Progress in Oceanography 83 (2009) 417–425

Contents lists available at ScienceDirect

Progress in Oceanography

journal homepage: www.elsevier.com/locate/pocean

Policy options for the northern Benguela ecosystem using a multispecies, multifleet ecosystem model

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ARTICLE INFO

Article history:
Received 17 July 2008
Received in revised form 18 February 2009
Accepted 16 July 2009
Available online 24 July 2009

ABSTRACT

Alternative policy options available to northern Benguela fisheries managers were explored using Ecopath with Ecosim. Scenarios were tested for optimizing the discounted profit from the fisheries in the ecosystem, maximizing the jobs that can be provided by the fisheries, maximizing a measure of ecosystem status, and analyzing tradeoffs between these management options. Additionally, two different discount rates were applied to calculate net present values: 4% indicating a more future generation friendly rate, where future generations are taken explicitly into consideration, and 15%, which is similar to the discount rate used by private businesses in Namibia. Basically a low discount rate puts more weight on future net benefits than high discount rates. The results show that the discount rate is most important when optimizing for profits, or when tradeoffs are being made between profit, jobs and ecosystem structure. Fishing effort of the most profitable fleet is significantly increased when discount rate is low, which increases the discounted profit to the fleet. When optimizing for jobs, the fisheries become non-profitable, although no significant difference is found between different fleets with different discount rates. Ecosystem longevity is only improved with a reduction in effort by all fleets while seaweed harvesting (at the lowest trophic level) would require the least reduction in fishing effort.

1. Introduction

The northern Benguela ecosystem is one of the most productive upwelling systems in the world (Carr, 2002; Carr and Kearns, 2003), with primary production values ranging from $0.3\ \mathrm{gC\,m^{-2}\,d^{-1}}$ at the Orange River to $5.1\ \mathrm{gC\,m^{-2}\,d^{-1}}$ at Walvis Bay (Shannon and Pillar, 1986; Wasmund et al., 2005) and catches in the late 1960s of over 2 million tonnes (Boyer and Hampton, 2001). Over the past 50 years, overexploitation in conjunction with environmental variation has caused the system to be much less productive in terms of fish yield (Willemse, 2002). During that time the main planktivorous fish in the system changed from sardines, *Sardinops oscellatus*, to horse mackerel, *Trachurus capensis*, and bearded gobies, *Suffoglobius bibarbatus* (Boyer and Hampton, 2001; Cury and Shannon, 2004). The system has been subjected to similar environmental variation as the southern Benguela, but the fish stocks were not as well managed prior to Namibian Independence from South Africa in 1990 and therefore the stocks are now not as robust as similar species in the south (Cury and Shannon, 2004). It seems to have changed from an efficient ecosystem dominated by sardine and anchovy, to the largely resilient system in the 1980s dominated by horse mackerel, mesopelagics and other small pelagics, and a less resilient system in the 1990s, where only horse mackerel dominated (Heymans et al., 2004).

As described in more detail in Heymans and Sumaila (2007), whaling, sealing and line fisheries (producing salted and sun-dried fish) started in the 1700s and 1800s and although whaling has ceased, the line fisheries and culling of fur seals, *Arctocephalus pusillus pusillus*, are still ongoing (Berry, 2002). The trap fisheries for lobster, *Jasus lalandii*, started in the 1930s (Hampton, 2003), and are also still ongoing (Anon, 2007). At present, the main commercial fisheries in the system include the purse seine, demersal trawl and mid-water trawl fisheries, although line fisheries and longlining are also prevalent. The purse seine fishery started fishing for sardine before 1947 and by that time the commercial line fishery was already fishing for snoek, *Thyrsites atun* (Hampton, 2003). In the 1950s demersal trawlers (Klingelhoeffer, 2006) and line fisheries (Hart and Currie, 1960) started fishing for hake (of which there are two species in Southern Africa, *Merluccius capensis* and *Merluccius paradoxus*), snoek, and various species of sharks, which were exploited for their liver oil. Horse mackerel is currently exploited both by the purse seine fleet (juveniles) and, since the 1960s, by mid-water trawlers (adults), which also catch hake as by-catch (Klingelhoeffer, 2006). Since 1964, the purse seine fleet has also targeted anchovy, *Engraulis japonicus* (Hampton, 2003). A longline fishery began in the early 1960s for albacore, *Thunnus alalunga*, and bigeye tuna, *Thunnus obesus*, but it also targets swordfish, *Xiphias*

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doi:10.1016/j.pocean.2009.07.013

gladius, and large pelagic sharks. In the early 1960s the commercial line fishery started targeting kob, *Argyrosomus* spp. and by the early 1970s they also targeted steenbras, *Lithognathus aureti* (Holtzhausen and Kirchner, 2004). In addition, these species are exploited by the recreational fishery, which also catch galjoen, *Dichistius capensis*, blacktail, *Diplodus sargus*, and various shark species (Holtzhausen and Kirchner, 2004). Fishing for deep-sea red crab, *Chaceon maritae*, began in the early 1970s (Beyers and Wilke, 1980) and since 1980 there has been an annual harvest of the seaweed, *Gracilaria gracilis*, and seaweed mariculture in Lüderitz (Hampton, 2003).

The sardine stock was severely exploited before Independence (1990) and has not recovered even though the total allowable catch (TAC) was set very low or at zero (Anon, 2006). Prior to Independence there were nine sardine quota holders sharing a TAC of 43,000 tonnes but by 2000 there were 22 rights holders that had access to a TAC of 25,000 tonnes (Anon, 2006). The fishery was closed in 2003 and has not reopened since (Anon, 2006). Anchovy is now severely depleted after large catches in the 1970s and 1980s and annual catches declined to virtually zero after the mid-1990s (Boyer and Hampton, 2001). By contrast, the horse mackerel stocks are growing, although there have been reports that the biomass of both adults and juveniles have fallen (Anon, 2006). The horse mackerel fishery is highly capital-intensive and 26 mid-water freezer trawlers have been licensed to fish for horse mackerel, but only 15 fished in 2005 (Anon, 2007). The TAC has declined from 410,000 tonnes in 2000 to 350,000 tonnes in 2005 (Anon, 2007).

The hake stocks have been on a slight upward trend over the past 20 years, although there has been some suggestion that the catch rate has declined and that there is an increasing proportion of small fish in the population, and the catch per unit effort has been falling (Anon, 2006). Prior to Independence the hake quota was 52,100 tonnes shared between 15 operators, but by 2001 the hake TAC had increased to 200,000 tonnes shared between 38 rights holders (Anon, 2006), which was reduced to 130,000 tonnes in 2006 (Anon, 2007). By 2007 there were 62 wet-fish trawlers, 25 freezer trawlers and 24 demersal longliners targeting hake (Anon, 2007). Of the line fish species, kob has become heavily exploited and there is concern that the stocks are becoming depleted (Kirchner and Stage, 2005). There are 16 industrial line fish vessels and 39 rock lobster vessels (Anon, 2007). The rock lobster quota has decreased from 1200 tonnes shared by two processors in 1989 to 400 tonnes in 2003, with the stocks remaining severely depleted (Anon, 2006). However, according to the National Plan of Action (NPOA) for the Fishery, the rock lobster stock is showing signs of continued growth (Anon, 2007). Similarly, the NPOA suggest that the red crab stock size is growing slowly, but red crab stocks have declined from about 40,000 tonnes in the early 1980s to about 10,000 tonnes in the 1990s (Anon, 2006) and catches in 2004 totalled only 2400 tonnes (Anon, 2007).

Prior to Independence the fisheries were only nominally managed. Horse mackerel and hake were assessed by the International Commission for Southeast Atlantic Fisheries (ICSEAF) between 1970 and 1990 (Anon, 2001) after which management of the fishery was taken over by the Ministry of Fisheries and Marine Resources (MFMR) of the new Namibian government. MFMR scientists base their recommendations on acoustic surveys and age- and length-based VPA estimates from commercial data (Maurihungirire, 2004). The government decided to manage the marine resources to the benefit of Namibians, by instituting a policy of Namibianisation, by looking at the sustainability of marine resources (Armstrong et al., 2004) and by developing an industrialized fleet rather than aiming for a larger artisanal fleet structure. The policy of Namibianisation has increased ownership of licensed fishing vessels and employment by Namibian citizens in most fishing fleets, but has cost the government taxes in the form of fees and rebates given to Namibian rights holders (Armstrong et al., 2004).

Fishing is limited through output controls that consist of individual non-transferable quotas and catches must be landed at one of two fishing ports (Boyer and Boyer, 2004). No marketable or edible fish taken as by-catch can be discarded, and this is monitored by ship-board observers (Boyer and Boyer, 2004). The government collects fees on by-catch and allocated quotas, and to finance fisheries research and training initiatives, a Marine Resources Fund levy is imposed based on the amount landed (Nichols, 2003). Monitoring of all landings at the two commercial fishing ports, Walvis Bay and Lüderitz, and the implementation of a national satellite-based vessel monitoring system (VMS) ensures that Namibian fisheries are as well managed as possible. All of these actions and management tools help the Namibian fishery to optimize the use of its marine resources at present.

Since Independence, Namibia has increased the economic contribution of fisheries to the Namibian economy while avoiding the subsidization of the industry (Lange, 2004). Fisheries have become an increasingly important asset, accounting for 13% of national wealth (Lange, 2004), while contributing 6% to the GDP (Reid et al., 2007), down from 8% in 2000 (Lange, 2003). In 2005 the gross value of fisheries output was US$ 592 million, while the fisheries export was valued at about US$ 376 million (http://www.fao.org/fishery/countrysector/FI-CP_NA/en). The number of vessels has increased from just over 250 in 1998 to nearly 350 in 2002, mainly due to an increase in demersal trawlers and longliners (Anon, 2006). The overall value of the fish stocks has increased by over 50% since independence and the fishing sector is seen as a potential future growth sector in Namibia (Reid et al., 2007). The percentage of Namibian ownership and employment in the fisheries subsequent to Independence has also increased from 60% to approximately 80% (Armstrong et al., 2004), while Lange (2003) suggests that the employment in the Namibian fishing industry more than doubled between 1991 and 1998. Employment in the formal fishing sector at sea and on land increased from approximately 11,000 (50% Namibian) to ~16,000 (75% Namibian) by 1998 (Batty et al., 2005).

Namibia seeks to achieve its socio-economic objectives for fisheries within an economically efficient, commercial fishing industry, but according to Lange (2003), designing policies to achieve both of these objectives presents a challenge. In addition, the Namibian constitution provides for sustainable utilization of natural resources, and that these resources should be managed according to the best-available scientific advice for the benefit of both current and future generations (Sumaila et al., 2004). Due to the Namibianisation policy of the government, fishing companies have entered into complex contracts with paper rights holders that create perverse incentives to keep quota prices down through collusion and does not necessarily match with long term sustainability (Anon, 2006). There are some suggestions that there may be some excess capacity in harvesting and processing, although the NPOA suggests that overcapacity is not a major issue (Anon, 2007).

With the large decline in the biomass of important living marine resources and the provision for sustainable management in the Namibian constitution, it is important to look at the alternative policy scenarios that may be available to the managers of this system. The policy of Namibianisation was instituted to correct the years of unjust resource allocation and policies and was based on an incentive-based system where reallocations were brought about through economic motivation (Armstrong et al., 2004). These policies went a long way to obtaining benefits for previously disadvantaged fishers. However, they do not take into account the benefits to future fishers.

Fisheries management in the past has focused more on maximizing the catch of a single target species, ignoring its predators and prey, and the social and economic costs of doing so (Pikitch et al., 2004). Ecosystem based management, which is necessarily based on multispecies or food web models has been suggested as a way to sustain healthy marine ecosystems and the fisheries they support by starting with the ecosystem rather than the target species (Pikitch et al., 2004). Thus, the benefits of fisheries for current and future generations can best be explored using multispecies, multifleet models as the interactions between species and fleets are co-dependent. There are many different multispecies models (Plagányi, 2007), but in this instance we chose to use an Ecopath with Ecosim (Christensen and Walters, 2004a) model constructed by Heymans and Sumaila (2007) to explore a range of possible policy options available to the Namibian fisheries managers in order to fulfil their sustainable management brief, although the study is not meant to be exhaustive.

In addition, two possible futures are modelled by applying two different discount rates to calculate the net present value of benefits from the fishery. It should be noted that the discount rate allows us to convert net benefits to be received in the future to their corresponding values today. The lower the discount rate the higher the weight given to future net benefits compared to those received today. For instance, a discount rate of 5% implies that a dollar to be received in a year's time is worth only 95 cents today while a discount rate of 10% means that dollar is only worth about 90 cents today. For this analysis, we applied the more future generation friendly discount rate of 4%, which is a rate within the 2–5% that both gamma (Weitzman, 2001) and intergenerational discounting (Sumaila and Walters, 2005) will find appropriate to use to ensure that the future benefits of natural and environmental resources are protected. On the other hand, we apply a discount rate of 15% to approximate the private discount rate of private businesses in Namibia (http://www.bon.com.na/content/markets/7,1,2.aspx).

2. Materials and methods

Ecopath with Ecosim (EwE) models of the northern Benguela system for the 1970s, 1980s and 1990s were constructed and compared by Heymans et al. (2004) and Shannon and Jarre-Teichmann (1999), among others, while the management in the northern Benguela was described by Roux and Shannon (2004), Boyer and Hamukuaya (2002), Sumaila and Vasconcellos (2000) and Sumaila et al. (2002). See Heymans and Sumaila (2007) for a more complete description of the ecosystem and the data used.

2.1. The Ecopath with Ecosim approach

Ecopath with Ecosim (http://www.ecopath.org) is a suite of algorithms used to describe static food webs of ecosystems (Ecopath) and dynamic interactions in these ecosystems (Ecosim). The algorithms and the theories behind the software have been described in detail by Walters et al. (1997, 2000), Walters and Kitchell (2001), and Christensen and Walters (2004a) and compared to other ecosystem modelling techniques and tools by Plagányi (2007). Ecopath with Ecosim is a whole ecosystem modelling technique that is generic and capable of explicitly including most ecosystem components as well as incorporating lower trophic levels and primary production (Plagányi, 2007). Of all the models compared by Plagányi (2007), Ecopath with Ecosim scored "Good" when looking at techniques that allowed analysis of different types of management controls in use and "Excellent" on its ability to conduct assessment and policy exploration. Ecopath with Ecosim was judged to be useful for: understanding the complete ecosystem, the impact of target species, the effect of top predators, competition between marine mammals and fisheries, rebuilding

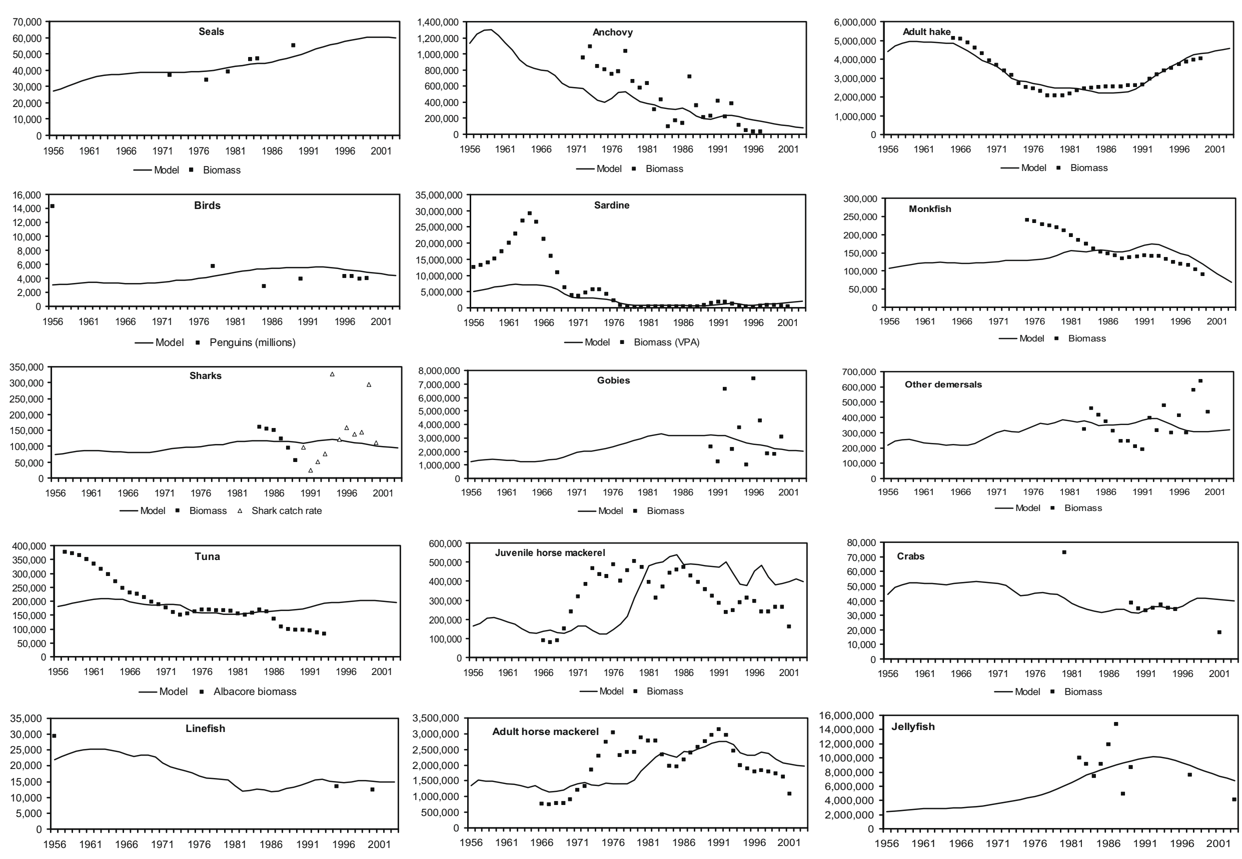

Fig. 1. Model of the northern Benguela ecosystem (lines) fitted biomass estimated to time series data (dots) of biomass (tonnes) from 1956 to 2003.

depleted fish stocks, biases in single-species assessment, ways to distribute fishing effort among fisheries, under-exploited species, changes in ecosystem state, spatial concentration of fishing, environmental/physical effects, effects of by-catch and the introduction of non-native species (Plagányi, 2007).

2.2. The northern Benguela model

An EwE model of the northern Benguela was constructed for 1956 as that was the year that the tuna fishery started and the hake, sardine, lobster, seal and snoek fisheries were already ongoing. The model covers the area from the shore to the 500 m depth contour and ranges from the Angola-Benguela front (around 15°S) to approximately the Orange River (29°S) – an area of approximately 179,000 km^2 (Brown et al., 1991). It consists of 32 compartments of which 18 are fish groups, two marine mammals, one sea bird group, eight invertebrate groups, two primary producers and one detritus. Six groups were split into adult and juvenile stanzas, namely, anchovy, sardine, gobies, horse mackerel, hake and jellyfish (Table S1). The two species of hake were combined into one group as most catch data were only available as generic hake. The ecosystem groupings and all the variables for the groups are given in Table S1, the catches of each species by gear in Table S2. Biomass time series data were obtained from VPA for the main species such as anchovy (Crawford et al., 1987), sardine (Hampton, 2003; Kreiner et al., 2001; le Clus et al., 1988; Schwartzlose et al., 1999; Thomas, 1986), and horse mackerel (Klingelhoeffer, 2006). Age-structured production models for hake (Butterworth and Geromont, 2001) were used also. Most of the data obtained from these sources was supplemented with data from the literature to cover the whole time series, as described in Heymans and Sumaila (2007). Catch estimates were obtained from the literature where possible and from the *Sea Around Us* database (http://www.seaaroundus.org) where no estimates were available from the literature. Where possible, the discards were estimated and included in the model (Heymans and Sumaila, 2007).

The model was fitted to time series data of catch and biomass, by changing the "vulnerability" parameters of all prey to their predator (Table S3). These parameters describe the interactions between each predator and prey combination, and as no information

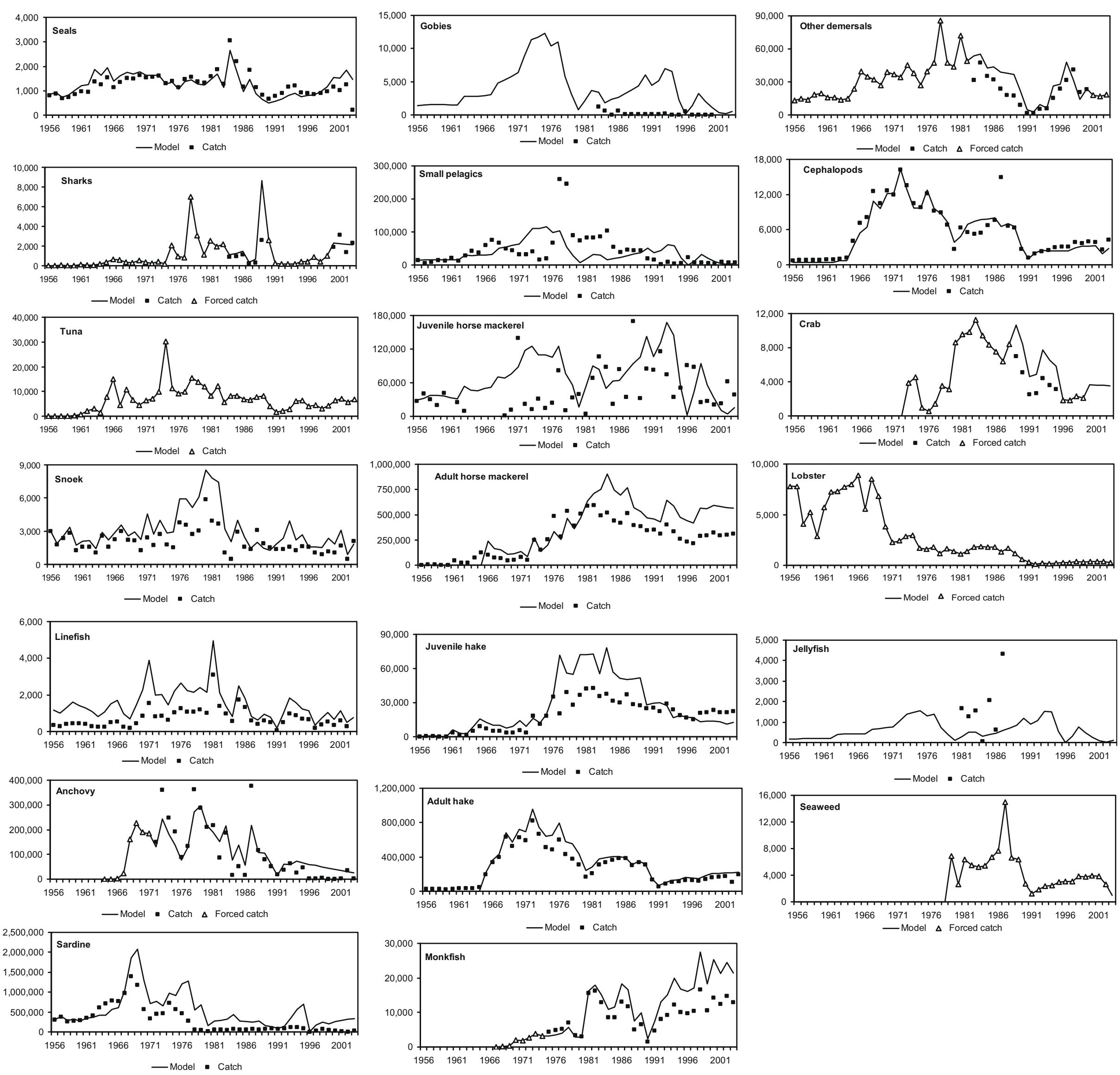

Fig. 2. Model of the northern Benguela ecosystem (lines) fitted catch estimated to time series data (dots) of catch (tonnes) from 1956 to 2003. "Forced catch" are data points of forced catches as the model was forced to extract catches when no biomass was available.

is available for them we estimated them by reducing the log likelihood sum of squares between the predicted and observed estimates of catch and biomass entered into the routine. However, when the best vulnerability settings were achieved, the residuals were still substantial, and an algorithm was then used to estimate a primary production time series anomaly. The anomaly is estimated by using a different primary production value in each time step, and the anomaly that reduces the sum of squares between the predicted and observed biomass the most was then correlated to the known environmental drivers such as wind stress and sea surface temperature. The anomaly showed a significant positive correlation ($r = 0.341$, $P < 0.05$, $DF = 43$) with the wind stress anomaly used in Klingelhoeffer (2006) and a significant negative correlation ($r = -0.36$, $P < 0.05$, $DF = 46$) with the sea surface temperature anomaly given by Sherman et al. (2007). The best fit of the northern Benguela model to the data is shown in Fig. 1 for biomass and Fig. 2 for catch. The model, even though fitted as well as possible, is still not fitted perfectly, as we will never have biomass estimates for most species prior to the 1980s. However, with the data available to us, this is the best fit of the model to the data, when driven by sea surface temperature. This model, fitted to both predator–prey interactions and environmental change, was then used to do the policy exploration.

2.3. Policy exploration

The Ecosim model of the northern Benguela, fitted to time series data from 1956 to 2000, was subjected to 'the optimum policy search' algorithm of EwE version 5 for 50 years from 2000 to 2050. When one compares the present value of a policy, it is standard practice to discount the net benefits that will accrue in the future compared to the net benefits that can be achieved today (Sumaila, 2003). This study therefore applied two different discount rates: 4%, which is a future generation friendly rate, and 15%, which depicts the private discount rate faced by businesses in Namibia.

The policy optimization module uses a nonlinear Davidson-Fletcher-Powell optimization procedure (Fletcher, 1987) to improve an objective function by iteratively changing relative fishing rates. Because nonlinear optimizations can easily hang up on local maxima, all single policy optimizations were started with random fleet efforts and repeated 30 times with an array of weighting factors described below (Christensen and Walters, 2004b). All other settings in the policy routine were left at default values. These 30 optimizations were then used to calculate statistically significant differences between the scenarios with the two different discount rates using a two tailed paired Student's *t*-test. Three different indices of ecosystem function were used: net present value for profit maximization, jobs per catch value for social maximization and the ecosystem's B/P ratio as described below. These indices are not the only indicators available for ecosystem function, but they are commonly used and have been tested by various authors such as Christensen and Walters (2004b), Araújo et al. (2008) and Arreguin-Sanchez et al. (2008).

2.3.1. Profit maximization

Under this maximization routine, we assumed that the objective of management was to maximize the net present value of profits from the ecosystem. Profit was estimated as the difference between the value of the catch and the cost of fishing in each year within the time horizon of the model, and these were obtained for each of the 10 fisheries (Heymans and Sumaila, 2007). The costs and catch values were obtained for 1997 (Table S4) as these were the best estimates available – also since our estimates are for 2000, it is very unlikely that economic parameters will vary significantly in the short time span of 3 years. Note that in 1997 both the purse seine and demersal fleets were unprofitable, kept in business partly through subsidies and partly through borrowing, fishing companies hoping that profitability would improve in the near future. The profit and costs of each fleet were used in conjunction with market prices (Table S5) to calculate the total profit that could be made under different policy scenarios. These were then discounted through time at the two different discount rates to obtain the present value of profits.

2.3.2. Employment maximization

Management authorities often seek to maximize the number of jobs that can be generated by their fisheries. Thus, we explored the consequences of this management strategy by running the model with the assumption that the objective was to maximize jobs. Jobs per catch value (Table S6) was estimated from the total number of employees in each fishery divided by the total value of the catch of that fishery (Heymans and Sumaila, 2007). As a ratio, the fleet that delivers the least jobs was the mid-water fleet while the tuna longlines brought in the most jobs per value of the catch (Heymans and Sumaila, 2007). These data were included in the model and simulations were run to determine the maximum number of jobs that could be generated, and its consequences in terms of the present value of profits and ecosystem status.

2.3.3. Maximizing 'ecosystem status'

Management also needs to incorporate conservation objectives, and to this effect we assumed that the objective was to maximize the 'ecosystem status' based on one of Odum's (1969) measures of ecosystem maturity, the B/P ratio. This was achieved by optimizing the longevity-weighted summed biomass of all the groups in the ecosystem. The longevity was calculated as the inverse of the production/biomass ratio from the standard Ecopath parameters in Table S1. Increasing this index would lead to an increase in the biomass of long-lived species (Christensen and Walters, 2004b) and therefore was proposed as an index of ecosystem health and structure, here called 'status'. We simulated our model under this assumption to determine the effect of maximizing ecosystem status on the present value of profits and the number of jobs that can be generated from the ecosystem.

2.3.4. Maximizing a weighted average of the three objective functions

In the previous maximization routines, a weighting of 1 was placed on either profit, jobs or ecosystem status, and zero on all other values, while in this maximization we optimized for all three by putting a weight of 1 on each. Thus the trade-off between profit, jobs and ecosystem status was studied by optimizing a weighted average of the three objective functions at the same time. Note that putting the same weight on the objective function does not mean that the same relative change will be obtained for each result as this will be dependent on how profitable fast growing species are or how quickly a species can change its turnover rate.

3. Results

Optimizing for discounted profits under 4% or 15% discount rates showed that significantly more profit and jobs would be obtained under the lower discount rate, while not having a significantly different impact on the ecosystem (Fig. 3). However, there would be a small reduction in the total longevity of the ecosystem over the 50 year period in both cases. This would be obtained by increasing the effort of the demersal trawl, commercial line, crab, lobster and purse seine fisheries (Fig. 3). To obtain the significant increase in the lower discount rate scenario, there would need to be significantly less effort by the purse seine fishery, demersal trawlers and the lobster fleet. However, in both discount scenarios, the effort of the longline, seal and seaweed fisheries could be in-

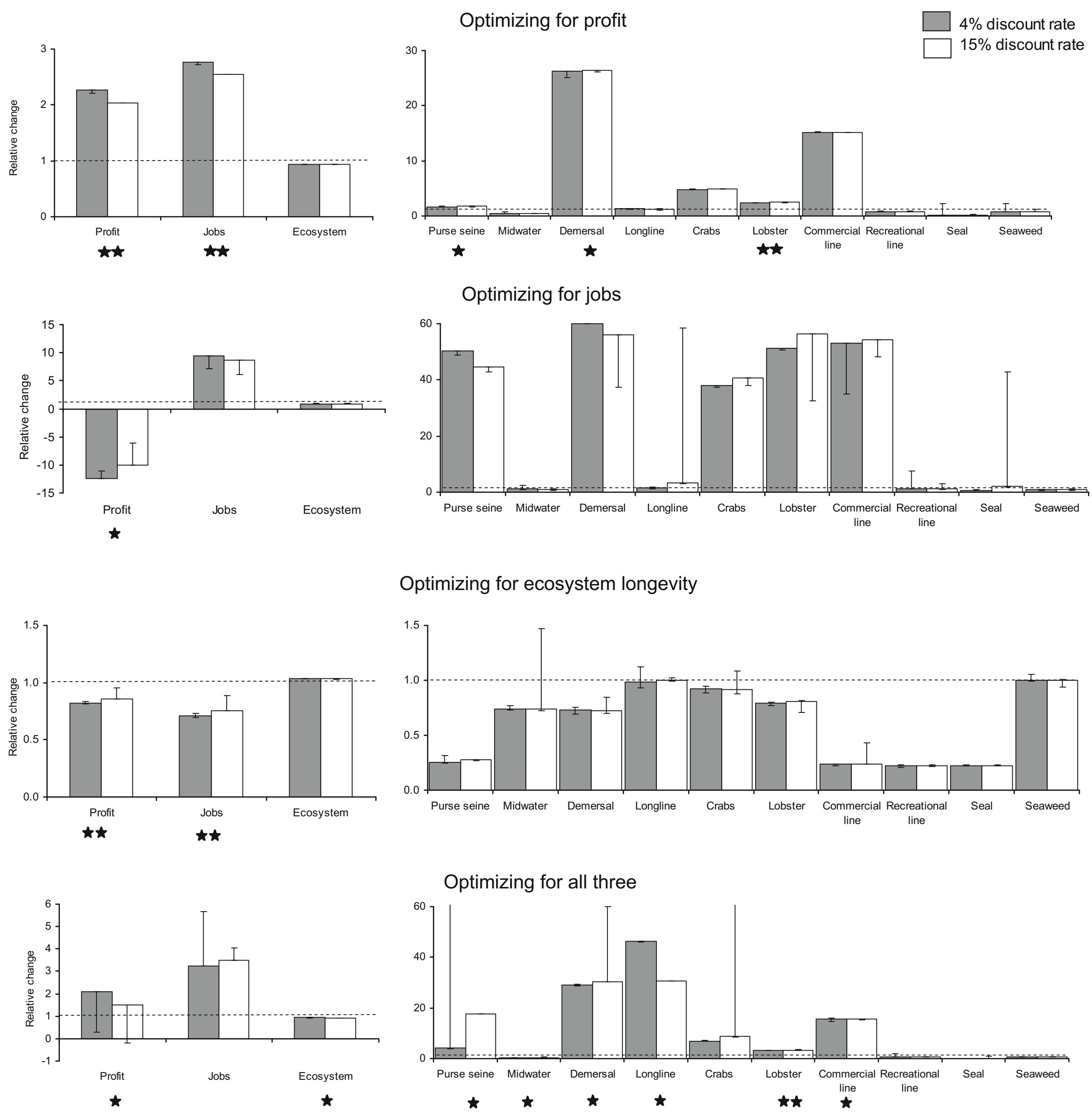

Fig. 3. Results from single objective optimizations for profit, jobs, ecosystem status and for all three objective functions combined. In the left hand side figures, values on the *y*-axis are relative to the baseline value from the Ecopath model, while in figures on the right, the *y*-axis indicates effort relative to Ecopath base and *x*-axis indicates different fleets. Broken lines indicate the Ecopath base line values for 2000 for profit, jobs and ecosystem longevity (figures on left) and for effort by fleet (figures on right). Error bars indicate the range of values obtained from 30 runs. Gray bars indicate 4% discount rate and white bars 15% discount rate. ** indicates $P < 0.001$ and * indicates $P < 0.05$.

creased on average. In both scenarios, profits would be increased by decreasing the effort of mid-water trawl, recreational line, seal and seaweed fisheries. This is explained by the fact that reducing fishing effort results in higher biomass, which reduces fishing cost and hence increases profits.

When maximizing for the number of jobs (expressed as a function of the catch value), the model shows that there would be large losses in profit, and it seems that the fisheries would make a loss in this case. Specifically, there would be significantly less profit made under the lower discount rate scenario because the high fishing capacity that job maximizing entails implies that future benefits are lost, no matter which discount rate is applied. It should be noted, however, that there is no significant difference in the number of jobs obtained or in the effort needed by the fleets (Fig. 3). More jobs would be obtained by increasing the effort of most fleets, with the highest fishing effort in the demersal, lobster, commercial linefish and purse seine fisheries, although there is no significant difference between the effort under different discount rate scenarios. It is interesting to note here that the fleets that seem to require the highest effort when optimizing for jobs per catch value (demersal, commercial linefishery, lobster) are not the fleets that have the highest jobs per catch value (longline, purse seine, crabs, seals). This is counter intuitive and not easily explained. However, some of the fisheries that have the highest jobs per catch value, specifically longlines and seals, catch mainly higher trophic level, longer turnover species, which cannot be fished as hard before they collapse. On the other hand, the purse seine fishery also has a high jobs per catch value rating, and catches mostly lower trophic level species, therefore its effort is increased over that of the longline and seal fisheries.

When optimizing for ecosystem longevity, all cases lead to a reduction in the profit and jobs obtainable from the system, and again a significant difference between the two discount rate scenarios. Significantly more profit and jobs will be made under the higher discount rate, when optimizing for ecosystem status, although it will still be below the 2000 baseline (Fig. 3). There is also no significant difference in how much the average longevity in the ecosystem would be increased using different discount rates. To maximize the ecosystem status, the effort in all fisheries will have to be reduced. Notably the seal fishery, recreational and commercial line fisheries and purse seine fisheries would have to be reduced considerably from the 2000 values, with the longline, crab and seaweed fisheries being the least reduced. Both the crab and seaweed fleets harvest species with fast turnover rates, which would not affect the overall longevity of the ecosystem, and the longline fleet catches mainly tuna and sharks, both of which are predators of other long-lived species. Thus, the overall impact of the longline fleet in this model is to increase the biomass of longer lived species by removing predation pressure by sharks and tuna. However, there is no significant difference in the effort required for the two discount rate scenarios, because the constraint imposed to ensure that ecosystem status is maximized limits the ability of the discount rate to impact the results of the analysis significantly.

Finally, if one puts the same weighting on profit, jobs and ecosystem longevity, the profit and longevity would again be significantly increased under the lower discount rate scenario, while the jobs would not be significantly different, although there would be at least three times more jobs compared to 2000 (Fig. 3). What is obvious from this scenario is that if the same weight is put on all objective functions, one does not get the same magnitude in the results, with more jobs being possible, but ecosystem status still below the year 2000 baseline. All three objective functions are maximized by increasing the purse seine, demersal, longline, crab, lobster and commercial line fisheries, with the mid-water trawl, recreational line fishery, seal and seaweed fisheries being reduced from year 2000 effort levels. The significant difference in the profit and longevity of the ecosystem under the lower discount rate is obtained with an increase in the purse seine, mid-water, demersal and crab fleets, while the effort of the longline and lobster fleets would be significantly reduced.

4. Discussion

Managing an ecosystem for future benefit is a challenge that is not easily met. In this study, we explored possible future fishing scenarios by using a whole ecosystem modelling approach that has been judged "excellent" in its ability to conduct assessment and policy exploration (Plagányi, 2007). However, any model is only as good as the data that are used to parameterize and validate it. The northern Benguela has been studied extensively over the past 50 years, but there will never be perfect information to construct models of the past. Specifically, it is not possible to get biomass, production and consumption estimates for species that were not being exploited at the time. It is possible to calculate most of the production and consumption ratios from empirical relationships (see Heymans and Sumaila (2007) for a description of how that was done) as most of these groups were not exploited at the time. In addition, the best estimates we have of biomass time series often comes from VPA or other modelling techniques that have their own associated uncertainties. Catch estimates are also often uncertain due to misreporting, etc. but this has been addressed extensively by the *Sea Around Us* project (Willemse and Pauly, 2004), and therefore we believe the catch estimates are probably as good as we would get. A further source of uncertainty is our estimates of jobs per catch value and market prices for some combined groups, which necessarily had to be calculated based on the price of the most caught species (Heymans and Sumaila, 2007). Nevertheless, Namibia's constitution calls for sustainable management, and using the best available information in different modelling techniques is the best chance there is to achieve it.

It is also important that the modelling techniques are used appropriately. Specifically, Ecopath with Ecosim has been misused in the past, by using the static Ecopath model without fitting it to time series, by using default settings for all parameters in Ecosim, and by using the model as a "black box", without understanding the parameters put into the model. These practices should be avoided and therefore this study has used the best available data fitted extensively to time series data and environmental variation (Heymans and Sumaila, 2007), to get the best possible model for forecasting future policy scenarios. However, this technique should still be seen as a theoretical exercise, as it applies a constant fishing rate for each fishery over 50 years and without taking into consideration future climate variation. The optimizations also do not include the effects of possible future regime shifts or future changes in catch value, costs such as fuel, etc. Obviously it would be wrong to commit a fishery to a fishing rate calculated 10, 20, or 50 years ago without using feedback policies where harvest goals are adjusted over time with the addition of new information (Christensen et al., 2005). This does not mean that this exercise is useless, as these analyses give directional guidance for where the system can or should be heading (Christensen et al., 2005).

With these caveats in mind, we used the policy optimization algorithm in Ecosim to give guidance to the managers within an adaptive management framework. We show the benefit to future generations by using a lower (future generation friendly) discount rate (4%) vs. the higher (private) discount rate (15%) used by Namibian businesses. The results show that in the long term (50 years) significantly more benefits in terms of profits and jobs can be obtained if a lower discount rate is used. In practice what this means is that managers need to use lower discount rates to help them set total allowable catches, in particular, and fishing policies, in general. However, improved benefits are not as easy as increasing the effort of one fishery, as it would come at the expense of others. Optimizing for profit or jobs seems to invariably entail an increase in the demersal and commercial line fishery while the purse seine fishery also seems to increase in those circumstances. On the other hand, optimizing for ecosystem longevity does imply that the effort of all fleets would have to be reduced.

It is also obvious that optimizing for the ecosystem longevity does not show as much change as optimizing for profit or jobs. This is because it is very difficult to change the turnover rate of a group or species, and in this case the routine is trying to maximize all the group-specific biomass/production ratios (Christensen et al., 2005). To optimize for ecosystem longevity implies that the model is calculating the summed biomass-weighted longevity over all groups with an average longevity of more than one month (i.e. P/B less than 12 per year). However, this index is only one of the indices of ecosystem health, and it does not say anything about extinction risk of specific species or protecting specific species that might be important for conservationists. It is evident that the indicators used here do not change at the same rate as it is easier to get a 10% improvement in profit than it is for ecosystem longevity to increase by 10%. Thus, the impact on ecosystem status would never be as variable as that on profit or jobs, and therefore one cannot say that optimizing for jobs or profit only seems to reduce the ecosystem longevity marginally, so it does not have much of an impact on the ecosystem. It is important to evaluate this in a practical setting, with stakeholder involvement, and change the weightings if one of the factors tends to take over.

This policy optimization routine assumes that there is a "sole owner" and that all incomes and costs are pooled and profits shared among fishers (Christensen et al., 2005). Of course this is not realistic in most systems. Specifically in the northern Benguela ecosystem this would not be the case, as the system is based on a free market although it does use incentives to reallocate wealth through economic motivations (Armstrong et al., 2004). However, the alternative is to assume that no fleets operate at a loss (Christensen et al., 2005), and that is not the case in Namibia, as both the demersal and the purse seine fleets have operated at a loss before. Unfortunately, that means that if one optimizes for ecosystem structure, there will be economic and job losses as seen in Fig. 3, and the Namibian government will have to find ways to compensate fishers for these losses. However, we see that if we reduce the discount rate used in Namibia from 15% to 4% this will often increase the profit possible over 50 years, and therefore it becomes imperative for managers to show the importance of managing for future generations.

The use of ecosystem models for policy exploration is a useful tool to test hypotheses of different future scenarios, and one of the main advantages of using an ecosystem model to do policy optimizations is that it shows the data gaps in the system. Specifically, the longline fishery seems to be the least reduced when optimizing for longevity. However, longlines are known to have large by-catch of sharks (Zeeberg et al., 2006), seabirds (Ryan et al., 2002) and turtles (Petersen et al., 2007), which were not included in this model. Thus, these simulations show the importance of including the by-catch data (even rough estimates of by-catch) in the models to include the impact that by-catch would have on these long-lived species and therefore on the overall ecosystem longevity. At present, this modelling technique does not take into consideration future climate change or other environmental drivers. Ecopath with Ecosim is continually evolving, however, and the uncertainty of the impact of future climate change on the system needs to be taken into consideration if the northern Benguela system is to be managed sustainably. The continual improvement of ecosystem models is part of adaptive management, and the importance of including new information (on by-catch etc.) is shown here. The model used in this study should be continually updated with new information and used to test scenarios for future generations, if we want to manage the ecosystem sustainably. Finally, the best way to evaluate these scenarios is with the participation of all stakeholders, who could then decide which of the objective functions to optimize; be it profit, jobs or ecosystem longevity, and what they would be prepared to sacrifice in order to achieve the desirable goal of long term fisheries sustainabilty.

Acknowledgements

The authors wish to thank the Ministry of Fisheries and Marine Resources in Namibia, Kevin Stephanus and Susan Alexander from the University of Namibia for their contribution to the data used in this paper. We also wish to thank Robin Harvey and Shona Magill from the Scottish Association for Marine Science and two unknown reviewers for their review of this manuscript. The work was funded by the European Union through the INCOFISH Project INCO-003739 (http://www.incofish.org) and RS and VC acknowledge support from the Sea Around Us Project, initiated and funded by the Pew Charitable Trusts.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.pocean.2009.07.013.

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