Part 3
Other FMSP analyses and guidelines

10. Comparisons of length- and age-based stock assessment methods

Graham M. Pilling, Robert C. Wakeford, Christopher C. Mees

10.1 INTRODUCTION

Length-based methods for the assessment of growth have, in the past, been the primary method used in tropical countries. The results, however, are only as good as the data to which they are applied (e.g. Majkowski *et al.*, 1987). Many commercially important species in the tropics are relatively long-lived and slow growing, with highly variable individual growth trajectories and protracted spawning periods (Manooch, 1987). These life history characteristics result in the super-imposition of successive modal classes, limiting the information used in length-based methods to estimate growth (Langi, 1990). Despite the historical perception that tropical fish would not show regular marks in hard parts (e.g. otoliths), an increasing number of studies have successfully validated increments deposited on a regular time scale (see Fowler (1995) for review). Therefore, potentially improved estimates of growth may be derived using length-at-age data.

Estimation of growth parameters cannot be examined in isolation. They are commonly used as inputs into a suite of biological and fishery assessment methods, as described in Chapter 3. Indeed, a major source of uncertainty in length-based stock assessments is the use of potentially biased growth parameter estimates to convert length into age. However, as there may be compensatory biases later in the stock assessment process, the use of more accurate growth parameter estimates may not necessarily result in more appropriate assessments, and hence management.

In this study, the performance of length- and age-based methods of growth parameter estimation was first assessed through computer simulation. Secondly, the performance of management based upon simple stock assessments derived using these growth parameters, and of more complicated age-based approaches such as VPA, were examined through management strategy simulation. Simulations were based on data from two species in the central Indian Ocean exhibiting different life-history strategies; a relatively long-lived, slow growing species of emperor (*Lethrinus mahsena*) and a moderately short-lived, fast growing species of rabbitfish (*Siganus sutor*). Conclusions are drawn on the performance of age- versus length-based methods for both tropical fish species.

10.2 METHOD

10.2.1 Growth parameter estimation

Monte Carlo simulations were performed to test the accuracy of length- and age-based growth parameter estimation methods for *Lethrinus mahsena* only. The approach used to model the population was comparable to the individual-based model described in Hampton and Majkowski (1987). In the current model, however, growth was described using a non-seasonal von Bertalanffy growth equation (Table 10.1). Estimates of individual growth variability within the population of *L. mahsena* were also incorporated (Pilling, Kirkwood and Walker, 2002). Recruitment was specified as a normal distribution and the variability as a lognormal distribution. The population was initiated at equilibrium with a set fishing mortality level. Individual fish were randomly assigned values from both growth and recruitment parameter distributions at birth. At each simulation step (approximately 1 month), whether each individual had survived or died was assessed, based upon their probability of survival. If they had died, the probability of capture (i.e. death due to fishing rather than natural mortality) was calculated based on the gear selectivity pattern (Table 10.1). If caught, the length and age of the fish was added to a catch matrix.

Length-based assessment of growth

Four hundred individuals were sampled from the simulated annual catch for five consecutive years to generate a time series of length frequency data for length-based growth parameter estimation. Growth parameters (L_∞, K and t_0) were estimated using the ELEFAN method (Pauly and David, 1981) within LFDA. The growth parameters with the highest score function identified using the amoeba search were accepted.

Age-based assessment of growth

A length-structured catch sampling design was simulated. Ten individuals were randomly sampled from designated 2 cm length classes. A von Bertalanffy growth model was then fitted to the length-at-age data through least squares methods.

For both length– and age-based approaches, simulations of *L. mahsena* were performed for a range of equilibrium fishing mortality levels seen in the field (F=0.05, 0.25, 0.7 and 1.2). For each mortality level, 100 sets of growth parameter estimates were developed for each approach through Monte Carlo simulation. A frequency distribution of parameter estimates was derived, and the mean value calculated. The bias in this mean, compared to the true "seed" population value (cf. Table 10.1), and coefficient of variation (CV) of the distribution were calculated as percentages.

10.2.2 Management strategy simulation

A management strategy simulation approach (Powers and Restrepo, 1998; see also Section 3.6.5) was used to investigate the knock-on effects of using alternative growth parameter estimates within different stock assessment approaches upon which management decisions were based. This approach models the underlying system (an operating model, based on parameter values in Table 10.1) and the perception of that system based upon catch data sampled from it (the assessment model) (see Figure 10.1). The key is that the entire management process relies on imperfect information. The simulation incorporates a range of uncertainties in the perceived model (Rosenberg and Restrepo, 1995), including process error (variability in growth) and model error (simplifying assumptions made in modelling biological processes).

The analysis was performed for both study species; *Lethrinus mahsena* and *Siganus sutor* (Table 10.1). Starting fishing mortalities for *L. mahsena* were identical to those described above. Those for *S. sutor* were F = 0.5, 0.75, 1.25 and 1.5.

Estimation of fishing mortality

Stock assessments provided estimates of current fishing mortality upon which management decisions could be based. Two assessment approaches were used.

The first was based upon estimates of total (Z) and natural mortality (M), which were then used to calculate F (F=Z-M; Figure 10.1a). Total mortality (Z) was itself estimated through three methods; Beverton and Holt's Z estimator (Beverton and Holt, 1956), a length-converted catch curve, and an age-based catch curve. The last approach did not require the use of growth parameter estimates, and hence eliminated one source of uncertainty. Two empirical estimates of natural mortality (M) were applied: Pauly (Pauly, 1980); and Ralston (Ralston, 1987).

The second approach used to estimate F was through direct application of either length- or age-based VPA models (see Wakeford *et al.*, 2004; Figure 10.1b).

Management rule

The selected management target level was $F_{0.1}$ (Caddy and Mahon, 1995). A management rule was used to define annual changes in fishing mortality which moved it toward $F_{0.1}$. Fishing mortality in the following year $F_{(y+1)}$ was determined by the relative values of the estimate of current fishing mortality ($F_{(y)}$) and of $F_{0.1}$:

If $F_{(y)} < 0.8*F_{0.1}$, then $F_{(y+1)} = F_{(y)}*1.2$,
else if $F_{(y)} > 1.17*F_{0.1}$, then $F_{(y+1)} = F_{(y)}/1.17$,[20]
else $F_{(y+1)} = F_{0.1}$.

The resulting change in fishing mortality directly affected the operating model; i.e. it modified the true underlying F (Figure 10.1). Twenty years of management were then simulated for each starting F level and each species. The 20 year simulation process was then repeated 100 times using each pair of estimated von Bertanaffy growth parameters. Pairs of L_∞ and K estimates and values of the other key parameters (e.g. M, $F_{0.1}$) used within the assessment were assigned at the start of the simulation and kept constant throughout the 20 years.

Performance measures

Performance of management based on different growth parameter estimation and assessment methods was examined using the following criteria:

- Ratio of exploitable biomass in year 20 of simulation relative to unexploited equilibrium levels.
- Frequency with which spawning stock biomass fell below a threshold value of unexploited levels during each of the 20 years.
- Fishing effort in the final year. Management target was F=$F_{0.1}$
- Average catch over the simulation period. Large fluctuations in total annual catch were identified at the start of the management period during VPA simulations (cf. Figure 10.1b). The average was therefore calculated from the last 10 years of management (i.e. 10-19 years) in this case.

Where VPA was not simulated, initial runs showed that the use of age-based parameters resulted in under-exploitation of the stock, while length-based parameters either under- or over-exploited the stock, dependent on starting fishing mortality. To compare performance directly, target fishing mortality was tuned so that $F_{0.1}$ was reached on average (see Pilling *et al.* (1999) for more details). No tuning was required for simulations using VPA assessment models (see Wakeford *et al.*, 2004).

10.3 RESULTS

10.3.1 Growth parameter estimation

Statistics for the distributions of 100 length- and age-based L_∞ and K estimates obtained at each of the four fishing mortality levels for *L. mahsena* are shown in Figure 10.2. Length-based methods over-estimated both L_∞ and K, compared to the mean input parameter values (Figure 10.2a). By comparison, at lower fishing mortalities, estimates of both growth parameters from age-based methods were less biased, and more precise. With increased levels of fishing mortality, however, the accuracy of length-based estimates of L_∞ improved, while performance of age-based estimation methods deteriorated. At higher fishing mortalities, therefore, estimates of L_∞ derived through

[20] Note that if F is increased by 20 percent when below the target, the equivalent is to decrease by 17 percent if above the target (e.g. the opposite of doubling effort (F*2) is to halve it (F/2)).

age-based methods were more biased, and less precise, than those from ELEFAN. Age-based estimates of *K* remained more accurate and precise than ELEFAN estimates (Figure 10.2b and d), which showed increasing over-estimation with increasing levels of fishing mortality.

10.3.2 Management strategy simulation

Particular combinations of total (*Z*) and natural mortality (*M*) estimation methods resulted in consistently more accurate and precise estimates of current fishing mortality dependent on the growth parameter estimation method. Where length-based growth parameter estimates were used, subtracting Pauly's *M* estimate from the Beverton and Holt *Z* estimate resulted in the best estimate of *F*, while subtracting Ralston's M from the length converted catch curve estimate of *Z* performed best where age-based growth parameter estimates were used.

Estimated values of current fishing mortality and $F_{0.1}$ after the first year of management were compared to examine the likely performance of annual management using length- or age-based growth parameter estimates. If the true fishing mortality was F=0.05, effort should be increased to reach $F_{0.1}$ (F=0.4 for *L. mahsena*). In contrast, if F=1.2, effort should be decreased drastically. For *L. mahsena*, the use of age-based growth parameters and the "best" performing combination of total and natural mortality estimates described above resulted in the most appropriate decisions at each starting fishing mortality level (Figure 10.3). Decisions showed the correct trend from confident to more cautious management decisions with increasing fishing mortality. In contrast, decisions based on length-based growth parameter estimates were less sensitive to increases in fishing mortality. Decisions were more cautious, calling for decreases in effort or drastic action at all levels. However, decisions also called for no change in effort in a high proportion of cases when fishing mortality levels were very high.

The comparison described above represents management decisions based upon the first year's assessment, when the population was essentially still at equilibrium with the fishing mortality level. The results of the management strategy simulations, which modelled the whole fishery assessment and management process over 20 years, were less clear cut. Performance resulting from the use of the two alternative growth parameter estimates for *L. mahsena* were compared at a starting fishing mortality level equal to $F_{0.1}$ (F=0.4), using the "most appropriate" total mortality estimation combination described above. Both sets of growth parameter estimates performed comparably in terms of the level of final year exploitable biomass and the number of years that spawning stock biomass was reduced below a threshold value (20 percent) of unexploited levels. However, results spanned a wide range of possible outcomes when using either set of growth parameter estimates. Age-based growth parameters resulted in a slightly narrower range of final year fishing mortality levels, and achieved the target level (F=0.4) in 25 percent of cases, as opposed to 15 percent of cases where length-based parameters were used. However, the range still spanned F = 0.1 to 0.9 (Figure 10.4). Age-based methods also performed slightly better for the average catch performance measure (not shown).

The use of age frequency distributions (age-based catch curves) in the estimation of fishing mortality for *L. mahsena* further improved the performance of management. The optimum in each performance measure was achieved in a greater proportion of runs, and the range of outputs was slightly narrower. However, the range of outcomes was still large, indicating that assessment outputs remained uncertain.

The use of either the length- or age-based VPA approaches (Figure 10.1b; Wakeford *et al.*, 2004) did not produce a notable improvement in management performance for *L. mahsena*. In addition, management performance was impaired by bias in growth parameters used to estimate natural mortality and the target fishing level ($F_{0.1}$) derived from the yield per recruit curve. This bias was notable for all starting fishing mortality levels with length-based methods but only at higher levels for age-based approaches (see Figure 10.2a and b).

The performance of length- and age-based VPA approaches was also examined for *Siganus sutor*. In contrast to *L. mahsena*, the use of age-based VPA, along with age-based growth parameters to estimate $F_{0.1}$, resulted in remarkable improvements in management performance. Age-based VPA achieved average catches at the MSY level in a greater number of cases (40-50 percent, dependent upon the starting fishing mortality) while the range of values was narrower and centred on the optimum value (Figure 10.5). A similar pattern was seen in the level of exploitable biomass. The use of age-based VPA also conferred benefits in terms of reducing the number of years in which SSB fell below a threshold level (22 percent of unexploited levels), although the result was highly influenced by the starting fishing mortality level. As for *L. mahsena*, management performance was often defined by biases in the estimate of $F_{0.1}$ (as a result of biases in the growth parameters) rather than the estimate of current F.

10.4 DISCUSSION

The results of this study are predicated upon the assumptions made within the operational model, and the values used to parameterize it. It is expected that results and conclusions will differ according to the geographic location of species and their particular life history strategy. Furthermore, it should be noted that the aim of this study was not to establish an optimum management strategy. Hence only one strategy was examined here ($F_{0.1}$ as target). Alternative management rules and targets may achieve different results in terms of management performance for these and other species, and might improve the performance of VPA approaches.

10.4.1 Growth parameters

Age-based growth parameter estimates for *L. mahsena* were generally more accurate and precise than those estimated through the use of ELEFAN, particularly at lower fishing mortality levels. The ELEFAN estimate of L_∞ was strongly influenced by the largest individuals present in the length frequency distribution. Although the seed mean value of L_∞ was 48.5 cm, individual growth variability resulted in individuals over 70 cm in length being present in the catch at low F levels. This positively biased the resulting L_∞ estimate. This bias reduced as fishing mortality increased, since larger individuals were preferentially selected out of the population. ELEFAN consistently overestimated K. Given the relatively slow growth of *L. mahsena*, modes in the length frequency data are comprised of a large number of age classes, and hence growth curves fitted through those modes will overestimate K. Negative correlation between the two parameters meant that as the value of L_∞ decreased, K became further overestimated. Age-based estimates were also influenced by the selection pattern of fishing. Relatively fast growing individuals survived through length classes, so that at high fishing mortalities, the larger length classes were comprised of relatively young individuals. This decreased the information available on L_∞, and indirectly affected the estimate of K.

Results suggest that age-based methods should be used to estimate growth in species like *L. mahsena*. There is benefit in sampling a population early in its exploitation, to ensure older, larger individuals are present, providing more information on L_∞. Smaller, younger individuals should also be sampled to improve estimates of K. Specific sampling gears may be required to do this.

10.4.2 Assessment of management performance

Under equilibrium conditions, use of age-based growth parameter estimates and accompanying estimates of current fishing mortality appeared to result in the best management decisions for *L. mahsena*. However, the management strategy simulations considered the inter-annual performance of management, and incorporated additional uncertainties compared to the simple study. It showed that while there was benefit for management performance in using age-based growth parameter estimates, there was still considerable uncertainty in outputs, and benefits were less clear cut. This, in part, was the result of using length-based total mortality estimation methods in the assessment process, since they required uncertain growth parameter estimates. Use of age-based catch curves further improved the performance of management for *L. mahsena*, while the use of VPA approaches appeared to confer little additional benefit. Normally, the derivation of age frequency distributions for catch curves would require reading of a large number of otoliths, or derivation of an age-length key. However, there is the potential to use otolith weight to derive realistic age frequency distributions for such a purpose (Pilling, Grandcourt and Kirkwood, 2003). If age-based catch curves cannot be derived, the use of age-based growth parameters and length-based methods appears the next best course. However, catch curves will not be appropriate for all situations. At high fishing mortality levels where stock age range is reduced, for faster growing species with few age classes, or where a species shows high recruitment variability, the accuracy of catch curves estimates is likely to be poor.

In contrast to *L. mahsena*, the use of age-based VPA resulted in considerable improvements in management performance for *Siganus sutor*, when compared with that of length-based VPA.

In all cases, uncertainty in management arose since the estimate of $F_{0.1}$ from the yield per recruit curve is strongly affected by the value of natural mortality. In this study, natural mortality was derived through empirical formulae based upon growth parameter estimates. Natural mortality is notoriously difficult to estimate, and is likely to vary between ages. However, its influence on assessments should be considered when deriving management. Indeed, it is sensible to treat the analytical assessments performed in the simulations as one piece of the assessment process. Other approaches, such as the use of catch per unit effort data, should be used to support the findings.

A final issue for the use of age-based methods of assessment is cost. However, cost-benefit analyses detailed in Pilling *et al.* (1999) indicated the higher costs of age-based methods when compared to length-based approaches was offset by additional benefits in terms of management performance (e.g. improved sustainable yields). This was particularly true if preparation of otoliths was outsourced. Alternatively, costs of age-based growth estimation may be reduced by establishing a regional otolithometry centre. This would reduce the high initial expenditure required for age-based methods, while opening an additional income stream preparing otoliths for other regional organizations. A cost-benefit analysis of the use of potentially more data-intensive approaches such as VPA has yet to be performed.

TABLE 10.1
Parameter values used to simulate *L. mahsena* and *S. sutor* populations

Parameter	*L. mahsena*	*S. sutor*
L_∞ (cm)	48.5	36.6
K	0.14	0.42
t_0	-0.78	-1.36
Length weight a	0.0000806	0.000059
Length weight b	2.74	2.75
M	0.4	0.93
L_{m50}	27.5	18.0
L_{m75}	27.5	18.0
Stock recruitment	Shepherd SRR	Beverton & Holt R = 25 million h = 0.879
Recruitment CV	61%	82%
Recruitment peak	Oct – Feb	Nov – Mar
T_{c50} (L_{c50})	3.75 yrs (22.8 cm)	1.49 yrs (18.0 cm)
T_{c75} (L_{c75})	4.17 yrs (24.3 cm)	1.57 yrs (18.6 cm)

FIGURE 10.1

Flow diagrams presenting the simulated assessment processes. Method for estimating fishing mortality using (a) total and natural mortality estimates (Pilling *et al.*, 1999), or (b) VPA approach (Wakeford *et al.*, 2004)

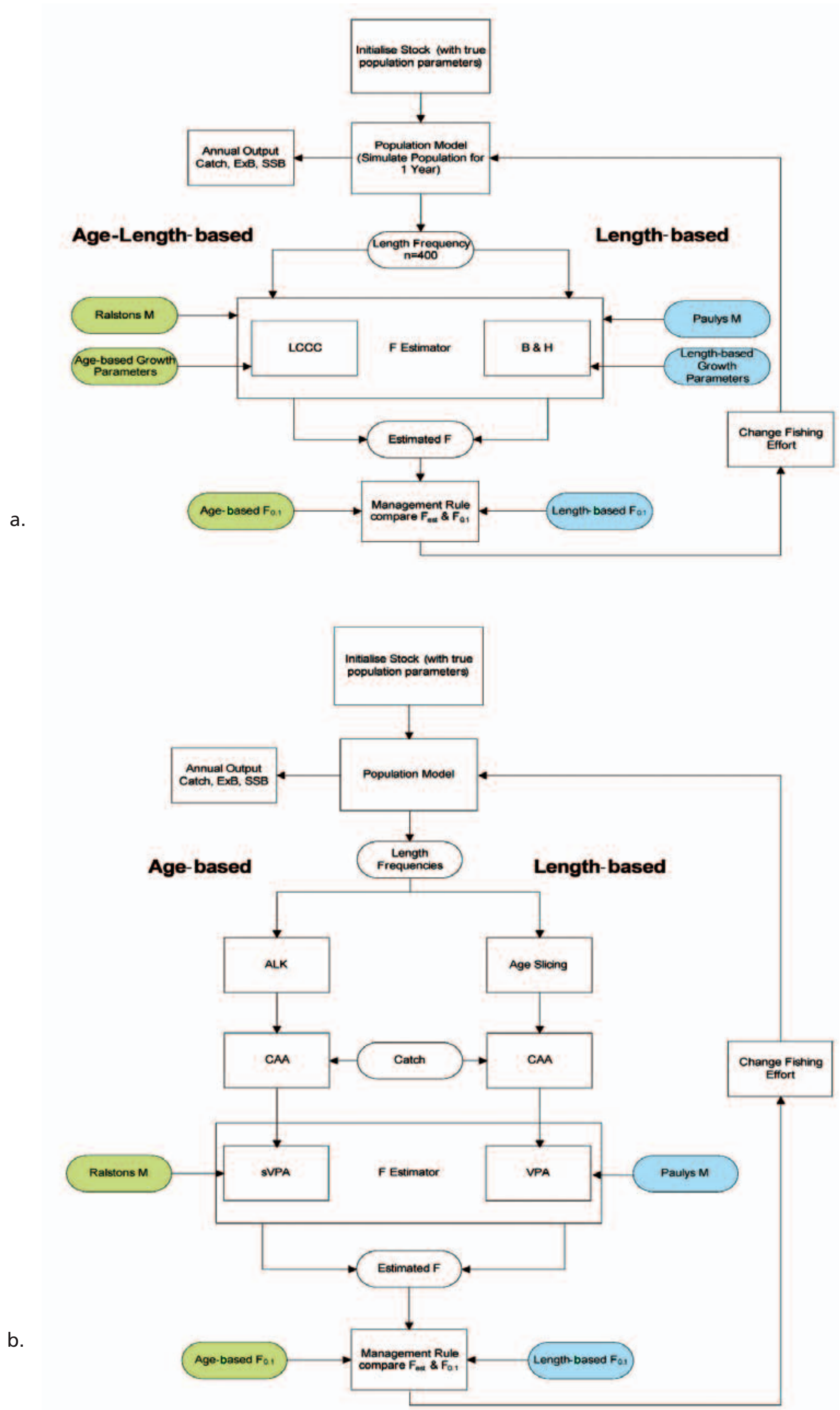

FIGURE 10.2

Statistics for length- and age-based von Bertalanffy growth parameter estimate distributions for *L. mahsena*. Bias (%) in the mean growth parameter estimate of L_∞ and K relative to the true "seed" value used in the simulation (L_∞=48.5, K=0.14) is displayed in graphs a and b respectively. Coefficient of variation (CV%) for L_∞ and K estimate distributions are in graphs c and d respectively

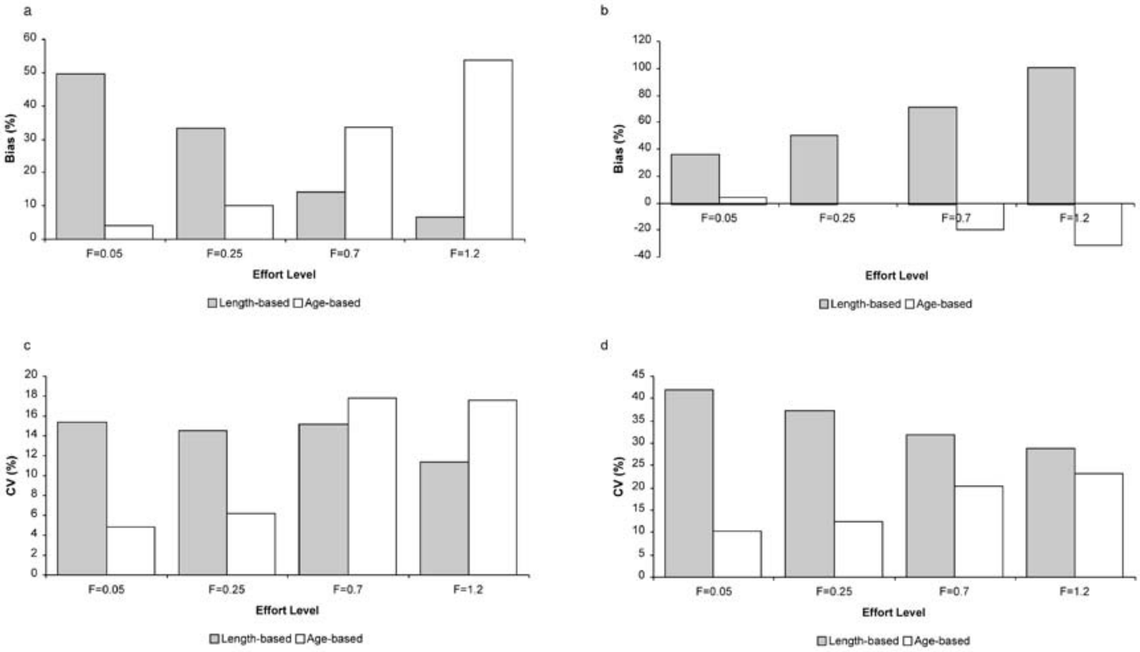

FIGURE 10.3

Distribution of management actions based on estimates of $F_{0.1}$ and current F derived for *L. mahsena* using length- and age-based growth parameter estimates, by initial fishing mortality level

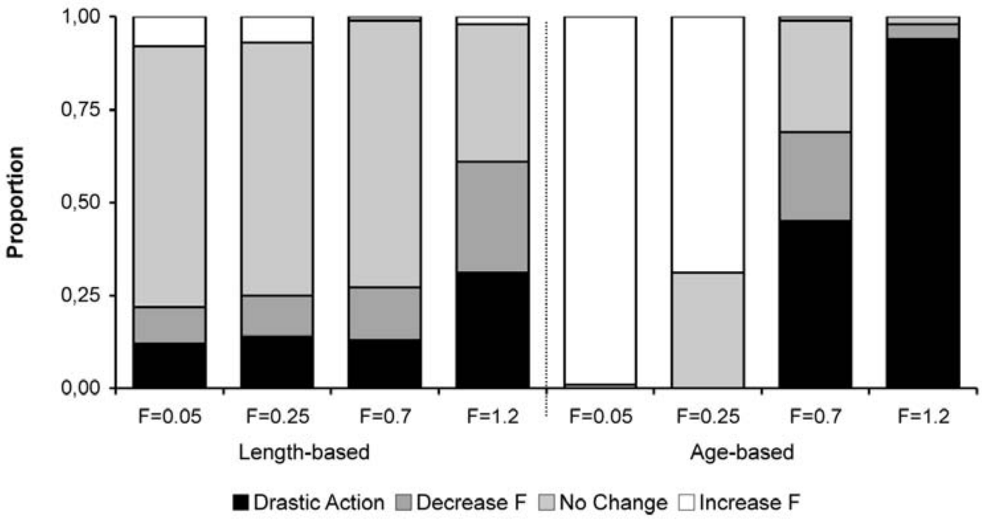

FIGURE 10.4
Final year fishing mortality level achieved using age-based and length-based parameters of *L. mahsena* for a starting fishing mortality of F=0.4. (Target=$F_{0.1}$=0.4)

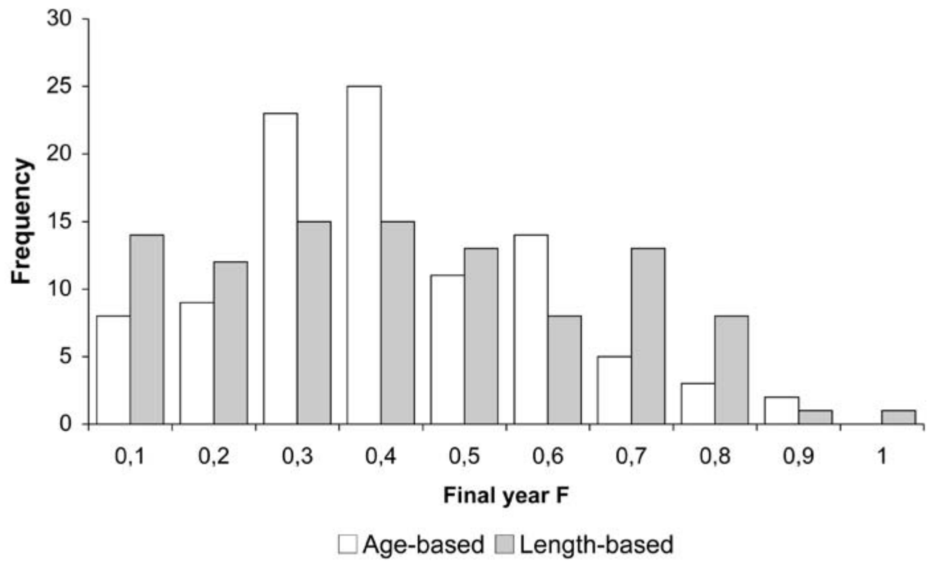

FIGURE 10.5
Histogram of the average catch for both length- and age-based methods for *Siganus sutor* for a starting fishing mortality of F=0.75 (MSY is 3 081 units)