\ln L_\infty,k,t_0)+\varepsilon_j \end{aligned} \tag{15}$$

Note that the expected value of L_j in the multiplicative model, $\mathrm{E}\left[L_j\right]$, is

$$\mathrm{E}\left[L_j\right] = L_\infty(1-e^{-k(t_j-t_0)})e^{\frac{1}{2}\sigma^2} \tag{16}$$

i.e., $\ln\left(\mathrm{E}\left[L_j\right]\right)$ is not equal to $\mathrm{E}\left[\ln L_j\right]$.

2.9.2 The maximum likelihood estimates of L_∞, k, and t_0 for the additive and multiplicative normal error models

Where an age-length dataset has been partitioned into i groups, such as by sex or area, where Y_{ij} is the actual length of the jth fish in the ith group, where $\hat{Y}_{ij}$ is the predicted length of the jth fish in the ith group from either the additive or multiplicative normal error models with parameters $\boldsymbol{\Theta}_i = \{L_{\infty,i}, k_i, t_{0,i}\}$, and assuming that the variance, σ^2, is the same across all of the i groups, and where n_i is the number of fish in the i^{th} group, the likelihood function for either the additive or multiplicative von Bertalanffy models can be written as

$$\mathrm{L}_i(\boldsymbol{\Theta}_i,\sigma^2) = \left(2\pi\sigma^2\right)^{-n_i/2} \exp\left[-\frac{1}{2\sigma^2}\sum_{j=1}^{n_i}(Y_{ij}-\hat{Y}_{ij})^2\right] \tag{17}$$

and the joint likelihood function for all i groups is

$$\mathrm{L}(\boldsymbol{\Theta},\sigma^2) = \prod_i \mathrm{L}_i(\boldsymbol{\Theta}_i,\sigma^2) \tag{18}$$

where $\boldsymbol{\Theta}$ is the vector of von Bertalanffy parameter estimates for all i groups.

From equation (17), $\mathrm{L}_i(\boldsymbol{\Theta}_i,\sigma^2)$ is maximised when the sum of squares of $(Y_{ij}-\hat{Y}_{ij})$ is minimised. Hence, the problem of finding the maximum likelihood estimates (MLEs), of $L_{\infty,i}$, k_i, and $t_{0,i}$, reduces to one of finding non-linear least squares estimates of $L_{\infty,i}$, k_i, and $t_{0,i}$ on the data in group i. Note that this is a general property of the normal error model and not peculiar to the von Bertalanffy equation. Note also that the sum of squares to be minimised depends on the form of the model fitted. When the additive model is fitted,

$$\sum_{j=1}^{n_i}(Y_{ij}-\mu_a(L_{\infty,i},k_i,t_{0,i}))^2 \tag{19}$$

is minimised, and

$$\sum_{j=1}^{n_i}(\ln Y_{ij}-\mu_m(\ln L_{\infty,i},k_i,t_{0,i}))^2 \tag{20}$$

is minimised in the multiplicative case. The MLE for σ^2 for either model is

$$\hat{\sigma}^2 = \frac{\sum_i \mathrm{RSS}_i}{\sum_i n_i} \tag{21}$$

where RSS_i is the residual sum of squares for the i^{th} group.

Once the MLEs of $\boldsymbol{\Theta}_i$ and σ^2 have been calculated, the maximum likelihood for group i is

$$\max\left[\mathrm{L}_i(\hat{\boldsymbol{\Theta}}_i,\hat{\sigma}^2)\right] = (2\pi\hat{\sigma}^2)^{-n_i/2}\exp(-n_i/2) \tag{22}$$

and the joint maximum likelihood for all i groups is

$$\max\left[L(\hat{\Theta},\hat{\sigma}^2)\right]=\max\left[\prod_i L_i(\hat{\Theta}_i,\hat{\sigma}^2)\right] \tag{23}$$

Estimation calculations are usually more easily done on a log-scale. The log-likelihood function for the ith group in the additive model is

$$l_i(\Theta_i,\sigma^2)=-(n_i/2)\ln(2\pi\hat{\sigma}^2)-\frac{1}{2\hat{\sigma}^2}\sum_{j=1}^{n_i}(Y_{ij}-\hat{Y}_{ij})^2 \tag{24}$$

and the joint likelihood function for all i groups is

$$l(\Theta,\sigma^2)=\sum_i l_i(\Theta_i,\sigma^2) \tag{25}$$

with the MLEs for $L_{\infty,i}$, k_i, $t_{0,i}$, and σ^2 calculated as described above. The maximum log likelihood for the ith group is hence

$$\max\left[l_i(\hat{\Theta}_i,\hat{\sigma}^2)\right]=-\frac{n_i}{2}\left[\ln(2\pi\hat{\sigma}^2)+1\right] \tag{26}$$

and the joint maximum likelihood for all i groups is hence

$$\max\left[l(\hat{\Theta},\hat{\sigma}^2)\right]=\max\left[\sum_i l_i(\hat{\Theta}_i,\hat{\sigma}^2)\right] \tag{27}$$

2.9.3 The likelihood ratio test for comparing von Bertalanffy models

The likelihood ratio test is used throughout statistics to quantitatively compare the fit of competing models. Conventionally, the fit of a more complex "full" model is compared with the fit of a less complex "reduced" model nested within the full model in a manner analogous to a conventional analysis of variance or deviance. The competing models *must* be fitted to the same dataset – the likelihood ratio test makes no sense otherwise.

The likelihood ratio test hence provides a framework to quantitatively compare the fit of different, nested von Bertalanffy models fitted to the same age-length dataset; e.g., to compare the fit of a von Bertalanffy model that assumes different parameters, L_∞, k, and t_0, for males and females for a given age-length dataset (full model) with one that does not (reduced model). In a simulation study comparing the performance of the likelihood ratio test with other statistical tests for the von Bertalanffy model, including univariate t- and χ^2-squared tests and the multivariate T^2 test, Cerrato (1990) found that the likelihood ratio test outperformed the competing tests considerably.

The likelihood ratio test comparing two von Bertalanffy models is as follows. Where Θ_F is a vector of parameters for the full model, and Θ_R is a vector of parameters for the reduced model, the null (H_0) hypothesis is

H_0: Θ_F and Θ_R satisfy some set of linear constraints, ω, such that $\Theta_F=\Theta_R$,

and the alternative (H_1) hypothesis is

H_1: $\boldsymbol{\Theta}_F$ and $\boldsymbol{\Theta}_R$ satisfy no linear constraints such that $\boldsymbol{\Theta}_F \neq \boldsymbol{\Theta}_R$.

Where a von Bertalanffy model assuming different parameters for males and females is compared with one that does not, the linear constraints may be of the form

$$\omega = \begin{Bmatrix} L_{\infty,\text{Male}} = L_{\infty,\text{Female}} \\ k_{\text{Male}} = k_{\text{Female}} \\ t_{0,\text{Male}} = t_{0,\text{Female}} \end{Bmatrix} \tag{28}$$

The likelihood ratio test statistic is

$$\chi^2 = -2(\max \text{l}_R - \max \text{l}_F) \tag{29}$$

where max l_R is the maximum log likelihood of the reduced model, where max l_F is the maximum log likelihood of the full model, and where χ^2 has an approximately chi-squared distribution with degrees of freedom, f, equal to the difference in the number of parameters between the full and reduced models. Thus, where a von Bertalanffy model assuming different parameters for males and females is compared with one that does not, and where σ^2 is assumed to be the same for all groups within the data in each model, the full model has 7 parameters, the reduced model 4, and hence the likelihood ratio test statistic has $f = 7 - 4 = 3$ degrees of freedom. Thus, the likelihood ratio test provides sufficient evidence to reject H_0 at the α level of significance, if χ^2 is greater than the critical value equal to the (1-α)th quantile of the $\chi^2_{f=3}$ distribution.

2.9.4 Von Bertalanffy models fitted and likelihood ratio tests carried out

We fitted 10 different models to our data, 6 to the final WCSI dataset, and 4 to the combined ECSI, SCSI, and WCSI dataset. Models assuming a common set of von Bertalanffy parameters for all the data, separate parameters by sex, and separate parameters by survey and sex were fitted to the final WCSI dataset; models assuming separate parameters by sex, and by area and sex, were fitted to the combined ECSI, SCSI, and WCSI dataset. Each model was fitted first using the additive model, then re-fitted using the multiplicative model. Each model, regardless of structure, assumed a single, common variance parameter.

As noted in section 2.9.2, the problem of finding maximum likelihood estimates of von Bertalanffy model parameters, assuming some normal error structure and constant variance across the data, reduces to one of finding non-linear least squares estimates of the parameters. We used the "nls" function in the "R" language to find non-linear least-squares estimates for each parameter in each group in each model and to compute analytical 95% confidence intervals around each estimate. We also calculated bootstrapped 95% confidence intervals around each estimate by sampling with replacement each dataset 1000 times, finding the non-linear least-squares estimates for each resampled dataset, then finding the 2.5th and 97.5th percentiles of the bootstrapped distributions produced for each estimate as a result. We used the "ellipse" function in "R" to find the approximate joint 95% confidence regions around the estimates for L_∞ and k. The MLE of σ^2 and the joint maximum log-likelihood for each model were calculated from the "nls" output produced for each model fit using the equations given in section 2.9.2,.

Model fit was investigated with standard residual diagnostics. For each model, a plot of model residuals against fitted values, and a plot of model residuals against the quantiles of the standard normal distribution, was produced. An even band of plotted points in the first plot, and plotted points distributed about a 1:1 line drawn through the first and third quantiles of the residuals and quantiles of the standard normal distribution, indicates that the model has fitted the data well, and that the model assumptions are justified.

Six likelihood ratio tests were carried out.

- To test for a sex effect in the final WCSI dataset, an additive model fitted to the data assuming separate parameters by sex was tested against a reduced model that did not assume separate parameters by sex.
- To test for a survey effect within sex in the final WCSI dataset, an additive model fitted to the data assuming separate parameters by survey and sex was tested against a reduced model assuming separate parameters by sex only.
- To test for an area effect within sex in the combined ECSI, SCSI, and WCSI dataset, an additive model fitted to the data assuming separate parameters by area and sex was tested against a reduced model assuming separate parameters by sex only.

The tests were repeated with the corresponding multiplicative models. All reduced models were fitted to the same dataset with the same error structure as the full models they were tested against. The null hypothesis for all tests was that the parameters in the full and reduced models satisfied a set of linear constraints such that the full and reduced models were equivalent. The alternative hypothesis for all tests was that the parameters satisfied no such constraints, i.e., the full and reduced models were not equivalent. The full and reduced models in each test, the number of parameters in each model, and the linear constraints for each test are summarised in Table 7.

2.9.5 Pairwise comparisons of differences between individual parameters between groups in each model

Following the likelihood ratio tests, pairwise significance tests of differences between individual parameters for groups in each model were made by comparing the overlap between the parameter estimate for the first group and the 95% confidence interval about the estimate for the parameter in the second group; an implicit hypothesis test at the 5% level of significance. If the interval for the second group does not contain the estimate for the first group, then the test provides sufficient evidence at the 5% level of significance to reject the null hypothesis that the two parameters are equal in favour of the alternative hypothesis that they are not equal.

3. RESULTS

3.1 Otolith readings

All 1887 otoliths prepared and read exhibited alternating light (opaque) and dark (translucent) regions under reflected light. Although alternating opaque and translucent zones were visible, the contrast between zones was generally poor. Translucent zones were typically quite diffuse with many growth checks present, which we assume to be false annual bands. The width between successive translucent zones narrowed with increasing age, with most new growth appearing to be deposited on the dorsal margin of the otolith. These results are consistent with previous studies (Sutton 1999, Sutton unpublished data, Manning unpublished data).

Both readers counted translucent zones along a line extending from the nucleus towards the dorsal margin. Due to the poor contrast between zones, the count produced along this axis was compared with counts produced along other axes, and a "most likely" count for each otolith recorded. Counting from the nucleus along the sulcus, and from the nucleus towards the ventral margin, were found to be especially useful.

Photomicrographs taken under reflected light of typical prepared otoliths from young, maturing, and mature fish are given in Figure 4. The translucent zones are marked with white dots and the "six-month" zones with white asterixes, giving our interpretation of each otolith and of giant stargazer otoliths generally.

All otoliths read are tabulated by survey and readability score in Table 8, and by survey and margin state in Table 9. Counts were produced for over 95% of all otoliths, even though many otoliths were found to be difficult to read (over 25% of all otoliths had a readability score of four or worse recorded).

3.2 Otolith reading precision

The IAPE and mean c.v. were 2.47% and 3.50% for the within-reader test and 8.73% and 12.35% for the between-reader test (Table 10). Diagnostic bias plots following Campana (1995) are presented in Figure 5. The symmetry of the histograms in Figure 5(A), the relatively even distribution of plotted points about the zero-line in Figure 5(B), and the position of the error bars about the 1:1 line in Figure 5(C) all suggest that no systematic bias exists either within or between readers.

3.3 Age-length relationship

Lengths-at-age were plotted by sex (Figure 6) and by survey and sex (Figure 7) for the final WCSI dataset, and by area and sex for the combined ECSI, SCSI, and WCSI dataset (Figure 8). In all plots there is a period of relatively fast initial growth that flattens out and appears to approach some mean asymptotic length as age increases. Females appear to grow larger than males, but the rate at which each sex approaches its mean length appears to be similar. These results are consistent with other giant stargazer age and growth studies (Sutton 1999, Sutton unpublished data, Manning unpublished data). The smallest and largest, youngest and oldest male and female fish in the final WCSI dataset are given in Table 11. Note that all otoliths from fish 15 cm or less in length had no other translucent zones present other than the "six-month" zone present in their otoliths (counts of "0" recorded), i.e., no fish 15 cm in length or smaller had seen its second winter. The sample minimum, maximum, mean, and standard deviation of length-at-age by sex for all distinct age classes in the final WCSI dataset are given in Table 12.

3.4 Length and age-frequency distributions

Estimated scaled length-frequency distributions for each sex for each survey in the WCSI trawl survey series are plotted in Figure 9. Corresponding estimated scaled age frequency distributions are plotted in Figure 10. The estimated scaled numbers-at-age and bootstrapped c.v.s for each age-class calculated from 300 resamples of the data are given in Appendix A. The sex and survey-specific subsets of length-at-age data used as age-length keys to convert the estimated scaled numbers at length to estimated scaled numbers at age are plotted in Figure 7.

Across the surveys, there are reasonably consistent, small modes in the estimated numbers-at-length at about 20–25 cm and 25–30 cm, with a much larger mode at about 40–60 cm. Although there does not seem to be the same amount of polymodality in the estimated numbers-at-age, some age-classes may be traced from survey to survey, e.g. "2+" males in KAH9504 appear to have shifted to the "4+" class in KAH9701. The overall shape of the estimated age frequency distributions, specifically the height and width of the tails containing older fish, does not seem to change greatly from survey to survey, suggesting that similar numbers of older, mature fish are present in the survey catch across the surveys.

As well as being larger, WCSI females seem to be somewhat longer lived than males, with slightly more females than males present in the older age classes, although roughly equal numbers by sex are present in the dataset as a whole (see Table 5). Sutton (unpublished data) found that about 4% of all male and over 10% of all female SCSI giant stargazer reached an age greater than 14; about 1% of all male and 5% of all female WCSI giant stargazer reach an age greater than 14 (see Table 5).

3.5 Total mortality estimates

Total mortality estimates for each sex for each survey assuming Age at Full Recruitment (AFR) is 3–8 years (inclusive) and analytical and bootstrapped 95% confidence intervals around each estimate are given in Appendix B. The densities of the bootstrapped distributions for each estimate are plotted in Figure 11.

Across the different assumed AFRs, the estimates range from 0.2092 (KAH9404, AFR = 3) to 0.5961 (KAH9504, AFR = 8) for males, from 0.1623 (KAH9204, AFR = 3) to 0.5772 (KAH9504, AFR = 8) for females, and from 0.1870 (KAH9204, AFR = 3) to 0.5870 (KAH9504, AFR = 8) for all fish. For assumed ages at full recruitment greater than 4, for both sexes and for all fish, the estimates are higher for the 1995 survey (KAH9504) than for any other survey in the trawl survey series.

3.6 Von Bertalanffy growth models fitted to the final WCSI and combined ECSI, SCSI, and WCSI datasets

Parameter estimates, and analytical and bootstrapped 95% confidence intervals about the estimates, are given for the additive and multiplicative models fitted in Table 13 and Table 14. The variance estimates for all models are given in Table 15. The fitted curves for all models are overlaid on the length-at-age plots in Figures 6 to 8. Cross-sections of approximate joint 95% confidence regions around the estimates for L_∞ and k, conditioning on t_0, are plotted by sex and by survey and sex for the final WCSI dataset in Figures 12 and 13, and by area and sex for the combined ECSI, SCSI, and WCSI dataset in Figure 14.

The L_∞ and k estimates suggest that growth varies by sex, and by survey within sex, for WCSI fish, and varies by area within sex for fish around the South Island.

- Estimates for L_∞ and k from the fit of the additive model assuming separate parameters by sex to the final WCSI dataset are 71.91 and 0.1442 for all males and 81.16 and 0.1443 for all females. Estimates from the fit of the corresponding multiplicative model are 73.52 and 0.1335 for all males and 85.91 and 0.1208 for all females.

- Estimates for L_∞ and k from the fit of the additive model assuming separate parameters by survey and sex to the final WCSI dataset range from 67.74 and 0.1882 (KAH0004) to 77.20 and 0.1285 (KAH9701) for males, and from 77.60 and 0.1575 (KAH9204) to 89.69 and 0.1160 (KAH9504) for females. Estimates from the fit of the corresponding multiplicative model range from 69.52 and 0.1702 (KAH0004) to 79.26 and 0.1050 (KAH9504) for males, and from 84.55 and 0.1313 (KAH9404) to 92.30 and 0.1072 (KAH9504) for females

- Estimates for L_∞ and k from the fit of the additive model assuming separate parameters by area and sex to the combined ECSI, SCSI, and WCSI dataset are 57.74 and 0.2156 for ECSI males, 60.92 and 0.1801 for SCSI males, 71.35 and 0.1647 for ESCI females, and 72.95 and 0.1706 for SCSI females. Estimates from the fit of the corresponding multiplicative model are 56.18 and 0.2345 for ECSI males, 59.89 and 0.1963 for SCSI males, 70.91 and 0.1652 for ECSI females, and 74.53 and 0.1525 for SCSI females.

3.7 Comparing the von Bertalanffy growth models fitted to the final WCSI and combined ECSI, SCSI, and WCSI datasets

The results of the likelihood ratio tests, calculated from the results presented in Tables 13 and 14, are given in Table 15. The p-values for all tests, the probability of obtaining the calculated test statistic given that the null hypothesis is true, are all very low, providing very strong evidence against the null hypothesis for all tests. Hence, the full and reduced models, both additive and multiplicative, appear not to be equivalent for any of the tests performed. Growth, therefore, appears to differ significantly by sex, and by survey within sex, for WCSI fish, and by area within sex for fish from different areas around the South Island. Diagnostic residual plots for the fits of all models are presented in Figures 15 to 18.

4. DISCUSSION

4.1 Otolith reading and interpretation

Although precision within reader was high (2.47% IAPE and 3.50% mean c.v.), precision between readers was somewhat lower (8.73% IAPE and 12.35% mean c.v.). We suggest this reflects how difficult giant stargazer otoliths are to interpret, specifically the diffuse nature of many translucent zones, the large number of presumably false annual checks present, and the natural interpretative differences between two people that result from the presence of these features, rather than any systematic bias; there is no evidence of systematic bias in any direction. However, because the interpretation protocol we used is unvalidated, we have no way of knowing whether the age estimates are accurate or not. Given that this is the fourth large age and growth study to be carried out on this species (Sutton 1999, Sutton unpublished data, Manning unpublished data), validating the interpretation protocol is an important topic of future research for this species.

Although the combined ECSI, SCSI, and WCSI dataset incorporates data merged from three different studies produced by two different readers, the same otolith preparation and interpretation protocol was used in all three studies, both readers were involved in the reader comparison tests carried out in this study, no evidence of systematic bias exists in any direction between the two readers, and before beginning reading in this study and in the two previous studies, both readers had read a standard protocol set of giant stargazer otoliths. Hence, the chance of a drift in interpretation over time by either or both or between readers is thought to be low.

4.2 Length and age frequency distributions

Although small modes (20–25 cm and 25–30 cm) are present in the estimated numbers at length for most surveys, because of the overlap in lengths-at-age, they are unlikely to be composed entirely of consecutive age-classes. The large mode between 40 and 60 cm is almost certainly the amalgamation of a number of age classes. These results are consistent with Sutton (1999, unpublished data) who noted little evidence of length mode progression in survey catches from either the ECSI (Sutton 1999) or SCSI (Sutton, unpublished data).

We infer from the profiles of the estimated age frequency distributions, which are reasonably similar from survey to survey, that similar numbers of older, mature fish have been present in the survey catch over time. Despite using a small-mesh codend (60 mm inside-mesh or 74 mm knot-to-knot, Drummond & Stevenson (1995a)), young and hence small fish are likely to be under-represented in the survey catch. Hence the true numbers of young fish are likely to be higher than is indicated. We infer from the relatively consistent, relatively large numbers of young fish in the estimated age frequency distributions for each survey that young fish have continued to recruit into the adult population over time. If both inferences are correct, then the age composition of giant stargazer in STA 7 has remained relatively stable, despite a doubling of the annual commercial catch since the 1990–91 fishing year.

The lack of exceptionally weak or strong year classes tracking through the survey catch may be real, or it may result from imprecision in the otolith readings, with strong year classes blurred with adjacent year classes due to the random misreading of some otoliths by some margin. We suggest that given the high degree of within-reader precision, and that the final WCSI dataset was composed solely of the groomed initial results produced by the first reader, that the lack of exceptionally strong or weak year classes in the survey catch is probably real; hence, the stock appears to be composed of a number of successful year-classes, rather than a few or a single year-class. Total mortality estimates

The Chapman-Robson estimator assumes that the population sampled is in a steady state. For assumed ages at full recruitment greater than four, for each sex and for all fish, the estimates calculated are higher for the 1995 survey (KAH9504) than for any other survey in the trawl survey series. This is probably because of the larger numbers of 5 to 10 year-old fish that appear to be present in the catch for that survey, leading to a steeper decline in the limb of the catch curve. This suggests that the steady-state assumption, including constant recruitment and mortality and hence a stable age structure, may not have been met. However, Dunn et al. (1999) found the Chapman-Robson estimator to be robust to departures from the steady-state assumption, including stochastic noise in sampling, mortality, recruitment, and age estimation.

Although the research trawl nets aboard RV *Kaharoa* may under-sample young fish, they probably sample maturing and mature fish, say fish 3–4 years old and over 30 cm in length, reasonably well. If large fish are equally selected for, then Z and L_∞ estimates produced for fish in the final WCSI dataset are unlikely to be biased by the sampling gear.

From the profiles of the numbers-at-age distributions, giant stargazer on the WCSI are probably fully recruited by age five or six. We suggest that reasonable estimates of total mortality for giant stargazer on the WCSI are the mean estimates by sex across the five surveys assuming that the age at full recruitment is five or six. This produces values of 0.33, 0.27, and 0.30 for males, females, and all fish when the age at full recruitment is assumed to be five, and values of 0.40, 0.32, and 0.35 for males, females, and all fish when the age at full recruitment is assumed to be six. These results are similar to estimates produced by Sutton (unpublished data) for male and female fish from the SCSI of 0.35 and 0.20 respectively.

Given the catch history, we are unable to calculate estimates for natural mortality, M, from the slopes of the catch curves. However, we infer that from the relatively few fish older than 10 years in the survey catch, that M is probably fairly high, at least on the same order as M estimates presented for other giant stargazer stocks, i.e., about 0.20 (Annala et al. 2003). Furthermore, we infer from the catch history and from the variation in the estimates across the surveys, that STA 7 may not have reached a state of exploited equilibrium; variation in fishing mortality, F, from year to year, or at least survey to survey, may be driving the variation in total mortality.

Assuming that the west coast South Island surveys are accurately sampling the age structure of the post-recruit STA 7 population, and validly reflect relative biomass, we may obtain better estimates of Z by tracking the relative abundance of age classes through successive surveys; even though the surveys are more than one year apart. This should be considered in a future study.

4.3 Fitting different von Bertalanffy models fitted to the final WCSI and combined ECSI, SCSI, and WCSI datasets and comparing the fit of the different models

Although the results of all likelihood ratio tests are highly significant, the approximate joint 95% confidence regions for L_∞ and k suggest that although all effects are statistically significant, the survey effect within sex may not be biologically significant. The regions by sex show wide separation in the parameter space; in contrast, the regions by survey and sex are close together, but the regions by area and sex are also widely separated. We suggest that the wide separation of regions by sex, and by area and sex, indicate biological significance, and that the relatively narrow separation of regions by survey and sex indicate statistical significance only. Therefore, considering the growth of WCSI giant stargazer separately by survey, and by extension from year to year, may not be meaningful. We speculate that it is the position of the KAH0004 region relative to the other regions in the parameter space causing the statistically significant survey effect. This could be tested by refitting the models excluding the KAH0004 data and re-running the relevant likelihood ratio tests. From the strength of the apparent differences in growth by area within sex for South Island fish, we suggest that giant stargazer around the South Island form different biological stocks with different biological properties, in particular growth.

We have assumed that the ECSI, SCSI, and WCSI surveys have sampled giant stargazer similarly, and hence that growth estimates can be compared validly across the areas in the combined ECSI, SCSI, and WCSI dataset. Although the same sampling design and otolith collection methods were used in all surveys, different sampling gear was used in each trawl survey series. Although large fish are probably fully selected for by the sampling gear used in each series, smaller fish may not have been. Nevertheless, small fish (under 30 cm) *were* caught in each series (Stevenson & Hanchet 2000, Beentjes & Stevenson 2001, O'Driscoll & Bagley 2001), had their otoliths collected, and were included in the combined ECSI, SCSI, and WCSI dataset.

Assuming that comparing growth between areas using the ECSI, SCSI, and WCSI dataset is valid, how can we best interpret the parameter estimates for the different areas and for other groups in the other models fitted? Francis (1996) suggested that comparing the rate at which asymptotic growth is approached, i.e., comparing estimates for parameter k, is the most natural method for comparing different growth curves where mean asymptotic maximum size differs, producing common sense results.

The estimates and 95% confidence intervals for L_∞ from the fits of the models assuming separate parameters by sex to the final WCSI dataset suggest that female giant stargazer on the WCSI grow to a larger mean asymptotic size than males, and that these differences are significant at the 5% level, regardless of whether the additive or multiplicative model is considered. The estimates for k, on the other hand, are almost identical for the fit of the additive model. Although different for the fit of the multiplicative model, these differences are not significant. Therefore, following Francis (1996), given that L_∞ differs by sex whereas k does not, male and female giant stargazer on the WCSI grow at roughly the same rate, although female fish tend to be larger on average than males after maturity.

The estimates and 95% confidence intervals for L_∞ from the fits of the models assuming separate parameters by area and sex to the combined ECSI, SCSI, and WCSI dataset, suggest that ECSI fish are smaller than SCSI fish, which are smaller than WCSI fish of the same sex following maturity, i.e., $\hat{L}_{\infty,(M,\,ECSI)} < \hat{L}_{\infty,(M,\,SCSI)} < \hat{L}_{\infty,(M,\,WCSI)}$ and $\hat{L}_{\infty,(F,\,ECSI)} < \hat{L}_{\infty,(F,\,SCSI)} < \hat{L}_{\infty,(F,\,WCSI)}$. Pairwise differences between areas are all significant at the 5% level for males for both models, as are the differences between ECSI and WCSI females, and between SCSI and WCSI females, but not between ECSI and SCSI females for either model.

Pairwise differences between the estimates for k between WCSI and ECSI fish, and between WCSI and SCSI fish, suggest that k is generally significantly less at the 5% level for WCSI fish than for fish of the same sex from the other two areas, i.e., generally $\hat{k}_{(M,\,WCSI)} < \hat{k}_{(M,\,SCSI)} < \hat{k}_{(M,\,ECSI)}$ and $\hat{k}_{(F,\,WCSI)} < \hat{k}_{(F,\,SCSI)} < \hat{k}_{(F,\,ECSI)}$; although the direction and significance of the relationship at the 5% level varies by sex and the error structure of the model fitted.

WCSI fish thus appear to grow at a slower rate than fish of the same sex from the ECSI and SCSI, although WCSI fish appear to be larger, on average, after maturity than fish of the same sex from the other two areas. Nevertheless, the k estimates for WCSI fish are still much greater than any of the estimates given by Tracey et al. (2000) for long-lived, slow-growing, deepwater species such as orange roughy, black and smooth oreos, rubyfish, and black cardinalfish. Black cardinalfish, for example, grow to a similar mean asymptotic size as WCSI giant stargazer ($\hat{L}_{\infty,\mathrm{Male}} = 67.8$ cm fork length and $\hat{L}_{\infty,\mathrm{Female}} = 70.9$ cm fork length; Tracey et al. 2000); however their k estimates ($\hat{k}_{\mathrm{Male}} = 0.034$ and $\hat{k}_{\mathrm{Female}} = 0.038$; Tracey et al. 2000) are about one-fourth of those for WCSI giant stargazer of the same sex. Although apparently slower growing than other South Island giant stargazer fishstocks, WCSI giant stargazer are still comparatively fast growing compared with other species.

The phenomenon of slower growth but larger mean asymptotic maximum size for WCSI fish may be caused by the strong negative correlation of parameters L_∞ and k in the von Bertalanffy model. Reparameterising the von Bertalanffy model with statistically more stable parameters, such as the parameterisations of Cerrato (1990) or Francis (1988), and re-fitting to the data may be useful to establish whether these differences are real or are artefacts of the models fitted.

Finally, although the residual plots suggest that all models fit the data fairly well, funnelling is present in the plots of residuals against fitted values for the additive models that is reduced in the plots of residuals against fitted values for the multiplicative models. This suggests that the multiplicative models fit the data slightly better than the additive models, and hence we prefer the fit of the multiplicative models. We suggest that future modelling of giant stargazer growth with the von Bertalanffy model use the multiplicative rather than the additive model, although alternative error structures should continue to be investigated; we agree with a reviewer who stated rather strongly that a case could be argued for preferring the fit of the additive models.

4.4 On fitting growth models to weighted length-at-age data

Davies et al. (2003) discussed how non-random, fixed allocation, otolith sampling design can introduce bias in growth estimates. A fixed sample size allocated to all length intervals in a sample can result in a sample that is not representative of the length composition of the population being sampled, leading to bias in estimates of mean length-at-age, mean weight-at-age, and consequently growth parameters (Goodyear 1995).

To overcome otolith sampling design bias, Davies et al. (2003) suggested that otolith samples should be weighted by the approximate population length composition to derive estimates of the population distribution of length-at-age. They found bias was evident in comparisons of von Bertalanffy curves fitted to weighted and unweighted snapper (*Pagrus auratus*) length-at-age data that varied depending on the otolith sample collected, and that calculating growth estimates from weighted length-at-age data avoided any bias introduced by the otolith sampling design. Refitting the von Bertalanffy models we used to weighted length-at-age data and comparing these results with the results presented in this paper may be useful.

4.5 On the implications of the results for the future management of STA 7 and suggestions for future research

The results presented here are the first on the productivity and demography of STA 7. Although they quantify some of the basic biology of giant stargazer in STA 7 and give some idea of the status of the stock (i.e., that it appears to have remained reasonably stable over time, that it seems to be composed of a number of successful year-classes rather than a few or a single year-class, and that fish in STA 7 appear to grow differently from fish of the same sex from other areas around the South Island), establishing whether the current TACC over-catch can be sustained, and what a reasonable harvesting regime might be if not, requires a quantitative stock assessment, involving, perhaps, the development and fitting of an age-structured stock assessment model.

Although the development of such a stock assessment model is the logical next step, doing so requires properly addressing some of the basic scientific issues and questions raised here. In particular, we suggest that validating the otolith interpretation protocol is of primary importance. In addition, we suggest that the otoliths collected aboard RV *Kaharoa* during the 2003 WCSI trawl survey be prepared and read, and the analyses presented in this paper be updated to see if the apparent trends in numbers-at-length and at-age continue. We also suggest that testing the multiple biological stocks hypothesis, advanced on the strength of the apparent differences in growth by area within sex, is pertinent to the development of a multi-stock assessment model. Finally, fitting a more stable parameterisation of the von Bertalanffy model to weighted length-at-age data may be useful to elucidate whether the apparent trends in growth between the areas are real or artefacts of the models fitted.

4.6 Conclusions

- Otolith reading precision was acceptable. No systematic bias in interpretation seems to exist either within or between readers.

- The length and age composition of the WCSI trawl survey catch seems to have remained reasonably stable, despite a doubling of the commercial catch from 1990–91 to 2001–02. The survey catch seems to be composed of a number of successful year classes.

- Reasonable estimates of total mortality are 0.33, 0.27, and 0.30 for males, females, and all fish when the age at full recruitment is assumed to be five, and 0.40, 0.32, and 0.35 for males, females, and all fish when the age at full recruitment is assumed to be six. It is unclear whether giant stargazer in STA 7 have reached a state of exploited equilibrium. Tracking the movement of successful year-classes over time may allow a better estimate of Z to be obtained, and should be considered by a future study.

- Growth appears to differ significantly by sex, and by survey within sex, for giant stargazer in STA 7, and to differ by area within sex for giant stargazer around the South Island (STA 3, 5, and 7). The differences by sex for fish in STA 7, and by area within sex for fish around the South Island, are probably biologically significant as well; the differences by survey within sex for fish in STA 7 probably are not.

- Male and female giant stargazer in STA 7 appear to grow at similar rates, but females are larger on average than males at maturity.

- Giant stargazer in STA 7 seem to grow at a slower rate and be larger on average at maturity than fish of the same sex in other areas around the South Island. From the strength of the apparent differences in growth between areas for fish of the same sex, giant stargazer around the South Island may form multiple biological stocks.

- Although the fits of all models to the data are acceptable, the fits of the multiplicative models are preferred. Using the multiplicative model for future modelling of growth for this species is suggested, although alternative error structures should continue to be investigated.

- Refitting the von Bertalanffy models using a statistically more stable parameterisation of the von Bertalanffy model to weighted length-at-age data, and comparing these results with the results presented in this paper, may be useful.

- Developing a quantitative stock assessment model of giant stargazer around the South Island requires properly addressing some of the basic scientific questions and issues raised in this paper, in particular validating the otoliths interpretation protocol.

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Table 1: Reported landings (t) of giant stargazer by QMA and fishing year from 1986–87 to 2001–02 (Annala et al. 2003). The TACC in STA 7 was increased in 1990–91 under the conditions of the AMP.

Fishing year	STA 1		STA 2		STA 3	
	Landings	TACC	Landings	TACC	Landings	TACC
1986-87	10	20	31	30	644	560
1987-88	3	20	46	33	783	581
1988-89	3	20	41	37	675	591
1989-90	9	21	53	37	747	703
1990-91	8	21	125	37	674	734
1991-92	18	50	105	100	756	900
1992-93	19	50	115	101	811	901
1993-94	8	50	73	101	871	902
1994-95	10	50	74	101	829	902
1995-96	17	50	69	101	876	902
1996-97	22	50	77	101	817	902
1997-98	29	21	54	38	667	902
1998-99	27	21	46	38	641	902
1999-00	36	21	42	38	719	902
2000-01	26	21	45	38	960	902
2001-02	34	21	58	38	815	902

Fishing year	STA 4		STA 5		STA 7	
	Landings	TACC	Landings	TACC	Landings	TACC
1986-87	72	2000	738	1060	487	450
1987-88	110	2005	886	1144	505	493
1988-89	134	2005	1215	1173	520	499
1989-90	218	2009	1150	1175	585	525
1990-91	790	2014	1061	1239	762	528
1991-92	366	2014	1056	1500	920	700
1992-93	231	2014	1247	1500	861	702
1993-94	113	2014	1327	1500	715	702
1994-95	223	2014	1216	1525	730	702
1995-96	259	2014	1159	1525	877	702
1996-97	149	2014	977	1525	983	702
1997-98	263	2014	544	1264	564	702
1998-99	137	2014	1145	1264	949	702
1999-00	161	2014	1327	1264	1184	702
2000-01	233	2014	1439	1264	1440	702
2001-02	391	2158	1137	1264	800	702

Fishing year	STA 8		STA 10		Total	
	Landings	TACC	Landings	TACC	Landings	TACC
1986-87	7	20	0	10	1990	4150
1987-88	5	20	0	10	2338	4306
1988-89	5	20	0	10	2593	4355
1989-90	1	22	0	10	2763	4502
1990-91	6	22	0	10	3426	4605
1991-92	18	22	0	10	3239	5296
1992-93	5	22	0	10	3289	5300
1993-94	4	50	0	10	3111	5329
1994-95	7	50	0	10	3089	5354
1995-96	4	50	0	10	3261	5354
1996-97	10	50	0	10	3034	5354
1997-98	10	22	0	10	2132	4973
1998-99	2	22	0	10	2946	4973
1999-00	3	22	0	10	3472	4973
2000-01	4	22	0	10	4146	4973
2001-02	3	22	0	10	3238	5117

Table 2: Giant stargazer catch, numbers measured, and numbers of otoliths collected during WCSI trawl surveys by RV *Kaharoa*, 1992–2000. TBGB, Tasman Bay–Golden Bay; WCSI, west coast.

Survey	Area	Calendar year	Survey catch (kg)	Fish measured	Otoliths collected	Otoliths prepared and read	Reference
KAH9204	TBGB	1992	18	20	0	0	Drummond & Stevenson (1995a)
	WCSI		4678.8	1342	386	373	
	All		4696.8	1362	386	373	
KAH9404	TBGB	1994	11.3	14	15	14	Drummond & Stevenson (1995b)
	WCSI		5899.8	1466	440	440	
	All		5911.1	1480	455	454	
KAH9504	TBGB	1995	14.7	18	18	18	Drummond & Stevenson (1996)
	WCSI		4140.1	1247	320	310	
	All		4154.8	1265	338	328	
KAH9701	TBGB	1997	38.9	63	19	19	Stevenson (1998)
	WCSI		3203.5	984	341	338	
	All		3242.4	1047	360	357	
KAH0004	TBGB	2000	26.5	34	19	19	Stevenson (2002)
	WCSI		1593.3	643	361	356	
	All		1619.8	677	380	375	
All	TBGB	-	109.4	149	71	70	The trawl survey series, except for KAH0004, was reviewed by Stevenson & Hanchet (2000)
	WCSI		19515.5	5682	1848	1817	
	All		19624.9	5831	1919	1887	

Table 3: Five-point "readability" score used in otolith readings.

Readability score	Description
1	Otolith very easy to read; excellent contrast between opaque and translucent zones; ± 0 between subsequent counts of this otolith
2	Otolith easy to read; good contrast between opaque and translucent zones, but not as marked as in 1; ± 1 between subsequent counts of this otolith
3	Otolith readable; less contrast between opaque and translucent zones than in 2, but alternating zones still apparent; ± 2 between subsequent counts of this otolith
4	Otolith readable with difficulty; poor contrast between opaque and translucent zones; ± 3 or more between subsequent counts of this otolith
5	Otolith unreadable

Table 4: Three-point "marginal state" score used in otolith readings.

Readability score	Description
Narrow	Last translucent zone present deemed to be fully formed; a very thin, hairline layer of opaque material is present outside the last translucent zone
Medium	Last translucent zone present deemed to be fully formed; a thicker layer of opaque material, not very thin or hairline in width, is present outside the last translucent zone; some new translucent material may be present outside the thicker layer of opaque material, but generally does not span the entire margin of the otolith
Wide	Last translucent zone present deemed not to be fully formed; a thick layer of opaque material is laid down on top of the last fully formed translucent zone, with new translucent material present outside the opaque layer, spanning the entire margin of the otolith

Table 5: Summary of final WCSI dataset.

Dataset	Survey	Males	Females	Unsexed	Sex All
All prepared otoliths	KAH9204	162	205	6	373
	KAH9404	218	234	2	454
	KAH9504	154	174	0	328
	KAH9701	168	189	0	357
	KAH0004	175	200	0	375
	All	877	1 002	8	1 887
Final WCSI dataset	KAH9204	153	193	0	346
	KAH9404	210	221	0	431
	KAH9504	146	163	0	309
	KAH9701	158	181	0	339
	KAH0004	171	188	0	359
	All	838	946	0	1 784

Table 6: Summary of combined ECSI, SCSI, and WCSI dataset.

Area	Source	Survey	Males	Females	Unsexed	Sex All
ECSI	Manning (unpublished data)	KAH9704	90	116	0	206
		KAH9809	138	156	0	294
		KAH9917	110	151	0	261
		KAH0014	78	96	0	174
		All	416	519	0	935
SCSI	Sutton (unpublished data)	TAN9301	107	146	0	253
		TAN9402	226	286	0	512
		TAN9502	209	261	0	470
		TAN9604	120	173	0	293
		All	662	866	0	1 528
WCSI	Final WCSI dataset	All	838	946	0	1 784
All	-	-	1 916	2 331	0	4 247

Table 7: Summary of all likelihood ratio tests carried out. Descriptions of the full and reduced models, number of parameters in each model, and linear constraints for each test are provided. The null hypothesis for all tests is that the parameters satisfy the set of linear constraints, ω, such that the full and reduced models are equivalent. The alternative hypothesis for all tests is that the parameters satisfy no such linear constraints, such that the full and reduced models are not equivalent. M, male; F, female.

Description			Number of parameters		Error structure	Linear constraints
Test	Full model	Reduced model	Full model	Reduced model		
Sex effect within the final WCSI dataset	Separate von Bertalanffy parameters assumed for each sex	Separate von Bertalanffy parameters not assumed for each sex	7	4	Additive	$\omega = \left\{ \begin{array}{c} L_{\infty,M} = L_{\infty,F} \\ k_M = k_F \\ t_{0,M} = t_{0,F} \end{array} \right\}$
(as above)	*(as above)*	*(as above)*	*(as above)*	*(as above)*	Multiplicative	*(as above)*
Survey effect within the final WCSI dataset	Separate von Bertalanffy parameters assumed for each sex from each survey	Separate von Bertalanffy parameters assumed for each sex only	31	7	Additive	$\omega = \left\{ \begin{array}{c} L_{\infty,(M, KAH9204)} = L_{\infty,(M, KAH9404)} = L_{\infty,(M, KAH9504)} = L_{\infty,(M, KAH9701)} = L_{\infty,(M, KAH0004)} \\ L_{\infty,(F, KAH9204)} = L_{\infty,(F, KAH9404)} = L_{\infty,(F, KAH9504)} = L_{\infty,(F, KAH9701)} = L_{\infty,(F, KAH0004)} \\ k_{(M, KAH9204)} = k_{(M, KAH9404)} = k_{(M, KAH9504)} = k_{(M, KAH9701)} = k_{(M, KAH0004)} \\ k_{(F, KAH9204)} = k_{(F, KAH9404)} = k_{(F, KAH9504)} = k_{(F, KAH9701)} = k_{(F, KAH0004)} \\ t_{0,(M, KAH9204)} = t_{0,(M, KAH9404)} = t_{0,(M, KAH9504)} = t_{0,(M, KAH9701)} = t_{0,(M, KAH0004)} \\ t_{0,(F, KAH9204)} = t_{0,(F, KAH9404)} = t_{0,(F, KAH9504)} = t_{0,(F, KAH9701)} = t_{0,(F, KAH0004)} \end{array} \right\}$
(as above)	*(as above)*	*(as above)*	*(as above)*	*(as above)*	Multiplicative	*(as above)*
Area effect within the combined ECSI, SCSI, and WCSI dataset	Separate von Bertalanffy parameters assumed for each sex from each area	Separate von Bertalanffy parameters assumed for each sex only	19	7	Additive	$\omega = \left\{ \begin{array}{c} L_{\infty,(M, ECSI)} = L_{\infty,(M, SCSI)} = L_{\infty,(M, WCSI)} \\ L_{\infty,(F, ECSI)} = L_{\infty,(F, SCSI)} = L_{\infty,(F, WCSI)} \\ k_{(M, ECSI)} = k_{(M, SCSI)} = k_{(M, WCSI)} \\ k_{(F, ECSI)} = k_{(F, SCSI)} = k_{(F, WCSI)} \\ t_{0,(M, ECSI)} = t_{0,(M, SCSI)} = t_{0,(M, WCSI)} \\ t_{0,(F, ECSI)} = t_{0,(F, SCSI)} = t_{0,(F, WCSI)} \end{array} \right\}$
(as above)	*(as above)*	*(as above)*	*(as above)*	*(as above)*	Multiplicative	*(as above)*

Table 8: All otoliths read by survey and readability score.

Survey	Readability score					
	"1"	"2"	"3"	"4"	"5"	Total
KAH9204	3	45	226	79	20	373
KAH9404	18	102	220	93	21	454
KAH9504	11	60	177	62	18	328
KAH9701	16	85	176	62	18	357
KAH0004	12	86	162	99	16	375
Total	60	378	961	395	93	1 887

Table 9: All otoliths read by survey and margin state.

Survey	Margin state				
	"Narrow"	"Medium"	"Wide"	No margin stage assigned	Total
KAH9204	163	68	55	89	375
KAH9404	106	73	82	112	373
KAH9504	164	157	44	89	454
KAH9701	157	68	32	71	328
KAH0004	122	78	67	90	357
Total	712	444	280	451	1 887

Table 10: Precision of results for within and between reader tests.

Precision metric	Within reader test	Between reader test
c.v. (%)	3.50	12.35
IAPE (%)	2.47	8.73

Table 11: Summary of smallest and largest and youngest and oldest fish in the final WCSI dataset by sex.

Sex	Attribute	Length (cm)	Estimated age (years)	Survey
Male	Smallest	12	0.76	KAH0004
	Largest	73	12.75	KAH9701
	Youngest	16	0.72	KAH9404
	Oldest	67	18.77	KAH9404
Female	Smallest	12	0.76	KAH9504
	Largest	83	15.76	KAH9504
	Youngest	20	0.73	KAH9504
	Oldest	74	25.78	KAH9404

Table 12: Summary of sample length-at-age by sex for all distinct age classes in the final WCSI dataset.

Age class	Males					Females				
	n	Max.	Min.	Sample Mean	Sample SD	*n*	Max.	Min.	Sample Mean	Sample SD
0	10	12	20	17.10	2.96	11	12	20	16.55	2.38
1	51	16	31	23.55	3.04	48	18	32	24.65	3.38
2	63	23	38	29.51	3.39	71	23	38	30.73	3.46
3	77	27	49	35.74	3.71	83	25	46	36.02	4.60
4	94	29	54	39.31	4.70	87	31	60	41.74	4.91
5	90	34	58	44.90	5.42	101	32	66	47.20	6.29
6	101	37	66	48.32	5.73	110	35	70	54.15	6.51
7	80	36	67	51.04	5.76	96	39	73	58.53	6.43
8	73	41	69	54.99	5.91	89	44	74	59.70	6.39
9	65	40	68	57.15	5.84	60	49	76	63.80	6.36
10	47	43	69	58.02	5.69	48	46	77	65.23	6.07
11	32	53	70	61.19	5.01	28	55	77	66.75	5.88
12	18	54	73	61.33	4.31	25	59	80	70.80	4.97
13	10	54	69	60.30	4.32	29	59	77	70.03	4.92
14	10	57	68	64.80	3.43	22	59	78	71.05	4.70
15	8	61	68	64.63	2.20	14	61	83	72.79	6.58
16	4	62	67	64.50	2.38	12	64	81	74.58	4.34
17	3	64	73	67.67	4.73	2	67	80	73.50	9.19
18	2	67	70	68.50	2.12	7	67	77	72.57	3.69
19	0	-	-	-	-	2	72	75	73.50	2.12
20	0	-	-	-	-	0	-	-	-	-
21	0	-	-	-	-	0	-	-	-	-
22	0	-	-	-	-	0	-	-	-	-
23	0	-	-	-	-	0	-	-	-	-
24	0	-	-	-	-	0	-	-	-	-
25	0	-	-	-	-	1	74	74	74.00	-

Age class	All fish				
	n	Max.	Min.	Sample Mean	Sample SD
0	21	12	20	16.81	2.62
1	99	16	32	24.08	3.24
2	134	23	38	30.16	3.47
3	160	25	49	35.89	4.18
4	181	29	60	40.48	4.94
5	191	32	66	46.12	5.99
6	211	35	70	51.36	6.79
7	176	36	73	55.13	7.17
8	162	41	74	57.57	6.59
9	125	40	76	60.34	6.93
10	95	43	77	61.66	6.89
11	60	53	77	63.78	6.07
12	43	54	80	66.84	6.63
13	39	54	77	67.54	6.39
14	32	57	78	69.09	5.20
15	22	61	83	69.82	6.67
16	16	62	81	72.06	5.94
17	5	64	80	70.00	6.52
18	9	67	77	71.67	3.74
19	2	72	75	73.50	2.12
20	0	-	-	-	-
21	0	-	-	-	-
22	0	-	-	-	-
23	0	-	-	-	-
24	0	-	-	-	-
25	1	74	74	74.00	-

Table 13: Results of fitting the additive von Bertalanffy models to groups within the final WCSI and combined ECSI, SCSI, and WCSI datasets. Non-linear least-squares estimates and analytical and bootstrapped 95% confidence intervals are provided for each parameter.

Group	n	RSS	L_∞			k			t_0		
			Estimate	95% CI (analytical)	95% CI (bootstrap)	Estimate	95% CI (analytical)	95% CI (bootstrap)	Estimate	95% CI (analytical)	95% CI (bootstrap)
Final WCSI dataset by sex											
Male	838	21119.96	71.91	(69.02, 74.81)	(69.75, 75.45)	0.1442	(0.1276, 0.1609)	(0.1311, 0.1618)	-0.983	(-1.280, -0.687)	(-1.204, -0.733)
Female	946	30945.04	81.16	(78.61, 83.71)	(79.23, 83.44)	0.1443	(0.1312, 0.1573)	(0.1336, 0.1551)	-0.570	(-0.804, -0.336)	(-0.753, -0.398)
All	1784	62355.08	78.85	(76.55, 81.14)	(76.84, 80.96)	0.1354	(0.1246, 0.1463)	(0.1269, 0.1451)	-0.847	(-1.055, -0.639)	(-0.993, -0.704)
Final WCSI dataset by sex and survey											
Males											
KAH9204	153	3862.08	70.65	(62.55, 78.75)	(65.38, 77.63)	0.1384	(0.0888, 0.1881)	(0.1030, 0.1834)	-1.105	(-2.246, 0.036)	(-2.200, -0.275)
KAH9404	210	5756.80	72.07	(66.75, 77.39)	(68.41, 76.47)	0.1452	(0.1138, 0.1765)	(0.1207, 0.1721)	-0.808	(-1.362, -0.255)	(-1.251, -0.445)
KAH9504	146	3369.43	74.00	(65.04; 82.96)	(68.76, 83.78)	0.1264	(0.0863, 0.1665)	(0.0946, 0.1577)	-1.235	(-2.042, -0.427)	(-1.892, -0.681)
KAH9701	158	3361.18	77.20	(69.15, 85.25)	(71.24, 85.98)	0.1285	(0.0939, 0.1631)	(0.0999, 0.1600)	-1.345	(-1.962, -0.729)	(-1.878, -0.920)
KAH0004	171	3359.70	67.74	(63.60, 71.89)	(64.25, 71.90)	0.1882	(0.1515, 0.2248)	(0.1611, 0.2199)	-0.363	(-0.821, 0.095)	(-0.669, -0.037)
All males	838	21119.96	71.91	(69.02, 74.81)	(69.76, 74.20)	0.1442	(0.1276, 0.1609)	(0.1318, 0.1576)	-0.983	(-1.28,0 -0.687)	(-1.203, -0.774)
Females											
KAH9204	193	8145.78	77.60	(72.01, 83.20)	(73.02, 82.64)	0.1575	(0.1180, 0.1970)	(0.1277, 0.2077)	0.060	(-0.728, 0.848)	(-0.579, 0.947)
KAH9404	221	5419.33	80.22	(76.24, 84.20)	(77.16, 83.68)	0.1555	(0.1327, 0.1783)	(0.1382, 0.1752)	-0.375	(-0.727, -0.023)	(-0.633, -0.095)
KAH9504	163	6748.28	89.69	(77.10, 102.29)	(81.5, 101.66)	0.1160	(0.0787, 0.1534)	(0.0885, 0.1464)	-0.929	(-1.629, -0.228)	(-1.366, -0.534)
KAH9701	181	4045.66	88.25	(80.86, 95.64)	(81.8, 97.88)	0.1167	(0.0922, 0.1413)	(0.0919, 0.1410)	-1.205	(-1.728, -0.681)	(-1.714, -0.814)
KAH0004	188	4446.16	78.40	(74.62, 82.18)	(75.95, 81.35)	0.1755	(0.1489, 0.2021)	(0.1560, 0.1990)	0.051	(-0.319, 0.422)	(-0.223, 0.393)
All females	946	30945.04	81.16	(78.61, 83.71)	(79.12, 83.34)	0.1443	(0.1312, 0.1573)	(0.1343, 0.1550)	-0.570	(-0.804, -0.336)	(-0.738, -0.395)
Combined ECSI, SCSI, and WCSI dataset by sex and area											
Males											
ECSI	416	9050.16	57.74	(55.08, 60.40)	(55.39, 60.49)	0.2156	(0.1833, 0.2480)	(0.1850, 0.2461)	-1.422	(-1.743, -1.102)	(-1.759, -1.164)
SCSI	662	6504.81	60.92	(59.51, 62.34)	(59.13, 63.25)	0.1801	(0.1604, 0.1998)	(0.1518, 0.2067)	-1.277	(-1.743, -0.812)	(-2.031, -0.789)
WCSI	838	21119.97	71.91	(69.02, 74.81)	(69.86, 74.39)	0.1442	(0.1276, 0.1609)	(0.1312, 0.1570)	-0.983	(-1.280, -0.687)	(-1.208, -0.770)
All males	1916	43137.17	66.04	(64.51, 67.57)	(64.59, 67.51)	0.1514	(0.1402, 0.1626)	(0.1421, 0.1622)	-1.653	(-1.867, -1.438)	(-1.845, -1.461)
Females											
ECSI	519	15750.29	71.35	(67.03, 75.67)	(66.85, 75.89)	0.1647	(0.1377, 0.1918)	(0.1406, 0.1940)	-1.436	(-1.785, -1.087)	(-1.746, -1.125)
SCSI	866	19540.32	72.95	(71.44, 74.46)	(71.64, 74.35)	0.1706	(0.1553, 0.1859)	(0.1583, 0.1849)	-0.208	(-0.557, 0.141)	(-0.466, 0.075)
WCSI	946	30945.04	81.16	(78.61, 83.71)	(79.16, 83.53)	0.1443	(0.1312, 0.1573)	(0.1338, 0.1546)	-0.570	(-0.804, -0.336)	(-0.742, -0.401)
All females	2331	74482.15	76.46	(75.05, 77.88)	(75.27, 77.86)	0.1445	(0.1359, 0.1532)	(0.1370, 0.1522)	-1.186	(-1.365, -1.007)	(-1.344, -1.042)

Table 14: Results of fitting the multiplicative von Bertalanffy model to groups within the final WCSI and combined ECSI, SCSI, and WCSI datasets. Non-linear least-squares estimates and analytical and bootstrapped 95% confidence intervals are provided for each parameter.

Group	n	RSS	L_∞			k			t_0		
			Estimate	95% CI (analytical)	95% CI (bootstrap)	Estimate	95% CI (analytical)	95% CI (bootstrap)	Estimate	95% CI (analytical)	95% CI (bootstrap)
Final WCSI dataset by sex											
Male	838	10.4667	73.52	(70.00, 77.05)	(70.73, 76.69)	0.1335	(0.1185, 0.1484)	(0.1199, 0.1492)	-1.140	(-1.345, -0.935)	(-1.375, -0.894)
Female	946	12.9814	85.91	(82.08, 89.75)	(82.97, 89.25)	0.1208	(0.1091, 0.1325)	(0.1106, 0.1316)	-0.949	(-1.116, -0.782)	(-1.129, -0.770)
All	1784	26.5088	81.65	(78.67, 84.63)	(79.29, 84.25)	0.1209	(0.1112, 0.1306)	(0.1120, 0.1296)	-1.089	(-1.231, -0.948)	(-1.246, -0.943)
Final WCSI dataset by sex and survey											
Males											
KAH9204	153	1.8389	71.85	(63.15, 80.54)	(64.47, 80.90)	0.1299	(0.0903, 0.1695)	(0.0953, 0.1865)	-1.257	(-1.991, -0.523)	(-2.241, -0.221)
KAH9404	210	2.9672	73.34	(66.50, 80.18)	(68.76, 78.56)	0.1360	(0.1057, 0.1663)	(0.1140, 0.1641)	-0.928	(-1.337, -0.518)	(-1.334, -0.496)
KAH9504	146	1.7548	79.26	(65.45, 93.07)	(70.88, 93.54)	0.1050	(0.0661, 0.1439)	(0.0763, 0.1405)	-1.637	(-2.348, -0.926)	(-2.252, -0.884)
KAH9701	158	1.4927	75.79	(68.25, 83.34)	(69.37, 85.22)	0.1334	(0.1029, 0.1639)	(0.1025, 0.1693)	-1.266	(-1.639, -0.894)	(-1.825, -0.776)
KAH0004	171	1.5676	69.52	(64.58, 74.45)	(65.54, 74.68)	0.1702	(0.1409, 0.1995)	(0.1427, 0.1980)	-0.571	(-0.834, -0.308)	(-0.853, -0.321)
All males	838	10.4667	73.52	(70.00, 77.05)	(70.75, 76.67)	0.1335	(0.1185, 0.1485)	(0.1201, 0.1481)	-1.140	(-1.345, -0.935)	(-1.376, -0.913)
Females											
KAH9204	193	3.2101	84.68	(75.78, 93.57)	(74.39, 92.96)	0.1161	(0.0880, 0.1442)	(0.0946, 0.1818)	-0.774	(-1.315, -0.233)	(-1.160, 0.595)
KAH9404	221	2.4733	84.55	(78.24, 90.87)	(80.30, 89.74)	0.1313	(0.1095, 0.1532)	(0.1134, 0.1512)	-0.711	(-0.983, -0.439)	(-0.977, -0.413)
KAH9504	163	2.7214	92.30	(77.29, 107.30)	(82.24, 108.96)	0.1072	(0.0743, 0.1402)	(0.0782, 0.1385)	-1.050	(-1.450, -0.650)	(-1.569, -0.613)
KAH9701	181	1.6618	91.28	(81.19, 101.36)	(84.05, 103.05)	0.1063	(0.0817, 0.1308)	(0.0822, 0.1279)	-1.401	(-1.807, -0.996)	(-1.900, -1.028)
KAH0004	188	1.9232	85.01	(78.44, 91.59)	(80.08, 89.99)	0.1344	(0.1116, 0.1571)	(0.1182, 0.1607)	-0.517	(-0.796, -0.238)	(-0.738, -0.094)
All females	946	12.9814	85.91	(82.08, 89.75)	(83.20, 89.13)	0.1208	(0.1091, 0.1325)	(0.1109, 0.1313)	-0.949	(-1.116, -0.782)	(-1.121, -0.777)
Combined ECSI, SCSI, and WCSI dataset by sex and area											
Males											
ECSI	416	7.5307	56.18	(53.01, 59.35)	(53.52, 59.04)	0.2345	(0.1983, 0.2706)	(0.2025, 0.2740)	-1.236	(-1.457, -1.015)	(-1.513, -0.995)
SCSI	662	2.7847	59.89	(58.69, 61.10)	(58.03, 61.05)	0.1963	(0.1809, 0.2116)	(0.1826, 0.2296)	-0.921	(-1.163, -0.678)	(-1.151, -0.374)
WCSI	838	10.4667	73.52	(70.00, 77.05)	(70.69, 77.04)	0.1335	(0.1185, 0.1485)	(0.1188, 0.1480)	-1.140	(-1.345, -0.935)	(-1.390, -0.909)
All males	1916	24.7101	65.86	(64.13, 67.59)	(64.28, 67.61)	0.1515	(0.1408, 0.1621)	(0.1404, 0.1632)	-1.607	(-1.751, -1.464)	(-1.809, -1.426)
Females											
ECSI	519	9.7164	70.91	(65.52, 76.29)	(66.95, 76.52)	0.1652	(0.1366, 0.1938)	(0.1384, 0.1916)	-1.400	(-1.653, -1.146)	(-1.700, -1.153)
SCSI	866	6.2406	74.53	(72.76, 76.30)	(72.77, 76.02)	0.1525	(0.1406, 0.1643)	(0.1423, 0.1684)	-0.603	(-0.830, -0.375)	(-0.834, -0.234)
WCSI	946	12.9814	85.91	(82.08, 89.75)	(83.09, 89.60)	0.1208	(0.1091, 0.1325)	(0.1100, 0.1310)	-0.949	(-1.116, -0.782)	(-1.127, -0.775)
All females	2331	33.3881	78.87	(76.92, 80.81)	(77.27, 80.77)	0.1291	(0.1212, 0.1370)	(0.1206, 0.1371)	-1.441	(-1.569, -1.313)	(-1.628, -1.285)

Table 15: Results of likelihood ratio tests comparing von Bertalanffy models fitted.

(A) Testing for a sex effect within the final WCSI dataset (n = 1784):

Additive models fitted:

Model	Number of parameters	RSS	$\hat{\sigma}^2$	Max. log-likelihood	χ^2	f	p-value
Full model	7	52065.00	29.1844	-5540.669	321.7481	3	$< 2 \times 10^{-16}$
Reduced model	4	62355.08	34.9524	-5701.543			

Multiplicative models fitted:

Model	Number of parameters	RSS	$\hat{\sigma}^2$	Max. log-likelihood	χ^2	f	p-value
Full model	7	23.4481	0.013144	1332.600	218.8723	3	$< 2 \times 10^{-16}$
Reduced model	4	26.5088	0.014859	1223.163			

(B) Testing for a survey effect within the final WCSI dataset (n = 1784):

Additive models fitted:

Model	Number of parameters	RSS	$\hat{\sigma}^2$	Max. log-likelihood	χ^2	f	p-value
Full model	31	48514.40	27.1942	-5477.665	126.0081	24	$< 2 \times 10^{-16}$
Reduced model	7	52065.00	29.1844	-5540.669			

Multiplicative models fitted:

Model	Number of parameters	RSS	$\hat{\sigma}^2$	Max. log-likelihood	χ^2	f	p-value
Full model	31	21.6111	0.012114	1405.373	145.5467	24	$< 2 \times 10^{-16}$
Reduced model	7	23.4481	0.013144	1332.600			

(C) Testing for an area effect within the combined ECSI, SCSI, and WCSI dataset (n = 4247):

Additive models fitted:

Model	Number of parameters	RSS	$\hat{\sigma}^2$	Max. log-likelihood	χ^2	f	p-value
Full model	19	102910.60	24.2314	-12795.20	567.3685	12	$< 2 \times 10^{-16}$
Reduced model	7	117619.30	27.6947	-13078.89			

Multiplicative models fitted:

Model	Number of parameters	RSS	$\hat{\sigma}^2$	Max. log-likelihood	χ^2	f	p-value
Full model	19	49.7204	0.011707	3418.145	661.3395	12	$< 2 \times 10^{-16}$
Reduced model	7	58.0982	0.013680	3087.476			

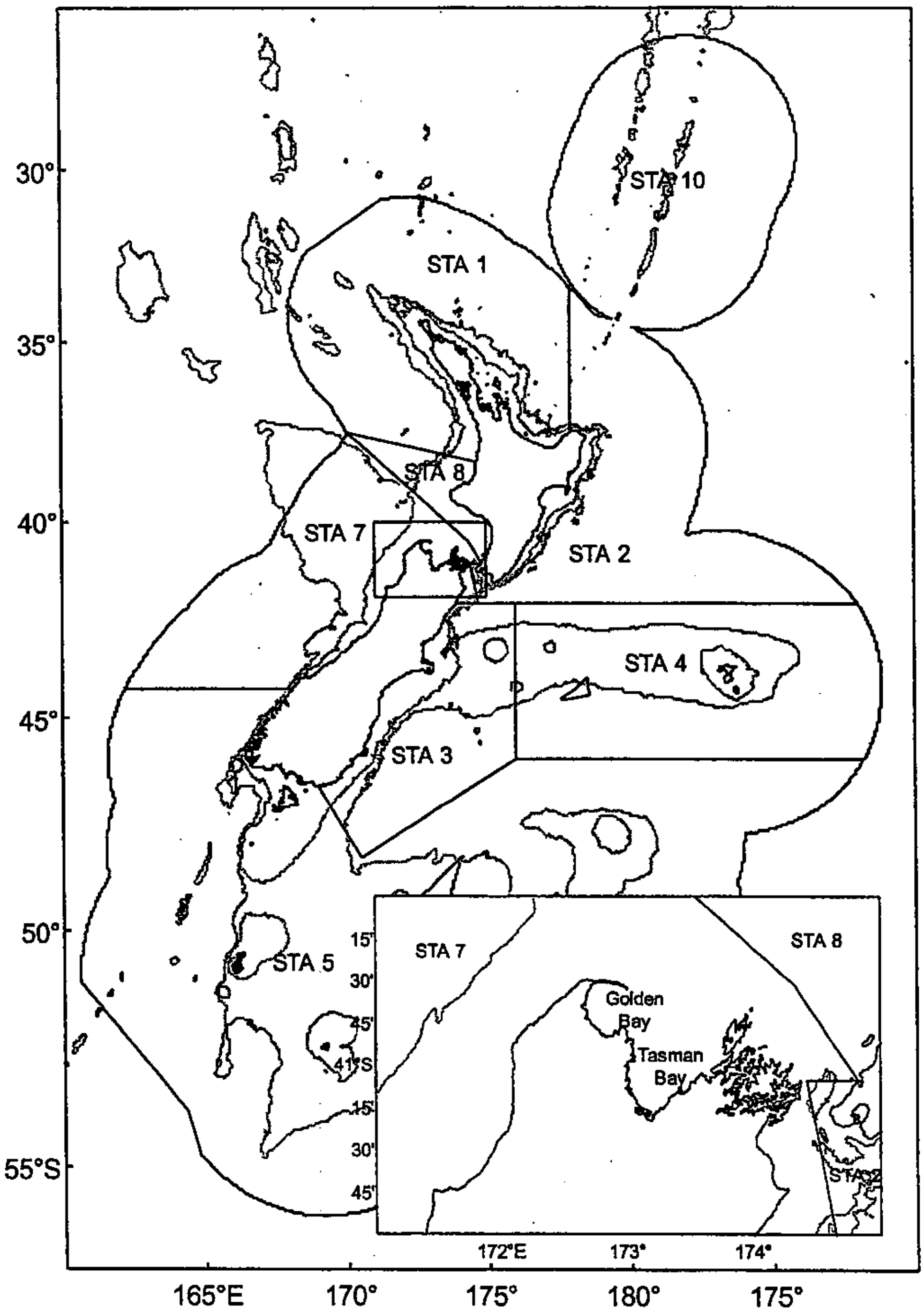

Figure 1: Map of the New Zealand EEZ showing the boundaries of giant stargazer fishstocks. The 250 m and 1000 m depth contours are overlaid in grey. The inset shows the location of Tasman and Golden Bays in fishtock STA 7.

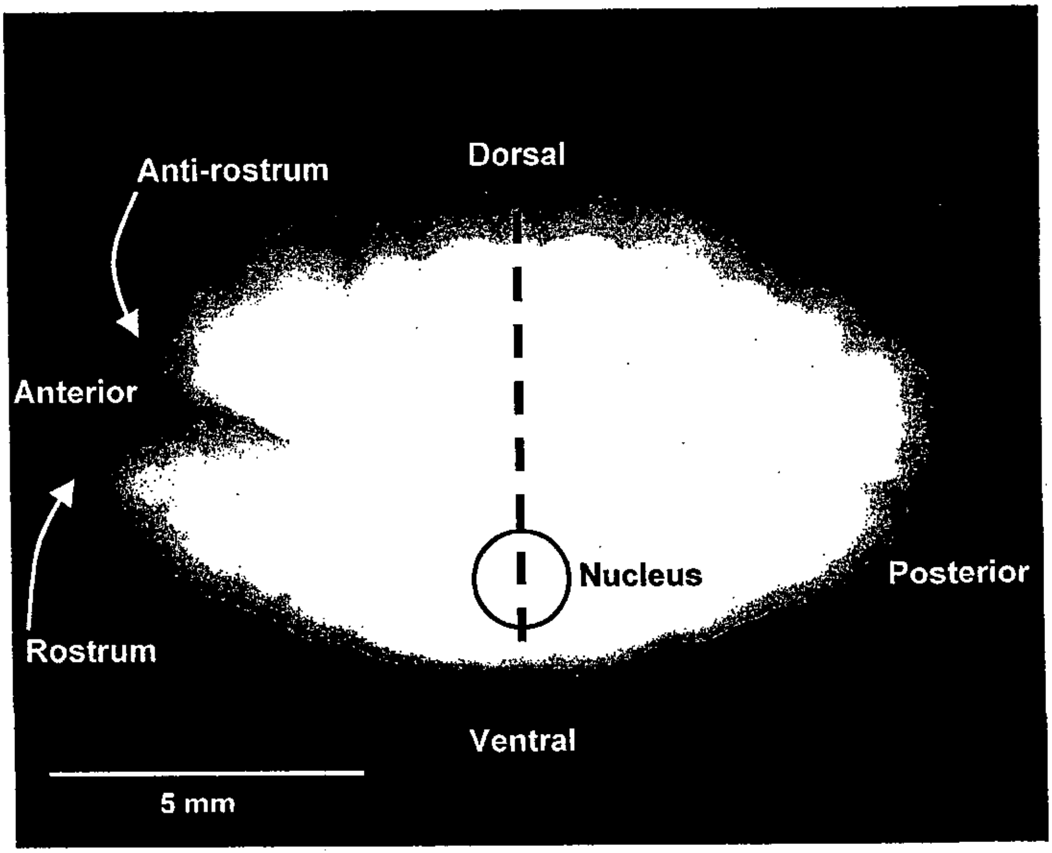

Figure 2: Photomicrograph of the distal surface of a whole giant stargazer left sagittal otolith, taken at x 10 magnification under reflected light. Orientation and some important features are noted. The position and approximate size of the nucleus is indicated by the black circle. The section plane is indicated by the red dashed line. The otolith is from a 69 cm female with an estimated age of 7.73 years (survey KAH9701).

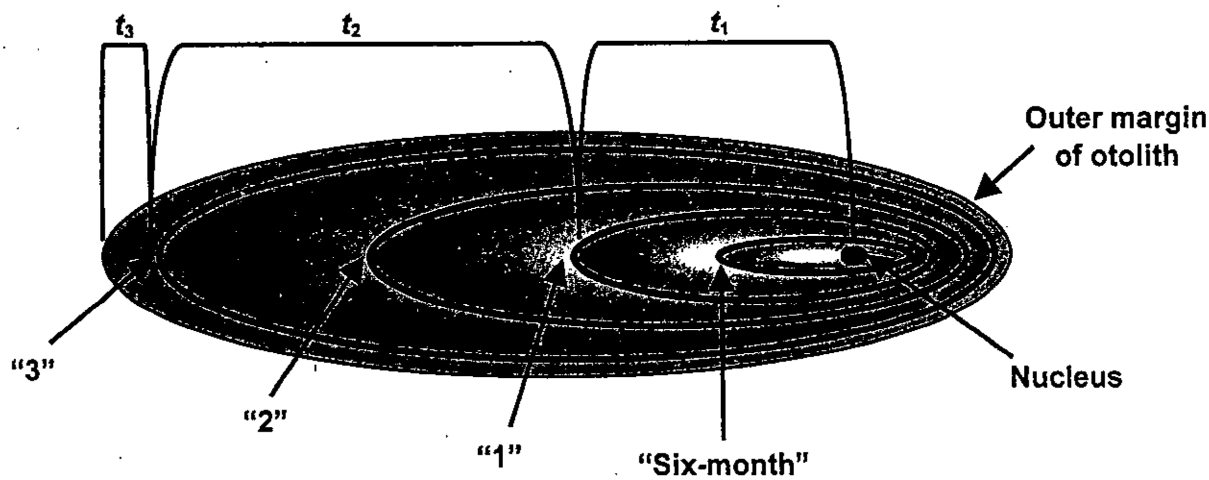

Figure 3: Diagram of a generalised giant stargazer otolith illustrating how translucent zone counts were converted to estimated ages. Four fully completed translucent zones are present in this example and are represented by the thick black lines. Following Sutton (1999), the translucent zone count for this otolith is "3" (the inner-most translucent zone, the "six-month" zone, is not counted). Assuming that the otolith was collected from a fish captured on 1-April, $\hat{a}$, the estimated age derived from this otolith, is $\hat{a} = t_1 + t_2 + t_3 = 1.33 + 3 + 0.42 = 3.75$.

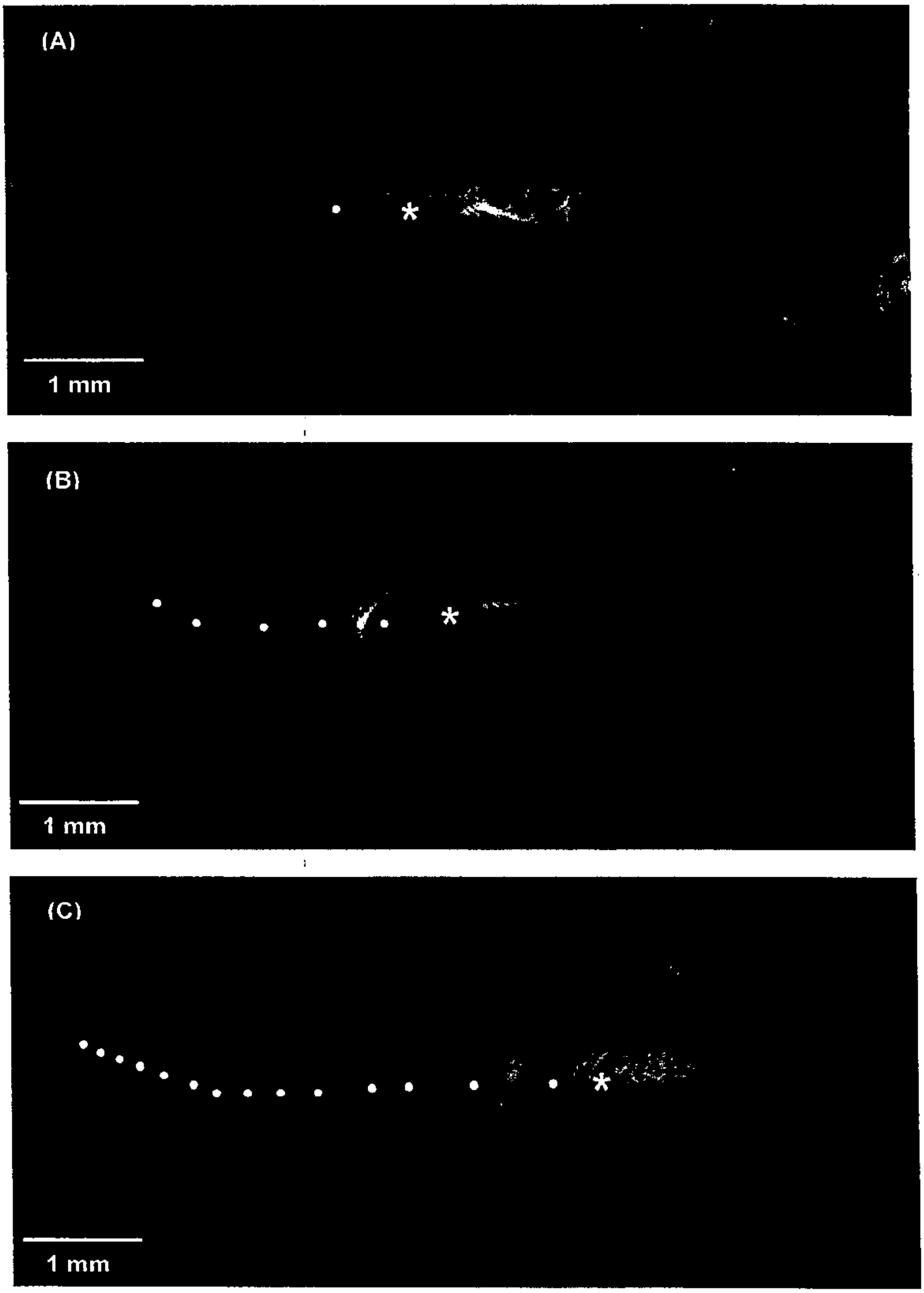

Figure 4: Photomicrographs of prepared giant stargazer otoliths from (A) young, (B) maturing, and (C) mature fish. Photomicrograph (A) is from a 19 cm female collected during KAH9404 (1 translucent zone counted; estimated age = 1.76 years), (B) is from a 60 cm female collected during KAH9404 (5 translucent zones counted; estimated age = 5.74 years), and (C) is from a 71 cm female collected during KAH9204 (14 translucent zones counted; estimated age = 14.76 years). Translucent zones are marked with white dots and the "six-month" zones are marked with white asterixes. All photomicrographs were taken at x 20 magnification under reflected light. All otoliths are orientated with their dorsal edge to the left and proximal surface upwards.

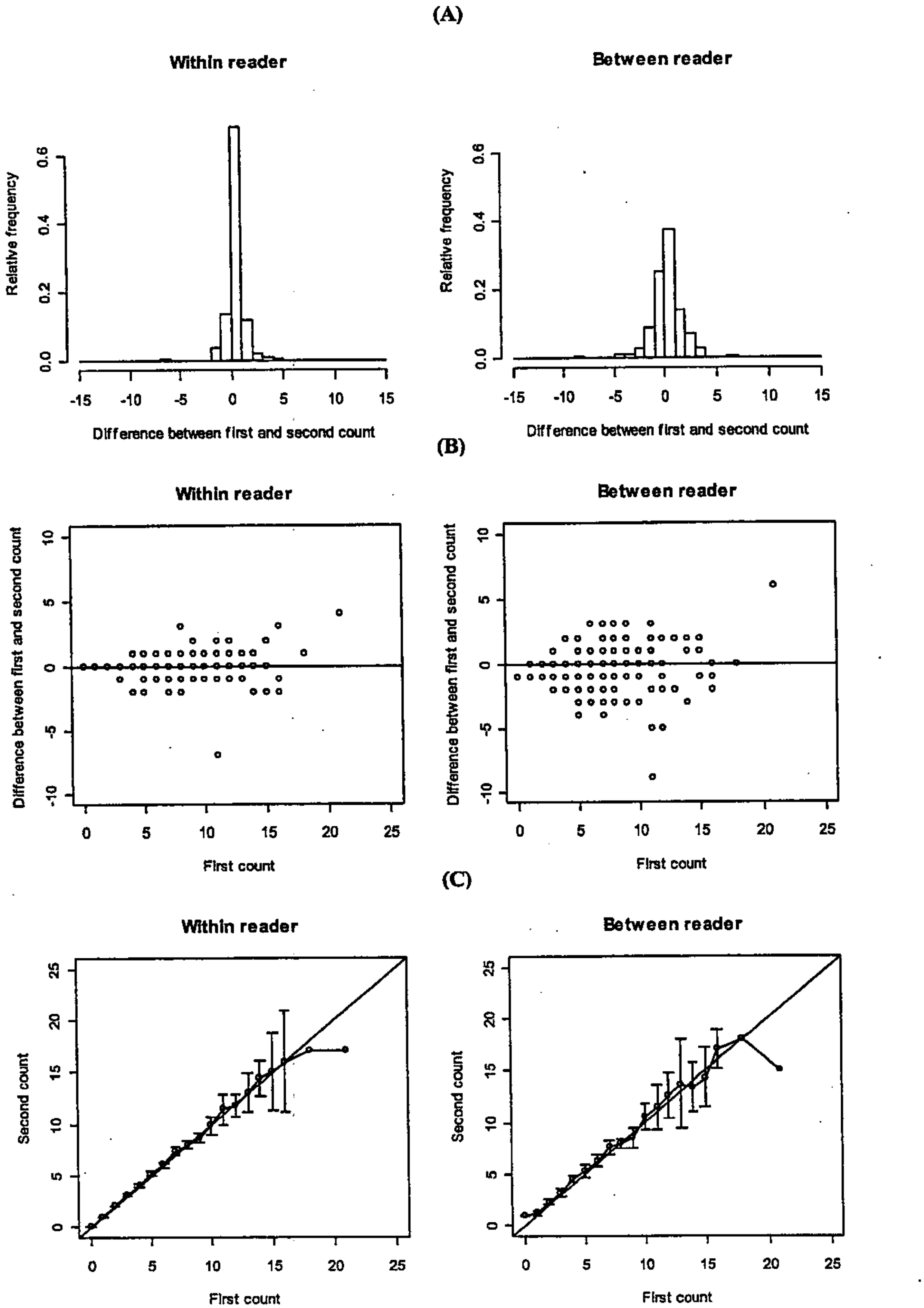

Figure 5: Results of within and between reader comparison tests: (A) histograms of differences between counts; (B) differences between first and second count relative to first count; and (C) bias plots. Note that each plotted point in (B) may represent more than one data point. Note also that each error bar in (C) is the 95% confidence interval about the mean count produced during the second reading for a given count from the first reading.

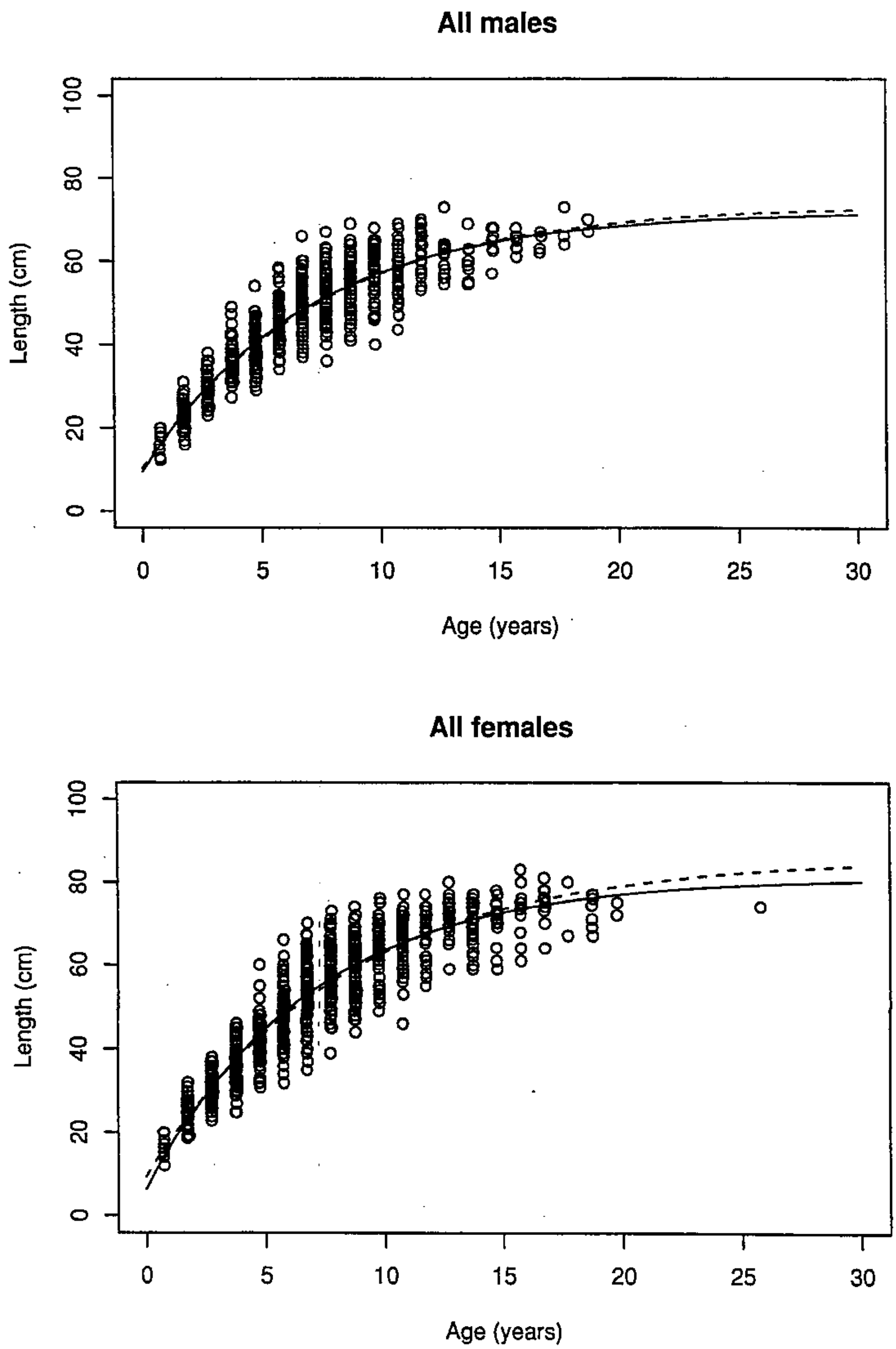

Figure 6: Length-at-age for all WCSI giant stargazer by sex. Fitted von Bertalanffy curves are overlaid: the solid line is the fitted additive model, the dashed line the fitted multiplicative model (see Table 13 and Table 14 for parameter estimates).

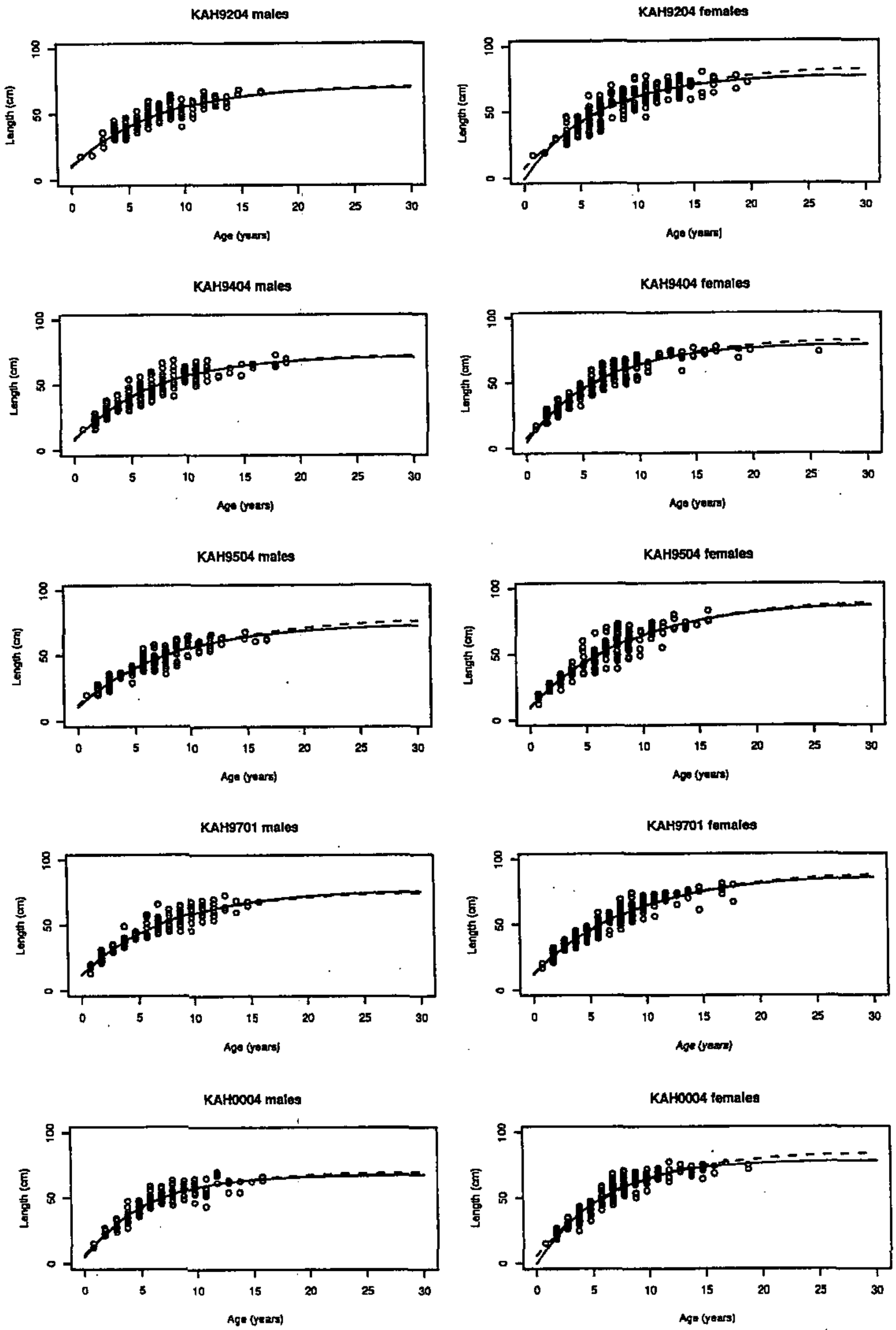

Figure 7: Length-at-age for all WCSI giant stargazer by sex and survey. Fitted von Bertalanffy curves are overlaid: the solid line is the fitted additive model, the dashed line the fitted multiplicative model (see Table 13 and Table 14 for parameter estimates). The sex and survey-specific subsets of data are the "age-length keys" used to convert the scaled length-frequency distributions in Figure 9 to the scaled age-frequency distributions in Figure 10.

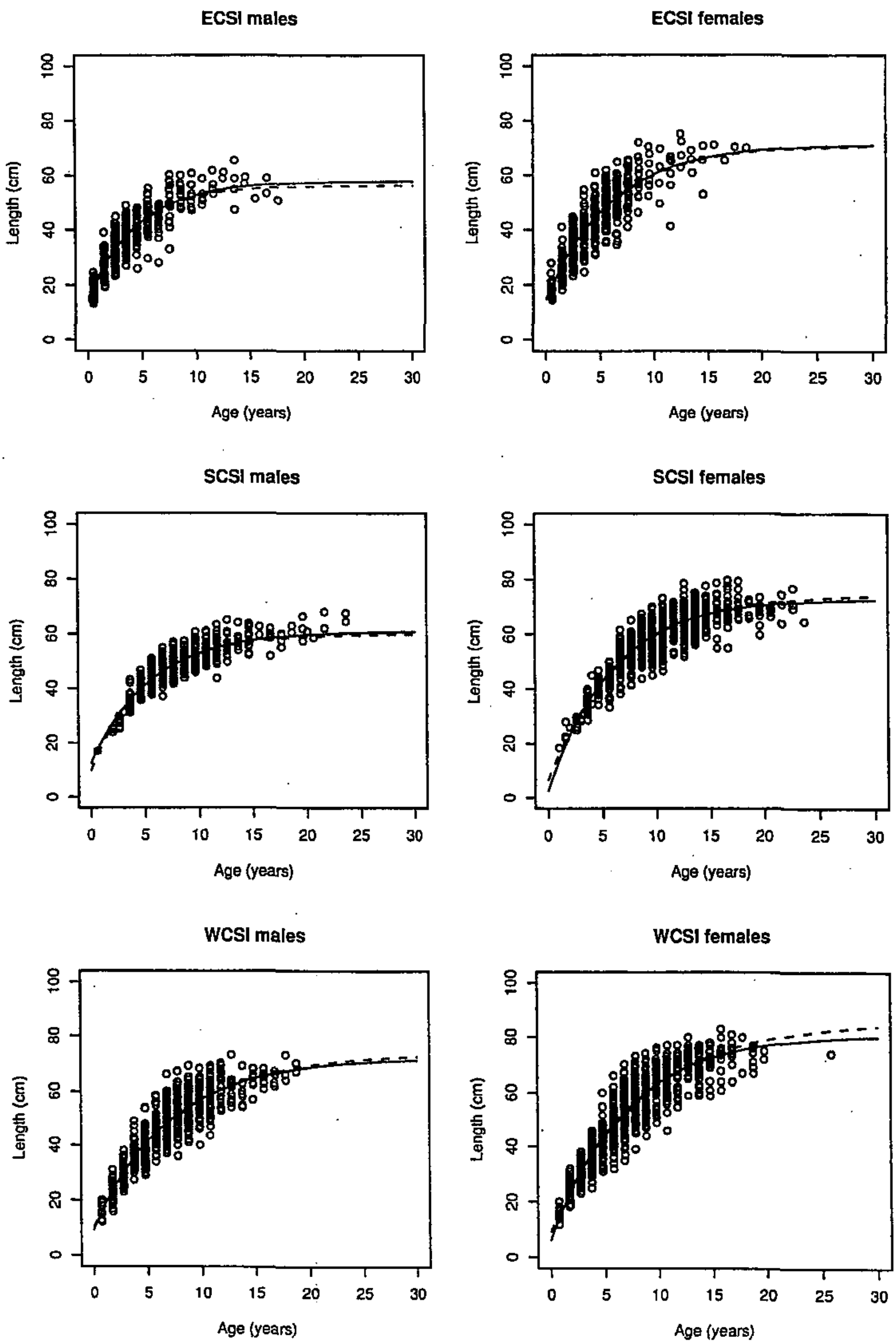

Figure 8: Length-at-age for all ECSI, SCSI, and WCSI giant stargazer by sex and area. Fitted von Bertalanffy curves are overlaid: the solid line is the fitted additive model, the dashed line the fitted multiplicative model (see Table 13 and Table 14 for parameter estimates).

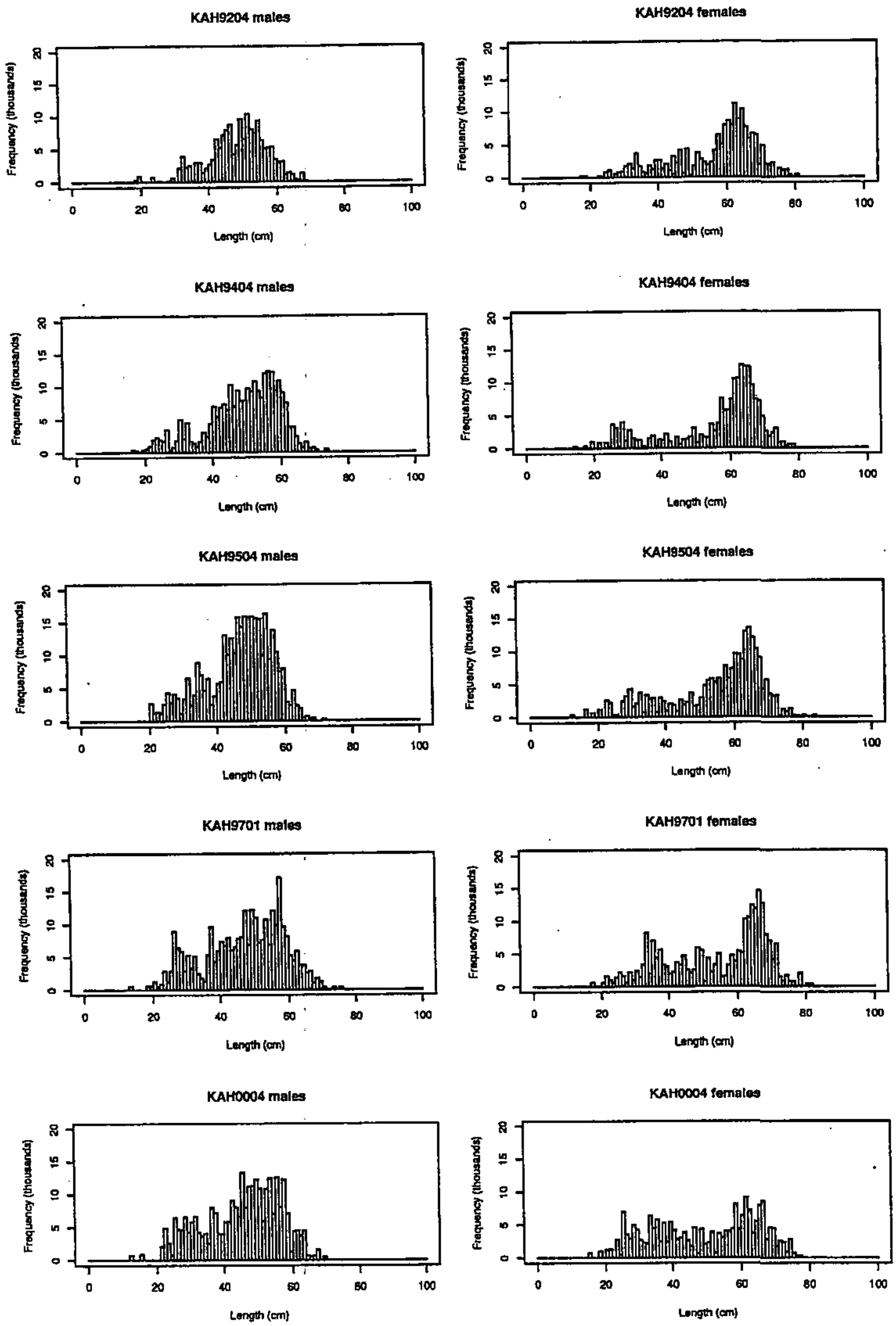

Figure 9: Male and female estimated scaled length-frequency distributions by survey for giant stargazer caught during WCSI trawl survey series, 1992–2000.

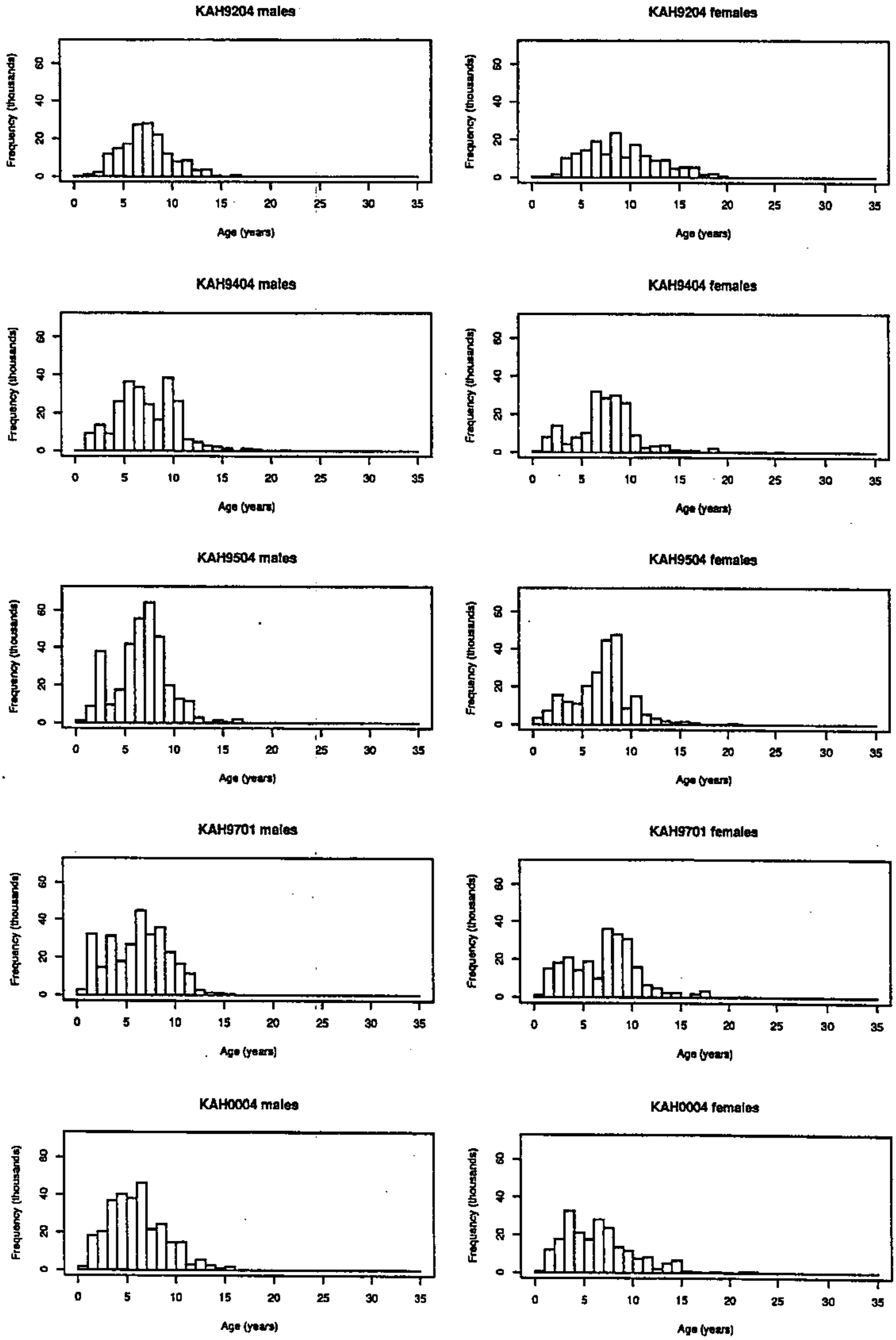

Figure 10: Male and female estimated age-frequency distributions by survey for giant stargazer caught during WCSI trawl survey series, 1992–2000. Estimated age-frequency distributions were calculated by applying the survey-specific age-length keys in Figure 7 to the estimated scaled length-frequency distributions in Figure 9.

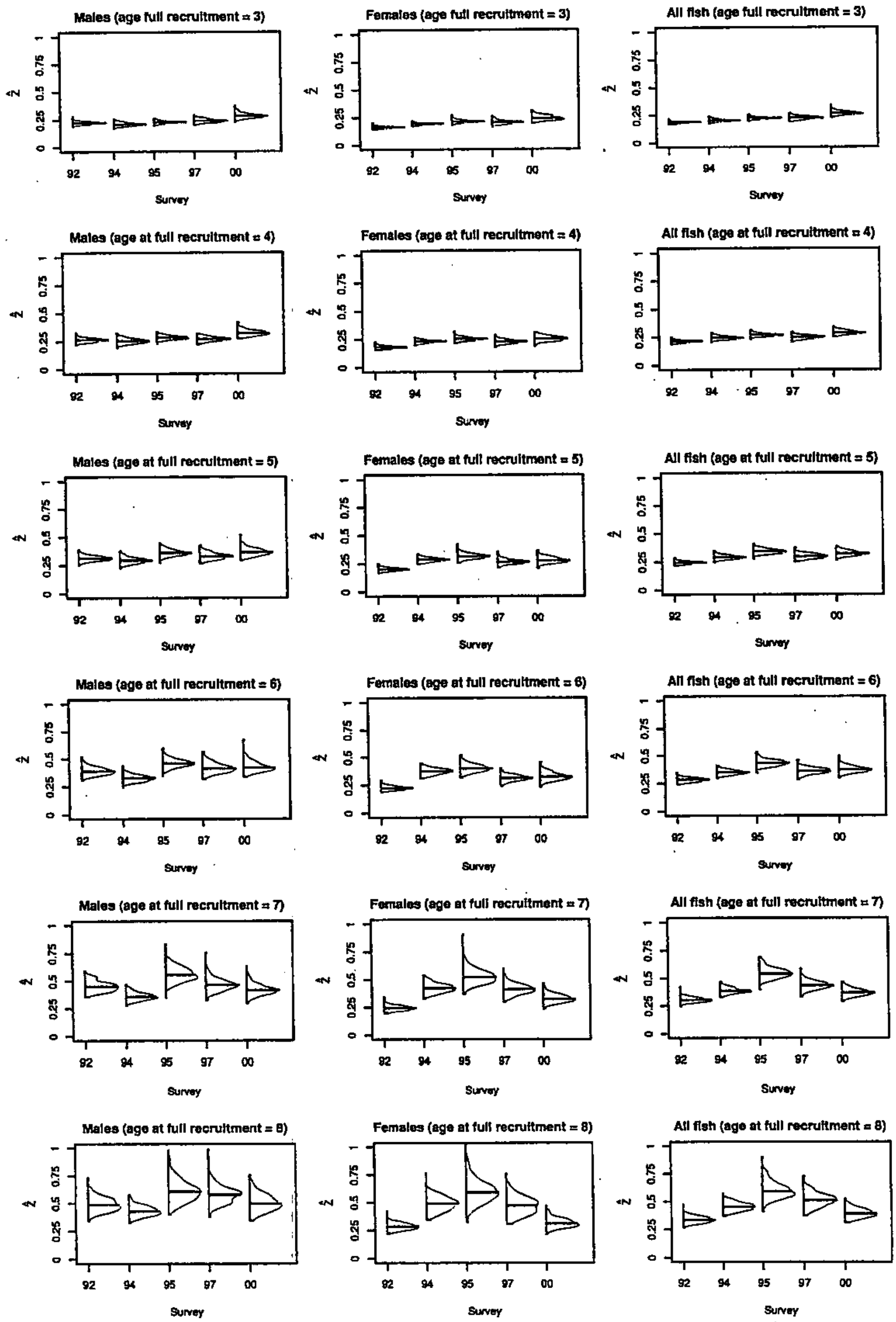

Figure 11: Density plots of bootstrapped $\hat{Z}$ estimates, calculated for male, female, and all fish by survey for WCSI trawl survey series, 1992–2000, assuming age at full recruitment = 3 to 8 (inclusive). 92, KAH9204; 94, KAH9404; 95, KAH9505; 97, KAH9701; and 00, KAH0004.

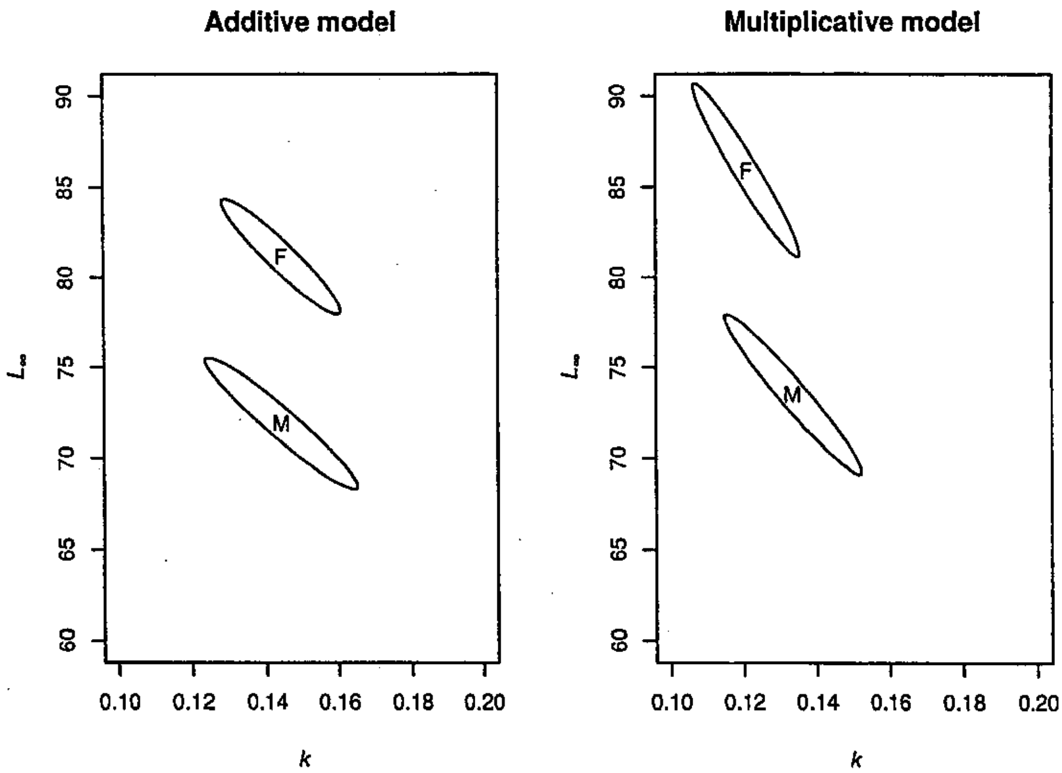

Figure 12: Cross sections of approximate joint 95% confidence regions around L_∞ and k from the fit of the additive and multiplicative models assuming separate parameters by sex to the final WCSI dataset. M, male; F, female.

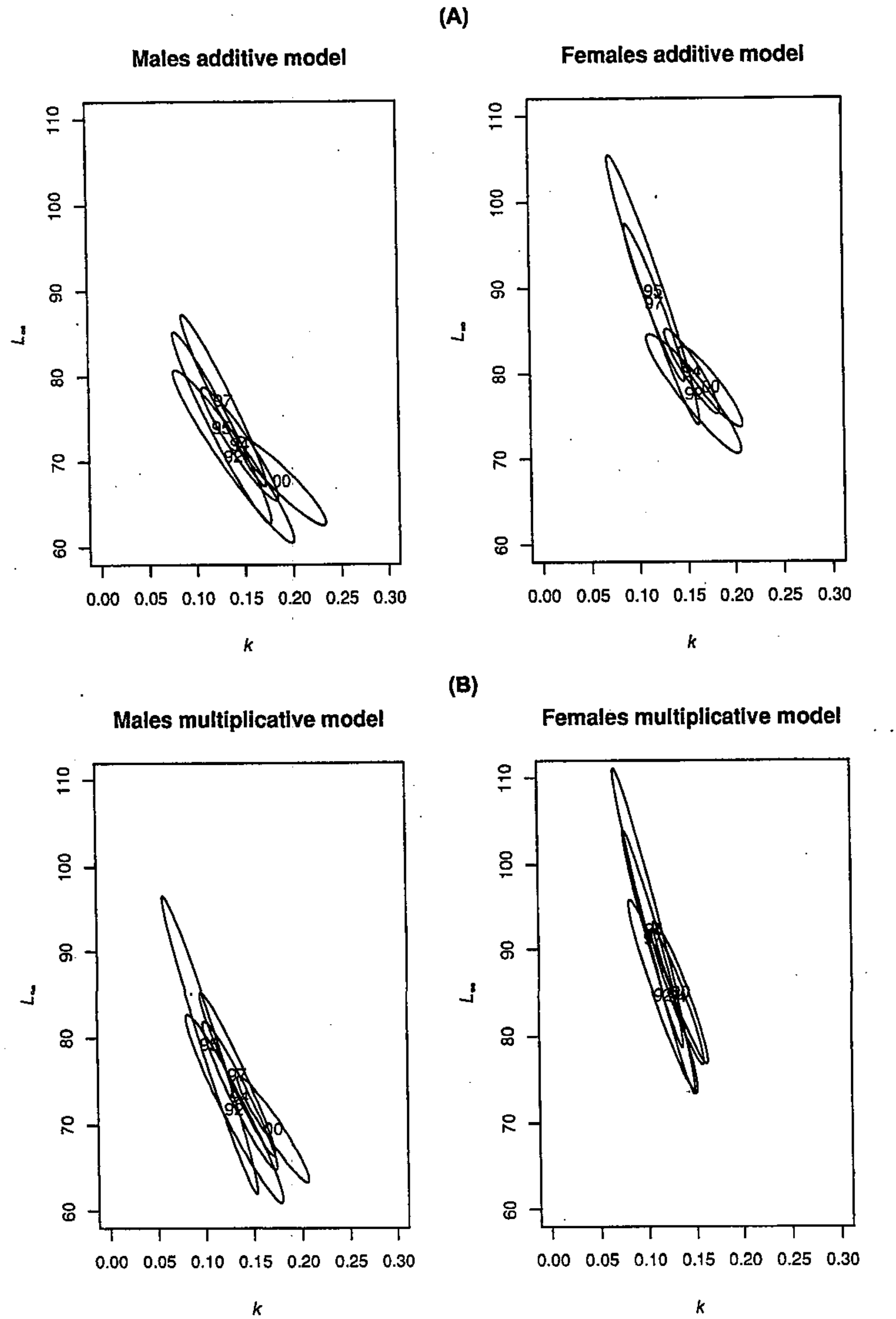

Figure 13: Cross sections of approximate joint 95% confidence regions around L_∞ and k from the fit of the (A) additive and (B) multiplicative models assuming separate parameters by survey and sex to the final WCSI dataset. 92 , KAH9204; 94, KAH9404; 95, KAH9505; 97, KAH9701; and 00, KAH0004.

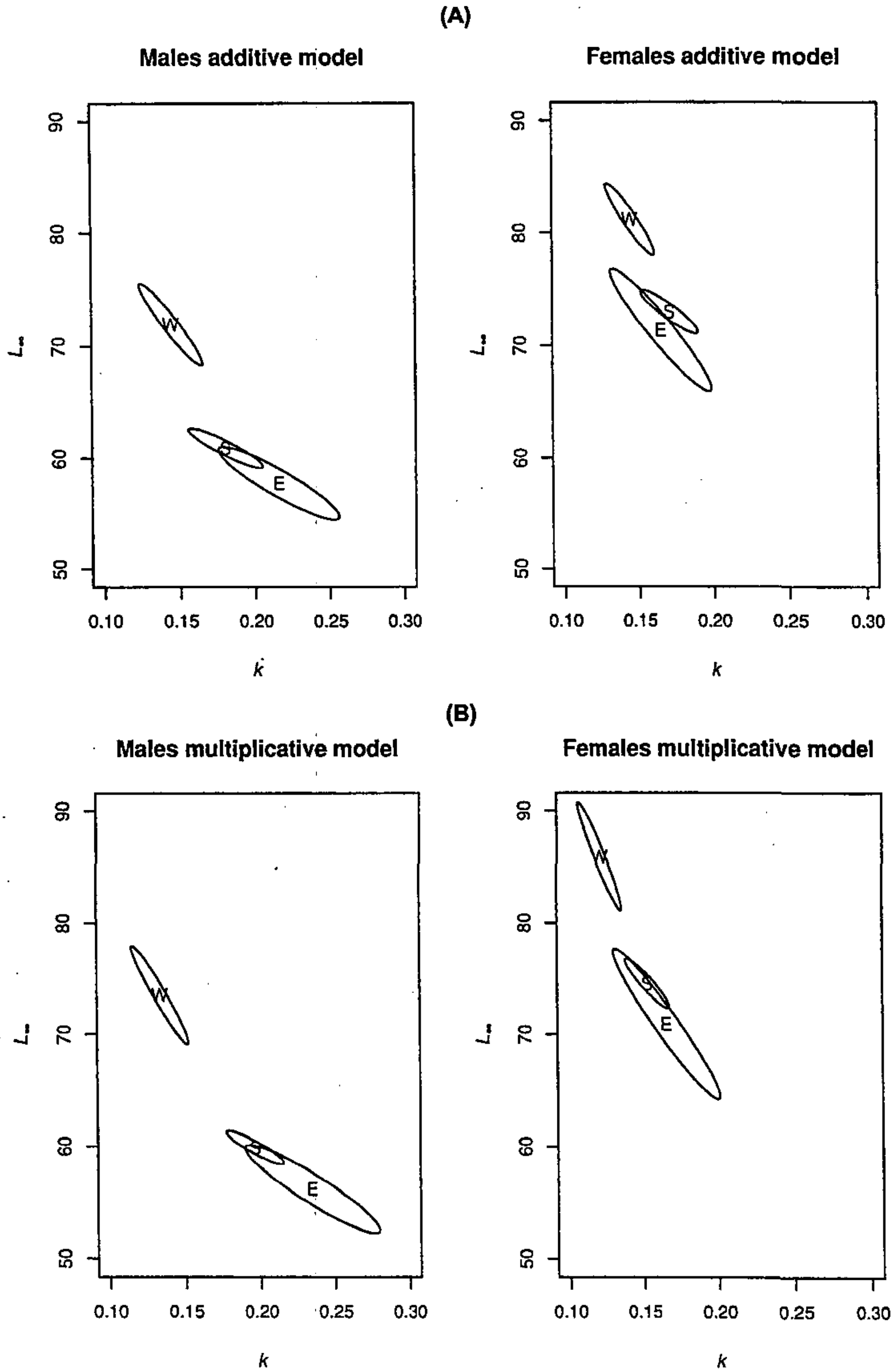

Figure 14: Cross sections of approximate joint 95% confidence regions around L_∞ and k from the fit of the (A) additive and (B) multiplicative models assuming separate parameters by area and sex to the combined ECSI, SCSI, and WCSI dataset. E, ECSI dataset; S, SCSI dataset; and W, WCSI dataset.

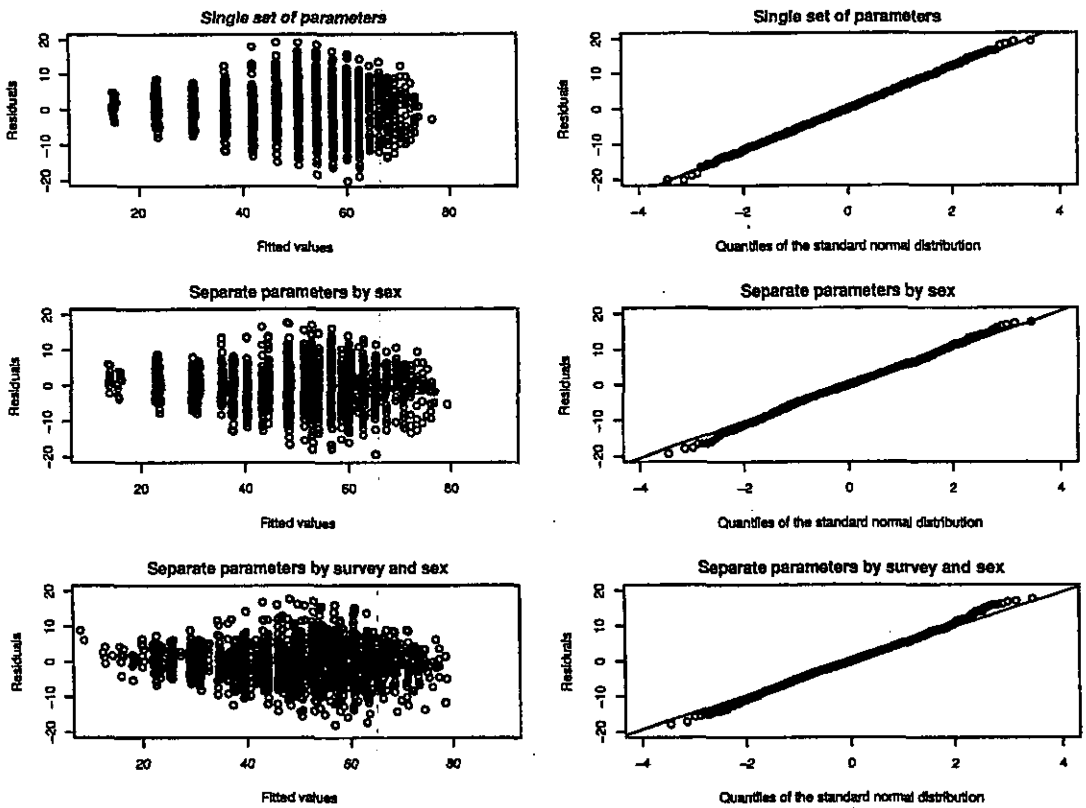

Figure 15: Diagnostic residual plots for the additive von Bertalanffy models fitted to the final WCSI dataset.

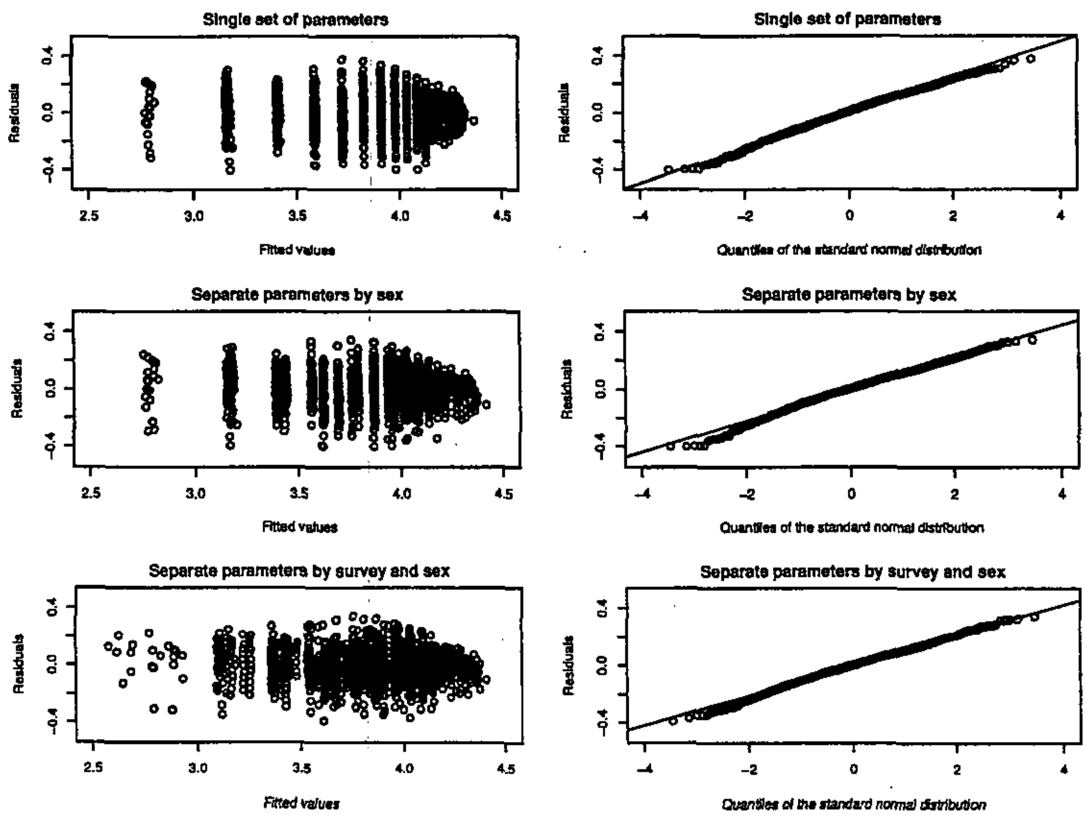

Figure 16: Diagnostic residual plots for the multiplicative von Bertalanffy models fitted to the final WCSI dataset.

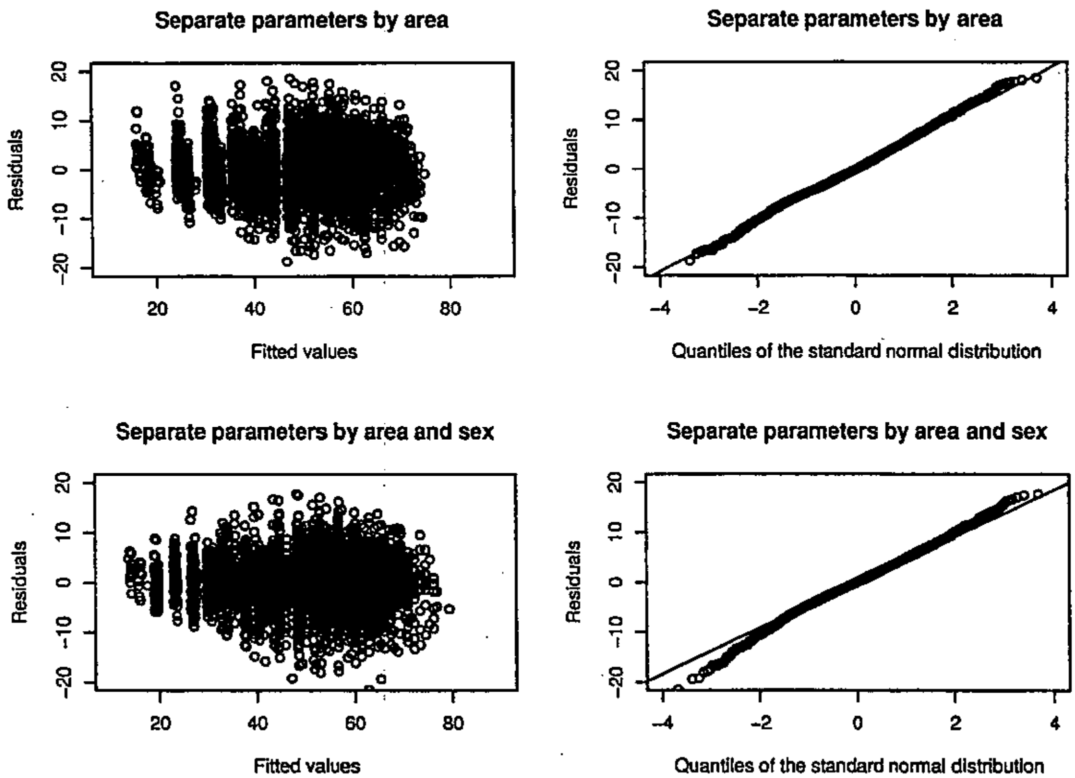

Figure 17: Diagnostic residual plots for the additive von Bertalanffy models fitted to the combined ECSI, SCSI, and WCSI dataset.

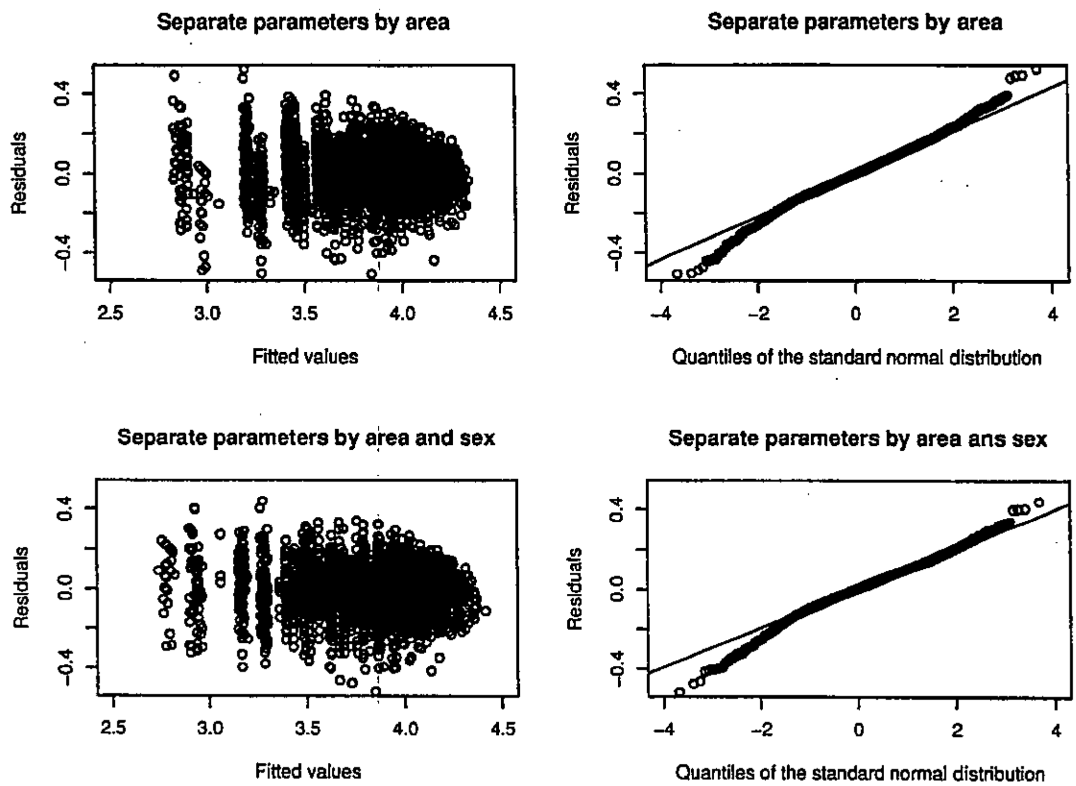

Figure 18: Diagnostic residual plots for the multiplicative von Bertalanffy models fitted to the combined ECSI, SCSI, and WCSI dataset.

Appendix A: Estimated scaled-numbers-at-age

Table A1: Estimated scaled-numbers-at-age (NAA) by sex for trawl survey KAH9204. Bootstrapped coefficients of variation (c.v.s) and overall Mean-Weighted Coefficients of Variation (MWCVs) are provided.

Age	Males		Females		Unsexed		All fish	
(years)	NAA	c.v. (%)	NAA	c.v. (%)	NAA	c.v. (%)	NAA	c.v. (%)
0	303	167.9	431	146.0	1938	83.1	2672	64.9
1	1256	145.8	712	157.9	269	174.0	2237	89.8
2	2428	66.8	1514	91.8	1317	136.0	5259	51.7
3	11862	28.7	10232	39.0	0	-	22094	23.9
4	14708	34.2	12775	34.8	0	-	27483	25.3
5	17149	30.9	14408	34.6	1283	122.4	32840	24.0
6	27132	28.6	19135	25.8	0	-	46267	20.3
7	28028	28.8	12255	35.0	0	-	40283	23.6
8	22163	28.7	23584	27.2	0	-	45747	20.0
9	12159	36.1	10676	37.5	0	-	22835	26.4
10	7890	52.8	17291	30.7	0	-	25181	27.5
11	8554	44.6	11500	39.4	0	-	20055	30.2
12	3576	57.4	8810	39.4	0	-	12386	34.3
13	3651	58.7	9023	45.9	0	-	12674	37.1
14	607	119.5	4676	58.8	0	-	5283	53.1
15	0	-	5339	55.6	0	-	5339	55.6
16	839	93.0	5361	60.1	0	-	6201	52.9
17	0	-	1586	119.3	0	-	1586	119.3
18	0	-	1959	87.3	0	-	1959	87.3
19	0	-	712	99.3	0	-	712	99.3
20	0	-	0	-	0	-	0	-
21	0	-	0	-	0	-	0	-
22	0	-	0	-	0	-	0	-
23	0	-	0	-	0	-	0	-
24	0	-	0	-	0	-	0	-
25	0	-	0	-	0	-	0	-
Undefined	0	226.7	0	197.0	82141	30.7	82141	30.2
MWCV (%)		35.7		38.9		35.3		28.7

Table A2: Estimated scaled-numbers-at-age (NAA) by sex for trawl survey KAH9404. Bootstrapped coefficients of variation (c.v.s) and overall Mean-Weighted Coefficients of Variation (MWCVs) are provided.

Age	Males		Females		Unsexed		All fish	
(years)	NAA	c.v. (%)	NAA	c.v. (%)	NAA	c.v. (%)	NAA	c.v. (%)
0	191	247.6	599	133.3	339	180.0	1128	107.5
1	9275	44.8	7974	41.5	0	-	17248	33.2
2	13621	31.4	14033	35.6	0	-	27654	26.9
3	8998	39.3	4182	44.0	0	-	13180	30.5
4	26170	32.2	7842	42.3	0	-	34012	30.5
5	36614	28.9	10269	32.0	0	-	46883	25.1
6	33577	31.6	31890	28.0	0	-	65467	23.4
7	24768	33.6	28630	28.6	0	-	53397	23.4
8	16397	40.0	29937	27.9	0	-	46334	24.7
9	38481	33.4	26057	29.2	0	-	64538	25.5
10	26407	36.1	8937	48.6	0	-	35344	30.6
11	6095	62.1	2230	73.2	0	-	8326	50.5
12	4488	84.2	3326	49.6	0	-	7814	54.9
13	2809	96.7	3498	62.2	0	-	6307	57.4
14	2220	99.3	1224	90.7	0	-	3444	75.2
15	1445	72.8	550	81.7	0	-	1994	57.1
16	0	-	931	100.2	0	-	931	100.2
17	1235	94.7	0	-	0	-	1235	94.7
18	740	137.9	2076	77.8	0	-	2816	67.4
19	185	166.0	189	130.2	0	-	373	110.2
20	0	-	0	-	0	-	0	-
21	273	166.1	0	-	0	-	273	166.1
22	0	-	0	-	0	-	0	-
23	0	-	369	132.2	0	-	369	132.2
24	0	-	0	-	0	-	0	-
25	0	-	172	130.8	0	-	172	130.8
Undefined	0	218.5	0	168.1	0	-	0	134.8
MWCV (%)		37.7		35.4		180.0		29.3

Table A3: Estimated scaled-numbers-at-age (NAA) by sex for trawl survey KAH9504. Bootstrapped coefficients of variation (c.v.s) and overall Mean-Weighted Coefficients of Variation (MWCVs) are provided.

Age	Males		Females		Unsexed		All fish	
(years)	NAA	c.v. (%)	NAA	c.v. (%)	NAA	c.v. (%)	NAA	c.v. (%)
0	1334	185.7	3494	74.8	0	-	4828	96.8
1	8764	84.1	7246	56.0	0	-	16010	55.7
2	37744	28.7	15529	37.2	0	-	53274	25.1
3	9434	58.4	12020	48.0	0	-	21454	37.6
4	17288	39.7	11085	47.2	0	-	28373	32.3
5	41844	40.0	20175	33.0	0	-	62019	32.0
6	55494	31.2	27499	34.0	0	-	82994	27.2
7	63923	29.9	44670	26.7	0	-	108594	21.9
8	45695	32.3	47492	25.6	0	-	93187	23.0
9	19650	43.4	8446	54.8	0	-	28096	36.1
10	12768	47.6	15031	46.6	0	-	27799	35.4
11	11635	57.8	5256	75.3	0	-	16891	46.2
12	2765	91.8	3278	72.1	0	-	6042	58.0
13	0	-	1819	97.4	0	-	1819	97.4
14	1339	93.0	1110	116.9	0	-	2449	75.9
15	471	126.1	1535	94.6	0	-	2007	77.6
16	1957	87.3	801	125.5	0	-	2757	70.8
17	0	-	0	-	0	-	0	-
18	0	-	0	-	0	-	0	-
19	0	-	0	-	0	-	0	-
20	0	-	768	113.6	0	-	768	113.6
21	0	-	0	-	0	-	0	-
22	0	-	0	-	0	-	0	-
23	0	-	0	-	0	-	0	-
24	0	-	0	-	0	-	0	-
25	0	-	0	-	0	-	0	-
Undefined	230	318.5	0	192.1	0	-	230	247.3
MWCV (%)		38.9		38.7		-		30.7

Table A4: Estimated scaled-numbers-at-age (NAA) by sex for trawl survey KAH9701. Bootstrapped coefficients of variation (c.v.s) and overall Mean-Weighted Coefficients of Variation (MWCVs) are provided.

Age	Males		Females		Unsexed		All fish	
(years)	NAA	c.v. (%)	NAA	c.v. (%)	NAA	c.v. (%)	NAA	c.v. (%)
0	2807	67.8	1081	155.7	0	-	3888	60.2
1	32284	35.0	15152	39.2	0	-	47436	29.0
2	14646	35.9	18033	42.1	0	-	32679	30.2
3	31068	28.7	20771	38.0	0	-	51839	25.5
4	17611	42.3	14304	40.6	0	-	31914	31.4
5	26601	33.1	18850	39.4	0	-	45451	26.4
6	44920	31.7	9847	40.1	0	-	54767	26.3
7	31777	35.5	36112	32.9	0	-	67888	24.6
8	35742	33.3	33203	34.0	0	-	68946	25.2
9	22574	37.8	30462	35.5	0	-	53036	28.3
10	16355	41.6	15821	40.5	0	-	32175	31.2
11	11358	57.6	6682	53.5	0	-	18039	41.1
12	2754	80.7	4869	90.2	0	-	7623	66.9
13	1423	100.8	2215	76.7	0	-	3638	64.0
14	1221	90.9	2430	81.0	0	-	3651	64.8
15	571	143.0	0	-	0	-	571	143.0
16	0	-	1776	87.1	0	-	1776	87.1
17	0	-	3544	103.5	0	-	3544	103.5
18	0	-	0	-	0	-	0	-
19	0	-	0	-	0	-	0	-
20	0	-	0	-	0	-	0	-
21	0	-	370	148.7	0	-	370	148.7
22	0	-	0	-	0	-	0	-
23	0	-	0	-	0	-	0	-
24	0	-	0	-	0	-	0	-
25	0	-	0	-	0	-	0	-
Undefined	351	125.3	0	219.7	0	-	351	114.6
MWCV (%)		37.1		41.6		-		30.0

Table A5: Estimated scaled-numbers-at-age (NAA) by sex for trawl survey KAH0004. Bootstrapped coefficients of variation (c.v.s) and overall Mean-Weighted Coefficients of Variation (MWCVs) are provided.

Age	Males		Females		Unsexed		All fish	
(years)	NAA	c.v. (%)	NAA	c.v. (%)	NAA	c.v. (%)	NAA	c.v. (%)
0	1597	143.5	725	175.8	0	-	2321	110.3
1	18157	45.7	12041	46.5	0	-	30197	33.3
2	20303	40.5	17726	37.1	0	-	38030	28.2
3	36659	30.8	32638	29.6	0	-	69297	23.0
4	40130	27.0	21217	35.3	0	-	61346	23.5
5	37961	30.6	17468	35.6	0	-	55429	24.2
6	46028	23.3	27932	29.5	0	-	73960	20.4
7	21608	32.1	23578	29.6	0	-	45185	23.0
8	24063	33.0	13377	40.6	0	-	37440	25.8
9	14528	38.5	11545	40.6	0	-	26072	29.4
10	14652	40.2	7391	53.0	0	-	22043	32.4
11	2821	65.2	7967	49.9	0	-	10788	41.9
12	5341	57.9	2120	71.8	0	-	7462	46.2
13	2345	92.9	4756	61.4	0	-	7101	50.3
14	938	145.0	6402	43.0	0	-	7339	42.6
15	1846	105.8	1010	90.9	0	-	2856	76.5
16	0	-	363	177.3	0	-	363	177.3
17	0	-	0	-	0	-	0	-
18	0	-	708	128.0	0	-	708	128.0
19	0	-	0	-	0	-	0	-
20	0	-	0	-	0	-	0	-
21	0	-	708	120.7	0	-	708	120.7
22	0	-	525	120.5	0	-	525	120.5
23	0	-	0	-	0	-	0	-
24	0	-	0	-	0	-	0	-
25	0	-	0	-	0	-	0	-
Undefined	0	220.3	0	187.6	0	-	0	146.0
MWCV (%)		34.6		38.6		-		27.4

Appendix B: Chapman-Robson estimates of total mortality

Table B1: The Chapman-Robson estimator of total mortality, $\hat{Z}$, calculated by sex for trawl survey KAH9204 assuming six different Ages at Full Recruitment (AFR; 3–8 years, inclusive). Analytical and bootstrapped 95% confidence intervals (95% CIs) are provided.

AFR	Sex	$\hat{z}$	95% CI (analytical)	95% CI (bootstrap)
3	Male	0.2222	(0.2211, 0.2233)	(0.2034, 0.2513)
	Female	0.1623	(0.1616, 0.1631)	(0.1477, 0.1832)
	All	0.1870	(0.1864, 0.1876)	(0.1760, 0.2036)
4	Male	0.2616	(0.2603, 0.2630)	(0.2380, 0.3029)
	Female	0.1810	(0.1801, 0.1819)	(0.1626, 0.2084)
	All	0.2130	(0.2122, 0.2137)	(0.1977, 0.2354)
5	Male	0.3133	(0.3116, 0.3150)	(0.2759, 0.3644)
	Female	0.2015	(0.2005, 0.2026)	(0.1793, 0.2309)
	All	0.2435	(0.2426, 0.2444)	(0.2226, 0.2701)
6	Male	0.3858	(0.3835, 0.3880)	(0.3333, 0.4700)
	Female	0.2247	(0.2235, 0.2260)	(0.1978, 0.2626)
	All	0.2787	(0.2776, 0.2798)	(0.2508, 0.3141)
7	Male	0.4452	(0.4422, 0.4482)	(0.3800, 0.5517)
	Female	0.2426	(0.2412, 0.2441)	(0.2062, 0.2921)
	All	0.3026	(0.3013, 0.3039)	(0.2705, 0.3497)
8	Male	0.4798	(0.4759, 0.4837)	(0.3928, 0.6254)
	Female	0.2807	(0.2790, 0.2825)	(0.2357, 0.3418)
	All	0.3317	(0.3301, 0.3333)	(0.2874, 0.3920)

Table B2: The Chapman-Robson estimator of total mortality, $\hat{Z}$, calculated by sex for trawl survey KAH9404 assuming six different Ages at Full Recruitment (AFR; 3–8 years, inclusive). Analytical and bootstrapped 95% confidence intervals (95% CIs) are provided.

AFR	Sex	$\hat{z}$	95% CI (analytical)	95% CI (bootstrap)
3	Male	0.2092	(0.2084, 0.2101)	(0.1858, 0.2427)
	Female	0.1919	(0.1909, 0.1928)	(0.1764, 0.2098)
	All	0.2017	(0.2011, 0.2023)	(0.1859, 0.2248)
4	Male	0.2532	(0.2521, 0.2542)	(0.2182, 0.2982)
	Female	0.2307	(0.2296, 0.2319)	(0.2109, 0.2559)
	All	0.2433	(0.2425, 0.2441)	(0.2214, 0.2756)
5	Male	0.2932	(0.2919, 0.2945)	(0.2488, 0.3551)
	Female	0.2832	(0.2818, 0.2847)	(0.2554, 0.3203)
	All	0.2888	(0.2878, 0.2897)	(0.2627, 0.3267)
6	Male	0.3243	(0.3227, 0.3259)	(0.2790, 0.3887)
	Female	0.3639	(0.3620, 0.3658)	(0.3177, 0.4260)
	All	0.3417	(0.3405, 0.3429)	(0.3101, 0.3904)
7	Male	0.3598	(0.3578, 0.3618)	(0.3039, 0.4395)
	Female	0.4140	(0.4115, 0.4164)	(0.3524, 0.5115)
	All	0.3830	(0.3814, 0.3845)	(0.3407, 0.4415)
8	Male	0.4272	(0.4245, 0.4298)	(0.3533, 0.5359)
	Female	0.4732	(0.4699, 0.4766)	(0.3679, 0.6090)
	All	0.4463	(0.4442, 0.4484)	(0.3852, 0.5264)

Table B3: The Chapman-Robson estimator of total mortality, $\hat{Z}$, calculated by sex for trawl survey KAH9504 assuming six different Ages at Full Recruitment (AFR; 3–8 years, inclusive). Analytical and bootstrapped 95% confidence intervals (95% CIs) are provided.

AFR	Sex	$\hat{z}$	95% CI (analytical)	95% CI (bootstrap)
3	Male	0.2257	(0.2249, 0.2265)	(0.2068, 0.2519)
	Female	0.2123	(0.2114, 0.2132)	(0.1932, 0.2426)
	All	0.2199	(0.2193, 0.2206)	(0.2074, 0.2427)
4	Male	0.2808	(0.2797, 0.2818)	(0.2525, 0.3175)
	Female	0.2515	(0.2504, 0.2526)	(0.2260, 0.2860)
	All	0.2681	(0.2673, 0.2688)	(0.2492, 0.2950)
5	Male	0.3621	(0.3606, 0.3635)	(0.3132, 0.4220)
	Female	0.3136	(0.3121, 0.3150)	(0.2726, 0.3668)
	All	0.3405	(0.3395, 0.3415)	(0.3103, 0.3812)
6	Male	0.4547	(0.4528, 0.4567)	(0.3856, 0.5472)
	Female	0.3953	(0.3934, 0.3973)	(0.3339, 0.4767)
	All	0.4276	(0.4262, 0.4290)	(0.3825, 0.4958)
7	Male	0.5580	(0.5552, 0.5608)	(0.4520, 0.7162)
	Female	0.5114	(0.5086, 0.5142)	(0.4177, 0.6820)
	All	0.5361	(0.5341, 0.5380)	(0.4634, 0.6584)
8	Male	0.5961	(0.5923, 0.5999)	(0.4505, 0.8534)
	Female	0.5772	(0.5733, 0.5811)	(0.4193, 0.8570)
	All	0.5870	(0.5843, 0.5898)	(0.4706, 0.7677)

Table B4: The Chapman-Robson estimator of total mortality, $\hat{Z}$, calculated by sex for trawl survey KAH9701 assuming six different Ages at Full Recruitment (AFR; 3–8 years, inclusive). Analytical and bootstrapped 95% confidence intervals (95% CIs) are provided.

AFR	Sex	$\hat{z}$	95% CI (analytical)	95% CI (bootstrap)
3	Male	0.2372	(0.2362, 0.2381)	(0.2119, 0.2707)
	Female	0.1996	(0.1987, 0.2005)	(0.1783, 0.2458)
	All	0.2186	(0.2179, 0.2192)	(0.1983, 0.2509)
4	Male	0.2660	(0.2649, 0.2672)	(0.2342, 0.3070)
	Female	0.2208	(0.2198, 0.2218)	(0.1994, 0.2641)
	All	0.2432	(0.2424, 0.2439)	(0.2218, 0.2759)
5	Male	0.3279	(0.3264, 0.3294)	(0.2835, 0.3927)
	Female	0.2581	(0.2568, 0.2593)	(0.2238, 0.3205)
	All	0.2916	(0.2906, 0.2926)	(0.2614, 0.3357)
6	Male	0.4083	(0.4063, 0.4102)	(0.3361, 0.5143)
	Female	0.3025	(0.3010, 0.3041)	(0.2578, 0.3702)
	All	0.3510	(0.3497, 0.3522)	(0.3035, 0.4086)
7	Male	0.4619	(0.4593, 0.4645)	(0.3756, 0.5937)
	Female	0.4000	(0.3978, 0.4021)	(0.3249, 0.5223)
	All	0.4271	(0.4254, 0.4287)	(0.3668, 0.5218)
8	Male	0.5734	(0.5697, 0.5772)	(0.4470, 0.7483)
	Female	0.4504	(0.4476, 0.4531)	(0.3240, 0.6386)
	All	0.5014	(0.4992, 0.5037)	(0.3992, 0.6323)

Table B5: The Chapman-Robson estimator of total mortality, $\hat{Z}$, calculated by sex for trawl survey KAH0004 assuming six different Ages at Full Recruitment (AFR; 3–8 years, inclusive). Analytical and bootstrapped 95% confidence intervals (95% CIs) are provided.

AFR	Sex	$\hat{z}$	95% CI (analytical)	95% CI (bootstrap)
3	Male	0.2779	(0.2768, 0.2789)	(0.2467, 0.3373)
	Female	0.2366	(0.2355, 0.2377)	(0.2066, 0.2854)
	All	0.2589	(0.2582, 0.2597)	(0.2362, 0.3008)
4	Male	0.3190	(0.3176, 0.3204)	(0.2794, 0.3761)
	Female	0.2465	(0.2452, 0.2478)	(0.2096, 0.2976)
	All	0.2847	(0.2838, 0.2856)	(0.2550 0.3252)
5	Male	0.3634	(0.3617, 0.3651)	(0.3139, 0.4403)
	Female	0.2734	(0.2719, 0.2749)	(0.2335, 0.3289)
	All	0.3190	(0.3179, 0.3202)	(0.2861, 0.3682)
6	Male	0.4179	(0.4157, 0.4202)	(0.3507, 0.5364)
	Female	0.3158	(0.3139, 0.3177)	(0.2639, 0.4083)
	All	0.3651	(0.3636, 0.3666)	(0.3175, 0.4376)
7	Male	0.4168	(0.4140, 0.4195)	(0.3357, 0.5450)
	Female	0.3225	(0.3203, 0.3247)	(0.2650, 0.4180)
	All	0.3657	(0.3639, 0.3674)	(0.3095, 0.4372)
8	Male	0.4948	(0.4910, 0.4986)	(0.3764, 0.6760)
	Female	0.3134	(0.3108, 0.3160)	(0.2475, 0.4111)
	All	0.3903	(0.3882, 0.3925)	(0.3240, 0.4844)