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A preliminary investigation into the effects of Indian Ocean MPAs on yellowfin tuna, *Thunnus albacares*, with particular emphasis on the IOTC closed area.

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1. Introduction

The Indian Ocean Tuna Commission (IOTC) is responsible for managing Indian Ocean tuna, including yellowfin tuna (*Thunnus albacares*) throughout the IOTC area of competence. The report of the IOTC performance review panel highlighted that it is necessary for IOTC to adopt the FAO Precautionary Principle which requires that management advice is based on the best scientific evidence, taking account of uncertainty (Anon, 2009). IOTC Resolution 10/01 established closed area management off Somalia (which we will refer to as the IOTC closed area) and requires that the Scientific Committee provide an evaluation of the closure and its impacts on yellowfin and bigeye stocks looking at catching of juveniles and spawners taken by all fisheries at its 2011 plenary session. Critically, the same Resolution also requires that the Commission adopts a quota allocation system or other relevant measure at its plenary session in 2012. Current management measures also include capacity (effort) controls (Resolution 09/02) and a ban on large scale drift nets on the high seas (Resolution 09/05). In the context of IOTC management of yellowfin tuna stocks, this paper will examine the effect of Indian Ocean closures on stock status, focussing on the potential impacts of the IOTC closed area.

Yellowfin tuna is a schooling species, located in tropical and subtropical oceanic waters. The tag recoveries of the RTTP-IO provide evidence of large movements of yellowfin tuna, supporting the assumption of a single stock for the Indian Ocean for management purposes (IOTC, 2009). Yellowfin tuna are exploited by a number of fleets in the Indian Ocean utilizing different gear. Purse seiners currently take the bulk (33%[2]) of the catch, followed closely by longliners (31%) (IOTC, 2011a).The most recent stock assessment of yellowfin tuna suggests that the stock is not currently overfished ($B_{2009}>B_{MSY}$, and spawning stock biomass was estimated to be between 31 and 38% of unfished levels), and that overfishing is not occurring ($F_{2009}<F_{MSY}$). Nevertheless, estimates of total biomass and spawning stock biomass have shown a marked decrease over the last decade, accelerated in recent years due to the high catches of 2003–2006. Recent reductions in effort have halted the decline, however there is still considerable uncertainty associated with the assessment (WPTT, 2011).

There is growing concern over the governance and conservation of pelagic resources globally. The use of Marine Protected Area (MPAs) to slow or reverse the decline in fish stocks and biodiversity in the oceans has been advocated in international policy documents, including the Plan of

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[2] gill net, 19.15%; line, 12.06%; baitboat, 4.27%; other, 0.56%. Source: IOTC Nominal Catch Database (averages 2005-2009).

Implementation of the World Summit on Sustainable Development (UN, 2002). Subsequently, there has been an increase in the number of marine areas protected globally. During 2010 three substantial closed areas were introduced in the Indian Ocean providing an opportunity to investigate the effects of large scale closures on yellowfin tuna. The closures were introduced with a range of objectives, not all related to fisheries management.

- The IOTC implemented seasonal closures in an area extending from the Somali Exclusive Economic Zone (EEZ) 0 ° - 10° North and 40° - 60° East (Figure 1). This area is closed to the longline fishery during February and the purse seine fishery during November (IOTC, 2010a). The IOTC closed area was the only one of the three established explicitly for fisheries management.
- In April 2010, the British government declared the Chagos EEZ a MPA, an area over 544,000 km^2 (Mangi et al., 2010). This MPA was created with aims related to biodiversity conservation and creating a scientific reference site within the region. The MPA, encompassing both coastal and pelagic areas, has doubled the area of ocean covered by MPAs worldwide and protects approximately half of the coral reefs in the Indian Ocean that are still classed as 'high quality'. There are about 10 Important Bird Areas, with some of the Indian Ocean's most dense populations of several seabird species. The area also includes undisturbed and recovering populations of Hawksbill and Green Turtles. Commercial fishing within 200 nautical miles of the islands ceased in November 2010, although recreational fishing is still permitted around the island of Diego Garcia (IOTC, 2009).
- The Maldivian government suspended all longline fishing licences in the outer EEZ (>75 miles) in March 2010, so this area is also protected from the longline fleet (IOTC, 2010b) This was implemented in order to limit the longline fishing effort for yellowfin and bigeye tuna, however, the government intends to introduce longline fishing by local fishermen in the outer EEZ of the Maldives (IOTC, 2011b).

It has been suggested that area closures might contribute to the replenishment of yellowfin stocks throughout the Indian Ocean (Koldewey *et al.,* 2010). However, there has been little research regarding the expected impacts of these closures on the highly mobile tuna species. This was highlighted in the 2011 Working Party on Tropical Tunas (WPTT, 2011), and the effectiveness of pelagic MPAs in protecting highly mobile species remains unclear (Game et al 2009; Kaplan et al, 2010). The majority of existing MPAs throughout the world have been primarily advocated to address specific, local-scale issues, whereas traditional fishery management has generally been employed to address regional-scale population issues (Greenstreet et al., 2009).Whether or not MPAs can deliver regional-scale management objectives, such as the fishery management objectives of IOTC, is much less certain (Greenstreet et al., 2009). While quota controls and alternative management measures are currently under consideration by the IOTC, it is crucial therefore that the impacts of the spatial closures on pelagic species are investigated in order to determine whether they can provide sufficient protection for the stocks, or whether additional measures are also required in combination with the MPAs.

It has been suggested that pelagic MPAs can be used to help protect highly mobile pelagic species as well as more sedentary, nearshore species as even for fish stocks which are only within the MPA for small proportions of their range, the overall fishing pressure may be reduced slightly which could allow for an increase of density and individual biomass which can lead to improved fitness and reproductive potential and so better recruitment to the stock (Murawski *et al.,* 2000; Game *et al.,* 2009; Grüss *et al.,* 2011). However MPAs are decreasingly effective with the increasing mobility of the adult or larval form of the species being protected (Apostolaki *et al.,* 2002, Martell *et al.,* 2005; West et al., 2009). This is mainly due to the limited time a highly mobile species spends within the MPA and the lack of protection against the impacts outside the MPA (Hyrenbach *et al.,* 2000). It has been argued that for an MPA to be effective for migratory species, it has to be of a very large size to cover a large proportion of the range of the species being targeted for protection (Martell et al., 2005). Stefansson and Rosenberg (2005) found that to reduce the probability of the spawning stock biomass (SSB) falling below the biomass threshold (the lower limit for the stock biomass, below which collapse is likely to occur), over 60% of the initial biomass needed to be protected and that to rebuild the stock without any other management strategies in place requires the protection of a very large percentage of the biomass. Dee Boersma and Parrish (1999) further suggested that on a global scale, MPAs may only be effective if they are substantively representative of all biogeographic zones (20% protection per zone). Another issue regarding MPA impacts is the concern that fishing may be displaced into other areas, resulting in an MPA potentially having no effect or causing wider ecological damage, depending on the effect of the redistribution (Roberts *et al.,* 2005).

A successful example of use of a pelagic MPA to conserve a migratory species was the closure of a section of the striped marlin fishery within the Mexican EEZ for three years, which provided benefits to the stock and a 240% increase in CPUE (Jensen *et al.,* 2010). Particular sites may affect the effectiveness of an MPA, such as targeting the protection of juveniles or spawning biomass, however, little work has been done to investigate the impacts of each.

This paper evaluates the effects of the network of protected areas in the Indian Ocean on yellowfin tuna. An age structured model is used to evaluate the effects of a number of scenarios principally related to the impact of the current IOTC and other closures, and extending the IOTC area closure year round. The model only considers the effects of the purse seine and longline (LL) fleets, which make up the majority of the Indian Ocean yellowfin tuna catch. Purse seine fleets were further separated into free school (FS) and FAD (LS) fleet categories to assess the effect of changes in the distribution of fishing mortality among age classes. The effect of the network of closures on fisher behaviour is uncertain, so for simplicity the scenarios tested here evaluated the two extremes that might occur: complete elimination of effort and total displacement of effort based on historic catches and effort in each area.

Scenarios tested:

Simulating the situation prior to the 2010 closures

1. *All areas open*

Simulating closure of the network with the current IOTC spatio-temporal closure

2. *Current network closure – catches eliminated*. IOTC area February for LL and November for LS and FS. Chagos catches eliminated all year (LL, FS and FS). Maldives EEZ catches (LL) eliminated all year.

3. *Current network closure - catches redistributed.* IOTC area catches redistributed in November for LS and FS. Chagos catches (FS and LS) redistributed (LL continue fishing in all areas).

Simulating closure of the network with year-round IOTC closure

4. *Network with IOTC closure all year - catches eliminated.* IOTC and Chagos areas catches eliminated all year (LL, FS and FS). Maldives EEZ catches (LL) eliminated all year.

5. *Network with IOTC closure all year – catches redistributed.* IOTC and Chagos area catches redistributed for LS and FS (LL continue fishing in all areas).

Longline catches could not be redistributed in scenarios 3 and 5 with the current model structure. However within the network area purse seine catches constitute 94% of the catch taken by the longline and purse seine fleets.

2. Methods

An age-structured simulation model of yellowfin tuna was developed based on data from the 2010 Indian Ocean yellowfin tuna stock assessment (Langley pers comm. 2011). Recruitment and fishing mortality were based on random sampling of previous years. The model was set up in quarterly time steps with 28 age classes and 24 fleet categories fishing 5 regions as defined in the stock assessment (Figure 2).

Population dynamics were represented by the standard equations for an age-structured fisheries population model (Equation 1 & Equation 2) where $N_{a,t}$ is numbers age a in time period t (both in quarters), $N_{a-1,t-1}$ is numbers in the previous age class and time step, M_{a-1} is natural mortality in the previous age class, $F_{a-1,t-1}$ is the fishing mortality in the previous age class (calculated in Equation 5) in the previous time step and $N_{a=28,t}$ is the plus group.

Equation 1
$$N_{a,t} = N_{a-1,t-1} e^{(-M_{a-1} - F_{a-1,t-1})}$$

Equation 2
$$N_{a=28,t} = N_{a-1,t-1} e^{(-M_{a-1} - F_{a-1,t-1})} + N_{a,t-1} e^{(-M_{a} - F_{a,t-1})}$$

Due to the weak relationship between SSB and recruitment, recruits were randomly sampled over all previous years. Fifty iterations were run to account for the variability inherent in historic sampling. Therefore the sensitivity of the stock biomass and other outputs to the sampled recruitment values is shown in the box plots displaying the outputs of these multiple model runs.

Spawning takes place between December and March (Langley *et al.,* 2010), so ¾ of annual recruitment was added in the first quarter of the year and ¼ in the last quarter of the year. The parameters maturity, natural mortality weight at age and selectivity were obtained from the 2010 stock assessment (Langley pers comm. 2011). Growth parameters were fixed at weight at age values that replicated the growth curve derived by Fonteneau (2008).

Total fishing mortality was randomly sampled based on historic data (1999-2009) but as the aim was to investigate changes in fishing mortality by fleet, these had to be calculated separately within the model. For each projected quarter, catches by fleet f at time t ($C_{f,t}$), total fishing mortality at age in each region at time t ($F_{t,a,r}$) and number of fish at age in each region ($N_{t,a,r}$) were randomly sampled from the corresponding quarter of the historic data . These data were used in Equation 3 to calculate the fishing mortality for each of the 24 fleets ($F_{f,t}$) multiplied by the selectivity at age for each fleet ($S_{a,f}$), estimated using a numerical root-finding algorithm. Age-specific mortalities were calculated based on time-invariant selectivities.

Equation 3 $$C_{f,t} = \sum_a \left(\frac{F_{f,t} S_{a,f}}{F_{t,a,r} + M_a} \right) N_{a,r,t} w_a \left(1 - e^{(-F_{t,a,r} - M_a)} \right)$$

where M_a is the natural mortality at age a and w_a is the weight at age a.

This method was followed for all fleets except for the long-line fleets. The catches for the long-line fleets were recorded in numbers so the fishing mortality of longline fleets ($F_{f,a}$)was calculated in terms of numbers using Equation 4.

Equation 4 $$C_{f,t} = \sum_a \left(\frac{F_{f,t} S_{a,f}}{F_{t,a,r} + M_a} \right) N_{a,r,t} \left(1 - e^{(-F_{t,a,r} - M_a)} \right)$$

Individual fleet fishing mortalities were summed and weighted by the number of fish in each region (Equation 5) to calculate the total fishing mortality.

Equation 5 $$F_{a,t} = \frac{\sum \left[N_{a,t,r} \sum_{f \in f,r} F_{f,t} S_{a,f} \right]}{\sum_r N_{a,t,r}}$$

where $F_{a,t}$ is the total fishing mortality at age a and at time t, $N_{a,t,r}$ is the numbers at age in region r and at time t, $\sum_{f \in f,r} F_{a,t,f}$ is the sum of the fishing mortalities of fleets for each region at age a and time t and $\sum_r N_{a,t,r}$ is the numbers at age a and time t and region r summed across all regions (Kleiber *et al.,* 2006).

To simulate a closure in which fishing effort was assumed to be eliminated, sampled purse seine and longline catches were reduced by the mean historic (1999-2010) proportion of catches that were taken by the corresponding fleets in that area in the corresponding quarter (IOTC 2011). Estimated fleet fishing mortalities ($\widetilde{F}_f$) and reduced fleet fishing mortalities ($\widetilde{F}^*_f$) were generated based on the original (C_f) and reduced catches (C^*_f) of each fleet from the approximations given in Equation 6, where B_f is the exploitable biomass for the fleet.

Equation 6 $$\widetilde{F}_f = -Ln\left(1 - \left(\frac{C_f}{B_f}\right)\right) \qquad \widetilde{F}^*_f = -Ln\left(1 - \left(\frac{C^*_f}{B_f}\right)\right)$$

The ratio of these estimated fleet fishing mortalities was used to scale the original fishing mortality by fleet calculated in the catch equation (F_f) to determine the reduced fishing mortality by fleet based on the area closure (F^*_f) (Equation 7).

Equation 7 $$F^*_f = F_f\left(\frac{\widetilde{F}^*_f}{\widetilde{F}_{f_e}}\right)$$

Mean total fishing mortality, $\overline{F}$ values reported in the results refer to the mean F_t from 2010 to 2030 (Equation 8).

Equation 8 $$F_t = \sum_a F_{a,t}$$

To simulate the redistribution of effort from inside to outside the closure, the predicted catches ($\hat{C}_f$) that would be taken with the same level of effort were estimated using the ratio of mean purse seine[3] CPUE inside ($CPUE_i$) and outside ($CPUE_o$) the closed area over the previous 10 years multiplied by the mean catches taken within the closed area during that quarter (Equation 9). Effort units were standardised based on 13hr fishing days. As the units of effort for the longline fleet could not be standardised, only purse seine fleets were considered in the redistribution scenarios.

Equation 9 $$\hat{C}_f = \frac{CPUE_o}{CPUE_i} C_{f,closedarea}$$

The CPUE could only be estimated for the purse seine fleet as a whole as effort was not reported separately for FAD and free school fishing. Therefore, the predicted catch ($\hat{C}_f$) that would be taken outside the closure for the same level of effort was then separated into free school and FAD catches based on the proportion of purse seine catches that were based on FADs and free schools outside the closed area.

The proportion of actual catches taken by each fleet within the closed area as a proportion of the total Indian Ocean catch by that fleet was then subtracted from the predicted catches that would be taken by each fleet as a proportion of the total Indian Ocean catch by that fleet to calculate the overall proportion by which each purse seine fleet catches should be adjusted, α_f. (Equation 10). These values are reported in (Table 4). Coordinate references selected to represent the approximate catches of each fleet within the networks of MPAs are given in Table 2.

Equation 10 $$\alpha_f = \left(\frac{\hat{C}_f}{C_{f,Indianocean}}\right) - \left(\frac{C_{f,closedarea}}{C_{f,Indianocean}}\right)$$

3. Analysis of results

For all scenarios, the stock biomass initially increased to a higher equilibrium. This is due to the fact that the fishing mortality is randomly sampled from historic values from 1999 and the mean of these values is lower than it was in 2010 (Figure 3a) therefore causing an apparent increase in biomass. Therefore the stock biomass remained above B_{MSY} ($2.15\text{x}10^6$ tonnes) in all simulations. For this reason, relative rather than absolute values form the focus of this paper. Thus, the effects of the extant

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[3] Catches were only redistributed for purse seine fleets as the longline effort data could not be standardised

network (scenarios 2 and 3) and the network with extended IOTC closure (scenarios 4 and 5) are all described relative to the baseline of no closure (scenario 1). This fishing mortality was distributed over the age classes resulting in a combined selectivity across fleets peaking at age 5, highlighting the high fishing pressure on young age classes (Figure 3b).

Scenario 2: Closure of network with current IOTC temporal closure (effort eliminated)

The longline catches of yellowfin tuna in the Maldives EEZ have historically been low (since 1999) relative to catches elsewhere in the Indian Ocean, so this closure had little impact on results. The highest reductions in fishing mortality relative to the scenario with no closures resulted from the removal of the purse seine fleet catches taken in the IOTC and Chagos areas. Total fishing mortality was marginally lower with the closures (0.868) than with no closures, resulting in a 54% probability of an increase in spawning stock biomass and the adult: juvenile ratio and a 56% probability of an increase in total biomass. Mean total catches across all fleets were reduced in 2030, associated with a 76% probability, but there was little change in the catches taken by free school and FAD associated purse seine fleets.

Scenario 3: Closure of network with current IOTC temporal closure (effort redistributed)

The redistribution of effort resulted in reduced fishing mortality on FADs compared with no closures due to the redistribution of effort outside the IOTC closed area, but a higher fishing mortality imposed by FAD fleets due to the redistribution of effort outside Chagos, so the overall impact on the distribution of fishing mortality across age classes was roughly stable (Figure 4). The mean ratio of adults to juveniles increased with a 56% probability, but stock biomass had a 64% probability of declining.

Scenario 4: Closure of network with year-round IOTC closure (effort eliminated)

Implementing the IOTC area closure throughout the year caused the biggest reduction in total fishing mortality (0.764) compared with no closures, with the main reduction in juvenile mortality (Figure 5). This resulted in an increase in the mean adult: juvenile ratio of 20.8% (±11.5) in 2030, with a 66% probability of increase. The mean spawning stock biomass in 2030 also increased 13.9% (±5), with a 76% probability of there being an improvement (Figure 6). This was associated with a 7.9% (±4.90) decline in total catch biomass. This decline was predominantly in the FAD fleet, whereas the free school catches showed a slight increase (Figure 7).

Scenario 5: Closure of network with year-round IOTC closure (effort redistributed)

Redistributing effort outside the IOTC closed area resulted in increased catches from purse seine fleets fishing on free schools outside the area in every quarter with a corresponding reduction in catches on FADs. However the increase on free schools reached a maximum of 106% increase in one quarter (Figure 7), whereas the maximum reduction in fishing on FADs only reached 38%, so the overall fishing mortality was slightly higher than the scenario with no closures (0.893) with relatively less of this targeted at juveniles (Figure 4). The ratio of adults to juveniles was 74% likely to decline, based on the redistribution, and there was little change in stock biomass, which was 54% likely to decrease with the redistributed effort.

4. Discussion

Considering first the extant situation in the Indian Ocean (network with seasonal IOTC closure), model results suggested that the current MPA network will have little impact on the status of stocks of yellowfin tuna whether effort is eliminated or redistributed. However, extending the IOTC area to a year-round closure within the network, and under the assumption that fishing effort was removed entirely resulted in the most beneficial conservation outcomes. This scenario resulted in the greatest reduction in total fishing mortality as well as a relative reduction in fishing mortality on lower age classes resulting in a significantly higher mean stock biomass in 2030 and recovery of older age classes. This is because the greatest reduction in fishing mortality occurred for purse seine fleets fishing with FADs in the IOTC closed area (Table 1). It has been suggested that MPAs placed in areas where juveniles are often caught could be beneficial in increasing juvenile survival and so recruitment into the spawning stock (Mees *et al.,* 2010, Grüss *et al.,* 2011a), and has been supported by a modelling study of bigeye tuna in the Pacific (Sibert et al.,2011).

Nevertheless, improvements were only recorded in scenarios based on the assumption of complete elimination of effort from all closed areas (i.e. no redistribution of effort to other locations). It is possible that overall effort may be somewhat reduced; a number of long-line vessels have already left the ocean due to the high threat of piracy and it has been suggested that a reduction in the area of ocean available for fishing may result in a decrease in fishing effort through vessel decommissioning (Koldeway *et al*., 2010). However, a more probable situation is that fishing would instead take place elsewhere in the ocean, and consideration of the impacts of this possibility is necessary for a precautionary approach to management of yellowfin tuna. Neither of the redistribution scenarios modelled here indicated any significant improvement in stock status relative to all areas remaining open, indicating the extent to which effort displacement can counteract the benefits (Baum *et al.,* 2003). This may also be partly because the network was only closed to purse seine fleets in the redistribution scenario. Therefore, the impact of the IOTC closed area may be greater than the results indicate. However, although artisanal gear types take a substantial proportion of total Indian Ocean yellowfin catch (~40%), there are zero historic catches reported in the IOTC database for the closed areas and therefore zero modelled protection afforded by the closed areas from fishing by these gear types. Artisanal catches would only be relevant to the IOTC area, as only purse seine and longline fleets were licensed to fish in Chagos prior to 2010, and the Maldives only licensed foreign longline vessels in addition to the domestic fleet. Furthermore, whilst the redistribution scenario only closed the network to purse seine gear, longline catches represent only 6% of total catch from within the network, and thus the greatest impact of the network is on purse seine catches (Table 5).

The catch removed from each area is also only accurate to the level of the data recorded, i.e., 1° x 1° for purse seine fleets and 5° x 5° for longline fleets. Therefore, coordinate references selected to represent the MPAs were necessarily approximations of the closed area boundaries dues to the scale of reporting. The model assumes a single stock structure, so there are no explicit assumptions about residency, rather the change in fishing mortality is based on previous catches within the closed areas. This method is simple enough to avoid the problems of the lack of information regarding exact movement patterns of the tuna. Furthermore, at the present time there are no fishery independent data or evidence from the Indian Ocean to verify an assumption that residency occurs. The tag recoveries of the RTTP-IO provide evidence of large movements of yellowfin tuna, supporting the assumption of a single stock for the Indian Ocean for management purposes (IOTC, 2009). If low or no residency is assumed this presents a more precautionary approach than the case where high residency is assumed.

The model was based on the outputs from the stock assessment conducted in 2010, which has a high degree of uncertainty associated with it, and therefore are translated into the model presented here. Nonetheless, this presents the best information currently available. There was also a high degree of uncertainty related to the modelled recruitment, which was based on historic estimates. Because of this, 50 iterations were run, resulting in the wide error bars. The assumptions regarding fleet dynamics here were highly simplistic, and incorporation of fleet dynamics to model the redistribution of fishing effort would provide a more realistic distribution of fishing effort, and the results presented here do not taken into account enforcement issues. For example, considering the case of the closure in the Gulf of Guinea introduced by ICCAT, due to lack of enforcement illegal fishing inside the area occurred and the MPA effectively broke down (Kaplan et al., 2009).

Nevertheless, despite the caveats, the results presented in this paper for yellowfin tuna are supported by similar results obtained through investigation into the effects of closures on bigeye tuna populations in the Pacific (Sibert et al., 2011). This modelling study used similar assumptions regarding the fleet dynamics and redistribution based on the average historic CPUE data and found that the beneficial effects of the closure on stock biomass were not detectable when effort was redistributed. With elimination of effort, benefits were apparent, but small which increased with the addition of another fleet to the closure (<4% and 7% respectively).

Game et al (2009) argued that MPAs represent a more precautionary approach to pelagic conservation than relying on other fishery management controls over a few species, however, based on these results, a precautionary approach to the conservation of yellowfin tuna would involve implementing additional management measures such as quotas or gear restrictions to be used alongside any closures. There is a danger that MPAs can generate a false sense of security if it assumed that they provide fisheries benefits as this may reduce the pressure for additional management measures (Kaplan et al., 2009), so it is prudent to not overestimate the impacts of the closures, particularly when they have been established to achieve a diverse range of objectives, not necessarily related to fisheries. The preliminary findings presented here suggest that the current network of closures alone is unlikely to achieve significant recovery of yellowfin tuna and a combination of management arrangements will still be required to be consistent with the precautionary principle.

5. Summary and Conclusions

A network of large scale closures with a range of objectives, not all related to fisheries, were introduced in the Indian Ocean during 2010, encompassing the region occupied by IOTC managed tuna fisheries. This paper examines the impact of the network of closures on the status of yellowfin tuna stocks compared to a baseline of no closures and discusses management options related to the precautionary principle. We examine the extant situation with the IOTC area closed for one month of the year each to the longline (February) and purse seine (November) gear, and a scenario where the IOTC area is closed all year for both the longline and purse seine fisheries. In both of these scenarios the Chagos and Maldivian closures also applied year round. We considered only the extremes of potential changes in fishing behaviour: complete elimination of effort that may have occurred inside the closed areas, and total displacement and redistribution of effort, based on historic catch and effort in each area. As redistribution of effort was only simulated for the purse seine fleet, modelling this with longline redistributed effort is an area for further work. There is also scope to refine this to account for a better understanding of fleet dynamics including potential infringements of the closed areas. Further research would also be useful to examine the ecological basis of the network; the IOTC area largely protects juveniles whilst the Chagos and Maldives areas protect a greater proportion of adults. Would additional areas be useful for fisheries management purposes?

We applied an age structured simulation model of yellowfin tuna populated with the best currently available information which, despite uncertainties, enables the provision of precautionary management advice in the absence of other data. Model results suggest that the extant network with only a two month IOTC closure has little impact on yellowfin tuna stocks either with the effort eliminated or redistributed. However, with a year-round closure of the IOTC area, the network could deliver conservation benefits improving the status of yellowfin tuna stocks under the assumption of total elimination of effort from the network area. Under the assumption that fishing effort was removed entirely, stock biomass increased, particularly in the larger age classes. However, in the scenario of a year round IOTC closure with effort reallocated evenly outside the area (for the purse seine fleet only) there was little impact on yellowfin stock status; with no change in biomass although a change in the age distribution of the population occurred due to the protection of juveniles in the IOTC area. Our findings are supported by a complementary study on the impact of Pacific closures on bigeye tuna (Sibert *et. al.* 2011).

Adoption of a precautionary approach to management requires us to consider that effort would be redistributed. This analysis suggests that neither the extant network of closures, nor a scenario where the IOTC closure is extended year round will provide sufficient management benefits for the protection of yellowfin tuna stocks. It would therefore be precautionary to supplement closures with additional management measures, either to reduce fishing effort, which as we have seen has the potential to provide conservation benefits, or to apply catch controls such as the quota allocation system required in Resolution 10/01.

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Table 1. Mean percentage changes in catch biomass of purse seine (FAD and free school, FS) and mean percentage change in catch numbers for longline (LL) fleets with each area closure. Estimated from the IOTC database from 1999 (IOTC, 2011a).

		Chagos closure (% change in catches)			**IOTC closure (% change in catches)**			**Maldives**
Scenario	Quarter	FAD	FS	LL	FAD	FS	LL	LL
4 IOTC (month), Chagos, Maldives eliminated	1	-4.51	-10.40	-0.58	-	-	-5.48	-0.13
	2	-	-	-1.38	-	-	-4.77	-0.35
	3	-	-	-3.59	-	-	-0.71	-0.44
	4	-0.78	-15.48	-4.14	-21.57	-8.97	-5.84	-0.53
5 IOTC (month), Chagos, Maldives redistributed	1	+10.37	+3.55	-	-	-	-	-
	2	-	-	-	-	-	-	-
	3	-	-	-	-	-	-	-
	4	+8.38	-7.67	-	-9.53	+1.90	-	-
6 IOTC (all yr), Chagos, Maldives eliminated	1	-4.51	-10.40	-0.58	-30.01	-4.54	-5.48	-0.13
	2	-	-	-1.38	-21.46	-2.97	-4.77	-0.35
	3	-	-	-3.59	-62.45	-4.66	-0.71	-0.44
	4	-0.78	-15.48	-4.14	-60.22	-12.99	-5.84	-0.53
7 IOTC (all yr), Chagos, Maldives redistributed	1	+10.37	+3.55	-	-24.12	+3.49	-	-
	2	-	-	-	-8.99	+12.44	-	-
	3	-	-	-	-18.92	+105.83	-	-
	4	+8.38	-7.67	-	-38.29	+34.99	-	-

Table 2. Coordinates used for selected areas. Of the 7 figure coordinates, the table below outlines the selected grid references used for each closed area

	Purse seine data		**Longline**				**Other**			
	Chagos	IOTC area	Chagos	IOTC area	Maldives	Maldives	Chagos	IOTC area	Chagos	IOTC area
Size	5	5	6	6	6	6	3	3	1	1
Quadrant	2	1	2	1	1	2	2	1	2	1
Latitude	2-9	0-9	0-5	0-5	0-5	0	0	0	0-5	0-5
Longitude	67-75	40-59	65-70	40-55	70	70	70	40-50	70	40-50

Table 3. Mean outputs in 2030 with 95% CIs.

	Scenario	Fishing mortality[4]	Stock numbers (millions)	Adults: juvenile ratio	Stock biomass (1000 tonnes)	Spawning stock biomass (1000 tonnes)	Total catch biomass (tonnes)
1	**All areas open**	0.899	275 (±16)	0.433 (±0.04)	3,885 (±122)	3,521 (±129)	98,998 (±6,670)
4	**IOTC (month), Chagos, Maldives closed - eliminated**	0.868	267 (±13)	0.474 (±0.05)	3,989 (±202)	3,658 (±205)	92,326 (±5,246)
5	**IOTC (month), Chagos, Maldives closed -redistributed**	0.903	250 (±19)	0.46 (±0.04)	3,631 (±173)	3,308 (±166)	91,872 (±6,209)
6	**IOTC (all yr), Chagos, Maldives closed - eliminated**	0.764	279 (±18)	0.52 (±0.05)	4,378 (±181)	4,009 (±176)	91,227 (±4,849)
7	**IOTC (all yr), Chagos, Maldives closed -redistributed**	0.893	286 (±16)	0.397 (±0.04)	3,809 (±131)	3,433 (±137)	95,483 (±5,776)

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[4] Mean total fishing mortality over projected years

Table 4. Differences (%) between mean values in 2030 for each closure scenario and the open scenario. 95% CIs are provided in the first set of brackets and the probability of the difference being positive is provided in the second set of brackets.

	Scenario	Fishing mortality[5]	Stock numbers (% difference)	Adults: juveniles (% difference)	Stock biomass(% difference)	Spawning stock biomass (% difference)	Total catch biomass (% difference)
2	**IOTC (month), Chagos, Maldives eliminated**	0.868	-3.23 (±4.64) (44%)	9.50 (±10.52) (54%)	2.66 (±5.21) (56%)	3.88 (±5.82) (54%)	-6.74 (±5.30) (24%)
3	**IOTC (month), Chagos, Maldives redistributed**	0.903	-9.13 (±6.75) (28%)	6.33 (±10.12) (56%)	-6.55 (±4.46) (36%)	-6.05 (±4.72) (40%)	-7.20 (±6.27) (36%)
4	**IOTC (all yr), Chagos, Maldives eliminated**	0.764	1.36 (±6.38) (38%)	20.81 (±11.46) (66%)	12.67 (±4.65) (76%)	13.86 (±5.00) (76%)	-7.85 (±4.90) (36%)
5	**IOTC (all yr), Chagos, Maldives redistributed**	0.893	3.997 (±5.91) (54%)	-8.28 (±9.65) (26%)	-1.96 (±3.36) (46%)	-2.50 (±3.88) (44%)	-3.55 (±5.83) (38%)

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[5] Mean total fishing mortality over projected years

Table 5. Mean monthly catches by gear type in metric tonnes from 1999-2009 (IOTC database, 2011). No catches by other gear types in these areas were recorded. Longline catches recorded in numbers were multiplied by the mean weight of an individual fish over the same time period (0.034t) to generate the biomass estimate

2	**Longline**					**Free school purse seine***				**FAD purse seine***			
month	Chagos	IOTC	Maldives	Total	protected	Chagos	IOTC	Total IO	protected	Chagos	IOTC	Total IO	protected
1	40	243	9	3549	8%	3086	963	15990	25%	242	92	845	39%
2	18	124	4	2894	5%	68	122	10515	2%	57	737	2386	33%
3	29	142	12	2696	7%	0	292	3812	8%	0	1163	3408	34%
4	24	243	11	2934	9%	0	17	2650	1%	0	456	2950	15%
5	50	163	18	2759	8%	0	79	2688	3%	0	277	1610	17%
6	29	31	8	1688	4%	0	249	6269	4%	0	713	2178	33%
7	48	32	4	1147	7%	0	185	7190	3%	0	1739	3487	50%
8	48	11	14	1226	6%	0	38	1234	3%	0	3884	5565	70%
9	55	17	9	1031	8%	0	227	1238	18%	0	4326	6880	63%
10	59	14	7	1066	7%	0	506	2738	18%	3	4548	7032	65%
11	76	54	10	1333	10%	116	1323	3372	43%	37	3043	5216	59%
12	70	227	8	2242	14%	2166	86	8633	26%	70	904	1858	52%

* mean catches from 1999-2006 (the most recent year available at the time of download: August, 2011).

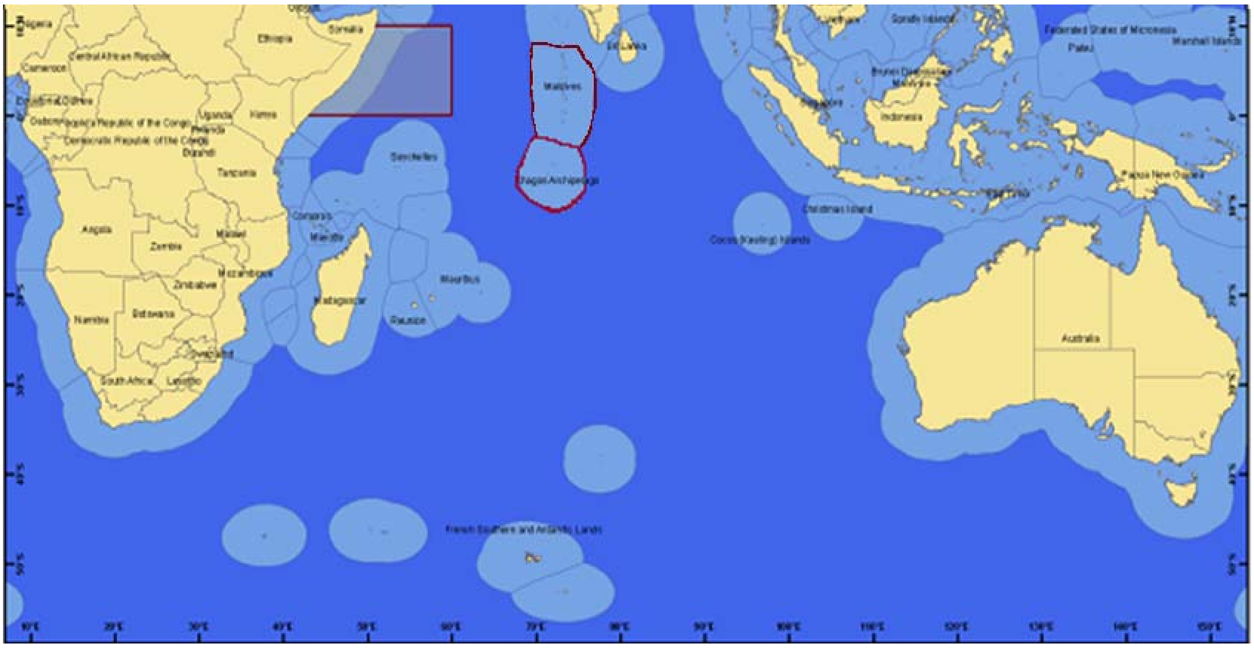


Figure 1.Location of the EEZs of Chagos and the Maldives and the IOTC closed area

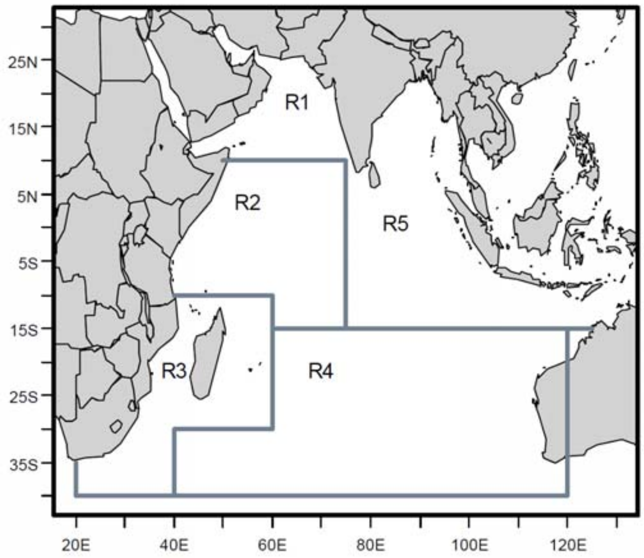
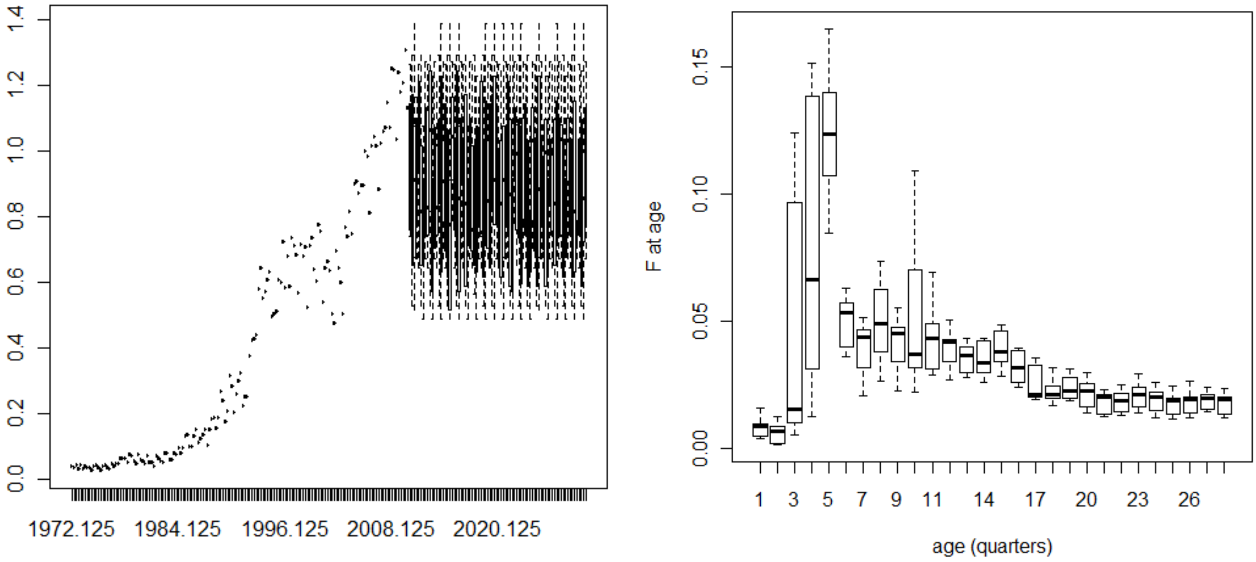


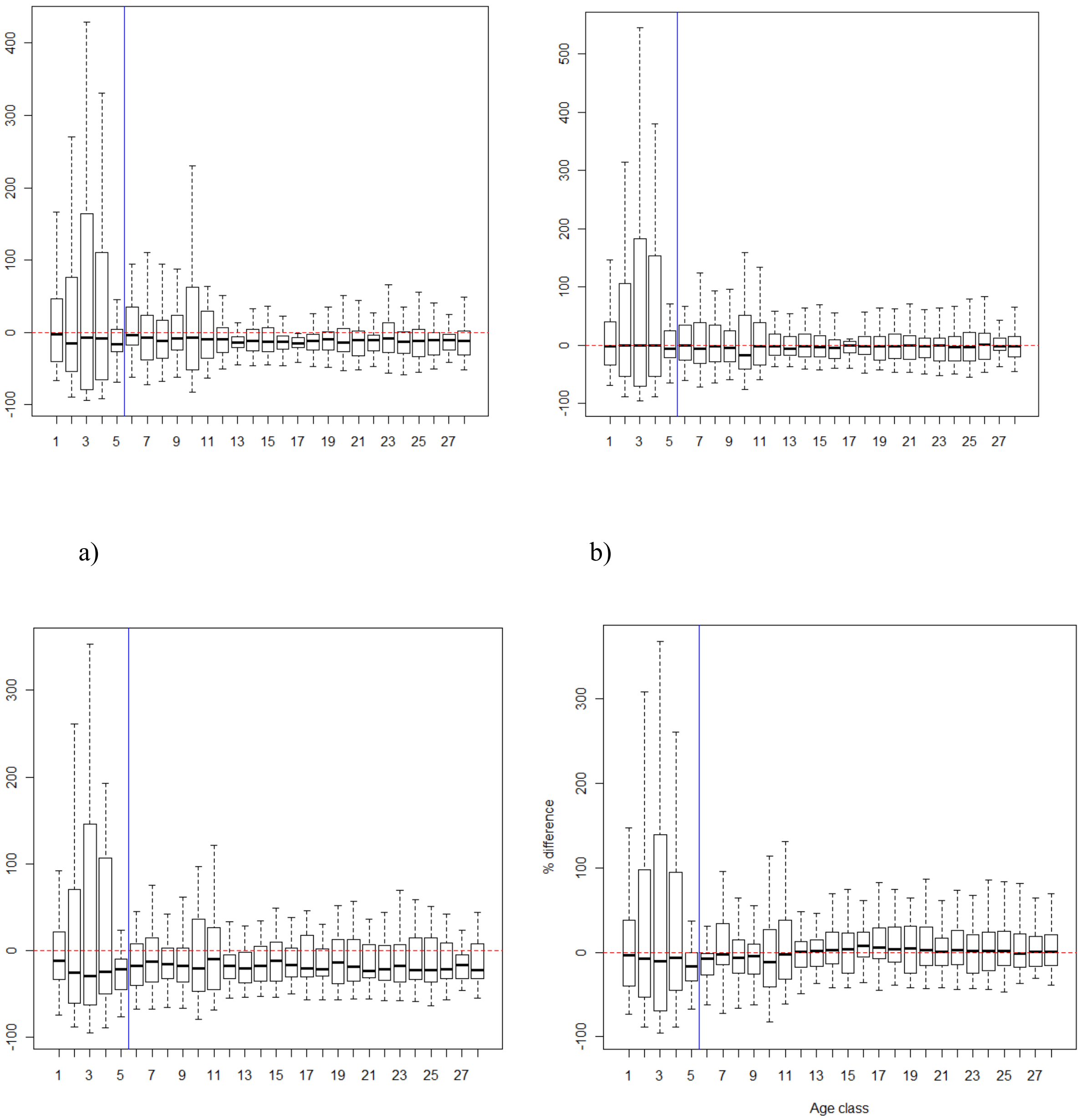
Figure 2. Spatial stratification of the Indian Ocean for the MULTIFAN-CL assessment (Langley *et al.*, 2010).



a)

b)

Figure 3: a) Total fishing mortality summed across all age classes over time (F_t) with all areas open; b) distribution of F over age classes when no area closures are in place.



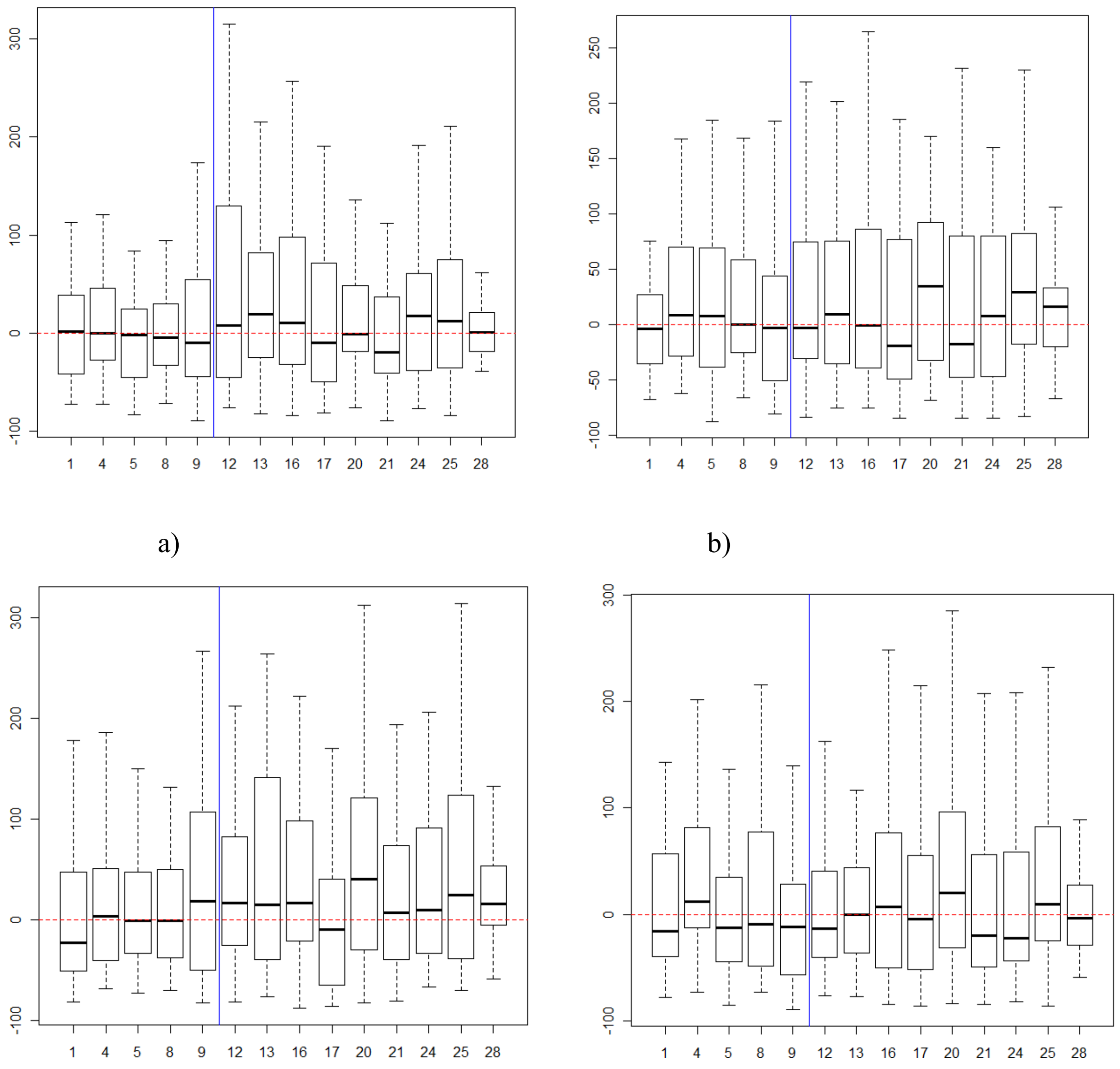
a)

b)

c)

d)

Figure 4. Difference (%) in fishing mortality-at-age for scenarios 2-5 (a-d). Age-at-maturity indicated by the solid blue line.



a)

b)

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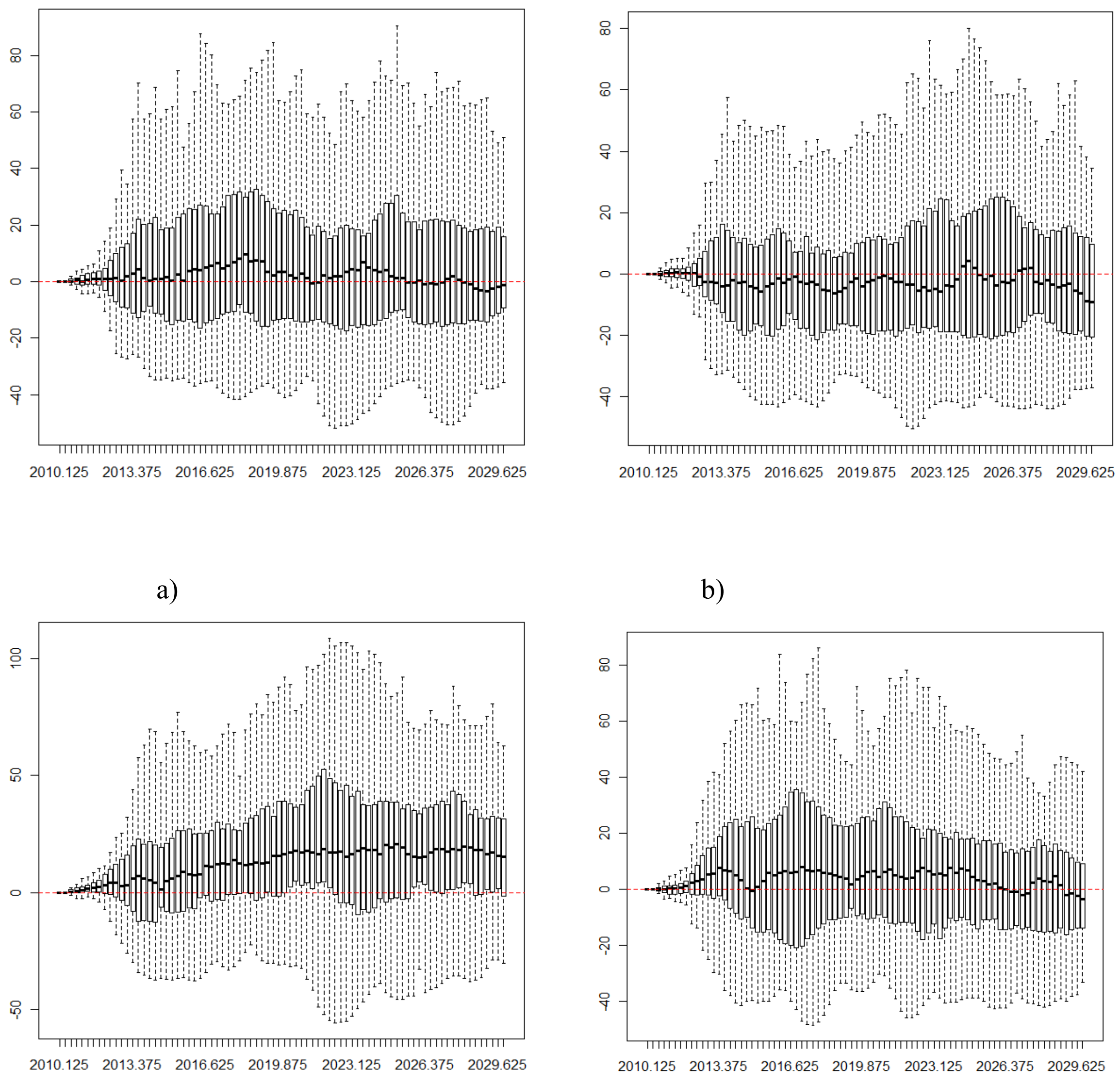
Figure 5. Difference (%) in the proportion of numbers at age, scenarios 2-5 (a-d)



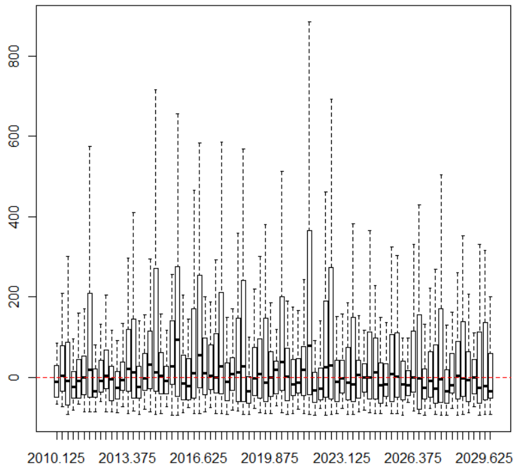
a)

b)

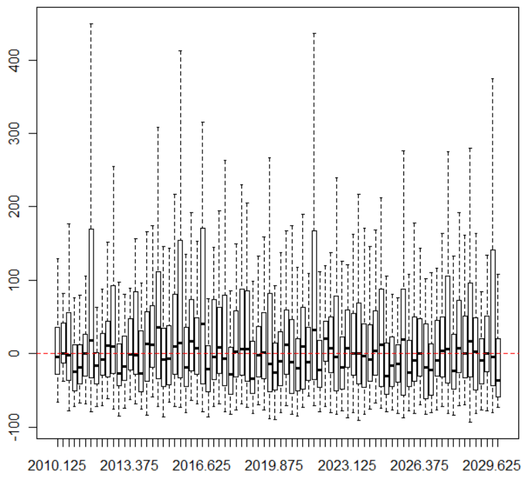
c)

d)

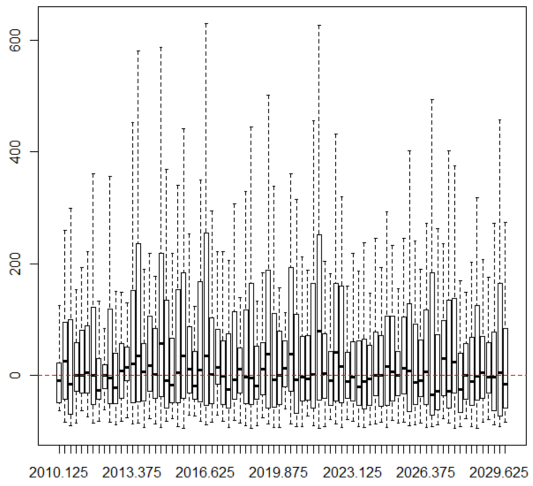
Figure 6. Difference (%) in spawning stock biomass for scenarios 2-5 (a-d)


800
600
400
200
0
2010.125
2013.375
2016.625
2019.875
2023.125
2026.375
2029.625

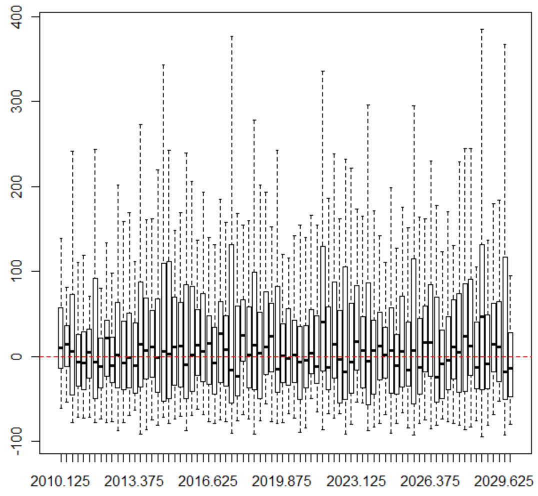
a)


400
300
200
100
0
-100
2010.125
2013.375
2016.625
2019.875
2023.125
2026.375
2029.625

b)


600
400
200
0
2010.125
2013.375
2016.625
2019.875
2023.125
2026.375
2029.625

c)


400
300
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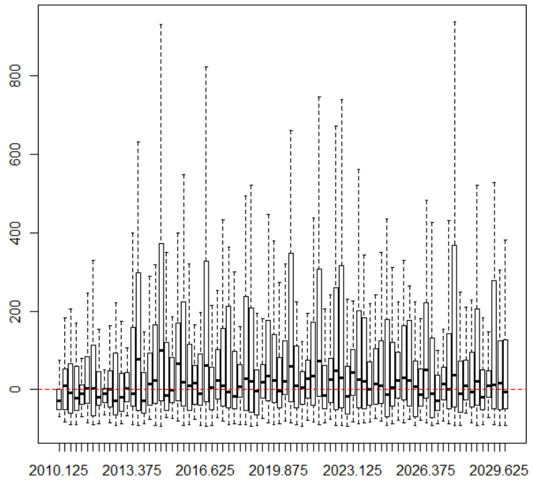
-100
2010.125
2013.375
2016.625
2019.875
2023.125
2026.375
2029.625

d)


800
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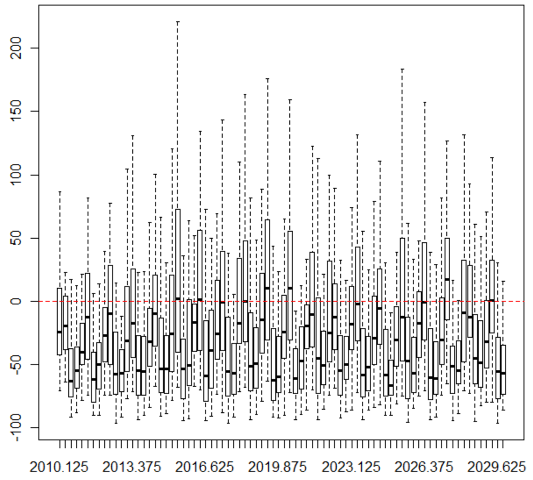
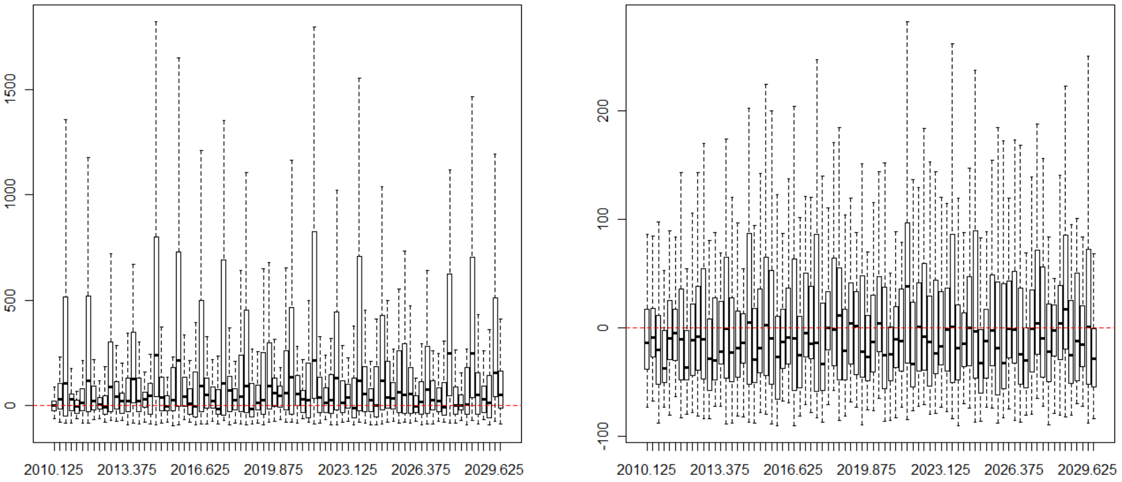
2010.125
2013.375
2016.625
2019.875
2023.125
2026.375
2029.625

e)


200
150
100
50
0
-50
-100
2010.125
2013.375
2016.625
2019.875
2023.125
2026.375
2029.625

f)



g) h)

Figure 7. Differences (%) in FS catches for scenarios 2-5 (a,c,e,g) and LS for scenarios 2-5 (b,d,f,h).