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Hake species (*Merluccius capensis* and *M. paradoxus*) assessment in the Benguela Current Large Marine Ecosystem

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ABSTRACT

An important resource of the Benguela Current Large Marine Ecosystem (BCLME) is the hake fisheries, and accurate assessments of hake stocks are essential. Traditionally, the two species *M. capensis* and *M. paradoxus* have been assessed combined as a single stock, since commercial catch data does not distinguish the two species, but differences in biology and ecology suggest that this could lead to a biased assessment. Here, we apply three state space models to assess BCLME hake stocks off Namibia: Two independent single-species assessments, one for each species, and one combined assessment which treats the two species as a single stock. Catch-at-age information from commercial fishery and annual swept-area biomass survey estimates conducted during 1998–2012 were used, together with information on maturity at age, stock mean weight-at-age and natural mortality. The results demonstrate that the estimated spawning stock biomass of *M. capensis* has been increasing in recent years while estimated fishing mortalities are higher on *M. paradoxus*. These observations are not visible in the species-combined assessment. However, the species-combined estimates of fishing mortality and biomass have less uncertainty than the sum of the single-species estimates. Hence, the choice between species-combined and species-specific assessment is an example of a generic trade-off between bias and variance in assessments of structured stocks: Combining data and treating the two species as one decreases the variance by enlarging the data base but introduces a bias originating from difference in rates between the two species, when their relative abundances change in time.

1. Introduction

The Benguela Current Large Marine Ecosystem (BCLME) is endowed with abundance of biodiversity including commercially important fish stocks (BCC, 2012). The ecosystem is shared by Angola, Namibia and South Africa, a situation that underscores the need for collaboration at the ecosystem level, in ensuring sustainable utilisation of transboundary fish stocks. This Ecosystem is home to a well-developed commercial trawl fishery, exploiting two species of Cape hake (shallow water *Merluccius capensis* and deep water *M. paradoxus*) that extend from southern Angola southwards through Namibia and into South African waters (Fig. 1). The total stocks between Namibia and South Africa represent over one-third of the world hake biomass (Sylvia, 1995).

Given the importance of hake stocks for the Namibian and South African fisheries, and their transboundary nature-BCLME was established to monitor the major transboundary fish resources in the region (Strømme et al., 2015). The BCLME programme has therefore supported appropriate research that contributed to conservation and management of these

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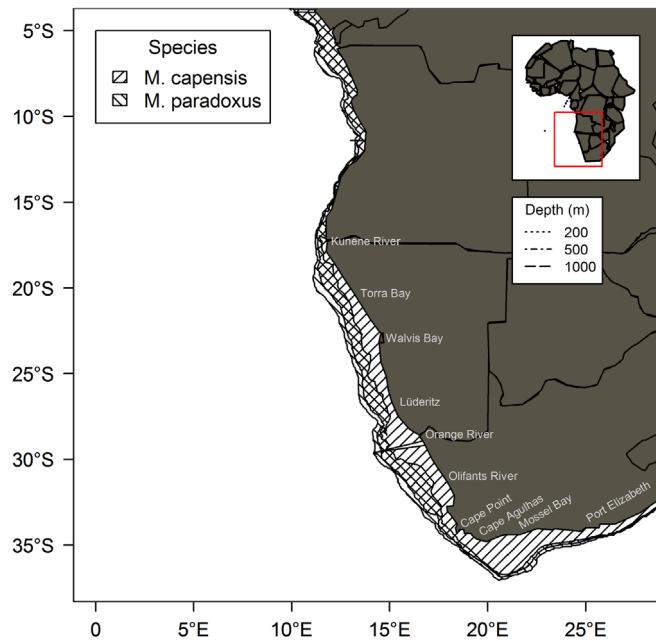


Fig. 1. Distribution of the BCLME shallow-water hake (*Merluccius capensis*) and deep-water hake (*M. paradoxus*) and place names referred in the text.

transboundary fish resources for many years (Strømme et al., 2015). Surprisingly transboundary stock assessment of these fish resources has not yet been carried out in the region and currently there is an ongoing international project Ecofish supporting effort to move towards split-species assessment, transboundary stock assessment and spatial explicitly assessment.

This work presents a stock assessment of two stocks *Merluccius capensis* and *M. paradoxus* off Namibia that have historically been assessed as a single stock (Butterworth and Geromont, 2001; Butterworth and Rademeyer, 2005; Kirchner et al., 2012) since commercial catch data does not distinguish between the two species and due to lack of a developed algorithm for separation of this data. The two hake species are morphologically very similar in appearance e.g. shape, structure and colour (Gordoa and Duarte, 1991; Lloris et al., 2005) but differing in numbers of vertebrae (von der Heyden et al., 2007) pigmentation of the gill rakers and colour of the anal fin (Gordoa et al., 1995) and the shape of otoliths and pectoral fin (Inada, 1981). The morphological similarity and overlapping distributions have made it difficult to register the two species separately in the commercial catches. This has prevented biologically plausible single-species stock assessments from being carried out. The species separating method in the commercial catches has since been developed (Johnsen and Kathena, 2012) and a single species assessment is now possible.

The purpose of this study is to illustrate the difference between combined and single species assessment and the implications thereof. The focus is on estimating species specific management quantities and assesses how that affects the current perceptions of the hake stock. A state-space model (Nielsen and Berg, 2014) is used to compare the joint species assessment using combined data with two independent single species assessments using data that has been separated into species. A key feature of the state-space assessment is time varying selectivity. Contrasting with the combined species assessment approach, a single species approach provides species specific estimates of spawning stock biomass and fishing mortality which are useful management quantities that can be used in management recommendation and ease the process of setting the total allowable catches (TAC).

The two stocks are characterized by marked differences in depth preference with *M. capensis* occupying 50–400 m bottom depth, while *M. paradoxus* inhabit deeper water 250–800 m (Gordoa and Duarte, 1991; Burmeister 2001). *M. paradoxus* overlaps with *M. capensis* between 250–400 m bottom depths (Botha, 1985, Boyer and Hampton 2001; Burmeister, 2001). Geographically *M. capensis* occupies shallower water and more northerly area than *M. paradoxus* (Burmeister, 2001), although, *M. paradoxus* is also observed in shallow water but only south of Lüderitz (Johnsen and Kathena, 2012). The survey data suggest that catches deeper than 600 m bottom depth are solely *M. paradoxus* (Johnsen and Kathena, 2012). Diel variation in bottom trawl catch rates of the two stock revealed that average catch rates were about 3.6 times higher around noon than during the night, but areas dominated by *M. capensis* recorded a higher diel variation (Johnsen and Iilende, 2007), indicating differences between the two species in vertical behaviour and catchabilities. Trophic analysis using stable isotopes has also suggested that *M. paradoxus* feed at higher trophic level than *M. capensis* (Iitembu et al., 2012).

Spawning patterns of the two hake species differ in area, depth and timing (Jansen et al., 2015). *M. paradoxus* spawn offshore 200–650 (Jansen et al., 2015), whereas *M. capensis* spawners were found in shallower water (Kainge et al., 2007). *M. paradoxus* are known to spawn off the coast of South African and the juvenile and adult fish migrate to Namibia (von der

Heyden et al., 2007). However a recent study (Jansen et al. 2015), has observed spawning *M. paradoxus* in the southern coast off Namibia during the month of August. *M. capensis* are known to spawn off Namibia (Kainge et al., 2007; Jansen et al., 2015), it has a very early onset of maturity and 50% maturity at around 1.34 years, while *M. paradoxus* have a later onset at around 2.8 years (Paulus et al., 2013). By the age of 4 years all fish in the *M. capensis* population are assumed to have matured while *M. paradoxus* population attain full maturity at age 7 (Paulus et al., 2013). Growth parameters for the two stocks are known to be different. *M. capensis* can attain a maximum length of around 150 cm, and *M. paradoxus* around 120 cm (Paulus et al., 2013).

Genetic study using mitochondria DNA has observed striking difference between the two species (von der Heyden et al., 2007). About 6 polymorphic sites were found in *M. paradoxus* and 61 polymorphic sites found in *M. capensis* (von der Heyden et al., 2007). These differences in the biology and population dynamics between the two species is ignored in both combined assessment and management decisions (Butterworth and Rademeyer, 2005). The combined assessments lead to a common TAC set.

Although our focus is entirely on hake off Namibia, the underlying question is ubiquitous in fisheries statistics and management: Single-stock assessments and TAC's still dominate the field, despite decades of efforts in multi-species assessment (Sparre, 1991; Lewy and Vinther, 2004) and multi-species management (May et al., 1979) and despite recent advances in the ecosystem approach to fisheries (Plagányi et al., 2014). In this situation, an important and non-trivial question is what the single stock comprises (Cadrin et al., 2013) and if a single-stock assessment is justified or the stock should be disaggregated for example according to sex, space, or spawning seasons. When stocks or stock components differ in underlying biological and ecological rates, a combined assessment that ignores such differences is likely to introduce a bias, in particular when the relative abundances change in time. However, disaggregation thins the data available for each assessment, and therefore increases the variance on final estimates of abundance, spawning stock biomass, and ultimately of reference points. Ideally, one could conceive simultaneous assessments where rates are allowed to differ between stocks to the extent that data suggests statistically significant differences in these rates. However, the computational complexity of stock assessment models calls for simpler approaches, and a reasonable such approach is to compare results from a single combined assessment with multiple isolated assessments of the different stocks or stock components.

2. Materials and methods

2.1. Assessment model

The assessment model used in this study is the SAM model (Nielsen and Berg 2014), which is available through its web interface <http://stockassessment.org>. The model is a single stock state-space model, where the unobserved processes are considered to be the logarithm of the age specific population sizes and logarithm of the age specific fishing mortalities. The logarithm of the age specific fishing mortalities are assumed to follow a multivariate random walk (with standard deviation σ_F and correlation between ages of $\rho_{|ai - aj|}$). The logarithm of the age specific population sizes are assumed to follow the classic stock equation with process noise (with standard deviation σ_S), and a simple random walk for the first age class (with standard deviation σ_R). The natural mortality is not estimated within the model, but given as input, assumed to be time invariant and the same for both species, but age specific. The same values for natural mortality are used as in previous assessments (see Kirchner et al., 2012). The observed log-catches at age are assumed normally distributed with mean given by the logarithm of the Baranov catch equation and common standard deviation (σ_{catch}). The observed log-survey catches at age are assumed normally distributed with mean $\log(Q_a * N)$, where Q_a is the catchability parameter for the age group and N is the stock size for the age group at the time of the survey. A common standard deviation (σ_{survey}) is used for all age groups and years for the log survey catches. The data made available to the estimation in the model comprises commercial catches and scientific survey indices. Underlying parameters are estimated using Maximum Likelihood; random effects are integrated out using the Laplace approximation. The underlying numerical engine is AD Model Builder (Fournier et al., 2012). From estimated parameters and states, auxiliary quantities such as the spawning stock biomass (SSB) can be computed, including confidence regions. This model has been used in commercial important stocks (e.g. North Sea cod stock, North Sea herring stock, North Sea blue whiting stock) and all code is publicly available from stockassessment.org. See further details in Nielsen and Berg (2014).

2.2. Input data

In this paper we use data for hake stocks for the period 1998–2012. Commercial catches from the earlier years, 1964–1997, could not be separated by species, due to differences in data recording procedures used during that period, which prevents single-species assessment. We used the annual estimates of total catch at age (ages 0–8 years) as reported in the Fisheries Information Management System (FIMS) a database for daily commercial logbook data held at National Marine Information and Research Centre (NatMIRC), Ministry of Fisheries and Marine Resources (MFMR). In addition species-age specific survey index estimated from the annual swept area biomass survey for age 0–8 years are used in the species specific models, and their sum is used for the combined assessment of both stocks.

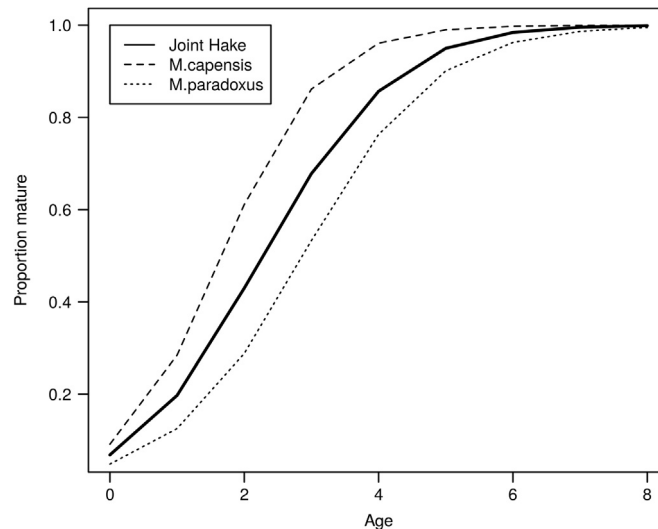


Fig. 2. Maturity ogives as a function of age for combined species (Hake), and for single species (*M. capensis* and *M. paradoxus*) data for the period 2000–2012 as described by Paulus et al. (2013).

Catch rates by species, weight and length from summer surveys (January/February) were obtained from the Nan-SIS (Strømme, 1992), a database of demersal biomass surveys conducted annually by the National Marine Information and Research Centre (NatMIRC), Ministry of Fisheries and Marine Resources (MFMR). The survey has a target to cover about 200 fixed trawl stations each year and lasts for about six weeks. In the routine assessment a depth-stratified swept area biomass estimate is used.

The maturity ogives for the two hake species are calculated annually for assessment purposes and to describe the age at maturity. The species-specific maturity data used in this study were gathered from a report by Paulus et al. (2013) (Fig. 2). The maturity staging used for the Namibian hake stocks are between zero (0) and five (5), where stage zero (0) and one (1) are considered immature and stages 3–5 are matured. A logistic regression functions was used and fitted to the observed data (Paulus et al., 2013). The species combined maturities were calculated as the weighted mean of the species-specific values, with weights being the numbers-at-age proportions by species as estimated by the species-specific assessments. The species-specific and species-combined (average over all years) maturities are shown in Fig. 2.

Otoliths samples are collected annually during the summer swept area biomass survey. These otoliths are microscopically read each year for every species. Successfully otoliths reading for each species are converted to age length keys (ALK). These ALK are then applied to both survey and commercial length frequencies. Species specific weight-at-length was estimated using the Von Bertalanffy Growth Function (VBGF) coefficients. The full procedure is described in Paulus et al. (2013). Species combined weight-at-age were calculated in the same manner as the maturities, i.e. as weighted means of the

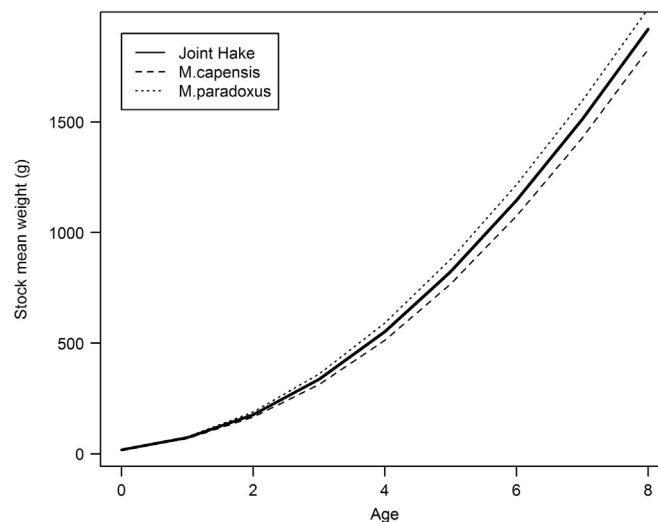


Fig. 3. Stock mean weight as a function of age for combined species and single species (*M. capensis* and *M. paradoxus*) for the period 2000–2012, as described by Paulus et al. (2013).

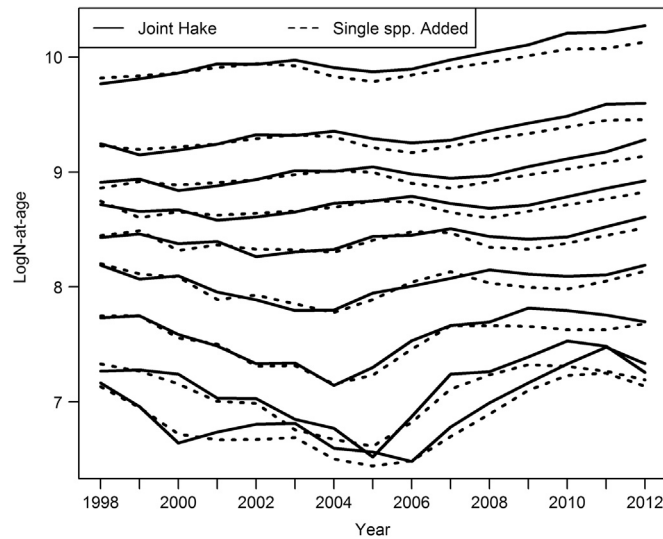


Fig. 4. Log numbers at age estimated from the combined assessment (solid lines) and single species (dashed lines) added together for the period 1998–2012. The top pair of lines shows age class 0; lower lines show older year classes.

species-specific values (Fig. 3). All this information is then used to produce a catch at age data which are subsequently fed into state-space stock assessment models.

3. Results

Fig. 4 shows the log transformed numbers at age estimates, from the combined species and separated species assessment added together. On a log scale the numbers at age from the two models are estimated about the same. There seem to be a slight diverging in numbers at age starting with the 2003 cohort. This slight shift is more visible in the added single species model. The combined species assessment seems to indicate a higher numbers at age from the period when the divergence was observed.

The survival process error parameter, σ_S , hits its lower bound (CV is approximately $\exp(-4.0)=0.018$) in all three cases, which means that this model effectively uses deterministic survival (Table 1). The catch observation errors, σ_{catch} , are higher in the single species assessments than in the combined species assessment (approximately double CV). Conversely, the fishing mortality process errors, σ_F , are smaller in the species-specific assessments. Hence, the species-combined assessment explains more of the variation in catches with variation in fishing mortality rather than with observation error when compared to the species-specific assessments.

Fig. 5 shows the total biomass estimates for *M. capensis* and *M. paradoxus* from the annual hake swept-area biomass survey during the period 1998–2012. Trends in the biomass estimates of the two hake species are similar with some exceptions in some years. *M. capensis* shows much higher estimates, almost three times higher than *M. paradoxus*. Conflicting trends were observed in 2009 and 2011.

The residual plots in the supplementary information show some systematic pattern in all three models (Figs. S1, S2 and S3). These patterns are more pronounced in the survey data in all three models. The younger age classes (0–1) shows huge under-estimations and over-estimations in all models, more pronounced in the survey data. It was attempted to resolve this by estimating a separate observation variance parameter for age group 0, however this model failed to converge.

The trends in the estimated spawning stock biomasses and fishing mortalities are similar between the species-combined

Table 1

Estimated variance parameters for the three models: Combined species assessment and the two independent single species assessments.

Variance parameters	Combined hake		<i>Merluccius capensis</i>		<i>Merluccius paradoxus</i>	
	Estimates	Std.dev	Estimates	Std.dev	Estimates	Std.dev
$\log \sigma_F$	-0.05	0.18	-0.59	0.26	-0.52	0.28
$\log \sigma_R$	-1.65	0.41	-1.72	0.54	-1.36	0.41
$\log \sigma_S$	-4.00	NA	-4.00	NA	-4.00	NA
$\log \sigma_{catch}$	-1.21	0.21	-0.47	0.11	-0.36	0.10
$\log \sigma_{survey}$	0.12	0.06	0.34	0.06	-0.01	0.07
ρ	0.84	0.06	0.80	0.10	0.94	0.05

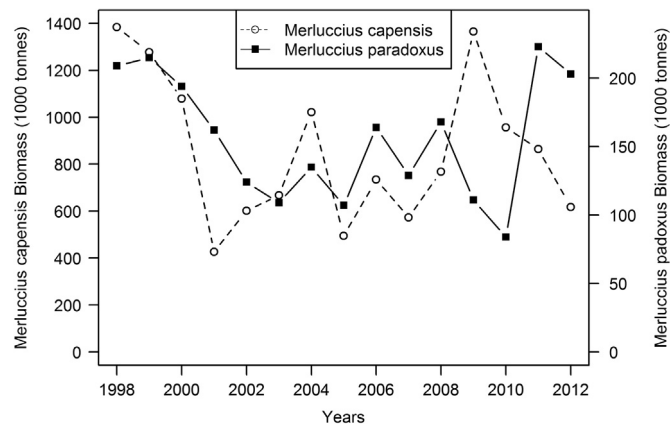


Fig. 5. Annual total biomass survey estimates from the swept-area survey for *M. capensis* and *M. paradoxus*, during the period 1998–2012.

assessment and *M. capensis* species-specific assessment (Figs. 6 and 7). However the level of magnitude is different. The combined assessment estimated the spawning stock biomass to be twice the level of *M. capensis*. The spawning stock biomass of *M. paradoxus* followed different patterns than *M. capensis* (Fig. 6). While the species-specific assessment for *M. capensis* shows an increase in the later years, the abundance of *M. paradoxus* has remained more or less constant of the whole time-series.

The main signal in fishing mortality is that the combined-species assessment estimated the F_{bar} to be roughly around the average of the two single species assessments, and showing similar trends (Fig. 7). F_{bar} for *M. paradoxus* is higher than the F_{bar} for the combined-species assessment.

The overall fishing mortality trend for the species-combined assessment looks very similar to that of *M. capensis*. It is worth noting that the *M. capensis* trend is much smoother with wider confidence limit in the first seven years.

The confidence limits for *M. paradoxus*, particularly the F , are substantially wider, when compared to species-combined assessment and species-specific *M. capensis* estimates (Fig. 7). The difference is mainly caused by the different level of the estimates, as the coefficient of variation is similar for species-combined assessment and species-specific estimates.

The estimated level of fishing mortality and the overall time trend are also similar between species-specific assessment and species-combined assessment (Fig. 7). There are however some notable exceptions (2003, 2007, and 2009), where *M. paradoxus* estimates are considerably different (Fig. 7). The estimated CVs of F_{bar} in the last year are 0.42, 0.34, and 0.30 for *M. paradoxus*, *M. capensis*, and the combined assessment respectively. Similarly, the estimated CVs of the SSB in the last year are 0.33 and 0.26 for the sum of single species assessments and the combined assessment respectively. This indicates that the uncertainty of the combined stock status is reduced when assessed as a single stock.

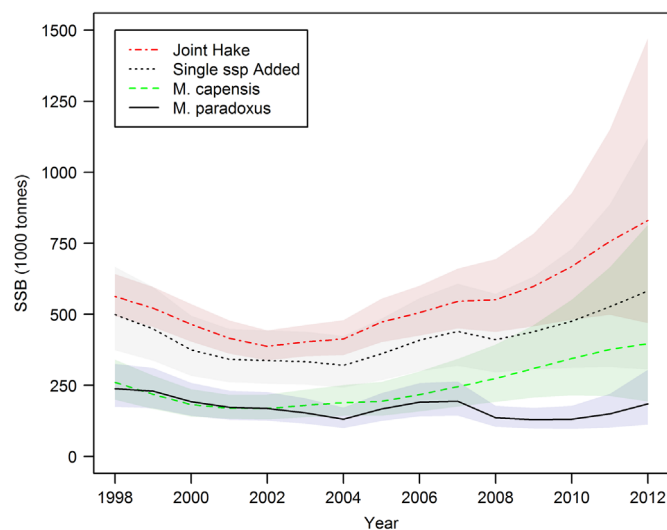


Fig. 6. Spawning stock biomass estimates with their associated 95% confidence interval as estimated by three model assessments: the combined assessment and the two independent single species assessment. Included is also the two single species assessments added together.

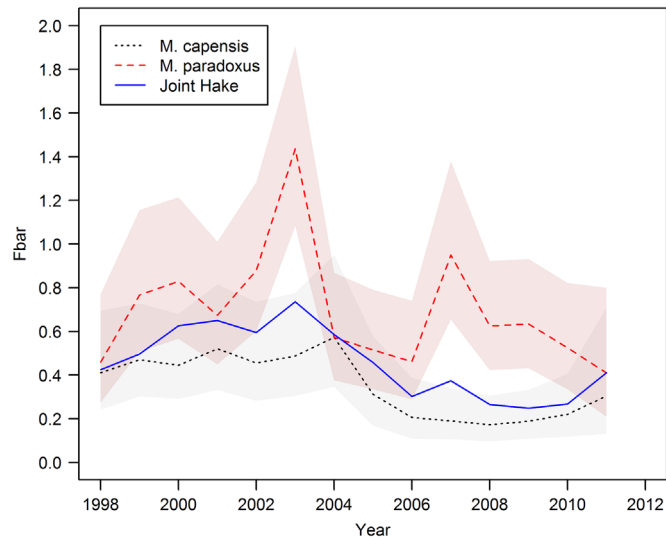


Fig. 7. Estimated F_{bar} and their associated 95% confidence interval over time for the two independent single species assessment. The combined assessment estimate is not presented with confidence interval.

4. Discussion

This study compared the results of applying a state-space species-specific assessment and a state-space species-combined assessment to Namibian hake (*Merluccius capensis* and *M. paradoxus*) data. This is the first time that the state-space framework is used to assess the Namibian hake stocks, which have been and are currently assessed as a single stock using the Statistical catch-at-age analysis (Butterworth and Rademeyer, 2005; Kirchner et al., 2012).

In the context of the present study, the morphological similarities between the two species, and the combined fishery, argues for a combined assessment, but differences in biological rates and spatial distributions speak for separate assessments of the two species. In this situation, it is important to understand quantitatively the differences in our perception of hake stocks that result from combined-species and split-species assessments. Ignoring the biological parameters of each species may lead to over-harvesting or under-harvesting of one stock.

The results showed that the two models generally gave comparable estimates and trends for the abundance in numbers, although marked differences were observed with regards to spawning stock biomass estimates (Fig. 5) and fishing mortalities (Fig. 6). In addition, the size of confidence limits differs markedly.

The difference in estimated spawning stock biomass between the sum of the single species assessments and the combined assessment is a consequence of the different estimates of the numbers-at-age in the later period starting with the 0-group in 2003 (Fig. 4), however the reason for this divergence is unclear. The higher fishing mortality on *M. paradoxus*, in turn, could be a result of diel variations. Such differences in rates between the two species speak against performing a combined-species assessment.

The species-specific assessment results showed that the *M. capensis* spawning stock biomass has increased in the last five years, while that of *M. paradoxus* has decreased. This observation is literally impossible to predict in the species-combined assessment. Such species specific assessment of abundance and trends can ultimately form the scientific bases for management recommendation in setting species specific TAC's, taking the biology and population dynamics of each species into account. Although species-specific management remains a big challenge, the first step is assessment of each species, as done in this study.

The assessment models reported here perform reasonably, taking into account the limited data and that this is the first state-space assessment model of the two hake stocks off Namibia. The catch at age residuals for all the models shows some systematic patterns, more pronounced in survey data. The catch data in all models provided better residuals. Although the systematic patterns in survey data are not considered too extreme to invalidate the results, some improvements can be envisioned. Most importantly, the species separated commercial catches time series are very short and need to be extended to separate all historical data, even if this would require a considerable effort, as stock assessment models can be sensitive to short time series often leading to poor convergence or poor estimation of the parameters. The survival process variance parameter hits the lower bound in all three cases (Table 1). This could be an indication that the model finds it difficult to estimate this variance parameter. This is common in assessment models, especially when the data time series are too short, or have conflicting signals.

The higher catch observation error in the two independent single species assessment could be related to how the two species are separated. This could also mean that the assessment time period is too short and the data are too few for a single species assessment. In contrast combining data leads to lower observation error on catches. The combined assessment was

also found to give smaller uncertainty on the estimates of biomass of fishing mortality when compared to the sum of the species-specific assessments. This is an example of the generic bias-variance trade-off problem in statistical modelling: Estimates from a combined model will exhibit less variance than the sum of the species-specific model estimates, because the combined model is based on aggregated data with larger underlying sample sizes. Also, the total number of parameters for the two single species assessments is twice as large as for the combined model. These additional parameters will also introduce more variance due to the uncertainty in the estimates, but will give less bias given that their true values are species specific. Best practice will depend on the specific situation, e.g. on the uncertainty of the splitting proportions between species, and how different the population dynamics of the two species are, but also on the feasibility of implementing species specific management.

This study has focused on the actual data for the two hake species (*capensis* and *paradoxus*). To more generally study the differences between combined-species and split assessment future studies could benefit from using a simulation approach as for example using separate natural mortality for the two species, which would be an easy way to mimic migrations.

5. Conclusion

Species-combined assessment ignore underlying species-specific processes of the two stocks. Although our estimates of numbers-at-age for Namibian hake are comparable, a species-combined assessment estimates a higher spawning stock biomass than the sum of species-specific assessment added together. Species-specific assessments show an increase in spawning stock biomass of *M. capensis*, while the biomass of *M. paradoxus* has remained more or less constant since 1998. Such opposing trends are impossible to observe in a species-combined assessment. Similarly, fishing mortality on *M. paradoxus* has been relatively higher than on *M. capensis*. The uncertainty of the estimates of SSB and fishing mortality in the combined assessment are lower than the those obtained from the species-specific assessments, i.e. there is a price to be paid for this extra information, and best practice will depend on the need for, and feasibility of, species specific management.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at <http://dx.doi:10.1016/j.envdev.2015.11.011>.

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