

Evaluation of the Status of the Namibian Hake Resource (*Merluccius* spp.) Using Statistical Catch-at- Age Analysis

Carola Kirchner, Paul Kainge, and Johannes Kathena



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Abstract

Namibian hake is the most important fish resource in Namibia. This monograph is a compilation of all the hake data, historic and recent, that has been used to inform stock assessment and management since the late 1970s. It presents the statistical catch-at-age analysis used to evaluate the state of the Namibian hake resource under different assumptions. This analysis treats the two hakes, *Merluccius paradoxus* and *M. capensis*, as a single stock. The data and modeling show that the stock has not as yet recovered to its maximum sustainable yield level, despite foreign fishing effort having been removed in 1990. Best estimates suggest the current stock to be roughly 20% of pre-exploitation levels; however this figure is sensitive to model assumptions. Signs indicate that the stock is slowly recovering from its all-time low in 2002-2004. Because the two hake species are pooled for assessment, the resource is currently managed on a relatively simple adaptive basis; 80% of the estimated replacement yield is reserved for fishing, the remainder being left for rebuilding.

Key Words: statistical catch-at-age analysis, data, management monitor graph, Namibian hake, stock assessment.

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Introduction

Namibia's 1500 km desert coastline is known for its highly productive ocean waters, the northern Benguela shelf, that forms part of the Benguela system, which is one of the world's four major eastern boundary upwelling systems. The northern Benguela has a strong upwelling cell off Lüderitz and a weaker one at Cape Frio. The combination of the persistent equator-ward winds, low water temperatures and abundant plankton blooms are features of this productive system (Hutching et al., 2009). However, most of Namibia's historically rich fish resources, such as sardine (*Sardinops sagax*) and hake (*Merluccius* spp.), are currently estimated to be at fairly low levels. Historically, sardine was the dominant species in the northern Benguela, but partly through extensive fishing in the 1960s (Boyer and Hampton, 2001), with average catches of 580 thousand tonnes per year in the period 1960-1977, this stock collapsed and the catch fell to a mere 46 thousand in 1978 (De Oliveira et al., 2007); it has since been replaced by the lesser valued *Trachurus capensis* (horse mackerel) (Kirchner et al., 2010) as the main pelagic species. It has been argued that the depletion of some of these resources was not due to overfishing alone, but also to poor recruitment, recruitment being dependent on combinations of environmental variables, such as the upwelling intensity and the extent of intrusion of species such as sardine from the Angola-Benguela front (Kirchner et al., 2009).

The most economically important species in Namibia are the hakes (Van der Westhuizen, 2001). There are two species in Namibia, shallow-water hake, *Merluccius capensis*, and deepwater hake, *Merluccius paradoxus*, which are also referred to as white and black hake respectively. *M. capensis* is the dominant species, but, because the two hake species look very similar, it is difficult to record data separately; hence these two species are managed as one stock. Since 1997, however, a 70-100% observer presence has been required on all commercial vessels (Nichols, 2004) and consequently the catch has been separated for the two species.

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Although recommendations for the total allowable catch (TAC) are still based on combined assessments, it is anticipated that future assessments will take the two-species nature into account as has been done in South Africa (Rademeyer et al., 2008).

Namibia, like South Africa, treats hake stocks as unshared (i.e. as their own unit stock), although Burmeister (2001) offered strong evidence, based on survey-based distributions of the two species, that the *M. paradoxus* stock is shared between Namibia and South Africa. This was further supported by a gonosomatic study, which found that no spawning of *M. paradoxus* takes place in Namibia (Kainge et al., 2007).

The objective of this paper is to document the data and stock assessment model on which the current management of Namibian hake is based.

Material and Methods

Total Allowable Catches and Landings

Exploitation of the Namibian hake resource commenced in 1964. The fishery was unregulated over the period 1964-1976. During this period, an average of about 500 000 tonnes of hake was reported landed per year (Figure 1, Table A1.1). The International Commission for South East Atlantic Fisheries (ICSEAF) was formed in 1969. A minimum mesh size of 110 cm was introduced in 1975. From 1977 through 1989, the fishery was managed through annual TACs. Between 1980 and 1990, the average annual catch was reduced to about 325 000 tonnes (Figure 1, Table A1.1). Foreign fleets accounted for all the hake caught off Namibia until 1990, and there is some concern regarding the accuracy of the statistics they reported to ICSEAF¹.

Before 1990, Namibia was still a mandated territory and not a nation state. Consequently its control of fishing stopped at the 3-mile limit, even though most of the world had shifted to a 200 mile Exclusive Economic Zone (EEZ). Since Namibia's Independence in 1990, hake fishing has been managed under the auspices of the Ministry of Fisheries and Marine Resources (MFMR) (van der Westhuizen, 2001). This ministry removed most foreign fishing effort, mainly European and Eastern bloc fleets, and declared a 200-mile EEZ in accordance with international law (MFMR, 1990). Since that time, the average annual catch has been reduced to about 148 000 tonnes (Figure 1, Table A1.1) in an attempt to rebuild the depleted stock. During the 1980s, assessments developed at ICSEAF meetings indicated that the resource was recovering;

¹The late Mr. Jose Ruiz, who was responsible for one country's shipments of hake from Walvis Bay during the 1980s, reported in a personal communication that these were substantially underreported.

however, this result followed primarily from a reported increase in Spanish catch per unit effort (CPUE) over this period. These CPUE data are no longer considered reliable (Butterworth and Rademeyer, 2005). Further measures introduced to promote stock rebuilding were the closure to trawling of the area shallower than 200m water depth and the introduction of a ‘No Discards’ policy and “at-sea-sampling” in 1997 (Nichols, 2004).

Historical Fishery Data

The data on the Namibian hake fishery, historic as well as more recent, are very rich, i.e. catch data are available for all years (Table A1.1) since fishing commenced in 1964. A few historic indices of abundance are available (Table A1.2). Two series of CPUE recorded during the ICSEAF period are included. One is for Division 1.3 + 1.4 (Figure A3.1), which represents the Spanish bottom trawlers in tonnage class 7 (1000-1999 GRT) (Andrew, 1986). The other is for Division 1.5 (Figure A3.1), which pools above-mentioned Spanish data with South African bottom trawlers in tonnage class 5 (300-600 GRT) data (Andrew, 1986). The values for the CPUE index for Division 1.5 differ from those published in Butterworth and Geromont (2001). Because the origin of these published values could not be traced in any other literature, this assessment used those published in Andrew (1986). Butterworth and Geromont (2001) included ICSEAF CPUE values for the years 1965-1988. However, it subsequently became apparent that any post-1980 ICSEAF CPUE data was positively biased and should not be included in the dataset (Ruiz, pers. comm.). A Namibian catch per unit effort (CPUE) series for commercial bottom trawl fishing was developed using general linear modeling by Brandão and Butterworth (2004, 2005) and has now been extended by NatMIRC to 2011. The trawl data per day for each individual vessel have been combined. The CPUE was standardized for months, gross tonnage of the different vessels, and fishing in different latitudes, as well as an interaction between the year and month variable. About 40% of the variability in the commercial CPUE can be explained by these variables (Carola Kirchner, unpublished results). In addition, an index representing combined catch rates of seven Spanish trawlers (“7-Vessel”) is included in the assessment.

Stratified random bottom trawl Spanish surveys were undertaken from 1983 to 1990. The biomass estimates of hake in these surveys, published in Macpherson and Gordo (1992), have since been recalculated (Table A1.2).

Demersal biomass surveys were undertaken by the Ministry of Fisheries using the R.V. *Dr Fridtjof Nansen* from 1990 to 1999, and subsequently using a commercial fishing vessel. In the 1990s, two surveys were undertaken annually, one in summer and one in winter. However, since 1997, only the summer (January-February) survey remained. Therefore, biomass for the winter surveys are available for 1990 and from 1992-1996 and for the summer surveys data from

1990 to 2012 (Table A1.3) (Van der Westhuizen, 2001). The research and commercial surveys were calibrated against one another (Rademeyer, 2003) (Table A.1.4) and the data collected by the commercial surveys are corrected accordingly in the model.

One of the most important sets of information for abundance estimations is catch-at-age data. The commercial ICSEAF catch-at-age data (1968-1988) used in the assessment is published in Butterworth and Geromont (2001). However, the origin of this data could not be traced in the ICSEAF documentation. In some assessments this data is referenced to ICSEAF (1989), which is a compilation of historical data series selected for Cape hake stock assessments. However, this ICSEAF (1989) does not include any catch-at-age data. In Punt and Butterworth (1989), this data is referenced as (B. Draganik, ICSEAF, pers. comm.). An alternative catch-at-age matrix (1968-1986) is published in Gordo, et al. (1995) and Gordo and Hightower (1991), and referenced to Draganik and Sacks (1987) (Table A1.5).

From 1990, age data was observed for some years by reading annual rings on otoliths (Margit Wilhelm, unpublished data). For the years for which such observed age data is not available, an iterative age-length key method (Lai et al. 1996) was used to estimate proportions in each age group from the proportions of the length frequency distributions (Clark, 1981) (Table A1.5). Also available is a recruitment index from 1994 to 2009, which was obtained on an annual basis by determining the proportion of *M. capensis* otoliths found in seal scat samples (Jean-Paul Roux, unpublished data).

Stock Assessment Model

A statistical catch-at-age analysis is used stochastically to estimate trends from indices of abundance such as CPUE series, survey biomass estimates, seal scat contents and past catches. This model, described in detail in Rademeyer (2003) and Rademeyer et al. (2008) (Appendix 2), is fitted to the CPUE series (Table A1.2) and the survey biomass estimates (Table A1.3), with the assumption that the survey biomass and the CPUE series provide an index of relative abundance, by minimizing the negative log-likelihood function. The unexploited equilibrium spawner-biomass, K^{sp} , the steepness parameter, h (which is the fraction of the recruitment at the unexploited equilibrium level of spawning biomass to be expected when this biomass is reduced to 20%), the natural mortality M (Table A1.7), and the constant of proportionality q (the catchability) are estimated within the model using the available data. Recruitment is modelled by using the Beverton and Holt stock-recruitment curve (Beverton and Holt, 1957). There is not enough information in the data to estimate all of these parameters simultaneously; therefore age-dependent natural mortality is set externally in the base case assessment (Table A1.7). The catchability constants (q) for all surveys were estimated in the base case assessment.

Some changes have been made to the model described in Rademeyer (2003). The commercial and survey fishing selectivity take the form of a logistic curve (Equation 1), which is modified to include a decrease in selectivity at older ages. Maturity-at-age is used instead of knife-edge maturity (Table A1.7).

$$S_a = \begin{cases} 0 & \text{for } a = 0 \\ \left[1 + \exp\left(-\left(a - a_c\right) / \delta\right) \right]^{-1} & \text{for } a \geq 1 \end{cases} \quad (1)$$

where a_c = age-at-50% selectivity and

δ = gradient of the ascending part of the logistic curve

Both the survey and commercial selectivities are modified for $a > a_{slope}$ by:

$$S_a \rightarrow S_a \exp\left(-s \left(a - a_{slope}\right)\right) \quad (2)$$

where s is called ‘slope’ measuring the rate of decrease in selectivity with age for fish older than a_{slope} for the fleet concerned, which was externally set at 4 years.

In addition to the base case, 11 sensitivity tests were executed to investigate the effects of some of the assumptions made for the assessment. The base case used the CPUE data as an indication of abundance. However, CPUE might not be a good indicator of abundance due to, for example, unpredictable fishermen behaviour and unknown gear change (e.g. technology creep) of the fleet. Therefore, in sensitivity test 1, all recent CPUE data (GLM and “7-vessel”) were omitted from the assessment. For sensitivity test 2, the variability of recruitment was decreased from 0.5 to 0.25, because it is expected that the variability in recruitment is lower for a longer lived fish (Butterworth and Rademeyer, 2005). For the sensitivity tests 3 and 4, constant natural mortality (age-independent) and natural mortality at infinity is estimated ($M_a = M_{inf\ age} * M_{inf} / a^{0.32192}$). Sensitivity tests 5 to 8 address the effect of variation in the catchability constant for the summer research surveys. In the base case, the variability around the different CPUE series is estimated (Equation A2.19); in sensitivity test 9, this is set externally at 0.2 for the ICSEAF and GLM data and 0.4 for the Spanish surveys and the “7-vessel” CPUE. The steepness parameter is estimated to be very low (around 0.35), which is unusual for a species like hake (Myers et al., 1999), as it means that the productivity is very low at low spawner biomass levels. An alternative interpretation could be that productivity levels have fallen in recent years due to environmental conditions. Therefore, for sensitivity test 10, two different productivity periods were estimated by assuming a gradual change in productivity from 1985 to

1990. In the 11th test, the selectivity for the surveys was set to be logistic without the right-hand slope of the curve, i.e. assuming that all the older fish are caught in the trawling.

In the past, the absolute values of stock assessments have shown great variability, so it was preferred to present results in relative terms; emphasis was placed on trends. This assessment treats *Merluccius capensis* and *M. paradoxus* as a single stock, because data for a split species assessment are not yet available, and therefore it is reasonable not to over-interpret the results. Notwithstanding, the current assessment estimates that the stock is far below the maximum sustainable yield level (MSY), which is considered the target reference point for all Namibian species. The approach taken here, however, is a step-wise stock recovery; therefore, the management quantity used as a first step in this assessment is based on the state of the stock in 1990. It is well known that, at independence in 1990, Namibia inherited a depleted stock (Nichols, 2004). To what extent the stock was depleted is uncertain, but it seems clear that cautious adaptive management was appropriate. If the stock at any stage falls below its 1990 level, a very conservative approach to management should be taken.

To illustrate the variability in the results, ninety percentiles of the current total biomass relative to the biomass before exploitation (virgin biomass) were obtained for the base case and the sensitivity tests. This was achieved by running the Monte Carlo Markov Chain (MCMC) routine in the AD Model Builder package (<http://Otter-rsch.com/admodel.htm>) one million times, saving every 1000th simulation for further analysis. It was assumed that the MCMC algorithm was converged if, by plotting the values of quantities of interest, no strong autocorrelation in the chain was detected (Raftery and Lewis, 1992). When using a Bayesian approach, priors have to be defined for the parameters (Punt and Hilborn, 1997); these are given in Table A1.8.

Results

The current state of the stock was determined over the whole range of model specifications, described in Table 1, and some of the results are given in Table 2. The current state of the stock relative to the state of the resource in 1990 is presented in Figure 2. The model fit, meaning the extent to which the model estimates the observed data, decreases from left to right in Figure 2 for the different model specifications, with the lowest Akaike's Information Criterion (AIC, Burnham and Anderson, 2002) indicating the best fit to the observed data. The Akaike value for the base case is the 5th lowest, but all graphical results are presented for the base case only, as this case is based on the most plausible biological assumptions. With the exception of two model specifications (different ways of estimation of natural mortality within the model), the resource appears to be either on the same level as in 1990 or above. Figure 3

present the depletion rates (current total biomass/pre-exploitation biomass). The probability intervals (95 percentile) indicate the variability within a specific model specification; the actual estimates show the between-model variation. Average current spawning biomass/pre-exploitation biomass values range between 14% and 26% (Table 2). The MSY was estimated to be between about 230 000 and 280 000 tonnes for all models, with the exception of sensitivity test 10, where a change of productivity was assumed in the mid-1980s; in that case, the MSY was estimated much lower, at 130 000 tonnes (Table 2). For the base case, the input sigma for recruitment was 0.5, and the model output sigma was estimated to be 0.33; for sensitivity test 2, the input sigma was reduced to 0.25 and the model output was 0.248. According to the Akaike values (Table 2), the base case fit the observed data much better than sensitivity test 2.

Figure 4 presents the model estimated data with the observed data. Visual inspection shows that most of the model estimated values fit the observed abundance data remarkably well, with the exception of the Spanish surveys (Figure 4d and 4e), the “7-vessel CPUE” (Figure 4f) and seal scat data (Figure 4i). Figure 5 illustrates the 95% confidence intervals for the observed research survey data, with the 95% probabilities of the estimated data. Figures A3.2 and A3.3 illustrate the observed and estimated catch-at-age data for the commercial fleet and survey, respectively. These figures indicate that the base case model reflects the observed catch-at-age very well. The strong cohort of 2002 is seen in the survey data in 2005 (Figure A3.2), but thereafter it disappears. Selectivities for three different management periods for the commercial fleet and the survey selectivity were estimated within the model and are depicted in Figure A.3.4.

Figure 6a presents model estimated recruitment from 1964–2011. Recruitment residuals (Figure 6c) and the estimated Beverton and Holt recruitment curve fit onto the estimated recruitment values (Figure 6b). Recruitment was estimated to have fallen appreciably since the mid 1980s. The model estimates that, if the stock is fished down to 20% of pristine, only about 35% of the recruitment expected under pristine conditions can be expected. In comparison to other demersal species, this steepness value is extremely low (Myers et al., 1999). From the residuals (Figure 6c), it can be seen that there might be some autocorrelation in the time series, probably indicating that recruitment is not only dependent on biomass, but also on other factors, e.g. environment (Kirchner et al., 2009).

According to the base case, the Namibian hake stock is estimated to be about 20% of its pre-exploitation level (Figure 7a), which would, in biological terms, be considered severely depleted. The probability density function is shown for the current depletion, which shows the probability for this extent of depletion to be very high (Figure 7b). Permitting unduly high catches after 1990 caused the stock to decline further until 2004. Since then, permitted catches have been decreased, allowing the stock to increase somewhat over the last eight years. The

estimated probability function for the predicted state of the stock in 2022, provided the TAC recommendations are followed over the next ten years, is indicated in Figure 7. The model estimated that the percentage of biomass older than 4 years increased between 2004 and 2010, which was partly due to the strong cohort in 2002 (Figure 8a). The biomass older than 4 years has been declining slightly, as of 2011. The mean length of fish in commercial catches has stayed relatively constant in the last few years (Figure 8b).

Management

The vertical line in the Management Monitor Graph (MMG, Figure 9) represents the state of the stock in 1990 rather than the more usual stock level consistent with MSY (Kirchner et al., 2010). The horizontal line indicates the level of fishing relative to the replacement yield of the stock (i.e. it indicates “sustainability”). This graph illustrates both management (along y-axis) and status of resource (along x-axis) and is therefore a useful tool to track past management and the subsequent increase or decrease in the resource. Above the horizontal line, the stock will decrease in the subsequent year as more catch is taken than the stock produced in that year (catch is higher than replacement yield – overfishing is taking place). To the left of the vertical line indicates the state of the resource to be below that in 1990. This means that, for the stock to at least return to 1990, catches have to be lower than the replacement yield (below the horizontal line) and should continue to be below the horizontal line in order for the stock to rebuild to the MSY level. Although the stock has steadily been increasing since 2007, catches much higher than the estimated replacement yield were taken in the past and therefore the current state of the stock is still around the 1990 level and far below the MSY level (not indicated on graph as it is actually off the chart).

Because the hake resource is estimated to be below the maximum sustainable yield level, rebuilding the resource is a priority. To rebuild the stock, only part of the replacement yield (RY) can be harvested, with the rest remaining to increase the resource. The total allowable catch (TAC) is therefore calculated by:

$$TAC_y = \beta * \left[\left(\sum_y^{y-4} RY_y \right) / 5 \right] \quad (3)$$

where β is the proportion harvested of the 5-year average of RY, in this case 0.80. TAC changes were capped by the 10% rule, which states that the annual TAC may not increase or decrease by more than 10% except for exceptional circumstances, in which case the TAC may go lower. This prescribed “management tool” has been documented in the approved Hake

Management Plan. Future TAC's have been calculated for the base case considering these rules (Figure 10). This analysis shows that catches higher than 200 000 tonnes, which were typical in the past, are not expected in future; in fact, TAC's lower than 150 000 tonnes will allow the resource to increase only slowly (Figure 7). The results showed that, for faster growth in the resource, TAC's would have to decrease to about 100 000 tonnes (not shown in this paper). The probability density function (Figure 10b) clearly indicates that the TAC of 180 000 tonnes that was allocated during the 2011 season cannot be supported by the stock².

Discussion

The results of the state of the hake stock for all 12 model specifications are similar (Table 2). Most models indicate the resource to be near or above the level of 1990. This suggests that permitted catches were too high until at least 2005.

During the most recent four years, together with substantially lower catches (about 130 000 tonnes from 2006 to 2008), above average recruitment was observed, hence the model estimates a small but steady increase from 2005 to 2011 in the stock. No further increase was estimated for the most recent year. The overall results of the assessment indicate that the resource is still well below the MSY level. In fact, it is estimated to be about one third of the MSY. Therefore, given present catch levels (above 150 000 tonnes), the resource will not recover to the MSY level in the near future.

It should also be mentioned that the dynamics of the hake stock have probably changed in the last 20 years. Due to the removal of the main pelagic species, ordinarily prey to hake, the natural mortality due to cannibalism may have increased. The consequence may be a new equilibrium whose MSY level is now lower, at about 130 000 tonnes (model specification 10), than estimated for the other model specifications in this assessment. It was further estimated that the current productivity of the stock is only about 37% of what it was estimated to have been before the 1980s. This has to be anticipated and therefore the fishery should be managed in a precautionary manner, meaning that great care should be exercised before increasing catches.

² In setting the quota for the coming season (2012-13), Namibia's Fisheries Minister elected to ignore the advice of both his hake scientists and his fisheries advisory council. The scientists advised that the hake quota be set at 130 000 tons, while the Advisory Council recommended 140 000 tons. The Minister decided on 170 000 tons. Source: *The Namibian*, June 15, 2012.

It was the aim of the Namibian government to manage the Namibian hake stock to recovery (MSY level) and to then exploit it on a sustainable basis. Neither has been achieved in 20 years. The hake stock is estimated to be around its 1990 levels despite the use of sophisticated, and internationally standard, management tools in the interim.

The assessment described here is more simplistic than those described for the South African hake stocks (Rademeyer et al., 2008). For South Africa, the combined species assessment has been in place since 1997 and various forms of management procedures have been adopted over the years; IMP (Butterworth and Geromont, 2001) and OMP (Rademeyer, 2003). In contrast to South Africa, Namibia did not follow those procedures diligently (Kirchner and Leiman, submitted) and therefore TAC's were higher than biologically allowed. Until recently, the Namibian government has tightened the regulations for the Namibian hake fishery (Kirchner and Leiman, submitted) and the hake resource has responded positively. Unfortunately, since then the TAC's have been much higher than recommended, which can only have a negative effect on the resource and ultimately on the fishery and the economy of Namibia.

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Appendix 1: Resource Data

Table A1.1. Catches Taken off Namibia from 1964-2008 in Thousand Tonnes

| Year | Catches | Year | Catches | Year | Catches | Year | Catches |
|-------------|----------------|-------------|----------------|-------------|----------------|-------------|----------------|
| 1964 | 48 | 1976 | 601 | 1988 | 336 | 2000 | 171 |
| 1965 | 193 | 1977 | 431 | 1989 | 309 | 2001 | 174 |
| 1966 | 335 | 1978 | 379 | 1990 | 132 | 2002 | 156 |
| 1967 | 394 | 1979 | 310 | 1991 | 56 | 2003 | 189 |
| 1968 | 630 | 1980 | 172 | 1992 | 87 | 2004 | 174 |
| 1969 | 527 | 1981 | 212 | 1993 | 108 | 2005 | 158 |
| 1970 | 627 | 1982 | 307 | 1994 | 112 | 2006 | 137 |
| 1971 | 595 | 1983 | 340 | 1995 | 130 | 2007 | 126 |
| 1972 | 820 | 1984 | 365 | 1996 | 129 | 2008 | 126 |
| 1973 | 668 | 1985 | 386 | 1997 | 117 | 2009 | 130* |
| 1974 | 515 | 1986 | 381 | 1998 | 107 | 2010 | 159 |
| 1975 | 488 | 1987 | 300 | 1999 | 158 | 2011 | 154 |

*Assumed catches; actual catches not available.

Note: Data provided by Ministry of Fisheries and Marine Resources, Namibia.

Table A1.2. Indexes Used within the Assessment from 1964 to 2011

| | ICSEAF area | ICSEAF area | GLM | Spanish summer | Spanish Winter | Spanish fleet: “7- vessel” |
|------|--------------------------|-------------------|-------------------|--------------------|--------------------|-------------------------------------|
| | (1.3 1.4) (t/hour) | + 1.5 (t/hour) | CPUE (kg/hour) | Surveys (1000t) | Surveys (1000t) | |
| 1964 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1965 | 1.78 | 2.1 | 0 | 0 | 0 | 0 |
| 1966 | 1.31 | 2.47 | 0 | 0 | 0 | 0 |
| 1967 | 0.91 | 1.36 | 0 | 0 | 0 | 0 |
| 1968 | 0.96 | 1.32 | 0 | 0 | 0 | 0 |
| 1969 | 0.88 | 1.08 | 0 | 0 | 0 | 0 |
| 1970 | 0.9 | 1.03 | 0 | 0 | 0 | 0 |
| 1971 | 0.87 | 1.34 | 0 | 0 | 0 | 0 |
| 1972 | 0.72 | 1 | 0 | 0 | 0 | 9.75 |
| 1973 | 0.57 | 0.94 | 0 | 0 | 0 | 10.67 |
| 1974 | 0.45 | 0.66 | 0 | 0 | 0 | 8.26 |
| 1975 | 0.42 | 0.76 | 0 | 0 | 0 | 9.16 |
| 1976 | 0.42 | 0.54 | 0 | 0 | 0 | 8.28 |
| 1977 | 0.49 | 0.65 | 0 | 0 | 0 | 6.58 |
| 1978 | 0.44 | 0.51 | 0 | 0 | 0 | 6.26 |
| 1979 | 0.41 | 0.69 | 0 | 0 | 0 | 7.72 |
| 1980 | 0.45 | 0.71 | 0 | 0 | 0 | 7.08 |
| 1981 | 0.55 | 0.85 | 0 | 0 | 0 | 7.95 |
| 1982 | 0.53 | 0.84 | 0 | 0 | 0 | 7.7 |
| 1983 | 0.58 | 0.90 | 0 | 556 | 0 | 6.95 |
| 1984 | 0.64 | 0.93 | 0 | 1581 | 1300 | 7.68 |
| 1985 | 0.66 | 1.03 | 0 | 917 | 0 | 10.21 |
| 1986 | 0.65 | 0.93 | 0 | 733 | 579 | 9.41 |
| 1987 | 0.61 | 0.88 | 0 | 1145 | 0 | 8.51 |
| 1988 | 0.63 | 0.84 | 0 | 640 | 689 | 7.78 |
| 1989 | 0 | 0 | 0 | 486 | 1738 | 6.63 |
| 1990 | 0 | 0 | 0 | 0 | 1957 | 4.8 |
| 1992 | 0 | 0 | 1178 | 0 | 0 | 8.87 |
| 1993 | 0 | 0 | 1502 | 0 | 0 | 15.27 |
| 1994 | 0 | 0 | 959 | 0 | 0 | 13.01 |
| 1995 | 0 | 0 | 596 | 0 | 0 | 11.99 |
| 1996 | 0 | 0 | 506 | 0 | 0 | 11.24 |

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| | | | | | | |
|-------------|---|---|------|---|---|---|
| 1997 | 0 | 0 | 581 | 0 | 0 | 0 |
| 1998 | 0 | 0 | 830 | 0 | 0 | 0 |
| 1999 | 0 | 0 | 733 | 0 | 0 | 0 |
| 2000 | 0 | 0 | 514 | 0 | 0 | 0 |
| 2001 | 0 | 0 | 440 | 0 | 0 | 0 |
| 2002 | 0 | 0 | 351 | 0 | 0 | 0 |
| 2003 | 0 | 0 | 421 | 0 | 0 | 0 |
| 2004 | 0 | 0 | 492 | 0 | 0 | 0 |
| 2005 | 0 | 0 | 391 | 0 | 0 | 0 |
| 2006 | 0 | 0 | 399 | 0 | 0 | 0 |
| 2007 | 0 | 0 | 411 | 0 | 0 | 0 |
| 2008 | 0 | 0 | 543 | 0 | 0 | 0 |
| 2009 | 0 | 0 | 648 | 0 | 0 | 0 |
| 2010 | 0 | 0 | 870 | 0 | 0 | 0 |
| 2011 | 0 | 0 | 1147 | 0 | 0 | 0 |

The numbers in italics have not been included in the analysis.

Table A1.3. Summer and Winter Survey Biomass Series

| | Summer | CV | Winter | CV | | Summer | CV | Winter | CV |
|-------------|--------|------|--------|-------|-------------|--------|------|--------|----|
| 1990 | 587 | 0.15 | 726 | 0.119 | 2002 | 725 | 0.29 | 0 | 0 |
| 1991 | 546 | 0.21 | 0 | 0 | 2003 | 776 | 0.25 | 0 | 0 |
| 1992 | 817 | 0.11 | 1006 | 0.093 | 2004 | 1157 | 0.29 | 0 | 0 |
| 1993 | 943 | 0.13 | 798 | 0.112 | 2005 | 601 | 0.20 | 0 | 0 |
| 1994 | 750 | 0.12 | 965 | 0.09 | 2006 | 601 | 0.20 | 0 | 0 |
| 1995 | 585 | 0.12 | 647 | 0.104 | 2007 | 701 | 0.26 | 0 | 0 |
| 1996 | 819 | 0.14 | 730 | 0.112 | 2008 | 936 | 0.30 | 0 | 0 |
| 1997 | 663 | 0.12 | 0 | 0 | 2009 | 1476 | 0.30 | 0 | 0 |
| 1998 | 1573 | 0.15 | 0 | 0 | 2010 | 1041 | 0.18 | 0 | 0 |
| 1999 | 1072 | 0.13 | 0 | 0 | 2011 | 1087 | 0.15 | 0 | 0 |
| 2000 | 1357 | 0.20 | 0 | 0 | 2012 | 820 | 0.15 | 0 | 0 |
| 2001 | 587 | 0.23 | 0 | 0 | | | | | |

In thousand tonnes with CV's from 1990 to 2011. Data provided by MFMR.

Table A1.4. Log CPUE Ratios between the Nansen and Commercial Trawlers in Calibration Experiments

| | Log CPUE ratios | s.e. |
|--------------------|------------------------|-------------|
| Nansen vs Oshakati | -0.2237 | 0.0713 |
| Nansen vs Garoga | +0.0567 | 0.0507 |
| Nansen vs Ribadeo | -0.1900 | 0.09494 |

Table A1.5. Catch-at-Age Data Used within the Assessment.

| | | Age | | | | | | | | |
|---|----------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| | Summer surveys | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8+ |
| I | 1990 | 0.000 | 0.258 | 0.553 | 0.078 | 0.065 | 0.004 | 0.012 | 0.030 | 0.000 |
| I | 1991 | 0.000 | 0.063 | 0.511 | 0.232 | 0.064 | 0.118 | 0.012 | 0.000 | 0.000 |
| I | 1992 | 0.000 | 0.435 | 0.308 | 0.083 | 0.071 | 0.048 | 0.026 | 0.029 | 0.001 |
| O | 1993 | 0.000 | 0.049 | 0.564 | 0.268 | 0.058 | 0.036 | 0.018 | 0.006 | 0.001 |
| I | 1994 | 0.000 | 0.312 | 0.485 | 0.016 | 0.090 | 0.018 | 0.045 | 0.032 | 0.001 |
| I | 1995 | 0.000 | 0.543 | 0.272 | 0.071 | 0.061 | 0.025 | 0.007 | 0.019 | 0.000 |
| I | 1996 | 0.000 | 0.186 | 0.498 | 0.114 | 0.084 | 0.029 | 0.084 | 0.003 | 0.000 |
| I | 1997 | 0.000 | 0.201 | 0.523 | 0.137 | 0.068 | 0.056 | 0.013 | 0.003 | 0.000 |
| I | 1998 | 0.000 | 0.316 | 0.453 | 0.004 | 0.149 | 0.003 | 0.032 | 0.044 | 0.000 |
| I | 1999 | 0.000 | 0.190 | 0.543 | 0.098 | 0.077 | 0.034 | 0.009 | 0.047 | 0.002 |
| O | 2000 | 0.000 | 0.218 | 0.568 | 0.162 | 0.021 | 0.024 | 0.004 | 0.003 | 0.000 |
| O | 2001 | 0.000 | 0.712 | 0.195 | 0.073 | 0.010 | 0.009 | 0.001 | 0.000 | 0.000 |
| O | 2002 | 0.000 | 0.790 | 0.165 | 0.017 | 0.018 | 0.006 | 0.003 | 0.001 | 0.001 |
| O | 2003 | 0.000 | 0.380 | 0.381 | 0.173 | 0.046 | 0.013 | 0.003 | 0.001 | 0.002 |
| O | 2004 | 0.000 | 0.691 | 0.241 | 0.045 | 0.016 | 0.005 | 0.002 | 0.000 | 0.000 |
| O | 2005 | 0.000 | 0.007 | 0.340 | 0.496 | 0.101 | 0.042 | 0.012 | 0.001 | 0.002 |
| O | 2006 | 0.000 | 0.127 | 0.578 | 0.218 | 0.062 | 0.012 | 0.003 | 0.001 | 0.000 |
| O | 2007 | 0.007 | 0.701 | 0.209 | 0.051 | 0.020 | 0.006 | 0.003 | 0.002 | 0.001 |
| O | 2008 | 0.241 | 0.239 | 0.288 | 0.147 | 0.050 | 0.023 | 0.008 | 0.002 | 0.002 |
| I | 2009 | 0.020 | 0.221 | 0.611 | 0.046 | 0.087 | 0.016 | 0.000 | 0.000 | 0.000 |
| I | 2010 | 0.200 | 0.171 | 0.427 | 0.043 | 0.084 | 0.011 | 0.015 | 0.049 | 0.000 |
| O | 2011 | 0.217 | 0.288 | 0.255 | 0.136 | 0.050 | 0.029 | 0.012 | 0.013 | 0.000 |

| Winter surveys | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8+ |
|-----------------------|----------|----------|----------|----------|----------|----------|----------|----------|-----------|
| 1990 | 0 | 0.1 | 0.606 | 0.213 | 0.045 | 0.03 | 0.003 | 0.002 | 0 |
| 1991 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1992 | 0 | 0.167 | 0.496 | 0.134 | 0.101 | 0.034 | 0.035 | 0.033 | 0 |
| 1993 | 0 | 0.019 | 0.475 | 0.364 | 0.071 | 0.04 | 0.021 | 0.01 | 0 |
| 1994 | 0 | 0.164 | 0.527 | 0.119 | 0.094 | 0.05 | 0.026 | 0.019 | 0 |
| 1995 | 0.112 | 0.472 | 0.197 | 0.07 | 0.054 | 0.037 | 0.024 | 0.034 | 0 |
| 1996 | 0.014 | 0.452 | 0.395 | 0.053 | 0.052 | 0.015 | 0.009 | 0.009 | 0 |

| | Commercial fleet | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8+ |
|---|-----------------------------|----------|----------|----------|----------|----------|----------|----------|----------|-----------|
| I | 1997 | 0.000 | 0.000 | 0.000 | 0.267 | 0.428 | 0.181 | 0.102 | 0.022 | 0.000 |
| I | 1998 | 0.000 | 0.002 | 0.035 | 0.059 | 0.455 | 0.346 | 0.029 | 0.067 | 0.007 |
| I | 1999 | 0.000 | 0.004 | 0.043 | 0.252 | 0.192 | 0.346 | 0.037 | 0.107 | 0.020 |
| O | 2000 | 0.000 | 0.005 | 0.038 | 0.187 | 0.336 | 0.307 | 0.075 | 0.043 | 0.008 |
| O | 2001 | 0.003 | 0.027 | 0.220 | 0.352 | 0.278 | 0.098 | 0.017 | 0.002 | 0.002 |
| O | 2002 | 0.000 | 0.064 | 0.240 | 0.188 | 0.301 | 0.137 | 0.041 | 0.017 | 0.010 |
| O | 2003 | 0.004 | 0.035 | 0.224 | 0.259 | 0.257 | 0.144 | 0.043 | 0.016 | 0.018 |
| O | 2004 | 0.000 | 0.019 | 0.094 | 0.366 | 0.312 | 0.138 | 0.049 | 0.014 | 0.007 |
| O | 2005 | 0.000 | 0.002 | 0.051 | 0.387 | 0.403 | 0.122 | 0.026 | 0.003 | 0.006 |
| O | 2006 | 0.000 | 0.003 | 0.063 | 0.332 | 0.433 | 0.129 | 0.033 | 0.005 | 0.002 |
| O | 2007 | 0.000 | 0.010 | 0.104 | 0.294 | 0.307 | 0.158 | 0.077 | 0.038 | 0.011 |
| O | 2008 | 0.000 | 0.012 | 0.108 | 0.264 | 0.354 | 0.179 | 0.054 | 0.016 | 0.012 |
| I | 2009 | 0.000 | 0.000 | 0.108 | 0.362 | 0.277 | 0.181 | 0.047 | 0.025 | 0.000 |
| I | 2010 | 0.001 | 0.020 | 0.085 | 0.237 | 0.276 | 0.189 | 0.108 | 0.085 | 0.000 |
| O | 2011 | 0.000 | 0.012 | 0.063 | 0.199 | 0.273 | 0.212 | 0.129 | 0.111 | 0.000 |

| Commercial fleet (ICSEAF data) | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8+ |
|---|----------|----------|----------|----------|----------|----------|----------|----------|-----------|
| 1968 | 0 | 0.002 | 0.094 | 0.548 | 0.244 | 0.081 | 0.024 | 0.005 | 0.003 |
| 1969 | 0 | 0.006 | 0.126 | 0.368 | 0.346 | 0.098 | 0.034 | 0.015 | 0.007 |
| 1970 | 0 | 0.000 | 0.155 | 0.402 | 0.269 | 0.127 | 0.031 | 0.011 | 0.004 |
| 1971 | 0 | 0.001 | 0.067 | 0.302 | 0.429 | 0.130 | 0.043 | 0.019 | 0.008 |
| 1972 | 0 | 0.004 | 0.101 | 0.468 | 0.282 | 0.095 | 0.034 | 0.014 | 0.003 |
| 1973 | 0 | 0.022 | 0.099 | 0.465 | 0.324 | 0.055 | 0.020 | 0.008 | 0.007 |
| 1974 | 0 | 0.068 | 0.278 | 0.278 | 0.147 | 0.127 | 0.073 | 0.024 | 0.005 |
| 1975 | 0 | 0.030 | 0.155 | 0.435 | 0.197 | 0.108 | 0.046 | 0.020 | 0.009 |
| 1976 | 0 | 0.054 | 0.280 | 0.416 | 0.192 | 0.043 | 0.011 | 0.003 | 0.001 |
| 1977 | 0 | 0.112 | 0.120 | 0.379 | 0.279 | 0.086 | 0.012 | 0.008 | 0.005 |
| 1978 | 0 | 0.059 | 0.399 | 0.341 | 0.112 | 0.055 | 0.023 | 0.008 | 0.002 |
| 1979 | 0 | 0.032 | 0.243 | 0.330 | 0.200 | 0.120 | 0.046 | 0.020 | 0.008 |
| 1980 | 0 | 0.143 | 0.157 | 0.267 | 0.217 | 0.112 | 0.065 | 0.025 | 0.013 |
| 1981 | 0 | 0.096 | 0.249 | 0.259 | 0.190 | 0.117 | 0.061 | 0.019 | 0.008 |
| 1982 | 0 | 0.148 | 0.354 | 0.236 | 0.127 | 0.061 | 0.041 | 0.022 | 0.010 |
| 1983 | 0 | 0.473 | 0.397 | 0.083 | 0.030 | 0.009 | 0.005 | 0.002 | 0.001 |
| 1984 | 0 | 0.058 | 0.532 | 0.294 | 0.077 | 0.025 | 0.009 | 0.003 | 0.001 |
| 1985 | 0 | 0.098 | 0.245 | 0.391 | 0.198 | 0.051 | 0.012 | 0.003 | 0.001 |
| 1986 | 0 | 0.048 | 0.391 | 0.251 | 0.169 | 0.094 | 0.032 | 0.013 | 0.003 |
| 1987 | 0 | 0.035 | 0.233 | 0.389 | 0.214 | 0.085 | 0.033 | 0.009 | 0.002 |
| 1988 | 0 | 0.023 | 0.268 | 0.451 | 0.202 | 0.041 | 0.011 | 0.003 | 0.001 |

Catch-at-age matrices for Namibian Winter and Summer surveys are provided by Wilhelm (unpublished data)

i-Iterated data, O-observed data

Table A1.6. M. Capensis Seal Scat Index

| | Average | CV | | Average | CV |
|-------------|----------------|-----------|-------------|----------------|-----------|
| 1993 | 2.40 | 0.47 | 2002 | 8.21 | 0.13 |
| 1994 | 2.06 | 0.37 | 2003 | 0.86 | 0.52 |
| 1995 | 0.41 | 0.36 | 2004 | 0.30 | 0.80 |
| 1996 | 7.18 | 0.23 | 2005 | 0.34 | 0.74 |
| 1997 | 0.94 | 0.27 | 2006 | 1.78 | 0.45 |
| 1998 | 4.67 | 0.20 | 2007 | 4.29 | 1.94 |
| 1999 | 2.09 | 0.59 | 2008 | 5.20 | 1.74 |
| 2000 | 3.03 | 0.32 | 2009 | 2.14 | 0.73 |
| 2001 | 0.24 | 0.82 | | | |

The seal scat series is provided by Roux (unpublished data).

Table A1.7. Natural Mortality-at-Age Set Constant in the Model

| Age | M (yr⁻¹) | Maturity | Start yr | Mid yr | length |
|------------|----------------------------|------------------------------|-----------------|---------------|---------------|
| | | Proportion mature | (g) | (g) | (cm) |
| 0 | 1.424 | 0.080 | 9 | 23 | 8.43 |
| 1 | 0.712 | 0.260 | 47 | 83 | 17.93 |
| 2 | 0.570 | 0.600 | 132 | 195 | 26.62 |
| 3 | 0.500 | 0.860 | 273 | 367 | 34.57 |
| 4 | 0.456 | 0.960 | 477 | 603 | 41.85 |
| 5 | 0.424 | 0.990 | 744 | 902 | 48.50 |
| 6 | 0.400 | 1.000 | 1075 | 1263 | 54.59 |
| 7 | 0.381 | 1.000 | 1465 | 1681 | 60.16 |
| 8 | 0.365 | 1.000 | 1911 | 2152 | 65.25 |

The weight-at-age (begin and mid-year) is calculated from the combination of the Von Bertalanffy growth equation and the mass-at-length function (Wilhelm, unpublished data).

Maturity-at-age set as constant in the model. Weight-at-age (begin and mid-year) (Wilhelm 2007, unpublished data).

Table A1.8.

For this analysis, the estimated parameters were subjected to the following priors:

| Parameter | Prior |
|--|-----------------------------------|
| Pre-exploitation biomass $\text{Log}(K)$ | U[1.0, 10.0] |
| Constant natural mortality (M) | U[0.1, 2.0] |
| Natural mortality at infinity (M_{infage}) | U[0.1, 0.5] |
| Selectivity at age (S_a) | U[0.5,10] |
| Selectivity slope (a_{slope}) | U[0.0, 1.0] |
| Survey age-at-50% selectivity (a_c) | U[0.0, 7.0] |
| Additional variability (σ_A) | U[0.0, 1.0] |
| Recruitment residuals (ζ) | $\text{logN}(\mu, \sigma_R^2)$ |
| Proportion of productivity change ($prop$) | U[0.2, 2.0] |
| Steepness (h) | U[0.21, 0.99] |
| Slope for survey selectivity (a_{slope}) | U[0.0, 1.0] |
| Catchability (q) | Scale parameter (Jeffrey's prior) |
| Variance (σ^2) | Scale parameter (Jeffrey's prior) |

Maximum likelihood estimates can be used when applying MCMC sampling, because Jeffrey's priors (Millar, 2002) are assumed for q and σ .

Appendix 2: Age-Structured Production Model

The Namibian hake stock is modelled according to the following equations. The original hake model had been developed by Rademeyer (2003) and the material that follows has either been reproduced or adapted from Rademeyer *op cit.* or Rademeyer et al. (2008a):

A2.1 Dynamics

$$N_{y+1,0} = R_{y+1} \quad (\text{A2.1})$$

$$N_{y+1,a+1} = \left(N_{y,a} e^{-M_a/2} - C_{y,a} \right) e^{-M_a/2} \quad \text{for } 0 \leq a < m-2 \quad (\text{A2.2})$$

$$N_{y+1,m} = \left(N_{y,m-1} e^{-M_{m-1}/2} - C_{y,m-1} \right) e^{-M_{m-1}/2} + \left(N_{y,m} e^{-M_m/2} - C_{y,m} \right) e^{-M_m/2} \quad (\text{A2.3})$$

where $N_{y,a}$ number of fish of age a at the start of year y ,
 R_y recruitment in year y ,
 $C_{y,a}$ number of fish of age a caught in year y , and
 m maximum age considered (taken to be a plus-group).
 M_a natural mortality at age

$$M_a = M_{\text{inf age}} * M_{\text{inf}} / a^{0.32192} \quad (*\text{Designed to give } M = 0.5 \text{ at age 3 and } 0.4 \text{ by age 6})$$

$$M_0 = M_1 * 2$$

A2.2 Total Catch and Catches-at-Age

The number of fish of age a caught in year y is given by:

$$C_{y,a} = N_{y,a} \cdot e^{-M_a/2} \cdot S_{y,a} \cdot F_y \quad (\text{A2.4})$$

Where $S_{y,a}$ is the age-specific commercial selectivity (three periods of constant selectivity were modelled 1964-1973, 1984-1989 and 1990-2010 as suggested by Rademeyer 2003, pg 56), and F_y is the fully selected fishing mortality in year y , given by:

$$F_y = \frac{Y_y}{\sum_{a=0}^m N_{y,a} \cdot e^{-M_a/2} \cdot S_{y,a} \cdot w_{a+1/2}} \quad (\text{A2.5})$$

where Y_y is the total observed catch (yield) by mass in year y , and $w_{a+1/2}$ is the mid-year mass of a fish of age $a+1/2$.

The estimated catch (yield) by mass in year y is given by:

$$C_y = \sum_{a=0}^m w_{a+1/2} N_{y,a} e^{-M_a/2} S_{y,a} F_y \quad (\text{A2.6})$$

The exploitable biomass in the middle of the year is calculated by

$$B_y = \left(\sum_{a=0}^m w_{a+1/2} S_a N_{y,a} e^{-M_a/2} \right) \quad (\text{A2.7})$$

and the survey estimates of biomass at the start of the year (summer) by

$$B_y^{sur} = \sum_{a=0}^m w_a S_a^{surv} N_{y,a} \quad (\text{A2.8})$$

and in the middle of the year (winter) by

$$B_y^{sur} = \sum_{a=0}^m w_{a+1/2} S_a^{surv} N_{y,a} e^{(-M_a/2)} \left(1 - \sum S_{y,a} F_y / 2 \right) \quad (\text{A2.9})$$

where S_a^{surv} is the survey selectivity.

A2.3 Spawner-Biomass Recruitment Relationship

The number of recruits at the start of year y is related to the spawning stock size by the Beverton-Holt stock-recruitment relationship:

$$R_y = \frac{\alpha_y B_y^{sp}}{\beta_y + B_y^{sp}} e^{(\zeta_y - \sigma_R^2/2)} \quad (\text{A2.10})$$

Where α_y and β_y are spawning biomass-recruitment relationship parameters per year

ζ_y is the fluctuation about the expected recruitment for year y , which is assumed to be normally distributed with standard deviation σ_R (set externally); the residuals are treated as estimable parameters in the model fitting process. Stock recruitment residuals can be estimated by using the information in the catch-at-age data. The $-\sigma_R^2/2$ term is to correct for bias given the skewness of the log-normal distribution; it ensures that, on average, recruitment will be as indicated by the deterministic component of the stock recruitment relationship

and B_y^{sp} is the spawning biomass at the start of year y , given by:

$$B_y^{sp} = \sum_{a=0}^m p_a w_a N_{y,a} \quad (\text{A2.11})$$

where w_a is the begin-year mass of fish of age a and p_a is the proportion of fish of age a that are mature.

The spawning biomass-recruitment relationship parameters (α_y and β_y) are estimated in terms of B_0^{sp} , and “steepness”, h , where “steepness” is the fraction of pristine recruitment that results when spawning biomass drops to 20% of its pristine level, i.e. $h \cdot R_0 = R(0.2 \cdot B_0^{sp})$ and also

$$h = \frac{0.2 \cdot [\beta + K^{sp}]}{[\beta + 0.2 \cdot K^{sp}]}$$

$$\alpha = \frac{4hR_0}{5h - 1} \quad (\text{A2.12})$$

and:
$$\beta = \frac{prop * K^{sp}(1-h)}{5h-1} \tag{A2.13}$$

where *prop* is equal to “1” in the year of initial exploitation and a fraction of one in the year of assumed productivity change if needed for sensitivity testing. This fraction is either estimated in the model or set constant to 1. Both, α and β will change after the years of assumed productivity change.

By assuming an initial equilibrium age structure and using the estimated value for the pre-exploitation spawning biomass B_0^{sp} , recruitment in the initial year can be calculated as:

$$R_0 = \frac{prop * K^{sp}}{\left[\sum_{a=1}^{m-1} p_a w_a e^{-\sum_{a'=0}^{a-1} M_{a'}} + p_m w_m \frac{e^{-\sum_{a'=0}^{m-1} M_{a'}}}{1 - e^{-M_m}} \right]} \tag{A2.14}$$

In the first year, 1964, the initial numbers at age corresponding to the deterministic equilibrium, are:

$$N_{0,a} = R_0 \cdot e^{-\sum_{a'=0}^{a-1} M_{a'}} \quad 0 \leq a \leq m-1 \tag{A2.15}$$

$$N_{0,m} = R_0 \frac{e^{-\sum_{a'=0}^{m-1} M_{a'}}}{1 - e^{-M_m}} \tag{A2.16}$$

A2.4 The Likelihood Function

A2.4.1 CPUE Abundance Data

The likelihood for the individual CPUE series and the Spanish winter and summer survey data is calculated by assuming that the observed abundance index is log-normally distributed about its expected value:

$$\varepsilon_y^i = \ln(I_y^i) - \ln(\hat{I}_y^i) \quad (\text{A2.17})$$

where I_y^i is the abundance index for year y and series i ,

$\hat{I}_y^i = \hat{q}^i \hat{B}_y^i$ is the corresponding model estimate, where B_y^i is the model

estimate of biomass, given either by equation A2.7 or A2.8 (for Spanish summer survey A2.8 is used),

\hat{q}^i is the constant of proportionality for abundance series i , and

ε_y^i from $N(0, (\sigma_y^i)^2)$.

which results in the following contribution to the negative of the log-likelihood:

$$-\ln L = \sum_i \left[\sum_y \ln \sigma_y^i + (\varepsilon_y^i)^2 / 2(\sigma_y^i)^2 \right] \quad (\text{A2.18})$$

Standard deviation is estimated within the model under the assumptions of homoscedasticity $(\sigma_y^i = \sigma^i)$,

$$\hat{\sigma}^i = \sqrt{1/n^i \sum_y (\ln I_y^i - \ln \hat{q}^i \hat{B}_y^i)^2} \quad (\text{A2.19})$$

where n^i is the number of data points for abundance series i and \hat{q}^i is estimated by its maximum likelihood value:

$$\ln \hat{q}^i = 1/n^i \sum_y (\ln I_y^i - \ln \hat{B}_y^i) \quad (\text{A2.20})$$

A2.4.2 Survey Abundance Data

Swept-area surveys usually estimate the sampling variance. The associated σ_y is either taken to be given by the corresponding survey coefficient of variation (CV) (A2.20) or it is estimated using equation A2.21.

$$(\sigma_y)^2 = \ln(1 + (CV)_y^2) \tag{A2.21}$$

$$\hat{\sigma} = \sqrt{1/n \sum_y (\ln I_y^i - \ln q B_y^i)^2} \tag{A2.22}$$

CV_y is the coefficient of variation of the survey estimate for year y and σ_y is the (sampling) standard error of the estimate for the survey in year y .

The contribution of the survey abundance series to the negative of the log-likelihood function is given by:

$$-\ln L = \sum_i \sum_y \left\{ \ln \sqrt{(\sigma_y^i)^2 + (\sigma_A^i)^2} + (\varepsilon_y^i)^2 / \left[2 * \left((\sigma_y^i)^2 + (\sigma_A^i)^2 \right) \right] \right\} \tag{A2.23}$$

where

σ_y^i is the minimum, when $\sigma_A^i = 0$, standard deviation of the residuals for the logarithms of survey i in year y .

σ_A^i is the square root of the additional variance for survey series i , which is an estimable parameter.

$$\varepsilon_y = \ln(I_y^i) - \ln(q^i \hat{B}_y^i) \tag{A2.24}$$

for log-normally distributed errors, where:

I_y^i is the observed survey estimate for year y

B_y^i is the estimated survey biomass, and

q^i is the multiplicative bias given as input or calculated by

$$\ln \hat{q}^i = 1/n \sum_y (\ln I_y^i - \ln \hat{B}_y^i) \tag{A2.25}$$

A2.4.3 Survey Catches-at-Age

The proportion of fish in the catches of the young and older year classes are often very low, due to gear selectivity and mortality for older ages. To overcome this problem, 7-year plus and 2-year minus age classes were defined. The contribution of the survey catch-at-age data to the log-likelihood function is given by:

$$-\ln L = \sum_i \sum_y \sum_a \left[\ln \left(\sigma^i / \sqrt{\hat{p}_{y,a}^i} \right) + \hat{p}_{y,a}^i \left(\ln p_{y,a}^i - \ln \hat{p}_{y,a}^i \right)^2 / 2(\sigma^i)^2 \right] \quad (\text{A2.26})$$

where

$p_{y,a}^i = C_{y,a}^i / \sum_{a=0}^m C_{y,a}^i$ is the observed proportion of fish of age a from the survey in year y

for survey i

$\hat{p}_{y,a}^i$ is the expected proportion of fish of age a in year y , given by:

$$\hat{p}_{y,a}^i = \frac{S_{y,a} N_{y,a} e^{-M_a/2}}{\sum_{a=0}^m S_{y,a} N_{y,a} e^{-M_a/2}} \quad (\text{A2.27})$$

σ^i is the standard deviation associated with the catch-at-age data for the survey, which is estimated in the fitting procedure by:

$$\sigma^i = \sqrt{\sum_y \sum_a \hat{p}_{y,a}^i \left(\ln \hat{p}_{y,a}^i - \ln \hat{p}_{y,a}^i \right)^2 / \sum_y \sum_a 1} \quad (\text{A2.28})$$

A2.4.4 Commercial Catch-at-Age

The proportion of fish in the young and older year classes are often very low, due to gear selectivity and mortality for older ages. To overcome this problem, 7-year plus and 2-year minus age classes were defined. The contribution to the negative of the log-likelihood function when assuming an “adjusted” log-normal error distribution is given by:

$$-\ln L = \sum_f \sum_y \sum_a \left[\ln \left(\sigma_{com}^i / \sqrt{\hat{p}_{y,a}^i} \right) + \hat{p}_{y,a}^i \left(\ln p_{y,a}^i - \ln \hat{p}_{y,a}^i \right)^2 / 2(\sigma_{com}^i)^2 \right] \quad (\text{A2.29})$$

where

$p_{y,a}^i = C_{y,a}^i / \sum_{a'=0}^m C_{y,a'}^i$ is the observed proportion of fish of age a , for each selectivity period, in

year y

$\hat{p}_{y,a}^i$ is the expected proportion of fish for each selectivity period of age a in year y , given by:

$$\hat{p}_{y,a}^i = \frac{S_{y,a} N_{y,a} e^{-M_a/2}}{\sum_{a=0}^m S_{y,a} N_{y,a} e^{-M_a/2}} \quad (\text{A2.30})$$

σ_{com}^i is the standard deviation associated with the catch-at-age data for the different selectivity periods, which is estimated in the fitting procedure by:

$$\sigma_{com}^i = \sqrt{\sum_y \sum_a \hat{p}_{y,a}^i (\ln \hat{p}_{y,a}^i - \ln \hat{p}_{y,a}^i)^2 / \sum_y \sum_a 1} \quad (\text{A2.31})$$

A2.4.5 Seal Scat Data

The likelihood for the seal scat data used in estimating the number of one-year old hake is log-normally distributed about its expected value:

$$\varepsilon_y = \ln(I_y) - \ln(\hat{I}_y) \quad (\text{A2.32})$$

where I_y is the seal scat index for year y ,

$\hat{I}_y = \hat{q}A_y$ is the matching model estimate, where A_y is the model estimate of one-year old hake per year.

\hat{q} is the constant of proportionality for the seal scat series, and

ε_y from $N(0, (\sigma_y)^2)$

which results in the following contribution to the negative of the log-likelihood:

$$-\ln L = \sum_y \ln \sigma_y + (\varepsilon_y)^2 / 2(\sigma_y)^2 \quad (\text{A2.33})$$

Standard deviation is estimated within the model under the assumptions of homoscedasticity

$(\sigma_y^i = \sigma^i)$,

$$\hat{\sigma} = \sqrt{1/n \sum_y (\ln I_y - \ln q A_y)^2} \tag{A2.34}$$

where n is the number of data points and q is estimated by its maximum likelihood value:

$$\ln \hat{q} = 1/n \sum_y (\ln I_y - \ln \hat{A}_y)$$

A2.4.6 Stock-Recruitment Function Residuals

The contribution of the of the recruitment residuals to the negative of the log-likelihood function under the assumption that the residuals are log-normally distributed is given by:

$$-\ln L = \sum_{y=y_1}^y \left[\frac{(\zeta_y)^2}{2\sigma_R^2} \right] \tag{A2.35}$$

where ζ_y is the recruitment residual for year y , which is estimated within the model for years 1965 to 2009 (years for which catch-at-age information is available) using equation A2.9 and σ_R is the standard deviation of the log-residuals, which is set externally either as 0.25 or 0.5 for one of the sensitivity tests.

A.2.4.7 Estimation of Mean Length of Fish

$$l_y = \frac{\sum_{a=0}^m N_{y,a} \cdot l_a \cdot S_{y,a}}{\sum_{a=0}^m N_{y,a} \cdot S_{y,a}} \tag{A2.36}$$

Where l_a is length-at-age given in Table A1.7

$N_{y,a}$ is number of fish per year at age

$S_{y,a}$ selectivity per year at age

Appendix 3: Figures and Tables

Figure A3.2. Old ICSEAF Subdivisions along the Southern African Coast

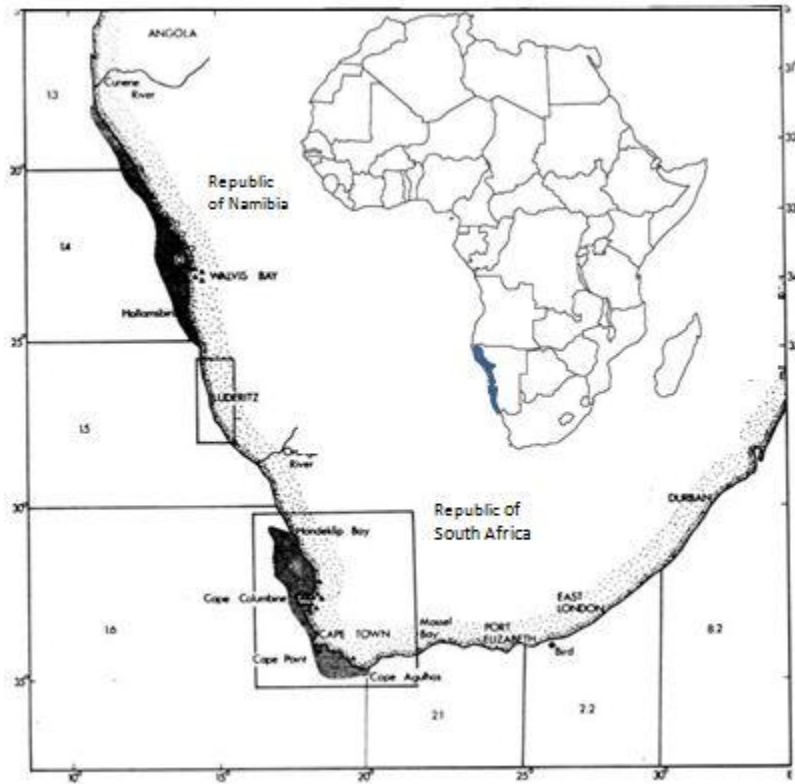
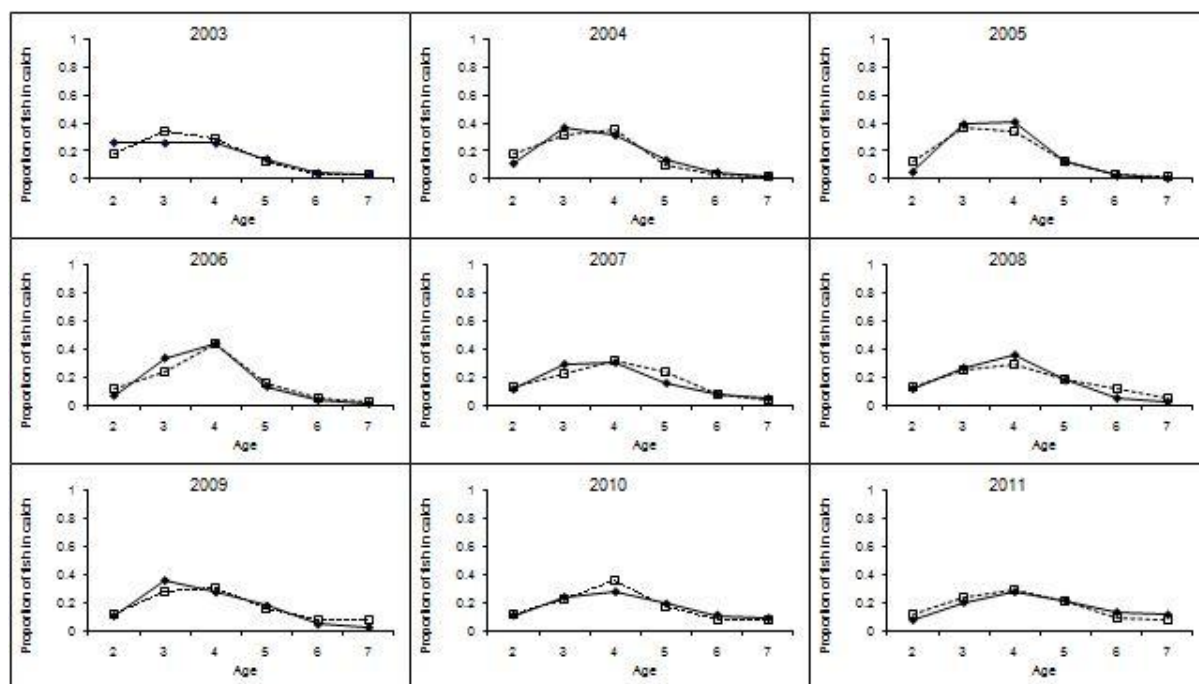
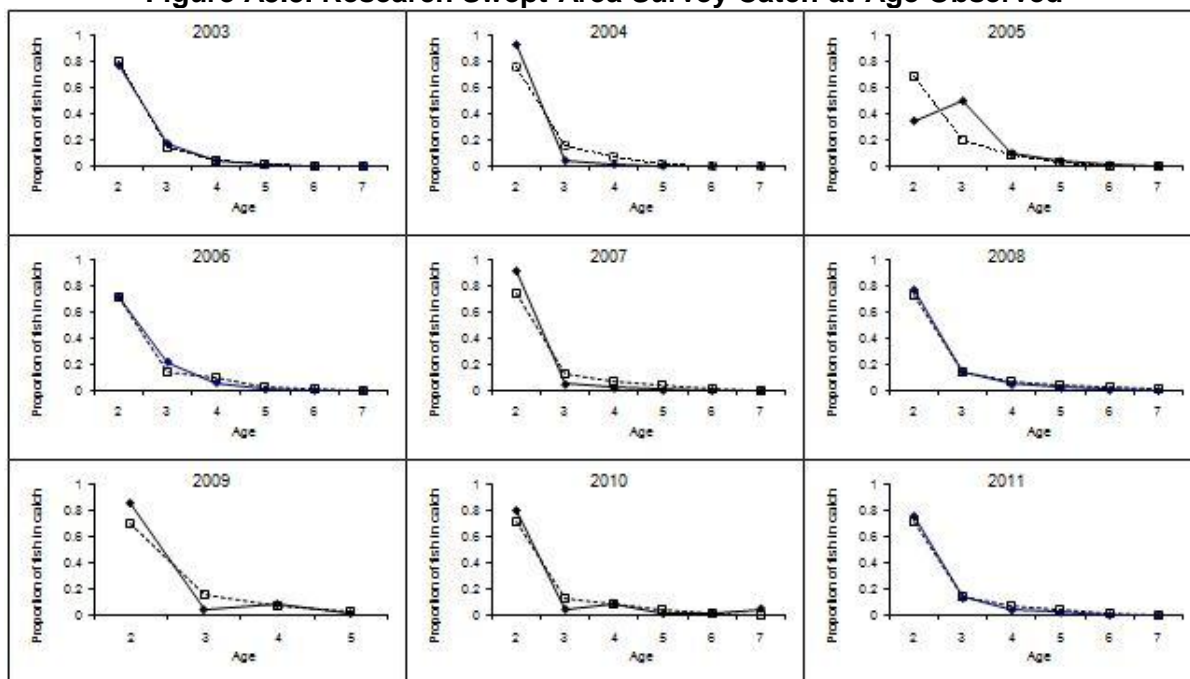


Figure A3.2. Commercial Catch-at-Age Observed



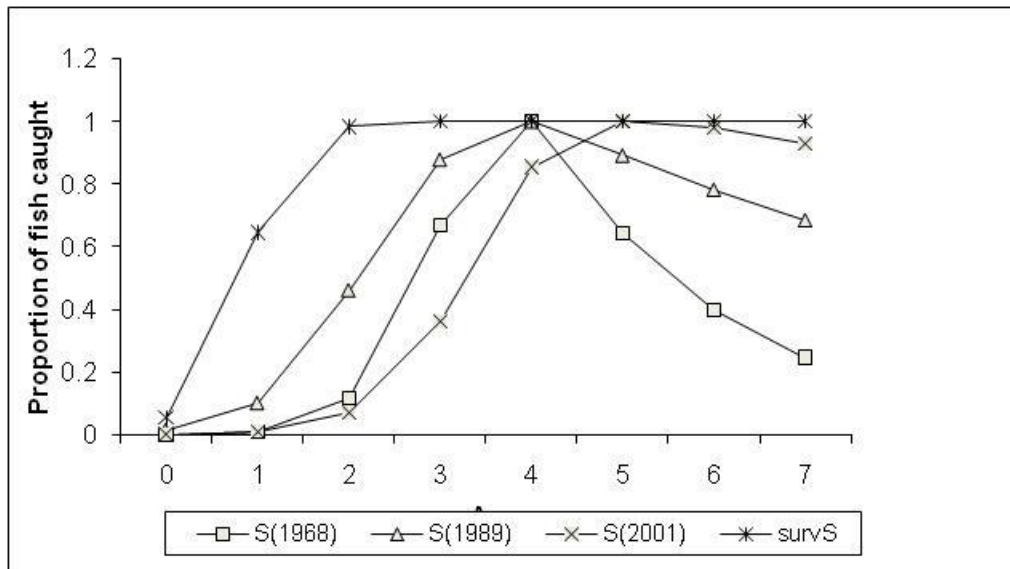
(solid diamonds-solid line) and estimated (open squares-dotted line) data from 2003 to 2011. Age of the minus group is 2 and the plus group 7.

Figure A3.3. Research Swept-Area Survey Catch-at-Age Observed



(solid diamonds, solid line) and estimated (open squares, dotted line) from 2003-2011. Age of the minus group is 2 and the plus group 7. In 2009 no observation of fish older than 5 years were made.

Figure A3.4. Estimated Commercial Selectivities for the Different Time Periods (Different Management Regulations) and the Estimated Research Survey Selectivity



List of Figures

Figure 1: Reported annual landings and TAC's of Namibian hake from 1964-2011. Pre-1990 catches were recorded by ICSEAF. Total allowable catches (TAC) were introduced in 1976 and are shown here up to 2011.

Figure 2: Current state of the stock relative to the state in 1990 for the total biomass for the base case (1) and the 11 sensitivity tests. The model fit decreases from left to right for the different model specifications, indicating that the base case is the 5th best fit model. Aikake values for test 1 and 9 are not comparable to the other test and therefore excluded.

Figure 3: Current state of the stock relative to the virgin total biomass (depletion) for the base case (1) and the 11 sensitivity tests. 90% probability intervals are shown.

Figure 4: Model fit to the observed data: Historic CPUE (a & b), GLM standardized commercial CPUE (c), Spanish survey data (d & e), "7-vessel" CPUE data (f) and research survey data (g & h) and seal scat data (i).

Figure 5: Model fit to the observed research summer survey biomass data with 95% confidence intervals (solid line). The model-predicted biomass data is given with 95% probabilities.

Figure 6: Model estimated recruitment (numbers) from 1964-2012 (a), Beverton and Holt recruitment curve fit onto the estimated recruitment values (b) and recruitment residuals (c). The grey triangles are recruitment values from 1964-1985; solid squares (1985-1990) and the open circles (1990-2012).

Figure 7: Spawning biomass/pre-exploitable spawning biomass and the 95% probability intervals from 1964-2012 (a). Probability density function (PDF) of current depletion (Total biomass/pre-exploitable biomass) and the estimated PDF function for year 2022, if the resource is fished under pre-described management regulations ($TAC = 0.8 * \text{replacement yield}$) as stipulated in the hake management plan (b).

Figure 8: Percentage of biomass of 4 years and older (a) and the mean size of the fish in the catch (b) are shown (1964-2012).

Figure 9: "Management Monitor Graph". The horizontal line indicates the points at which catch is equal to replacement yield and the vertical line indicates a biomass equal to the biomass in 1990. Usually the vertical line would be the MSY level, but this line would be to the far right, in this case well off the chart.

Figure 10: Total allowable catches in thousand tonnes for the next 10 years (a). The average and ninety percentiles are indicated. The probability density function for the estimated TAC for the 2012 season (b).

List of Tables

Table 1. The Base-Case and the Following 11 Sensitivity Tests were Run and Their Results were Evaluated

| Model number | Model specifications and changes |
|---------------------|---|
| Base Case | Base case, includes all available data, assumed known age-dependent M (set externally), h estimated, all q 's are estimated, sigma for CPUE's are estimated, single K_{sp} period, sigma for $R=0.5$, selectivity curve has a right-hand slope for fisheries and survey. |
| 1 | GLM CPUE and "7-vessel" CPUE data is omitted from the assessment |
| 2 | Sigma set externally for $R=0.25$ |
| 3 | Estimating an age-independent M |
| 4 | Estimating M at infinity |
| 5 | $q=0.4$ |
| 6 | $q=0.6$ |
| 7 | $q=0.8$ |
| 8 | $q=1$ |
| 9 | sigma's for CPUE series are set externally (0.2 for ICSEAF and GLM) (0.4 for Spanish surveys and "7 vessel" CPUE series) |
| 10 | Change in productivity in mid 1980's |
| 11 | Survey selectivity is logistic (No descending right-hand limb) |

Table 2: Some Results for the Base Case and the 11 Sensitivity Tests

| | Baseline | Test 1 | Test 2 | Test 3 | Test 4 | Test 5 | Test 6 | Test 7 | Test 8 | Test 9 | Test 10 | Test 11 |
|---|----------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| Negative loglikelihood values | | | | | | | | | | | | |
| overall | -125.95 | -106.32 | -102.31 | -127.63 | -127.49 | -116.02 | -117.78 | -119.52 | -120.48 | -121.23 | -126.71 | -125.68 |
| CPUE | -41.93 | -19.93 | -39.44 | -41.02 | -41.85 | -36.81 | -40.47 | -41.61 | -41.97 | -38.72 | -43.26 | -42.08 |
| Surveys | -21.68 | -22.24 | -23.39 | -19.63 | -20.00 | -16.76 | -15.65 | -15.66 | -16.61 | -20.83 | -21.21 | -21.43 |
| CAA(commercial) | -94.01 | -95.04 | -87.41 | -102.74 | -98.37 | -95.00 | -91.96 | -92.75 | -93.90 | -94.28 | -91.74 | -93.91 |
| CAA(surveys) | 12.47 | 12.13 | 15.61 | 15.58 | 13.39 | 12.48 | 10.64 | 10.96 | 12.77 | 12.88 | 11.37 | 12.45 |
| Recruitment residuals | 10.59 | 10.16 | 23.72 | 11.39 | 10.59 | 11.07 | 10.70 | 10.72 | 10.59 | 11.02 | 9.46 | 10.66 |
| Number of one-year old's | 8.61 | 8.61 | 8.60 | 8.79 | 8.76 | 9.00 | 8.95 | 8.82 | 8.65 | 8.71 | 8.67 | 8.63 |
| Num parameters estimated | 65 | 65 | 65 | 66 | 66 | 65 | 65 | 65 | 65 | 65 | 66 | 64 |
| Akaike_info_crit (Akaike) | -121.91 | -82.64 | -74.63 | -123.27 | -122.98 | -102.04 | -105.56 | -109.04 | -110.96 | -112.47 | -121.41 | -123.37 |
| Estimated management quantities | | | | | | | | | | | | |
| Ksp (Pre-exploitation spawning biomass) | 5976 | 6596 | 5940 | 5946 | 6019 | 7987 | 6671 | 6131 | 5860 | 6203 | 5106 | 5944 |
| Kexp (Pre-exploitation exploitable biomass) | 2562 | 2787 | 2597 | 3000 | 2825 | 3231 | 2782 | 2608 | 2528 | 2641 | 2344 | 2553 |
| Spawning biomass (Bsp) (2012) | 809 | 879 | 756 | 985 | 1004 | 2173 | 1386 | 1044 | 873 | 863 | 859 | 841 |
| Exploitable biomass (Bexp) (2012) | 492 | 515 | 446 | 597 | 568 | 1124 | 828 | 639 | 538 | 531 | 522 | 512 |
| Spawning biomass at MSY | 2610 | 2908 | 2585 | 2703 | 2781 | 3626 | 2950 | 2676 | 2548 | 2718 | 762 | 2591 |
| Exploitable biomass at MSY | 1794 | 1887 | 1747 | 1791 | 1733 | 1918 | 1802 | 1740 | 1765 | 1877 | 473 | 1782 |
| MSY | 280 | 271 | 280 | 255 | 248 | 229 | 248 | 269 | 287 | 287 | 129 | 283 |
| Bsp(2012)/Ksp | 0.14 | 0.13 | 0.13 | 0.17 | 0.17 | 0.27 | 0.21 | 0.17 | 0.15 | 0.14 | 0.17 | 0.14 |
| Bexp(2012)/Kexp | 0.19 | 0.18 | 0.17 | 0.20 | 0.20 | 0.35 | 0.30 | 0.24 | 0.21 | 0.20 | 0.22 | 0.20 |
| steepness (h) | 0.35 | 0.33 | 0.35 | 0.30 | 0.30 | 0.29 | 0.32 | 0.34 | 0.36 | 0.35 | 0.46 | 0.36 |
| TotalB(2012)/TotalB(1990) | 1.05 | 1.07 | 1.09 | 0.95 | 0.97 | 1.22 | 1.17 | 1.16 | 1.18 | 1.08 | 1.06 | 1.10 |
| Bsp(2012)/Bsp(MSY) | 0.31 | 0.30 | 0.29 | 0.36 | 0.36 | 0.60 | 0.47 | 0.39 | 0.34 | 0.32 | 1.13 | 0.32 |
| Average replacement yield (AveRY) | 136.81 | 137.46 | 138.62 | 132.52 | 132.35 | 155.58 | 146.20 | 142.84 | 142.18 | 138.07 | 137.75 | 139.03 |
| Catch(2011)/AveRY | 1.13 | 1.12 | 1.11 | 1.16 | 1.17 | 0.99 | 1.06 | 1.08 | 1.09 | 1.12 | 1.12 | 1.11 |
| Bexp(2012)/Bexp(MSY) | 0.27 | 0.27 | 0.26 | 0.33 | 0.33 | 0.59 | 0.46 | 0.37 | 0.30 | 0.28 | 1.10 | 0.29 |
| MSYL/Ksp | 0.44 | 0.44 | 0.44 | 0.45 | 0.46 | 0.45 | 0.44 | 0.44 | 0.43 | 0.44 | 0.15 | 0.44 |
| MSYL/Kexp | 0.70 | 0.68 | 0.67 | 0.60 | 0.61 | 0.59 | 0.65 | 0.67 | 0.70 | 0.71 | 0.20 | 0.70 |
| ICSEAF CPUE1 (σ) | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 | 0.12 | 0.11 | 0.11 | 0.11 | 0.11 | 0.10 | 0.11 |
| ICSEAF CPUE2 (σ) | 0.16 | 0.16 | 0.16 | 0.17 | 0.16 | 0.17 | 0.16 | 0.16 | 0.16 | 0.16 | 0.15 | 0.16 |
| GLM CPUE (σ) | 0.26 | 0.30 | 0.27 | 0.26 | 0.26 | 0.34 | 0.30 | 0.27 | 0.25 | 0.24 | 0.26 | 0.25 |
| "7-vessel" CPUE (σ) | 0.36 | 0.40 | 0.39 | 0.35 | 0.34 | 0.28 | 0.28 | 0.33 | 0.36 | 0.37 | 0.31 | 0.36 |
| ICSEAF CPUE 1 (q) | 5.4E-04 | 4.8E-04 | 5.3E-04 | 4.5E-04 | 4.8E-04 | 4.0E-04 | 4.8E-04 | 5.3E-04 | 5.5E-04 | 5.2E-04 | 6.0E-04 | 5.4E-04 |
| ICSEAF CPUE 2 (q) | 8.2E-04 | 7.3E-04 | 8.0E-04 | 6.8E-04 | 7.3E-04 | 6.1E-04 | 7.4E-04 | 8.0E-04 | 8.3E-04 | 7.9E-04 | 9.2E-04 | 8.2E-04 |
| GLM CPUE (q) | 1.6E+00 | 1.4E+00 | 1.6E+00 | 1.2E+00 | 1.3E+00 | 6.7E-01 | 9.6E-01 | 1.3E+00 | 1.6E+00 | 1.6E+00 | 1.5E+00 | 1.6E+00 |
| "7-Vessel" CPUE (q) | 1.1E-02 | 1.0E-02 | 1.2E-02 | 8.9E-03 | 9.5E-03 | 7.2E-03 | 9.3E-03 | 1.1E-02 | 1.1E-02 | 1.1E-02 | 1.2E-02 | 1.1E-02 |
| Seal index (q) | 2.3E-01 | 2.2E-01 | 2.4E-01 | 6.3E-01 | 1.1E-01 | 1.3E-01 | 1.8E-01 | 2.1E-01 | 2.3E-01 | 2.3E-01 | 2.3E-01 | 2.3E-01 |
| Spanish Winter survey (σ) | 0.32 | 0.32 | 0.33 | 0.33 | 0.33 | 0.36 | 0.35 | 0.33 | 0.32 | 0.33 | 0.33 | 0.32 |
| Spanish Summer survey (σ) | 0.64 | 0.64 | 0.66 | 0.60 | 0.61 | 0.54 | 0.58 | 0.62 | 0.65 | 0.64 | 0.61 | 0.64 |
| Spanish Winter survey (q) | 0.61 | 0.58 | 0.65 | 0.49 | 0.51 | 0.35 | 0.46 | 0.55 | 0.62 | 0.57 | 0.63 | 0.61 |
| Spanish Summer survey (q) | 0.89 | 0.85 | 0.96 | 0.71 | 0.70 | 0.49 | 0.66 | 0.79 | 0.91 | 0.84 | 0.90 | 0.89 |
| Addvariance | 0.05 | 0.05 | 0.04 | 0.06 | 0.06 | 0.05 | 0.06 | 0.06 | 0.05 | 0.06 | 0.05 | 0.05 |
| Nansen Summer survey (q) | 1.07 | 0.98 | 1.09 | 0.84 | 0.83 | 0.40 | 0.60 | 0.80 | 1.00 | 1.04 | 1.01 | 1.07 |
| Nansen Winter survey (q) | 1.02 | 0.96 | 1.07 | 0.77 | 0.79 | 0.40 | 0.60 | 0.80 | 1.00 | 0.99 | 0.94 | 1.03 |
| Commercial catch-at-age (σ) | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 |
| Summer survey catch-at-age (σ) | 0.15 | 0.14 | 0.15 | 0.15 | 0.15 | 0.14 | 0.14 | 0.14 | 0.15 | 0.15 | 0.14 | 0.15 |
| Winter survey catch-at-age (σ) | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.11 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 |
| Seal index (σ) | 0.91 | 0.92 | 0.91 | 0.91 | 0.91 | 0.93 | 0.92 | 0.91 | 0.90 | 0.90 | 0.91 | 0.91 |
| Additional seal σ | 0.53 | 0.53 | 0.53 | 0.55 | 0.54 | 0.56 | 0.55 | 0.55 | 0.54 | 0.54 | 0.54 | 0.54 |
| Natural mortality at age 0 | 1.42 | 1.42 | 1.42 | 0.50 | 1.68 | 1.42 | 1.42 | 1.42 | 1.42 | 1.42 | 1.42 | 1.42 |
| Natural mortality at age 1 | 0.71 | 0.71 | 0.71 | 0.50 | 0.84 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 |
| Natural mortality at age 2 | 0.57 | 0.57 | 0.57 | 0.50 | 0.67 | 0.57 | 0.57 | 0.57 | 0.57 | 0.57 | 0.57 | 0.57 |
| Natural mortality at age 3 | 0.50 | 0.50 | 0.50 | 0.50 | 0.59 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| Natural mortality at age 4 | 0.46 | 0.46 | 0.46 | 0.50 | 0.54 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 | 0.46 |
| Natural mortality at age 5 | 0.42 | 0.42 | 0.42 | 0.50 | 0.50 | 0.42 | 0.42 | 0.42 | 0.42 | 0.42 | 0.42 | 0.42 |
| Natural mortality at age 6 | 0.40 | 0.40 | 0.40 | 0.50 | 0.47 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 |
| Natural mortality at age 7 | 0.38 | 0.38 | 0.38 | 0.50 | 0.45 | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 |
| Natural mortality at age 8 | 0.36 | 0.36 | 0.36 | 0.50 | 0.43 | 0.36 | 0.36 | 0.36 | 0.36 | 0.36 | 0.36 | 0.36 |
| Natural mortality at infinity (Minf) | 0.36 | 0.36 | 0.36 | 0.36 | 0.42 | 0.36 | 0.36 | 0.36 | 0.36 | 0.36 | 0.36 | 0.36 |

Figure 1. (Kirchner et al.)

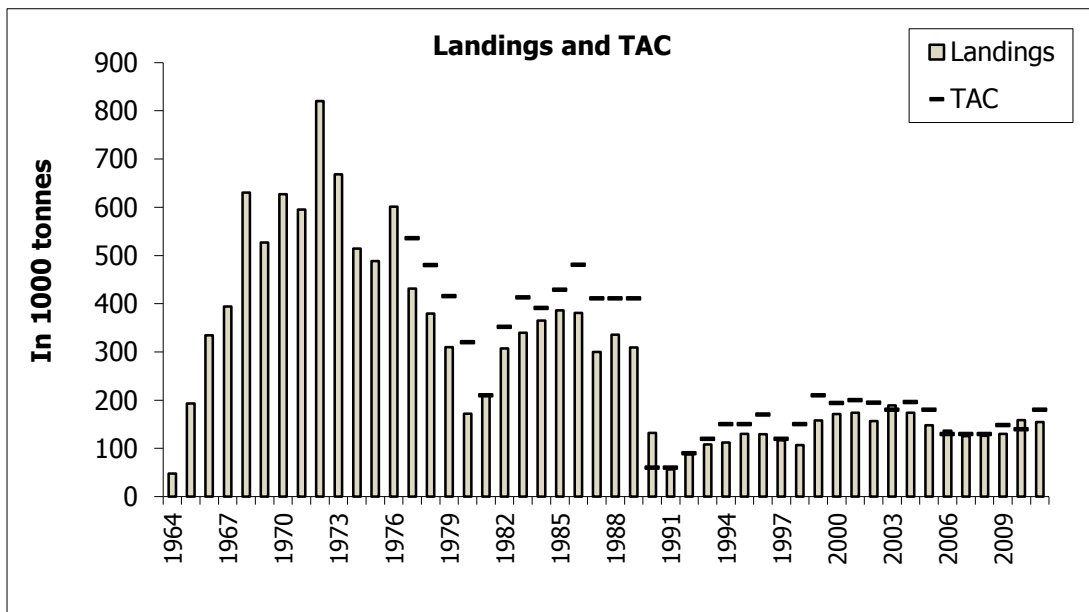


Figure 2. (Kirchner et al.)

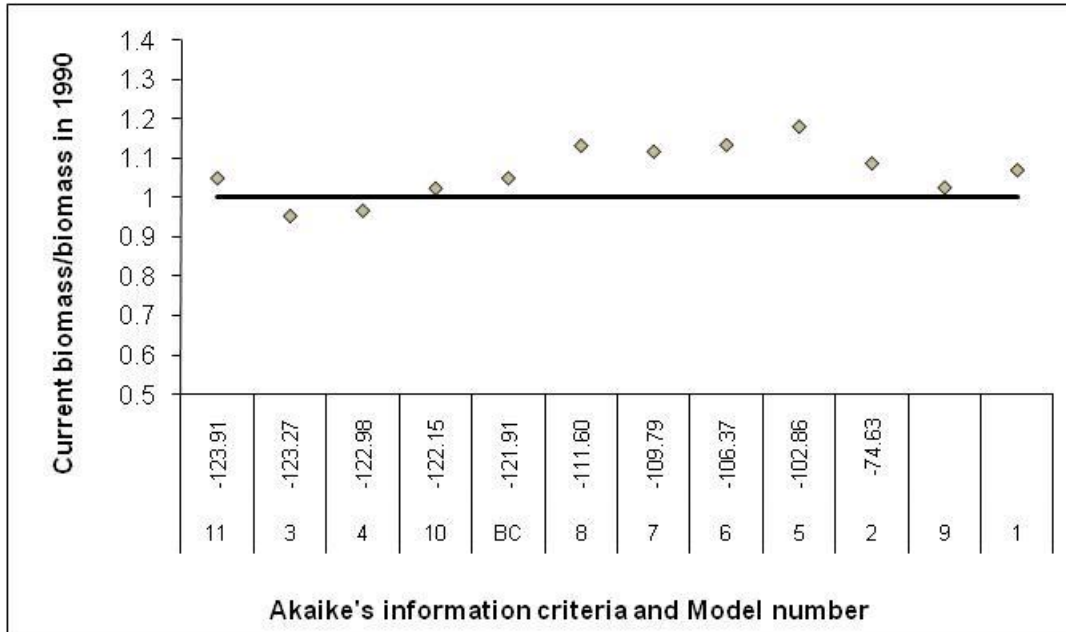


Figure 3. (Kirchner et al.)

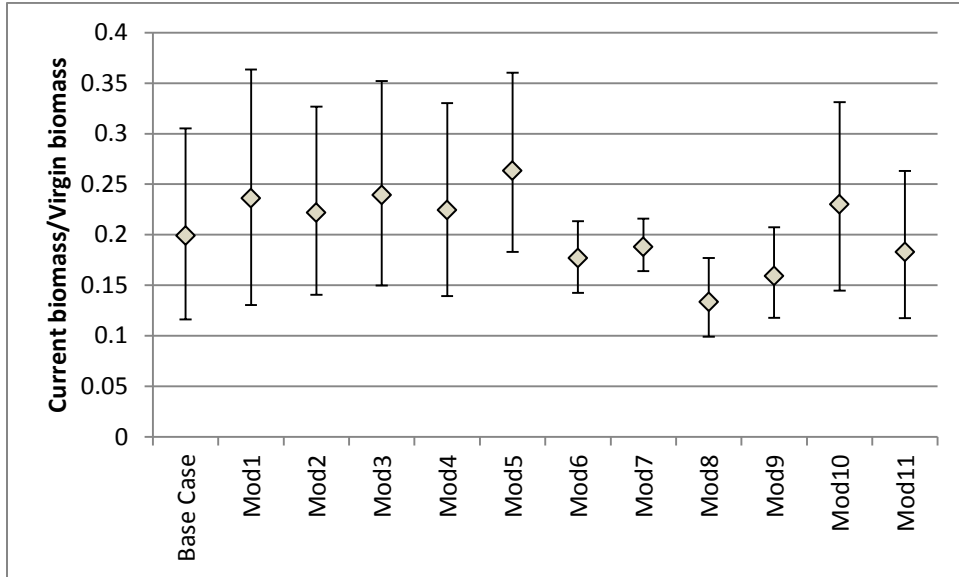


Figure 4. (Kirchner et al.)

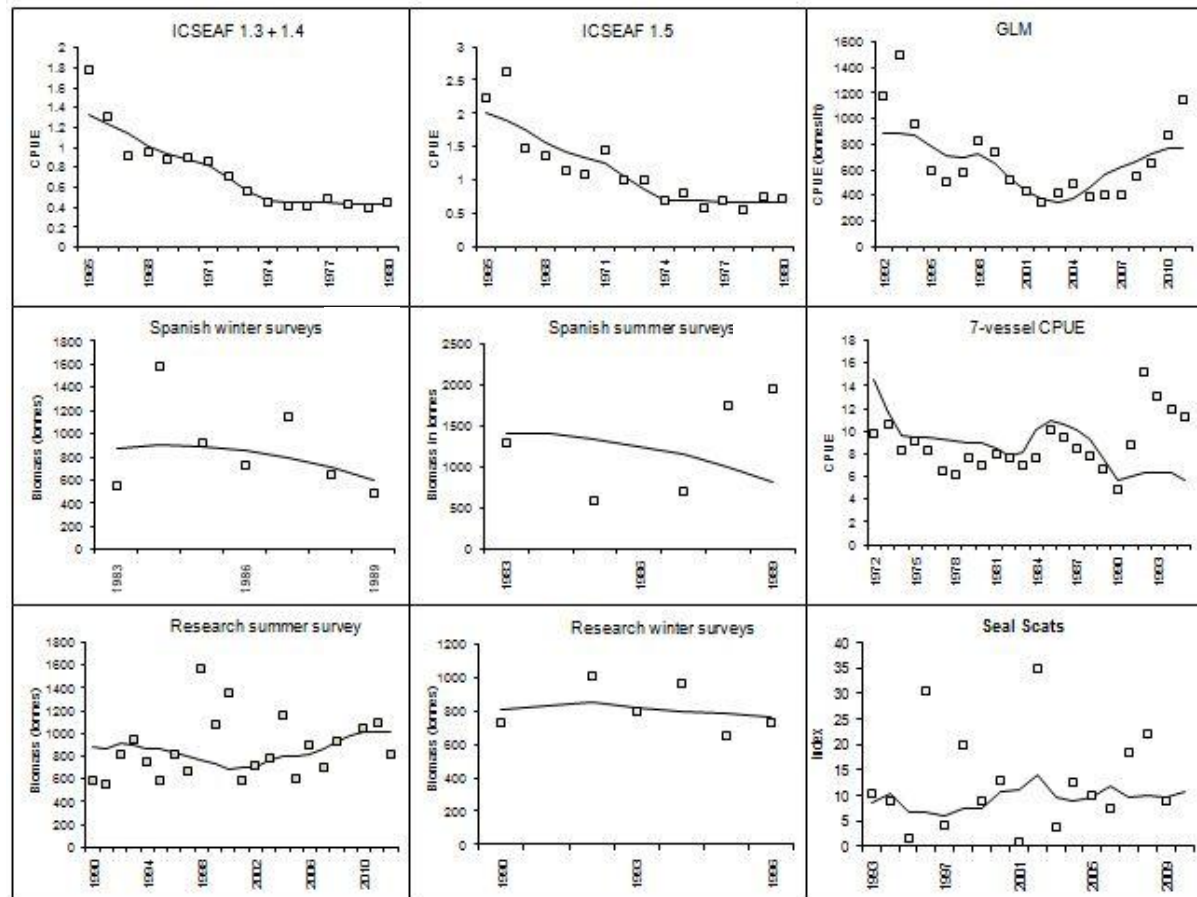


Figure 5. (Kirchner et al.)

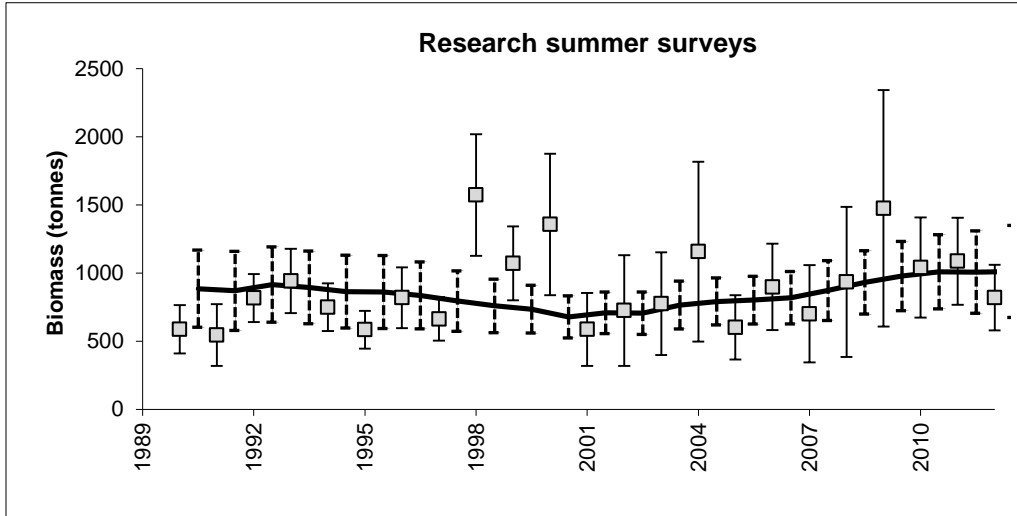


Figure 6. (Kirchner et al.)

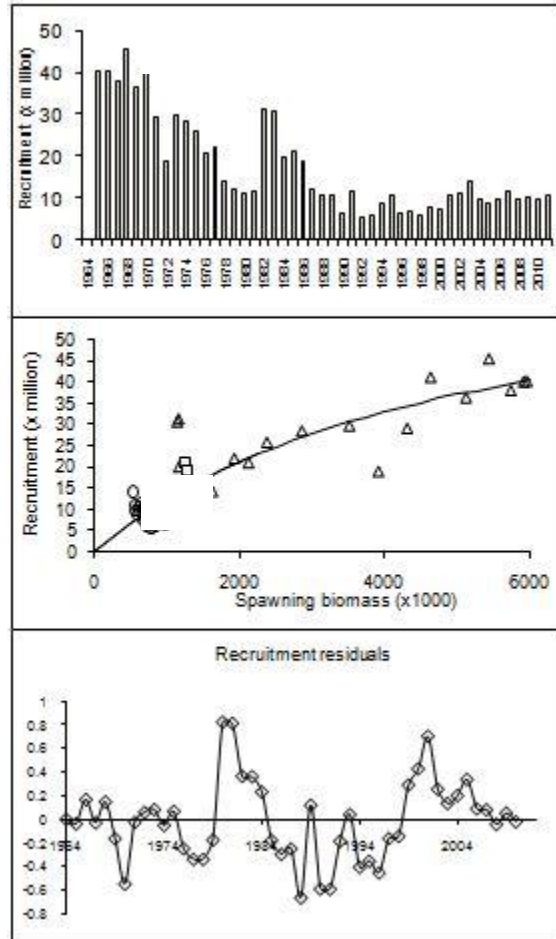


Figure 7. (Kirchner et al.)

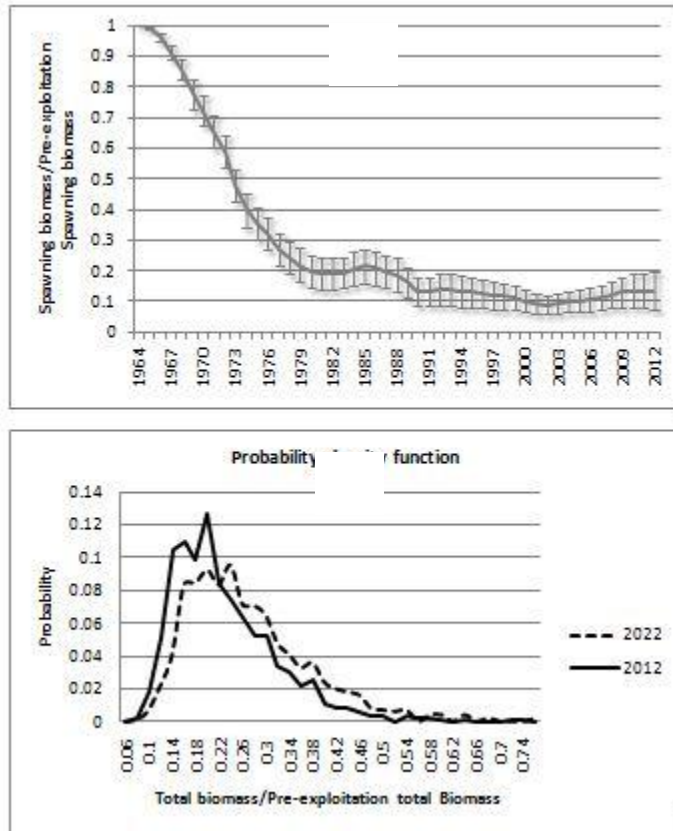


Figure 8. (Kirchner et al.)

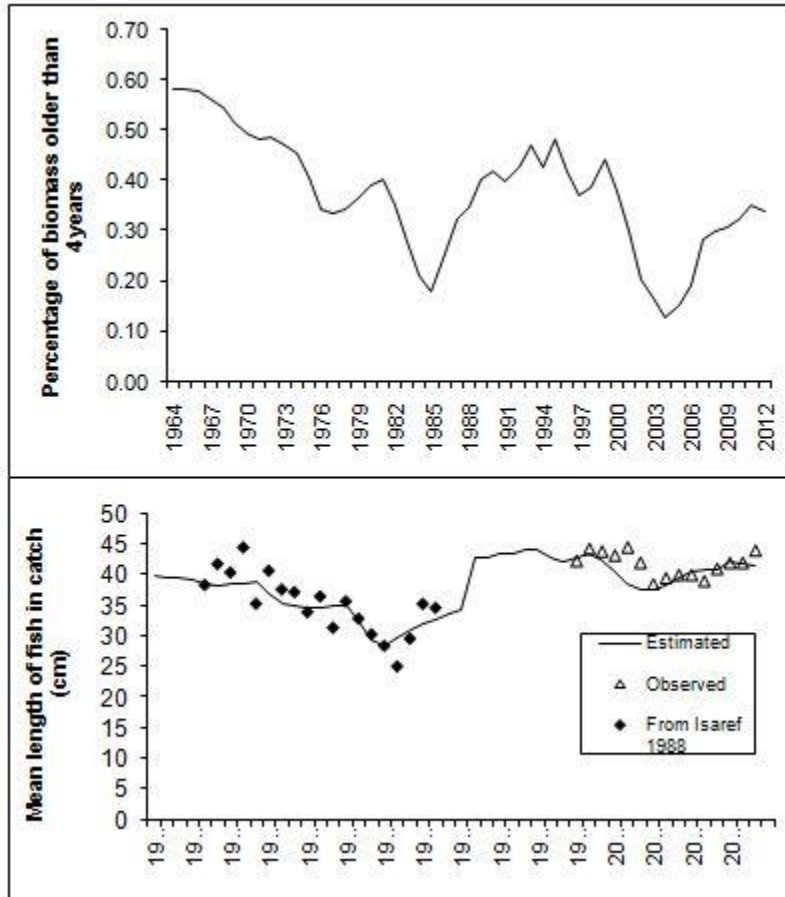


Figure 9 (Kirchner et al.)

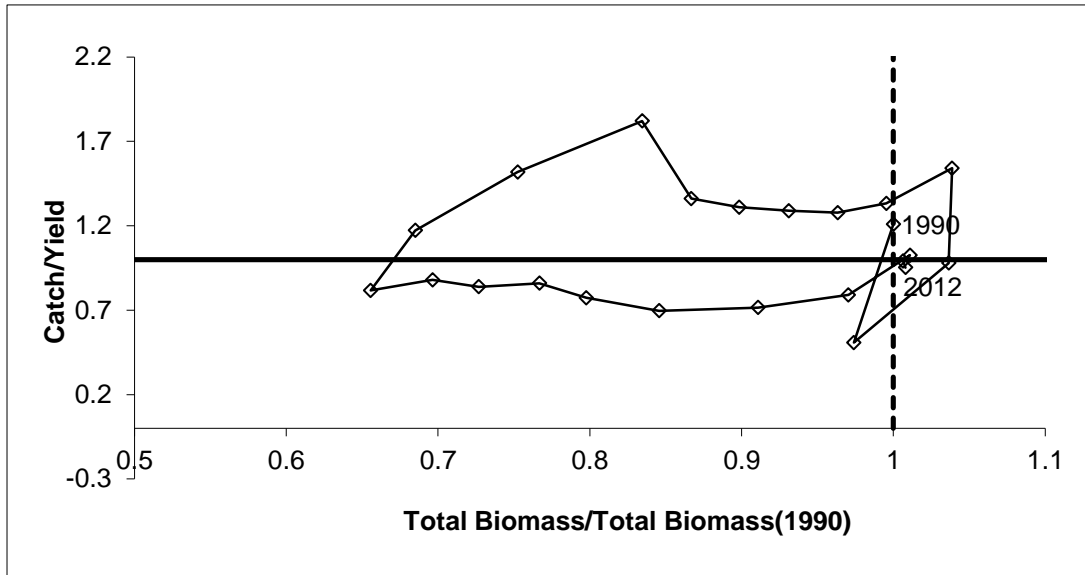


Figure 10. (Kirchner et al.)

