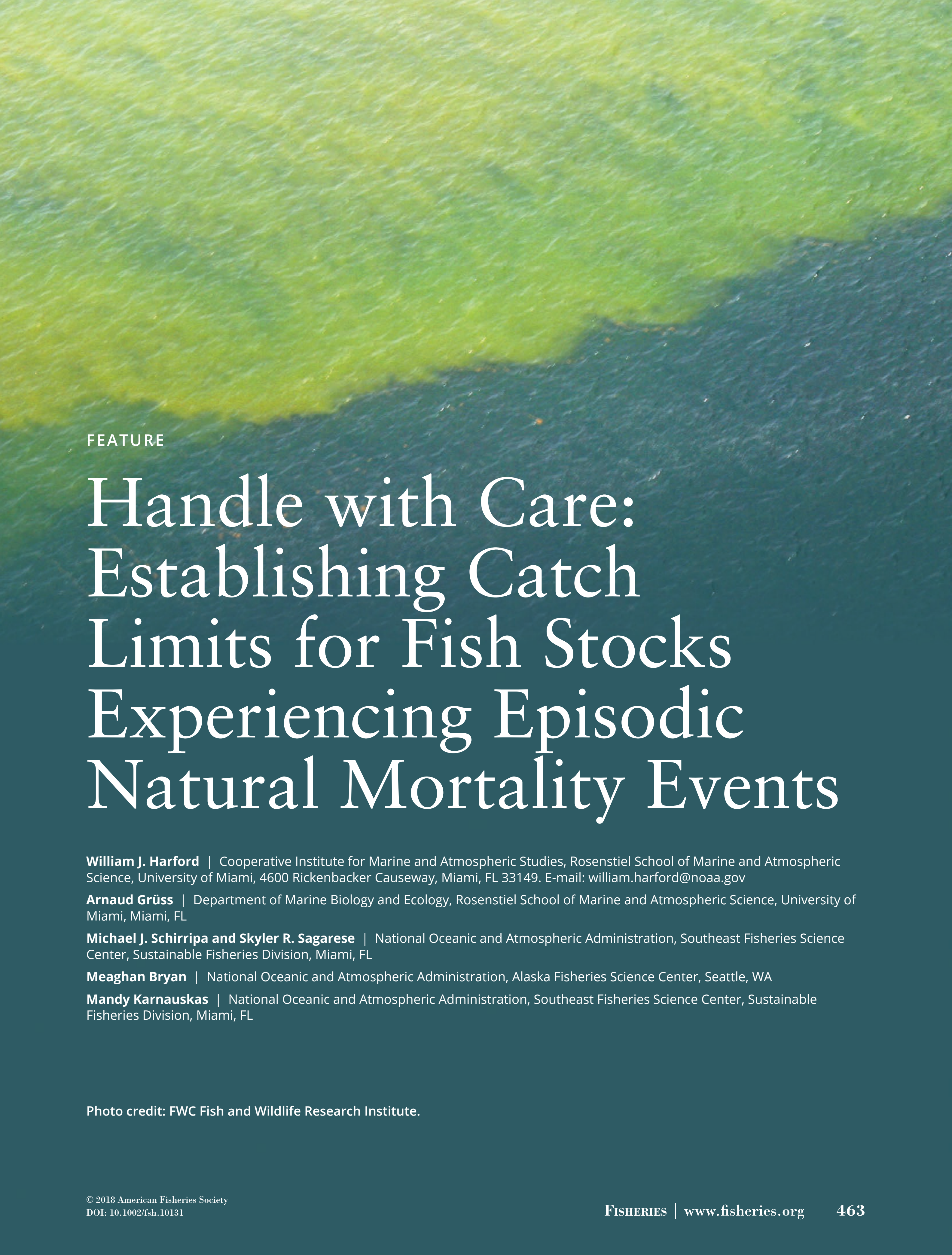

FEATURE

Handle with Care: Establishing Catch Limits for Fish Stocks Experiencing Episodic Natural Mortality Events

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DOI: 10.1002/fsh.10131

Harmful blooms of the dinoflagellate *Karenia brevis*, known as "red tides," are responsible for major episodic fish kills in the Gulf of Mexico. In response to management concerns, we conducted a management strategy evaluation to examine whether decision-making reactivity to event occurrence or precautionary catch limit reductions could aid in achieving fishery objectives. Simulated stock dynamics were representative of Gulf of Mexico Red Grouper *Epinephelus morio*, and assessment of simulated data involved estimation of time-varying natural mortality. We found that both unresponsive yet precautionary catch limits and reactive decision making could improve achievement of fishery objectives, although practical impediments to reactive strategies abound. Where catch limit reductions were introduced to buffer against scientific uncertainty, a trade-off was evident that required recognizing constraints in stock assessment reliability (given the complexities of estimating time-varying natural mortality) and balancing these constraints against desirability for high catch rates. Our study provides a narrative on the ways in which management guidance can be structured to address uncertainty about future occurrences of episodic natural mortality events.

Occasional die-offs of fishes and invertebrates are well known to coastal communities and often follow hurricanes, harmful algal blooms, or extreme fluctuations in environmental conditions (Lewitus et al. 2012). Lost tourism and lost fishing opportunities have been associated with die-offs of American lobster *Homarus americanus*, red abalone *Haliotis rufescens*, and Red Grouper *Epinephelus morio* (Pearce and Balcom 2005; Rogers-Bennett et al. 2012; Driggers et al. 2016). Freshwater ecosystems are also susceptible to fish die-offs, including those affecting Muskellunge *Esox masquinongy* and Freshwater Drum *Aplodinotus grunniens* of the Laurentian Great Lakes (CCWHC 2005; Casselman 2011). Although episodic natural mortality events may often be difficult to anticipate, their occurrence remains an ongoing resource management concern.

In the Gulf of Mexico, fish die-offs attributed to harmful algal blooms are among the most obvious ecological issues, affecting not only fisheries but also human health and tourism (Backer 2009). The "red tide" dinoflagellate *Karenia brevis* may cause fish mortality through acute exposure to or bioaccumulation of the neurotoxin brevetoxin and also through asphyxiation from associated areas of hypoxic water (Landsberg et al. 2009). Harmful algal blooms are known to have occurred in the Gulf of Mexico for hundreds of years, and severe events pose fish mortality threats that can substantially exceed average natural mortality rates (Steidinger 2009). A severe red tide event in 2005 was estimated to have killed over 11,000 metric tons of Red Grouper, reflecting a threefold increase over the average natural mortality rate (SEDAR 2015).

The red tide of 2005 spurred increased awareness of the effects of episodic natural mortality events on Gulf of Mexico fisheries, and since that time, the effects of red tide events have been recognized in stock assessments and decision making. Stock assessments that were finalized in 2006 and 2007 for the Gag *Mycteroperca microlepis* and Red Grouper recognized red tides only in the context of research recommendations (SEDAR 2006a, 2006b). The first attempt to quantify red tide severity for use in stock assessments was based on statistical modeling using satellite data (Walter et al. 2013). This model was later used to delineate spatial and temporal overlap between red tide presence and Red Grouper abundance (Sagarese et al. 2014a). Multispecies modeling approaches were also considered, with the goal of understanding not only the effects of red tide mortality on groupers but also on species that interact with groupers via trophic connections (Grüss et al. 2016). These research efforts were effective in establishing the magnitude of red tide mortality in groupers and improving fits to abundance indices within recent stock assessments (SEDAR 2014, 2015). However, research was not directed toward informing management decisions to face unpredictable future occurrences of natural mortality increases—a deficiency that became apparent at the outset of another red tide event in 2014 (Driggers et al. 2016). Lacking information on whether established management approaches were sufficient to buffer the stock against these episodic mortality events, the Gulf of Mexico Fishery Management Council (GMFMC) temporarily postponed decisions on catch limits for Gags in 2014 to wait for additional scientific analysis (GMFMC 2015).

In response to these management concerns, the GMFMC passed a motion in June 2014 to "…evaluate the current Red Grouper harvest control rule to determine if it is robust to possible future changes in intensity and frequency of episodic events of non-fishing mortality" (GMFMC 2014). Our study was conducted in response to this request, under the advice of the GMFMC's Scientific and Statistical Committee and the auspices of the National Oceanic and Atmospheric Administration's (NOAA) Gulf of Mexico Integrated Ecosystem Assessment Program, which supports efforts to transfer scientific knowledge from ecosystem-based assessments to management. We used management strategy evaluation (MSE) to explore decision-making responses to prevailing episodic natural mortality events to achieve pre-agreed management objectives. Specifically, we addressed two questions about how decision makers could be equipped to face future episodic natural mortality events (e.g., red tides): (1) "Does the existing GMFMC management approach need to be modified to achieve management objectives due to effects of episodic natural mortality events?"; and (2) "If modifications are considered, what are their effects on and trade-offs for maintaining sustainable fisheries?" To answer these questions, the interconnections between environmental conditions, a fish stock, a fishery, and a management strategy were specified in a simulation model. We focused on two types of harvest control rule (HCR): one based on dynamic decision-making frequency in response to occurrences of severe red tide events, and the other based on static decision-making intervals coupled with precautionary catch reductions. By varying these aspects of decision making, we sought to provide a narrative on structuring management guidance in the face of uncertain futures about episodic natural mortality events.

METHODS

A management strategy usually consists of a monitoring program to collect data, a stock assessment to analyze data, management reference points, and an HCR. Management strategy evaluation is the process of simulating the workings of a fisheries system to test management strategies and determine whether their likely effects on a fishery and a fish stock will achieve pre-agreed management objectives (Butterworth and Punt 1999; Smith et al. 1999; Sainsbury et al. 2000). Within our simulation of a defined management strategy, the HCR functions as a pre-stated set of criteria for implementing regulatory changes to fishing, through restrictions on total catches. Catch restrictions determined by the HCR are implemented for some short period of time (e.g., 1–5 years) and accordingly affect the fishing mortality level imposed on the simulated stock. The fish stock concurrently undergoes its own population processes (e.g., growth, births, and natural deaths). When the next management decision point occurs, the HCR is again used to re-evaluate total catch restrictions based on updated information provided by a stock assessment (Figure 1). This cycle can be specified to continue for any duration of time. Simulating management strategies differs from what is sometimes termed "stock assessment projections." Stock assessment projections do not take into account management responses to new information, whereas MSE examines how a management strategy will perform in responding to changing circumstances, like environmental events that are otherwise difficult to anticipate, relative to pre-agreed management objectives (Punt et al. 2016).

Simulated stock dynamics

Stock dynamics used in our simulations constituted an age-structured representation of Gulf of Mexico Red Grouper (Table 1; SEDAR 2015). Within each annual time step, growth occurred first, followed by reproduction and then total mortality (i.e., natural mortality plus fishing mortality). Fish growth followed a von Bertalanffy function, and lengths (mm) were converted to whole weights (kg) according to an exponential function. Maturity was an asymptotic function of age (age at 50% maturity was 2.8 years), and we also specified the proportional transition from female to male as a function of age, as the Red Grouper is a protogynous hermaphrodite. Numbers at age were modeled as a single sex, and hermaphroditism was addressed in the calculation of fecundity at age. Recruitment of age-0 fish was calculated according to the Beverton–Holt stock–recruitment function with a steepness of 0.8, which is consistent with expectations for demersal fishes of the Gulf of Mexico (Shertzer and Conn 2012; SEDAR 2015). Reproductive output (eggs per female) was a power function of age. Simulated fishery selectivity was specified as knife edge at age 5 years, although actual selectivity patterns differ considerably among commercial and recreational sectors (SEDAR 2015). Average age-specific natural mortality, defined as the time-invariant rate expected in the absence of episodic natural mortality fluctuations, was expressed as an inverse function of length and scaled to a longevity-based lifetime natural mortality of 0.14 year^{-1} (Then et al. 2015).

Episodic natural mortality events were generated using a lognormal distribution consistent with the recorded historical pattern of red tide events occurring on the west Florida shelf (Figure 2). Episodic events were specified as multipliers of average natural mortality rates at age, with lognormal variance chosen to generate a distribution of natural mortality multipliers that approximately mirrored historical red tide intensities and a resulting lognormal mean of 1.0. The specified distribution of historical red tide intensities was derived from a unitless index based on statistical modeling of satellite imagery (Walter et al. 2013). In our simulated sampling distribution, a threefold natural mortality multiplier occurred at the 97th percentile, and the maximum multiplier value was bound at approximately 6.0. Our approach recognized the threefold increase in natural mortality as the maximum recorded event strength estimated for Red Grouper while also recognizing the possibility that more severe events could arise (with low probability) as part of the lognormal sampling distribution (SEDAR 2015).

Episodic natural mortality multipliers were translated to an observable red tide index according to the function

$$env_t = \log(\theta_t)/c, \qquad (1)$$

where θ_t is the episodic natural mortality multiplier in year t; env is the corresponding value of the red tide index; and c is a scaling constant. Accordingly, total natural mortality at age was

$$M_{Total,age,t} = M_{Ave,age} \cdot \exp(c \cdot env_t), \qquad (2)$$

where $M_{Ave,age}$ is the specified average natural mortality at age. Our assumption that red tide events affected all age-classes was consistent with the manner in which red tide mortality has been included in stock assessments (SEDAR 2015). Equation (2) states that changes in red tide concentrations can cause both increases and decreases in natural mortality around an average natural mortality rate at age. Thus, our use of a longevity-based estimate to specify average natural mortality at age reflects the assumption that annual exposure to higher-than-average or lower-than-average natural mortality fluctuations is reflected in the average observed life span upon which the longevity-based average natural mortality estimate is based.

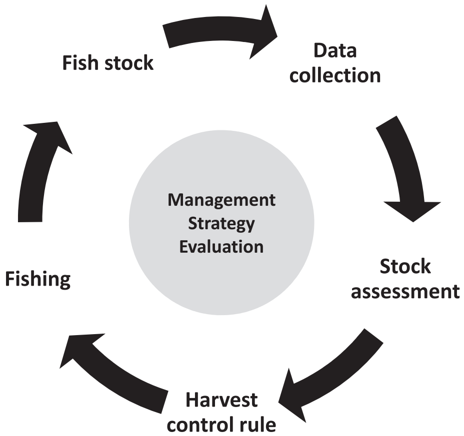

Figure 1. Management strategy evaluation is conducted by simulating interconnections between a fish stock, its fishery, and a management strategy, the latter of which includes data collection, stock assessment, and a harvest control rule.

Management strategy design

Our simulated HCRs each adhered to aspects of National Standard 1 (NS1) guidelines produced by the National Marine Fisheries Service (NMFS 2016). These guidelines specify (1) an overfishing limit (OFL) as the catch above which the capacity for long-term yields is jeopardized and (2) acceptable biological catch (ABC) as equal to or less than the OFL to account for scientific uncertainty. An annual catch limit (ACL) is set equal to or less than the ABC to account for additional ecological, social, and economic factors as well as uncertainty in management implementation. Arguably, catch reductions that are introduced to reflect management precaution about future natural mortality fluctuations could be made through adjustments to ABCs or ACLs. We maintained the existing ABC control rule for Red Grouper as distinct from management precaution related to episodic natural mortality events

Table 1. Life history information used in simulating Gulf of Mexico Red Grouper stock dynamics (SEDAR 2015). In equations, t is annual time step, age is annual age-class, and FL is fork length.

Processes	Equations and parameters
Age-0 recruitment (R)	$R_t = \left[\dfrac{0.8R_0hB_t}{0.2B_0\,(1-h)+(h-0.2)\,B_t}\right]\exp\left[\text{Normal}\,(0,\sigma^2)-\sigma^2/2\right]$ where R_t = number of age-0 recruits; B_t = spawning biomass; R_0 = unfished number of recruits (1.6×10^7); h = steepness (0.8); and σ = log-scale recruitment variation (0.96)
Spawning biomass (B)	$B_t = \sum_{age} N_{age,t}Mat_{age,t}Female_{age,t}Fecundity_{age,t}$ where N = abundance; Mat = proportion mature; $Female$ = proportion female; and $Fecundity$ = eggs per female
Abundance	$N_{age+1,t+1} = N_{age,t}\exp\left(-F_tSel_{age}-M_{age,t}\right)$ where Sel is fishery selectivity; F = fishing mortality; and M = natural mortality, including episodic fluctuations in natural mortality
Proportion mature	$Mat_{age} = \exp\left\{-\exp\left[-\left(-2.55+1.05\times age\right)\right]\right\}$
Proportion female	$Female_{age} = \exp\left\{-\exp\left[-\left(2.14-0.16\times age\right)\right]\right\}$
Fecundity (eggs per female)	$Fecundity_{age} = 3.878\times age^{2.12}$
von Bertalanffy growth (mm FL)	$L_{age} = L_\infty\left\{1-\exp\left[-K\left(age-t_0\right)\right]\right\}$ where L_{age} = length at age; L_∞ = asymptotic length (827.2 mm FL); K = Brody growth coefficient (0.12 year^{-1}); and t_0 = theoretical age at zero length (−0.89 year)
Whole weight conversion (kg)	$W_{age} = \left(5.46\times10^{-9}\right)L_{age}^{3.18}$ where W_{age} = whole weight at age
Average natural mortality (M; year^{-1})	From age 0 to age 29 (maximum age for Red Grouper): M = 0.584, 0.395, 0.308, 0.258, 0.226, 0.204, 0.187, 0.175, 0.165, 0.158, 0.151, 0.146, 0.142, 0.139, 0.136, 0.133, 0.131, 0.129, 0.128, 0.126, 0.125, 0.124, 0.123, 0.122, 0.122, 0.121, 0.121, 0.120, 0.120, and 0.119

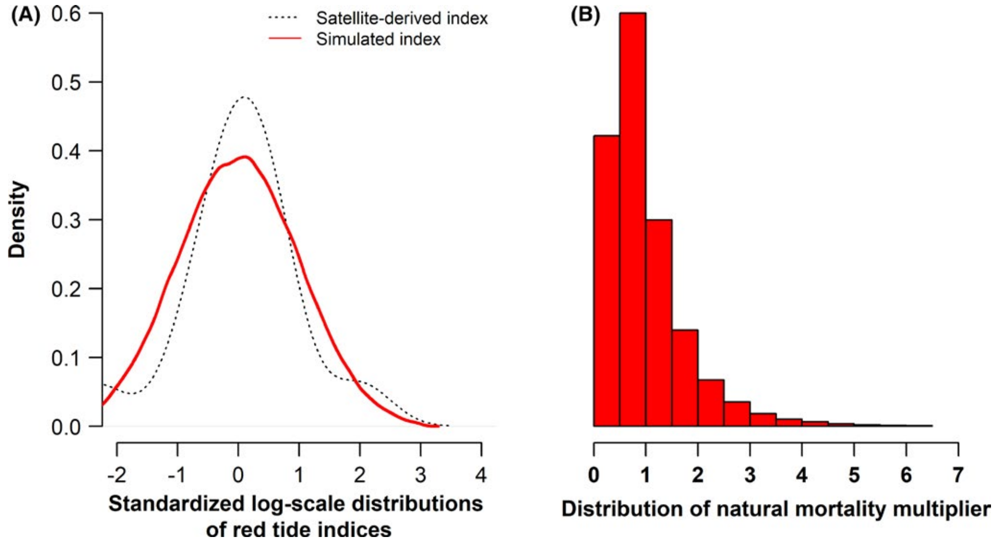

Figure 2. Distribution of **(A)** historical occurrences of red tide events based on satellite imagery and **(B)** corresponding natural mortality fluctuations of Gulf of Mexico Red Grouper (as a multiplier of average natural mortality rate).

and opted to evaluate precautionary catch reductions through adjustments to ACLs. Central to our choice of adjusting ACLs was being able to disentangle the GMFMC's existing management approach used in ABC calculation from the evaluation of precautionary catch reductions aimed at buffering against future natural mortality events. During the most recent Red Grouper stock assessment, the GMFMC's ABC control rule determined that ABC was equal to 0.98 × OFL, which was based on criteria related to stock assessment complexity, characterization of estimation uncertainty in the statistical estimate of OFL, and inclusion of environmental covariates in the assessment (GMFMC 2016). These considerations are formalized within an approach known as "P*" (Prager and Shertzer 2010). We adopted this approach and specified ABC as being 98% of the OFL in all management strategy variants we evaluated.

We simulated error in the observation of fishery CPUE with a lognormal SD of 0.3; we simulated observation of the age composition of the catches as a multinomial process with an effective sample size of 100, and we assumed that the catches (kg) were known without error. Data sources available for 28 years spanning 1986 to 2013 were used in the model before the first assessment of the simulated stock was generated. Observation of a red tide index, used in stock assessment for estimating time-varying natural mortality, was simulated with a Gaussian error structure using a coefficient of variation of 0.3. Observation of the red tide index was not generated prior to 1998, which reflects the actual availability of satellite imagery.

The simulated stock was assessed using an integrated statistical age-structured population model known as Stock Synthesis version 3.3 (Methot and Wetzel 2013). Growth, average natural mortality at age, and the SD of annual recruitment were specified to be known without error. The steepness parameter of the Beverton–Holt stock recruitment relationship, unfished recruitment (R_0), annual recruitment deviations, instantaneous fishing mortality in each year, and the parameters of an asymptotic selectivity function for the fishery were estimated. An informative Gaussian prior for the steepness parameter was obtained from the meta-analysis conducted by Shertzer and Conn (2012) and was bound between 0.2 and 1.0. Time-varying natural mortality was estimated through a linkage between the observed red tide index and each natural mortality-at-age parameter. This relationship was of the same functional form as equation (2), where scaling parameters (*c*; one for each age-class) were estimated under the constraint of being non-negative values. Time-varying natural mortality was not estimated prior to 1998 because observations of the red tide index were unavailable prior to this year. The fish stock was assessed as a single sex, with protogynous hermaphroditism addressed in the specification of fecundity at age.

Stock Synthesis was also used to estimate management benchmarks, which were based on maximum sustainable yield (MSY). These calculations used average natural mortality rates (i.e., life history parameters specified for 1986, the first year of the time series). Based on estimates of fishing mortality producing MSY (F_{MSY}), fishery selectivity, and stock size in the last year of the assessment model, Stock Synthesis was then used to provide OFL projections that were subsequently used in the HCRs we evaluated.

Each HCR we examined confronted uncertainty about episodic natural mortality through either (1) the degree to which ACLs were reduced or (2) the temporal pattern in which ACL decisions were made: fixed intervals every 5 years, or 5-year reactive intervals. A reactive interval consisted of an interruption to a 5-year decision interval in any year after a severe episodic natural mortality event (Figure 3). In this situation, a stock assessment would be made and newly calculated ACLs would be implemented. If no other severe event occurred, the next decision would occur in 5 years. If another severe event occurred before the fifth year, new ACLs would be calculated, and the 5-year decision clock would be reset. We defined a severe event as an observed value in the upper 10% of the index distribution. Thus, in any simulation run, 10% more stock assessments would be triggered, on average, by a reactive HCR than by a 5-year fixed-interval HCR. Our choice of 5 years for fixed decision intervals was based on the actual frequency of Gag and Red Grouper stock assessments, which have taken place every 3–6 years.

For each OFL projection provided by a stock assessment, the corresponding annual ABC was specified as 98% of this value. For fixed-interval HCR simulations that included a subsequent ACL reduction, each annual ABC was reduced by a specified percentage. In all simulations, the fishery harvested the entire ACL every year, even during red tide events. This ability of the fishery to achieve the ACL during a red tide event is based on fishery performance documented during a severe red tide event in 2005 (SEDAR 2015).

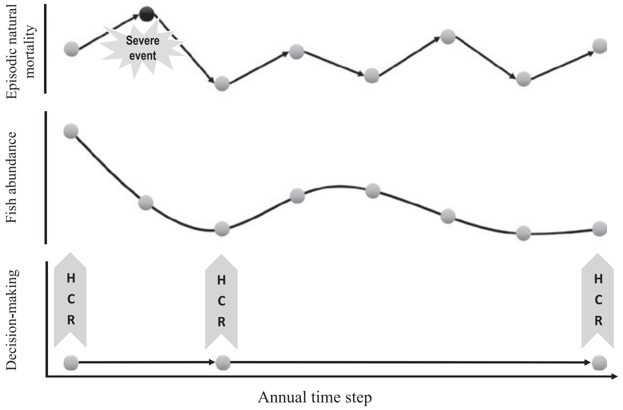

Figure 3. Example of a concurrent simulation of episodic natural mortality events (upper panel), Gulf of Mexico Red Grouper stock abundance (middle panel; i.e., abundance changes resulting from growth, births, and deaths), and a harvest control rule (HCR) that depicts reactive decision making following severe episodic increases in natural mortality (lower panel).

Simulated evaluation of management strategies

Simulated stock dynamics and designed management strategies were combined into an MSE. Stock dynamics were initialized for 1986 assuming that the ratio of existing spawning biomass to unfished spawning biomass was 0.3, which was consistent with an actual estimate of stock status (SEDAR 2015). Changes in stock size between 1986 and 2013 were simulated using the relative total fishing effort trend obtained from the actual stock assessment (SEDAR 2015). Simulated annual stochastic recruitment deviations occurred during the historical time period (1986–2013) as well as during the subsequent 25-year forecasted time period. Simulated annual episodic natural mortality events occurred during 1986–1997, actual historical values of the red tide index were applied between 1998 and 2013, and simulated events again occurred during the 25-year forecasted time period. Consequently, temporal patterns in stock size were generally consistent with actual stock assessments during this period, although each simulation run produced a somewhat different historical reconstruction due to stochastic annual recruitment and due to natural mortality fluctuations during the early part of the time series. All stochastic events were generated and saved ahead of simulation runs. This enabled each management strategy to be evaluated against the same sequences of events to ensure that performance was not influenced by chance differences inherent in a sample of random draws (Punt et al. 2016).

Five-hundred 25-year simulations were run under each of six HCRs: a reactive decision interval with no additional ACL reduction, and five HCRs consisting of a fixed decision interval with precautionary ACL reductions of 0 (i.e., no reduction), 10, 20, 30, and 40%. For comparative purposes, we also simulated a fixed decision interval with 0% ACL reduction, but which also assumed that the stock assessment was made without error. This allowed us to separate the effects of stock assessment errors on performance outcomes from the effects of episodic mortality events occurring after specification of multiyear ACLs.

In evaluating HCR performance, we calculated the propensity for overfishing as well as the propensity for the stock to become overfished, as these considerations are codified in NS1 guidelines (NMFS 2016). An "overfished" metric was calculated as the percentage of simulation runs during which spawning biomass in the 25th year was below the simulated target threshold of 0.5 × the biomass producing MSY (B_{MSY}). Overfishing was calculated as the percentage of simulation runs in which ACLs that were specified via the management strategy exceeded the simulated "true" OFLs in at least 50% of years over a 25-year duration. Thus, the overfishing metric determined the percentage of simulation runs, for a given management strategy, that exceeded a maximum overfishing allowance under NS1 guidelines. Two additional performance metrics were calculated in the 25th year of each simulation to reflect food production and recreational benefits on the basis of MSY: (1) the ratio of catches to true simulated MSY and (2) the ratio of spawning biomass to B_{MSY}. These metrics are instructive when compared to stock status in the first year of the simulations to evaluate whether a given management strategy generally works to guide the stock toward achievement of management objectives consistent with the fishery management plan for Gulf of Mexico reef fish resources (GMFMC 1984).

RESULTS

The HCR consisting of a fixed decision interval and no ACL reduction was meant to represent the current management approach to Red Grouper in the Gulf of Mexico. Relative to the first year of simulation runs, this management strategy either stabilized or slightly improved sustainability on the basis of MSY management objectives (Figure 4). Median performance across all simulation runs indicated that spawning biomass stabilized above B_{MSY}, while catches were stabilized near a median value of 0.79·MSY. Under this management strategy, the maximum allowable overfishing probability of 0.5, as codified in NS1 guidelines, was exceeded in 36% of simulation runs (Table 2). This means that 36 of 100 simulations would produce ACLs that exceed the simulated target OFLs in more than 12 years of each 25-year simulation. Our results also suggested that 20 of 100 simulations would result in an overfished stock after 25 years.

To examine how other management approaches might modify management outcomes resulting from the current approach, we first considered the reactive decision interval that consisted of additional stock assessments and updated ACL calculations in response to severe red tide events (i.e., the largest 10% of event magnitudes). The MSE suggested that such an approach could reduce the occurrence of overfishing relative to our representation of the current management approach (Table 2). This occurred because more frequent decision-making intervals performed better at keeping the stock and its fishery on track toward achieving fishery objectives.

Precautionary ACL reductions—in which 5-year fixed decision intervals were maintained in combinations with 10, 20, 30, or 40% ACL reductions—were then considered as alternatives to decision-making reactivity. A 10% ACL reduction increased spawning biomass but decreased median long-term catches (Table 2). All of the ACL reductions we examined lowered the occurrence of overfishing and thus decreased the

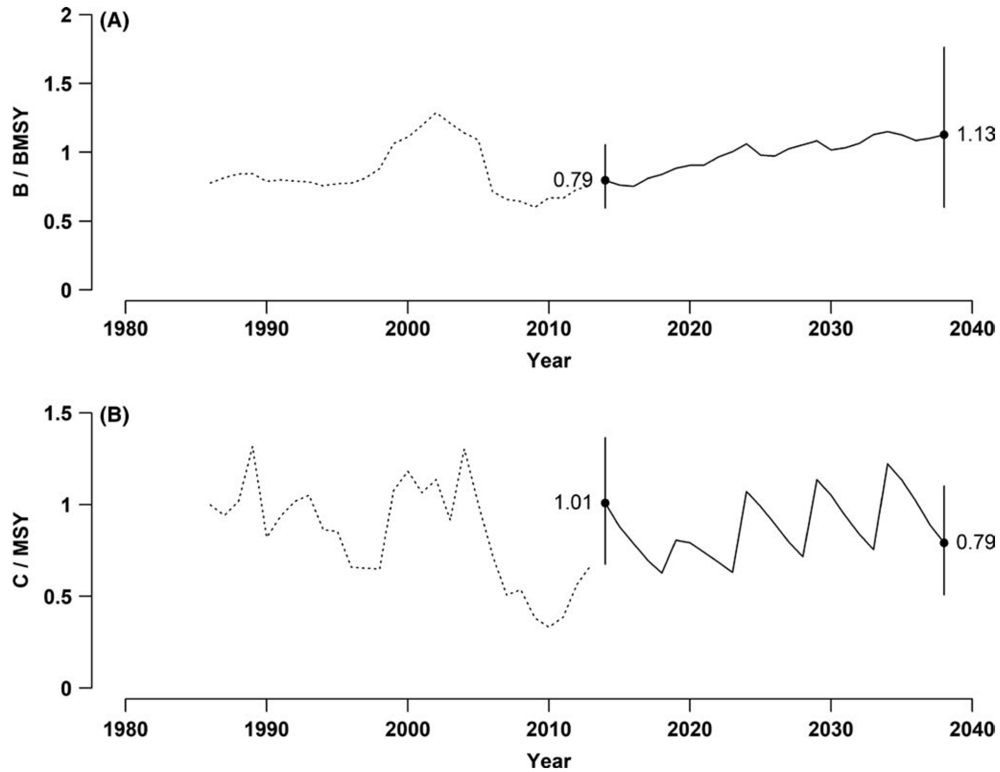

Figure 4. Median performance outcomes based on 500 25-year simulation runs of a management strategy similar to the current approach for Gulf of Mexico Red Grouper: **(A)** B/B_{MSY} is spawning biomass as a fraction of biomass producing maximum sustainable yield (MSY); and **(B)** C/MSY is catch weight relative to MSY. Dashed lines are median historical trends prior to implementing the management strategy, and solid lines are median trends during simulations of the management strategy. Filled dots represent median performance values (numeric labels), and thin vertical lines denote interquartile ranges of simulation outcomes.

Table 2. Performance metrics calculated from 500 25-year simulations for each harvest control rule examined under a scenario of episodic natural mortality fluctuations for Gulf of Mexico Red Grouper (C = catch [kg]; ACL = annual catch limit; MSY = maximum sustainable yield; B = spawning biomass; B_{MSY} = spawning biomass that produced MSY). Numbers in parentheses represent the centered 50% credibility envelope.

Harvest control rule	Overfishing occurrence (%)	Overfished occurrence in the 25th year (%)	Median C/MSY in the 25th year	Median B/B_{MSY} in the 25th year
Stock assessment conducted				
Fixed decision interval				
0% ACL reduction	36	20	0.79 (0.51–1.10)	1.13 (0.60–1.76)
10% ACL reduction	23	14	0.75 (0.51–1.02)	1.18 (0.71–1.98)
20% ACL reduction	12	12	0.71 (0.51–0.99)	1.37 (0.80–2.11)
30% ACL reduction	4	9	0.70 (0.50–0.91)	1.51 (0.90–2.27)
40% ACL reduction	1	7	0.63 (0.46–0.83)	1.65 (1.02–2.49)
Reactive decision interval				
0% ACL reduction	38	18	0.94 (0.59–1.40)	1.13 (0.66–1.81)
Perfect stock assessment				
Fixed decision interval				
0% ACL reduction	5	16	1.00 (0.66–1.51)	1.04 (0.64–1.59)

chances of the stock becoming overfished at the end of the 25-year simulation period. The ACL reductions of 20, 30, and 40% exhibited a trend of decreasing overfishing and increasing stock biomass at the expense of reduced long-term catches. These MSE results provide guidance in selecting the most appropriate management strategy to employ in order to achieve pre-agreed management objectives.

Finally, simulating the performance of various management strategies was also useful in identifying the effects of different management strategy components on performance outcomes. By evaluating an HCR with perfect information about stock status and management reference points, we were able to separate the effects of stock assessment errors from natural mortality fluctuations due to red tides (Table 2). Evaluating this "perfect information" management strategy, which was similar to the current management approach (i.e., in terms of having a fixed decision interval with no ACL reduction) suggested that stock assessment reliability contributes substantially to the occurrence of overfishing. Thus, stock assessment reliability should be given special consideration in management strategy design, especially when dealing with the estimation of time-varying natural mortality fluctuations.

DISCUSSION

We feel that our results have answered both of the questions we posed at the outset of this article. We now revisit these two questions.

First, does the existing GMFMC management approach need to be modified to achieve management objectives due to effects of episodic natural mortality events? Under the HCR that reflected aspects of the current management approach consisting of a fixed decision interval and no ACL reduction, our simulations had an occurrence of overfishing in 36% of the simulation runs and an occurrence of the stock becoming overfished in 25 years for 20% of the simulation runs. Such a performance outcome suggests that this approach may commonly result in the implementation of rebuilding plans and other costly policy adjustments and thus may require further examination by fishery decision makers. Stock assessment was also made considerably more complicated by the presence of episodic natural mortality events. Uncertainty related to stock status determination and OFL projections that arise from estimation of time-varying natural mortality parameters may not be adequately addressed within the GMFMC's existing ABC control rule. However, complications in stock assessments related to estimation of time-varying natural mortality are only beginning to be explored (Johnson et al. 2015), and, like the inclusion of other sources of environmental variation, decisions made in conducting stock assessments will affect the reliability of estimated stock status and management reference points (Punt et al. 2014; Sagarese et al. 2014b). As we have shown in this study, if stock assessments estimate time-varying natural mortality, management strategies built around these assessments may require buffers in setting catch limits as a consequence of considerable uncertainty.

Second, if modifications are considered, what are their effects on and trade-offs for maintaining sustainable fisheries? Our simulations demonstrated the effects and trade-offs that are likely to occur under various management strategy modifications. We found that both precautionary ACL reductions and decision reactivity can improve the achievement of fishery objectives. This conclusion is supported elsewhere, both in the use of buffers to account for uncertainty in setting catch limits and in the frequency of decision making as a means to avoid undesirable stock depletion (Punt et al. 2012; Li et al. 2016). The terms "reactive" or "reactionary" are often associated with ad hoc decision making in fisheries management; however, we used these terms to mean an established decision process designed to respond to an event that has unpredictable timing. As an alternative to reactivity, precautionary harvest policies attempt to avoid undesirable situations altogether and under as many circumstances as possible (Restrepo and Powers 1999). Precautionary buffers also offer a simple means of addressing the effects of natural variability on fish stock dynamics without requiring these events to be predictable. Because buffering catches works to maintain higher average biomass levels, natural fluctuations in stock size are expected to have lower probabilities of falling below management thresholds. This conclusion is borne out by our study. Additionally, given that practical limitations in stock assessment reliability will continue to persist, especially for complex assessments that estimate time-varying natural mortality, buffers appear suitable for maintaining higher average biomass levels. However, selection of buffer sizes is not straightforward and will require a balance between maintaining low probabilities of falling below biomass thresholds and achieving the highest possible catch rates.

The viability of reactive HCRs as management options will depend on both the timeliness of event detection and whether reasonable judgments about event severity can be used as a trigger for management intervention. Limitations in funding will affect data collection and analysis as well as the ability to conduct stock assessments. In the Gulf of Mexico, more than 35 stocks require establishment of ACLs under the Magnuson–Stevens Fishery Conservation and Management Act (NOAA 2007). Several families of fish are susceptible to red tide events, with members of the family Serranidae (e.g., larger groupers like the Red Grouper and Gag) appearing to be particularly vulnerable (Sagarese et al. 2017). The variety of fish stocks potentially affected by red tide events poses additional considerations about whether reactivity would trigger multiple stock assessments, how these assessments would be prioritized, and whether non-affected stocks would as a consequence be assessed less frequently. The level of anxiety experienced by stakeholders and managers in response to a severe natural mortality event may be reduced by more steady management actions, like catch limit buffers. The temporary postponement of setting Gag catch limits in 2014 suggests that some level of management intervention to changes in environmental conditions is needed (GMFMC 2015).

A central statement of the GMFMC's 2014 motion to evaluate the current Red Grouper HCR emphasized better knowledge of future changes in the intensity and frequency of episodic events. We evaluated management strategy performance in response to historical patterns in intensity and frequency of red tide events, assuming that these would continue into the foreseeable future. However, observations indicate that the intensity and frequency of these events are already changing in coastal regions (Glibert and Burford 2017). Evaluating harsher environmental conditions will involve simulating scenarios that convey different levels of mortality risk associated with red tide events and highlighting the corresponding consequences of alternative fishery management actions. The most appropriate management strategy might be the one that best ensures the achievement of minimum performance standards across a variety of conditions or at least across the most severe of plausible conditions. This approach would require consensus on the suite of scenarios or "states of nature" under which management strategies would be judged but does not necessarily require any one scenario to be favored over another (Miller and Shelton 2010). In doing so, specific guidance on whether a precautionary ACL reduction should be considered at all—and to what extent an ACL buffer may be needed—can be more thoroughly explored and explained to decision makers and stakeholders.

Our study reflects the growing emphasis on accounting for natural variability in the design of single-species management strategies. Operationally, single-species HCRs can advance U.S. policy toward ecosystem-based fisheries management (EBFM; NOAA 2016). Because EBFM is supported by a wide spectrum of assessment and decision-making tools, single-species approaches that address the effects of ecological variability on management decisions have the potential to alter thinking about the design of decision-making frameworks (Link and Browman 2014). Furthermore, expansion of existing management approaches to account for ecological and environmental conditions, including anthropogenic climate change, would be an important shift toward "climate-ready" fisheries management and an important step toward EBFM implementation (Pinsky and Mantua 2014).

ACKNOWLEDGMENTS

We thank L. Barbieri, A. Punt, and an anonymous reviewer for comments that led to the improvement of the manuscript. This work was funded by the NOAA Integrated Ecosystem Assessment Program. This research was carried out, in part, under the auspices of the Cooperative Institute for Marine and Atmospheric Studies, a cooperative institute of the University of Miami and NOAA (Cooperative Agreement NA10OAR4320143).

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