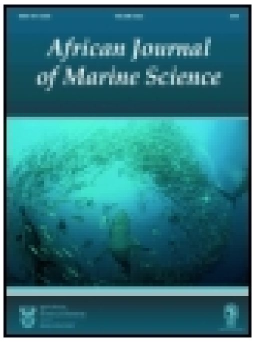

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The effects of ageing biases on stock assessment and management advice: a case study on Namibian horse mackerel

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We explore the influence of age-estimation errors on the results of the age-structured production model (ASPM) used for horse mackerel stock assessment in Namibia for the period 1961–2003. The analysis considered age data from eight readers collected during an otolith-reading workshop. Four scenarios of age-estimation errors were assumed: Case 1 — a reference age computed as the modal age of estimates obtained by the four most experienced readers; Case 2 — age readings from a precise and experienced (Namibian) reader of horse mackerel otoliths; Case 3 — age estimates from a reader that displayed positive bias compared with the reference ages; and Case 4 — age estimates from a reader that displayed negative bias compared with the reference ages. The age–length key of each case was applied to length distributions of survey, pelagic fleet and midwater fleet landings (1991–2003) to obtain catch-at-age data. These data were then used in the ASPM. Results obtained from Case 3 differed most significantly from the others and appeared to be unrealistic in terms of the state of the stock and negative log-likelihood estimates. The conclusion is that more resources need to be directed towards age determination, because management recommendations are highly sensitive to errors in ageing. Most effort should be placed into age estimation of age groups 3–5 (20–30 cm total length), but significant effort needs to be devoted to age estimation of midwater commercial samples. Finally, the extent of sampling and the raising strategy of length frequencies should be improved.

Keywords: age-structured production model, ageing error, ageing precision, sampling effort, *Trachurus capensis*

Introduction

Since Namibia's independence in 1990 and the establishment of an Exclusive Economic Zone (EEZ), fish stocks have contributed appreciably to the national income and exports, and they constitute a significant component of national wealth (Lange 2004). Effective management of the resources in terms of biological, social and economic considerations is therefore essential. Clearly, a severe socio-economic loss could be incurred through the depletion of Namibian fish stocks, so stock assessments should be rigorous. An age-structured production model (ASPM) is used to provide advice to management on the sustainable utilisation of fish stocks off Namibia.

The results of a stock assessment model can only be as accurate as their input data. When assessment results are presented to management, often they are regarded as truth (i.e. as completely accurate estimates of abundance), instead of being acknowledged as heavily dependent on the quality and quantity of the input data. Apart from recorded landings, indices of abundance such as fisheries-independent research survey estimates, fisheries-dependent catch per unit effort (CPUE) data as well as proportions of catch-at-age (CAA) for each series are needed as input data for an ASPM. Indices of abundance, accompanied by length frequency distributions or catch-at-length (CAL) data, are usually readily available, but CAA information is usually lacking. The age structure of a population is a key data requirement for age-structured stock assessments (Megrey 1989) and the importance of using annual age–length keys (ALKs) to calculate the respective annual age distribution of a population has been emphasised in the literature (e.g. Westrheim and Ricker 1978). In practice, however, age determination is sometimes not treated with the importance it deserves.

As fisheries science is an expensive and time-consuming exercise, it is crucial that management systems be evaluated per species or stock in light of the extent of inaccuracy and imprecision that can be tolerated while still achieving the goals of effective management (Roughgarden 1998, Sullivan *et al.* 2000). Because the current Namibian stock assessment approach relies heavily on accurate age information, and it is expensive and time consuming to obtain such information, the main goal of this study was to quantify possible ageing errors and to test the extent of the effect of ageing biases on CAA information and the resulting management advice. Further, considering resource (human capacity) limitations throughout marine science and especially now in Namibia, it is imperative to establish where reading effort should be directed. The assessment of the Namibian horse mackerel *Trachurus capensis* from 1961 to 2003 was used as a case study. It is a key commercial fisheries resource in the northern Benguela (Boyer and Hampton 2001), and is assessed using a fleet-segregated ASPM (CHK and co-workers, unpublished data). Management advice is provided in the form of an annual proposed total allowable catch (TAC), based on the current state of the stock with the objective of maintaining it at the maximum sustainable yield level (MSYL). Before 2003, CAA data used for the Namibian horse mackerel assessments were based on the only available (1987) age–length keys.

The age data used for this study were collected during an otolith-reading workshop (BENEFIT 2003) to (i) quantify age-estimation errors and test whether differences in the otolith interpretation criteria employed by the different readers give rise to significant differences in the resulting CAA data, and (ii) test the sensitivity of the stock assessment to different CAA information resulting from ageing errors in terms of the model output and subsequent management recommendations.

Material and Methods

Age estimates

Age estimates for Namibian horse mackerel were obtained during the Third BENEFIT Horse Mackerel Otolith Reading Workshop (BENEFIT 2003). In all, 240 otoliths from horse mackerel of 12.5–43.5 cm total length (TL) were read, collected during two acoustic surveys conducted in June 1996 and September/October 1996. Details on otolith preparation and ring enumeration methods are provided in ICSEAF (1986) and the BENEFIT otolith-reading workshop reports (BENEFIT 2001, 2003). Eight readers performed three replicate readings with no reference to either fish size information or the results of previous readings. Four Namibian readers tasked with routine age determination of Namibian horse mackerel (Readers 2, 4, 6 and 8) performed three or more age readings on each otolith. These data were then used in the assessment model according to different cases based on each reader's (i) precision relative to themselves and the reference age and (ii) bias of each reader relative to the reference age.

Quantifying age-estimation errors

Precision

The precision of each reader's otolith interpretation was quantified using the calculation of coefficient of variation (CV in %) described by Chang (1982):

$$\mathrm{CV}_j = 100 \times \sqrt{\sum_{i=1}^{R} \frac{\left(x_{ij} - x_j\right)^2}{R-1}} \Big/ x_j \qquad (1)$$

where R is the number of times each fish was aged, x_{ij} is the ith age estimation of the jth fish and x_j is the modal age of the jth fish (for that reader). Modal age was replaced with the mean age of the fish for otoliths when either no mode could be determined (all age readings were different) or the modal age was 0. The CV was calculated for each otolith and the values were averaged over all otoliths to provide precision indices for each reader.

For the purposes of quantifying age-estimation errors and bias among all the readers, a reference age for each otolith was defined. This was calculated as the mode of the first three replicate readings of four readers (Readers 1, 3, 6 and 7), who showed a within-reader agreement >70% (BENEFIT 2003). An among-reader CV was then calculated for each otolith using Equation (1), where x_j is the reference age of the jth fish. CVs were again averaged over all otoliths for each reader.

Bias

In order to assess the degree of bias of each reader relative to the reference age, the mean age (±2 SE) calculated from all replicate readings performed by each individual reader on each otolith was plotted against the reference age for that otolith (Campana *et al.* 1995).

Stock assessment model

Data used to assess the stock status in this study were catch statistics from two fishing fleets, a midwater fleet (midwater trawl fishery) and a pelagic fleet (purse-seine fishery) for the period 1961–2003, commercial CPUE data for the midwater fleet (1990–2003) and annual acoustic biomass survey estimates between 1999 and 2003. The model uses CAA data, obtained by applying an ALK to CAL data from each fishing fleet and the acoustic biomass survey, to estimate selectivity and recruitment. The ASPM (CHK and co-workers, unpublished data) was implemented deterministically and fitted to two indices of abundance: midwater CPUE series and survey biomass estimates. The fitting process also relates CAA data for the pelagic purse-seine and the midwater fishery, as well as survey CAA to estimate selectivity. The log-likelihood function to be minimised was a function of the unexploited equilibrium (pristine) spawner biomass (B_0^{sp}), the steepness parameter (h, the fraction of the recruitment at the unexploited equilibrium level of spawning biomass to be expected when this biomass is reduced to 20% of B_0^{sp}), the natural mortality (M) and the CPUE constant of proportionality (q). Pristine spawner biomass B_0^{sp}, individual selectivity-at-age, the slope when the selectivity was <1 for older age groups and q for the commercial CPUE data were estimated within the model. Values of the parameters *h*, *M* and survey *q* were fixed at h = 0.8, M = 0.3 and q = 1.5 (pre-selected by minimising the negative log-likelihood, while maintaining realism for horse mackerel). These selected parameters were kept constant for comparisons between the four cases described below. CAA data representing each case were used in the ASPM. The resulting state of the stock in terms of model-estimated current biomass, depletion level (biomass as a proportion of pristine stock biomass or carrying capacity *K*), maximum sustainable yield (MSY), biomass at MSY and B_{MSY} as a proportion of *K* (MSYL), and the resulting TAC recommendations, were compared.

Assessing sensitivity of the ASPM to age-estimation errors

Data obtained by different readers were used to construct four ALKs, selected with the intention of assessing three scenarios of age-estimation error:

Case 1: An ALK based on the reference age, which was considered to be the control (reference ALK — assumed to reflect the true age structure of the population).
Case 2: An ALK based on age data of the sixth replicate reading of Reader 6; a reader tasked with routine fish age determination in Namibia. Of the Namibian readers, this dataset was closest to the reference set, Case 1, and hence represented minimal error.
Case 3: An ALK based on the sixth replicate reading of another reader tasked with routine age determination in Namibia (Reader 2), who tended to overestimate age relative to reference age (Case 1).
Case 4: An ALK based on modal age of six replicate readings of Reader 4, a reader also tasked with routine age determination in Namibia, who generally underestimated age compared with the reference age.

Annual catch-at-age

Annual CAA over the period 1991–2003 were estimated based on annual CAL from both commercial fleets (pelagic and midwater) as well as from research surveys over the entire period (updated from Bauleth-D'Almeida *et al.* 2001). The ALK for each case was used to convert the CAL in numbers to CAA, which was then converted to proportions to be used within the ASPM. In age groups where the criterion that at least 10% of the catches should be represented in an age group could not be fulfilled, the age group was pooled into either the age group above (minimum age group) or below (maximum age group).

Results

Age-estimation errors

Readers showed within-reader CVs between 13% and 50% (Table 1). Readers 7, 1 and 2 were the most consistent readers (13–14% within-reader CVs). Reader 4 was the least precise, with a CV of 50%. Interestingly, Readers 7 and 1 also had the lowest CV values compared with the reference age, but Reader 2 showed the second highest CV compared with the reference age. Reader 4 showed the highest among-reader CV in terms of reference age (Table 1).

The age–bias plots (Figure 1) revealed that Readers 3 and 4 tended to underestimate age, Reader 3 showing a bias towards older age groups and Reader 4 underestimating all younger and older age groups (being more accurate on age groups 3 and 4). Readers 2 and 5 tended to overestimate ages for fish in most age groups. Readers 2 and 8 showed a strong positive bias towards the middle age groups (3–5).

Because the midwater trawl dataset spanned most age groups and consisted of a longer time-series, purse-seine and survey age data had a minimal influence on the results. Catches-at-age of the midwater trawl fishery, averaged over all years for each of the four cases, are therefore illustrated in Figure 2. Cases 1 and 2 showed similar distributions, with 2-year-olds making up the largest proportion of the catches, the proportions decreasing with increasing age. CAA distributions of Cases 3 and 4 differed considerably from Cases 1 and 2. In Case 3, age group 3 constituted most of the catch, and larger proportions of age groups 4–7 were present than in the other cases. Case 4 differed from the other cases in that most of the catch consisted of younger fish of age groups 1–3.

Stock assessment results

Stock assessment results and the resulting TAC proposals are presented in Table 2 for each of the four cases. The

Table 1: Age-reader precision: the number of otoliths considered readable (*n*), the number of replicate readings on one otoliths (readers with six replicate readings are routine readers in Namibia), and indices of within-reader and among-reader precision (within-reader CV, among-reader CV) are shown for each reader. Also shown are the maximum deviations, the largest difference between replicate age estimates for an otolith recorded (max dev), and the number of otoliths where replicate estimates were all identical (100% agree) or all different (0% agree) for each reader

Reader	*n*	Replicate readings	Within-reader CV (%)	Among-reader CV (%)	Max dev	100% agree	0% agree
1	275	3	14.31	19.82	4	123	20
2	259	6	14.46	43.25	4	48	0
3	276	3	16.78	21.45	3	93	14
4	276	6	49.55	46.98	6	4	7
5	276	3	27.02	40.21	7	43	88
6	276	6	20.68	31.74	6	48	1
7	276	3	12.94	18.89	3	117	27
8	275	6	38.20	38.33	8	24	4

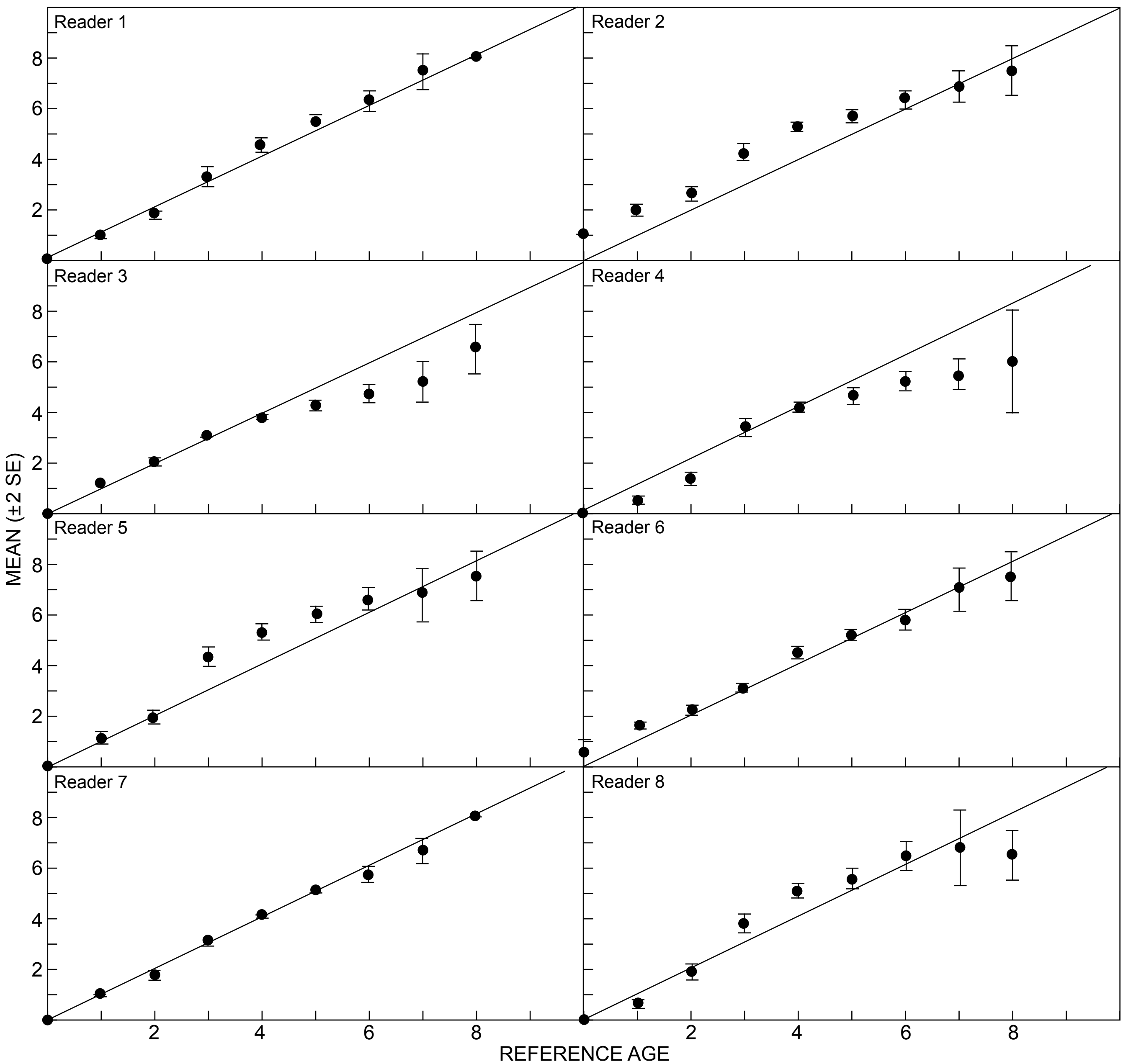

Figure 1: Age bias plots of eight readers of Namibian horse mackerel otoliths (data from the BENEFIT otolith-reading workshop). Each reader's mean ±2 SE at the four-reader mode (reference age, taken as true age, Case 1) is plotted against this reference age

ASPM run using the Case 1 CAA data revealed an overexploited resource at a current depletion level of 29% of pristine. A TAC recommendation of 320 000 t resulted from this case. The results of Cases 2 and 4 indicated 34% and 38% depletion respectively, suggesting that the resource was currently at its MSYL, and with corresponding TAC proposals of 350 000 and 400 000 t respectively. Case 3 results were considerably different from the other three, suggesting that the stock is currently underexploited, at a depletion level of ~79%. Case 4 showed the best fit to the model (least negative log-likelihood) and Case 3 the worst.

Discussion

The CVs of some of the readers were considerably higher than the 5% level generally used as a reference point in work of this nature (Campana 2001). However, as most readers performed their first age reading at the start of the workshop, and their sixth readings generally displayed greater precision than their first, precision was still expected to improve. Also, most importantly, age readings of the routine reader that showed an overall CV of 21%, but a small degree of bias (Reader 6, Case 2) still resulted in similar age distributions and stock assessment results

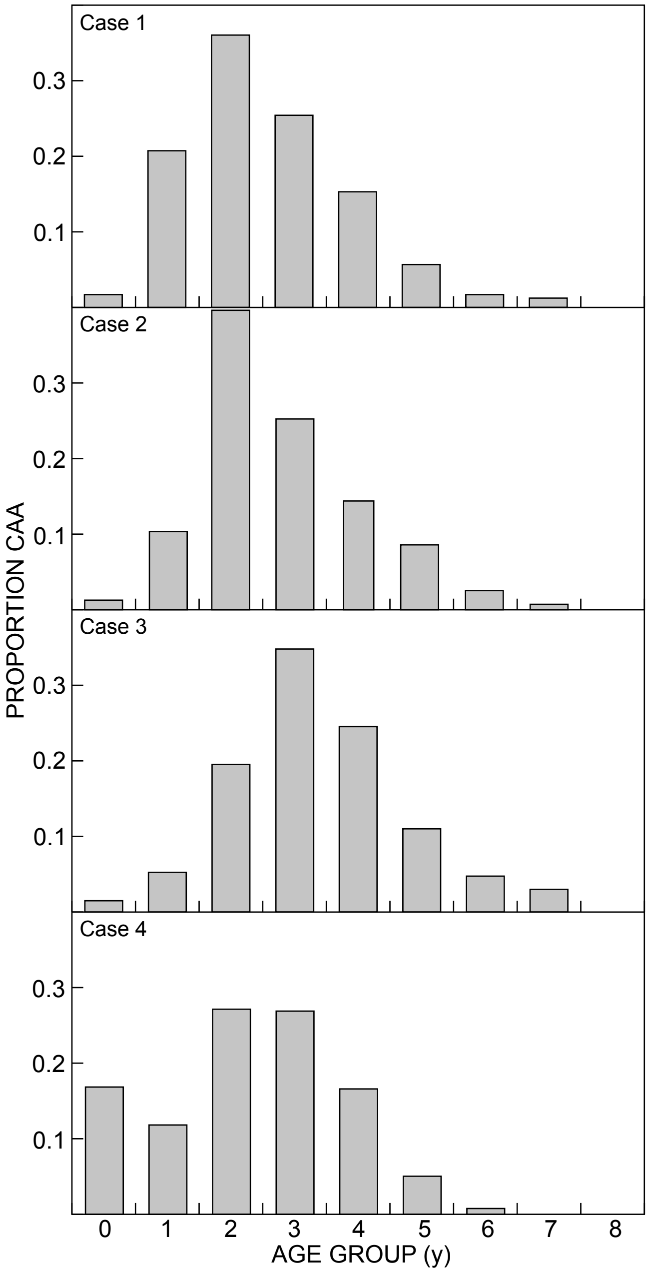

Figure 2: Proportions catch-at-age (CAA) calculated using the different age–length keys (ALK) of Cases 1–4 (see text) applied to catch-at-length (CAL) data from the midwater fleet operating on Namibian horse mackerel. The CAA proportions were calculated for the period 1991–2003 and averaged over all years

as the reference (Case 1; Figure 2, Table 2). Therefore, although indices of within-reader precision provide a valuable indication of the stability of the interpretation criteria employed by each reader and the initial potential of each as a routine age reader, in situations where more than one person is responsible for routine age estimation, as is the case with Namibian horse mackerel, age bias analyses should be considered more important. The measure of precision is a measure of random error, whereas bias reflects directed error, which indicates mistakes in interpretation (Campana 2001). The example of Reader 2 (Table 1) also showed that a high level of within-reader precision does not imply that the reader's age estimation is similar to the reference (or true) age. However, if one reader is biased relative to a reference age, it appears to have more profound implications on the results of the CAA data, the stock assessment and resulting management proposals (Table 2).

Case 1, the reference age dataset, yielded a similar TAC proposal as suggested over the period 1999–2003 (average of 360 000 t; Ministry of Fisheries and Marine Resources, unpublished data). CAA data based on underestimated age readings (Case 4) resulted in a proposal of 400 000 t, an 80 000 t increase over that resulting from Case 1. However, the sensitivity of the model to CAA data from overestimated ages (Case 3) proved to be much greater, resulting in a TAC proposal of 640 000 t, double that of Case 1. The midwater horse mackerel trawl fleet is the largest fleet in Namibia (Boyer and Hampton 2001) and landings were valued at about US$300 million in 2001 (Anon. 2001). Large year-on-year changes in TAC, such as those described above, would have a tremendous influence on the fishery. Clearly, the nature of the age data on which the stock assessment is based is vital to the management of horse mackerel in Namibia, so greater attention needs to be given to the quality of the age data collected.

In general, proposed TACs follow the MSYL, which is estimated from the relationship between total biomass and pristine biomass, or carrying capacity of the stock. Case 3 was most dissimilar to the rest and a management decision based on such a case would be of greatest concern for the stock. Age overestimation (Case 3) had a large impact on biomass, primarily because the age distribution was skewed towards older age groups (Figure 2). The proportions of CAA in age group 3 and older therefore appear to be crucial in terms of the biomass and the resulting MSYL output from the model. In contrast, age underestimation (Case 4) resulted in greater proportions of younger age groups in the catch than all other cases, but showed a similar shape of the CAA curve in the older age groups, as did Case 1, and also similar results in terms of the state of the stock and management proposals. Large differences in the proportions of CAA age groups 0–2 from survey and pelagic data did not seem to have a great effect on stock assessment results. The reason for this may be that only age groups 3 and older are fully selected into the midwater fishery, so greater proportions of fish in age groups older than 3 (e.g. Case 3) would mean that the model minimises the effect of fishing mortality in terms of selectivity and estimate the stock to be more productive, thus showing a much more healthy stock and a much higher sustainable TAC.

However, although proportions of age groups up to group 8 are presented in Figure 2, age groups 6–8 were pooled with age group 5 to form a 5+ group in the model, because their proportion to the total numbers is usually <10%. Therefore, the actual results in terms of CAA proportions that are important are those of age groups 3–5. Taking these results into consideration, more effort should be devoted to estimating the age of groups 3–5, because

Table 2: Stock assessment results of the Namibian horse mackerel stock using an age-structured production model with catch-at-age data derived from catch-at-length data of the midwater fleet, pelagic fleet and acoustic biomass surveys, and four different cases of age–length keys (ALKs) generated from 1996 otoliths as well as different age readers (second column)

Case	ALK case description 1996 (n = 240)	Model fit (–ln L)	Current biomass (million t)	Current biomass depletion (B/K)	MSY (t)	MSYL (B_{MSY}/K)	State of the stock	TAC recommendation (t)
1	Readers 1, 3, 6 and 7, mode of first three readings	–34.87	1.22	0.29	357 000	0.37	Overutilised	320 000
2	Reader 6, sixth reading	–24.03	1.43	0.34	360 000	0.37	(Slightly) overutilised	350 000
3	Reader 2, sixth reading	1.84	5.91	0.79	639 000	0.37	Underutilised	640 000
4	Reader 4, mode of six readings	–54.92	1.85	0.38	405 000	0.38	Sustainable	400 000

–ln L = Negative log-likelihood
B/K = Current biomass/pristine biomass
MSY = Maximum sustainable yield
MSYL = MSY level
B_{MSY} = Biomass at maximum sustainable yield
TAC = Total allowable catch that would be recommended in each case

those groups have the greatest influence in terms of stock assessment. Age-reader performance on age groups 3–5 needs to be evaluated on a regular basis before any results are used in the ASPM.

As the gradients indicating bias did not seem to change significantly from the first to the third or sixth reading of most readers, it appears unnecessary to conduct replicate readings of the same sample for the purposes of routine ageing. Rather, it appears more important to collect and read more samples in certain length classes in order to reduce the impact of individual 'difficult' specimens on the proportions in the ALK, as shown by Baird (1983). The important length classes are those containing age groups 3–5, i.e. fish of 20–30 cm TL. Consequently, survey sampling should be increased on those length classes. In addition, length classes most common in the catch may vary from year to year, and the age data from the midwater trawl fishery plays a great role in influencing the stock assessment results. Sampling effort on the midwater fishery should therefore be increased in terms of enhancing increase sample size and decreasing variability in the data. As length distributions also influence the eventual CAA estimate, sampling and raising length distributions from midwater catches should be improved, as described by Quinn *et al*. (1983), Kimura (1989) and Lai (1993).

As age groups younger than six years are the most important in the model results, and the time-consuming burn-and-slice technique is recommended for the otoliths of larger (older) horse mackerel, we suggest that the whole otolith or surface-reading method be revisited for horse mackerel in Namibia to reduce otolith preparation effort and hence permit an increase in the number of otoliths of key lengths read. Such a method allows the reader to gain a perception of fish size through the size of the otolith viewed whole, likely reducing the third common ageing error (incorrect identification of annuli vs false rings, or the grouping problem) considerably.

Currently, constant recruitment is assumed for the annual assessment, but year-class strength more than likely varies year-on-year, so applying a single ALK to length distributions over several years can mask strong year classes. An example is the case of the strong 3-year-old cohort of 1996. The influence of that cohort would have been reduced if an ALK were produced annually from current data. Therefore, the production of annual ALKs for this stock is crucial.

Summary Proposals for Age Determination of Namibian Horse Mackerel

Management advice is extremely sensitive to the catch-at-age information used in the model, suggesting that adequate resources (funding and human capacity) need to be allocated to routine age determination. Moreover, we propose that:

- Age–length keys be produced annually, for both survey and commercial catches.
- Simpler, more cost-effective, methods such as the whole otolith method or even the use of otolith weight as an estimation tool should be investigated (Boehlert 1985, Francis and Campana 2004).
- Most reading effort should be directed at age groups 3–5, and the performance of each reader should be assessed in terms of those age groups. Fewer 6+ otoliths should be read; these take disproportional preparation time (only otoliths of larger fish are sliced) and reading effort, whereas they are not well represented in the catches.
- Age subsampling should be proportional to the length distributions of the midwater fleet, as opposed to the currently applied fixed age subsampling. This would automatically provide more weight to the common length classes and hence the age groups most abundant in a given year, so reducing the variability at age. Overall precision would be enhanced in this manner, and scarce resources would be deployed optimally.
- All readers (even those with poor precision) could be involved in age reading, given that their bias is negligible and their enumeration of age groups 3–5+ is comparable. Age-reader performance could be evaluated by testing for

age bias in the most abundant age groups (3–5+) by χ^2 or likelihood ratio tests (e.g. Lai *et al.* 1996).

- A cost-precision analysis needs to be conducted for Namibian horse mackerel, looking at model-induced variation vs between-reader variation and reader effect vs estimating proportion-at-age (predicting age/reading age; e.g. Richards *et al.* 1992).
- There is utility in compiling age data along with an age–error-at-age matrix. For example, the CV of the comparison of readers' ages and reference age (Chang 1982) could be used for this purpose in the stock assessment model. However, caution is necessary because there are practical limitations in correcting for ageing error (Campana 2001).

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