Working Paper 20

Defining Projections and Biological Reference points for Atlantic Cod in a Changing Ecosystem

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Background

Biological reference points (BRPs) are the benchmarks by which we determine stock status (i.e., desired and undesired states) and can trigger management actions in the context of a harvest control rule. BRPs are typically estimated from static characterizations of a stock's productivity and may not reflect a stock's future productivity under persistent, directional changes in temperature that have impacted the productivity of fish stocks (Pershing et al. 2015, Le Bris et al. 2018) and elicited changes in spatial distribution (Nye et al. 2009, Pinsky et al. 2013), or as a result of changes in the stock sizes of predators or prey species. Failure to account for non-stationarity may increase the risk of management decisions that are either unsustainable or overly cautious, resulting in stock collapse or foregone yield (Szulwalski and Hollowed 2016, Mazur et al. 2023).

For US federally managed marine fisheries, MSY reference points should represent "prevailing ecological, environmental conditions" (NOAA 2009). In the most recent Gulf of Maine cod stock assessments the overfishing threshold was the FMSY proxy ($F_{40\%}$) and the biomass target (SSB_{MSY} proxy) was based on long-term stochastic projections of fishing at the F_{MSY} proxy (NEFSC 2013). This is consistent with the choice of proxy in the previous assessment and the SAW 55 working group's recommendation. A deterministic value of $F_{40\%}$ was calculated from a spawner per recruit analysis using 5-year average SSB weights, catch weights, selectivity and maturity. Recruitment was sampled from 1982 - 2017 and natural mortality was assumed equal to 0.2 (Figure 1). Due to the lack of an analytical assessment of Georges Bank Cod no reference points have been estimated since the transition to the PlanBsmooth approach in 2015.

The reference period used in the calculation of BRPs is particularly critical and can potentially lead to unrealistic expectations for stock rebuilding when conditions change directionally and the factors influencing the stock are no longer the same as those observed during a reference period. Furthermore, there are fundamental questions of whether $F_{40\%}$ remains a good proxy for

F_{MSY} in cases where current recruits per spawner for a stock are much lower than historical estimates.

The current short term projections for Gulf of Maine Cod were based on a harvest scenario fishing at the F_{MSY} proxy between 2022 and 2024. Recruitment was sampled from a cumulative distribution function between the years 1982- 2017, with the 2020 recruitment calculated as the geometric mean of the 2015-2019 estimates. The M-ramp model assumed a short-term natural mortality rate of M=0.4 which differs from the assumption used in reference point calculation. SSB projections for this stock have exhibited a tendency to overestimate future biomass values for both models (Figure 2). Several factors likely contribute to this bias, including the potential overestimation of the initial stock size, underestimation of fishing mortality in the projection bridge year, and reduced recruitment in recent years. It is important to note that the underestimation of F and overestimation of SSB are likely to have a more substantial impact on short-term projections than reduced recruitment, as existing biomass has a stronger influence on short-term projections than future recruitment. Regarding Georges Bank cod, no projections have been computed with PlanBsmooth, thus warranting further investigation or alternative methods.

Here we evaluate the following questions with respect to the definition of reference points for revised Atlantic cod stocks:

1. What is the appropriate time window of data for characterizing recruitment, growth, maturity, natural mortality in the calculation of reference points?
2. Should assumptions informing short-term projections mirror reference point assumptions?

Furthermore, we provide additional context and characterize WG discussion on the following questions:

3. Does F40% remain an appropriate proxy for Fmsy for Atlantic cod?
4. In cases where a WHAM model is adopted should we project random effects (default) and environmental covariates (4 options) ?

Methods

Recruitment & Growth

Data

We estimated recruitment success using seasonal (fall & spring) indices of abundance at age 1 from the Northeast Fisheries Science Center (NEFSC) bottom trawl survey between the years

1982-2019. The timing of the seasonal NEFSC varies by region, with the fall survey generally running from September-December, and the spring survey running from February-May. These data represent the standardized stratified mean number per tow of age 1 Atlantic cod, in strata 1380 and 1390 for Eastern Gulf of Maine (EGOM), 1090, 1100, 1230-1280, 1370, and 1400 for Western Gulf of Maine (WGOM), 1130-1220 for Georges Bank (GBK), and 1010, 1020, 1050, 1060, 1690, 1730, and 1740 for the Southern New England (SNE) stock area.

Spawning stock biomass (SSB) was estimated using spring and fall NEFSC bottom trawl survey numbers at age and weights at age for cod ages 4+ as an index. The stratified mean biomass for these indices was calculated for each year (1982-2019) and for each season, in units of kg/tow. Annual abundance of age 1 fish from the NEFSC trawl survey were used for recruitment data and recruits per spawner was used as a metric of recruitment success (Perretti et al. 2017) and calculated as recruitment = index of abundance at age 1 in year *t* per SSB in year *t-1* , e.g., R_t/SSB_{t-1}.

Growth analyses utilized cod relative condition and weight-at-age (WAA) data. Relative condition index data were calculated as the ratio of observed weight to predicted weight at a given length from the fall and spring NEFSC trawl surveys from 1992-2019, using the same estimation methodology as in the State of the Ecosystem New England report (2022). Atlantic cod WAA anomalies were calculated from the NEFSC Bottom Trawl survey for ages 1-9+ from 1982-2019. Weight at age data were limited, especially for SNE and EGOM stocks. Only stocks and ages which had >30 years of data were used and 1982-2011 base-period guidelines (data availability permitting) were used to calculate the means for the anomaly calculations. Fall WAA anomaly data includes ages 1-6 for WGOM, age 2 for EGOM, and ages 1-5 for Georges Bank. WAA anomaly data used for the spring growth analysis included ages 1-7 for WGOM, age 1 for EGOM, and ages 1-7 for GBK. There were not enough WAA data for SNE to run any WAA change point analysis for that region.

<u>Statistical analysis</u>

We used statistical methods, specifically change point analysis, to test for significant changes in recruitment and growth from the null hypothesis of stationarity. The “EnvCpt" and “changepoint” R packages were used for these analyses (Killick et al. 2014; 2021; 2022). The changepoint package can calculate the optimal positioning of changepoints in a time series dataset and has the ability to identify the number of changepoints for data if multiple changepoint methods are specified (“PELT” method; Killick et al. 2012), though the default of the package is to identify a single changepoint ("AMOC" method; Killick et al. 2022). The EnvCpt package was built upon the changepoint package and can detect change points simultaneously in mean and variance and can automatically infer the number of change-points. This analysis was run across these packages in effort to explore potential sensitivity differences in the changepoint results identified. However, results will focus on those derived from the "EnvCpt" package, with supplemental figures referenced from the "changepoint" package. For the changepoint package runs, the "cpt.mean" function was used and the "meancpt" model was used for the EnvCpt package runs. These packages have the ability to set and adjust the minimum segment length (number of observations between identified changepoints), where the number and location of changepoints is dependent upon the minimum segment length set (Beaulieu and Killick 2018). In this analysis, the default minimum segment length of 5 years was kept for all model analysis runs. Although a mean-based changepoint analysis is commonly used (Thomson et al. 2010; Gaertner 2010; Patel et al. 2015), one limitation of using mean-based changepoint analysis is that it may misinterpret or ignore the possibility of underlying trends in long time-series data (Beaulieu and Killick 2018).

Analyses were run for each stock region and season when sufficient data were available. Recruits per spawning stock biomass and weight at age change point analyses were not run for the SNE stock area due to insufficient data.

Maturity

See WP:
https://docs.google.com/document/d/1ebjhf8yOo7TMwSdPyXElwuDVazLul8T0/edit?usp=sharing&ouid=103711285632845486085&rtpof=true&sd=true

Natural Mortality

See WP:
https://docs.google.com/document/d/13Z_rOvh47z6LGEyPr34GkAYwnSbbx5NX/edit?usp=sharing&ouid=103711285632845486085&rtpof=true&sd=true

Results

Recruitment

Results from the changepoint analyses suggest there may have been a regime shift in recruitment of Atlantic cod stocks (Figures 3 & 4). The results of changepoint analysis on age-1 abundance suggests a possible shift to a lower recruitment regime since 2010 for the WGOM stock and since the early 1990s for the EGOM stock. The GB stock exhibited a shift to lower recruitment in the early 1990s and subsequent increase in the 2000s (Figures 3). However, these same patterns are not consistently seen in the R/SSB time series (Figure 4). This suggests that effects from fishing pressure may confound the results seen in the age 1 abundance data, such that identified significant changepoints may be a result of fishing pressure rather than environmental effects on the productivity of the stock. Changepoint analysis of R/SSB indicated evidence of the shift to lower R/SSB in 2010 for the WGOM stock although this was only evident in the spring survey data (Figure 4). Data limitations prevented conclusions for the EGOM stock (Figure 4). The GB stock showed a shift to lower R/SSB in the middle of the time series and then a return to higher R/SSB in the 2000s. Fewer changepoints were found for R/SSB data than for age 1 abundance data (Figure 4). These findings also indicate that alternative time windows should be considered for different stocks. Finally, overall fewer changepoints were identified by the "changepoint" package (Supplemental Figures 1 & 2) than by the "EnvCpt" package, which suggests different sensitivities between packages and the importance of package/methodology choice for a change-point analysis.

Growth

For groundfish stocks in the Northeast US, it is typical to use the most recent 5 year average WAA to inform and update reference points with each stock assessment. WGOM and GB cod stocks show some significant shifts in WAA over time that support continuing to characterize growth over the recent time window (i.e. most recent 5 years; Figures 5-7; Supplemental Figures 3 - 5).

Maturity

For groundfish stocks in the Northeast US, it is typical to use the most recent 5 year average MAA to inform and update reference points with each stock assessment. Analyses of maturity patterns revealed that, except for the SNE stock, all other stocks were best described by including temporal variation in maturity (WP 12). In line with the status quo approach, the utilization of the five-year recent average MAA remains supported by the current findings. The results indicate a degree of stability in the A50 over the most recent five-year period for the EGOM and SNE stocks, a slight decline in A50 for WGOM and more prominent decline for GB. The changes over time provide justification for adhering to the typical approach of characterizing maturity over the recent time window (Figure 8). The declining trends in A50 in WGOM and GB should continue to be monitored.

Natural Mortality

For groundfish stocks in the Northeast US, it is typical to utilize a time-invariant natural mortality rate (M) as a basis for determining reference points. However, Gulf of Maine cod was somewhat unique as two assumptions regarding natural mortality were considered to inform projections (M=0.2 and M-ramp), however, M=0.2 was used to inform reference points. Although the exact measurement of natural mortality for each Atlantic cod stock was not directly obtained, it was estimated using life-history proxies, as detailed in the Natural Mortality WP (WP 14). This research provided estimates of lifetime M and M-at-age, but it cannot inform whether M has increased in recent years. The ToR1 subgroup recommended exploring the incorporation of time-varying M in assessment models where appropriate. The results of this analysis within the assessment will serve as a basis for informing assumptions in projections.

Discussion

What is the appropriate time window of data for characterizing recruitment, growth, maturity, natural mortality in the calculation of reference points?

It is recommended to continue using recent averages of WAA and MAA to update stock-specific reference points and projections. In addition, exploratory analyses revealed recurring negative relationships between growth and temperature indicators, which corroborate with literature suggesting poor cod growth under warming temperature conditions (Pershing et al. 2015). The impact of changing ocean conditions on stock productivity, specifically natural mortality and recruitment, should be considered in parameterization to inform short-term projections and biological reference points. For recruitment, there is some evidence to support consideration of alternative time windows for different stocks. For example, exploratory analyses suggested a negative relationship between WGOM Atlantic cod recruits/spawner and temperature indicators (ie. bottom and sea surface temperature anomaly), suggesting that warmer water temperatures negatively impact Atlantic cod recruitment (see ToR 1). Additionally, adjustments to biological reference points should be explored to account for changes in natural mortality. Further exploration of the incorporation of time-varying M in assessment models where appropriate is recommended.

Should assumptions informing short-term projections mirror reference point assumptions?

Consistency in parameters used to inform short-term and long-term projections has been recommended (NEFMC SSC report) if we believe that changes in aspects of stock dynamics are not expected to return to historical conditions (i.e., future low recruitment).

Does F40% remain an appropriate proxy for Fmsy for Atlantic cod?

$F_{40\%}$ represents the fishing mortality that aims to preserve 40% of the maximum spawning potential. Proxies are utilized to define overfishing due to the challenges in accurately estimating F_{MSY}, which is usually due to the lack of a well-defined stock-recruitment relationship. However, SPR-based F reference points, which exclude recruitment, fail to account for the full range of productivity conditions. Consequently, when productivity declines to low levels, these reference points result in an overestimation of sustainable F levels.

Cadrin (2012) evaluated performance of F_{MSY} proxies by comparing estimated spawning stock biomass and recruitment (SSB/R ratios) with expected spawning biomass per recruit (SPR) at alternative fishing mortalities (F=0, $F_{30\%}$, $F_{40\%}$) to investigate the potential for replacement under equilibrium assumptions (i.e., constant F over the lifespan). This study found $F_{40\%}$ to be an overly-conservative proxy of F_{MSY} for cod based on an analysis of Gulf of Maine and Georges Bank cod data in 2008. (i.e., F_{MSY} is greater than $F_{40\%}$). However, if productivity of cod stocks has changed there is a need to re-examine the stock-recruit relationship to confirm the justification for using $F_{40\%}$ and $SSBF_{40\%}$ as proxy reference points.

In cases where a WHAM model is adopted should we project random effects (default) and environmental covariates (4 options) ?

WHAM conducts its projections internally. When it comes to random effects, the default setting is to carry forward the random effects in projections, except for selectivity. Regarding environmental covariates, the default setting is to continue the ecov process model, by the setting “cont.ecov = TRUE”. It's important to note that deciding whether to continue autocorrelated processes into the projection years has significant implications for short-term SSB forecasts.

Figures

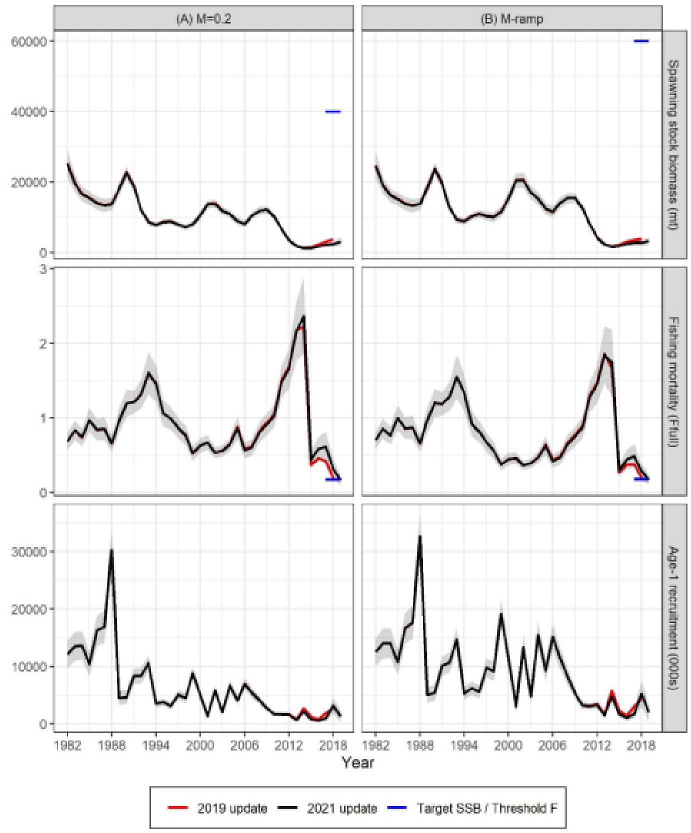


Figure 1: Estimated trends in the spawning stock biomass, fishing mortality and age-1 recruitment of Gulf of Maine Atlantic cod from 1982 to 2018 based on the M=0.2 (A) and Mramp (B) model scenarios. The 2017 update results (NEFSC 2017) are shown in red for comparison.

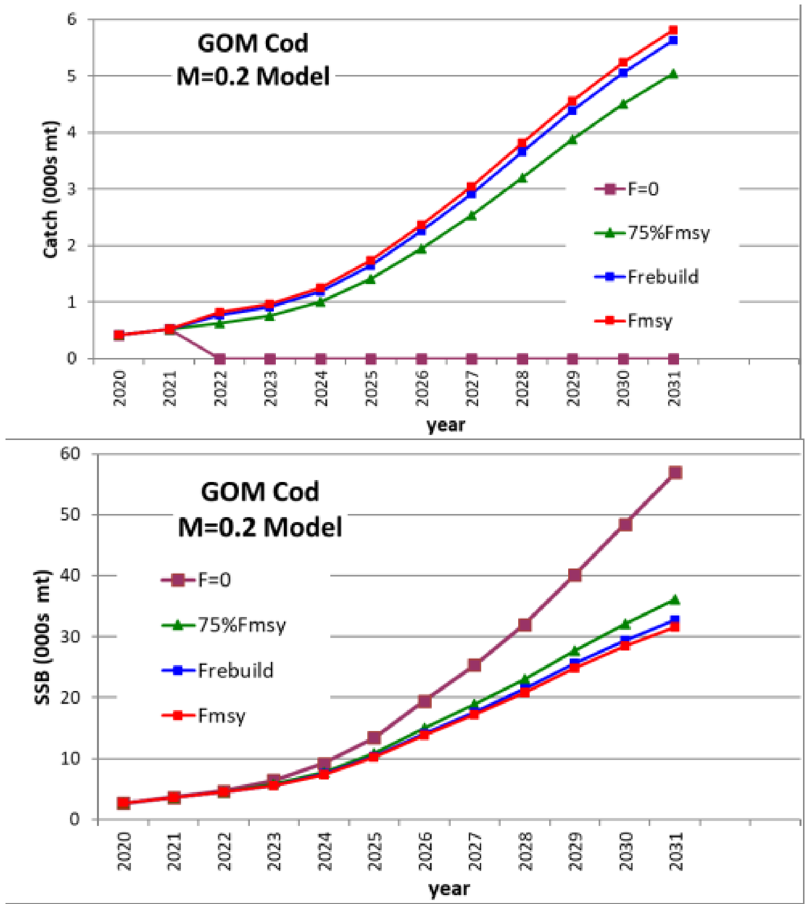


Figure 2: Short-term projections from the 2021 Gulf of Maine cod models (M=0.2 and M-ramp; NEFSC 2021).

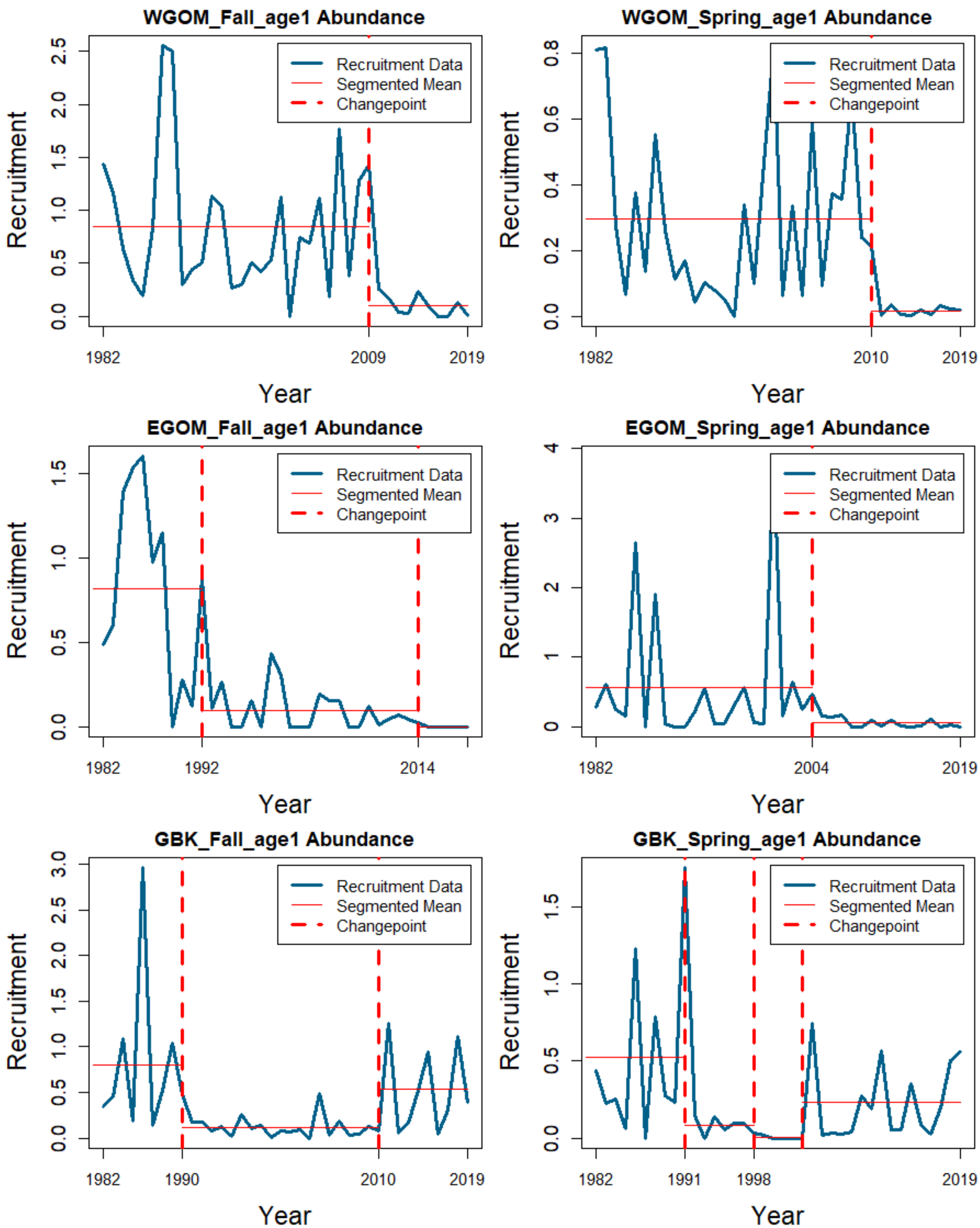


Figure 3: Recruitment changepoint point analysis results from “EnvCpt” package using age 1 abundance data (as proxy of recruitment) from the NEFSC bottom trawl survey.

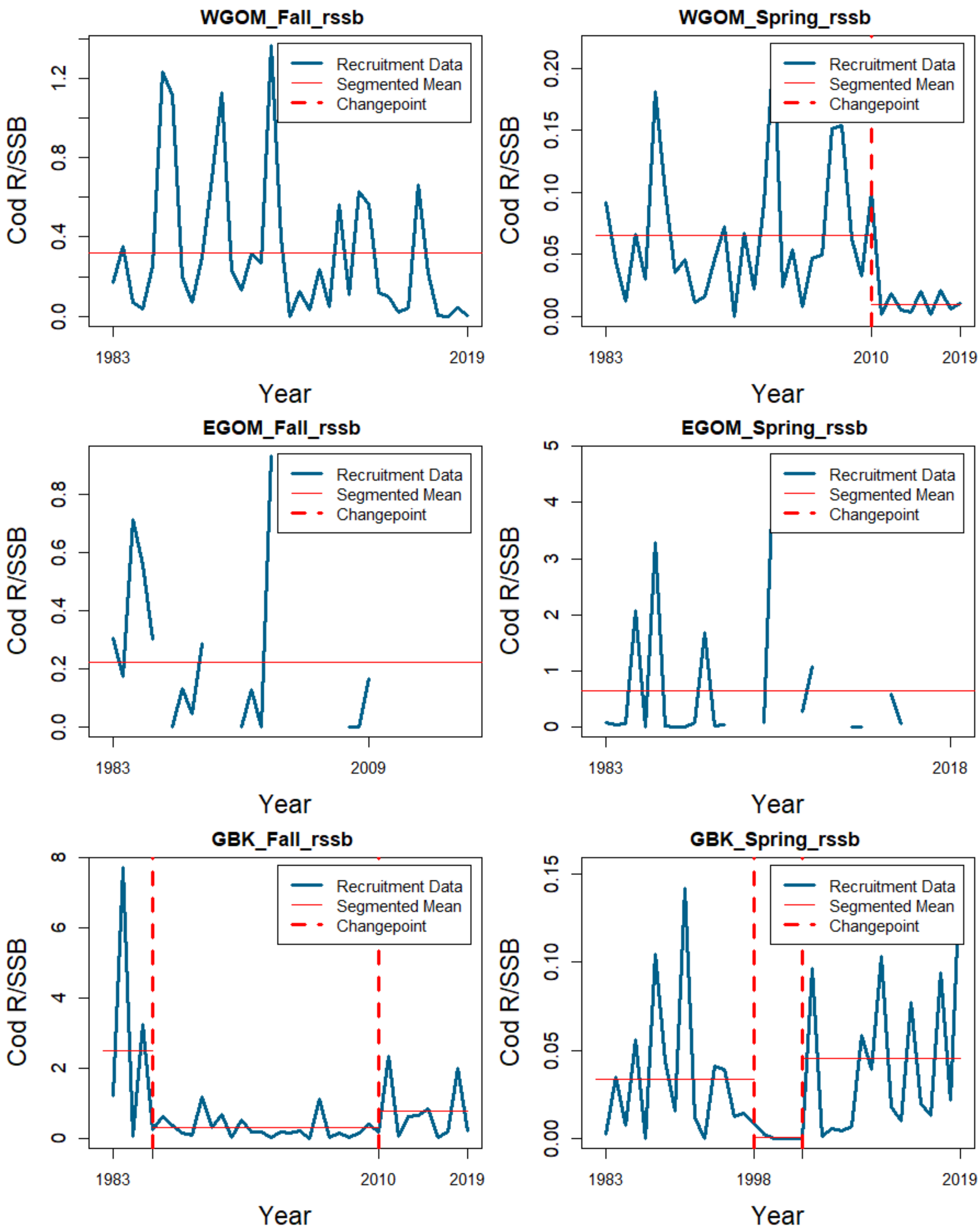


Figure 4: Recruitment changepoint point analysis results from the “EnvCpt” package using recruits (age 1 abundance) per spawning stock biomass (R/SSB) data.

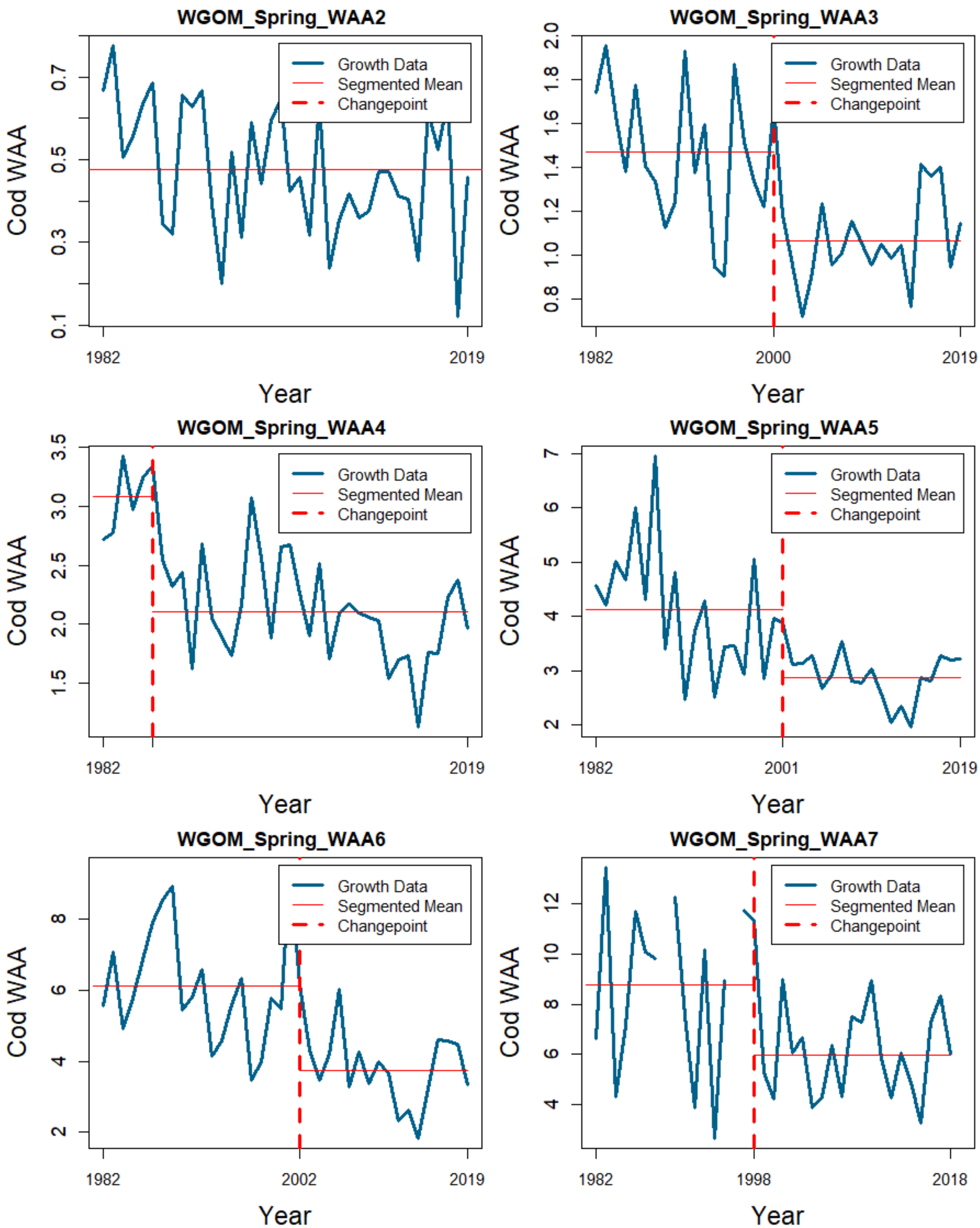


Figure 5: WGOM Spring Growth changepoint point analysis results from the “EnvCpt” package using weight at age (WAA) anomaly data.

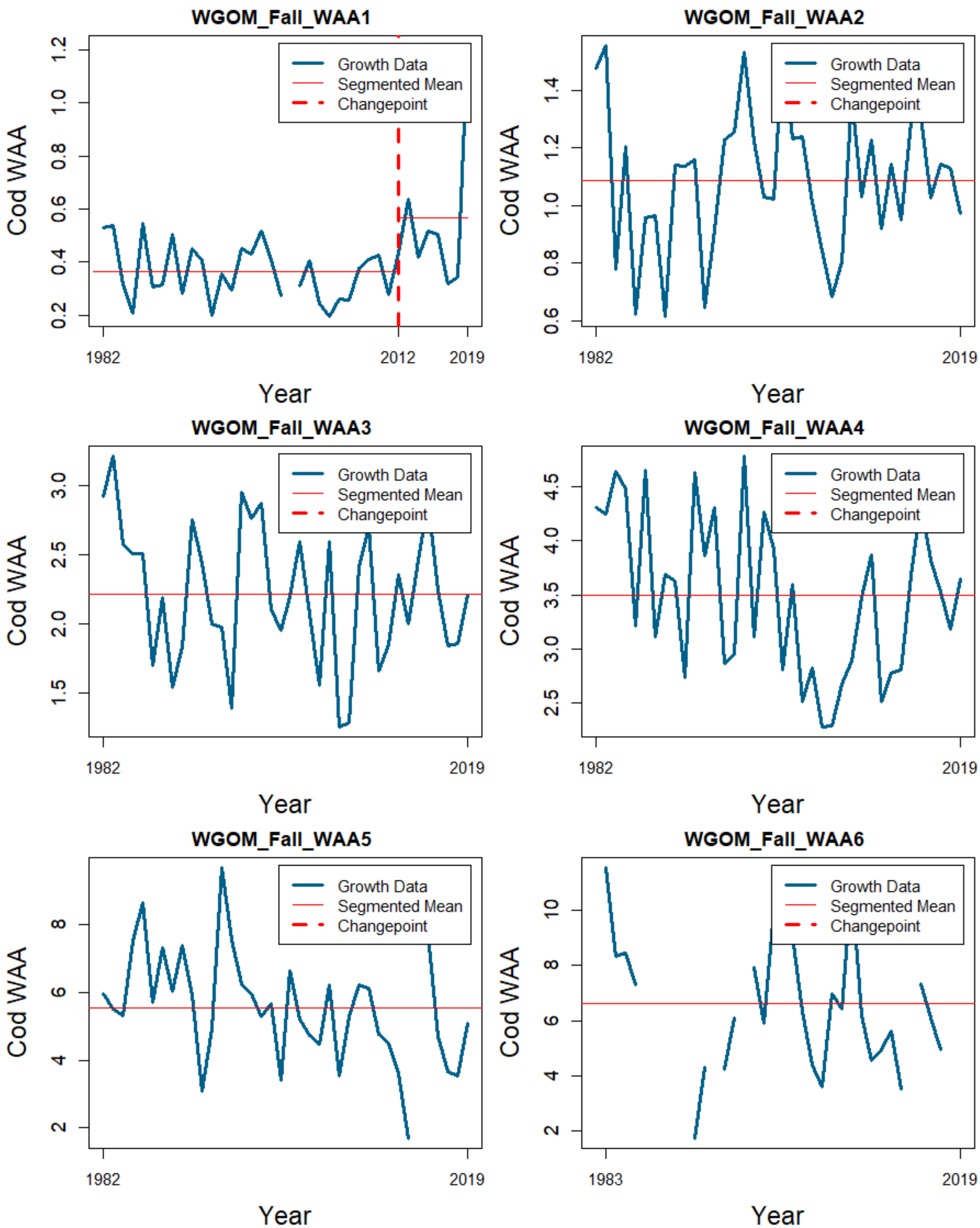


Figure 6: WGOM Fall Growth changepoint point analysis results from the "EnvCpt" package using weight at age (WAA) anomaly data.

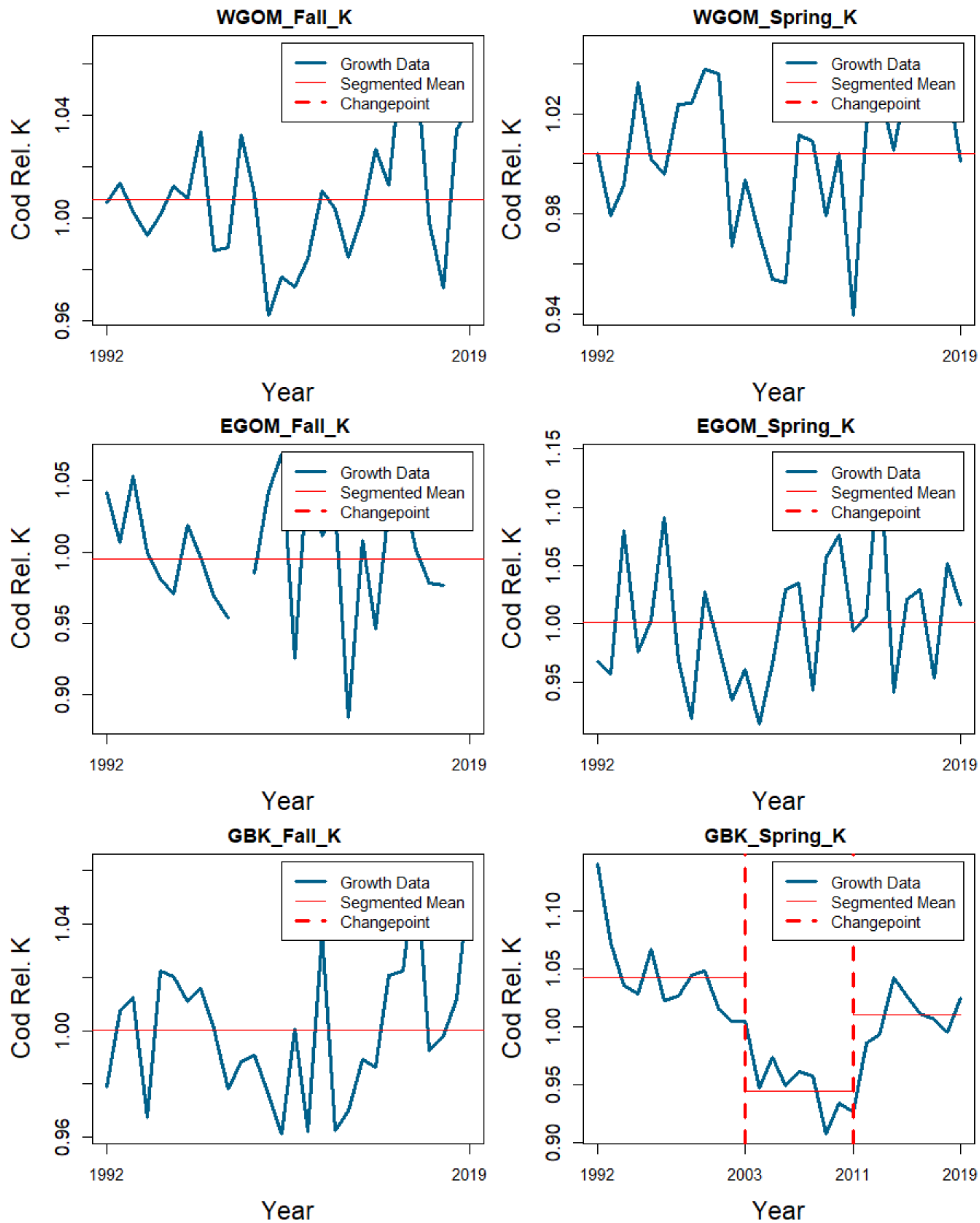


Figure 7: Growth changepoint point analysis results by stock area from the "EnvCpt" package using relative condition data.

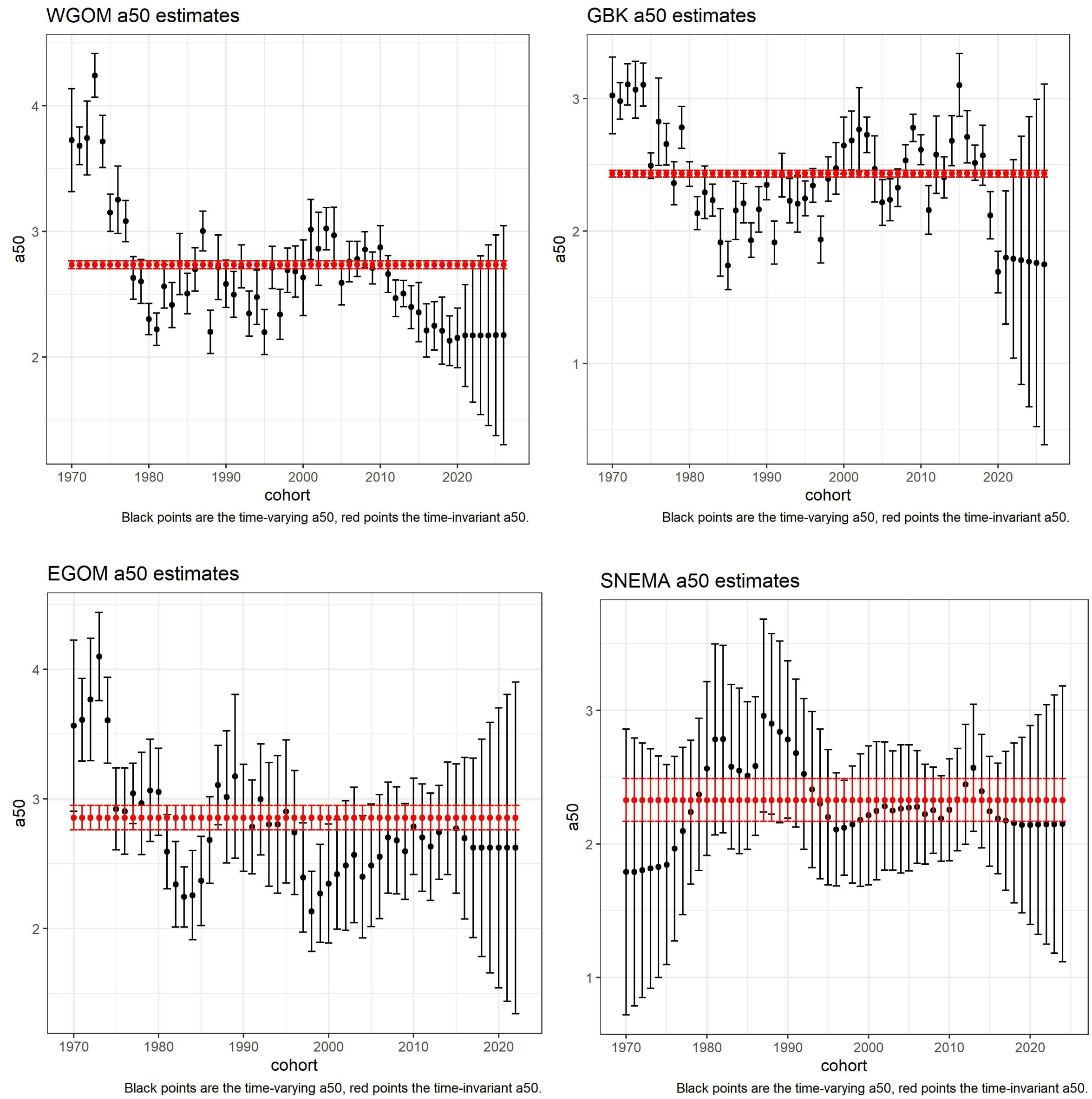


Figure 8: Estimates of maturity (A50) over time for Altantic cod stocks.

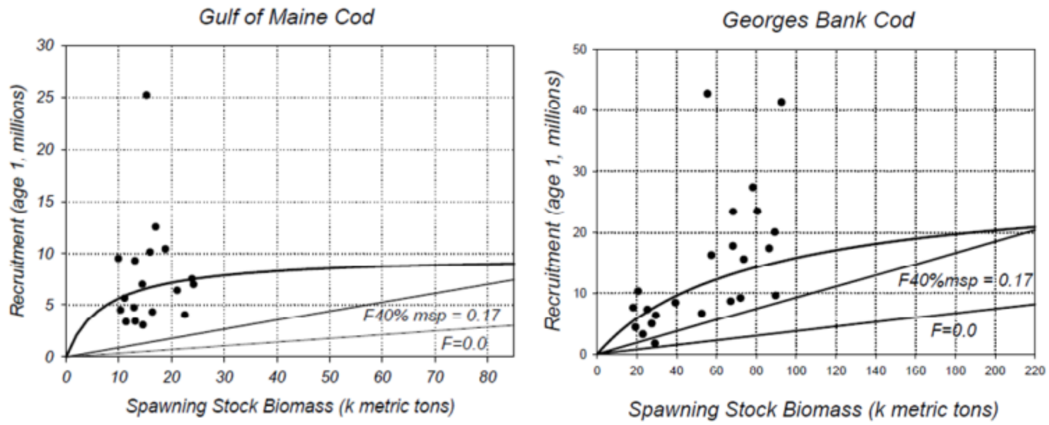
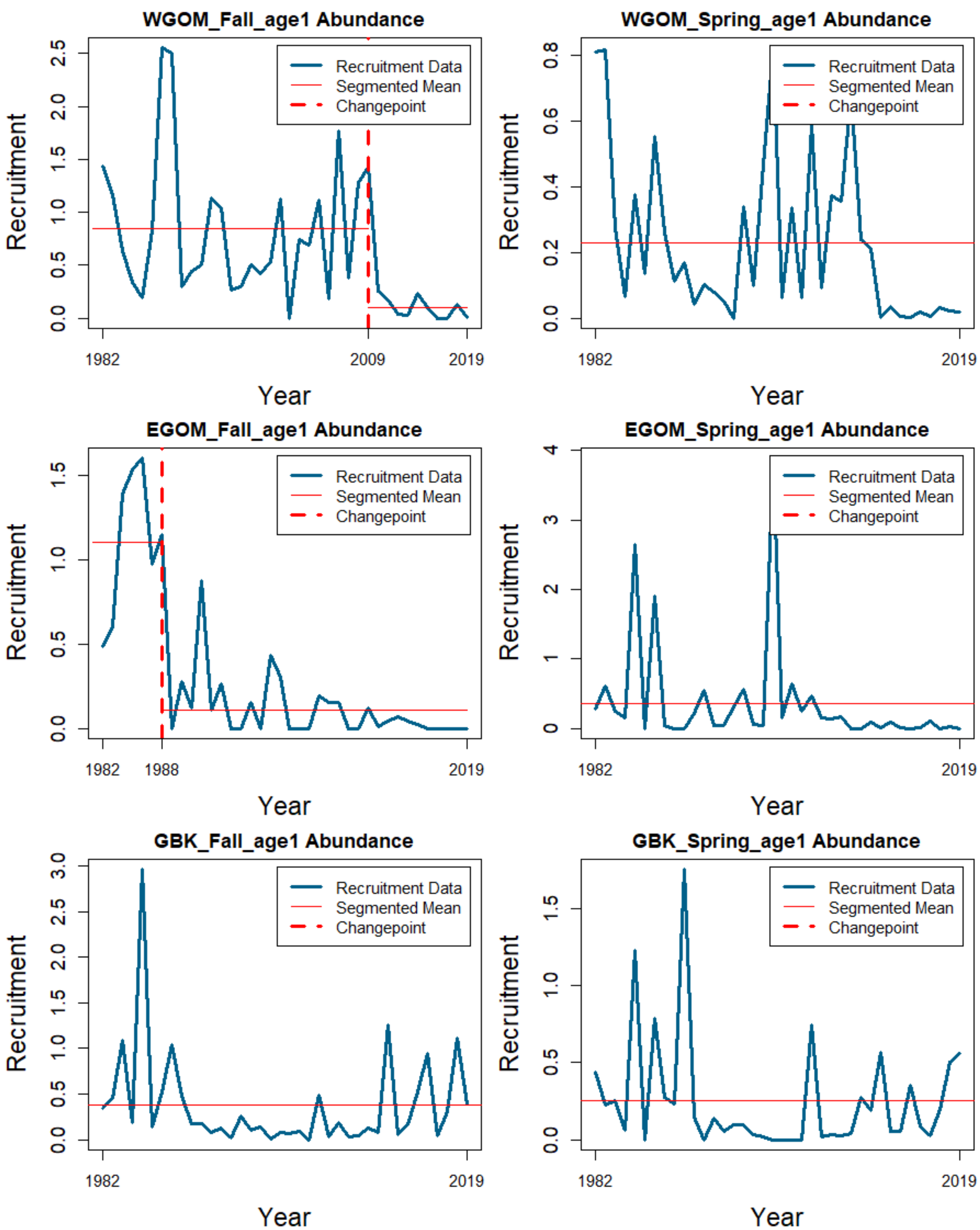
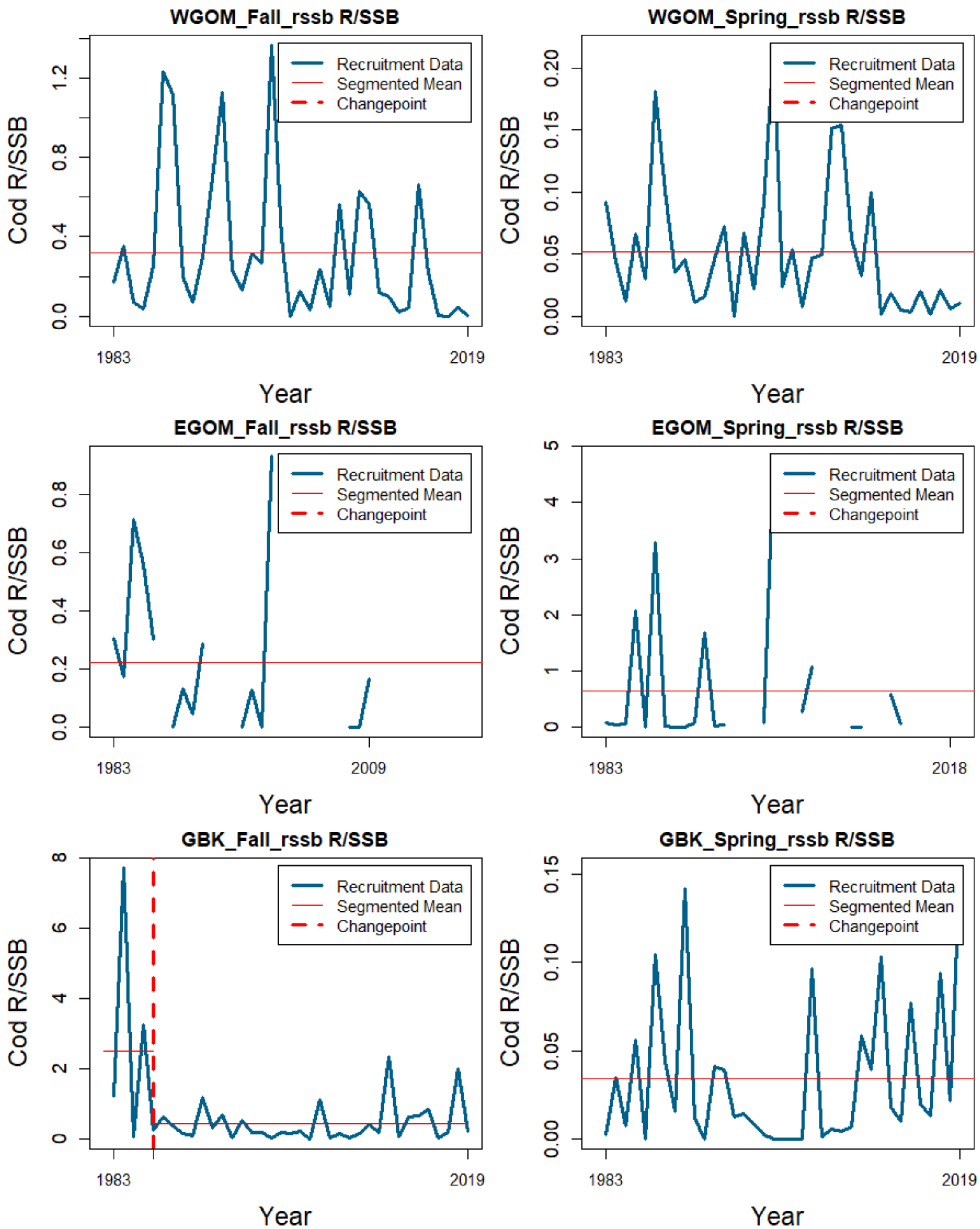


Figure 9 *Comparison of the F=0 and F40% replacement line and stock-recruit pairs for New England groundfish (adapted from NEFSC 2002, 2003). From Cadrin 2012.*

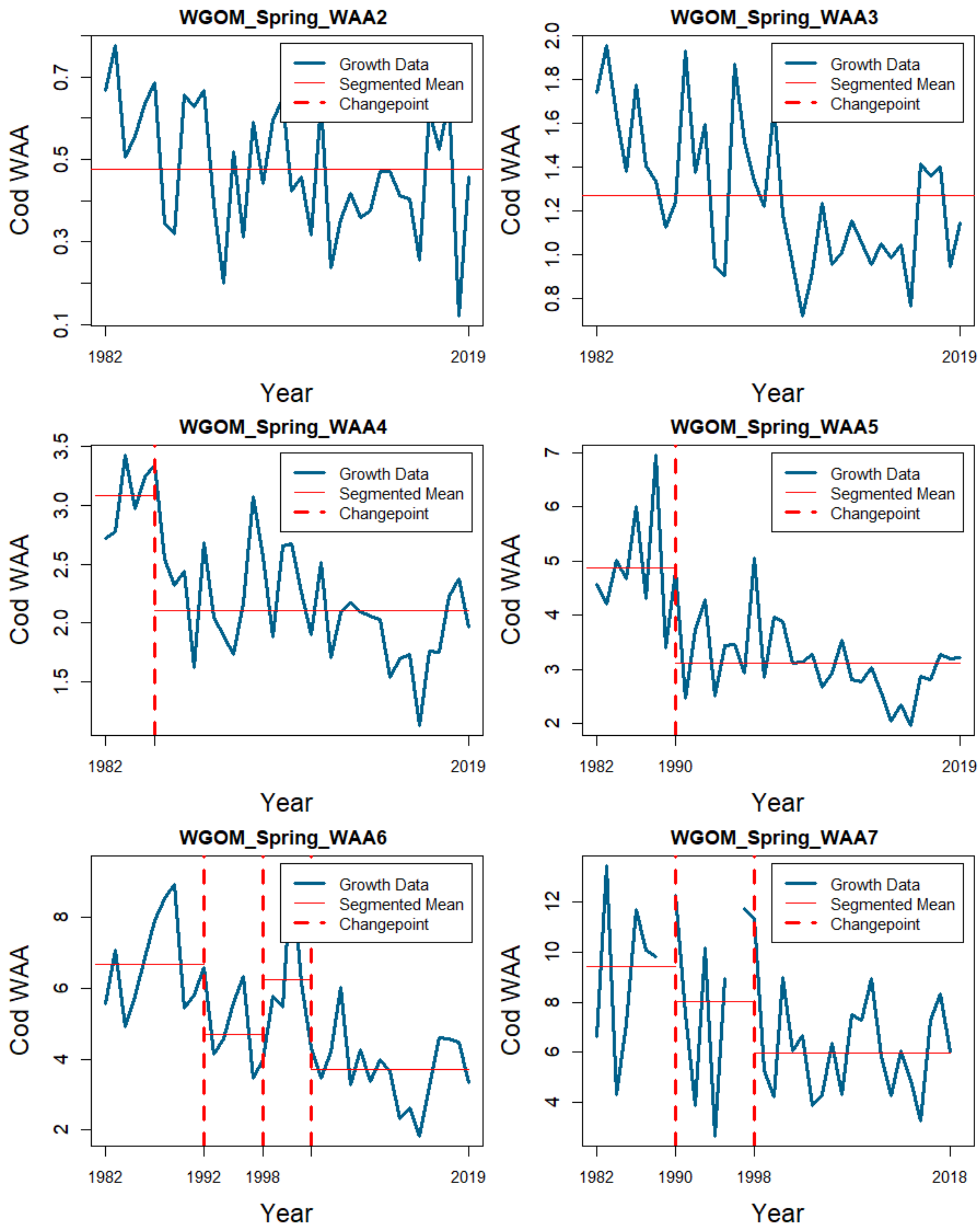
Supplementary Figures



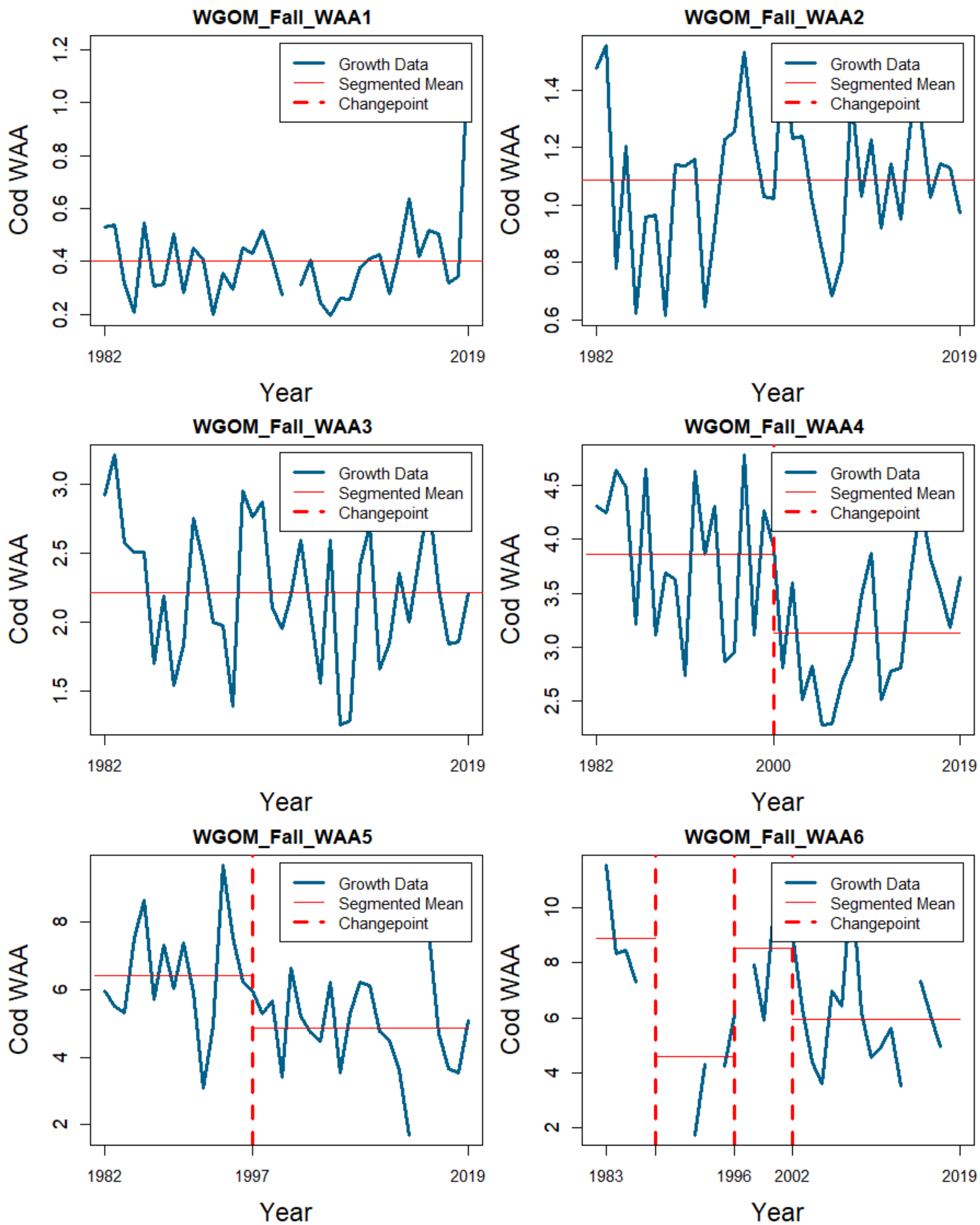
Supplementary Figure 1: Recruitment changepoint point analysis results from the “changepoint” package using age 1 abundance data (as proxy of recruitment) from the NEFSC bottom trawl survey.



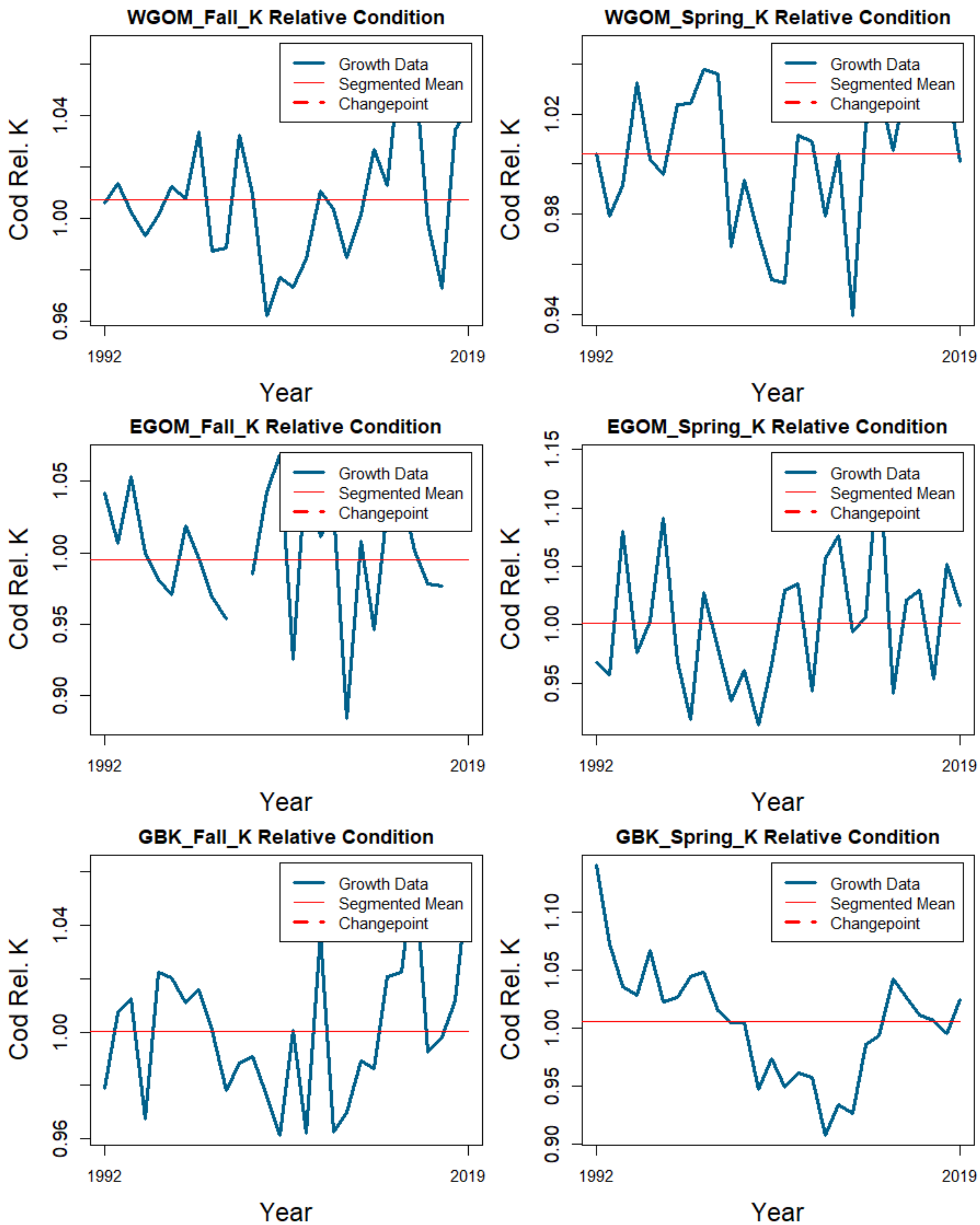
Supplemental Figure 2: Recruitment changepoint point analysis results from the “changepoint” package using recruits (age 1 abundance) per spawning stock biomass (R/SSB) data.



Supplementary Figure 3: WGOM Spring Growth changepoint point analysis results from the "changepoint" package using weight at age (WAA) anomaly data.



Supplementary Figure 4: WGOM Fall Growth changepoint point analysis results from the "EnvCpt" package using weight at age (WAA) anomaly data.



Supplementary Figure 5: Growth changepoint point analysis results by stock area from the “changepoint” package using relative condition data.

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