# Incorporating ecosystem considerations within the Stock Synthesis integrated assessment model for Gulf of Mexico Red Grouper (*Epinephelus morio*)

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**Incorporating ecosystem considerations within the Stock Synthesis integrated assessment model for Gulf of Mexico Red Grouper (*Epinephelus morio*)**

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## Abstract

Significant progress has been made within the Gulf of Mexico (GOM) in terms of incorporating ecosystem products into single-species stock assessments. In this study we assessed the impact of incorporating two environmental processes within the benchmark 2015 GOM Red Grouper assessment conducted using Stock Synthesis: (1) red tide mortality and (2) recruitment anomalies due solely to oceanographic factors. For red tide, we: (1) determine whether inclusion of red tide mortality increases the plausibility of the model; (2) evaluate different configurations for incorporating red tide mortality; and (3) identify age classes susceptible to red tide mortality given the model and data used. For recruitment, we test whether the inclusion of an index of recruitment anomalies based solely on oceanographic factors increases the plausibility of the model. Natural mortality due to the 2005 red tide event was estimated between 0.44 and 0.48 by both methods tested. Incorporation of red tide mortality improved model fit in comparison to the model with no red tide. Recruitment deviations produced by SS were not significantly related to the index of recruitment anomalies.

## Introduction

Accounting for environmental influences on population processes within stock assessment models can improve estimation of model parameters and derived quantities (Maunder and Watters 2003) and can enhance confidence in model predictions by reducing scientific uncertainty. The need for ecosystem considerations within fisheries management has been reinforced by updated management measures mandating consideration of ecological processes within stock assessments (MSFCMA 2007). Responsible incorporation of environmental considerations into an assessment model requires theoretical grounds for inclusion (i.e., biological justification), environmental covariates, and appropriate methodology (Sagarese et al. 2014b). Recent advancements in integrated analysis (see Methot and Wetzel 2013 for review) have enabled linkage of life-history processes such as natural mortality and recruitment to external stressors within a traditional single-species stock assessment framework (Maunder and Watters 2003; Methot 2009).

Stock assessment models frequently do not explicitly incorporate the impact of environmental influences on population dynamics. However, spikes in natural mortality from episodic events such as red tides could have important implications for biological reference points and for population modeling (Schirripa and Methot 2013). For Red Grouper *Epinephelus morio*, a significant impact of red tide events on natural mortality has been hypothesized because much of their habitat on the West Florida Shelf (WFS) coincides with areas susceptible to red tide blooms (Walter et al. 2013; Sagarese et al. 2014a). In addition, Red Grouper exhibit strong site fidelity (Saul et al. 2013) and maintain burrows on the WFS (Coleman et al. 2010; Coleman et al. 2011), which may reduce their mobility to vacate areas affected by red tide events. The 2009 update assessment model for Red Grouper initiated consideration of red tide by allowing extra mortality during 2005 (SEDAR 2009). Model fits to indices of abundance were improved because this configuration accounted for the sudden decline in abundance observed during the 2005 red tide. Anecdotal evidence of red tide mortality has sporadically been documented on serranids such as Red Grouper throughout the eastern Gulf of Mexico (GOM) (Smith 1975; Walter et al. 2013). More recently, Red Grouper were observed in fish kills during the 2014 red tide event by the NOAA Panama City Laboratory (D. DeVries, *pers. comm.*).

Environmental factors which can affect recruitment strength (e.g., sea surface temperature) are typically excluded from assessment models, and can manifest themselves as anomalies from the stock-recruitment relationship or biased estimates of other parameters. The accuracy and/or precision of the assessment can be improved by explaining some of this variation with an index representing external environmental forces hypothesized as drivers of recruitment. Rather than use correlations between recruitment deviations and environmental variables, mechanistic approaches such as the Connectivity Modeling System (CMS) (Paris et al. 2013) can simulate the transport of larvae based on oceanographic features. For both Red Snapper *Lutjanus campechanus* and Gag Grouper *Mycteroperca microlepis*, resultant recruitment anomaly indices explained roughly 33% and 58% of the variation in the estimated stock-recruitment deviations, respectively (Karnauskas et al. 2013a; Karnauskas et al. 2013b). Such indices provide valuable insight into cohort strength in the recent years of the assessment, and can inform recruitment potential during model projections.

Significant progress has been made within the GOM in terms of incorporating ecosystem products into single-species stock assessments, most notably for Gag Grouper (Sagarese et al. 2014b; SEDAR 2014). For the 2015 GOM Red Grouper stock assessment, the objectives of this study were to: (1) determine whether consideration of red tide mortality and recruitment anomalies enhanced model plausibility; (2) evaluate different configurations for incorporating each process into the Stock Synthesis (SS) model; and (3) identify age classes susceptible to red tide given the model and data used. For both natural mortality and recruitment, various scenarios for inclusion were tested, with the best method of incorporation selected on the basis of performance criteria (e.g., mean errors) and model selection criteria where appropriate.

## Methods

### *Environmental data*

**Red tide indices –** Walter et al. (2013) provided indices of red tide severity over various temporal and spatial domains between 1998 and 2010. Generalized additive models were used to predict the bloom probability as a function of satellite derived remote sensing products (e.g., chlorophyll, backscatter, etc.) and cell counts from the Florida Fish and Wildlife Research Institute harmful algal bloom (HAB) database (Walter et al. 2013). Of seven indices developed, three were recommended for testing within the stock assessment model: (1) 10mMCP75 (MCP), an index where spatial coverage is focused on depths > 10 m and the 75% minimum convex polygon of the HAB cell count data; (2) Grouper (GRP), an index where spatial coverage is focused on critical grouper habitat; and (3) Threshold (THR), a binary index where red tide events are depicted as present (= 1, above threshold value for MCP) or absent (= 0) (Figure 1A). Further details on model development, validation, and selection can be found in SEDAR33-DW08. Although work is currently underway to extend this index to 2014, updated indices were not available at the time of the Assessment Workshop. Based on evidence of no severe red tides in the field between 2011 and 2013, the THR Index was extended through 2013 (2011 – 2013 = 0). This assumption is corroborated by results of a modeling study conducted by Dave Chagaris (FWC), details of which were presented at the Gulf of Mexico Fishery Management Council meeting in January 2015.

The WFS Red Tide Ecopath with Ecosim model was customized to incorporate both red tide and predator/prey dynamics on Red Grouper population dynamics (Gray et al. 2013; Gray 2014; Sagarese et al. 2015). A pseudo-fishery was created with red tide acting as a relative effort driver (Gray et al. 2013). Within the model, red tide mortality is forced across a realistic range of species using a forcing pattern developed from a combination of two data sources: *Karenia brevis* cell counts (FWRI 2015) and a composite red tide index including reflectance and other features (Walter et al. 2013). The index of red tide mortality (MRT) produced for adult Red Grouper between 1998 and 2009 was considered within this analysis (Figure 1A). Years prior to 1998 were not considered within the present study because of concerns over the realistic representation of red tide mortality prior to data collection (i.e., prior to harmful algal counts and satellite data). Further details can be found in SEDAR42-AW01.

**Natural mortality vector incorporating ecosystem considerations** − The spatially-structured, individual-based and multispecies OSMOSE modeling approach was applied to the WFS to describe the trophic structure of this ecosystem in the 2000s (Grüss et al. 2015a; Grüss et al. 2015b). The resultant model is referred to as 'OSMOSE-WFS'. The OSMOSE-WFS model relies on both size-based interactions and explicit implementation of the entire life cycle of high trophic level groups of species (Shin and Cury 2001; Shin and Cury 2004). The basic units ("super-individuals") of OSMOSE-WFS are schools, which consist of marine organisms belonging to the same high trophic level group, which have the same body length, age, food requirement and, at a given time step, the same spatial coordinates. Grüss et al. (2015b) provided an age-specific vector of natural mortality which estimates mortality due to predation, starvation, and other processes not explicitly considered in OSMOSE-WFS (e.g., red tide events, diseases, mortality due to other marine organisms [e.g., marine mammals]) (Figure 2). Additional details on model development, calibration, and results can be found in Grüss et al. (2014b) and (Grüss et al. 2015b).

**Recruitment** − The CMS model described in (Grüss et al. 2014a) was modified as requested by the SEDAR 42 life history working group to produce an index of recruitment anomalies due solely to oceanographic factors (Figure 1B). Here, we briefly discuss changes made to the modeling framework detailed in SEDAR42-DW03. Spatial maps of adult Red Grouper distribution were modified to include Panama City Trap data which greatly enhanced coverage on the northern WFS. To account for the higher fecundity of large adult females compared to small adult females, the number of eggs released at each Red Grouper spawning site was estimated based on (1) the probability of presence of adult Red Grouper at that site; and (2) the relative fecundity by depth. The revised CMS index covers 2003 to 2014 and provides insight into potential recruitment for the first year of projections in 2014.

### *Modeling approach*

An integrated analysis modeling approach was utilized to describe the population dynamics of Red Grouper within the GOM. The Stock Synthesis (SS) assessment framework (Methot 2012) consists of three sub-models built using multiple data sources to provide a more comprehensive picture of abundance and impacts of fishing on stock dynamics (Methot and Wetzel 2013). The population sub-model parallels those found in most statistical catch-at-age models. The observational sub-model takes the various sources of data and calibrates the model. The statistical sub-model quantifies the goodness of fit statistic by comparing values expected (i.e., from population and observed models) with those observed (i.e., from data). Stock Synthesis is highly flexible in model configuration and prior values and can easily accommodate ecosystem considerations (Schirripa and Methot 2013).

### *Justification*

**Natural mortality −** A variant of the 2015 GOM Red Grouper base assessment model (with no red tide consideration) was parameterized to allow natural mortality to deviate freely between 1998 and 2010, leading to a vector of additional mortality expected by the model given the input data. Due to the large number of age classes in the base model, an abbreviated model was used which included 3 breakpoints instead of 21. Natural mortality rates ($M$) were input as a fixed vector for ages 0 – 1 ($M = 0.584$), ages 1 – 2 ($M = 0.355$), and ages 3+ ($M = 0.159$). Natural mortality deviations were regressed against each red tide index for adult Red Grouper to explore their association under a null hypothesis of no linear relationship (i.e., slope of 0) (Schirripa and Methot 2013). A significant regression ($\alpha = 0.05$) would support the incorporation of red tide as a time-varying process to reduce variability in natural mortality (Schirripa and Methot 2013).

**Recruitment −** Annual recruitment deviations were estimated within the 2015 GOM Red Grouper base model, leading to a vector of variation in recruitment expected by the model given the input data. Recruitment deviations were extracted between 2003 and 2013 and regressed against the index of recruitment anomalies to explore their association under a null hypothesis of no linear relationship (i.e., slope of 0) (Schirripa and Methot 2013). As discussed above, a significant regression ($\alpha = 0.05$) would support the incorporation of the recruitment index as a time-varying process to reduce variability in recruitment (Schirripa and Methot 2013).

### *Incorporating environmental processes into Stock Synthesis*

**Red tide −** Four scenarios incorporating red tide mortality into the SS model were tested to determine whether the plausibility of the base model increased with this environmental consideration (Table 1):

(i) Scenario 1: no red tide effect and no method of incorporation. This model fixed $M$ as a vector of 21 breakpoints starting at age 0 and ending at ages 20+ with the overall trend mimicking a Lorenzen curve (Figure 2). Estimates of *M* were provided by the SEDAR 42 life history working group at the Data Workshop (SEDAR 2015).

(ii) Scenario 2: incorporating extra mortality ($M_{rt}$) solely in 2005. Similar but not identical to the procedure used in the 2009 SEDAR 12 Update, a constant was added to each fixed *M* at age during 2005 in the assessment model (SEDAR 2009). Two constants were considered: a) 0.25, the episodic mortality rate ($M_{rt}$) estimated using the 2010 Update ASAP red tide model (SEDAR 2009); and b) the value identified as the best estimate by likelihood profiling in SS ($M_{rt}$ = 0.48) (Figure 3).

(iii) Scenario 3: a red tide fishing fleet with effort driven by the: (1) THR index, (2) MCP index, (3) GRP index or (4) MRT index. All fish encountered by the red tide pseudo-fishery were discarded with 100% mortality. A catchability parameter (*q*) was estimated and used to scale the effort series (i.e., red tide index) to the estimate of dead discards (Methot 2012). Selectivity of the red tide fishing fleet was modeled by age and assumed equal to 1.0 for ages 0 to 20+ due to the lack of available data on size-specific red tide mortality.

*(iv)* Scenario 4: an age-specific vector of *M* estimated from OSMOSE-WFS which explicitly considers mortality due to ecological processes.

**Recruitment** − Two scenarios incorporating the recruitment index were tested to determine whether the plausibility of the base model increased with this environmental consideration (Table 1):

A. Scenario A: model method. The environmental index drives the expected recruitment deviations through an estimated link parameter (*β*):

(1) $$\hat{R}_t = f(SSB_t)\ x\ exp(\beta E_t)$$

where *β* is the slope parameter relating the environmental time-series ($E_t$) to the recruitment deviation ($\hat{R}_t$) and $SSB_t$ is the spawning biomass (Maunder and Watters 2003; Schirripa et al. 2009; Schirripa and Methot 2013).

B. Scenario B: data method. This method uses an index of recruitment as a survey of age-0 recruitment abundance to tune the time-series of annual recruitment deviations from the fitted stock-recruitment curve (Schirripa and Methot 2013).

***Model evaluation***

**Model selection among comparable scenarios** − Likelihood components and model selection criteria were directly comparable for red tide scenarios 1, 2, and 4. Changes in negative log-likelihood (*NLL*) components for each CPUE index were compared to determine which CPUE indices benefited from consideration of red tide and how its inclusion affected expected trends in abundance. Both Akaike's Information Criterion (AIC; Akaike 1974) and Bayesian Information Criterion (BIC; Schwarz 1978) were calculated when appropriate (Helu et al. 2000). Since the number of parameters (*K*) was relatively similar compared to sample size (*n*) ($n/K << 40$) (Burnham and Anderson 2004), a small-sample AIC (AICc) was calculated for each environmental scenario using the following equation:

(2) $$AIC_c = 2\ NLL + 2K + \frac{2K\ (K+1)}{n-K-1}.$$

where $n$ was approximated by adding the number of survey and discard observations to the number of length and age bins (Helu et al. 2000; Stewart 2006). Bayesian Information Criterion was calculated using the following equation:

(3) $$BIC = 2\,NLL + K\log(n)$$

with the parameters defined as above (Burnham and Anderson 2004). Both AICc and BIC were reported in terms of Δ and model weights to determine conditional probabilities of which was the more probable model given the input data (Wagenmakers and Farrell 2004).

**Performance comparison among all scenarios** − Direct comparison of likelihood components and calculation of model selection criteria was not feasible for red tide scenario 3 or between recruitment scenarios A and B. Therefore, model performance across all red tide scenarios was compared by examining fits to indices of abundance using typical estimators of model fit. Mean error was described by the root mean square error (*RMSE*) with the following equation:

(4) $$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}([\hat{y}_i - y_i]^2 + \sigma_i)}$$

where $n$ is the sample size, $y_i$ is the observed value in year $i$, $\hat{y}_i$ is the expected value in year $i$ (Potts and Elith 2006), and $\sigma_i$ is the year-specific standard error. Correlation coefficients were examined for both strength of the relationship ($r$, Pearson) and rank of observed and expected values ($r_{sp}$, Spearman). Calibration was evaluated with a simple linear regression between observed and expected values (observed =$m$ (expected) + $b$) (Piñeiro et al. 2008), with the intercept term indicative of bias and the slope indexing the consistency of predictions. Perfect calibration would produce a line with a slope = 1 and an intercept = 0 (Potts and Elith 2006). Lastly, model behavior was examined by assessing the relationship between the difference and the mean (of binned responses) within a Bland-Altman plot (Bland and Altman 1986).

For the purpose of selecting the best scenario, model convergence and biological realism of model outputs (e.g., realistic biomass estimates) were examined in conjunction with performance metrics. Model convergence was considered adequate when the gradient, or the vector of partial derivatives of the objective function with respect to the parameters, was low (i.e., <1).

***Investigating age-specific selectivity by the red tide fishing fleet***

Parameterizing red tide as a fishing fleet enabled an investigation of potential hypotheses regarding age-specific selectivity patterns. The purpose of this analysis was to identify which age classes were susceptible to red tide by testing selectivity patterns varying by the minimum age (0, 1, … 20) selected. For all affected ages, selectivity was assumed equal to 1.0. Since data remained consistent between runs, model selection criteria were used to determine the best selectivity pattern given the data and model used.

## Results

### *Justification*

**Natural mortality** − When $M$ deviations were estimated freely between 1998 and 2010 within the abbreviated 3 breakpoint base model for adult Red Grouper, relatively large $M$ deviations were estimated during 1998, 2005, 2007, and 2008 (Figure 4). Whereas the large positive deviation in 2005 matched expectations given the 2005 red tide event, the relatively large negative deviations (> 0.3) resulted in biologically unrealistic values (i.e., < 0). Deviations in $M$ were significantly ($p < 0.05$) related to all three red tide indices, with larger $M$ deviations associated with higher red tide values (Table 2; Figure 5).

**Recruitment** − Between 2003 and 2013, recruitment deviations were largest in 2004 and 2005, with 2004 showing the largest negative deviation and 2005 showing the largest positive deviation (Figure 4). Recruitment deviations were consistently negative from 2009 to 2013 (Figure 4). Between 2003 and 2013, no significant ($p > 0.05$) relationship was detected between recruitment deviations and the index of recruitment anomalies due solely to oceanographic factors (Table 2; Figure 6).

### *Incorporating environmental processes into Stock Synthesis*

**Red tide** − Overall, most red tide scenario runs resulted in a positive definite hessian and acceptable convergence (Table 3). Convergence was dependent upon which red tide index was driving fleet effort, with both the MRT and MCP indices resulting in relatively large gradient values >1.

For scenario 2, an episodic $M_{rt}$ of 0.48 produced the lowest overall *NLL* in the likelihood profile generated from SS outputs (Figure 3). This value was similar to *F_2005* estimated for the red tide fishing fleet (Table 3). Estimates of $q$ and *F_2005* (i.e., red tide mortality) were relatively realistic for all red tide indices, with *F_2005* ranging from 0.077 (MRT) to 0.442 (THR) (Table 3).

**Recruitment** – Results from recruitment scenarios are not reported due to the lack of biological justification deriving from the regression analysis.

### *Model evaluation*

**Model selection among comparable scenarios** − Among scenarios 1, 2 and 4, scenario 2 possessed the highest conditional probability (wAICc, wBIC) of being the best model (Table 3). Notable improvements for Scenario 2 with episodic $M_{rt} = 0.48$ were observed in the total *NLL* (↓10 units) and the survey *NLL* (↓10 units) with the majority of surveys displaying lower *NLL* when red tide was considered (Table 3). Consideration of red tide in SS generally led to better fits to indices of abundance (Figure 7). Additional mortality during 2005 enabled a steeper drop-off in expected abundance, which better matched observed trends, as in the previous assessment model.

**Performance comparison among all scenarios** − Evaluation criteria based on fits to indices of abundance were generally similar between scenarios 2 ($M_{rt} = 0.48$) and 3. Within scenario 3, the

THR index exhibited lower *RMSE* and Bland-Altman $R^2$ values, higher correlations, and slopes approaching 1 for most fleets and surveys (Figure 8). Relative to scenario 1, the red tide fleet model configurations lead to slightly higher bias for the comLL, HB, and NMFS_BLL according to the Bland-Altman plots. For the red tide fishing fleet with the THR index driving effort, expected fits to indices of abundance were very similar to those estimated for episodic $M_{rt}$ = 0.48 (Figures 7, 9).

***Comparison of trends in spawning biomass, recruitment, and fishing mortality***

Annual biological reference point estimates were generally similar in trend among scenarios but varied by magnitude (Figure 10). Scenario 4 produced very different results for all reference points examined, particularly by estimating higher recruitment and lower spawning biomass throughout the time series (Figure 10). Trends in spawning biomass differed depending upon the red tide scenario, with the largest discrepancies occurring in the early- to mid-2000s (Figure 10). During this period, models which considered red tide mortality estimated higher spawning biomass estimates and a steeper drop in biomass following the 2005 red tide (Figure 10). Annual estimates of recruitment were similar among scenarios, with the exception of Scenario 4 which estimated larger recruitments for all years (Figure 10). Annual estimates of fishing mortality (*F*) revealed divergent trends, mainly during the mid-2000s where fleet-combined *F* estimates ranged between 0.1 and 0.48 (Figure 10). The largest difference in *F* was observed in 2005, due to the estimation of red tide mortality.

***Investigating age-specific selectivity by the red tide fishing fleet***

Out of the 21 minimum age classes tested within the red tide fishing fleet model with the THR index, the best selectivity pattern given the data and model suggested was red tide selecting for ages 0+. This configuration displayed the lowest *NLL* (2837), AICc (-13645) and BIC (7584) values and exhibited 86% model weights for both selection criteria. All model selection criteria degraded as the hypothesized minimum age affected by red tide increased.

## Discussion

The results of this study highlight two important benefits of incorporating ecosystem considerations into single species stock assessment models. First, inclusion of red tide mortality helped explain historic trends in abundance, specifically by enabling a steeper drop off in indices of abundance between 2005 and 2006 as a result of the severe red tide in 2005. Improved fits to indices of abundance enhanced the plausibility of the assessment model, thereby warranting the added complexity of incorporating ecosystem considerations. Regression analysis of natural mortality deviations against the red tide indices for adult Red Grouper suggested a significant impact of red tide on stock dynamics. Second, the index of recruitment anomalies provides some insight into potential recruitment during the first year of model projections, although expected trends in recruitment anomalies did not match expected recruitment from the model. Regression analysis did not reveal a significant relationship between recruitment deviations and the index of recruitment anomalies. While the preferred metric of determining the utility of incorporating environmental times series in the integrated model framework is improvement in fit criteria (Schirripa et al. 2009) it is useful nonetheless to evaluate the relationship between environmental indices and the parameters assumed to be affected by them, external to the model. This is not strictly using model outputs as 'data' as cautioned by Brooks and Deroba (2015) but rather part of the necessary due diligence approach to incorporating environmental indices into integrated assessments. Such an approach involves first developing a hypothesis and a mechanistic explanation for why an environmental index might affect certain parameters, evaluating the relationship between the parameter and the process (as explored here), and then hypothesis testing within the integrated model framework. Such an approach is prone to multiple hypothesis testing, or worse, exploring multiple indices until one is significant, each of which are particularly concerning for several reasons. First, the nature of integrated assessments – high numbers of parameters to data, poor agreement with distributional assumptions and sensitivity to data weighting – mean that they are more prone to type I errors – finding significant indices – than not. Second, confronting the assessment model with multiple indices raises the issue of multiple hypothesis testing and it is not clear how to adequately account for this. Lastly, from the perspective of the main goal of the stock assessment, to provide robust harvest advice based upon forecasts, there is the danger that using a spurious index that fits historical data will provide very poor predictions. As the incorporation of environmental indices into assessments becomes routine, it will be necessary to develop criteria for inclusion that balance biological and mechanistic explanation, statistical significance and predictive performance.

The potential impacts of red tide on grouper population dynamics pose a challenge to fishery management, particularly because our understanding of potential interactions comes primarily from anecdotal information. The 2014 red tide event served as a cautionary event, in that it raised awareness for the effects of red tides on grouper population dynamics. The Gulf of Mexico Fishery Management Council postponed the setting of Acceptable Biological Catch (ABC) limits for Gag Grouper because of considerable uncertainty around the magnitude of the 2014 red tide event. Fishermen reported massive fish kills offshore, which included groupers. However, both the NMFS bottom longline and NMFS Panama City surveys were on site but did not encounter massive grouper kills. Preliminary modeling results for red tide mortality rates of Red Grouper and Gag Grouper suggest the 2014 red tide was minimal in comparison to the 2005 event (D. Chagaris, *pers. comm.*). With this insight, the Council set the ABC for Gag Grouper at the January 7 2015 meeting under the notion of no additional mortality in 2014, although limitations of the presented study were discussed including the lack of correlation between HAB cell counts and toxicity.

For the 2015 GOM Red Grouper base model, differences in model performance were observed between scenarios. Scenario 3, which parameterized red tide as a fishing fleet, performed best according to model performance measures. Estimates of red tide mortality were similar between scenarios 2 and 3, with an episodic $M_{\mathrm{rt}}$ estimated between 0.44 and 0.48. The benefit of parameterizing red tide as a fishing fleet is that it allowed the model to use information from data sources therein to scale red tide removals. The estimated effect of red tide mortality on Red Grouper is lower compared to the estimate for GOM Gag Grouper ($M_{\mathrm{rt}}$ = 0.71) (SEDAR 2014). The majority of observations of groupers in fish kills are of Red Grouper (Walter et al. 2013). However, it is possible that because red tide events start at depth (Steidinger and Vargo 1988), there is a substantial impact on deeper-dwelling groupers that goes unnoticed. Additional research is needed to determine the potential impacts of red tide events on offshore species.

Exploration of alternative selectivity patterns at age by the red tide fleet suggested the base model supported susceptibility of ages 0+ and older. While selectivity modeling results suggest that red tide causes mortality on all ages, additional research is needed on age-specific mortality of groupers. Recovery of specimens from red tide-induced fish kills is difficult due to the highly decomposed state of the fish (M. Campbell, *pers. comm.*) and the human health hazards associated with field collection. However, collection and analysis of specimens is necessary to reduce uncertainty regarding the susceptibility of groupers and other species to red tide events. Although costly, pre-planned response teams, either for field collections or SCUBA surveys (e.g., Smith 1975), could provide much-needed insight. In addition, participation by fishers could greatly improve understanding of red tide events, whether through careful field collections or photographs of surface fish kills.

The lack of a discernable correlation between the index of recruitment anomalies and the model estimated recruitment deviations was surprising given its utility for both Red Snapper and Gag Grouper (Karnauskas et al. 2013a; Karnauskas et al. 2013b). The index of recruitment anomalies predicted the highest recruitment event in 2012, which was not supported by modeling results or data sources. It may be driven by a lack of precise knowledge of where and when red grouper actually spawn. Our assumption that adult distribution was a proxy for the spatial distribution of spawning biomass may not be accurate. The SS model estimated low recruitment over the last 5 years, largely driven by the SEAMAP groundfish index. This index is considered a recruitment index because it generally encounters juvenile Red Grouper. At present, no age-0 surveys are available for Red Grouper, leaving a critical gap in our understanding of early life history dynamics for this species. Additional sensitivity runs regarding known release sites may better capture potential spawning sites, rather than assuming Red Grouper may spawn at any location they are captured.

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**Table 1**. Environmental consideration scenarios based on environmental indices and methods for inclusion in the 2015 Stock Synthesis Gulf of Mexico Red Grouper base model. Further details on environmental indices are provided in the text. +*K* refers to the additional parameter(s) estimated (Parm) within each scenario, *q* = catchability coefficient, *β* = slope of relationship between recruitment deviations and environmental index.

| Scenario | Environmental Index | +*K* | Parm | Description |
|---|---|---|---|---|
| Red Tide | | | | |
| 1 | − | 0 | − | No red tide |
| 2 | − | 0 | − | Extra mortality ($M_{rt}$ = 0.25) in 2005 |
| | − | 0 | − | Extra mortality ($M_{rt}$ = 0.48) in 2005 |
| 3 | Threshold (THR) | 1 | *q* | Red tide fishing fleet |
| | 10mMCP75 (MCP) | 1 | *q* | |
| | Grouper (GRP) | 1 | *q* | |
| | Red tide mortality (MRT) | 1 | *q* | |
| 4 | OSMOSE-WFS | 0 | − | OSMOSE-WFS *M* vector |
| Recruitment | | | | |
| A | Recruitment anomalies (CMS) | 1 | *β* | Model method: link recruitment deviations to environmental index |
| B | CMS | 0 | 0 | Data method: input environmental index as an age-0 survey |

**Table 2**. Relationship between freely estimated natural mortality deviations (*MDev*), recruitment deviations (*RDev*), and environmental indices for Gulf of Mexico Red Grouper. Environmental indices are as defined in Table 1. *N* is the number of years with data available, Equation reflects the fitted regression line, $R^2$ is the coefficient of determination, and *p* is the probability value. Significance (bolded) is based on an $\alpha = 0.05$. Note that *MDev* values correspond to adult Red Grouper (ages 3+) and were estimated with an abbreviated 3-breakpoint base model.

| Environmental Index | | *N* | Equation | $R^2$ | *p* |
|---|---|---|---|---|---|
| Red Tide | | | | | |
| | MCP | 13 | *MDev* = 0.172 MCP – 0.018 | 0.42 | **0.010** |
| | GRP | 13 | *MDev* = 0.156 GRP – 0.018 | 0.33 | **0.024** |
| | MRT | 12 | *MDev* = 0.182 MRT – 0.017 | 0.43 | **0.012** |
| Recruitment | | | | | |
| | CMS | 11 | *RDev* = −0.262 CMS – 0.149 | 0.00 | 0.989 |

**Table 3**. Red tide scenario results for the 2015 Stock Synthesis Gulf of Mexico Red Grouper base model. Red tide scenarios are as defined in Table 1. AIC = Akaike's Information Criterion, BIC = Bayesian Information Criterion, w = estimated model weight (Wagenmakers and Farrell 2004). Italics represent results from non-converged scenarios based on predetermined criteria (grad > 1). *q* is the estimated catchability coefficient; *F_2005* is the estimated fishing mortality during 2005 (i.e., red tide mortality). Note that negative log-likelihoods and model selection criteria are not directly comparable in Scenario 3 due to changes in input data.

| | Environmental Scenario | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | | 3 | | | | 4 |
| | NoRT | 0.25 | 0.48 | THR | *MCP* | GRP | *MRT* | OSMOSE |
| **Performance** | | | | | | | | |
| Gradient | 0.005 | 0.047 | 0.021 | 0.300 | *1.019* | 0.104 | *10.115* | 0.030 |
| Number of parameters (*K*) | 179 | 179 | 179 | 331 | *331* | 331 | *331* | 179 |
| Number of observations (*n*) | 305 | 305 | 305 | 321 | *318* | 318 | *317* | 305 |
| *n*/*K* | 2 | 2 | 2 | 1 | *1* | 1 | *1* | 2 |
| AICc | 6723 | 6708 | 6703 | -13645 | *-9264* | -9221 | *-8256* | 6866 |
| ΔAICc | 20 | 5 | 0 | - | - | - | - | 163 |
| wAICc | 0.00 | 0.08 | 0.92 | - | - | - | - | 0.00 |
| BIC | 6873 | 6858 | 6853 | 7584 | *7680* | 7724 | *7640* | 7016 |
| ΔBIC | 20 | 5 | 0 | - | - | - | - | 163 |
| wBIC | 0.00 | 0.08 | 0.92 | - | - | - | - | 0.00 |
| **Negative log-likelihood** | | | | | | | | |
| Total | 2925 | 2917 | 2915 | 2837 | *2887* | 2908 | *2867* | 2996 |
| Discard | 320 | 318 | 316 | 311 | *312* | 310 | *312* | 318 |
| Length composition (L comp) | 1079 | 1083 | 1086 | 1086 | *1082* | 1085 | *1082* | 1142 |
| Age composition (A comp) | 1454 | 1453 | 1452 | 1451 | *1453* | 1452 | *1453* | 1453 |
| Recruitment (Recr) | 18 | 17 | 17 | 17 | *17* | 17 | *17* | 18 |
| Survey (Surv) | -80 | -88 | -90 | -164 | *-115* | -93 | *-134* | -75 |
| Commercial handline (comHL) | -10 | -11 | -12 | -12 | *-11* | -12 | *-11* | -9 |
| Commercial longline (comLL) | -17 | -18 | -18 | -18 | *-18* | -18 | *-18* | -17 |
| Recreational headboat (HB) | -11 | -15 | -18 | -18 | *-14* | -16 | *-13* | -6 |
| Recreational Charterboat/Private (CBT_PRSurv) | -22 | -20 | -18 | -18 | *-19* | -18 | *-19* | -22 |
| Combined Video Survey (SEAMAP_Vid) | -13 | -14 | -15 | -15 | *-14* | -14 | *-14* | -13 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| SEAMAP Groundfish Survey (SEAMAP_GF) | -4 | -4 | -4 | -4 | *-4* | -4 | *-4* | -4 |
| NMFS Bottom Longline Survey (NMFS_BLL) | -3 | -5 | -5 | -5 | *-3* | -4 | *-3* | -3 |
| **Parameters of interest** | | | | | | | | |
| Red tide | | | | | | | | |
| RT q | - | - | - | 0.816 | *0.713* | 0.394 | *0.208* | - |
| F_2005 | - | - | - | 0.442 | *0.095* | 0.224 | *0.077* | - |

**Figure 1**. Annual trends in relative indices of (A) red tide severity and (B) Red Grouper recruitment anomalies (both as z-scores) on the West Florida Shelf. See text for details.

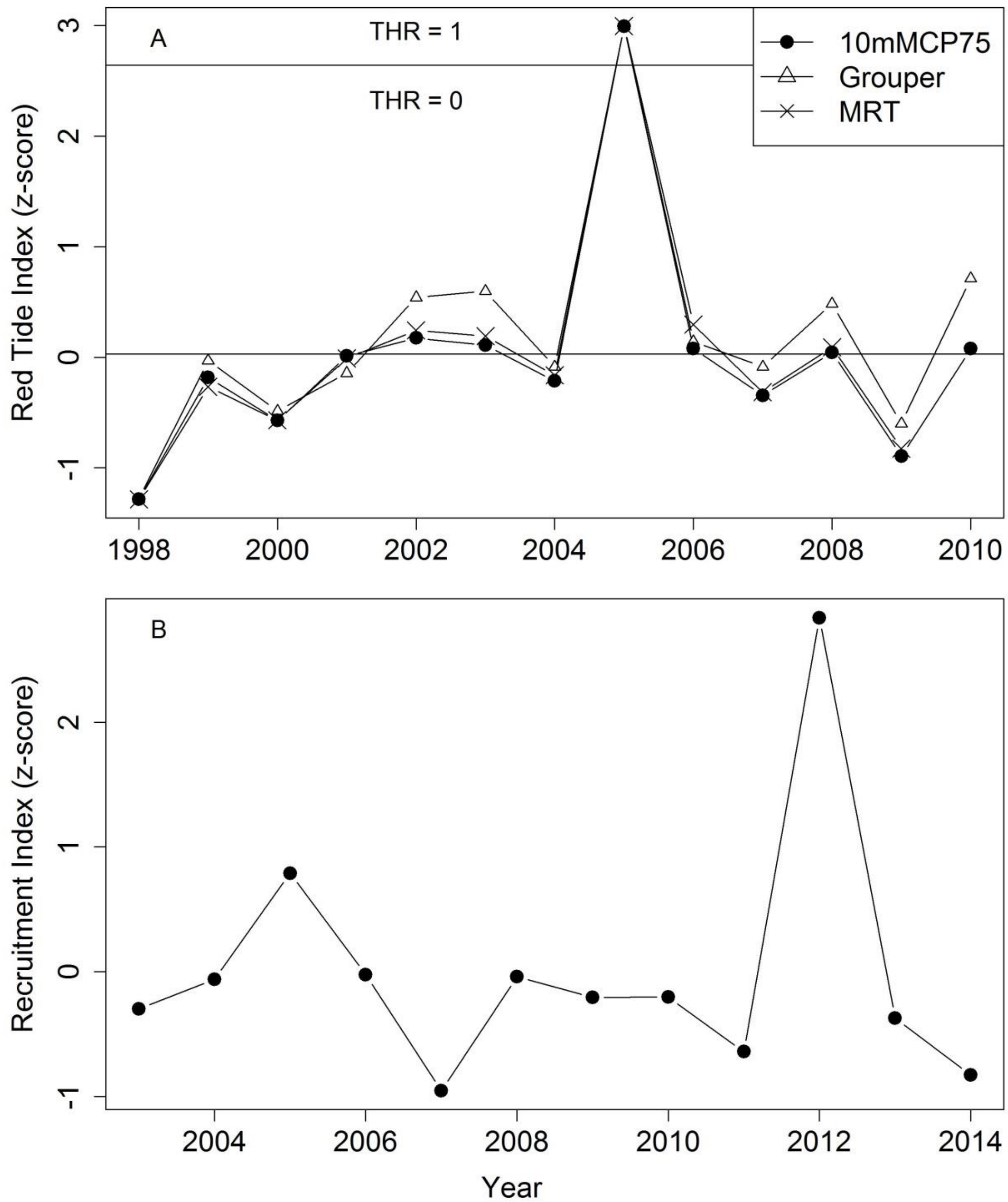

**Figure 2**. Age-specific natural mortality rates fixed within the 2015 Stock Synthesis Gulf of Mexico Red Grouper base stock assessment model. Solid line reflects the Lorenzen natural mortality rate recommended by the SEDAR 42 life history working group. Dashed line reflects the total mortality rate predicted by the ecosystem-based model, OSMOSE-WFS.

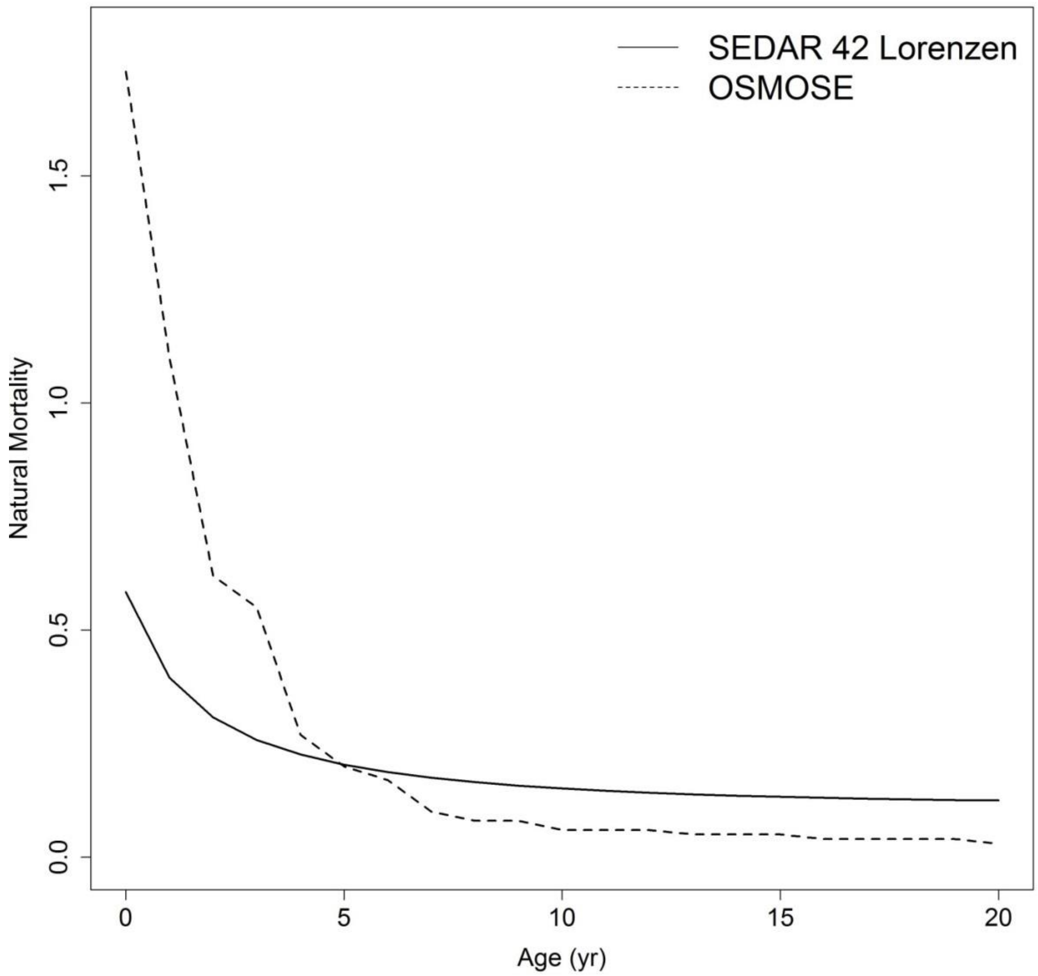

**Figure 3**. Likelihood profiling of the episodic natural mortality due to red tide ($M_{rt}$) in 2005 for Gulf of Mexico Red Grouper. NLL = negative log-likelihood.

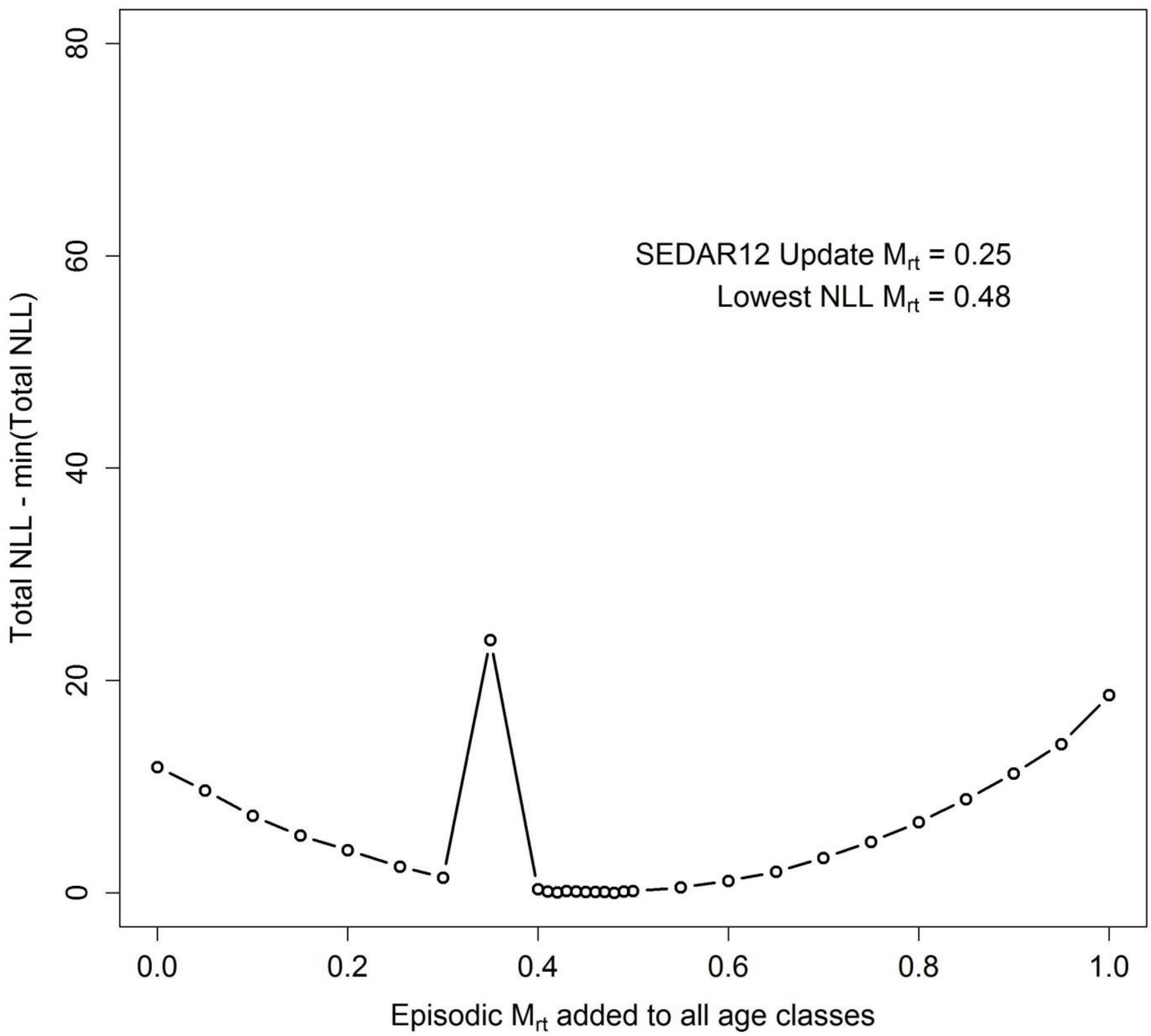

**Figure 4**. Freely estimated deviations in adult (ages 3+) natural mortality and recruitment for the 2015 Stock Synthesis Gulf of Mexico Red Grouper base model. White bar identifies *M* deviation estimated during the severe red tide event documented in 2005. Note that *M* deviations correspond to adult Red Grouper (ages 3+) and were estimated with an abbreviated 3-breakpoint base model. Recruitment deviations were estimated within the 2015 GOM Red Grouper base model.

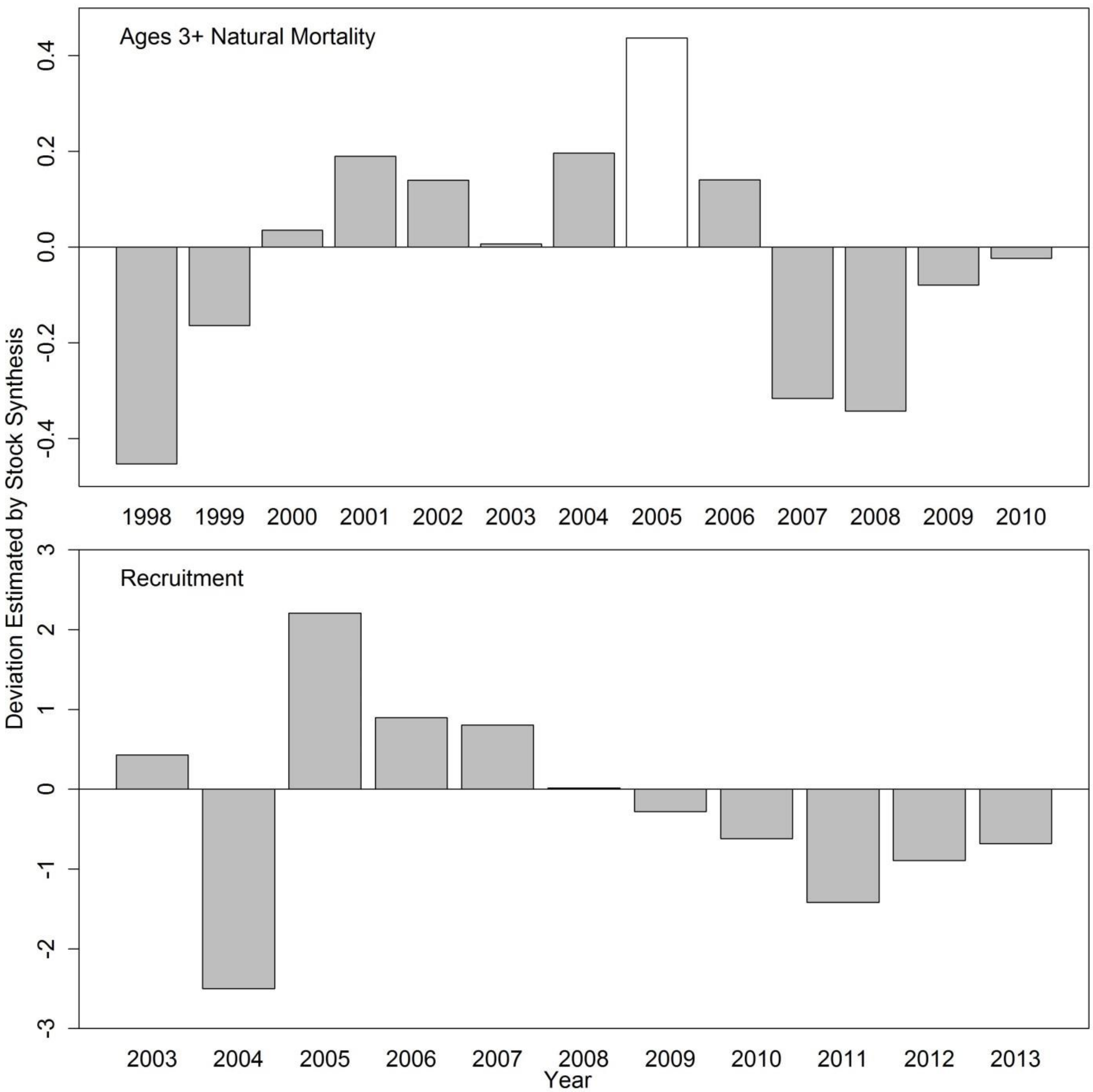

**Figure 5**. Estimated relationships between natural mortality deviations and red tide indices (as z-scores) between 1998 and 2010. Points are annual observations, solid lines represent fitted regressions, and dashed lines reflect 95% confidence intervals. Note that these results are dependent upon the selected model configuration and assumptions therein.

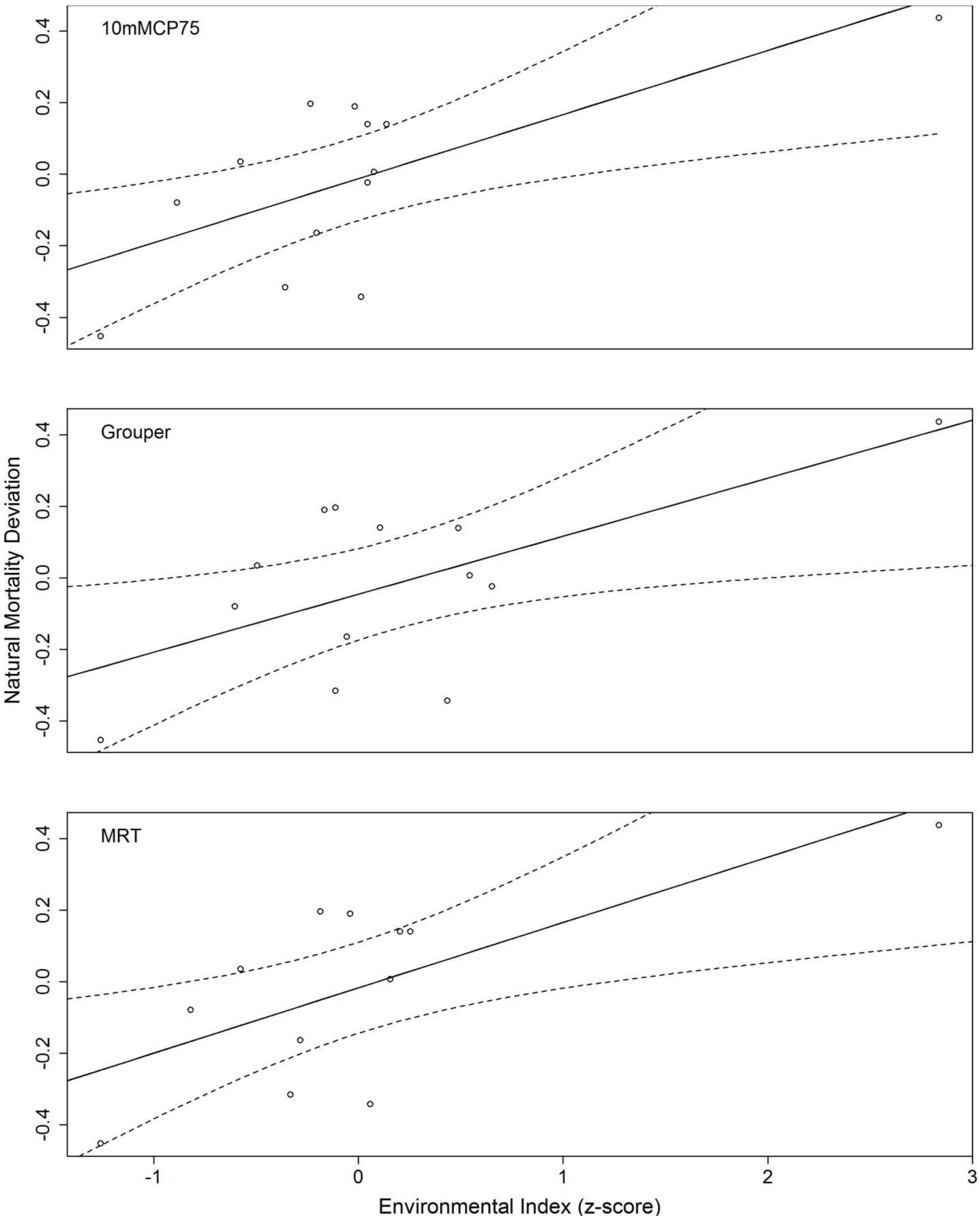

**Figure 6**. Estimated relationship between recruitment deviations and recruitment index (as z-scores) between 2003 and 2013. Points are annual observations, solid lines represent fitted regressions, and dashed lines reflect 95% confidence intervals. Note that these results are dependent upon the selected model configuration and assumptions therein.

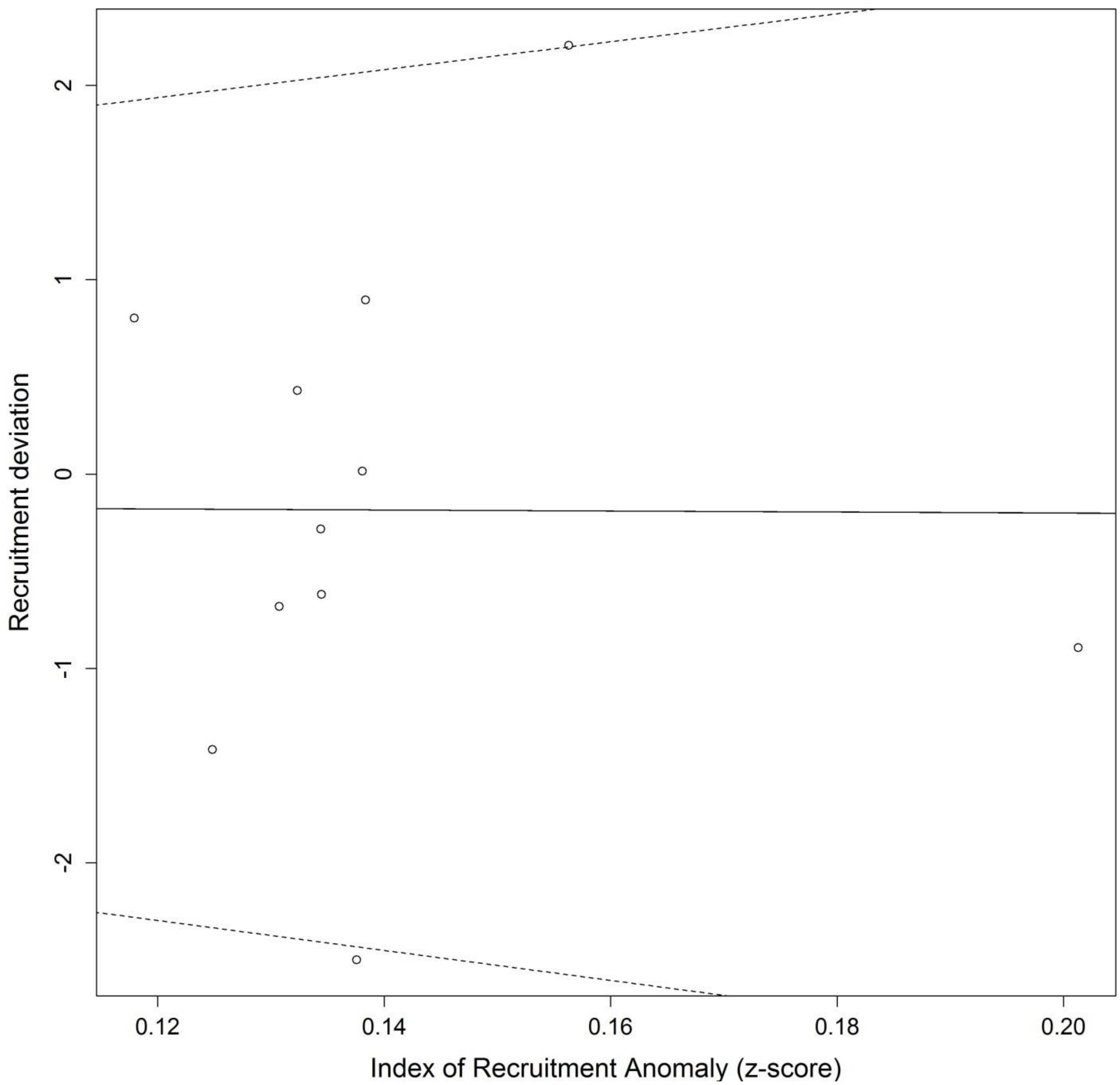

**Figure 7**. Comparison of model fits to indices of abundance both without (first and third columns) and with (second and fourth columns) the inclusion of red tide. The episodic natural mortality due to red tide ($M_{\mathrm{rt}}$) deemed most likely by likelihood profiling in SS was estimated at 0.48 and is shown. Indices of abundance are as defined in Table 3.

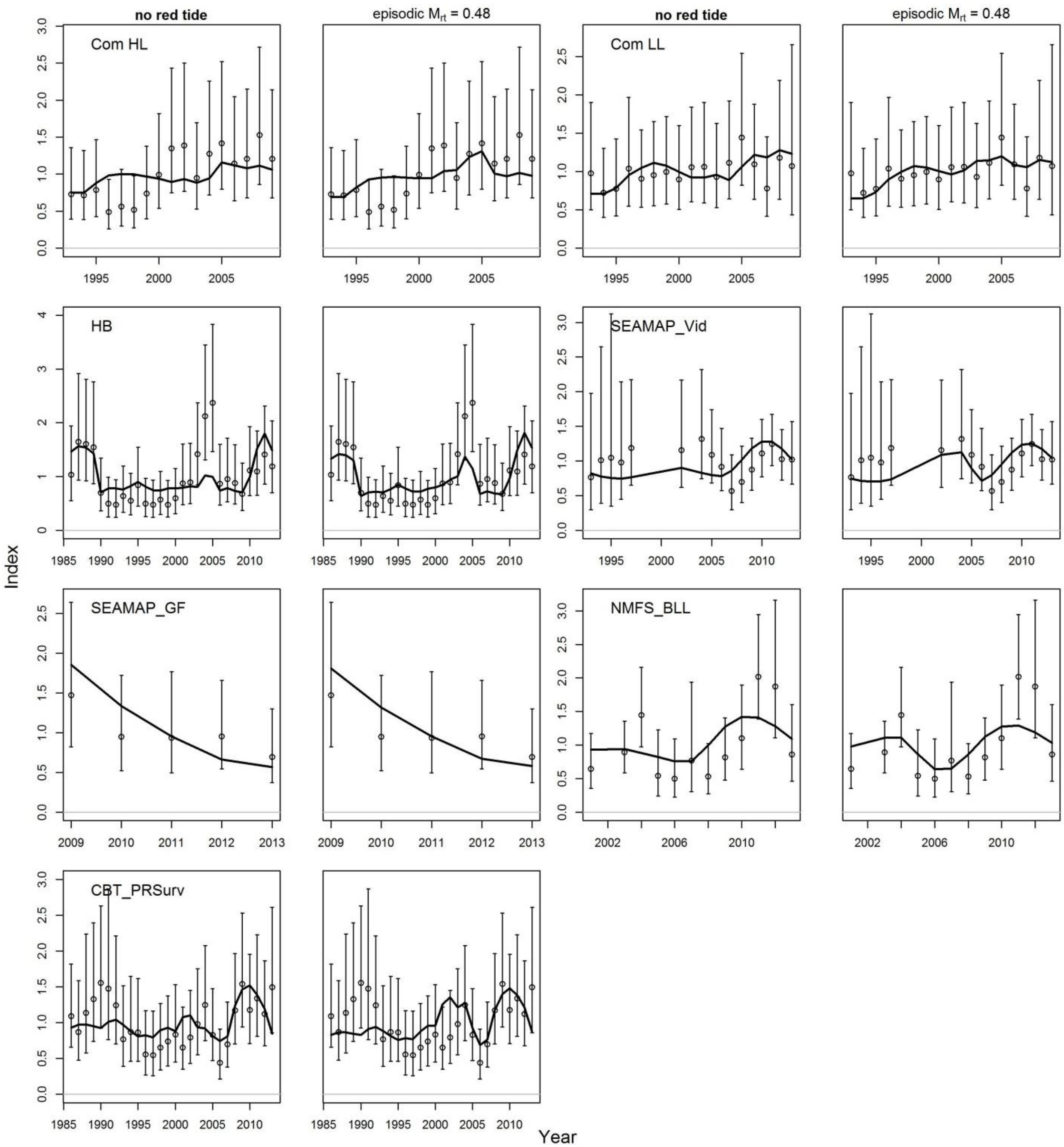

**Figure 8**. Model evaluation for scenarios 1 through 4 of the 2015 Stock Synthesis Gulf of Mexico Red Grouper base model. Analyses are based on fits to indices of abundance (i.e., observed versus expected). Red tide scenarios, indices, and surveys/fleets are as defined in Tables 1 and 3, respectively. Horizontal gray lines indicate target values of 0 (*RMSE*, $R^2$ of Bland-Altman plot) or 1 (Pearson's correlation coefficient, slope of calibration line). Vertical gray lines separate scenarios.

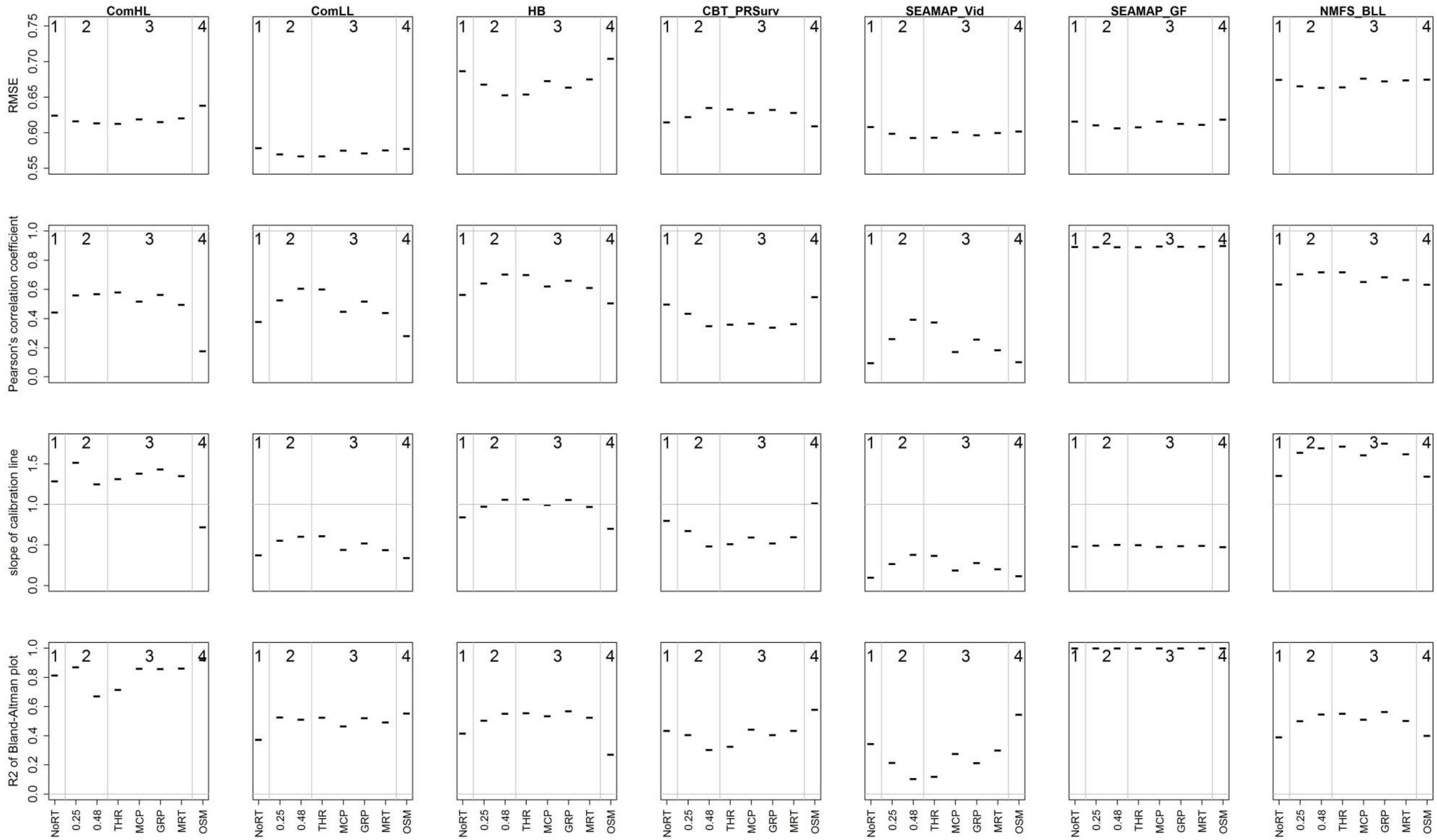

**Figure 9**. Comparison of model fits to indices of abundance both without (first and third columns) and with (second and fourth columns) the inclusion of red tide. The red tide fishing fleet with the threshold index was deemed the best model among all scenarios and is shown. Indices of abundance are as defined in Table 3.

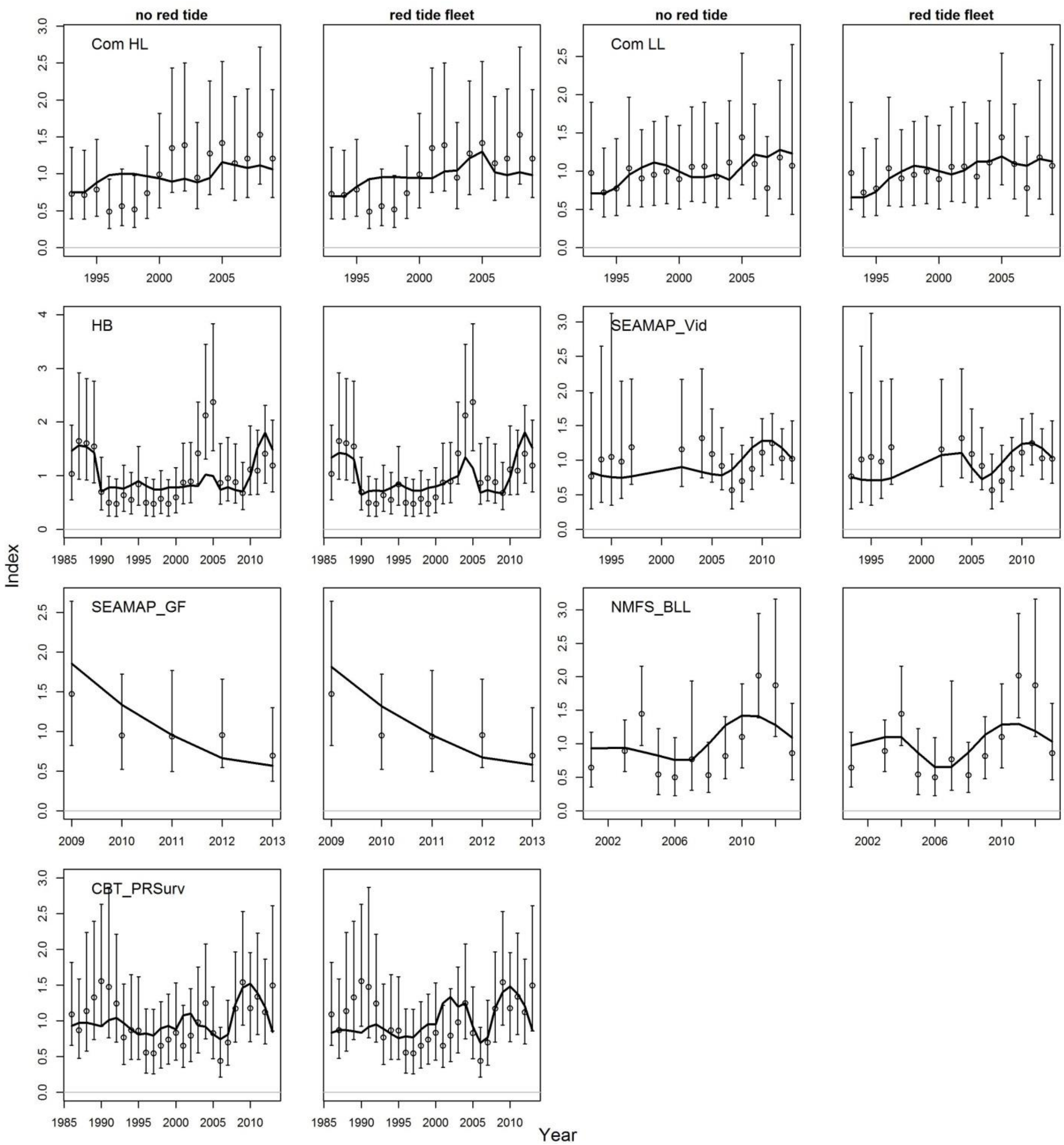

**Figure 10**. Comparison of annual estimates of spawning stock biomass, recruits, and fishing mortality for Gulf of Mexico Red Grouper between 1986 and 2013. Red tide scenarios and environmental indices are as defined in Table 1. Note that y-axes differ between panels for recruits.