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EASTERN BLUEFIN TUNA (*THUNNUS THYNNUS*) MANAGEMENT USING A HARVEST CONTROL RULE BASED ON PRECAUTIONARY APPROACH AND MAXIMUM SUSTAINABLE YIELD PRINCIPLES

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SUMMARY

The behavior of several F_{target}s, (0.09, 0.15, 0.19 and 0.29), applying an ICES HCR to the E BFT stock are tested by making stochastic projections of 50 years to the 2012 assessment results, assuming a hockey stick S-R relationship, a Blim = 136000 t and a Bpa = 223000 t. To compare the performance of different Fs, trends in the probability of the Spawning Stock Biomass (SSB) to be below Blim, Bpa and on F to be above F_{target} are analyzed, together with the trends of the mean values of F, SSB, R and yield along the projected period. The results show that using of the proposed HCR whit a F_{target} in the range 0.09 to 0.15, combines the stability in the fishery, with a very low probability that the stock loses full reproductive capacity and with high long-term average yields that exceed between 17% and 31% those estimated by the SCRS for F_{01} in the "Medium Recruitment Scenario", Therefore it can be considered a better estimate of MSY. This strategy would stabilize long term SSB at similar levels to those recorded in 2012, which would be at around 0.78 and 0.48 the estimated values by the SCRS for F_{01} in the "Medium Recruitment Scenario". This implies that the SSB of stock already in 2012 next to the B_{MSY}. F0.19, although produces similar long-term yield, seem to give a wider variability on TACs which is not good for the fishery. Fs > 0.2, as 0.29, produce an oscillatory pattern in SSB, F and yields, which is associated with to higher risk of SSB to fall below Blim forcing fishery closures.

RÉSUMÉ

Le comportement de plusieurs Ftargets, (0,09; 0,15; 0,19 et 0,29), en appliquant une HCR de la CIEM au stock de thon rouge de l'Est est testé en faisant des projections stochastiques de 50 ans aux résultats de l'évaluation de 2012, en postulant une relation S-R de bâton de hockey, un Blim = 136.000 t et une Bpa = 223.000 t. Pour comparer les performances des différents Fs, on a analysé les tendances de la probabilité que la biomasse du stock reproducteur (SSB) soit en-dessous de Blim, Bpa et que F se situe au-dessus de Ftarget , ainsi que les tendances des valeurs moyennes de F, SSB , R et de la production le long de la période projetée. Les résultats montrent que l'utilisation de la HCR proposée avec un Ftarget de l'ordre de 0,09 à 0,15, combine la stabilité dans la pêcherie, avec une très faible probabilité que le stock perde la capacité totale de reproduction et avec une production moyenne à long terme élevée qui dépasse de 17 % à 31 % celles estimées par le SCRS pour F01 dans le "scénario de recrutement moyen". C'est pourquoi, elle peut être considérée comme la meilleure estimation de la PME. Cette stratégie devrait stabiliser la SSB à long terme à des niveaux similaires à ceux enregistrés en 2012, qui seraient autour de 0,78 et 0,48 des valeurs estimées par le SCRS pour F_{01} dans le "scénario de recrutement moyen". Cela implique que la SSB du stock était déjà en 2012 proche de B_{PME}. Même s'il produit une production similaire à long terme, $F_{0.19}$ semble fournir une plus grande variabilité au niveau des TAC, ce qui n'est pas bon pour la pêcherie. FS > 0,2, comme 0,29, produit un schéma oscillatoire dans la SSB, le F et les rendements, ce qui est associé à un risque plus élevé que la SSB chute en-dessous de Blim, ce qui obligerait à fermer la pêcherie.

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RESUMEN

Este trabajo, analiza el comportamiento del stock de atún rojo del Este, sometido a una regla de explotación de ICES y a diferentes niveles de mortalidad por pesca $F_{targets}$ (0,09, 0,15, 0,19 y 0,29) a través de proyecciones estocásticas a 50 años, de los resultados de la evaluación de 2012, asumiendo una relación S-R en palo de hockey, un B_{lim} = 136000 t y un B_{pa} = 223.000 t. Para comparar los resultados para las distintas F, se analizan las tendencias, durante el período proyectado, de que la biomasa reproductora (SSB) caiga por debajo de B_{lim}, de B_{pa} y de que la F se sitúe por encima de F_{target}, junto con las tendencias de los valores medios de las F, las SSB, los reclutamientos (R) y los rendimientos. Los resultados muestran que la utilización conjunta de la HCR propuesta y una F_{target} en el rango 0,09 – 0,15 combina la estabilidad en la pesquería, con una muy baja probabilidad de que el stock pierda la capacidad reproductora plena y con unos buenos rendimientos medios a largo plazo, que superan entre un 17% y un 31% a los estimados por el SCRS para F_{01} en el escenario de "reclutamientos medios", por ello pueden considerarse una mejor estimación del RMS. Esta estrategia estabilizaría la SSB a largo plazo en niveles similares a los registrados en 2012, que se encontrarían en torno a un 0.78 y un 0,48 de los valores estimados por el SCRS para F01 en el escenario de "reclutamientos medios". Esto implica que en 2012, la SSB del stock ya se encontraba en valores cercanos a B_{RMS}. Una $F_{0,19}$, *aunque produce rendimiento similar a largo plazo, parece dar una mayor variabilidad en los* TAC *que no es bueno para la pesquería. F> 0,2, como 0,29, producen un patrón oscilatorio en* SSB, F *y rendimientos, que está asociado a un mayor riesgo de SSB a caer por debajo de B_{lim} forzando el cierre de la pesca.*

KEYWORDS

Bluefin tuna, Reference points, Harvest Control Rules (HCR), Management

Introduction

Several international agreements on fisheries management promote a wide application of precautionary approach (*PA*) in fisheries management.

For instance, the United Nations Fisheries Stock Agreement (UNFSA) (UN, 1995) committed States and RFMOs to apply the *PA* widely in conservation, management and exploitation. In implementing the PA, States and RFMOs shall determine, on the basis of the best scientific information available, stock-specific reference points and pre-agreed conservation and management actions to be taken if they are exceeded (art. 6).

These benchmarks, referred by UNFSA are the limit reference points (LRPs) and they must be avoided with high probability.

LRPs could be related to stock fecundity (B_{lim}) or fishing mortality rate at which it is exploited (F_{lim}).

UNFSA also states that "The fishing mortality rate which generates maximum sustainable yield should be regarded as a minimum standard for limit reference points.

On the other hand, the World Summit for Sustainable Development (UN, 2002) states that "To achieve sustainable fisheries, the following actions are required at all levels: (a) Maintain or restore stocks to levels that can produce the maximum sustainable yield with the aim of achieving these goals for depleted stocks on an urgent basis and where possible not later than 2015".

In the determination of these *LRPs*, it must be taken into account that fisheries management must guard against recruitment overfishing. Thus one of their keys objectives is to maintain populations at levels where the biomass of adults does not limit the production of new young fish, although some types of overfishing (growth, localized and pulse) may be permissible (Mace & Sissenwine, 1993; Myers & Barrowman, 1996; Rosenberg 2003; Beddington *et al.,* 2007).

For stocks, for which quantitative information on stock status and reference points is available, ICES uses a harvest control rule (HCR) which combines the foundations of PA and MSY principles. The objective of this HCR is to exploit the stock at MSY level but imposes lower catch levels, or even zero catch, when the spawning stock biomass of the stock (SSB) is below some biomass reference points, which in general can be B_{pa} and B_{lim}.

ICES suggests that a limit spawning biomass reference point (B_{lim}) may be identified as the stock size below which there may be reduced reproduction resulting in reduced recruitment. A precautionary safety margin incorporating the uncertainty in ICES stock estimates leads to a precautionary reference point B_{pa}, which is a biomass reference point designed to avoid, with high probability, reaching B_{lim}. Therefore, when SSB is above B_{pa} the probability of impaired recruitment is expected to be low (ICES, 2012).

Once defined B_{pa} and B_{lim}, a Harvest Control Rule (HCR) needs to set pre-agreed management measures to be implemented if these limits are exceeded.

In this work we evaluated for Eastern Bluefin tuna (*Thunnus thynnus*) the HCR used by ICES under a Management Strategy Evaluation framework. The operating model (OM) was conditioned using the output of the 2012 assessment. For MSY target different levels were tested and *PA* reference points were defined based on historical development of the stock.

Material and methods

MSE approach was simulated using *FLBEIA* model (Jardim *et al*., 2013) in order to analyze the consequences of different fishing mortality targets, F_{target}s in the stock evolution of the Eastern Atlantic bluefin tuna during the next 50 years. The chosen target *F*s were: 0.09,0.15,0.19,029.

Two different conditionings were carried; one using the output of the assessment with reported catches and a second one using the output with inflated catches. Different scenarios were run using these two data sets. In both cases, for last three historical years medium level recruitment was assumed. 500 iterations from the assessment working group were taken but only 100 of them were chosen randomly and analyzed due to computational limitations, although not big changes were expected due to this. The stock was extended up to 50 age classes not to have a large plusgroup in the projections. In this way problems with the suitability of the weight at age in the plusgroup were overcome. The weight at age from age 10 onwards was parameterized using the length-age-weight relationships, and the maturity, selectivity and natural mortality was assumed constant and equal to that of age 10.

The population was projected from 2012 onwards using an exponential survival equation for existing age classes and a hockey stick stock recruitment model to generate yearly recruitments, considering it is more cautious than a Ricker model, although the best *S-R* fit for both “Inflated” and “Reported” assessment results were obtained using Ricker models (*de Cárdenas*, 2014).

The stock recruitment parameters were estimated from historical data and for each iteration a different set of parameters was obtained. Besides a log-normal error was multiplied to the point estimate, in each year and iteration, this error had median equal to one and the standard deviation was equal to the one observed in the historical period (0.507).

Management procedure model

It was not considered any assessment and therefore, in the observation model it was assumed that the stock status (numbers and fishing mortality) was known without error. The only difference between the population in the OM and the one in the MP was derived from the time lag between the assessment and the management. In year y, when the TAC for year y+1 was generated, the population was observed up to year y-1. Then the observed population was projected up to 1st January year *y+1*, assuming a geometric mean recruitment for years y and y+1 (of the previous 10 years to the year y) and assuming a fishing mortality equal to *Fsq* in year y and a selection pattern in years y and *y+1* equal to the average selection patterns in the last three observed years.

The HCR used to generate the annual TAC was that used by ICES in the MSY framework. The HCR is shown in **Figure 1.**

B_{lim}, the limit spawning biomass reference point, should correspond with a stock size below which there may be reduced reproduction resulting in reduced recruitment. It was not possible to identify any *SSB* point in which there may be reduced reproduction resulting in reduced recruitment for this stock; in fact it seems that the highest recruitments appear at the lowest *SSB*s in both reported and observed series. So B_{lim} was estimated as the average of the reported and inflated series $B_{loss.}$. This approach lead to a B_{lim} = 136.000 t (*de Cárdenas, 2014*).

A precautionary safety margin incorporating the uncertainty in stock estimates leads to a precautionary reference point B_{pa}, which is a biomass reference point designed to avoid, with high probability, reaching B_{lim}. Therefore, if the reference points were adequately selected, when *SSB* is above B_{pa} the probability of impaired recruitment would be low (ICES, 2012).

Cadima (2003) suggest in determining B_{pa}, to estimate B_{lim} and from these apply the empirical rule:

$$B_{pa} = B_{lim} * e^{1.645 * \sigma}$$

The results obtained in various fisheries indicate values of σ in the interval 0.2 - 0.3 (ICES, 1997). In practice, by applying this approach, B_{pa} may be found in the range between $1.39 * B_{lim}$ and $1.64 * B_{lim}$. This approach lead to a *Bpa* placed in the range 189 000 t – 223 000 t (de Cárdenas, *2014*).

The management measures to be tested worked at follow (**Figure 1**):

$$F_{y+1} = \begin{cases} Ftg & SSB > Bpa \\ Ftg \times \dfrac{SSB_{y+1} - Blim}{Bpa - Blim} & Bpa < SSB < Blim \\ 0 & SSB < Blim \end{cases}$$

Long-term average figures for each variable analyzed are presented as the average of projected results for three periods (2025-60, 2035-60 and 2045-60).

Results and discussion

General view

The projections tend to underestimated SB at the beginning of the period, which is translate in an underestimation of TAC for the next year, producing a smaller Fs than expected when the TAC is caught. This problem is gradually reduced and the general pattern for different Fs could be considered fixed after 2030.

Target Fs in the range 0.09 – 0.15 combine stability in the fishery, with high long-term yields.

$F_{0.19}$, although produces similar long-term yield, seem to give a wider variability on TACs which is not good for the fishery.

$F_{0.29}$, and greater produce an oscillatory pattern in *SSB*, *F* and yields, which is better to avoid (**Figure 2**).

How the HCR works in relation with F (Figure 3)?

F, in median, was always (except in the scenarios were F_{target} = 0.09) below the predefined target. This occurred because the probability of being below B_{pa}, in all these scenarios, was above 30% and increase as *F* rises (**Figure 4**), hence the *F*-advice used to generate the TAC was, in more than 30% of the iterations, below F_{target}. This fact together with the uncertainty derived from the time lag between the data-year and the TAC-year resulted in a true fishing mortality below the target in more than 50% of the iterations.

*F*s generated in the 2 first projected years are quit smaller than expected; taking into account that SSB in 2012 is well above B_{pa}. A possible explanation for these low *F*s could be the 'time lag' between the moment in which the assessment takes place and when the catch occurs, combined with huge increase in SB taking place at that moment. In the model, the TAC for the year '*y*', is calculated using data up to 'y_{-2}', as happens in reality. In this case there is a huge growth in the SB during the first year, which is not taking into account in the management, since in the year y_{-1} it is assumed that everything will be more or less as in the prior status quo, so the *SB* at the beginning of the year and the resulting TAC are sub estimated. So to catch the TAC in year, the resulting *F* is lower than expected. As the SB is stabilizing, the difference between the SB used in the management model and the real in the operational model decreases and so the *F* converges increasingly to F_{target}, whenever we are above *Bpa*.

*F*s below 0.2 progressively reach stability with time and remain more or less at the same level from 2030 onwards.

Fs greater than 0.2, reduce SSB below B_{lim}, with more than 50% probability, meaning fishery closures, this produces an oscillatory pattern in SSB which is translated by the *HCR* to *Fs* **(Figure 3).**

The probability that *F* exceeds F_{target} in a given year increases with time. It remain at low level (<20%) for F< 0.2. The probability for *Fs* higher than 0.2, presents an oscillatory pattern (**Figure 5**).

How good is the HCR to prevent recruitment overfishing?

Spawning Stock Biomass

Long term equilibrium *SSB* is reached about 2030 for fishing mortalities below *0.2*. As *F* increases, the risk of *SSB* to falls below *Bpa* rises, this is the case of $F = 0.29$, where *SSB* decrease dramatically in the short time, nevertheless, when it falls below *Bpa* the *HCR* works reducing *F* progressively, as *SSB* approach *Blim*. As result of *F* reductions *SSB* increase again above *Bpa* in the following years and *F* recover its target value, reducing SSB again. This produces a characteristic oscillatory pattern (**Figure 6**).

The long term equilibrium average SSB for $F_{0.09}$ or $F_{0.15}$ are between 0.78 and 0.49 (Reported) or between 0.73 and 0.49 (Inflated) the values proposed by the SCRS as B_{MSY} in the “Medium Recruitment Scenario” (**Table 1**). The SSB in 2012 was between 0.87 and 1.98 times the long-term equilibrium average SSB reach for target *Fs* between 0.09 and 0.15 (**Table 2**).

The HCR, combined with *Fs* lower than 0.2 demonstrate that it works very well to prevent recruitment overfishing, as the probability for *SSB* to fall below B_{lim} is very low (near 0). Above this level, probably increases and the HCR reproduce the oscillatory pattern observed in *SSB*s (**Figure 7**).

Recruitment

Since the probability of falling below B_{lim} is very low for *Fs* lower than 0.2, the stock will maintain its full reproductive capacity over the time and recruitment will fluctuate randomly at these mortality levels. However, for *Fs* greater than *0.19*, the likelihood of *SSB* to be below B_{lim} increases in an oscillatory way, thus the line for $F = 0.29$ runs slightly below the rest. This is clearer in the “Inflated” scenario (**Figure 8**).

Yield

It very difficult to say anything about short-term projections taking into account the uncertainty associated to the assessment (ICCAT, 2013). Having said that, the projected catches increase in the range 1.31 to 2.16 in the first year projected for $F_{0.09}$ and $F_{0.15}$, remain at this level in the second year and sharply increase in the thirst reaching gradually the long term equilibrium afterward which is get about 2030.

The long-term average equilibrium yield produced by target *F*s in the range 0.09 - 0.15 are about 36.000 t in the “Reported” scenario and 48.000 t in the “Inflated”, which are between a 1.16 or 1.33 times the maximum sustainable yield estimated by *SCRS* for the “Medium Recruitment Scenario” (**Table 3**).

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Table1. SSB used as possible B_{MSY} reference point for E. BFT (ICCAT, 2013).

$SSB_{F0.1}$		
Low recruitment scenario (1970s)	318,500 t	342,500 t
Medium recruitment scenario (1950-2006)	452,500 t	524,100 t
High recruitment scenario (1990s)	774,700 t	1,087,000 t

Table 2. SSB_{2012}/long term average SSB ratio for target Fs at 0.09 and 0.15.

Reported	*SSB*	*2012/long term*
2012	302103	
Long-term F0.09	346033	0,87
Long-term F0.15	223254	1,55

Inflated	*SSB*	*2012/long term*
2012	498300	
Long-term F0.09	383838	1,30
Long-term F0.15	252180	1,98

Table 3. Maximum sustainable yield estimated by SCRS for different scenarios (ICCAT, 2013).

	Reported catch	Inflated catch
Maximum Sustainable Yield[1]		
Low recruitment scenario (1970s)	21,500 t	23,370 t
Medium recruitment scenario (1950-2006)	30,700 t	35,900 t
High recruitment scenario (1990s)	52,900 t	74,900 t

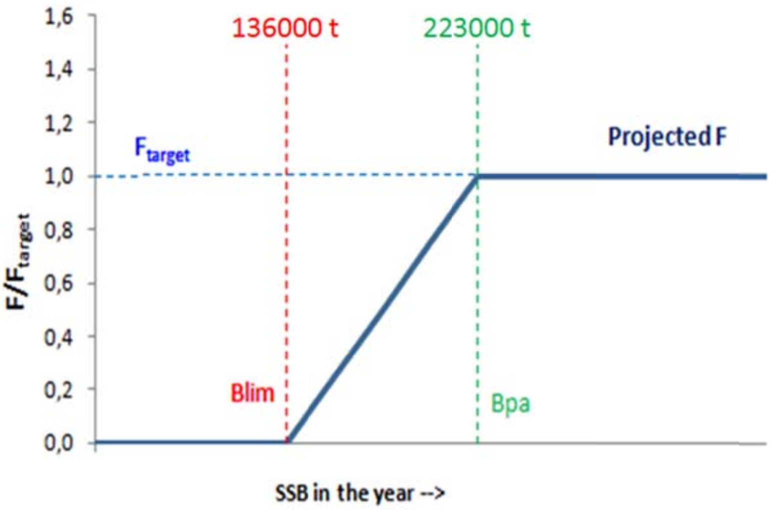


Figure 1. Projected F for the next year in relation with the current SSB.

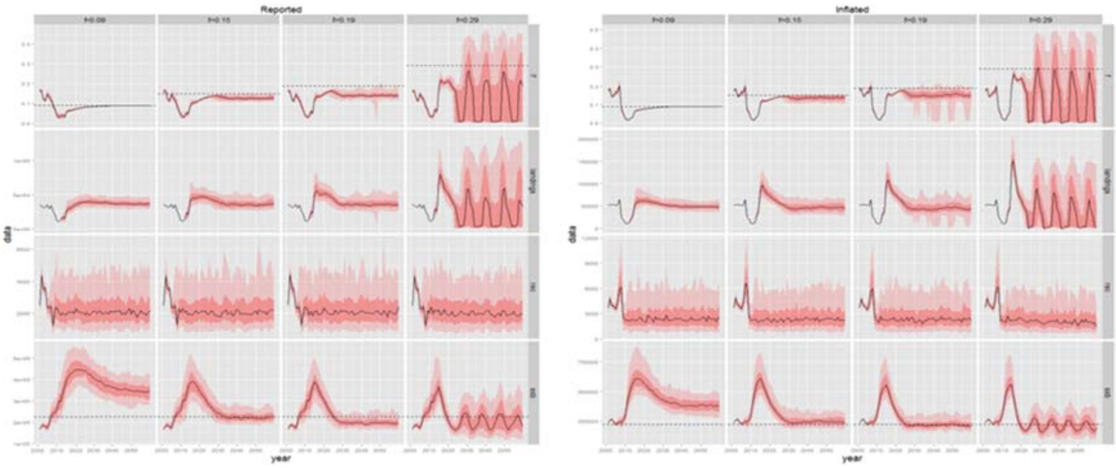
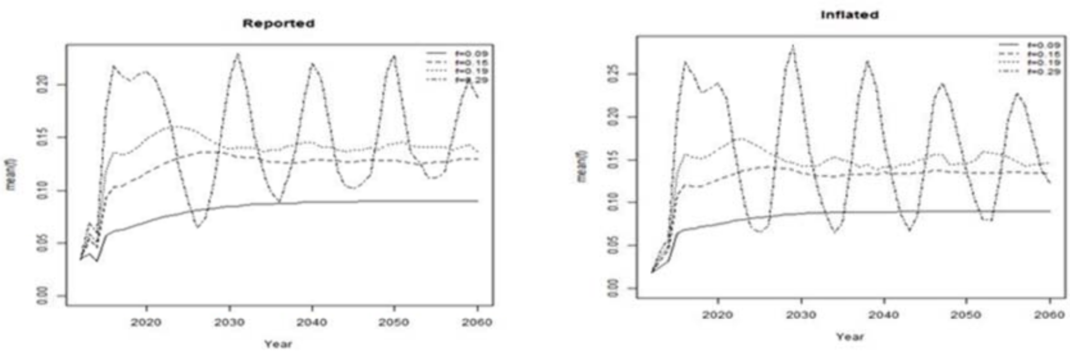


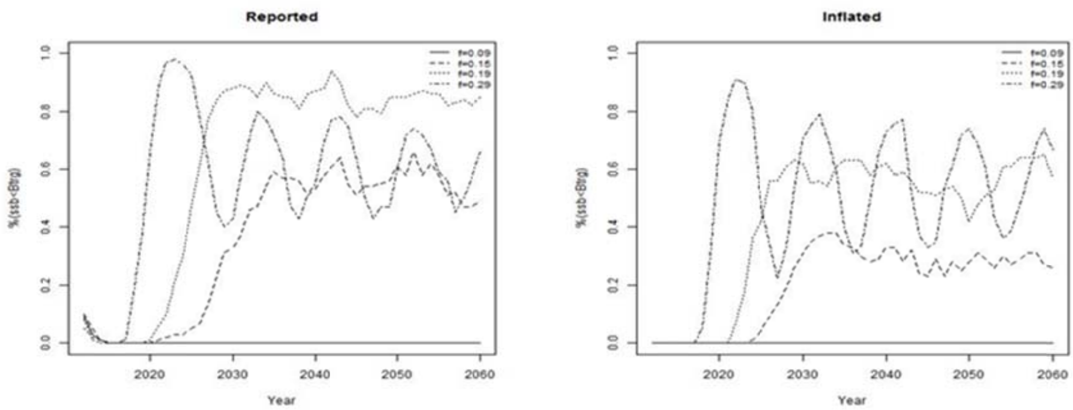
Figure 2. General trends in F, Y, R and SSB, for the period 2000-60 at different *Ftargets* ranging 0.09 – 0.29, using stochastic projections with the proposed HCR.



Period	Mean F0.09	Mean F0.15	Mean F0.19	Mean F0.29
2025-60	0,09	0,13	0,14	0,15
2035-60	0,09	0,13	0,14	0,15
2045-60	0,09	0,13	0,14	0,15

Period	Mean F0.09	Mean F0.15	Mean F0.19	Mean F0.29
2025-60	0,09	0,14	0,15	0,16
2035-60	0,09	0,13	0,15	0,16
2045-60	0,09	0,14	0,15	0,16

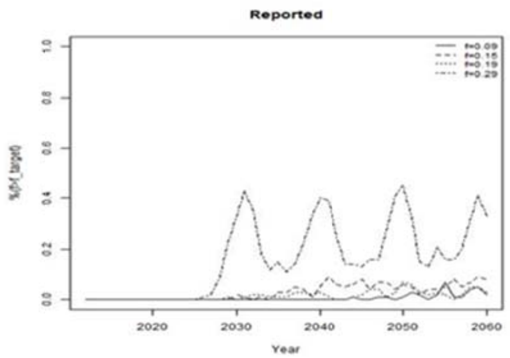
Figure 3. F trends in 50 years of stochastic projections for F values ranging 0.09 – 0.29.



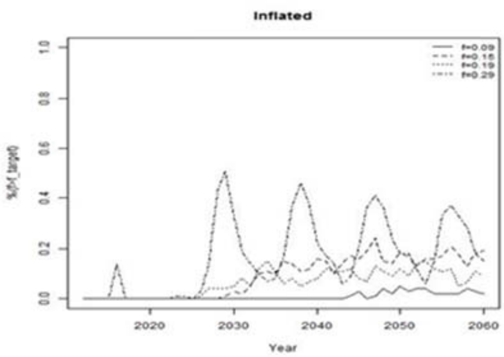
Period	Mean F0.09	Mean F0.15	Mean F0.19	Mean F0.29
2025-60	0,00	0,49	0,83	0,61
2035-60	0,00	0,56	0,85	0,60
2045-60	0,00	0,55	0,83	0,58

Period	Mean F0.09	Mean F0.15	Mean F0.19	Mean F0.29
2025-60	0,00	0,28	0,57	0,55
2035-60	0,00	0,29	0,57	0,55
2045-60	0,00	0,28	0,56	0,56

Figure 4. Probability of SSB<B_{target} in 50 years of stochastic projections for F values ranging 0.09 – 0.29.

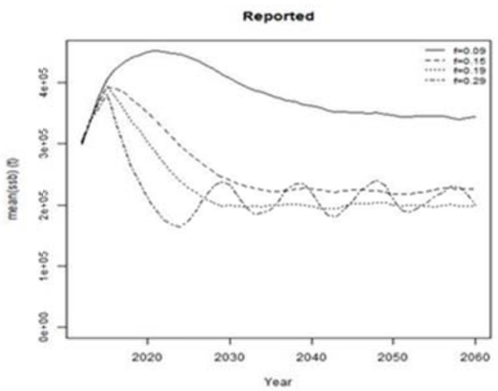


Period	Mean F0.09	Mean F0.15	Mean F0.19	Mean F0.29
2025-60	0,01	0,04	0,02	0,22
2035-60	0,01	0,05	0,03	0,24
2045-60	0,02	0,06	0,03	0,25

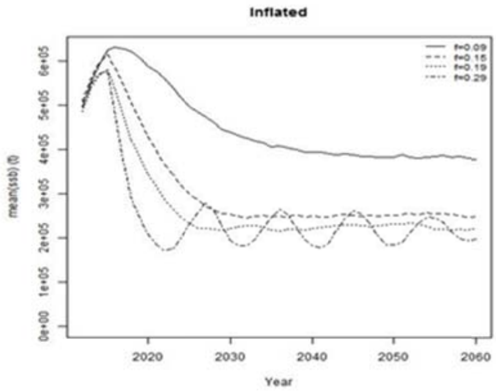


Period	Mean F0.09	Mean F0.15	Mean F0.19	Mean F0.29
2025-60	0,01	0,12	0,09	0,22
2035-60	0,02	0,16	0,10	0,23
2045-60	0,03	0,17	0,10	0,25

Figure 5. Probability of $F>F_{target}$ in 50 years of stochastic projections for F values ranging 0.09 – 0.29.

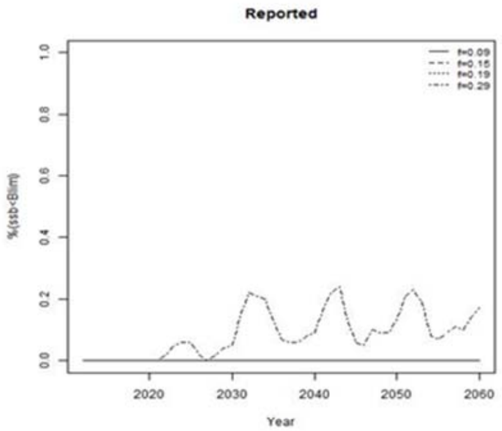


Period	Mean F0.09	Mean F0.15	Mean F0.19	Mean F0.29
2025-60	369157	230305	200685	209952
2035-60	352812	223493	199182	211476
2045-60	346033	223254	200050	214462

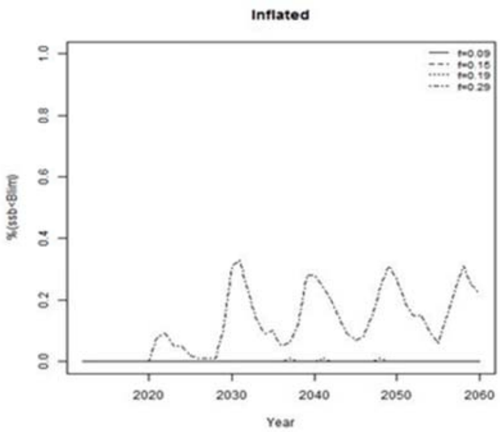


Period	Mean F0.09	Mean F0.15	Mean F0.19	Mean F0.29
2025-60	406064	254437	224571	220455
2035-60	389042	251317	224691	219185
2045-60	383838	252180	226106	218616

Figure 6. SSB trends in 50 years of stochastic projections for F values ranging 0.09 – 0.29.

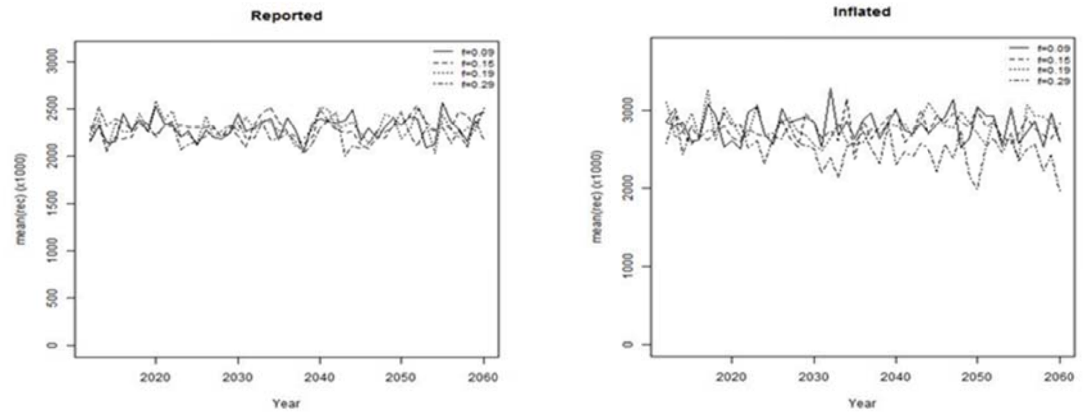


Period	Mean F0.09	Mean F0.15	Mean F0.19	Mean F0.29
2025-60	0,00	0,00	0,00	0,11
2035-60	0,00	0,00	0,00	0,12
2045-60	0,00	0,00	0,00	0,12



Period	Mean F0.09	Mean F0.15	Mean F0.19	Mean F0.29
2025-60	0,00	0,00	0,00	0,16
2035-60	0,00	0,00	0,00	0,17
2045-60	0,00	0,00	0,00	0,18

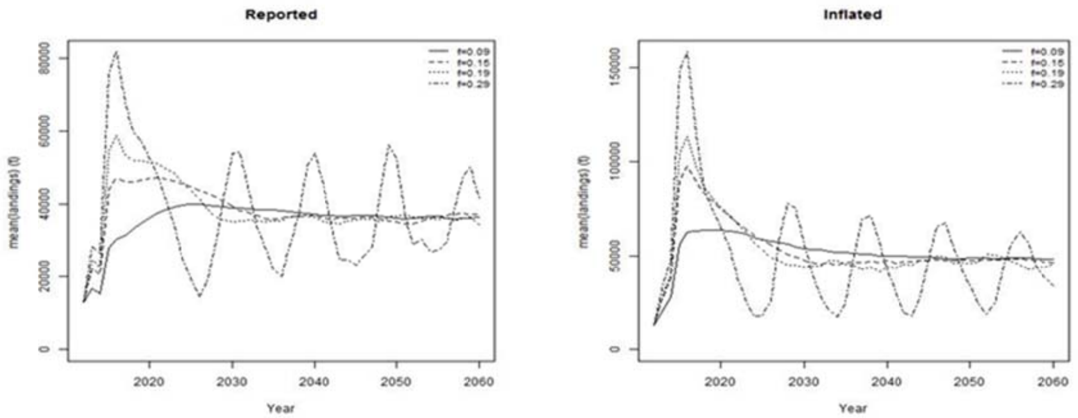
Figure 7. Probability of $SSB<B_{lim}$ in 50 years of stochastic projections for F values ranging 0.09 – 0.29.



Period	Mean F0.09	Mean F0.15	Mean F0.19	Mean F0.29
2025-60	2302	2306	2302	2225
2035-60	2312	2306	2301	2220
2045-60	2307	2324	2298	2235

Period	Mean F0.09	Mean F0.15	Mean F0.19	Mean F0.29
2025-60	2816	2786	2761	2466
2035-60	2803	2791	2784	2451
2045-60	2804	2806	2786	2404

Figure 8. Recruitment trends in 50 years of stochastic projections for F values ranging 0.09 – 0.29.



Period	Mean F0.09	Mean F0.15	Mean F0.19	Mean F0.29
2025-60	37374	37234	36214	35083
2035-60	36709	36099	35831	35617
2045-60	36335	36054	35936	36621

Period	Mean F0.09	Mean F0.15	Mean F0.19	Mean F0.29
2025-60	50783	47869	46014	43020
2035-60	49221	47171	45794	43475
2045-60	48619	47541	46805	44998

Figure 9. Yield trends in 50 years of stochastic projections for F values ranging 0.09 – 0.29.