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Which Came First? The Chicken, The Egg or The Tortilla

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SUMMARY

In this paper we look for evidence of a stock recruitment relationships for bluefin, yellowfin and albacore tuna. Evidence of the existence of a SRR for any of the stock was weak and the data instead appear to support the argument that recruitment fluctuates around a mean level for a period and then a regime shift occurs. This has obvious important implications for stock assessment and management advice.

KEYWORDS: albacore, bluefin, yellowfin, recruitment, spawning stock biomass, stock recruitment relationships, stock assessment, management, eggs, onions, chickens

Contents

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1. Introduction

That there is a stock recuitment relationship (SRR) is a main assumption of many stock assessment models. Management advice based on reference points and projection are highly sensitive to the estimated or assumed functional form and parameters of the SRR. The SRR is also often the only form of density dependence assummed in stock assessment models despite the fact that it can occur in many biological processes Lorenzen and Enberg [2002] and in different forms; mainly because it is difficult to detect in practice [Sinclair et al., 2002]. This is despite the fact that the need for caution in selecting the type of density dependence and specifying its parameters has long been recognised in population ecology.

Density dependence is used to stabilise population models has important effects on extinction risks Ginzburg et al. [1990] and population growth rates Hassell [1975] and hence on limit and target reference points If population growth is driven solely by density independent factors then a population will shown a random walk and, no matter how severely the vital rates fluctuated around their long term averages, the population would eventually increase or decrease without bound May [1986].

The information in stock assessment data sets is seldom sufficient to derive the relationship between stock and recruitment Lee et al. [2012]. It has also been known for nearly a century [Hjort, 1926] that fish stocks can fluctuate extensively over a large range of spatial and temporal scales independent of human exploitation. **?** argued that recruitment may shift between regimes independently of stock biomass and that spawning stock biomass (SSB) is a function of recruiment. Periods of high or low recruitment generate periods of high or low stock biomass respecitively as fish mature.

What came first? the need of stock assessment working groups for a stock and recruitment relationships to make the tortilla, (i.e. fitting statistcally integrated models, deriving reference points and making stock projections) or evidence that stock biomass drives recruitment.

Determing the relationship between stock and recruitment is complicated by the fact that values of stock and recruitment used in most analyses are based on stock assessment data sets where SSB is used as a proxy for spawning potential (SRP). SSB assumes that fecundity is proportional to mass-at-age irrespective of the demographic composition of adults and that processes such as maturity are simple functions of age. However, changes in growth and egg production (EP) are well documented and may impact on productivity and hence reference points and management advice (see Kell at al. submitted). Recruitment is not measured but estimated along with mortality (Z) which may involve fixing natural mortality (M), since M is a difficult parameter to actually estimate Lee et al. [2012]. However if M varies with time (e.g. due to the environment or density dependence) then the estimated stock recruitment relationship assuming M is time invariant will be biased. For example Nash et al. [2009] estimated a Ricker SRR for North Sea herring, which disappeared when natural mortality was allowed to vary over time (Kell et al. submitted).

2. Material and Methods

We explore non-parameteric stock recruitment relationship, auto-correlation in recruitment, cross correlations between recruiment and SSB and regime shifts for stock and recruit time series obtained from age based ICCAT stock assessments

2.1 Data

Time series of SSB and recruitment were obtained from the most recent ICCAT stock assessments for North Atlantic albacore (ref), the Eastern and Western Altantic bluefin tuna stocks (ref) and yellowfin tuna (ref). The albacore assessment was conducted using Multifan-CL **?** with no constraint on the SRR parameters. For the other stocks the assessment was based on virtual population analysis (VPA) again with no constraint on the SRR. In the case of Western Altantic bluefin two catch time series were considered, i.e. the reported catches and an inflated catch series which allowed for the misreporting of catch levels.

2.2 Methods

2.21 Stock Recruitment Relationships

The Beverton and Holt SRR [Beverton and Holt, 1993] is derived from a simple density dependent mortality model where it is assumed that mortality of pre recruits is proportional to their density and the number of recruits increases towards an asymptotic level (R_{max}) as egg production increases.

The Ricker SRR assumes that density dependent mortality is proportional to the initial number of eggs or larvae. This may be appropriate when a prey species is temporarily massed in unusual numbers and the number of prey eaten depends on the abundance of predators, but not on the abundance of prey. Hence such situations cannot last long, and the predators cannot make the prey in question their principal yearly food, Ricker [1987]. Alternative mechanisms include cannibalism, habitat limitations, and aggregation [Rose et al., 2001, Brooks and Powers, 2007, Powers, 2004].

The majority of fisheries stock assessment modelling is parametric. However when modelling the relationship between stock and recruitment models may not adequately explain the data or the data may not informative enough to estimate the parameters Hillary et al. [2012]. Therefore we fitted a LOESS smoother [Cleveland et al., 1992] to allow the relationship between stock and recruitment to be explored without specifying in advance the assumed process (i.e. compensation, over compensation or depensation) as required when fitting one of the standard functional forms. We then look for patterns in the residuals that may indicate that other processes influence recruitment.

2.22 Cross correlations

In order to evaluate whether there is a monotonic relationship between recruitment and SRP (see Szuwalski et al, submitted) cross correlations were calculated based on Spearman's correlation [Spearman, 1904]. If there is compensation (for example recruitment follows a Beverton and Holt stock recruitment relationship) then there will be a significant correlation equal to the age at recruitment.
[***The significance levels in the plots are probably wrong due to auto-correlation in the time series. 2 options either to i) remove the CI or ii) calculate new corrected ones based on Pyper and Peterman [1998]***]

However if stock biomass is driven by recruitment as a result of fluctuations in the environment [**?**] then there will be negative lags at corresponding to the mature ages. Only if SSB has a larger and significant influence on recruitment than recruitment does on SSB then is the existence of a S-R is supported (Szuwalski et al, submitted).

2.23 Regime Shifts

Evidence for regime shifts are explored using a a sequential t-test algorithm (STARS; Rodionov [2004]) as modified by Szuwalski et al., (submitted)

3. Results

Time series of recruitment and SSB are shown in **Figure** 1 and 2. Recruitment is then plotted against SSB along with a non-parameteric LOWESS fit in **Figure** 3. The residuals to the fits are shown in **Figure** 4. Results for Eastern Atlantic bluefin series based on the inflated catch are in red.

Auto correlation in the recruitment time series are evaluated by plotting correlogrammes in **Figure** 5 for recruitment and for recruitment residuals from the non-parameteric fits in **Figure** 6; non-randomess can be investigated by comparing correlations by lag with the upper and lower bounds at the 5% significance level.

To check the assumption that there is monotonic relationships between recruitment and SSB (e.g. a Beverton and Holt stock recruitment relationship without over compensation) the cross Spearman correlations are plotted in **Figure** 7; again non-randomess can be investigated by comparison with the 5% significance levels. For yellowfin the righhand limb of the Ricker curve was due to the early points in the time series, these were removed prior to calculating the cross correlations.

Sequential t tests for regime shifts Rodionov [2004] in recruitment are shown in **Figure** 8 and for recruit residuals from the non-parameteric fits in **Figure** 9 and in **Figure** 10 for SSB.

The Relationships between Recruitment and Stock is explored in **Figure** 3. A Ricker stock recruitment relationship is suggested for yellowfin, however the points on the righthand limb of the Ricker curve all come from the early period of the time series and could also be explained by a regime shift. For albacore a Beverton and Holt or Ricker for albacore could be fitted to the data. For the bluefin time series the picture is less clear. For the eastern stock low recruitments are seen with higher levels of SSB, which could be consistent with over compensation. For the western stock, recruitment declined year-on-year from the start of the time series until stablising in recent years to a low level about which recruitment has fluctuated.

Residual patterns in **Figure** 4 shows a systematic pattern, in that recruitment in the early years was lower than predicted. There is no systematic pattern in the albacore residuals. For eastern bluefin recent recruitment is lower than the predicted values, this is a result of the under reporting of catches on the VPA estimates. For Western bluefin in the mid period, when recruitment was declining year-on-year the residuals are all positive. **Figures** 3 and 4 indicate problems with all the fits apart from albacore.

Autocorrelation plots in **Figure** 5 show significance autocorrelation for all time series other than albacore. In the albacore assessment recruitment deviates were estimated as a random walk and so autocorrelation was removed from the residuals. The residuals from the non-parameteric fits show less autocorrlation (**figure** 6) since the smoother has removed some of the trends since recruitment and SSB are correlated as seen by the cross correlations.

Cross correlation plots (**figure** 7) do not support recruiment being driven by SSB, since there a a lag of 1 for recruitment (i.e. at age 1) with SSB is no more important than other lags. For Eastern Atlantic bluefin the cross correlations are negative with lags less than 1 being the most significant. If there was overcompensation then there should be a significant negative correlation with a lag of 1. The cross correlations therefore do not support the existence of a stock-recruitment relationship. Teleosts generally produce a large number of eggs with only a small number survive to recruitment. This has nothing to do with fishing since the stock recruitment relationship only considers the pre-exploitation stage and fishing reduces the spawning stock not recruitment. Therefore positive lags are not affected by fishing. However, negative lags are as the numbers surviving to maturity are determined by mortality levels.

Regime shifts are explored in **Figures** 8 and 9 overlay the regime shifts on the recruitment and recruit residual time series. If it is believed that there is no stcok recruiment relationship then in all stocks there are regime shifts (i.e. in both the mean and variance) in recruitment about every 10 years. The regime shifts in SSB for Western Atlantic bluefin and yellowfin coincide with those in recruitment. However, the regime shifts in Eastern bluefin and albacore show large variatons which do not obviuously coincide with those in recruitment.

4. Discussion

The results show that evidence supporting the existence of a SRR for any of the stock is weak and instead appear to support the argument of **?** that recruitment fluctuates around a mean level for a period and then a regime shift occurs. This has obvious important implications for stock assessment and management advice provided by ICCAT and other Regional Fisheries Management Organisations (RFMOs).

Quantification of uncertainty in stock assessments The SCRS provides advice on management measures within the Kobe framework, which includes integrating various scenarios based on key uncertainties e.g. about recruitment processes and SRR assumptions.

For the Western bluefin stock there two scenarios are considered when providing advice, i.e. either a Beverton and Holt or segmented regression SRR. Both assume that dynamics are stationary i.e. that the dynamics are "either or" and the main issue is to identify which are the true dynamics rather than that there may have been a change in the dynamics. However, recent work now suggests that there has been a regime shift Fromentin et al. [2013].

For the Eastern bluefin stock two scenarios were considered for historic catch levels (i.e. reported and inflated) and three for future recruitment levels (i.e. low, medium or high re-sampled from different periods of the historic series). From the VPA estimates of SSB and recruits it could be argued that the SRR is of a Ricker functional form and that the stock is has always been on the right-hand limb of the Ricker curve. However it is hard to find a biological explanation to support this argument especially as there appeared to be no relationship between SSB and recruitment. The analysis would suggest instead that there has been a series of regime shifts.

In the case of the Eastern and Western stocks the complex evolution of the bluefin fisheries and the use of VPA to estimate recruitment and SSB from reported catches means that it is difficult to understand the actual processes.

For yellowfin and albacore no stock recruitment hypotheses were considered when developing scenarios. Albacore was assessed using Multifan-CL **?** and there was no significant relationship between SSB and recruitment. The yellowfin assessment was conducted using VPA, which does not involve a stock recruitment relationship and the projection to provide advice on catch quotas assumed constant recruitment, i.e. that there was no SRR.

Advice for the case study stock is based assuming stationarity. However, the evidence of regime shifts in the data means that it is important to provide advice on that takes into account changes in recruitment dynamics and the consequences of a transition from current recruitment levels to higher or lower levels rather than to determine the 'corrrect' recruitment model or to combine several models when providing advice.

Characterisation of quality of the fisheries data and biological information This simple study showed that there is considerable uncertainty about the knowledge of key biological processes and that current advice is unlikely to be robust to that uncertainty. Especially since recruitment processes are assumed to be stationary and estimates of SSB assume time invariant growth and fecundity.

Limit Reference Points, Harvest Control Rules, and Management Strategy Evaluations Reference points should be evaluated as part of a feedback HCR using MSE where Operating Models (OMs) are conditioned on hyotheses about the stock recruitment dynamics. This will allow robust HCR and reference points to be developed

Incorporation of Ecosystem, Climate, and Habitat (ECH) information into stock assessments The ability of management strategies to achieve management goals are impacted by environmental variation, Punt et al. [2013] in a review found that most studies showed that modifying management strategies to include environmental factors does not improve the ability to achieve management goals much, if at all, and only if the manner in which these factors drive the system is well known. They concluded that until the skill of stock projection models improves, it seems more appropriate to consider the implications of plausible broad forecasts related to how biological parameters may change in the future as a way to assess the robustness of management strategies, rather than attempting specific predictions.

5. Conclusions

Most stock assessment models implicitly assume some types of density dependence. For example surplus production (either explicitly in a biomass dynamic model **?** or implicitly when performing an age based projection with a SRR or constant recruitment) means that there is an equilibrium population abundance, K or B_0, which if the population falls below K the population growth rate (r) will on average be greater than 1 and in the abscence of fishing the population will increase. Alternatively if the population grows above K r will fall below 1 and the population will decline.

However if the population is subject to "systemic" pressure Shaffer [1981] such as a regime shift then assuming density-dependent regulation may cause an underestimation of the risk of decline or result in forgone yield. The population may be subject to trends due to a change in survival rates or fecundities in which case it may not be appropriate to use density dependence models such as Ricker, Beverton-Holt, logistic, etc.

? pointed out that ecosystem variability can involve a variety of climate to ecosystem transfer functions. These can be expected to convert red noise of the physical system to redder (lower frequency) noise of the biological response, but can also convert climatic red noise to more abrupt and discontinuous biological shifts, transient climatic disturbance to prolonged ecosystem recovery, and perhaps transient disturbance to sustained ecosystem regimes. All of these ecosystem response characteristics are likely to be active for at least some locations and time periods, leading to a mix of slow fluctuations, prolonged trends, and step-like changes in ecosystems and fish populations in response to climate change. Which provide challenges for management advice.

A solution is to use Management Strategy Evaluation (MSE) to develop management strategies that are robust to uncertainty about the recruitment and stock dynamics dynamics. This requires the development of Operating Models (OMs) to simulate the main uncertainties about system dynamics and to test the performance of alternative management strategies. MSE involves a number of steps **?** i.e.

- identification of management objectives and mapping these to performance measures in order to quantify how well they have been achieved.
- selection of hypotheses about system dynamics.
- conditioning of OMs on data and knowledge and possible rejecting and weighting the different hypotheses.

- identifying candidate management strategies and coding these up as MPs
- projecting the OMs forward using the MPs as feedback control procedures; and
- agreeing the MPs that best meet management objectives.

The performance of management strategies and hence the eventual selection of the strategy to be implementation depends upon the hypotheses included in the OM. The choice of scenarios for use in provision of management advice is therefore critical. In the case studies the scenarios are not consistent across stocks. In some cases the scenarios were selected from assessment runs which had been initially been conducted as sensitivity tests to evaluate the relative importance of model assumptions.

Scenarios should include ones for which it is important that management advice is robust to. For example the occurrence of regime shifts. Therefore management strategies evaluated should include ones which can respond to regime shifts, i.e. allow for non-stationarity. This will allow the robustness of current advice to be evaluated and alternative strategies to be developed.

Fisheries independent time series of recruitment and spawning stock biomass will of extreme importance in better understanding the relationship between recruitment and spawning reproductive potential.

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6. Figures

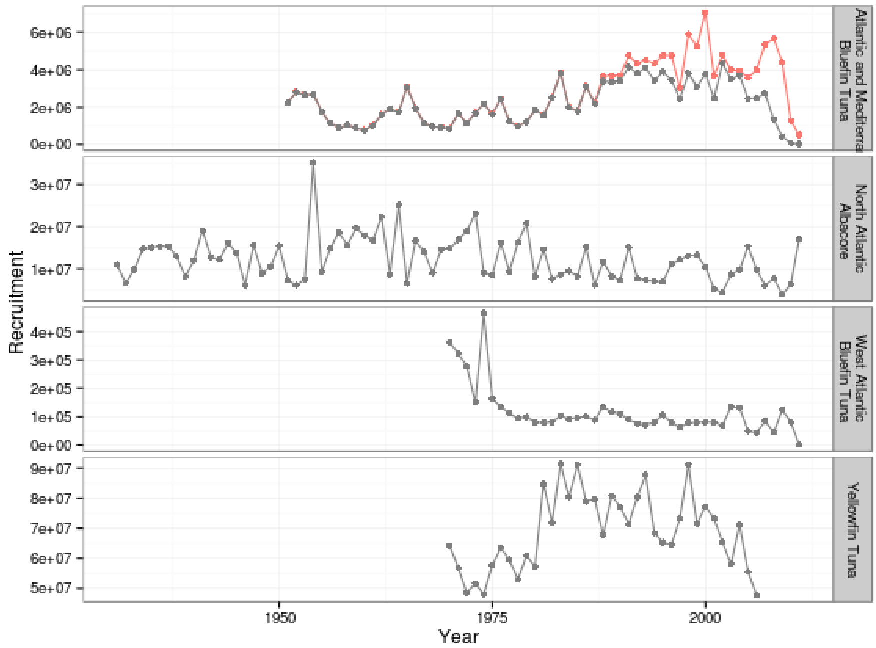

Figure 1: **Time series of recruitment; the red lines repesent the Eastern Atlantic bluefin series based on the inflated catch.**

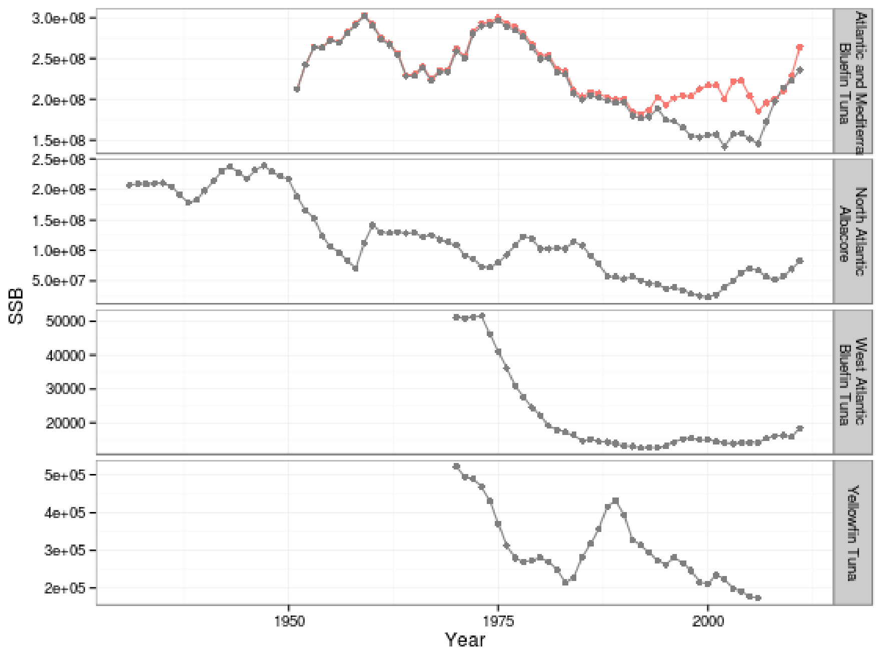

Figure 2: **Time series of Spawning Stock Biomass**

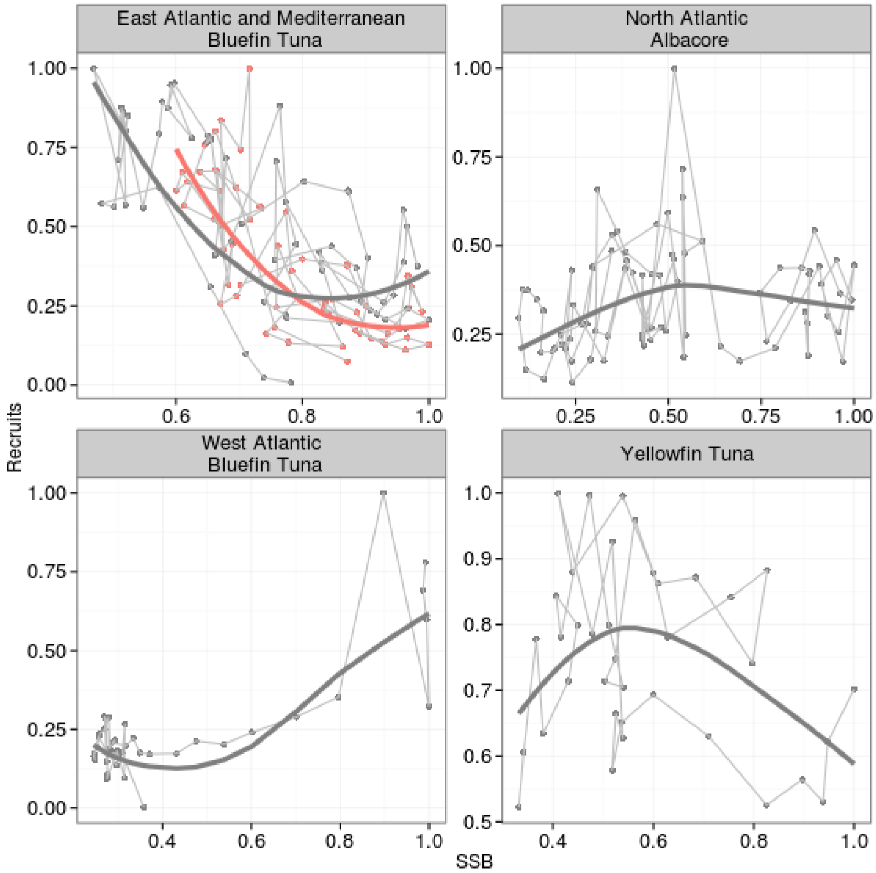

Figure 3: **Plots of Recruitment against Spawning Stock Biomass, with non-parameteric fits using a LOWESS smoother.**

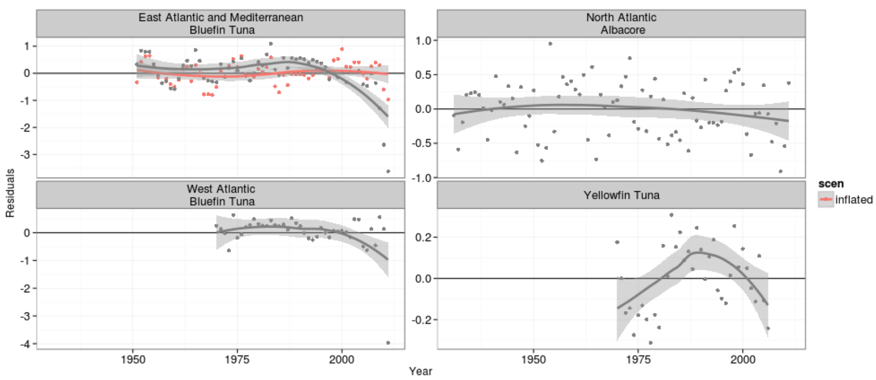

Figure 4: **Plots of residuals from non-parameteric fits to Recruitment as a function of Spawning Stock Biomass.**

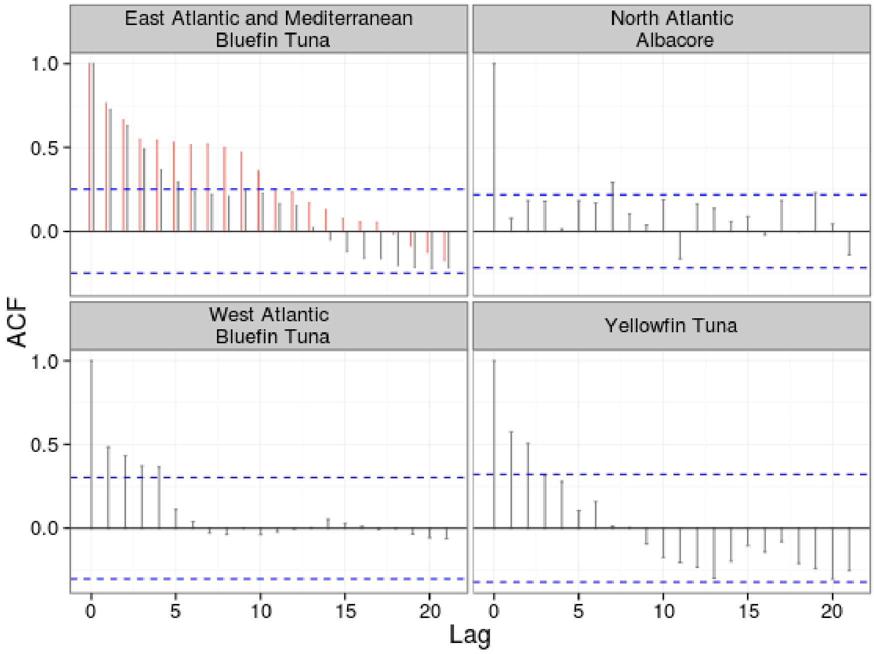

Figure 5: **Plots of recruitment auto correlation, horizontal lines are the 5% CIs**

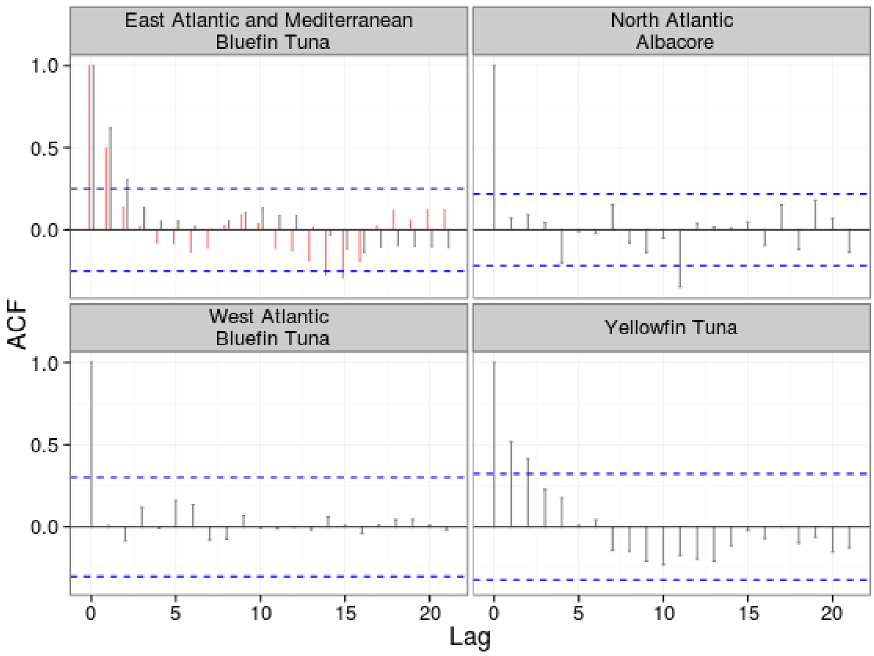

Figure 6: **Plots of recruitment residuals auto correlation, horizontal lines are the 5% CIs**

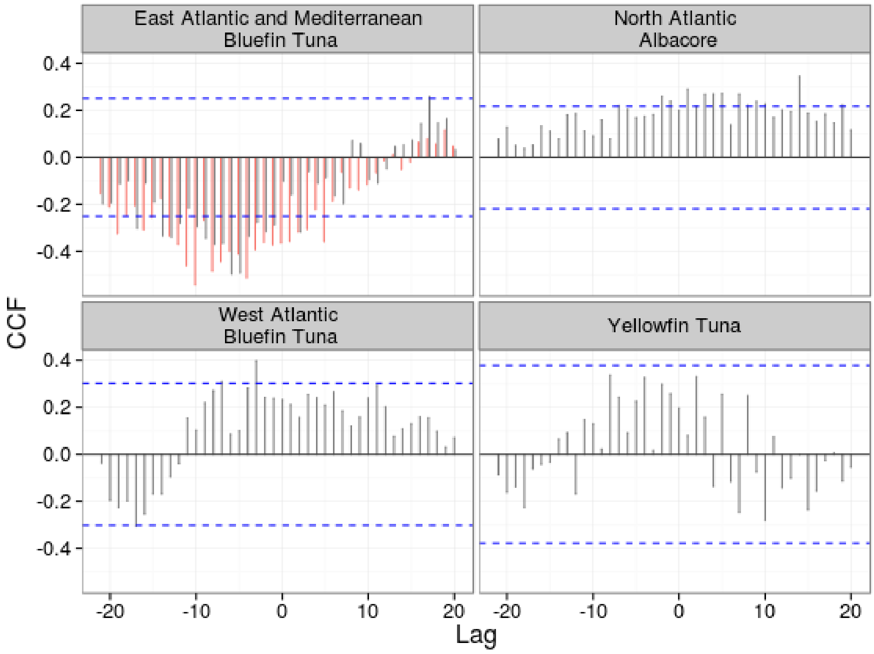

Figure 7: **Plots of cross correlation between recruitment and SRP, horizontal lines are the 5% CIs**

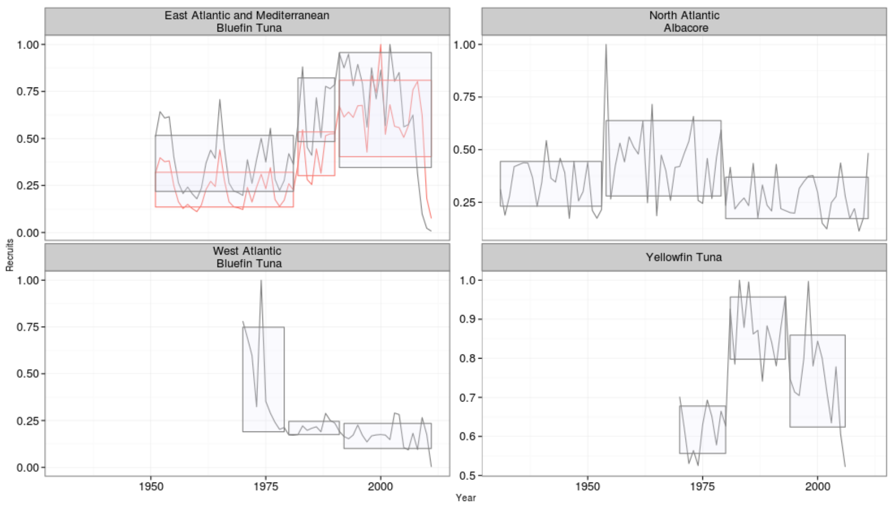

Figure 8: **Recruitment by year Sequential t test for regime shifts (Rodionov, 2004) in recruitment**

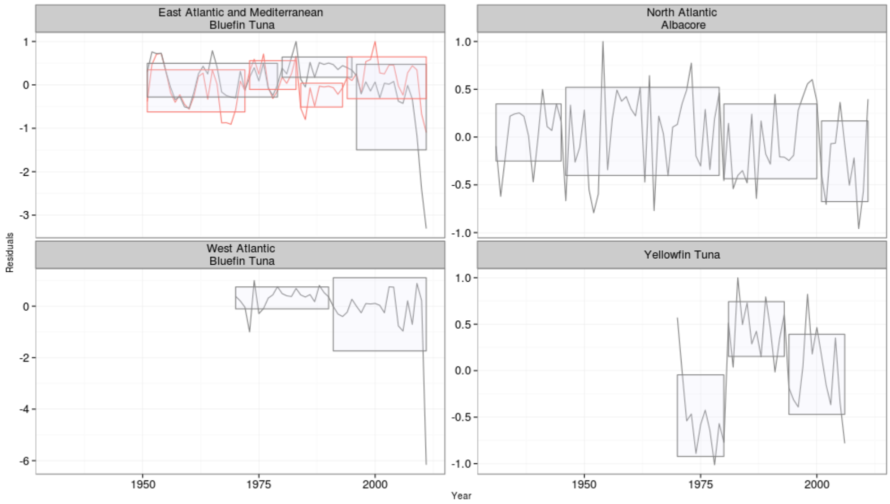

Figure 9: **Recruitment by year Sequential t test for regime shifts (Rodionov, 2004) in recruitment residuals**

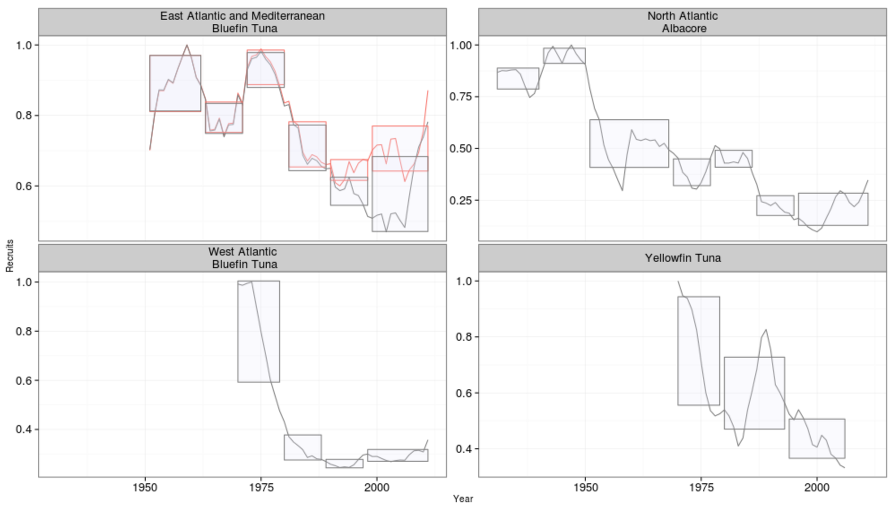

Figure 10: **Recruitment by year Sequential t test for regime shifts (Rodionov, 2004) in SSB**