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Consequences of bias in age estimation on assessment of the northern stock of European hake (*Merluccius merluccius*) and on management advice

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Abstract:

The results of a pilot tagging study on hake (*Merluccius merluccius*), conducted in the northern part of the Bay of Biscay in 2002, indicate that growth rates for this stock may be currently underestimated because of biased estimates of age. The impact that such a bias may have on the stock dynamics and the trends of the key population parameters, recruitment, spawning-stock biomass (SSB), and mortality are investigated. Assuming new growth parameters, a new age–length key is derived and used to produce and catch-at-age data and abundance indices, which are then used to assess the stock. Bias in estimating age affects the absolute levels of fishing mortality and stock biomass estimates, and also impacts the trend in SSB. However, trends in fishing mortality and recruitment are comparable, and the stock status with respect to precautionary reference points is broadly the same. As expected, the simulation also shows that the stock may be more reactive to changes in fishing levels, which affect medium-term forecasts. Long-term sustainable yields may also be impacted.

Keywords: age estimation, European hake, growth, management, simulation, stock assessment, tagging

Introduction

In June 2002, a pilot tagging experiment on European hake (*Merluccius merluccius*) was conducted by Ifremer on the "Grande Vasière", a nursery area located in the northern part of the Bay of Biscay. A total of 1307 hake in the size range 13–58 cm (with a mode at 28 cm) was tagged and released (de Pontual *et al.*, 2003). To date, 41 have been recovered with a time at liberty from 1 to 1066 days. Results from the experiment indicate that current estimates of age could be biased and, as a consequence, that growth could be underestimated (de Pontual *et al.*, 2006). The somatic growth of the recoveries was twofold higher than expected from published von Bertalanffy growth functions for the species in the Bay of Biscay. Growth underestimation was related to age overestimation, which was demonstrated by two independent analyses. First, blind interpretation of marked otoliths by two experts involved in the routine age estimation of the species showed that the age estimates were neither accurate (inconsistent with oxytetracycline mark position) nor precise. Second, the predicted otolith growth was inconsistent with the observed otolith growth. Both types of otolith analyses invalidated the internationally agreed otolith ageing method for hake.

Age estimation plays a vital role in the age-based assessments of many stocks in the North Atlantic. The northern stock of hake is no exception, being assessed annually by the ICES Working Group on the Assessment of Southern Shelf Stocks of Hake, Monk, and Megrim (ICES, 2005) using Extended Survivors Analysis (XSA, Darby and Flatman, 1994), an age-based sequential population analysis model. Since 1992, otolith analyses have been employed routinely to build annual age–length keys (ALKs), which are subsequently used to estimate catch-at-age data, age-structured indices of catch per unit effort (cpue), and catch- and stock weights-at-age. Moreover, maturity-at-age is used to estimate spawning-stock biomass (SSB), although it is not updated every year and is also based on an ALK (Martin, 1991; ICES, 1993). Hence, bias in the age estimations may impact the assessment results and management of the stock.

Here, we look at the potential effects that such a bias may have on the assessment of the stock conducted by ICES and on subsequent management. For this purpose, we have chosen a deterministic simulation approach.

Material and methods

Errors in ageing in catch-at-age models are frequently accounted for by supplying an ageing-error matrix (Fournier and Archibald, 1982; Richards *et al.*, 1992). This matrix defines the probability of assigning a particular age to a fish with a given true age. For instance, this approach was used by Bradford (1991) and Reeves (2003) to test, by way of simulations, the general implications of age-reading errors on stock assessment and management. Here, however, we decided not to follow this approach, partly because data on hake age-reading errors available from tagging are still scarce, and partly because our objectives are somewhat more restricted, because we are primarily interested in investigating the impact of systematic over-ageing. Instead, a new average ALK based on theoretical growth parameters was generated. This simulated ALK was then used to build alternative age-structured data sets for use in the age-based assessment model during assessment of the hake stock in 2005 (ICES, 2005). An assessment (referred to as "simulated ALK" herein) was then carried out with these new data sets and compared with the 2005 assessment based on current ALKs (referred to as "current ALKs").

Simulating an ALK

The simulation is based on an approach described by Salthaug (2003) to model changes in ALKs over time. That model is based on the usual assumption that fish lengths are distributed normally in each age group a, with expectation μ_a and standard deviation σ_a. Then, given that a fish has age a, the probability that its length lies in the lth interval is given by

$$P_{a,l} = \frac{1}{\sqrt{2\pi}\,\sigma_a}\int_{x_l - w/2}^{x_l + w/2} \exp\left\{\frac{-\left(x-\mu_a\right)^2}{2\sigma_a^2}\right\} \mathrm{d}x, \qquad (1)$$

where x_l is the midpoint of the lth length interval, and w is the width of the length frequency intervals.

$P_{a,l}$ needs to be normalized across length groups for each age in order to remove any possibility of having fish outside the valid size range. Then,

$$P_{a,l} \rightarrow \frac{P_{a,l}}{\sum_l P_{a,l}}, \text{ so that } \sum_l P_{a,l} = 1. \quad (2)$$

$P_{a,l}$ is formed by assuming the von Bertalanffy growth equation with assumed parameters to compute the expectations of length at age μ_a (L_∞ = 120 cm; K = 0.2; t_0 = 0). These values are a "rough" update from ICES (1993) to obtain growth rates close to observations made during the tagging experiment (de Pontual *et al.*, 2006). Next, another usual assumption is made by considering that the standard deviation of length-at-age is directly proportional to the mean size-at-age so that an age-invariant coefficient of variation exists. We simulated constant CVs of length at age to be 0.1 and 0.2.

The simulated ALK is obtained by combining the proportion of fish of given age belonging to a given length with the proportion of fish in the population belonging to a given age, using the following equation:

$$Q_{a,l} = \frac{P_{a,l} \times r_a}{\sum_a P_{a,l} \times r_a}, \quad (3)$$

where r_a is the proportion of fish at age a. This proportion is unknown but could be estimated from survey data (Salthaug, 2003). In our case, however, such data were not available. It was therefore approximated using a simple population model with a total mortality rate Z. The proportion can thus be calculated as

$$r_a = \frac{\exp(-Za)}{\sum_a \exp(-Za)}. \quad (4)$$

We are aware that this introduces some circularities; indeed, the estimates of fishing mortality rates obtained from the assessment will depend on the assumed value of Z. In order to investigate the sensitivity of the results to this assumption, three values of Z were used in the simulations (Z = 0.4, Z = 0.6, and Z = 0.8). We chose this range of values because with the "simulated ALK", we can reasonably anticipate an estimated average total mortality rate larger than that obtained with the "current ALK", which was around 0.4 (ICES, 2005).

Quarterly and annual simulated ALKs are generated using equation 3. They are then used to produce, with the same procedure as in the assessment of the hake stock in 2005 (ICES, 2005), the catch-at-age matrix, the average weight-at-age in the catch, the indices of abundance by age group for the fishing fleets and surveys used to "tune" the assessment, and a new maturity ogive at age from the corresponding length distributions.

Assessment

Both assessments were conducted with the same rationale, using similar model settings (ICES, 2005). Discards, although significant in this fishery, were removed from the catch data, and age 0 was then removed from the resulting landings-at-age matrix because of data inconsistencies in recent years. This age group is, however, still used in the assessment, because indices for age 0 are available from the survey. An XSA was carried out for each individual "tuning" fleet separately in order to screen possible trends and large residuals in catchabilities-at-age and also to select ages, years, and fleets to tune the model. For the "simulated ALK" assessment, this leads to the use of age-structured cpue data from three fishing fleets, one fewer than in the "current ALKs" case (Table 1). Changes in the age distribution of the tuning indices generated by the simulated ALK also produce a different selection of age classes.

Management and precautionary reference points

In 1997, ICES adopted the precautionary approach for its fisheries advice by establishing reference points in terms of spawning-stock biomass and fishing mortality (ICES, 2001). Management advice is formulated on the basis of the stock status (as estimated from the assessment) in relation to these reference points.

Here, we estimated precautionary (pa) reference points separately for each assessment, assuming that the ageing bias would impact all aspects of the assessment, including the estimation of reference points. They were defined using the 2003 ACFM rationale (ICES, 2005) applied to the "current" situation. As the stock-recruitment scatter plots indicated no clear impairment in recruitment at low SSB and as the range of SSB values is large, then the biomass reference points were estimated by taking the lowest observed spawning stock (B_{loss}) as the limit SSB B_{lim}, a level at which, in this case, the dynamics of the stock are unknown. To ensure with high probability that the stock avoids that limit point, a threshold, B_{pa}, was set by adjusting B_{lim} using a fixed multiplier: $B_{pa} = B_{lim} \times 1.39$ (ICES, 2001). Similarly, limit fishing mortality rate was taken as F_{loss} (Cook, 1998), a mortality rate above which the stock would be expected to decline to an equilibrium spawning stock below the lowest observed value. F_{pa} was set by adjusting F_{lim} using a fixed multiplier: $F_{pa} = F_{lim} \times 0.72$.

To estimate the state of the stock, current SSB was taken as the estimated SSB in the final year of the assessment and current mean F was estimated by averaging F-at-age in the final year of the assessment over ages 2–6 for the "current ALKs" assessment and ages 1–3 for the "simulated ALK" assessment. This corresponds to age ranges where the catches in numbers are highest.

Medium-term forecast and yield-per-recruit analysis

To carry out a medium-term forecast, an age-based sequential population model was used to predict the hake population assuming constant recruitment and the current exploitation pattern. This exploitation pattern is equal to the average F-at-age over the last three years of the assessment. Recruitment was taken as the geometric mean of the assessment estimates over recent years, excluding the last years, which were not well estimated, and limiting the recruitment series to the period of corresponding low estimates of SSB (ICES, 2005).

Assuming the current exploitation pattern, a yield-per-recruit model (Thompson and Bell, 1934) was used to examine the effect of ageing bias on long-term management. Long-term yield per recruit, based on catch weight, F-at age, and natural mortality (M)-at-age were calculated for a series of levels of F.

Results

As expected, the catch-at-age matrix (Figures 1 and 2) shifts towards younger ages with far fewer catches above age 3. Compared with this major shift, the impact of our assumptions on the values of the CVs on length-at-age distributions and on total mortality rates Z for estimating the average proportion at age in the population is minor. Not surprisingly, with increasing Z, the shift towards younger ages is larger.

For the EVHOE French surveys, the new age group distributions among the observed quarterly length distributions are more consistent than in the original data, because they fit better the observed first two modes (Figure 3).

The trends in key variables (recruitment R, SSB, and mean F) of stock dynamics for all assessments are presented in Figure 4. As in recent assessments (ICES, 2005), the estimate of the last year's recruitment (here, 2004) is not considered reliable because it is based on very little information. It has therefore been removed from the analysis. This estimate is usually revised when the corresponding cohort is integrated further into the catch-at-age matrix and abundance indices, providing more information for the stock assessment model (ICES, 2005). Some differences in absolute values of estimated mean F and SSB can be observed depending on both the specific assumptions on CVs on length-at-age and the level of Z for the "simulated ALK". These differences are smaller, however, than those observed between, on one side, the "simulated ALK" assessments and on the other side, the "current ALKs" assessment. Recruitment and SSB are estimated to be much lower in the "simulated ALK" assessments than in the "current ALKs" assessment (recruitment from

100 to 250 million fish and from 150 to 350 million fish, respectively, and SSB from 50 000 t to 125 000 t and from 100 000 t to 250 000 t, respectively). Mean *F* is estimated to be much higher (from 0.45 to 1.0 y^{-1} and from 0.20 to 0.40 y^{-1}, respectively). This is because higher mortality rates (and as a consequence lower stock sizes, because these two variables are inversely related) are needed to accommodate the new age structure of the catch obtained with the simulated ALK. For SSB and *F*, this is somewhat mitigated by the use of a lower *Z*: in the "simulated ALK" assessments, for any given value of CV, decreasing *Z* from 0.8 to 0.4 leads to greater estimates of SSB and lower estimates of *F*, without impacting on the general trend. With a lower *Z*, there is more survivors in older age classes of the catch-at-age matrix, leading to lower estimates of *F* and larger stock numbers.

For all fits, trends in historical mean *F*s are similar. Recruitment trends are also comparable between all fits, with a tendency to decrease over the assessment period. On examining the SSB trends (Figure 5), however, two different periods are highlighted. Before 1998, the fits show large differences, giving different perceptions of stock status. After peaking prior to 1986, SSB decreased sharply to a low level when the "current ALKs" were used. The decrease was slower when the "simulated ALK" was used and the minimum SSB was offset by several years (1998 instead of 1992). After 1998, the three trends are comparable, and SSB has increased.

The stock status with respect to precautionary reference points is summarized in Figure 6. Contrasting results were obtained for biomass reference points: with the "current ALKs", the current SSB situation is just below the precautionary reference point, whereas it is above in all "simulated ALK" assessments. This result is attributable to the differences in the variation rate of the SSB with respect to reference points.

Changes in the rate of fishing mortality have an important impact on yield (Figure 7). With the "current ALKs", the maximum yield is obtained for a 30% reduction in *F*, whereas for the "simulated ALK", the maximum is obtained at larger reductions of 40–70%, depending on the assumptions on CVs and *Z*. In the latter case, however, the gains to be expected are greater, up to a 40% increase in equilibrium yield per recruit for a "simulated ALK" with CV = 0.1 and *Z* = 0.8, compared with just 3% for the "current ALKs" situation. It is also of note that the absolute values of yield per recruit vary with the ALK selected.

The analysis of medium-term landings and SSB presented in Figure 8 was carried out by comparing the effect of a 30% reduction in *F* with the *status quo* situation (i.e. *F* maintained constant at its "current" level). After a short-term decrease, a reduction in *F* leads to increased medium-term landings in each assessment. These increases are minor (<2% after 10 years) for the assessment based on the "current ALKs", but are greater in the "simulated ALK" assessments (from 7 to 17%, depending on assumptions on CVs and *Z*). Moreover, the landings increase faster, the *status quo* level being exceeded after 3–5 years (2008–2010) instead of after 7 years (2012) for the "current ALKs" assessment. Similar results are obtained for SSB: 40% increase obtained after 10 years using the "current ALKs" assessment, whereas the same level is reached after just 3–5 years with the "simulated ALK" assessment. After 10 years, the increases are from 47% to 57% using the "simulated ALK" assessment.

Discussion

The current assessment of the northern hake stock assumes that age estimation is error-free. This is rarely the case for fish stocks (Richards *et al.*, 1992), and for hake recent findings from a tagging experiment revealed that the current age estimations may be positively biased (de Pontual *et al.*, 2006). Here, we show that there could be repercussions on our perception of past stock dynamics and more importantly on fishery management in the medium and long term.

Although ageing bias leads to comparable trends in estimated recruitment and *F*, the estimates of these two parameters differ significantly in terms of level. If hake are assumed to grow faster, stock biomass and numbers are much lower and fishing mortality is much higher. This is the consequence of a skewed catch-at-age matrix towards younger ages, leading to greater mortality and hence lesser stock abundance. For SSB, we find that estimated levels and trends are different if bias is assumed, the minimum value in the series being offset by several years between the "current ALKs" and "simulated ALK" assessments. These results are consistent with findings previously published by Rivard (1989), who tested the impact of over-ageing, but are, to some extent, different from those obtained by Reeves

(2003). The difference could be explained by the smaller order of magnitude of age-estimation biases used in Reeves' (2003) simulation, which may not have given clear trends in the SSB level estimation and by the fact that the age range used to calculate mean *F* was kept constant between scenarios. If so, this would have led to a systematic decrease in mean *F* whatever the ageing bias assumption used (Reeves, 2003). We note, however, that, in Reeves' study, under-ageing tends to result in a higher estimated mean *F* than over-ageing, a result somewhat consistent with our own in which the "current ALKs" situation would equate to an over-ageing bias.

The large differences in levels of estimated population parameters resulting from age estimation bias do not necessarily constitute an issue, because in terms of management advice given by ICES, the relative trends of *F* and SSB are more important than absolute values. If we examine the stock status with respect to precautionary reference points, the three assessments give similar results in terms of mean *F* classification, each assessment being below F_{pa}. For SSB, the current levels estimated by the assessment model could lead to different stock classification depending on the ALK used. For both parameters, however, the current situation is very close to the limit reference points B_{pa} and F_{pa}. To avoid the drastic classification we obtained here, it may have been preferable to use a stochastic approach that could include uncertainties in population parameter estimates as well as ageing errors, and not just bias, as we have done here.

The effect of bias on medium- and long-term predictions is more significant than on the stock status. An assumption of faster growth by hake could lead to a greater sustained equilibrium yield and to faster and greater increases in landings following management measures such as a reduction in *F*. Yet again, this is consistent with previous simulation studies using age-structured stock assessment models (Lai and Gunderson, 1987; Tyler *et al.*, 1989; Kimura, 1990; Coggins and Quinn, 1998). At present, this may not be considered as a significant impact by managers, because management objectives are defined mainly in terms of precautionary reference points (ICES, 2000). However, this situation may change in future. During the World Summit on Sustainable Development held in Johannesburg (United Nations, 2002), an international commitment was passed to move stocks to levels where they produce maximum sustainable yields by 2015. Our study shows that, in such a context, the consequences of a reduction in fishing mortality may well be much more important than what we believe today using the current ageing criteria.

When deriving the "simulated ALK", several assumptions were made on the values of the CVs for the distributions of length-at-age and on the relative abundance-at-age in the population. The differences between "current ALKs" and "simulated ALK" in stocks trends and medium- and long-term projections were somewhat less severe with the use of larger CVs and lower values of *Z*. The use of a lower *Z*, which tends, as stated above, to distribute more fish into the older age classes of the catch-at-age matrix, counteracts to some extent the effect of an assumed faster growth. Furthermore, assuming a larger CV on the length-at-age distribution leads to lower estimates of average stock weights-at-age for older ages, which are then used to estimate SSB and landings in the stock projections. The expected gains in medium-term landings and SSB and in long-term yields are therefore lower, and even for a CV of 0.2 and a *Z* of 0.4, quite close to the assessment based on the "current ALKs". However, such values of CV and *Z* can reasonably be considered as a limit assumption. A *Z* of 0.4 is close to the estimate of average total mortality rate obtained with the "current ALKs" (ICES, 2005), whereas we can reasonably expect larger values with the "simulated ALK". Further, CV values of 0.2 generate unrealistically large lengths-at-age for the older ages in the population.

All predictions in this study were made on the assumptions of constant recruitment and exploitation pattern, and without discarding. If the exploitation pattern is modified to increase some fish escapement and if discards are included in the analysis, reductions in *F* will exert even more substantial effects on medium-term predictions and sustainable yields. Moreover, variations in recruitment would also impact predictions.

The objectives of this work were rather case-specific and limited to the examination, in an *ad hoc* manner, of the consequences of possibly revising the ageing criteria for hake in annual assessments conducted at ICES. We do not propose here an alternative to the current assessment of the stock, but the different perceptions of hake stock status we present do emphasize the importance of validating the age estimation method carefully. To date, validated data on hake age are insufficient to develop an alternative and robust age estimation method for the species. However, we expect that recent and forthcoming tagging experiments will provide such data and perhaps help to address this issue.

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Table 1. Fleet, age, and years selected for tuning the model in both assessments.

Abundance indices (commercial fleets and surveys)	**"Current ALKs"**		**"Simulated ALK"**	
	Years	**Ages**	**Years**	**Ages**
Trawlers from A Coruña (Spain) fishing in Sub-area VII	1985–2004	3–7	–	–
Trawlers from Vigo (Spain) fishing in Sub-area VII	1982–2004	2–7	1982–2004	1–5
Pair trawlers from Ondarroa (Spain) fishing in Sub-area VIII	1994–2004	2–6	1994–2004	1–3
Pair trawlers from Pasares (Spain) fishing in Sub-area VIII	1994–2004	3–6	1994–2004	1–3
RESSGASC survey (Bay of Biscay)	1987–2001	0–5	1987–2001	0–5
EVHOE survey (Bay of Biscay and Celtic Sea)	1997–2004	0–5	1997–2004	0–4
WCGFS survey (Celtic Sea)	1988–2003	1–2	1988–2003	1–2

Figure 1. Average number at age (and 95% confidence intervals) of hake over the period 1978–2004 from landings-at-age matrices used in the analysis (current and simulated ALKs, with two hypotheses for CVs and $Z = 0.6$). The shading will not show clearly in print - adjust it.

Figure 2. Average number at age (and 95% confidence intervals) of hake over the period 1978–2004 from landings-at-age matrices used in the analysis (current and simulated ALKs, with three hypotheses for *Z* and CV = 0.2). The shading will not show clearly in print - adjust it. Age class can be singular, but italicize *Z*

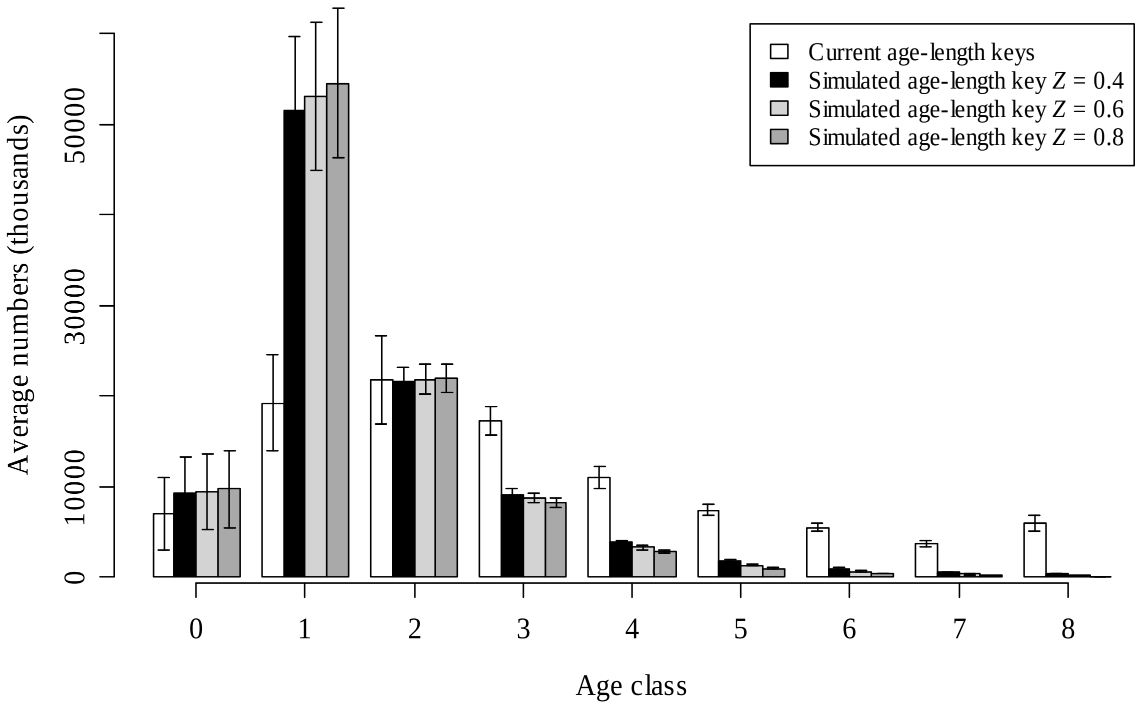

Figure 3. Length distributions with age group distribution (use a different word) for the 2001–2004 EVHOE survey tuning indices. “Current ALKs" (left) and “simulated ALK” with CV = 0.1 and *Z* = 0.6 (right). The y-axes need a caption.

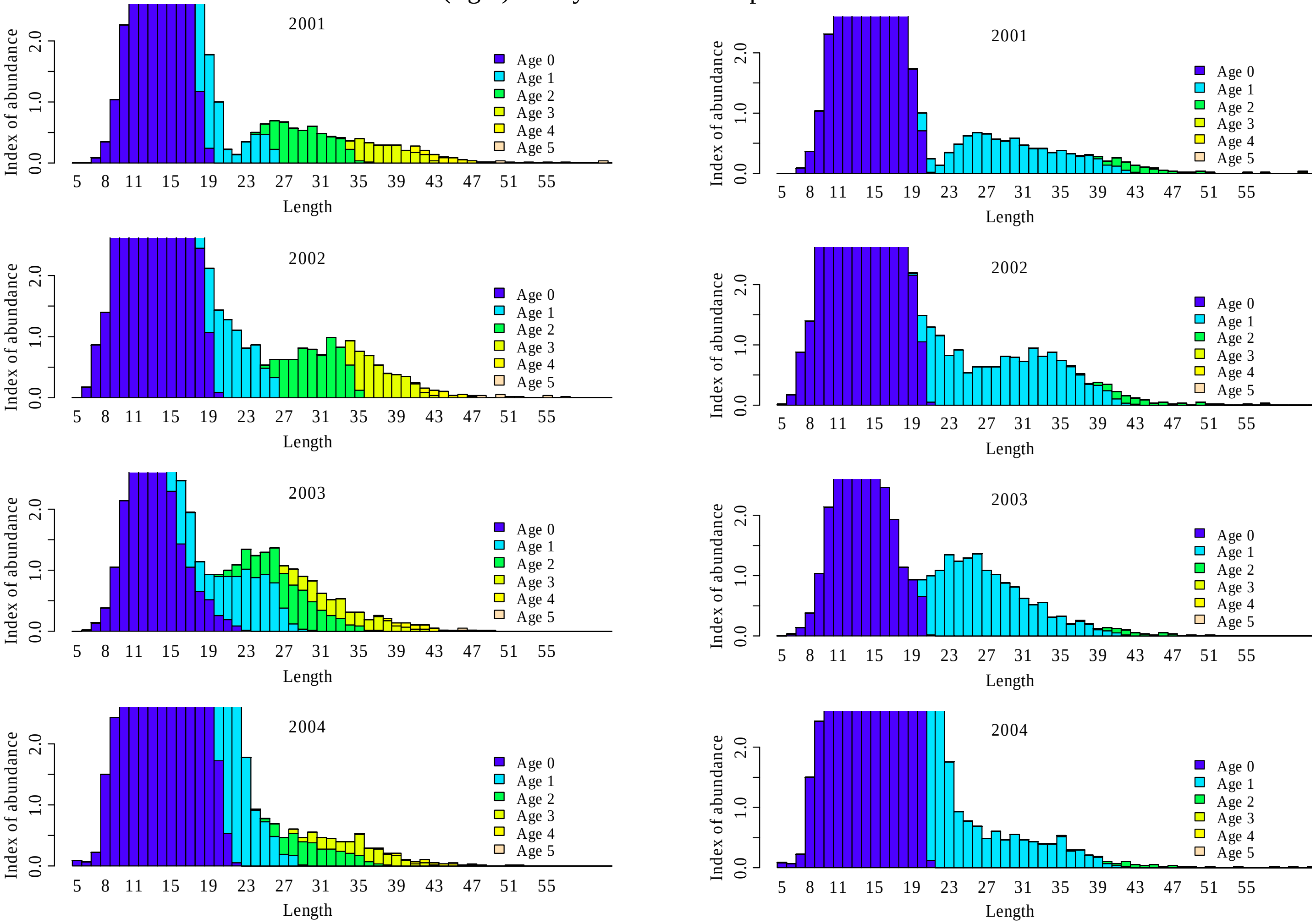

Figure 4. Comparison of stock trends from assessments conducted with “current ALKs" (thick solid line) and “simulated ALK” under several hypotheses on CVs of lengths at age and *Z* (dashed line with symbols). Italicize all *Z* and *F*

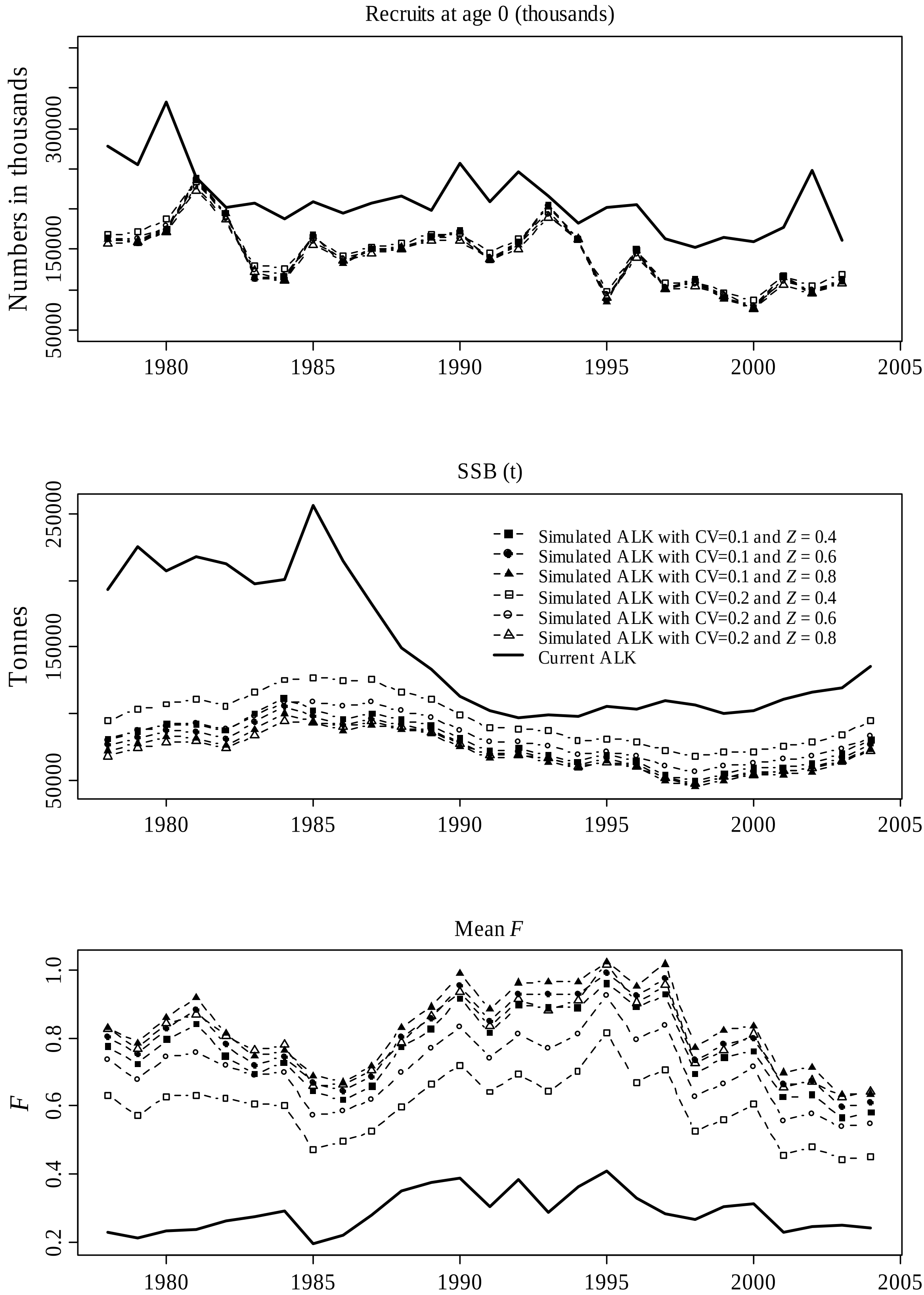

Figure 5. Comparison of SSB trends from assessments conducted with the “current ALKs" (thick solid line) and a “simulated ALK” with a CV = 0.1 on length-distributions-at-age and *Z* = 0.6 (dashed line with dots). Delete "SSB (t)"

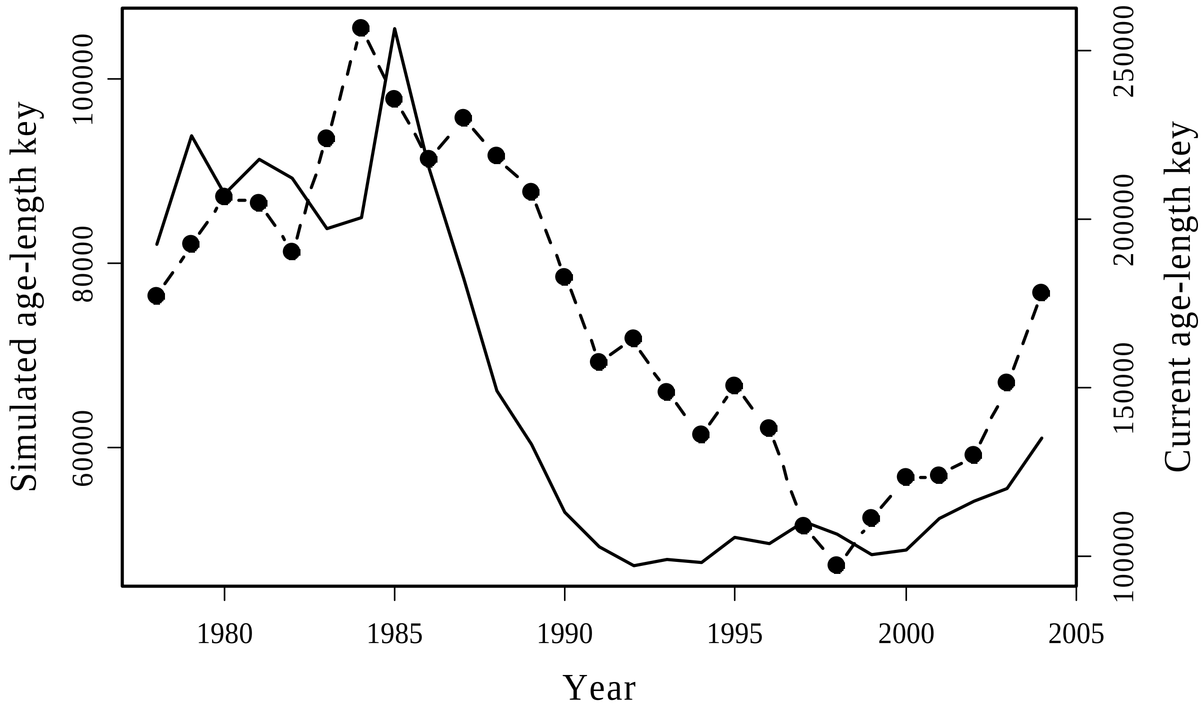

Figure 6. Status of the stock with respect to precautionary reference points obtained from assessments conducted with the “current ALKs” (grey dot) and the “simulated ALK” under various assumptions (*Z* = 0.4, squares; *Z* = 0.6, circles; *Z* = 0.8, triangles; CV = 0.1, black symbols; CV = 0.2, white symbols). Use pa in lower case as subscripted, but the top left box should read "Within precautionary values". Italicize all cases of *B* and *F*, but not their subscripts

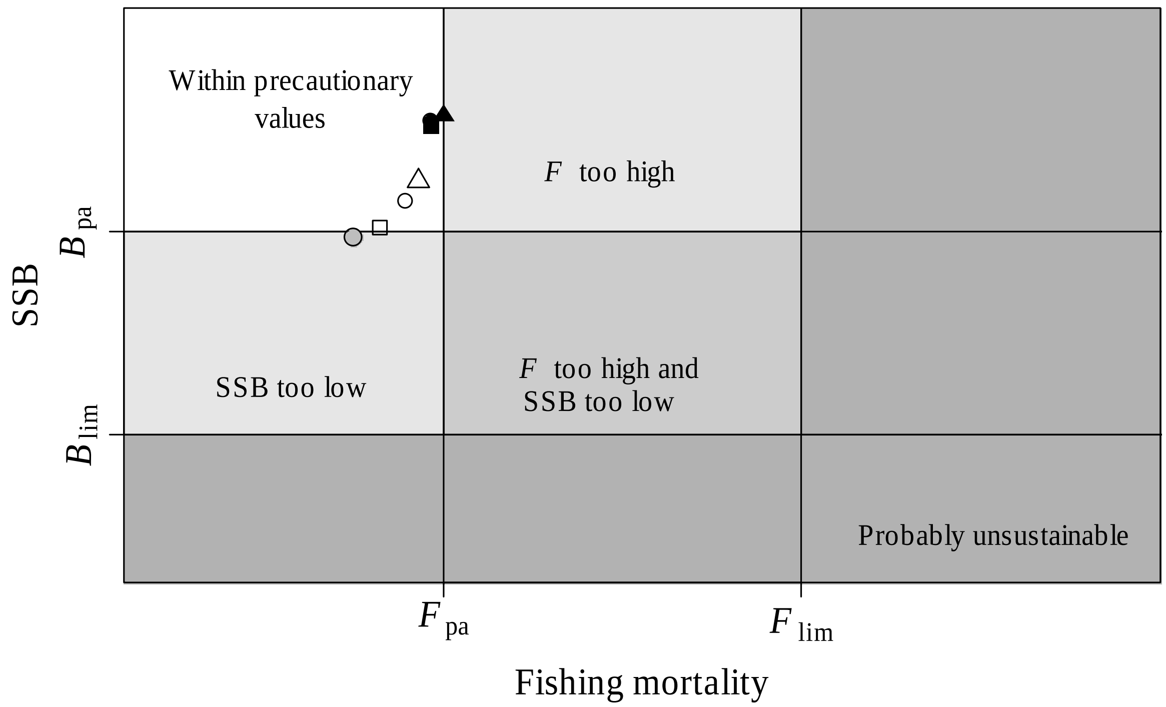

Figure 7. Comparison of yield per recruit (kg) for different levels of fishing mortality multiplier (m*F*) obtained from assessments conducted with the “current ALKs" (thick solid line) and “simulated ALK” under several hypotheses for CVs of lengths-at-age and *Z* (dashed line with symbols). Italicize all *Z* and *F*

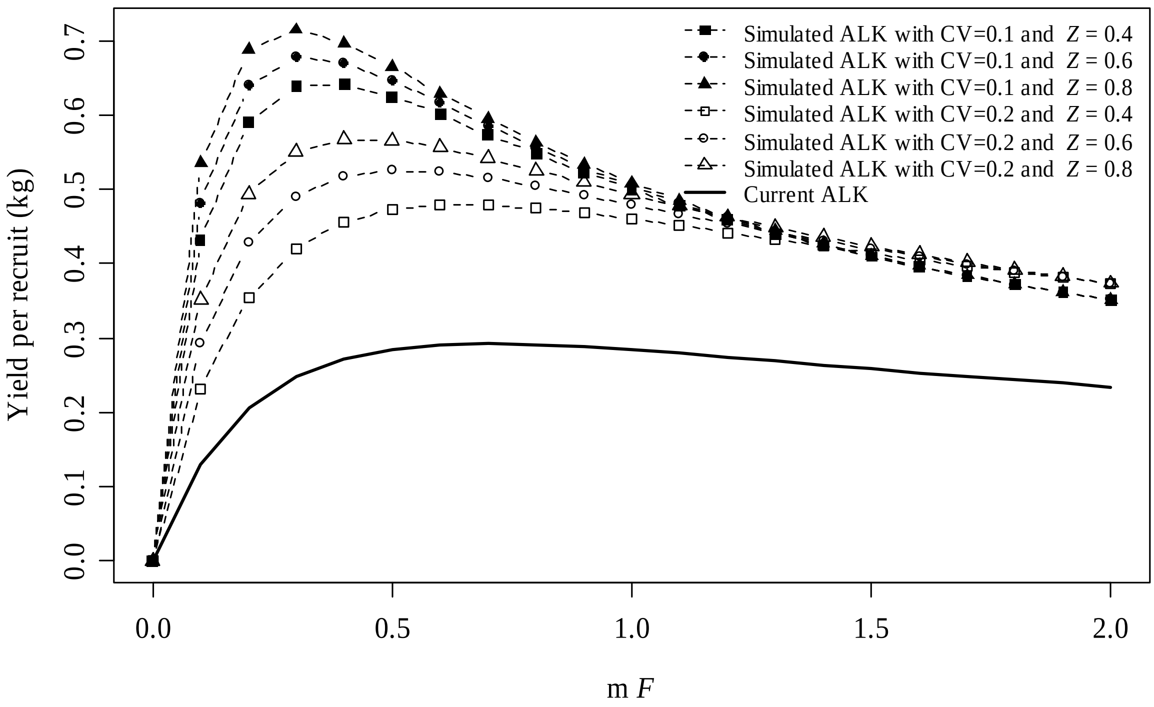

Figure 8. Medium-term relative gains (in %) of a 30% decrease in fishing mortality compared with the *status quo* obtained from assessments conducted with the "current ALKs" (thick solid line) and "simulated ALK" under several hypotheses for CVs of lengths-at-age and *Z* (dashed line with symbols). Italicize all *Z*