SCRS/2010/019 Collect. Vol. Sci. Pap. ICCAT, 66(5): 1857-1866 (2011)

AN EVALUATION OF CHANGES IN STOCK PRODUCTIVITY AND CONSEQUENCES FOR MANAGEMENT. AN EXAMPLE BASED ON NORTH ATLANTIC ALBACORE *THUNNUS ALALUNGA*

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SUMMARY

*Reference points are important elements of fisheries management and the supporting scientific advisory frameworks. However, fish stocks can fluctuate extensively over a large range of spatial and temporal scales independent of human exploitation and there has been a classical tendency to assume a dichotomy, i.e., that changes in fish populations are primarily attributable either to exploitation or to environmental variability. Therefore we look at variability in surplus production and examine the relative impacts of the environment and exploitation on the productivity of North Atlantic albacore (*Thunnus alalunga*). The analysis revealed that variations were driven by environmental effects. It was also found that substantial variations in time-series of biomass and catch could be expected even under a constant F equal to* F_{MSY}.

RÉSUMÉ

Les points de référence sont des éléments importants de la gestion des pêcheries et des cadres consultatifs scientifiques d'appui. Toutefois, les stocks de poissons peuvent grandement fluctuer sur de vastes échelles spatio-temporelles indépendantes de l'exploitation humaine et il existe une tendance classique visant à postuler une dichotomie, c'est-à-dire que des changements dans les populations de poissons sont essentiellement attribuables soit à la variabilité de l'exploitation, soit à la variabilité environnementale. C'est pourquoi nous étudions la variabilité dans la production excédentaire et examinons les impacts relatifs de l'environnement et de l'exploitation sur la productivité du germon de l'Atlantique Nord (Thunnus alalunga). *L'analyse a révélé que les variations ont été causées par des effets environnementaux. On a également découvert que des variations considérables dans les séries temporelles de la biomasse et de la capture pouvaient être escomptées même avec un F constant égal à* F_{PME}.

RESUMEN

*Los puntos de referencia son elementos importantes de la ordenación pesquera y de los marcos de trabajo de asesoramiento científico que los respaldan. Sin embargo, los stocks de peces pueden fluctuar enormemente entre un amplio rango de escalas espaciales y temporales independientes de la explotación humana y ha existido la tendencia clásica a asumir una dicotomía, es decir, que los cambios en las poblaciones de peces se deben principalmente bien a la explotación o bien a la variabilidad medioambiental. Por lo tanto, examinamos la variabilidad en la producción excedente y los impactos relativos del medio ambiente y la explotación sobre la productividad del atún blanco del Atlántico norte (*Thunnus alalunga*). El análisis reveló que las variaciones estaban motivadas por efectos medioambientales. Asimismo, se descubrió que podían esperarse variaciones sustanciales en la serie temporal de la biomasa y la captura incluso bajo una F constante igual a* F_{RMS}.

KEYWORDS

Thunnus alalunga, albacore, fisheries management, FLR, reference points, stationary processes, surplus production.

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1. Introduction

In this paper we propose an approach that can be applied to a range of stocks and data sets to evaluate historical changes in stock dynamics that may help when reviewing apparent regime shifts and the biological reference points that scientific management advice are based upon.

Reference points are important elements of fisheries management and the supporting scientific advisory frameworks. For example, ICCAT's basic texts require stocks to be maintained at levels which will permit the maximum sustainable catch, commonly interpreted as maximum sustainable yield or MSY. Subsequently the World Summit on Sustainable Development (WSSD; COFI, 2003) committed signatories to maintain or restore stocks to levels that can produce MSY by 2015. While, the precautionary approach (FAO, 1996) requires the use of limit as well as such target reference points that incorporate the major sources of uncertainty to constrain harvesting within safe biological limits.

However, It has been known for almost a century (see Hjort, 1914, 1926) that fish stocks can fluctuate extensively over a large range of spatial and temporal scales independent of human exploitation. This in turn may impact on the performance of reference points use to provide advice on sustainability. For example, Cunningham and Maguire (2002) noted that, although unsustainability is often associated with overexploitation, fish stocks can be threatened with biological unsustainability even if the resource is not exploited. DeYoung *et al*. (1999), in a summary of Canadian groundfish stocks, concluded that although some stocks collapsed as a result of overfishing, other stocks may not have collapsed at all without unfavourable environmental conditions. Despite this evidence, there has been a classical tendency among marine scientists to assume a dichotomy, i.e. that changes in fish populations are primarily attributable to either exploitation or environmental variability (see Alheit and Hagen, 1997; Myers *et al*., 1997; Pauly *et al*., 1998; Stenseth *et al*., 2004; Gröger, *et al*., 2010). However, the effects of environmental variability, e.g. climate change, and exploitation are probably strongly linked in many cases, and their effects may interact (Hilborn *et al*., 2003; Hsieh *et al*., 2008; Rouyer *et al*., 2008). Consequently, it can be difficult, and sometimes even irrelevant, to distinguish between natural and anthropogenic effects. For example, when spawning-stock biomass (SSB) is low as a consequence of overexploitation, climate conditions such as temperature may have a compounding effect on recruitment success and so contribute to recruitment failure. This is illustrated by the recent warming of the North Sea and subsequent reduction in the size and abundance of copepods and euphausiids available to larval cod (*Gadus morhua*) during their critical growth period (Beaugrand et al., 2003). As high fishing pressure, which had already reduced the spawning potential of cod, did not decline fast enough in line with the environmentally induced decline in recruitment, the stock collapsed (Caddy and Agnew, 2004). Therefore, environmental conditions may cause a failure of fishery management because exploitation has disrupted the ability of a population to withstand, or adjust to, such extrinsic changes (Planque *et al*., 2010).

The performance and, in particular, the robustness of scientific management advice based on reference points will depend on the relative impacts of the environment and exploitation on stock status and productivity. Although reference points, such as MSY, are often calculated assuming there is no particular trend over time, Ricker´s (1975) original definition did consider environmental variability, i.e. "The largest average catch or yield that can continuously be taken from a stock under existing environmental conditions.", and also noted that "For species with fluctuating recruitment, the maximum might be obtained by taking fewer fish in some years than in others." However, determining the causes of fluctuations in stocks can be difficult, as illustrated above and also by two recent reviews of Northeast Atlantic fish stocks. In one, Niwa (2007) concluded that variability in populations was unbounded (i.e. non-stationary), so there was no stable equilibrium point such as MSY to be used to manage the stocks. In the other review, Sparholt *et al*. (2007) concluded that fishing mortality was the main influence on fish stocks. An implicit assumption underpinning the conclusions of Sparholt and his co-workers is that processes such as productivity are stationary. This assumption is in contrast with Niwa (2007) and several past reviews on demersal and pelagic fish (see Cushing and Dickson, 1976; Schwartzlose *et al*., 1999; Lehodey *et al*., 2006; Ravier and Fromentin, 2001), who concluded that such processes were time-dependent and therefore non-stationary.

Examining the productivity of a stock should allow the relative impacts of the environment and exploitation to be the evaluated. Sparholt *et al*. (2007) would predict that productivity will vary with biomass (being greatest at a biomass equivalent to B_{MSY}), whereas Niwa (2007) would predict that productivity will vary with time. Therefore, we look at the variability in the productivity of North Atlantic albacore (*Thunnus alalunga*) and discuss the consequences for reference points such as MSY. A problem in interpreting whether the observed trends in surplus production are related to biomass or time is that exploitation and potential environmental drivers are often confounded (see above). This means that it is difficult to identify whether fishing mortality was the main driver of historical stock fluctuations. To explore this, simulation is used to predict the expected variability in productivity and stock status under perfect implementation of an MSY-based management plan. We then discuss the consequences for single-species biological reference points.

2. Materials and methods

2.1 Data

Time series of biomass, recruitment, catch, and fishing mortality-at-age, and data on life history traits were obtained from the (ICCAT, 2008). The definition of the North Atlantic albacore stock is that used by ICCAT to perform stock assessment and provide management advice, i.e. the stock is assumed to be homogeneous and without significant immigration or emigration.

2.2 Productivity

The productivity (P_t) of a stock can be defined as the surplus production, following Hilborn (2001):

$$P_t = B_{t+1} - B_t + C_t, \qquad (1)$$

where B_t is total stock biomass, and C_t total catch weight (also referred to as yield) at time t. Productivity is greatest at a biomass equivalent to B_{MSY} and a total catch equivalent to MSY.

According to Sparholt *et al.* (2007), who presupposed that fishing mortality was the only key factor, the productivity could be calculated from the equilibrium or expected values of catch and biomass from an age-based equilibrium model, because at equilibrium, $B_{t+1} = B_t$, so productivity equals the expected yield. This approach combines partial fishing mortality-at-age (F_a), natural mortality-at-age (M_a), proportion mature-at-age (Q_a), and weight-at-age (W_a) data, with a stock–recruitment relationship (SRR), where a is age, n the plus group, and r the age-at-recruitment. Spawners-per-recruit (S/R) is given as a function of F by

$$\mathrm{S/R} = \sum_{a=r}^{n-1} \mathrm{e}^{-\sum_{i=r}^{a-1} F_i + M_i} W_a Q_a + \mathrm{e}^{-\sum_{i=r}^{n-1} F_i + M_i} \frac{W_n Q_n}{1-\mathrm{e}^{-F_n + M_n}}, \qquad (2)$$

where the second term is the plus group, i.e. a summation of all ages from the last age to infinity. Yield is derived from the yield-per-recruit ratio (Y/R):

$$\mathrm{Y/R} = \sum_{a=r}^{n-1} \mathrm{e}^{-\sum_{i=r}^{a-1} F_i + M_i} W_i \frac{F_i}{F_i + M_i}(1-\mathrm{e}^{-F_i - M_i}) + \mathrm{e}^{-\sum_{i=r}^{n-1} F_i + M_i} W_n \frac{F_n}{F_n + M_n}. \qquad (3)$$

Spawning-stock biomass (S) and yield (Y) can be derived from the spawner-per-recruit ratio by rearranging the stock–recruitment model so that recruitment is a function of S/R (Sissenwine and Shepherd, 1987). A compensatory (Beverton and Holt, 1957) stock–recruitment relationship was fitted. Recruitment, R, can be derived from the spawner-per-recruit ratio, i.e. for Beverton and Holt:

$$R = \alpha - \frac{\beta}{\mathrm{S/R}}, \qquad (4)$$

and for Ricker:

$$R = \ln(\alpha \mathrm{S/R}) \frac{\beta}{\mathrm{S/R}}. \qquad (5)$$

Albacore are annual spawners (producing one cohort per year), with spawning occurring mid-year. Fecundity is assumed to be linearly proportional to weight, with the proportion mature-at-age and natural mortality time-invariant. Weight-at-age of the stocks and all other technical assumptions (e.g. about the plus-group) are taken to be the same as used in the ICCAT assessment. Finally, expected (under equilibrium assumptions) SSB and yield can be obtained as the products of Equations (2) and (3), and (4) and (5).

Comparing the observed and expected surplus production over time allows potential trends or pseudocycles in productivity to be identified. Therefore, we analysed the relative difference in the observed productivity from the expected ones using Eigen Vector Filtering (EVF; Colebrook, 1978; Ibanez and Dauvin, 1988). The EVF decomposes the total variance of a time-series into independent components by applying a principal component analysis (PCA) on the original time-series and a number of copies of it incrementally lagged and collected in a multivariate matrix. Reconstructing the signal using only the most representative eigenvectors filters the signal so that we see any main trends without the distraction of random noise. Here, we used the first axis (i.e. eigenvector) of the EVF to reconstruct the trend, and noted the associated percentage of total variance to evaluate its magnitude.

2.3 Simulations

Simulations were conducted to project populations based on the age-structured equation using the approach of Fromentin and Kell (2007):

$$N_{a,t} = N_{a-1,t-1} \mathrm{e}^{-Z_{a,t}} , \qquad (6)$$

where $N_{a,t}$ is the number of fish aged a at time t, and $Z_{a,t}$ is the total mortality from age a–1 to age a. Here, $Z_{a,t} = M_a + F_{a,t}$, where M_a is the natural mortality-at-age a, and $F_{a,t}$ the fishing mortality at age a in year t.

The recruitment processes were modelled using stock–recruitment relationships defined for the productivity analysis above. The stocks were projected over the historical range and trends in growth (i.e. observed weight-at-age), and recruitment residuals were used to preserve the trends and annual variability. Two scenarios of fishing mortality were run: constant fishing mortality equal to F_{MSY}, and fishing mortality increasing from F_{MSY} to $2F_{\mathrm{MSY}}$ over the simulation period.

The initial stock abundances were at equilibrium, at a level equivalent to being fished at F_{MSY}. All modelling was performed in R using the FLR framework (Kell *et al.*, 2007).

3. Results

Time-series of biomass, recruitment, surplus production, exploitation rate, and yield are displayed by column in **Figure 1**. Biomass declined through the entire time-series, inspection of the plots of recruitment and surplus production reveal that peaks in surplus production followed peaks in recruitment. Exploitation increased in the early part of the time-series, before levelling off, and yield initially increased along with exploitation, before declining, suggesting that maximum sustainable yield, biomass and exploitation rate is equivalent to the levels in the 1970s.

Surplus production is plotted against biomass in **Figure 2**, the first panel shows the expected (lines) and observed (points) surplus production, and the second panel the relative difference between the observed and expected surplus production along with the smoothed time-series.

The curve maxima represent MSY and B_{MSY}; points to the left of the maximum represent an overfished state, although the maxima are not very well defined. The plots of the difference between expected and observed surplus production show that there have been sustained periods when productivity has been either greater or less than expected.

The difference between expected and observed productivity shown in the second column of **Figure 2** has a blue line as the first axis of the EVF. The first axis explained 69%of the variance. This means that there is a dominant trend, implying that the differences between the expected and observed productivity are caused by a non-stationary environmental driver.

To evaluate the effect of varying productivity, time-series of SSB and catch were generated using simulations by projecting the stocks forward in time with the two alternative F-scenarios. Recruitment was modelled using the stock–recruitment relationships defined above. To simulate the year effect, the predicted recruits were modified by the observed stock–recruit residuals. Two F-scenarios (F_{MSY} and linearly increasing from F_{MSY} to $2F_{\mathrm{MSY}}$) were considered and contrasted with the observed time-series (**Figure 3**).

For the increasing F-scenario, the stock halved in size over the period of the time-series (as indicated by the blue line). Fishing at constant F_{MSY} (the black line) suggests that the stock would still have declined, but not by the same proportion. For both F-scenarios albacore yields declined with biomass, the decline being approximately the same for the constant and increasing F-scenarios. As initially the stocks were at B_{MSY}, this means that even fishing at the optimum level would result in a reduction in yield, suggesting a strong year-effect influence. The simulated time-series of biomass for both fishing scenarios displayed mainly decadal variations. Variability appeared to be less for the simulations of increasing F, but the relative inter-annual variation was similar.

4. Discussion

The analysis revealed that:

(i) the environment plays a significant role in causing variation
(ii) variations seem to driven by environmental effects as well as by fishing.
(iii) substantial variations in time-series of biomass and catch may be expected even under a constant $F = F_{\mathrm{MSY}}$, and that importantly.

Even at a constant $F = F_{\mathrm{MSY}}$, large variations in productivity, and hence yield and SSB, can be expected as a consequence of variations in recruitment, possibly environmentally driven. A consequence is that a decrease in F may not immediately be followed by stock recovery or a stock decline by an increase in F, because biomass and yield are also driven by changes in year-class strength, which may vary independently of fishing. The consequences for stock collapse and recovery is that luck plays a role. Periods of poor environmental conditions combined with overfishing will increase the chance of a collapse, whereas reducing fishing pressure may only yield a recovery during periods of favourable environmental conditions. Conversely, scientific advice might be undermined if there is overfishing at times of good environmental conditions, or recovery at times of bad conditions. The argument is not necessarily about whether stock collapse is attributable to the environment or fishing, but more about how fishing increases the risk of stock collapse in a varying environment. For example, should the stock be maintained at a higher level and exploitation at a lower level in a varying environment compared with a more stable one?

Our study is likely to be conservative, because we only explored two sources of natural variation (from the stock–recruitment relationship, and variations in weight-at-age), and we ignored other sources of variation such as changes in migration, stock substructure, habitat, somatic growth, multispecies effects, and genetics.

Aloncle and Delaporte (1974), proposed that there are at least 3sub-populations that have been exploited by the albacore surface fisheries. This heterogeneity of the stock is not been taken into account in the present ICCAT stock assessment by SCRS and as Fonteneau (2010) pointed out it could play a major role in the apparent change in productivity and hence estimation of MSY based reference points.

Our findings are consistent with many past and recent studies that have shown that most exploited marine populations are not stationary, but display strong natural spatial and temporal variations (Hjort, 1926; Cushing and Dickson, 1976; Walters, 1987; Ottersen and Sundby, 1995; Schwartzlose *et al*., 1999; Ravier and Fromentin, 2001; Dorner *et al*., 2008). A further practical difficulty is that stocks managed to produce MSY may not lead to sustainable and/or optimal management because of the uncertainties and simplifying assumptions made when modelling the biological processes that can mask the effects of exploitation (Sissenwine, 1978; Rosenberg and Restrepo, 1994).

Our results also mean that it may be difficult to predict future yields accurately, something implied by Sparholt *et al*. (2007). This does not mean that the conclusion of Niwa (2007) about the inappropriateness of MSY-based reference points is correct, but rather that it is important to have long-term management plans against which trends in stock status can be assessed and managed. This is particularly important because the benefits of management plans may not be seen immediately and apparent short-term increases in yields may eventuate in the absence of any plan. Both of these situations mean that it might be difficult to gain agreement on implementation of a recovery plan or sustainable management until the stock has declined substantially. It can be argued that the more important the stock, the more likely this is to happen.

The respective impacts of fishing vs. environment and/or biological processes are, in many cases, relative to the status of the stocks. A reduction in fishing mortality is necessary and crucial, but not always sufficient for the recovery of overexploited stocks. More importantly, we now know that the effects of exploitation, environmental variations, and biological processes are not simply additive, but multiplicative (Planque *et al*., 2010), because even a moderate level of exploitation can result in a population being reduced to a very low level if it is heavily concentrated in space, so the fishing eliminates a key subpopulation, or happens at a critical period, e.g. during adverse environmental conditions. The timing of these interactions is obviously a key element in understanding the dynamics of exploited populations. To ensure the sustainability of exploited natural resources, and other species within their ecosystem, it is important to maintain population resilience to both exploitation and environmental variations, such as climate change or eutrophication. To do this, a range of factors needs to be preserved at a variety of levels.

Current advice implies that the survival rates of offspring do not substantially change with the age or the size of the spawners. However, both can be crucial (i.e. the process known as the parental effect, see Cardinale and Arrhenius, 2000, for cod, and Birkeland and Dayton, 2005, for a recent review). Evidence also exists of spatial differences in fecundity within stocks defined for management purposes (Kennedy *et al*., 2007), so ignoring the spatial and age structures of fish populations (Berkeley *et al*., 2004) can lead to reduced recruitment. However, the definition of stocks used to provide management advice assumes that stocks are spatially homogenous, i.e. that the stock is not a metapopulation that can display different life history characteristics and local adaptations to environmental conditions (Hilborn *et al*., 2003). Assuming a single population can result in local extirpation of populations (Kell *et al*., 2009), and important ecological and evolutionary factors may be ignored (Waples and Gaggiotti, 2006). Other important factors are the implications in terms of genetic diversity/erosion, and evolution of the exploited populations (see Conover and Munch, 2002; Hauser *et al*., 2002), because by fishing large individuals, exploitation induces a loss of natural genetic variability that potentially results in reduced adaptability, persistence, and productivity of the exploited populations. The generality for all fish species remains unclear, but the fact that in this study the productivity of the heavily exploited longer-lived demersal species seems to have declined would seem to support these concerns.

Traditionally, fisheries management has tended to focus on single species or stocks. However, as the productivity of many stocks and the economic activities they support has become compromised (Pauly *et al*., 1998; FAO, 2002; Garcia and Grainger, 2005; Hilborn *et al*., 2005), there has been a move towards an ecosystem-based approach to fisheries management (EBFM). The principles of this are open to interpretation, but according to FAO (2005), they are " *... to ensure that, despite variability, uncertainty and likely natural changes in the ecosystem, the capacity of the aquatic ecosystems to produce food, revenues, employment and, more generally, other essential services and livelihood, is maintained indefinitely for the benefit of the present and future generations*". A key objective of an EBFM will be to ensure that fishery-management decisions do not adversely impact the productivity of either the exploited populations or the ecosystem as a whole, so that exploitation of fish stocks (and resultant economic benefits) is sustainable in the long term.

A fully comprehensive EBFM would require taking into account many interactions, e.g. between a given exploited stock and its predators, competitors, and prey, and/or with exploitation, climate variation, and habitat loss. As complete understanding of ecosystems is an unrealistic goal of science, the implementation of an EBFM will require progressive implementation through stages building upon current management frameworks. Among these there will still be the need for indicators of sustainability, such as target and limit reference points, a move away from reactive short- towards long-term strategic objectives, and agreement of management objectives that incorporate wider ecosystem factors along with those for the target stock. This implies a consideration of a range of conflicting objectives within an appropriate monitoring, assessment, and management framework, and a need to build consensus (http://www.jncc.gov.uk/page-1576).

Notwithstanding the above, single-species management plans will continue to be important for many commercially exploited fish stocks, and management strategy evaluation (MSE; Smith *et al*., 1999; Rademeyer *et al*. 2007; De Oliveira *et al*., 2008) will be important in developing robust assessment–management rules prior to implementation. These rules will ideally be tested against a range of plausible scenarios using process-driven models such as Gadget (Howell and Bogstad, in press) which can explicitly model a range of biological processes such as migration, reproduction by closing the life cycle, multispecies interactions, other causes of residual mortality, growth, and maturation, as well as fishing.

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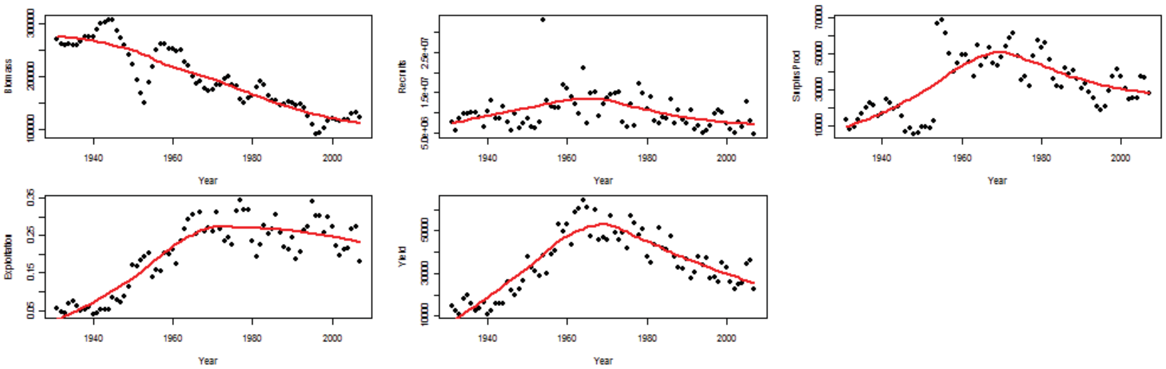

Figure 1. Time-series of biomass, recruitment, surplus production, exploitation rate, and yield as estimated by the ICCAT stock assessment.The line shows the trend determined by a lowess smoother.

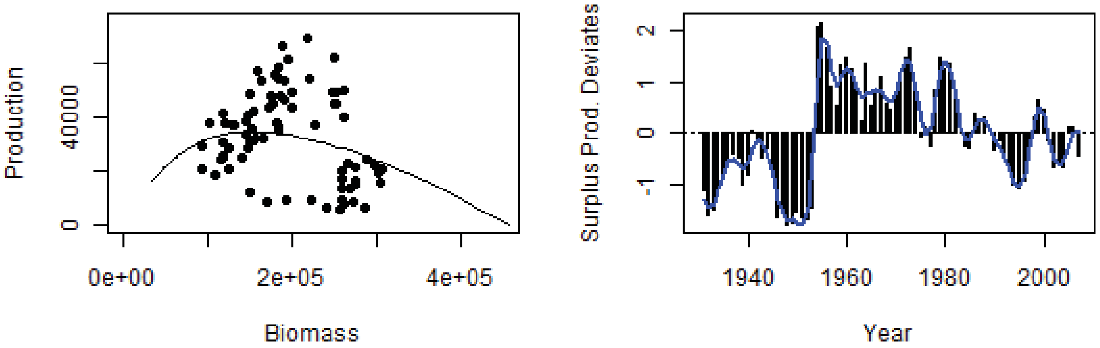

Figure 2 Plots of surplus production against biomass . The left column of panels shows the expected (lines) and observed (points) surplus production, and the right column the relative difference between the expected and observed surplus production. Lines are smoothed time-series, and the blue line shows the first axis of the EVF.

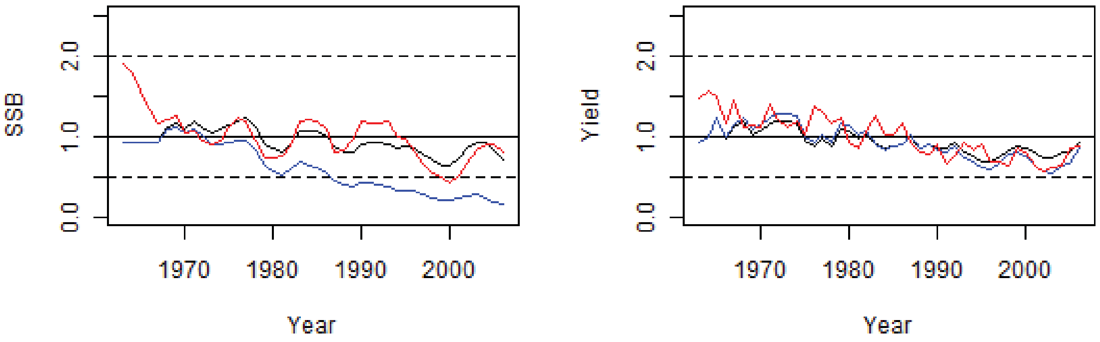

Figure 3 Time-series of SSB and yield; the red line shows historical estimates, the black line the simulated values when the population is fished at F_{MSY}, and the blue line a doubling of F from F_{MSY} at the start of the period. Values are relative to B_{MSY} and MSY for the simulated values, and to the mean for the historical values.