Evaluation of the status of the Namibian hake resource (*Merluccius* spp.) using statistical catch-at-age analysis

Carola Kirchner, Paul Kainge[*] and Johannes Kathena*

University of Cape Town, Graduate School of Business, South Africa
Carola.Kirchner32@gmail.com
[*]*Ministry of Fisheries and Marine Resources, P.O. Box 912, Swakopmund, Namibia*

Abstract

Namibian hake is the most important fish resource in Namibia. This paper is a compilation of all hake data, historic and more recent, that was used in stock assessment and management advice since the late 70's. An age-structured production model is used to evaluate the state of the Namibian Hake resource under different assumptions. Both hakes, Merluccius paradoxus and M. capensis, are treated as one unit stock. It was estimated that the stock has not as yet recovered to its maximum sustainable yield level since the foreign fishing effort has been removed in 1990. Best results estimate the stock to be around 18% of pre-exploitation levels, however the results are very variable within and across different model assumptions. Signs indicate that the stock is slowly recovering from its all-time low in 2002-2004. Since the two hake species are assessed by pooling their data, the resource is currently managed on a relatively simple adaptive basis, only 80% of the replacement yield is reserved for fishing, the remainder being left for rebuilding.

Age-structured production model, data, Management monitor graph, Namibian hake, stock assessment,

Introduction

Namibia's 1500km 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 high plankton blooms are features of this productive system (Hutching et al. 2009). However, most of Namibia's historically rich fish resources, like 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 1960's (Boyer and Hampton 2001), with average catches of 580 thousand tonnes per year in the period 1960-1977, which dropped off to a mere 46 thousand in 1978, this stock has collapsed (De Oliveira et al. 2007) and 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 the Angola-Benguela front e.g. sardine (Kirchner et al. 2009).

The most important species in Namibia are the hakes (Van der Westhuizen 2001). There are two species of hake 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 since 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. 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. 2008a).

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. This biological model underpins the bio-economic assessment described in Kirchner (2011, submitted).

Material and methods

Total allowable catches and landings

Exploitation of the Namibian hake resource commenced in 1964 and over the period 1964-1976 the fishery was unregulated. 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 and in 1975 a minimum mesh size of 110 cm was introduced. Subsequently over 1977-1989, the fishery was managed through annual TACs. Between the years 1980 to 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 ICSEAF (Ruiz pers. comm. - who during the 1980's was responsible for one country's shipments of hake from Walvis Bay, reports that these were substantially underreported).

Before 1990 Namibia was still a mandated territory and not a nation state, consequently its control over fishing stopped at the 3-mile limit, even though most of the world had shifted to a 200mile 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) which removed most foreign fishing effort; mainly European and Eastern bloc fleets, and declared a 200-mile (EEZ) (MFMR 1990) in accordance with the international law. Since that time the average annual catch has been reduced to about 148 000 tonnes (Figure 1, A1.1) in an attempt to rebuild the depleted stock. During the 1980's, assessments developed at ICSEAF meetings had indicated that the resource was recovering; however this result followed primarily from a reported increase in Spanish CPUE over this period. These CPUE data are no longer considered reliable (Butterworth and Rademeyer 2005). A further measures introduced to promote stock rebuilding was the closure of the area shallower than 200m water depths to trawling. No discards were allowed and 'at-sea-sampling' was introduced 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. complete. Catches (Table A1.1) have been recorded since fishing commenced in 1964. A few historic indices of abundance are available (Table A1.2); two series of catch per unit effort (CPUE) recorded during the ICSEAF period are included, one for the Division 1.3 + 1.4, which represents the Spanish bottom trawlers in tonnage class 7 (1000-1999 GRT) (Andrew 1986). The other is for Division 1.5, which are the pooled above-mentioned Spanish data and 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). Since 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 CPUE values for the years 1965-1988. However, since then, it became apparent that any post-1980 ICSEAF CPUE data was positively biased and should therefore 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 modelling by Brandão and Butterworth (2004 & 2005) and has now been extended by NatMIRC to 2010. 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 for 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).

Stratified random bottom trawl Spanish surveys were undertaken from 1983 to 1990. The biomass estimates of hake of these surveys, published in Macpherson and Gordoa (1992), have since been recalculated (Gordoa, pers. comm.), (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 1990's, two surveys, one in summer and one in winter were undertaken annually. 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 2010 (Table A1.3) (Van der Westhuizen 2001). The research and commercial surveys were calibrated against one another (Butterworth *et al.* 2001) (Table A.1.4)

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 Gordoa, et al. (1995) and Gordoa and Hightower (1991), and referenced to Draganik and Sacks (1987) (Table A1.5).

From 1990, for all years for which no observed age data, obtained by reading annual rings on otoliths (Margit Wilhelm, unpublished data.), were 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). The commercial catch-at-age data is iterated for 1997 and 1998, and the remaining data is observed. For the summer surveys, 1990, 1994- 1998, 2008-2010 used iterated data and for 1991-1993, and 2001-2007 used otolith based catch-at-age data. For the winter surveys 1990, and 1994-1996 used iterated data and 1991-1993 used observed otoliths (Table A1.4). Further, a recruitment index from 1994 to 2009 is obtained by determining the proportion of

M. capensis otoliths found in seal scat samples on an annual basis (Jean-Paul Roux, unpublished data).

Stock assessment model

A statistical catch-at-age analysis is implemented 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. (2008a) (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 in the base case assessment age-dependent natural mortality is set externally (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). Seal scat data (Table A1.6) is used to estimate the strength of the one-year old cohort. 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).

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

where $\boldsymbol{a_c}$ = age–at-50% selectivity and

$\boldsymbol{\delta}$ = gradient of the ascending part of the logistic curve

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

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

where $\boldsymbol{s}$ 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, 13 sensitivity tests were executed to investigate the effect of some of the assumptions made for the assessment. For the base case, it is assumed that the CPUE data is an indication of abundance, however, the CPUE might not be a good indicator and therefore in sensitivity test 1 all recent CPUE data has been omitted from the assessment. For sensitivity test 2, the variability of recruitment has been decreased from 0.5 to 0.25. For the tests 3 and 4, constant natural mortality and natural mortality at infinity is estimated. The catchability constant is set externally for sensitivity test 5 to 8. In the base case the variability around the different CPUE series is estimated (Equation A2.19) and this is set externally in the sensitivity test 9. The steepness parameter is estimated to be very low (around 0.35), which is unusual for a species like hake as it means that the productivity is very low at low spawner biomass levels. An alternative could be that the productivity level is lower in more recent years due to environmental conditions and therefore for sensitivity test 10, two different productivity periods were estimated by assuming a gradual change in productivity from 1985-1990. In the 11^{th} test, the selectivity for the surveys was set to be logistic without the right-hand slope of the curve i.e. that all the older fish are caught in the trawling. The seal scat data is a very good indicator of recruitment (J-P Roux, pers comm.), therefore in test 12, the seal scat data is weighted 10 times more in the loglikelihood function. The 13^{th} sensitivity test excludes all historic catch-at-age data and only includes the newly developed catch-at-age matrix provided by Margit Wilhelm. (Table A1.8).

In the past the results of the stock assessments have shown great variability as absolute values, therefore it was preferred to present results in relative terms; emphasis was placed on trends. This assessment treats *Merluccius capensis* and *M. paradoxus* as one stock as data for a split species assessment are not yet available and therefore it reasonable not to over-interprete the results. Notwithstanding, the current assessment estimates that the stock is far below the maximum sustainable yield level (MSY), which is considered to be 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 in 1990 (Reference to be included), at independence, Namibia inherited a depleted stock. To what extent the stock was depleted is uncertain, but it presents a direction in which management should move; cautious adaptive management. For example, if the stock is believed to be 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 1000'th simulation for further analysis.

Results

The current state of the stock was determined over the whole range of model specifications (Table 1) and the results relative to the state of the resource in 1990 are represented 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 model results are presented for the base case only as this case is based on the most plausible biological assumptions. With the exception of three model specifications, the resource appears to be either on the same level as in 1990 or above. It should be noted that the estimation of natural mortality within the model produces the best fit to the observed data and results in a stock level below that of 1990.

Figure 3 presents the depletion rates (current total biomass/virgin biomass). The probability intervals (90 percentile) indicates the variability within a specific model specification and the actual estimates show the between-model variation. Overall, the depletion values range from about 16-30%; outliers are tests 12 and 13. The results of the 13th sensitivity test are based on a new catch-at-age matrix, which indicates faster growth of hake and therefore reflects an under-exploited hake resource (68% depletion). Moreover, if we assume that the seal scat data is a good indicator of recruitment, the resource is estimated to be at very low levels (13% depletion).

Figure 4 presents the model estimated data with the observed data and it shows that some of the model estimated values fit the observed abundance data relatively well, with the exception of the Spanish surveys (Figure 4g and h) and the seal scat data (Figure 4f). The observed variability in the recruitment observed in the seal scat data is not seen in the catch-at-age data. This is shown in Figures A3.1 and A3.2, where the estimated and observed catch-at-age data for the commercial fleet and survey are reflected, respectively. From these figures it is clear 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. For the 12th sensitivity test the seal scat data is given more weight in the model; this specification cannot be compared to the other sensitivity tests in terms of the AIC (Figure 2). Intuitively, the extreme variability in the recruitment seen in the seal scat data means that increasing its weight causes the fit of the catch-at-age to deteriorate.

Figure 5a presents model estimated recruitment from 1964-2011, recruitment residuals (c) and a Beverton and Holt recruitment curve fit onto the estimated recruitment values (b). Recruitment was estimated to be appreciatively lower since the mid 80's. 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. This is extremely low (Reference of Ram Meyers to be included here). From the residuals (Figure 5c) it can be seen that there is 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 18% of its pre-exploitation level, which would, in biological terms, be considered to be severely depleted. Permitting unduly high catches since 1990 caused the stock to further decline until 2004. Since then permitted catches have been decreased, allowing the stock to increase somewhat over the last 7 years. The model estimated that the percentage of biomass older than 4 years increased between 2004 and 2007, which was due to the strong cohort in 2002 (Figure 6a). Since then the biomass older than 4 years has been declining slightly, however an increase was estimated for 2011. The mean length of fish in commercial catches has stayed relatively constant in the last few years (Figure 6b).

Management

The vertical line in the Management Monitor Graph (MMG, Figure 7) 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). To the left of the vertical line indicates that the state of the resource is 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). 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 of the chart).

Currently, the hake resource is estimated to be below the maximum sustainable yield level, which means that rebuilding of 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:

$\boldsymbol{TAC}_y = \boldsymbol{\beta} * \left[\left(\sum_{y}^{y-4} \boldsymbol{RY}_y \right) / 5 \right]$ where $\boldsymbol{\beta}$ 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 annual increases or decreases may not be more than 10% but for exceptional circumstances in which the TAC may go lower. Future TAC’s have been calculated for the base case considering these rules (Figure 8). From this analysis, it is shown that catches higher than 200 000 tonnes, as 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 9). The results showed that for faster growth in the resource TAC’s would have to be decreased to about 100 000 tonnes (not shown in this paper).

Discussion

The results of the state of the hake stock for all 14 model specifications are similar. 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), above average recruitment was observed, hence the model estimates an increase since 2007 in the stock. However, the overall results of the assessment indicate that the resource is still well below the MSY level - estimated to be about one third of the MSYL , therefore, given present catch levels, the resource will not recover to the MSY level in the near future.

It should also be mentioned that it is highly likely that the dynamics of the hake stock has 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 has increased (J-P Roux, unpublished data). The consequence may be a new equilibrium whose MSY level is now lower, at about 150 000 tonnes (model specification 10), than estimated for the other model specificiations in this assessment. This has to be anticipated and therefore the fishery should be managed by using the precautionary approach, meaning that great care should be exercised before increasing catches.

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. 2008a). 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, 2011, submitted) and therefore TAC's were mostly higher than biologically allowed.

Acknowledgements

I hereby would like to thank Dr James Ianelli for some valueable guidance in the assessment. Also, the Ministry of Fisheries and Marine Resources for providing the data.

References

Armstrong CM, Sumaila UR. 2004. The Namibian-South Africa hake fishery: costs and non-cooperative management. In: Sumaila U.R., Boyer D., Skogen M.D. & Steinshamn S.I. (eds). *Namibia's fisheries: ecological, economic and social aspects.* Eburon, Delft, the Netherlands, 231-243.

Andrew PA. 1986. Dynamic catch-effort models for the southern African hake populations. *Benguela Ecology Programme.* (CSIR, South Africa). Report No 10. pp. 248.

BENEFIT 2000. Report of the BENEFIT stock assessment workshop. University of Cape Town. 20 – 24 November 2000. Unpublished report, BENEFIT Programme, Swakopmund, pp 53.

BENEFIT 2001. Report of the BENEFIT stock assessment workshop. University of Cape Town. 19 – 24 November 2001. Unpublished report, BENEFIT Programme, Swakopmund, pp. 37.

BENEFIT 2004. Report of the BENEFIT stock assessment workshop. University of Cape Town. 12 – 17 January 2004. Unpublished report, BENEFIT Programme, Swakopmund, pp. 48.

Beverton RJH, Holt SJ. 1957. Mathematical representation of the four primary factors. In Beverton RJH, Holt SJ (eds). *On the dynamics of exploited fish populations. Fishery Investigations Series 2,* Vol. 19. London: HMSO. pp 27-35.

Boyer DC, Hampton I. 2001. An overview of Namibia's living marine resources. In *A Decade of Namibian Fisheries Science.* Payne, A.I.L., Pillar, S.C. and R.J.M. Crawford (Eds). *South African Journal of Marine Science.* 23. 5-35.

Burmeister LM. 2001. Depth-stratefied density estimates and distribution of the cape hake *Merluccius capensis* and *M. paradoxus* off Namibia deduced from survey data, 1990-1999. In *A Decade Of Namibian Fisheries Science.* Payne, A.I.L., Pillar, S.C. and R.J.M. Crawford (Eds). *South African Journal of Marine Science* 23: 347-356.

Burnham KP, Anderson DR. 2002. *Model Selection and Multimodel Inference: A Practical Information-Theoretic Approach*, Springer

Brandão A, Butterworth DS. 2004. Standardisation of commercial catch per unit effort data of Namibian hake for the period 1992 to 2003. HWG/WKShop/2004/doc2.

Brandão A, Butterworth DS. 2005. Further analysis of Namibian Hake CPUE and associated data queries. HWG/WkShop/2005/02/Doc.2

Butterworth DS, Rademeyer R A. 2005. Sustainable management initiatives for the southern African hake fisheries over recent years. *Bulletin of Marine Science. 76*(2). 287-319.

Butterworth DS, Geromont HF. 2001. Evaluation of a range of possible simple interim management procedures for the Namibian hake fishery. In *A Decade of Namibian Fisheries Science.* Payne, A.I.L., Pillar, S.C. and R.J.M. Crawford (Eds). *South African Journal marine Science.* 23*.* 357-374.

Clark WG. 1981. Restricted least-squares estimates of age composition from length composition. *Can. J. Fish. Aquat.* 38: 297-307.

De Oliveira JAA, Boyer HJ, Kirchner CH. 2007. Developing age-structured production models as a basis for management procedure evaluations for Namibian sardine. *Fisheries Research* 85. 148-158.

Draganik B, Sacks R. 1987. Stock assessment of Cape hakes (*Merluccius capensis* and *M. paradoxus*) in the convention area. Divisions 1.3 + 1.4. *Collect. Doc. Pap. Int. Commn SE.Atl. Fish*. Doc. 18b.

Gordoa A, Hightower JE. 1991. Changes in catchability in a bottom-trawl fishery for Cape hake (*Merluccius capensis*). *Can. J. Fish. Aquat. Sci.* 48: 1887-1895.

Gordoa A, Macpherson E, Olivar M-P. 1995. Biology and fisheries of Namibian hakes (*M. paradoxus* and *M. capensis*). In *Hake: Biology, Fisheries and Markets.* Alheit J. and T.J. Pitcher(eds). London; Chapman & Hall: 49-88.

Hutchings L, van der Lingen CD, Shannon LJ, Crawford RJM, Verheye HMS, Bartholomae CH, van der Plas AK, LouwD, Kreiner A, Ostrowsk, M, Fidel Q, Barlow RG, Lamont T, Coetzee J, Shillington F, Veitch J, Currie JC, Monteiro PMS. 2009. The Benguela Current: An ecosystem of four components. *Progress in Oceanography.* 83. 15-32.

Isarev AT. 1988. Biological analysis of the present state of Cape hake (*Merluccius M. Capensis)* stock in the Namibian zone. *Collect. Doc. Pap. Int. Commn SE.Atl. Fish*.*15*II. 29-34.

Kainge P, Kjesbu OS, Thorsen A, Salvanes AG. 2007. *Merluccius capensis* spawns in Namibian waters, but does *M. paradoxus*? *African Journal of Marine Science*. 29(3): 379-392.

Kirchner CH, Bartholomae CH, Kreiner A. 2009. Use of environmental parameters to explain the variability in the spawner recruitment relationships of Namibian sardine *Sardinops sagax. African Journal of Marine Science.* 31(2). 157-170.

Kirchner CH, Bauleth-D'Almeida G, Wilhelm M. 2010. Assessment and management of Cape horse mackerel (*Trachurus capensis)* off Namibia based on a Fleet-disaggregated Age-Structured Production Model. *African Journal of Marine Science.* 32(3). 525-541.

Kirchner CH. Leiman A. (submitted) Are the current policies, incentives and management procedures of the Namibian Hake contributing to resource rent loss? *African Journal of Marine Science*

Kirchner CH, (submitted). A bio-economic evaluation of present and future profit streams within the Namibian hake industry. *African Journal of Marine Science*

Lai HL, Gallucci VF, Gunderson DR. 1996. Age determination in fisheries: methods and application to stock assessment. In *Stock Assessment. Quantitative methods and applications for small-scale fisheries.* (Chapter 3) Gallucci, V.F., Saila, S.B., Gustafson, D.J. and B.J. Rothschild (Eds). Boca Raton, Florida; Lewis Publishers: 82-178.

ICSEAF 1989. Historical series data selected for Cape hakes assessment. ICSEAF document. SAC/89/Doc3. pp. 10.

Macpherson E, Gordoa A. 1992. Trends in the demersal fish community off Namibia from 1983-1990. *South African Journal of Marine Science*. *12*. 635-649.

Ministry of Fisheries and Marine Resources (1990). Territorial sea and exclusive economic zone of Namibia. Act 1990 (Act No 3. of 1990).

Nichols P. 2004. Marine fisheries management in Namibia: Has it worked? In: Sumaila U.R., Boyer D., Skogen M.D. & Steinshamn S.I. (eds). *Namibia's fisheries: ecological, economic and social aspects.* Eburon, Delft, the Netherlands, 319-332.

Punt AE, Butterworth DS. 1989. Application of an ad hoc tuned VPA assessment procedure to the Cape hake stocks in the ICSEAF Convention Area. *Int. Commn SE. Atl. Fish*. SAC/89/S.P./23: pp. 54. (mimeo)

Rademeyer R. 2003. Assessment of and management procedures for the hake stocks off southern Africa. PhD thesis. The University of Cape Town. Pp. 209 and Appendices.

Rademeyer RA, Butterworth D S, Plagányi ÉE. 2008a. Assessment of South African hake resource taking its two species nature into account. *African Journal of Marine Science*. 30(2).263-290.

Sumaila UR, Vasconcellos M. 2000. Simulation of ecological and economic impacts of distant water fleets on Namibian fisheries. *Ecological Economics* 32. 457-464.

Van der Westhuizen A. 2001. A decade of exploitation and management of the Namibian hake stocks. In *A Decade of Namibian Fisheries Science.* Payne, A.I.L., Pillar, S.C. and R.J.M. Crawford (Eds). *South African Journal of marine. Science.* 23. 357-374.

Appendix 1: Resource data

Table A1.1: Catches taken by the Namibian fishing fleet from 1964-2008 in thousand tonnes. (Data provided by MFMR).

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**	135*
1975	488	**1987**	300	**1999**	158	**2011**	140*

*Assumed catches, actual catches not available

Table A1.2: Indexes used within the assessment from 1964 to 2009

	ICSEAF area (1.3 + 1.4) (t/hour)	**ICSEAF area 1.5 (t/hour)**	**GLM CPUE (kg/hour)**	**Spanish summer Surveys (1000t)**	**Spanish Winter Surveys (1000t)**
1964	0	0	0	0	0
1965	1.78	2.1	0	0	0
1966	1.31	2.47	0	0	0
1967	0.91	1.36	0	0	0
1968	0.96	1.32	0	0	0
1969	0.88	1.08	0	0	0
1970	0.9	1.03	0	0	0
1971	0.87	1.34	0	0	0
1972	0.72	1	0	0	0
1973	0.57	0.94	0	0	0
1974	0.45	0.66	0	0	0
1975	0.42	0.76	0	0	0
1976	0.42	0.54	0	0	0
1977	0.49	0.65	0	0	0
1978	0.44	0.51	0	0	0
1979	0.41	0.69	0	0	0
1980	0.45	0.71	0	0	0
1981	*0.55*	*0.85*	0	0	0
1982	*0.53*	*0.84*	0	0	0
1983	*0.58*	*0.90*	0	556	0

1984	*0.64*	*0.93*	0	1581	1300
1985	*0.66*	*1.03*	0	917	0
1986	*0.65*	*0.93*	0	733	579
1987	*0.61*	*0.88*	0	1145	0
1988	*0.63*	*0.84*	0	640	689
1989	0	0	0	486	1738
1990	0	0	0	0	1957
1992	0	0	1197	0	0
1993	0	0	1526	0	0
1994	0	0	972	0	0
1995	0	0	604	0	0
1996	0	0	512	0	0
1997	0	0	589	0	0
1998	0	0	840	0	0
1999	0	0	742	0	0
2000	0	0	521	0	0
2001	0	0	445	0	0
2002	0	0	356	0	0
2003	0	0	426	0	0
2004	0	0	499	0	0
2005	0	0	396	0	0
2006	0	0	422	0	0
2007	0	0	414	0	0
2008	0	0	549	0	0
2009	0	0	647	0	0
2010	0	0	906	0	0

The numbers in italic have not been included in the analysis

Table A1.3: Summer and winter survey biomass series in thousand tonnes with CV's from 1990 to 2011. (Data provided by MFMR)

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

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+**
1990	0.031	0.25	0.544	0.069	0.058	0.014	0.02	0.016	0
1991	0.005	0.222	0.284	0.285	0.116	0.055	0.017	0.01	0.007
1992	0.11	0.489	0.187	0.074	0.058	0.049	0.011	0.012	0.011
1993	0	0.049	0.564	0.268	0.058	0.036	0.018	0.006	0.001
1994	0.005	0.311	0.485	0.016	0.09	0.017	0.046	0.029	0.001
1995	0.001	0.543	0.272	0.07	0.061	0.025	0.007	0.019	0
1996	0.04	0.181	0.492	0.109	0.076	0.031	0.069	0.002	0
1997	0	0.202	0.523	0.137	0.068	0.056	0.013	0.003	0
1998	0.032	0.313	0.448	0.005	0.146	0.005	0.038	0.013	0
1999	0.253	0.267	0.299	0.115	0.042	0.017	0.005	0.003	0.001
2000	0.022	0.213	0.555	0.159	0.021	0.023	0.004	0.003	0
2001	0.041	0.206	0.448	0.206	0.055	0.033	0.007	0.003	0.001
2002	0.33	0.529	0.111	0.011	0.012	0.004	0.002	0.001	0.001

2003	0.04	0.365	0.366	0.166	0.045	0.012	0.003	0.001	0.002
2004	0.05	0.656	0.229	0.043	0.015	0.005	0.002	0	0
2005	0	0.007	0.34	0.496	0.101	0.042	0.012	0.001	0.002
2006	0.001	0.127	0.578	0.218	0.062	0.012	0.003	0.001	0
2007	0.007	0.701	0.21	0.051	0.02	0.006	0.003	0.002	0.001
2008	0.146	0.121	0.493	0.132	0.038	0.033	0.033	0.003	0
2009	0.02	0.221	0.611	0.046	0.087	0.016	0	0	0
2010	0.2	0.171	0.427	0.043	0.084	0.011	0.015	0.049	0
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+**
1997	0	0	0	0.267	0.428	0.181	0.102	0.022	0
1998	0	0.002	0.035	0.059	0.455	0.346	0.029	0.067	0.006
1999	0.002	0.017	0.128	0.207	0.269	0.189	0.101	0.056	0.029
2000	0	0.005	0.038	0.187	0.336	0.307	0.077	0.041	0.008
2001	0	0.008	0.126	0.264	0.346	0.191	0.044	0.013	0.008
2002	0	0.064	0.24	0.188	0.301	0.137	0.041	0.017	0.011
2003	0.004	0.036	0.224	0.259	0.257	0.144	0.043	0.016	0.018
2004	0	0.019	0.094	0.367	0.312	0.138	0.049	0.014	0.007
2005	0	0.002	0.051	0.387	0.403	0.122	0.026	0.003	0.006
2006	0	0.003	0.063	0.332	0.433	0.129	0.033	0.005	0.002
2007	0	0.01	0.104	0.294	0.307	0.16	0.077	0.037	0.011
2008	0	0.003	0.018	0.24	0.476	0.19	0.067	0.006	0
2009	0	0	0.108	0.362	0.277	0.181	0.047	0.025	0
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)

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. Maturity-at-age set as constant in the model (Wilhelm, unpublished data). Weight-at-age (begin and mid-year) (Wilhelm 2007 and Wilhelm 2010, unpublished data). The slow growth weight-at-age data is used for all models except for model specification 13.

Age	M (yr^{-1})	Maturity	(slow growth)		(fast growth)	
		Proportion mature	Start yr (g)	Mid yr (g)	Start yr (g)	Mid yr (g)
0	1.424	0.080	9	23	11	32
1	0.712	0.260	47	83	72	135
2	0.570	0.600	132	195	224	343
3	0.500	0.860	273	367	496	684
4	0.456	0.960	477	603	910	1175
5	0.424	0.990	744	902	1481	1828
6	0.400	1.000	1075	1263	2217	2649
7	0.381	1.000	1465	1681		
8	0.365	1.000	1911	2152		

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).

Table A1.8: Alternative catch-at-age data used within the assessment in sensitivity test 13 (provided by Margit Wilhelm, unpublished data).

	Age						
Summer surveys	**0.00**	**1.00**	**2.00**	**3.00**	**4.00**	**5.00**	**6.00**
1990	0.03	0.64	0.29	0.02	0.01	0.01	0.00
1991	0.00	0.21	0.60	0.11	0.07	0.01	0.01
1992	0.02	0.58	0.26	0.07	0.05	0.02	0.01
1993	0.00	0.61	0.27	0.06	0.05	0.01	0.00
1994	0.00	0.66	0.20	0.05	0.07	0.03	0.00
1995	0.01	0.67	0.17	0.07	0.04	0.01	0.03
1996	0.05	0.47	0.32	0.06	0.07	0.03	0.00
1997	0.01	0.26	0.54	0.10	0.09	0.02	0.00

1998	0.03	0.74	0.13	0.08	0.02	0.00	0.00
1999	0.18	0.34	0.39	0.06	0.02	0.00	0.00
2000	0.02	0.33	0.60	0.02	0.03	0.00	0.00
2001	0.05	0.58	0.28	0.05	0.04	0.00	0.00
2002	0.33	0.63	0.02	0.01	0.01	0.00	0.00
2003	0.04	0.37	0.53	0.04	0.02	0.00	0.00
2004	0.05	0.87	0.06	0.02	0.01	0.00	0.00
2005	0.00	0.22	0.61	0.12	0.04	0.01	0.00
2006	0.00	0.69	0.23	0.06	0.02	0.00	0.00
2007	0.01	0.70	0.26	0.02	0.01	0.00	0.00
2008	0.16	0.28	0.39	0.05	0.06	0.06	0.00
2009	0.03	0.81	0.13	0.01	0.02	0.00	0.00
Winter surveys	**0.00**	**1.00**	**2.00**	**3.00**	**4.00**	**5.00**	**6.00**
1990	0.01	0.26	0.56	0.07	0.06	0.04	0.00
1991	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1992	0.01	0.35	0.43	0.13	0.06	0.03	0.01
1993	0.00	0.49	0.37	0.07	0.06	0.01	0.00
1994	0.01	0.40	0.35	0.12	0.08	0.04	0.00
1995	0.14	0.43	0.16	0.09	0.08	0.01	0.09
1996	0.03	0.58	0.20	0.08	0.05	0.01	0.06
Commercial fleet	**0.00**	**1.00**	**2.00**	**3.00**	**4.00**	**5.00**	**6.00**
1997	0.00	0.00	0.21	0.56	0.18	0.04	0.01
1998	0.00	0.01	0.07	0.58	0.30	0.03	0.00
1999	0.00	0.02	0.27	0.32	0.30	0.08	0.02
2000	0.00	0.01	0.23	0.34	0.37	0.06	0.00
2001	0.00	0.02	0.38	0.34	0.24	0.02	0.00
2002	0.00	0.09	0.41	0.31	0.17	0.03	0.00
2003	0.00	0.04	0.48	0.26	0.19	0.03	0.01
2004	0.00	0.04	0.44	0.31	0.19	0.02	0.00
2005	0.00	0.01	0.43	0.42	0.12	0.02	0.01
2006	0.00	0.01	0.39	0.43	0.16	0.01	0.00
2007	0.00	0.01	0.40	0.31	0.24	0.04	0.00
2008	0.00	0.01	0.21	0.61	0.16	0.01	0.01
2009	0.00	0.02	0.38	0.43	0.14	0.03	0.00

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

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

$$\boldsymbol{N}_{\boldsymbol{y}+1,\boldsymbol{a}+1} = \left(\boldsymbol{N}_{\boldsymbol{y},\boldsymbol{a}}\, \boldsymbol{e}^{-\boldsymbol{M}_{\boldsymbol{a}}/2} - \sum \boldsymbol{C}_{\boldsymbol{y},\boldsymbol{a}} \right) \boldsymbol{e}^{-\boldsymbol{M}_{\boldsymbol{a}}/2} \quad \text{for } 0 \le \boldsymbol{a} < \boldsymbol{m} - 2 \qquad \text{(A2.2)}$$

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

where $N_{y,a}$ number of fish of age *a* at the start of year *y*,

R_y recruitment in year *y*,

$\boldsymbol{C}_{\boldsymbol{y},\boldsymbol{a}}$ number of fish of age *a* caught in year *y*, and

m maximum age considered (taken to be a plus-group).

$\boldsymbol{M}_{\boldsymbol{a}}$ natural mortality at age

$$M_a = M_{\inf age} * M_{\inf} / a^{0.32192}$$

Designed to give M=0.5 at age 3 and 0.4 by age 6. Age 0 = 2* Age 1.

A2.2 Total catch and catches-at-age

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

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

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 $\boldsymbol{F}_{\boldsymbol{y}}$ is the fully selected fishing mortality in year y, given by:

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

where $\boldsymbol{Y}_{\boldsymbol{y}}$ is the total observed catch (yield) by mass in year y, and

$\boldsymbol{w_{a+1/2}}$ is the mid-year mass of a fish of age a+½.

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

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

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

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

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

$$B_y^{sur} = \sum w_a S_a^{surv} N_{y,a} \qquad \text{(A2.8)}$$

and in the middle of the year (winter) by

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

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:

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

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

ς_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:

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

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

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

and:

$$\beta_y = \frac{prop*K^{sp}(1-h)}{5h-1} \qquad \text{(A2.13)}$$

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:

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

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.

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

$$N_{0,a} = R_0 \cdot e^{-\sum_{a'=0}^{a-1} M_{a'}} \qquad 0 \le a \le m-1 \qquad \text{(A2.15)}$$

$$N_{0,m} = R_0 \frac{e^{-\sum_{a'=0}^{a-1} M_a}}{1-e^{-M_m}} \qquad \text{(A2.16)}$$

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:

$$\boldsymbol{\varepsilon}_y^i = \ell\text{n}\left(\boldsymbol{I}_y^i\right) - \ell\text{n}\left(\hat{\boldsymbol{I}}_y^i\right) \qquad \text{(A2.17)}$$

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 $N\left(0, \left(\sigma_y^i\right)^2\right)$.

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

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

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

$$\hat{\sigma}^i = \sqrt{1/n^i \sum_y \left(\ell\text{n}\, I_y^i - \ell\text{n}\, q^i B_y^i\right)^2} \qquad \text{(A2.19)}$$

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

$$\ell\text{n}\, \hat{q}^i = 1/n^i \sum_y \left(\ell\text{n}\, I_y^i - \ell\text{n}\, \hat{B}_y^i\right) \qquad \text{(A2.20)}$$

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.

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

$$\hat{\boldsymbol{\sigma}} = \sqrt{1/\boldsymbol{n}\sum_{\boldsymbol{y}}\left(\ell\text{n}\,\boldsymbol{I}_{\boldsymbol{y}}^{\boldsymbol{i}} - \ell\text{n}\,\boldsymbol{q}\;\boldsymbol{B}_{\boldsymbol{y}}^{\boldsymbol{i}}\right)^2} \qquad \text{(A2.22)}$$

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:

$$-\ln\boldsymbol{L} = \sum_{\boldsymbol{i}}\ \sum_{\boldsymbol{y}}\left\{\ell\boldsymbol{n}\sqrt{\left(\boldsymbol{\sigma}_{\boldsymbol{y}}^{\boldsymbol{i}}\right)^2 + \left(\boldsymbol{\sigma}_{\boldsymbol{A}}^{\boldsymbol{i}}\right)^2}\ + \left(\boldsymbol{\varepsilon}_{\boldsymbol{y}}^{\boldsymbol{i}}\right)^2 / \left[2*\left(\left(\boldsymbol{\sigma}_{\boldsymbol{y}}^{\boldsymbol{i}}\right)^2 + \left(\boldsymbol{\sigma}_{\boldsymbol{A}}^{\boldsymbol{i}}\right)^2\right)\right]\right\} \qquad \text{(A2.23)}$$

where

$\boldsymbol{\sigma}_y^{\boldsymbol{i}}$ is the minimum, when $\boldsymbol{\sigma}_{\boldsymbol{A}}^{\boldsymbol{i}} = 0$, standard deviation of the residuals for the logarithms of survey i in year y.

$\boldsymbol{\sigma}_{\boldsymbol{A}}^{\boldsymbol{i}}$ is the square root of the additional variance for survey series i, which is an estimable parameter.

$$\varepsilon_y = \ln\left(I_y^s\right) - \ln(q^i \hat{B}_y^i) \qquad \text{(A2.24)}$$

for log-normally distributed errors, where:

$\boldsymbol{I}_y^{\boldsymbol{i}}$ is the observed survey estimate for year y

$\boldsymbol{B}_y^{\boldsymbol{i}}$ is the estimated survey biomass, and

$q^{\ i}$ is the multiplicative bias given as input or calculated by

$$\ell\text{n}\,\hat{\boldsymbol{q}}^{\boldsymbol{i}} = 1/\boldsymbol{n}\ \sum_{\boldsymbol{y}}\left(\ell\text{n}\,\boldsymbol{I}_{\boldsymbol{y}}^{\boldsymbol{i}} - \ell\text{n}\,\hat{\boldsymbol{B}}_{\boldsymbol{y}}^{\boldsymbol{i}}\right) \qquad \text{(A2.25)}$$

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:

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

where

$p^i_{y,a} = C^i_{y,a} / \sum_{a'=0}^{m} C^i_{y,a'}$ is the observed proportion of fish of age a from the survey in year *y* for survey *i*

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

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

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

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

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:

$$-\ln \boldsymbol{L} = \sum_{\boldsymbol{f}} \sum_{\boldsymbol{y}} \sum_{\boldsymbol{a}} \left[\ln\left(\boldsymbol{\sigma}^{\boldsymbol{i}}_{\boldsymbol{com}} / \sqrt{\hat{\boldsymbol{p}}^{\boldsymbol{i}}_{\boldsymbol{y,a}}}\right) + \hat{\boldsymbol{p}}^{\boldsymbol{i}}_{\boldsymbol{y,a}} \left(\ln \boldsymbol{p}^{\boldsymbol{i}}_{\boldsymbol{y,a}} - \ln \hat{\boldsymbol{p}}^{\boldsymbol{i}}_{\boldsymbol{y,a}}\right)^2 / 2\left(\boldsymbol{\sigma}^{\boldsymbol{i}}_{\boldsymbol{com}}\right)^2 \right] \quad \text{(A2.29)}$$

where

$\boldsymbol{p}^{\boldsymbol{i}}_{\boldsymbol{y,a}} = \boldsymbol{C}^{\boldsymbol{i}}_{\boldsymbol{y,a}} / \sum_{\boldsymbol{a}'=0}^{\boldsymbol{m}} \boldsymbol{C}^{\boldsymbol{i}}_{\boldsymbol{y,a'}}$ is the observed proportion of fish of age a, for each selectivity period, in year *y*

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

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

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

$$\boldsymbol{\sigma}^{\boldsymbol{i}}_{\boldsymbol{com}} = \sqrt{\sum_{\boldsymbol{y}} \sum_{\boldsymbol{a}} \hat{\boldsymbol{p}}^{\boldsymbol{i}}_{\boldsymbol{y,a}} \left(\ln \hat{\boldsymbol{p}}^{\boldsymbol{i}}_{\boldsymbol{y,a}} - \ln \hat{\boldsymbol{p}}^{\boldsymbol{i}}_{\boldsymbol{y,a}}\right)^2 / \sum_{\boldsymbol{y}} \sum_{\boldsymbol{a}} 1} \quad \text{(A2.31)}$$

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:

$$\boldsymbol{\varepsilon}_y = \ell\text{n}\left(\boldsymbol{I}_y\right) - \ell\text{n}\left(\hat{\boldsymbol{I}}_y\right) \qquad \text{(A2.32)}$$

where $\boldsymbol{I}_y$ is the seal scat index for year *y*,

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

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

$\boldsymbol{\varepsilon}_y$ from $\boldsymbol{N}\left(0, \left(\boldsymbol{\sigma}_y\right)^2\right)$

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

$$-\ell\text{n}\boldsymbol{L} = \sum_{\boldsymbol{y}} \ell\text{n}\boldsymbol{\sigma}_y + \left(\boldsymbol{\varepsilon}_y\right)^2 / 2\left(\boldsymbol{\sigma}_y\right)^2 \qquad \text{(A2.33)}$$

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

$$\hat{\boldsymbol{\sigma}} = \sqrt{1/\boldsymbol{n} \sum_{\boldsymbol{y}} \left(\ell\text{n}\boldsymbol{I}_y - \ell\text{n}\boldsymbol{q}\ \boldsymbol{A}_y\right)^2} \qquad \text{(A2.34)}$$

where $\boldsymbol{n}$ is the number of data points and $\boldsymbol{q}$ is estimated by its maximum likelihood value:

$$\ell\text{n}\hat{\boldsymbol{q}} = 1/\boldsymbol{n} \sum_{\boldsymbol{y}} \left(\ell\text{n}\boldsymbol{I}_y - \ell\text{n}\hat{\boldsymbol{A}}_y\right)$$

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:

$$-\ln L = \sum_{y=y_1}^{y} \left[\left(\varsigma_y\right)^2 \Big/ 2\sigma_R^2 \right] \qquad \text{(A2.35)}$$

where ς_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.

Appendix 3:

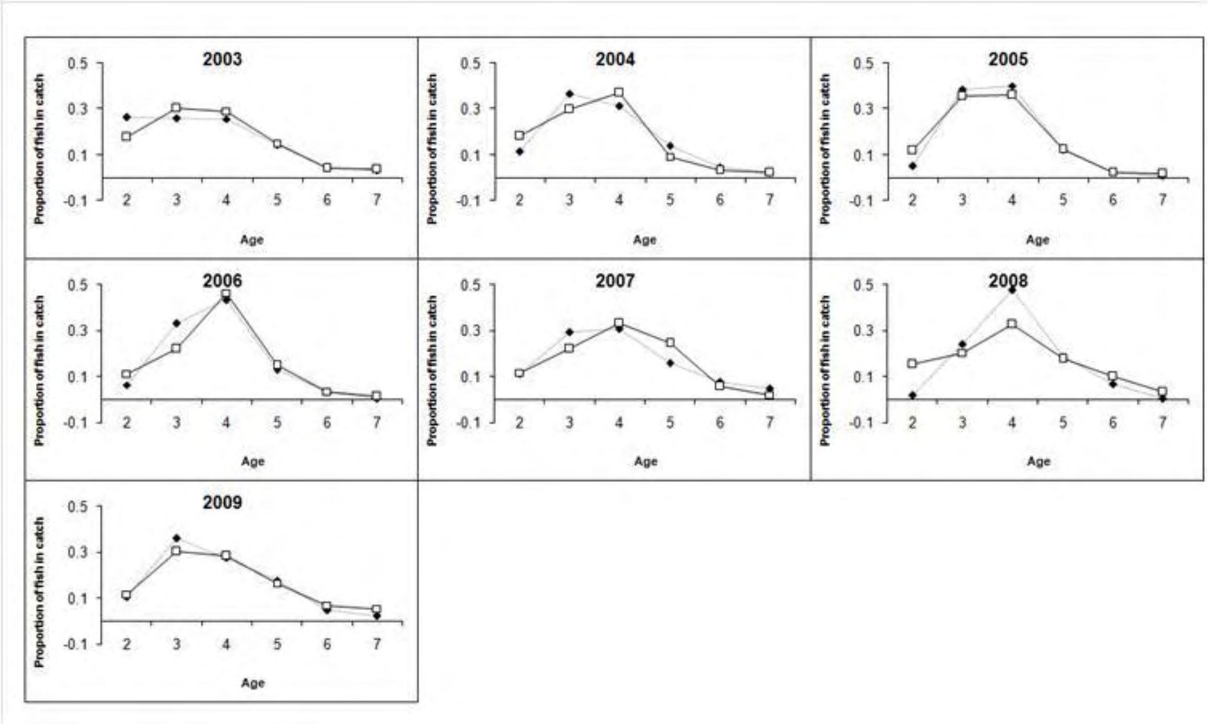

Figure A3.1: Commercial catch-at-age observed (solid diamonds) and estimated (open squares) data from 2000 to 2009. Age of the minus group is 2 and the plus group 7.

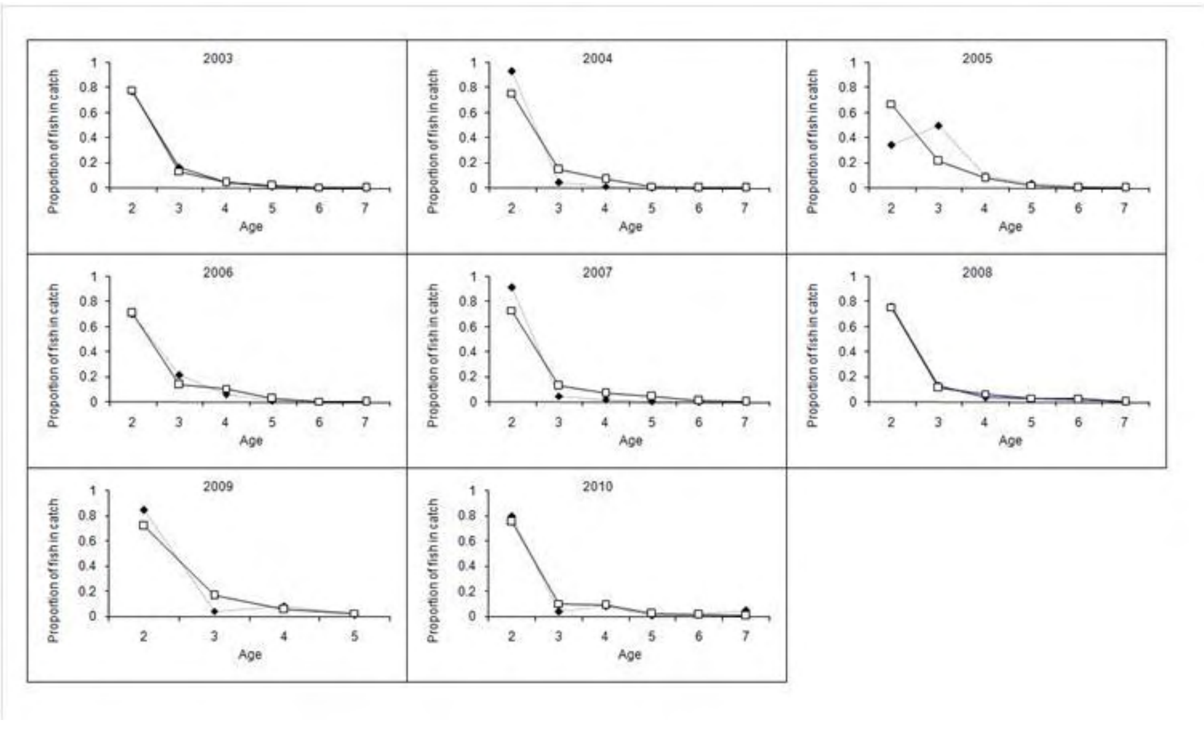

Figure A3.2: Research swept-area survey catch-at-age observed (solid diamonds) and estimated (open squares) from 2000-2010. Age of the minus group is 2 and the plus group 7. In 2009 no observation of fish older than 5 years were made.

List of Figures

List of Tables

Table 1: The base-case and the following 13 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 Ksp period, sigma for R=0.5, selectivity curve has a right-hand slope for fisheries and survey.
1	GLM 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
10	Change in productivity in mid 1980's
11	Survey selectivity is logistic
12	Weighting the seal scat data 10x higher than any other data
13	Using Margit Wilhelm's catch-at-age matrix

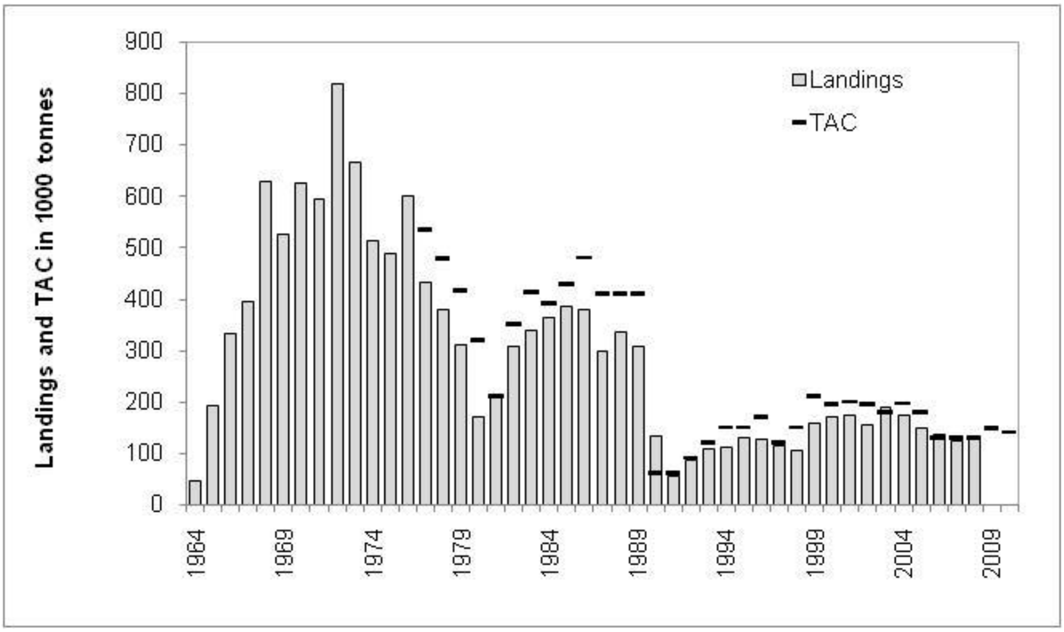

Figure 1 (Kirchner et al.)

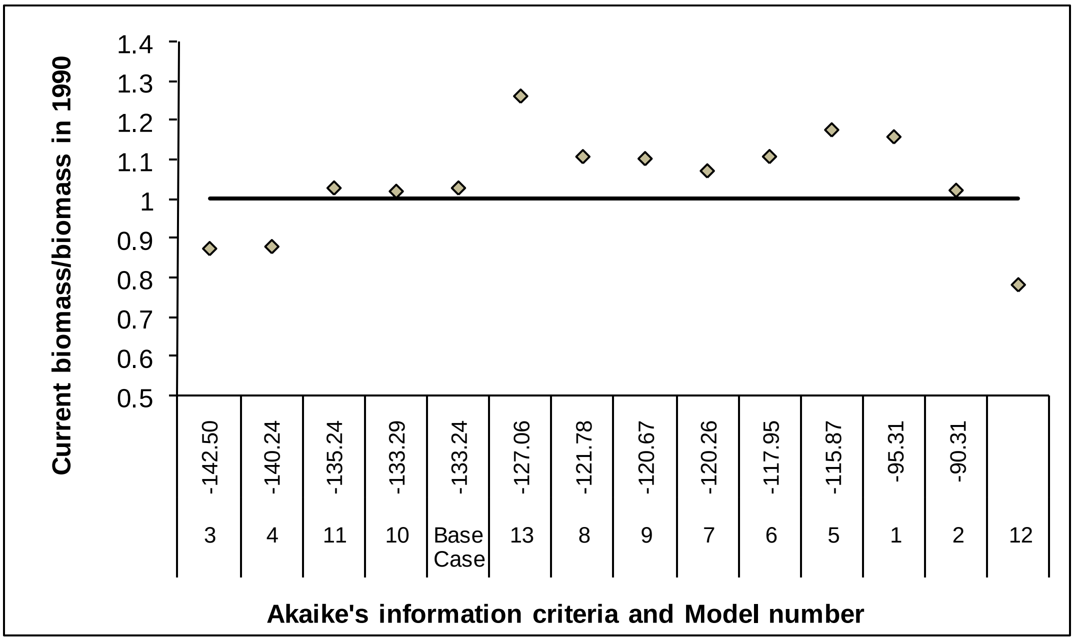

Figure 2 (Kirchner et al.)

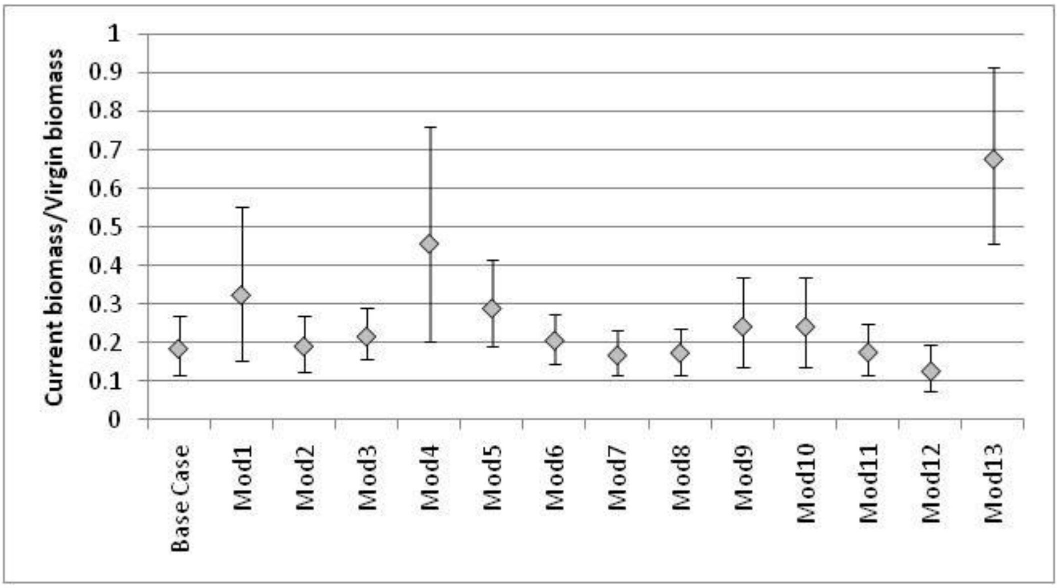

Figure 3 (Kirchner et al.)

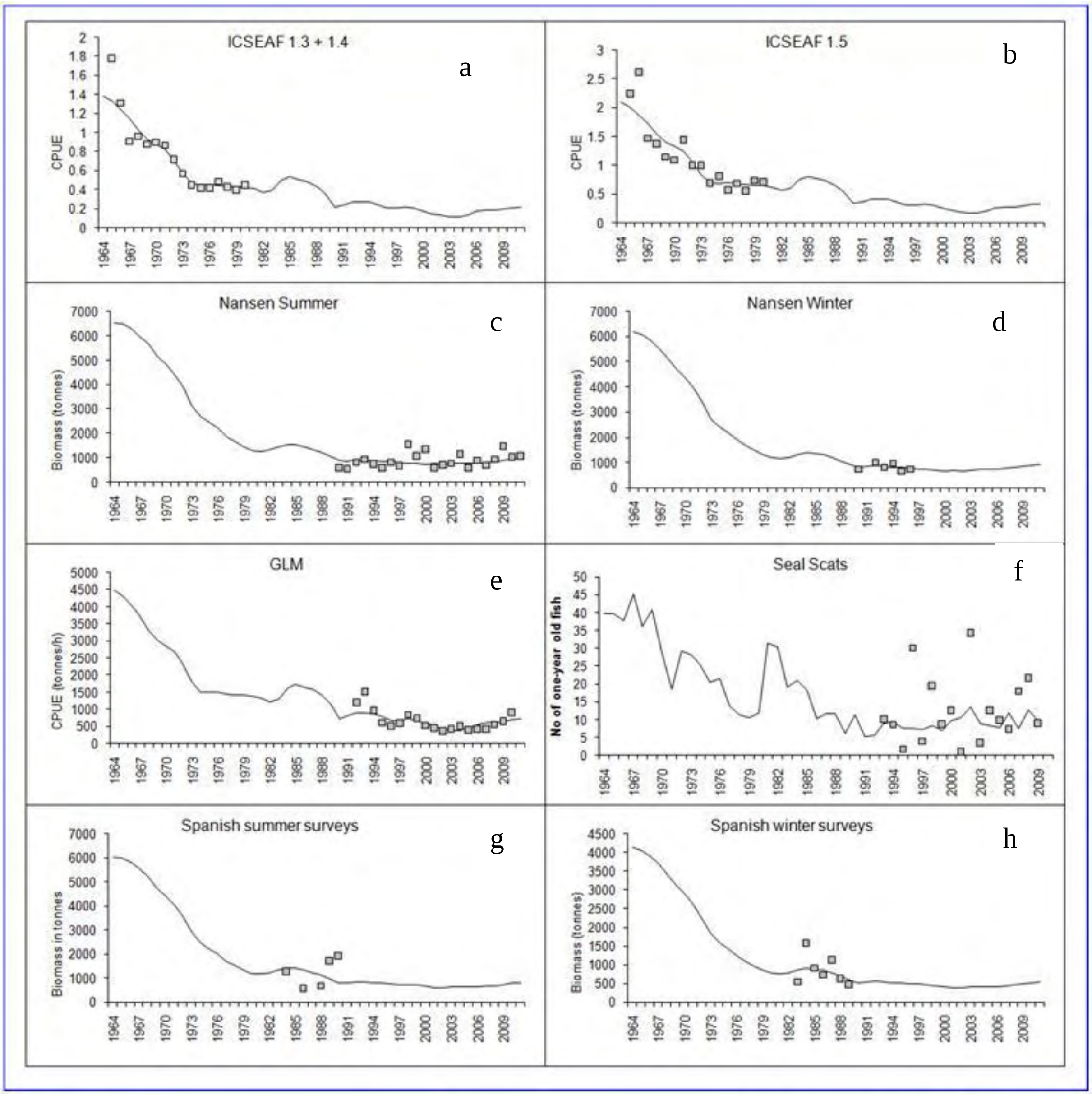

Figure 4 (Kirchner et al.)

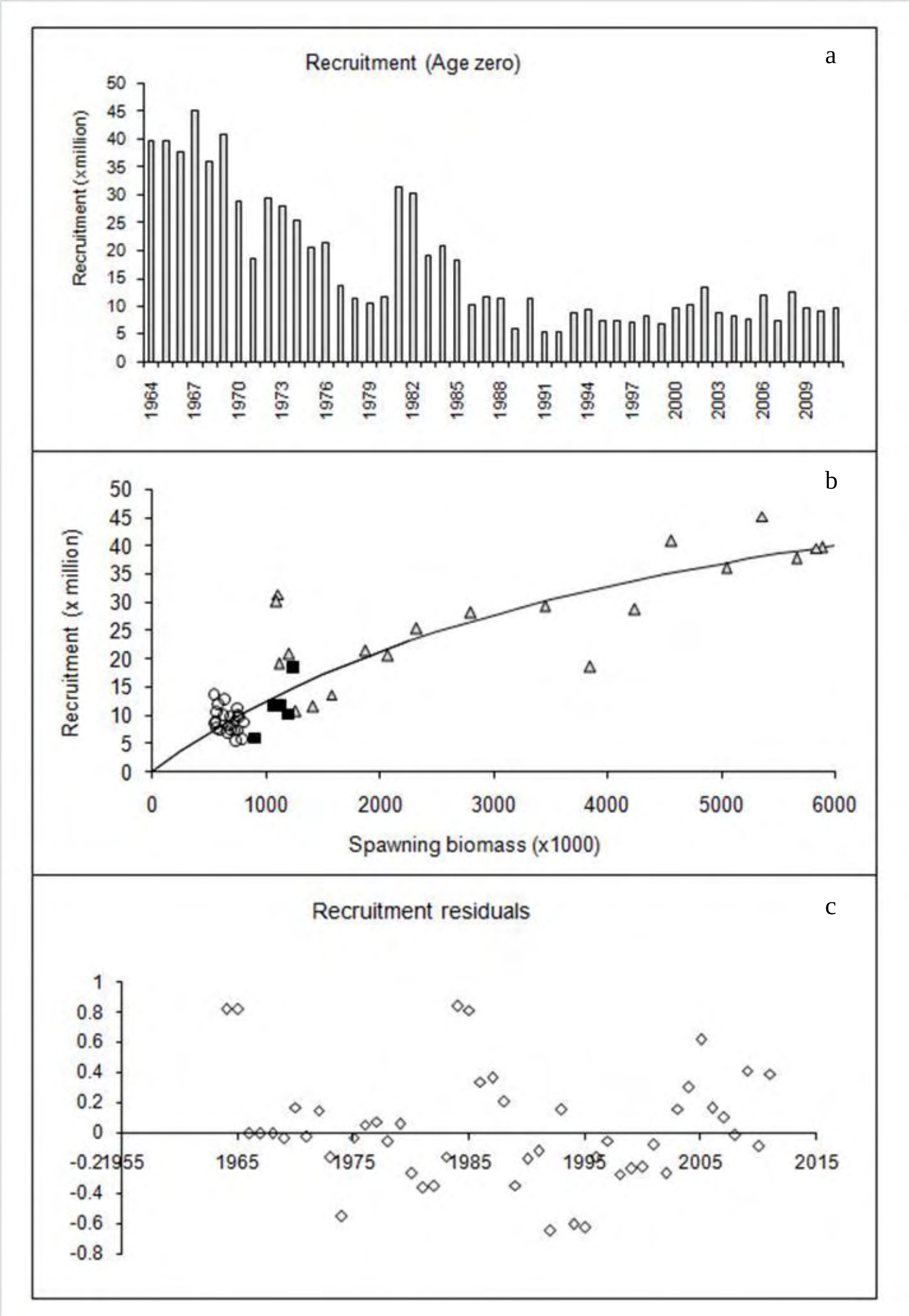

Figure 5: (Kirchner et al.)

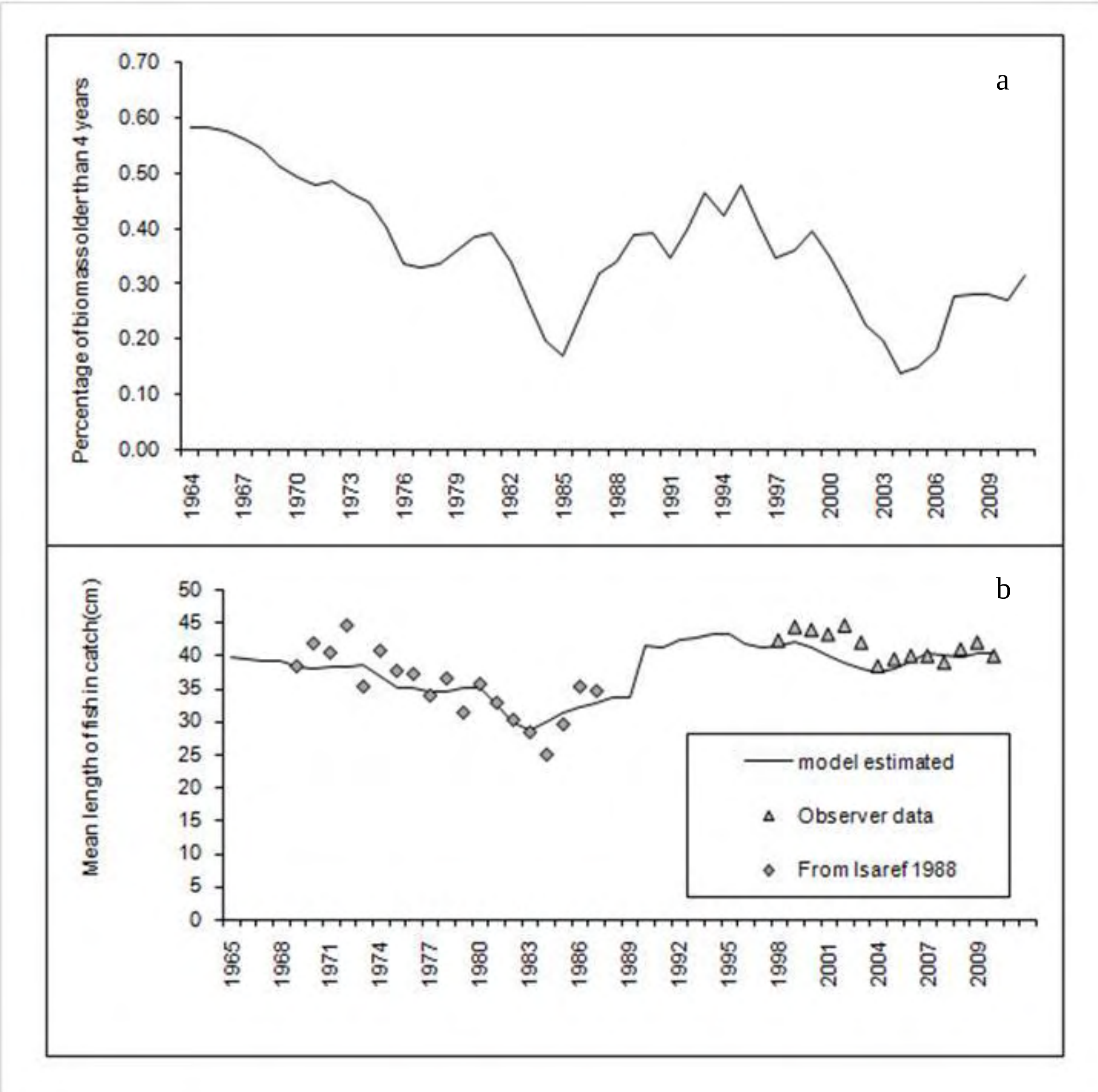

Figure 6 (Kirchner et al.)

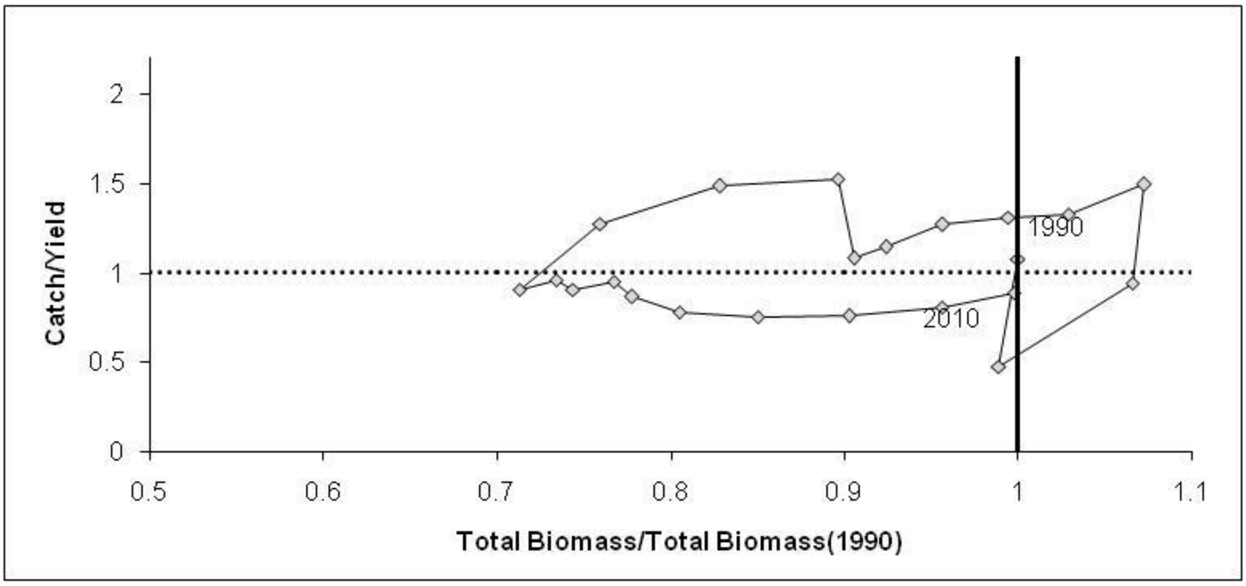

Figure 7 (Kirchner et al.)

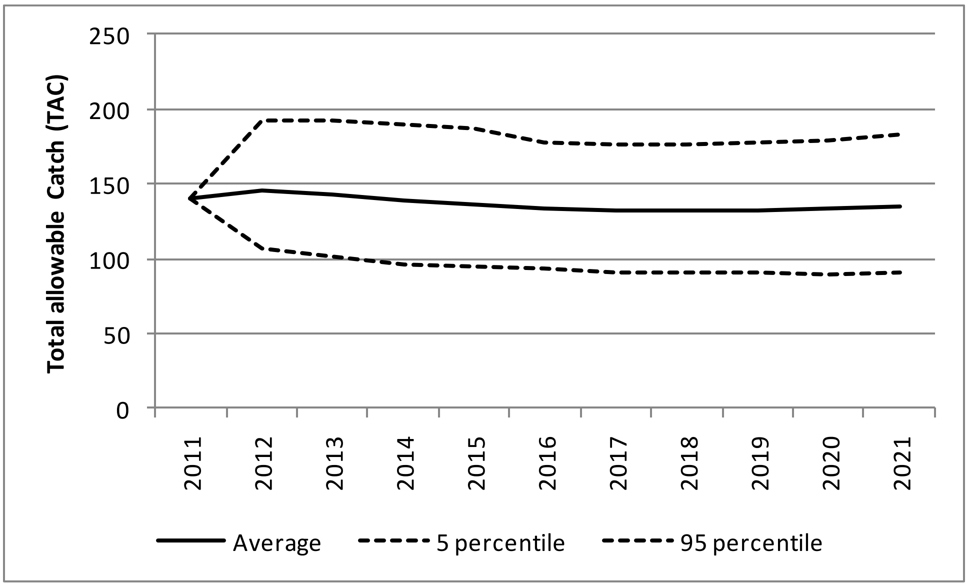

Figure 8 (Kirchner et al.)

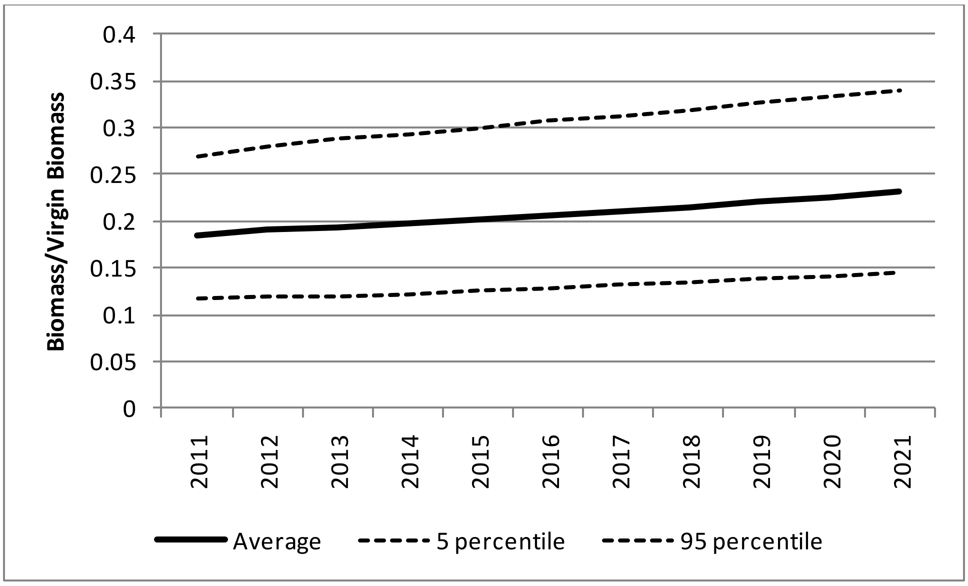

Figure 9 (Kirchner et al.)