Modelling the effect of alternative management strategies on the catch and effort in the carpenter (*Argyrozona argyrozona*) linefishery

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27/09/2013
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Abstract

In South Africa, linefishing increased in the mid-1800s and eventually reached a peak in the 1980s/90s. A legal linefishery emergency was declared in 2000 in accordance with the Marine Living Resources Act of 1998. This was a large blow for the commercially important industry. Nonetheless, the carpenter stocks had already been overexploited to such a high degree by linefishing, and also as part of trawling bycatch, that even at an effort less than half of the effort that produces a maximum sustainable yield, carpenter stocks were still found below the biomass found at the maximum sustainable yield. In order to explore three different management strategies for the carpenter stock on the offshore Central Agulhas Bank, an age-structured, non-stochastic model was set up. The influences of the following strategies - Total Allowable Catch (TAC), as well as revised minimum size limit and closed season – on a stock found at a dismal 19.2% of carrying capacity, are projected using this model on a monthly time-step. The objectives of this fishery are to achieve a biomass in the final year equal to the biomass found at a maximum sustainable yield (7243 t) and to maximise effort (employment) and catch. The overall recommendation for this stock was a reduction in minimum size limit from 35 cm to 30.48 cm in combination with a flexible TAC starting at 790 t. It is also recommended that even though models are important for fisheries management, no model should be taken in isolation without first considering life history traits and other important information about a stock.

Introduction

Fish are some of the most important natural resources in the world. Even so, these creatures of the deep now face considerable management problems that are concerned with all facets of the species and individual stocks (Ormerod, S. J. 2003). The main issues seen in fisheries worldwide are the overexploitation of many fish species, combined with the destruction of important, often rare, habitats (Ormerod, S. J. 2003) and decreases in catch and effort (Jennings, et al. 2001). Most of the main issues seen in fisheries are due to and exacerbated by the growing human population and its demands (Jennings, et al. 2001) and technological advances (Garcia and Grainger 2005). Most fisheries have now joined the ranks of the unmanaged and collapsed, though scientific literature is full of management recommendations (Garcia and Grainger 2005). Fisheries now have the added setback of an overabundance of competitive fishers. When this competition reaches too great a level, fisheries are drawn into economic collapses (Jennings, et al. 2001).

It is obvious that most fisheries need to be managed more effectively. There are a number of different types and subtypes of management strategies. This first method of control is catch control and it includes total allowable catches (TACs) and taxing controls. TACs can also be split into individual quotas (IQs) and are the most commonly used strategy for managing a fishery (Jennings, et al. 2001). The second method of control is effort control. It includes limiting the number of boats and fishers on each boat, as well as the size of the vessels and the periods for which these vessels may fish. These types of controls are designed to reduce the catching power of fishers and thus the rate of fishing mortality of the stock. These controls are rarely effective if not implemented in conjunction with either catch controls or technical measures or both (Jennings, et al. 2001). Technical measures are the third method for managing a fishery. The measures include restricting the size and sex of the fish being caught, as well as the types of fishing gear used and the periods during and areas in which fish may be caught. There are many advantages to implementing these strategies, such as protecting the stock during a vulnerable period. There are however also disadvantages, such as causing an increase in the cost of fishing without producing the desired effect of reducing the rate of fishing mortality (Jennings, et al. 2001).

Often none of these controls are effective when implemented in isolation. It is therefore important to select a combination of strategies that will both protect the stock effectively and achieve the management aims for the fishery. In developed countries, individual transferrable quotas (ITQs) are used in conjunction with technical measures, such as minimum size limit or closed season. ITQs are effective as each fisher is allowed a proportion of the total quota. This leads to a reduction in competition between fishers. This is particularly true for ITQs as the quotas can be traded among the fishers, ensuring that the total quota is caught even if a certain vessel cannot handle its quota.

In order to do non-invasive testing of the effectiveness of these different strategies in conserving a stock and bolstering its economy, a model must be constructed. Each model must stick to a set of guidelines, be based on a set of parameters and aim to achieve a set of objectives for the fishery. There are several different types of models that are used in fisheries management (Jennings, et al. 2001). There are also many examples of the use of different types of models for fisheries management (Attwood and Bennett 1990; Smith, et al. 1999; Brouwer and Griffiths 2006; Kerwath, et al. 2012), each with its own set of benefits. South Africa was one of the forerunners in implementing this multidisciplinary approach to fisheries management (Hutchings, et al. 2009). The long-standing history of fishing in this country has contributed to this leadership status in fisheries management.

The boat-based linefishing industry is a multispecies fishery (Winker, et al. 2013) that targets fishes on reef or soft sediment. The linefishing industry in South Africa started in the mid-1800s, eventually peaking from the 1980s to the 1990s (Van der Lingen, et al. 2012). During the peak linefishing period, more than 3 linefishing boats could be found per kilometre of coastline, as opposed to between 0.12 and 0.37 boats per kilometre of coastline approximately 80 years earlier (Van der Lingen, et al. 2012). This large increase in fishing effort, along with a rapid increase in fishing technology, led to the overfishing of most linefish stocks and, thus, to the formulation of the first comprehensive linefishing management framework in 1985 in South Africa.

Though a legal emergency in the South African linefishing industry was declared in 2000, carpenter (*Argyrozona argyrozona*) stocks continued to plummet in size. The carpenter species is one of 20 economically important linefish species in South Africa (Griffiths, M. H. 2000) and this continual decrease was of great economic concern. The continual decrease was due to the long-term overexploitation of these fish by the linefishing industry (1850 – present), the trawling industry (1900 – present) and Japanese fleets (1970 – 1992). However, to this day, carpenter still forms a large component of the bycatch in the trawl industry. Attwood et al. (2011) found that trawls caught 107 t of carpenter per annum as bycatch. This is a quantity similar to the linefishery carpenter catch of 187 t per annum.

Owing to the reduction in effort effected by the emergency in 2000, there has been a slight recovery in carpenter stocks (Van der Lingen, et al. 2012). The commercial industry is managed by a Total Allowable Effort (TAE) allocation. Only the number of boats and their crew allocation are restricted. There is no explicit limit on catch. The recreational linefishing sector, on the other hand, is managed by species-specific daily bag limits and size limits.

The carpenter population that lives in the waters surrounding South Africa must be treated as two separate stocks (Brouwer and Griffiths 2005a). One of these stocks can be found on the Central Agulhas Bank. This area is vital to the survival of the species, with 88% to 93% of the annual reproductive output originating here (Brouwer and Griffiths 2005a). The offshore Central Agulhas Bank is, therefore, the site of the stock being modelled in this study.

Despite all these regulations, the stock on the Central Agulhas Bank is currently at 19.2% of carrying capacity, when tested using an age-structured model (Kerwath, et al. 2012). This suggests that the current management strategies are not as effective as once thought, leading to the stock not being protected as well as it should be. The carpenter stock requires effective management strategies that will eventually bring the stock back to the optimal biomass (B_{msy}) that will lead to the maximum sustainable yield or catch (MSY).

To better protect this fishery, effective management strategy options could include one or a combination of the following regulations. A total allowable catch (TAC) can be implemented. This limits the number and biomass of carpenter caught by linefishers. A TAC provides a continuous form of stock control (Attwood and Bennett

1990) by essentially distributing the allowable catch among the boats in the fishery, in the form of quotas.

A limitation can also be put on the minimum size of allowable catches. This is already an active regulation in the recreational sector. The minimum legal size limit of carpenters increased from 25 cm to 35 cm in the beginning of 2005 on the strength of a biological analysis (Winker, et al. 2013). The slight recovery of the carpenter stock in recent years may partly be a response to the increase in the minimum size limit. However, the increase in the minimum size limit has never been simulation tested.

Since the offshore Central Agulhas Bank is a reef area, this study assumes that when the boats are fishing on the reef, carpenter is being caught. The regulation of fishing effort is therefore a viable method of regulating this fishery and has already been implemented in the commercial linefishing sector (Van der Lingen, et al. 2012). This can be done in a number of ways. The number of boats in the fishery and crew size can be regulated or the number of boat days that each boat is allowed can be regulated.

The last fishery regulation method which could protect this fishery is the closed season method. Closed seasons are often implemented to coincide with species' breeding seasons when they are most vulnerable and in a worse than usual condition (Brouwer and Griffiths 2005a). Closed seasons can, however, prove tricky to implement and monitor, making this strategy a less favourable regulation choice.

Since fishery management objectives are often far too vague (Attwood and Bennett 1990), it is important to outline the fishery objectives clearly. By implementing and monitoring any one or combination of these strategies, the carpenter stock should eventually be allowed to return to B_{msy}. For such a viable commercial species and fishery, it is also important to choose a regulation option that delivers the highest maximum employment or the best maximum profit depending on the economic needs of the fishery. The improvement of economic efficiency must always be an important fisheries management objective (Crutchfield, J. A. 1961). Even though a number of different objectives can be named, the primary objectives assumed for this fishery could include bringing the stock back to B_{msy} and maximising the effort and corresponding catch.

Maximum effort can be used as a proxy for employment as it is measured in boat-days per year and catch per unit effort (CPUE) can be used to determine profit. A strategy that maximises either or both of these and allows for the least amount of change or variation should be implemented to regulate the fishery.

Since this stock has already been overexploited, these strategies and their effectiveness cannot be primarily tested on the actual stock. A model simulation must, therefore, be used to test the strategies mentioned above.

This study aims to fit an age-structured model with a Beverton-Holt Recruitment function and a Von Bertalanffy Growth equation to the carpenter fishery in order to make informed recommendations for the fishery. The main aim of the model in this study is to test a number of fishery regulating strategies for this stock and measure the effectiveness of each. The effectiveness of the strategies will be measured by the amount of effort expended to acquire a certain catch and whether or not the spawner biomass in 2032 (the final year of the model) reaches the optimal value of B_{msy}.

Methods

The modelling parameters

Since most of the catch history of this species has already been highlighted and the growth parameters are outlined in Appendix 1, it is necessary to highlight the reproductive information of this species. The age-at-50%-maturity is 4 years for males and 3 years for females that live on the offshore Central Agulhas Bank (Brouwer and Griffiths 2005a). This parameter estimates the age at which most individuals in the stock become sexually mature and join the ranks of the spawner biomass. The spawning season of the stock is also a vital piece of information. Even though spawning on the Central Agulhas Bank starts a month later than other carpenter stocks, the duration of the season remains the same. The Central Agulhas Bank spawning season therefore lasts from November to May each year (Brouwer and Griffiths 2005a) and the peak spawning period lasts from February to March. During this period the sexually mature individuals experience minimal growth and all individuals are a number of complete years and zero months old (Brouwer and Griffiths 2005b). The sex ratio of the offshore Central Agulhas Bank stock varies between size classes, but all size classes show a female bias in this area (Brouwer and Griffiths 2005a). It is also worth noting that this species is long-lived and slow-growing and can therefore grow to 80cm and live to 30 years of age (Brouwer and Griffiths 2004).

The modelling approach

An age-structured simulation model was developed to explore the effectiveness of a number of strategies for the carpenter line-fishery. This model was run on a monthly time-step for two decades. The following strategies were explored: the introduction of a total allowable catch (TAC), revising the minimum size limit, regulating fishing effort (TAE) and introducing a closed season. These strategies were evaluated in terms of catch and effort objectives. The simulations were run for 20 years starting at a biomass value at 19.2% of carrying capacity, the current estimate (Kerwath, et al. 2012), and a fishing mortality rate (F) of 0.16 y^{-1}, which is close to the current fishing mortality rate ($F_{current}$). In each case, the regulation was adjusted to ensure that B_{msy} is attained after 20 years. The evaluations of the strategies were done on the basis of the final values of catch and effort (E).

The operating model

All symbols and parameters used in the simulations are described in Appendix 1. Recruitment (R) was calculated annually using the Beverton and Holt Recruitment Model where R is a function of spawner biomass from the previous year.

$$N(4) = R = \frac{\alpha \cdot SB}{1 + \beta \cdot SB} \qquad \text{Eq. 1}$$

where α is the Beverton and Holt steepness parameter, β is the Beverton and Holt density-dependence parameter and SB is the spawner biomass from the end of the previous year. The values of the constants, α and β, were selected to realise a value of 0.800 for $\frac{R}{(\alpha / \beta)}$ when SB/SB_K was equal to 0.2 (Figure 1). The numbers at age 4 (N(4)) were derived from the number of recruits (R).

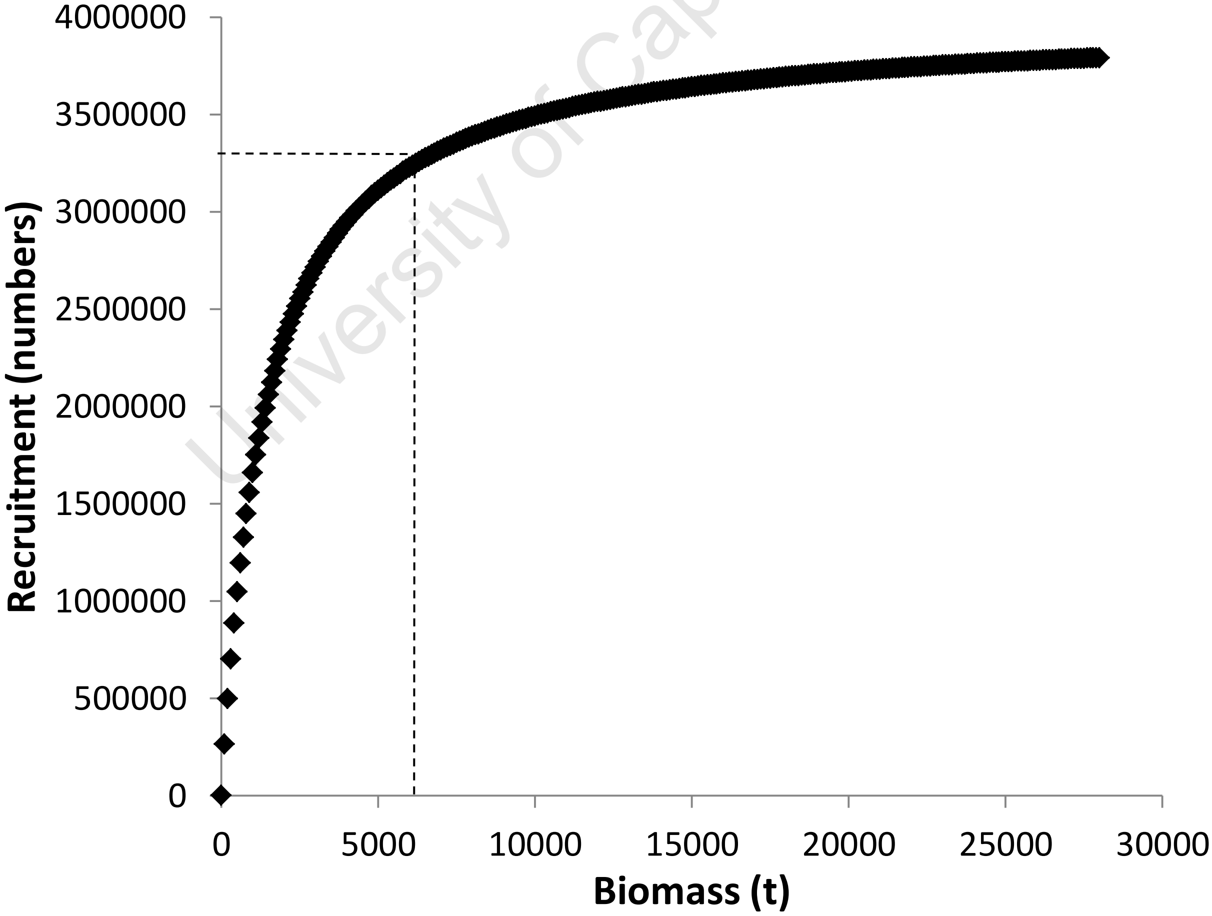

Figure 1: The relationship between the biomass of the stock and the number of recruits produced, showing 20% of biomass carrying capacity corresponding to 80% recruitment

Numbers at age (N(a)) were updated from the previous year:

$$N(a) = N(a-1) \qquad \text{Eq. 2}$$

Each month the numbers at age underwent mortality according to the following equation:

$$N(a) = N(a) \times e^{(-F'-M')} \qquad \text{Eq.3}$$

where F' is the rate of fishing mortality (F) divided by 12 and M' is the rate of natural mortality (M) divided by 12. M was the natural mortality rate suggested by Brouwer and Griffiths (2006). The value of F was selected as the fishing mortality rate that brought SB down from SB at carrying capacity (B_K) to 19.2% of B_K. The following ratios were used to derive this rate of depletion of 19.2% from a differently structured model that suggested a model-specific depletion rate of 32% (Kerwath, et al. 2012).

$$\frac{B}{B_K} \text{ and } \frac{B_{MSY}}{B_K} \qquad \text{Eq.4 \& 5}$$

where B is the current biomass, B_K is the biomass at carrying capacity and B_{MSY} is the biomass at a maximum sustainable yield.

Catch at age (C(a)) was also calculated monthly as a function of numbers at age.

$$C(a) = N(a) \times (1 - e^{(-F'-M')}) \times (\frac{F}{F+M}) \qquad \text{Eq. 6}$$

The Von Bertalanffy Growth Model was used to determine the length of fish (L) at each age (Brouwer and Griffiths 2005a).

$$L = (L_{\inf} \times (1 - e^{((-k)\times(a_m - t_0))})) \qquad \text{Eq. 7}$$

where L_{inf} is the Von Bertalanffy length at infinity constant, k is the Von Bertalanffy growth rate constant and t_0 is the Von Bertalanffy time zero constant. These constants are species- and stock-specific (Brouwer and Griffiths 2005a).

The length-weight relationship for carpenter was used to determine the weight or biomass of fish (B) at each age as a function of numbers at age (Kerwath, et al. 2012).

$$B = N(a) \times LW1(L^{LW2}) \qquad \text{Eq. 8}$$

where LW1 and LW2 are length-weight relationship parameters.

The catch biomass and biomass (B(a)) were calculated in this way from the catch at age and numbers at age. At the end of each year, catch biomass was accumulated.

The operating model was run repeatedly for a number of different F values ranging from 0 to 0.3 y^{-1} in intervals of 0.005 y^{-1}.

The catch biomass in the final year was used to determine the maximum sustainable yield (MSY) and its corresponding fishing mortality rate (F_{msy}). F_{msy} was used to determine its corresponding optimal biomass value (B_{msy}). The biomass at carrying capacity (B_K) was determined using a fishing mortality rate of 0 y^{-1}.

Total Allowable Effort

Effort (E) was expressed as the number of boat-days expended in a year. The value of E_{msy} (the optimal effort that results in a maximum sustainable yield) and all other values of E were equated to F as follows:

$$E = \frac{F}{q} \qquad \text{Eq. 9}$$

where q is the catchability of the carpenter stock.

The number of boats corresponding to the different values of effort was calculated using the following equation:

$$Number\ of\ Boats = \frac{E}{200} \qquad \text{Eq. 10}$$

where 200 is the approximate average number of times (or days) per year a boat goes to sea.

The TAE, where E was set at E_{MSY}, was taken as the default model. Two higher values of E, corresponding to 1.5 E_{msy} and 2.0 E_{msy}, were also used. These higher values of E were used as possible scenarios involving excessive effort against which other strategies could be tested for their ability to restrain catches and maintain B at or near B_{MSY}.

Minimum Size Limit

The minimum size limit was introduced by implementing a minimum age limit to which a certain size corresponded according to the age-length equation (eq. 7). The age limits ranged from 4 (age at first capture) to 24 years with a corresponding size limit range of 24.72 cm to 50.70 cm (Brouwer and Griffiths 2005a). Owing to the monthly time-step, the age-limits could be varied by $\frac{1}{12}$ years. The biomass value in 2032 for each size limit tested was divided by the target biomass value (B_{msy}) to provide a biomass ratio. The average catch over the two decades, and the biomass ratio in 2032, were plotted against the size limit to estimate the optimal size limit for each effort scenario.

Closed Season

The closed season strategy was implemented with the default minimum size limit of 24.72 cm - the size corresponding to the age at first capture, age 4. The length of the closed season was varied from 1 to 3 months in length. No adjustment was made to the effort in the remaining months for each of the three effort scenarios. The average catch over the two decades, and the biomass ratio in 2032, were plotted against the length of the closed season to estimate the optimal length of the closed season for each effort scenario.

Total Allowable Catch

The total allowable catch (TAC) strategy was implemented without a closed season and with the default minimum size limit of 24.72 cm. A range of a hundred TAC values was tested. These TACs ranged from 2% of the maximum sustainable yield (MSY) to 200% of MSY. When implementing the model, it was not possible to divide the TAC by 12 to calculate a monthly harvest, as the catch needed to be distributed among the age classes. Instead, a constant F' value was used across all ages in a month. The F' value was adjusted at the end of the month by comparing the cumulative catch for the year to the cumulative monthly fraction of the TAC. F' was adjusted by dividing by this ratio, from one month to the next, until the end of the year. This strategy ensured that for most of the TACs, the actual catch did not deviate from the TAC by more than 40%, except at very small, unreasonable TACs and at very large TACs that cause the stock to crash. If the demand for fish exceeded availability in cases of severe over-exploitation, the trial was terminated and labelled "Unobtainable". The average effort over the two decades, and the biomass ratio in 2032, were plotted against the range of TACs to estimate the optimal TAC.

Results

Model Dynamics

The following estimates pertain to the maximum sustainable yield (Appendix 1, Figure 2 and Figure 3).

$MSY = 897$ t

$F_{msy} = 0.12\ y^{-1}$

$B_{msy} = 7243$ t

$E_{msy} = 60000$ Boat-Days.y^{-1}

$B_K = 24129$ t

The following three ratios were determined from the output of the model, when the default size limit and no closed season had been applied:

1) $B_{msy}/B_K = 0.300$
2) $MSY/B_{msy} = 0.124$
3) $MSY/B_K = 0.037$

It is valuable to note that the MSY that corresponds to F_{msy} (Figure 2) is less than the actual MSY previously stated. Figure 2 shows the average catch over the two decades and not the annual catch values in the final year from which MSY was calculated.

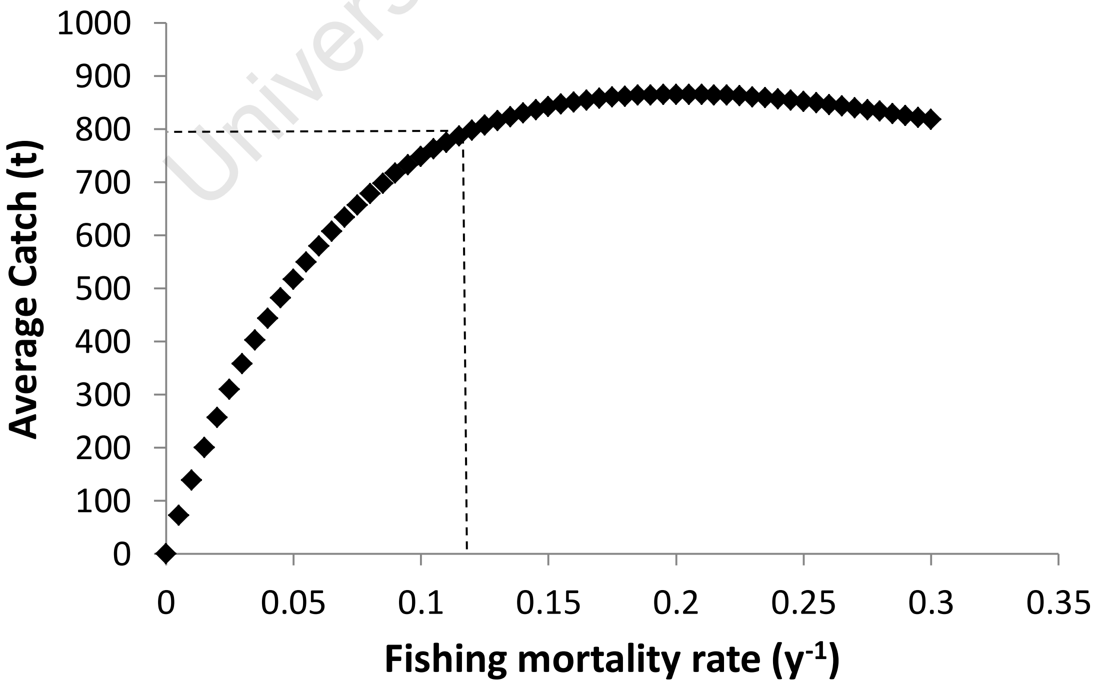

Figure 2: The projected average catch from 2013 to 2032 at different fishing mortality rates, showing F_{msy} and the corresponding MSY

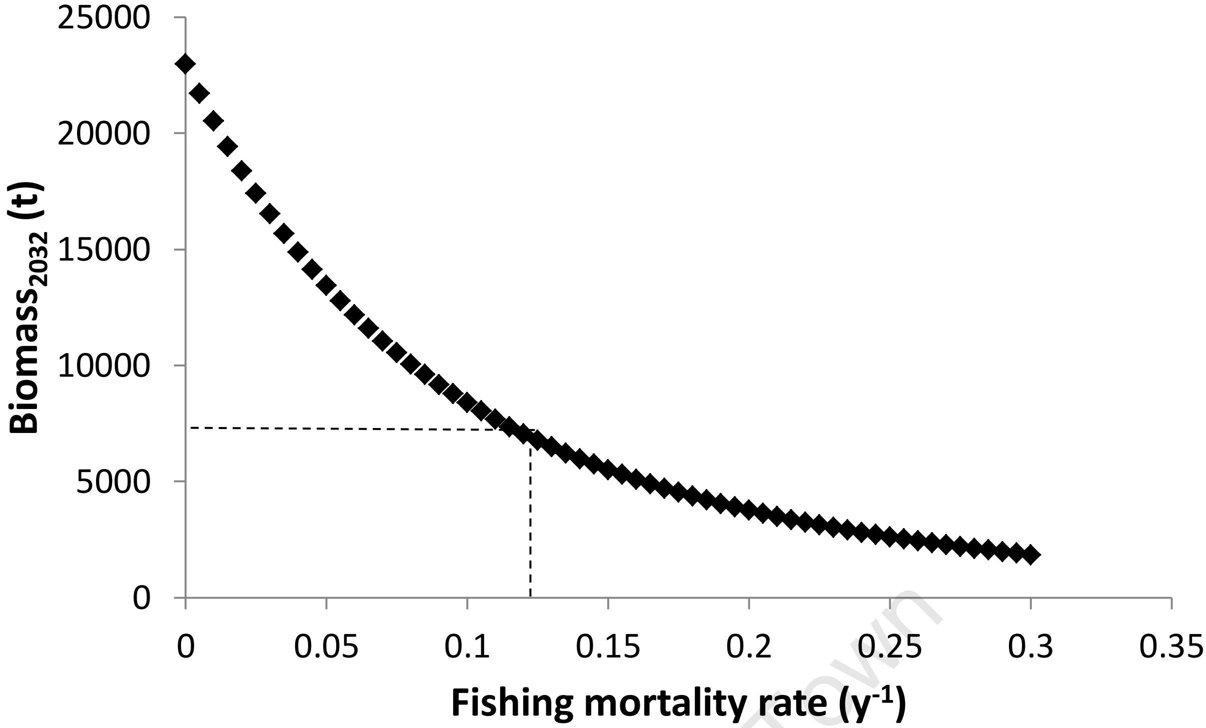

Figure 3: Projected biomass in the final year at different fishing mortality rates, showing F_{msy} and the corresponding biomass (B_{msy})

Total Allowable Effort

There is a greater penalty for undershooting than overshooting E_{msy} (Figure 4). The effort that results in the maximum sustainable yield (E_{msy}) is equal to 60000 Boat-Days.y^{-1} (Figure 4) and the number of boats that corresponds to E_{msy} is 300 boats. The higher values of effort are equal to 90000 Boat-Days.y^{-1} and 120000 Boat-Days.y^{-1} and the numbers of boats that correspond to these values of effort are 450 boats and 600 boats, respectively.

Minimum Size Limit

At E_{msy} with no closed season and with the default minimum size limit of 24.72 cm (the size that corresponds to age at first capture), the maximum projected average catch was equal to 797 t, but the biomass ratio was equal to only 0.97 (Figure 5). For the biomass ratio to be equal to one, the minimum size limit must be increased to 25.61 cm (Figure 5). When fishing at E_{msy}, this increase in the minimum size limit does not cause a change in the maximum projected average catch (Figure 5). At 1.5E_{msy} with no closed season, a minimum size limit of 27.72 cm resulted in the maximum projected average catch of 876 t (Figure 5). The biomass ratio was, however, not equal to one at this minimum size limit. The minimum size limit had

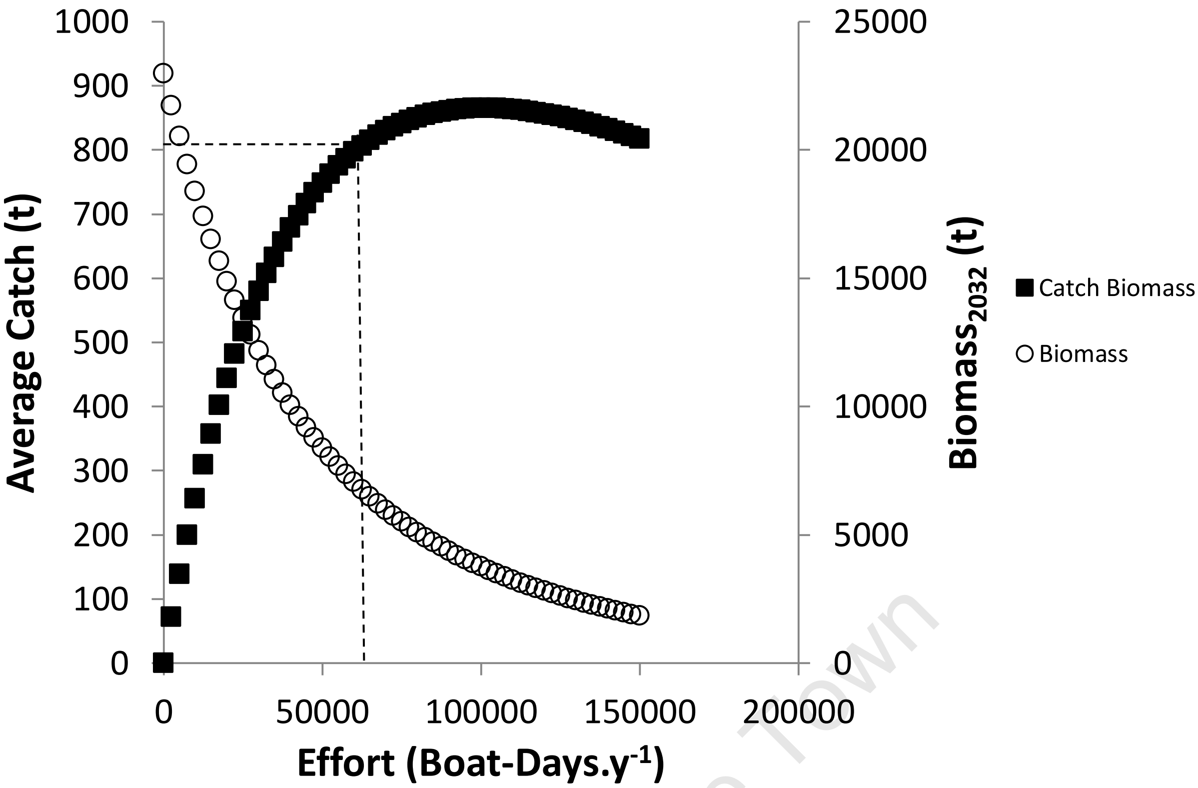

Figure 4: The projected average catch from 2013 to 2032 and the projected biomass in the final year over a range of values of effort, showing the effort that produces maximum sustainable yield (E_{msy}) and the corresponding catch (MSY)

to be increased to 30.48 cm to allow the biomass ratio to be equal to one (Figure 5). This increase in the minimum size limit resulted in a slight decrease in the maximum projected average catch to 862 t (Figure 5). At $2E_{msy}$ with no closed season, the maximum projected average catch was 911 t when the minimum size limit was equal to 29.71 cm (Figure 5). The biomass ratio was less than one at this minimum size limit and the minimum size limit had to be increased to 32.66 cm to allow the biomass ratio to be equal to one (Figure 5). This increase in the minimum size limit at $2E_{msy}$ resulted in a decrease in the maximum projected average catch to 887 t (Figure 5).

Closed Season

When fishing at E_{msy} at the default size limit of 24.72 cm, the projected average catch was at a maximum of 797 t, when there was no closed season (Figure 6). The biomass ratio was, however, only equal to one when a one month closed season was implemented (Figure 6). When a closed season of one month was implemented at E_{msy}, the maximum projected average catch was 774 t (Figure 6). When fishing at

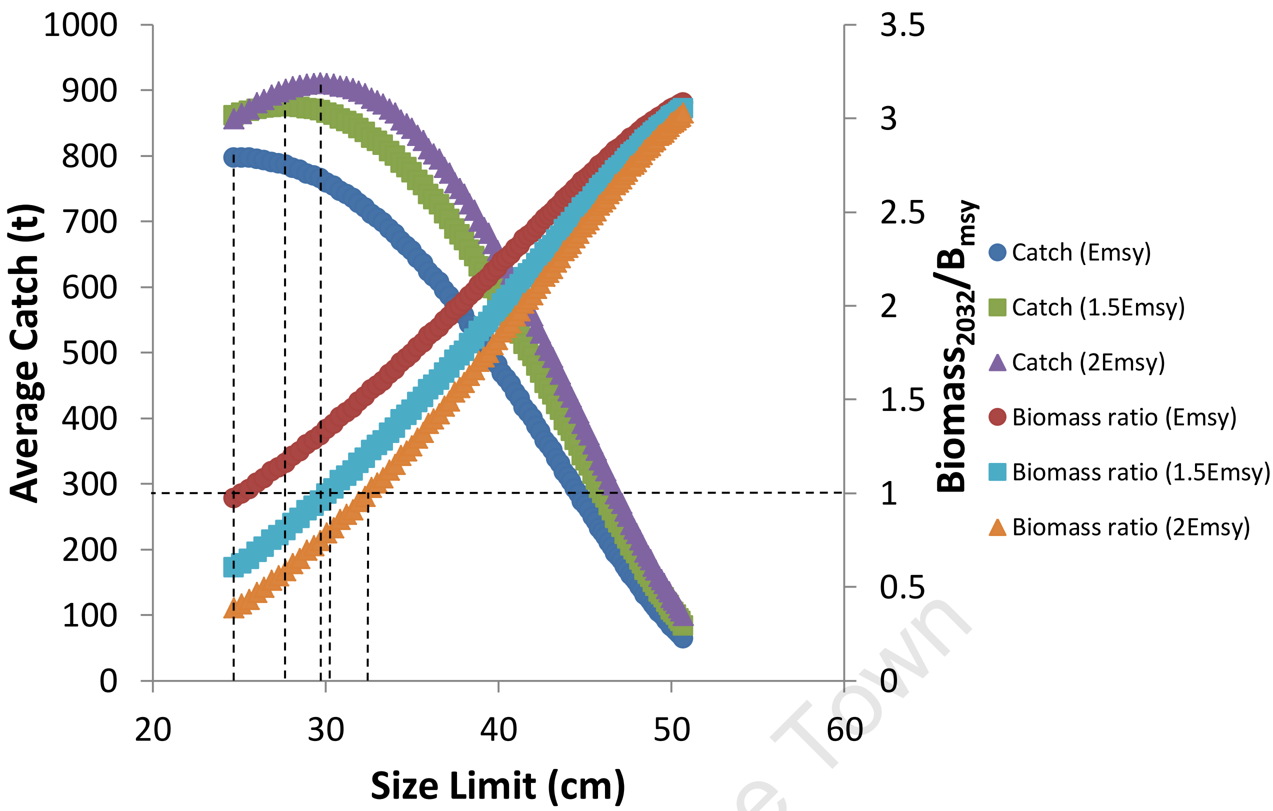

Figure 5: Projected catch from 2013 to 2032 for a range of minimum size limits for three values of effort and the biomass ratio for a range of minimum size limits for three values of effort, showing the minimum size limits that result in the biomass ratio being equal to one and the minimum size limits that correspond to the projected maximum catch for the three values of effort

$1.5E_{msy}$ at the default size limit of 24.72 cm, the projected average catch was at a maximum of 862 t when no closed season was implemented (Figure 6). When fishing at $2E_{msy}$ at the default size limit of 24.72 cm, the projected average catch was at a maximum of 860 t when a one month closed season was implemented (Figure 6). However, neither of these higher efforts allowed the biomass ratio to be equal to one (Figure 6). The maximum effort that allowed the biomass ratio to equal one, when a three month closed season was implemented, was 77500 Boat-Days.y^{-1}. This is equivalent to 388 boats.

Total Allowable Catch

When the default size limit of 24.72 cm was implemented and there was no closed season, the largest TAC that allowed the biomass ratio to be equal to one was 790 t (Figure 7). This TAC required a projected average effort of 61116 Boat-Days.y^{-1} which is equivalent to 306 boats (Figure 7). If the TAC was allowed to increase

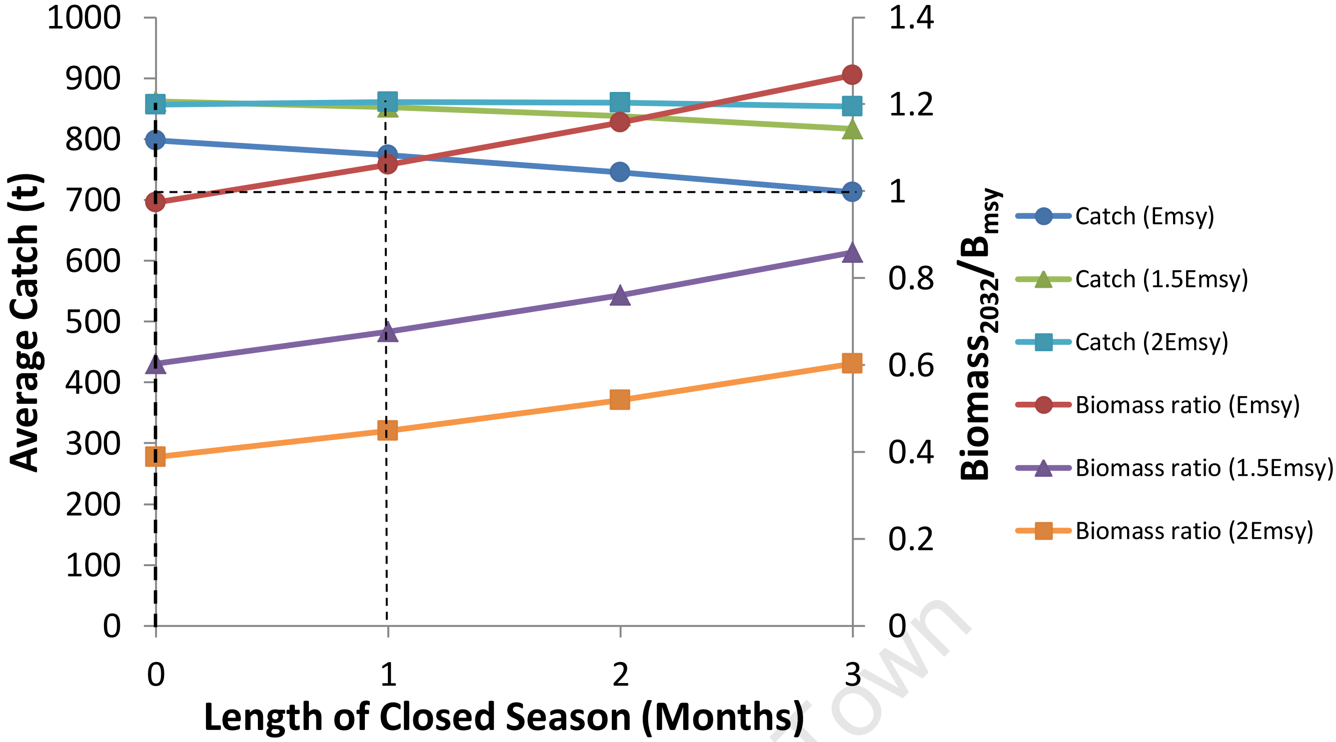

Figure 6: Projected average catch from 2013 to 2032 after the implementation of closed seasons of different lengths for three effort values, showing the projected maximum catch for the three values of effort. The biomass ratio after the implementation of closed seasons of different lengths for three values of effort, showing the lengths of the closed season that result in the biomass ratio being equal to one

beyond the point of 790 t, the biomass ratio would steadily decrease and quickly drop off to zero (Figure 7).

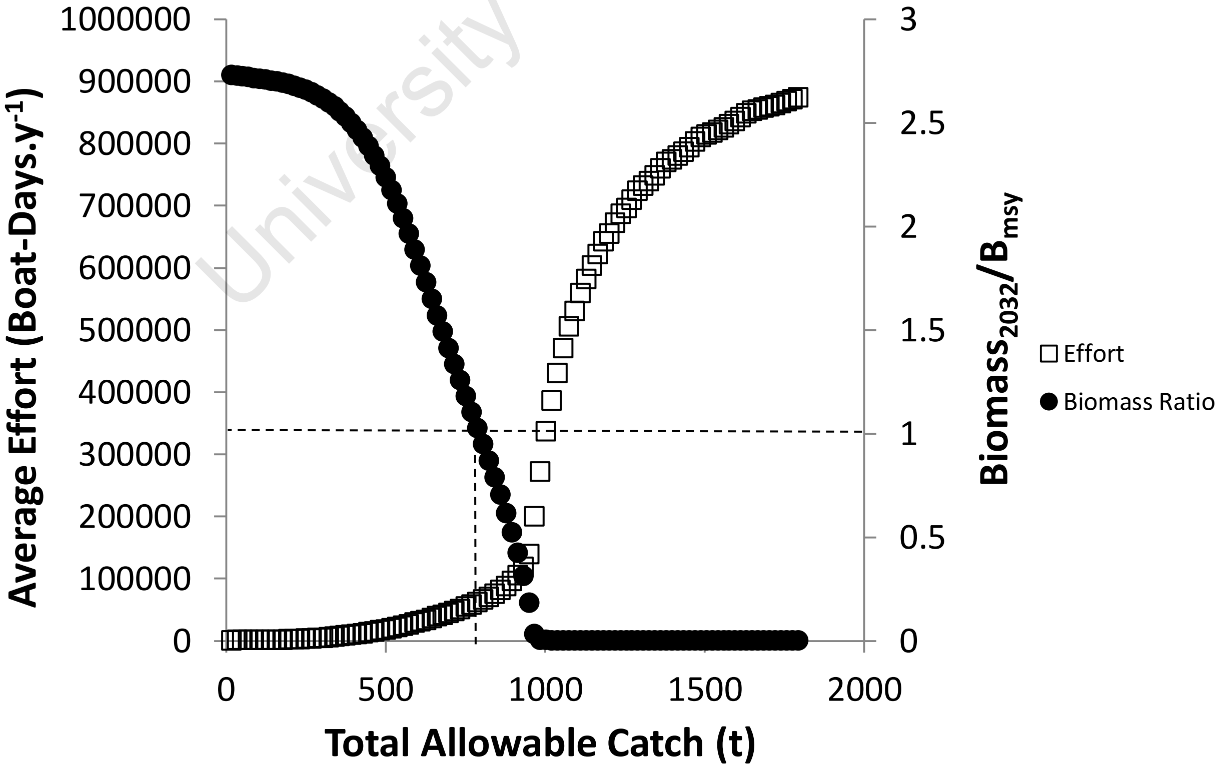

Figure 7: Projected average effort expended from 2013 to 2032 for a range of Total Allowable Catch quotas and the biomass ratio for a range of Total Allowable Catch quotas, showing the TAC that results in the biomass ratio being equal to one

Discussion

Fisheries are important commodities. This is especially true in South Africa where the linefishing industry alone is worth R2.2 billion per annum (Van der Lingen, et al. 2012). It is therefore important to manage fisheries effectively. Modelling is an important tool used to make informed recommendations regarding the effective management of fisheries.

In this study, the age-structured model indicates that the closed season strategy is less useful than the minimum size limit and total allowable catch (TAC) strategies for the management of the offshore Central Agulhas Bank carpenter fishery. The minimum size limit strategy, which has already been implemented for carpenter in the recreational sector, is useful as it allows smaller fish to become sexually mature and contribute to the spawner biomass of the stock. This strategy might need to be explored for the commercial sector, depending on the effort expended on this stock.

The target effort for all fisheries is the effort that results in the maximum sustainable yield (E_{msy}). For this stock, the E_{msy} is 60000 Boat-Days.y^{-1} with 300 boats. Since this is an ideal fishing effort, it is common for the actual effort expended on a certain fishery to be more or less than E_{msy}. For the offshore Central Agulhas Bank carpenter stock, the maximum projected average catch decreases more dramatically when fishing effort is less than E_{msy} than when it is greater than E_{msy}. The current fishing mortality rate ($F_{current}$) of 0.15 y^{-1} (Brouwer and Griffiths 2006) for this carpenter stock is greater than the fishing mortality rate of 0.12 y^{-1} that results in the maximum sustainable yield (F_{msy}). Given that effort can be equated to the fishing mortality rate using catchability (q), the current fishing effort ($E_{current}$) of 75000 Boat-Days.y^{-1}, exceeds the target effort, E_{msy}. This equates to 375 boats fishing this stock. Since the penalty for overshooting Emsy is not as great as for undershooting, it is predicted that this higher effort will not affect catch as badly as it might affect the recovery of the stock.

The effects of current fishing rates and practices can be considered by examining the model dynamics. The ratio of maximum sustainable yield to exploitable biomass (Ratio 2) is a low 0.124. This is however, a plausible value for the slow-growing, long-lived carpenter (Brouwer and Griffiths 2004), especially when compared to the faster-growing horse mackerel species that has a ratio of 0.3 (Attwood and Bennett

1990). The projected average catch at the current fishing mortality rate is 842 t. When replacing the maximum sustainable yield (MSY) in the ratio with this projected current catch ($C_{current}$), the resulting ratio is 0.116. Therefore, at the current fishing mortality rate, the harvest as a percentage of the exploitable biomass is almost 1% less than it could be at F_{msy}. When incorporated, the ratio of the maximum sustainable yield to the biomass at carrying capacity (Ratio 3) determines that at the current fishing mortality rate, 0.21% of the carrying capacity that is available for catching, is being left behind. This translates to an approximate 50 t of catchable biomass being left behind.

The ratio of the optimal biomass at a maximum sustainable yield (B_{msy}) to the biomass at carrying capacity (B_K) is 0.300 (Ratio 1). The same ratio was determined by Kerwath, et al. (2012), using the Schaeffer production model. This ratio is 0.5 by the Schaeffer production model (Attwood and Bennett 1990). In comparison to the ratio determined by Kerwath, et al. (2012), the ratio of 0.300 from this study is low. Since this model is age-structured, it differs from the Schaeffer model. It is expected that the age-structured model ratio will be less than the Schaeffer model ratio as the longevity of the fish (Brouwer and Griffiths 2004) influences the age-structured model. The projected biomass in the final year of the model at the current fishing mortality rate is 5513 t. When this biomass replaces B_{msy} in the ratio, the resulting ratio is 0.228. This ratio is higher than the ratio of 0.192 at which the model was initiated. It is however, much lower than the B_{msy} to B_K ratio of 0.300. At the current fishing mortality, the health of the stock improved by only 3.6% over two decades. Since the biomass of the stock must recover to a level of 30% of carrying capacity by 2032, the current fishing mortality is unsuitable for the recovery of the stock if no regulations are implemented.

Often in fisheries management, precedence is given to management strategies that allow for high fishing effort and/or a large harvest. Effort is a proxy for employment, as it dictates the number of boats in the fishery. Harvest can be used to determine profit, as the harvest is the final product that is sold. It is therefore reasonable to assume that the managers of the carpenter fishery will not want to downregulate the current effort to meet the target effort of E_{msy}, especially considering a total allowable effort allocation has already been implemented in the commercial sector of this fishery. This will require removing 75 boats from the carpenter fishery. The managers might even want to upscale the number of boats or effort in the fishery in order to create more jobs in the fishery. Additional, more practical strategies must therefore be suggested.

The model predicted that the current recreational minimum size limit of 35 cm is too high for the carpenter stock, even when fishing at an effort double that of E_{msy}. At an effort of 60000 Boat-Days.y^{-1} (E_{msy}), a minimum size limit of 25.61 cm is necessary to allow the biomass ratio of biomass in the final year to B_{msy} to return to one. When this ratio returns to one, it signals that the biomass in the final year has returned to B_{msy}. This is a non-negotiable target, as it allows the stock to return to a sustainable level. At an effort of 90000 Boat-Days.y^{-1}, a minimum size limit of 30.48 cm must be implemented to allow the biomass ratio to return to one. Since the current fishing effort of 75000 Boat-Days.y_{-1} is midway between these two points and is more likely to increase than decrease, a minimum size limit of 30.48 cm is proposed.

It is important to consider the drawbacks of implementing the minimum size limit strategy. The major problem with the minimum size limit strategy is the problem of barotrauma. Barotrauma damages the fish due to the large pressure changes when reeling in the fish. Most fish that are affected by barotrauma die, even after being released (Brouwer and Griffiths 2006). This causes the minimum size limit strategy to be less effective than predicted. The carpenter species has however been found to be resilient to barotrauma issues and a study done on this species found that most of the fish released, survived (Brouwer and Griffiths 2006). The minimum size limit strategy could be costly to implement and enforce (Jennings, et al. 2001). Since fish under the minimum size limit must be thrown back, this strategy could also be costly to the fishers who might have to fish harder for longer periods of time to acquire the same yield.

The maximum total allowable catch (TAC) projected by the model is 790 t. This projected TAC allows the biomass ratio to return to one and requires an effort of 61116 Boat-Days.y^{-1} which amounts to approximately 306 boats. The current effort and current number of boats exceeds this effort and will therefore need to be reduced. This reduction will be equivalent to removing approximately 69 boats from the fishery.

The TAC strategy also has a number of drawbacks associated with its implementation as a management strategy. The first problem with the TAC strategy is the high cost of implementation. There is also a large amount of administration that is required in order to control the weighing of the harvest and ensure that the harvest does not exceed the TAC. This strategy often leads to unnecessary discard of smaller or lower quality dead fish by fishers, while still out at sea. Therefore, TACs do not always directly control the catch and fishing mortality rate, but rather the actual landings of the fishers (Jennings, et al. 2001). TACs also tend to increase racing among the fishers in order to maximise their share of the TAC. This could lead to increased discard and unsafe fishing practice (Jennings, et al. 2001).

The closed season strategy is projected not to be as successful in managing the stock as the other two strategies. At the current fishing effort of 75000 Boat-Days.y^{-1}, a three month closed season would be required if fishing at a minimum size limit of 24.72 cm. When the fishing effort exceeds 77500 Boat-Days.y^{-1}, the closed season strategy is no longer successful in allowing the biomass ratio to return to one. This suggests that the closed season strategy will only be useful until the number of boats is increased by more than approximately 13 boats from the current number.

Even though closed seasons are able to protect species during specific, generally vulnerable, phases of their life history, there are also disadvantages to the closed season strategy. The largest problem with implementing this strategy as a management tool for the carpenter fishery is that it is a multispecies fishery. It would therefore be incorrect to allocate all the effort expended during a trip to this one species (Winker, et al. 2013). Implementing a closed season for only the carpenter species will mean that when fishers go fishing for other species and catch carpenter, the carpenter will have to be thrown back. This will increase the cost of and effort needed to acquire a certain yield. Barotrauma can also then be a problem. The other major problem is the effect on the market. At the beginning of the fishing season, there will inevitably be an oversupply of carpenter which will flood the market and can cause a drop in price (Jennings, et al. 2001).The processors of this species will also have to invest in equipment and staff that can handle a high capacity of carpenter. This investment in capacity might then be idle for the rest of the year. Before plausible fisheries management strategies can be obtained, the aforementioned concerns need to be taken into consideration. In order to maximise the effort and/or the yield while still achieving the fixed target of the biomass ratio equalling one, the following options are available:

1) Impose a size limit of 30.48 cm in the commercial sector.
2) Implement a TAC of 790 t and reduce the current effort by 18.51%.
3) Introduce a three month closed season between January and March and do not allow the effort to increase by more than 3.33%.

If the first option is implemented as a management strategy, the projected catch is between 797 and 862 t for an effort of between 60000 and 90000 Boat-Days.y^{-1}. However, it is unlikely that effort will increase to 90000 Boat-Days.y^{-1}, as this is equivalent to 450 boats that will be focusing on the carpenter fishery only. In 2012 there were only 455 boats in operation in the entire commercial linefishery (Van der Lingen, et al. 2012). The higher projected catch of 862 t is therefore likely to be unattainable in the current state of the stock. Since a minimum size limit is already in place for the recreational sector of the carpenter fishery, the implementation of a minimum size limit in the commercial sector might be an easier, less costly process than if no size limit strategy was in place.

The second option, the TAC option, requires a decrease from current effort to the lower projected effort. The TAC is less than the maximum sustainable yield; whereas, the projected effort is greater than E_{msy}. This means that more effort is being expended for less catch than if carpenter were being fished at F_{msy}. A decrease in effort also contradicts the aim of maximising effort. The TAC implemented by the model is a constant TAC over two decades. A more flexible TAC that changes as the stock starts to recover, could allow for an increase in effort and catch over time. TAC or quota regulation is often valuable in a multispecies fishery. Species that are not quota-regulated are often targeted instead of quota-regulated species (Attwood, et al. 2011).

The third option, the closed season option, is the least favourable of the three options. As mentioned, the closed season strategy is not always beneficial to the market. In South Africa, part of the projected closed season falls during the summer holidays during which the coastal areas fill up with people and the market demands in these areas increase. This strategy is also likely to increase the cost of fishing, yet is projected to produce the lowest yield of the three options. Effort is also restricted and cannot be maximised.

The overall recommendation for the offshore Central Aghulas Bank carpenter fishery is, therefore, a combination of option one and option two. The minimum size limit should be set at 30.48cm and a TAC of 790 t should be implemented. This TAC can be made flexible and increased as the stock recovers. These strategies should be implemented in conjunction with the total allowable effort (TAE) strategy that has already been implemented in the commercial sector of this fishery. This TAE strategy can therefore become more flexible, as the minimum size limit and TAC start to regulate the fishery, allowing the stock to recover.

The implementation of this overall recommendation is projected to achieve the target of the biomass ratio being one and the aims of maximising either effort or catch or both. However, if the carpenter stock varies hugely from its current state, the aforementioned options and recommendations might no longer be effective management tools. This is due to the limitation of the model. These limitations include a lack of stochasticity and possible errors in age of maturity and sex ratio distributions. This age-structured model is not stochastic which means that it does not allow for major random variations of the parameters of the stock. If the stock undergoes major variation, the model projections will no longer be adequate for the stock. Although no additional information or advantages might be discovered by integrating stochasticity into a model, future projects should attempt this integration. There are also possible flaws in the age of maturity and sex ratio distributions in the model. The age-at-50%-maturity of carpenter females is 3 years; whereas, the age-at-50%-maturity of carpenter males is 4 years. The model considers 4 years the age of maturity where individuals of that age or older become part of the spawner biomass, and the default minimum size limit starts. The model might therefore be underestimating spawner biomass. This will however, be a small underestimation, as 3 year old carpenter individual is not likely to constitute a large biomass contribution. The sex ratio of the carpenter stock has a slight female bias. Since the carpenter species is a late gonochoristic species, it is unexpected that the sex ratio of this species should deviate from 1:1 (Buxton and Garratt 1990). Brouwer and Griffiths (2005a) suggest that a reason for this is that male carpenters experience a higher mortality in heavily fished areas. It might therefore be beneficial for future models to take this slight deviation from the 1:1 sex ratio into account.

Even though the model used in this study has limitations, it is applicable to the stock in its current state and is useful to project future catch and effort values. It is also useful to project the effects of management strategies on the catch and effort values and on the stock as a whole. This does not mean that a model and its outputs can be used in isolation for the management of a fishery. Other complications and methods of regulation must also be taken into account, since attempts to manage fisheries could be compromised by other, unconstrained aspects of the fishery, such as trawl bycatch (Attwood, et al. 2011). Marine Protected Areas (MPAs) also make up an important component of linefish management and should therefore be considered when modelling a fishery (Van der Lingen, et al. 2012). This consideration is particularly important for this carpenter stock, as this stock produces approximately 90% of the reproductive output of the species. A model is therefore useful for fisheries management. It is used to make informed recommendations to management parties, but should always be considered in conjunction with other important factors pertaining to the stock.

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Appendix 1: A list of the symbol definitions and parameters used in the model to test the fishery regulation strategies

Symbol	Definition	Value	Unit
N_{init}	Initial estimates for numbers at age that result in 19.2% SB_K		
N_K	The sum of the numbers at age that result in SB_K		
N(a)	Numbers at age a		
SB_{init}	The initial value of spawner biomass read into the model	8481	t
B_K	Biomass when the population is at carrying capacity (K)	24129	t
$B_{0.20K}$	Biomass at 20% of carrying capacity	4826	t
$B_{current}$	Biomass at the current fishing mortality rate	5513	t
SB	Biomass (sum of biomass of fish ages 4 - 30 years) at the end of each year		t
R	Number of Recruits per year		
R_K	The recruitment from the spawner biomass at carrying capacity	3761530	
$R_{0.20K}$	The recruitment from the spawner biomass at 20% of carrying capacity	3084993	
α	Beverton and Holt Recruitment Curve steepness parameter	2.8435078	
Catch	Catch Biomass of fish at the end of each year		t
$C_{current}$	Current catch biomass at the current fishing mortality rate		t
β	Beverton and Holt Recruitment Curve density-dependence parameter	0.0000007145	
y	Year		
month	Month		
a	Age of fish		y
a_m	Age of fish on a monthly scale		y
M	Natural Mortality rate (Brouwer and Griffiths 2006)	0.1	y^{-1}
M'	Natural Mortality rate per month (M/12)	0.008333333	$month^{-1}$
F	Fishing Mortality rate	0.160120333	y^{-1}
F'	Fishing Mortality rate per month (F/12)	0.013343361	$month^{-1}$
$F_{current}$	Current Fishing Mortality rate (Brouwer and Griffiths 2006)	0.15	y^{-1}
q	The catchability of this carpenter stock (Kerwath, et al. 2012)	0.000002	$Boat\text{-}Days^{-1}$
E	Fishing effort		$Boat\text{-}Days.y^{-1}$
$E_{current}$	Current fishing effort	75000	$Boat\text{-}Days.y^{-1}$
L	Length of fish at age		cm
k	Von Bertalanffy Growth Rate Constant (Brouwer and Griffiths 2005a)	0.06	y^{-1}
L_{inf}	Von Bertalanffy Length at Infinity Constant (Brouwer and Griffiths 2005a)	61.9	cm
t_0	Von Bertalanffy Time Zero Constant (Brouwer and Griffiths 2005a)	-4.5	y
B	Biomass of fish at age		t
LW1	Length-Weight Relationship Parameter (Kerwath, et al. 2012)	0.00000002	
LW2	Length-Weight Relationship Parameter (Kerwath, et al. 2012)	2.924	
F_{msy}	Optimal Fishing Mortality rate that results in the Maximum Sustainable Yield	0.12	y^{-1}
MSY	The maximum sustainable yield (the optimal catch) for the year	897	t
B_{msy}	The optimal biomass when the stock is being fished at MSY	7242	t
E_{msy}	The effort used to fish until MSY	60000	$Boat\text{-}Days.y^{-1}$
A_{Lim}	The age limit of the fish allowed to be caught		y
S_{Lim}	The size limit of the fish allowed to be caught, corresponding to the age limit		cm