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REVIEW

A garden of forking paths: an ecosystem-based fisheries management case study of Florida red tides

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Abstract Ecosystem-based fisheries management is a crucial advancement to address natural and anthropogenic stressors on marine ecosystems. Although there has been a shift toward more holistic management approaches over the past few decades, Fishery Management Councils still face challenges in implementing ecosystem-based strategies. Here, we present a case study on incorporating harmful algal blooms, known as red tides, into U.S. federal fisheries management on the West Florida Shelf. Red tides are first defined as a fishery ecosystem issue by outlining their ecological, economic, and societal impacts on the relevant fisheries. We then review the history of including red tides in the stock assessment process and how management actions have responded to episodic mortality attributed to devastating red tides. Fishery managers have encountered significant challenges when addressing red tides because the root causes are beyond fisheries management jurisdiction. The primary method to account for red tides in fisheries management has been to incorporate extra mortality in stock assessments. While integrating ecosystem information can reduce scientific uncertainty in stock assessments, the setting of catch limits also benefits from such information. Red tide-related management actions have been reactive, and frequent reversals of catch advice highlight the complexity of red tide impacts. The directionality of catch advice for Gulf groupers has been dependent upon additional information such as ecosystem modeling results and stakeholder observations. We offer a review of potential fishery management policy options that include, but are not limited to, the management of fishing mortality. We outline research recommendations to better characterize impacts and inform fisheries management's response to red tides. Effective ecosystem-based fisheries management necessitates a clear definition of the problem, goals, expectations, metrics to measure progress, and a work plan that includes stakeholder engagement.

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Introduction

Dynamic environmental conditions pose significant challenges to sustainable fisheries management, demanding the inclusion of ecosystem information into the policy-making process. Acute and extreme environmental phenomena such as marine heatwaves (Hobday et al. 2016; Amaya et al. 2023), marine cold spells (Schlegel et al. 2017), harmful algal blooms (HABs; Griffith and Gobler 2020), tropical cyclones (Olin et al. 2020; Correia et al. 2024), and hypoxic events (Driggers et al. 2016) are indiscriminate and largely disruptive to marine ecosystems and their associated ecosystem services, including fisheries. The frequency and magnitude of these events may be changing (Jentsch et al. 2007; Keeling et al. 2010; Wang et al. 2010; Doney et al. 2012; Oliver et al. 2018; Holbrook et al. 2019; Gobler 2020), increasing the likelihood that fishermen and fisheries managers will have to deal with the cumulative effects of successive shocks (Bellquist et al. 2021). Extreme environmental phenomena contribute to marine community restructuring driven by immigration and episodic mortality (Lirman et al. 2011; Bond et al. 2015; Driggers et al. 2016; Santos et al. 2016). Of particular concern in fisheries management is episodic mortality because it increases the probability of a stock falling below its target biomass threshold, requiring managers to consider the implications of such events in projections and catch advice (Holsman et al. 2020). Total mortality of a species–from fishing and other various sources of natural mortality–is accounted for in stock assessment models and then used to specify the maximum catch allowed that prevents the stock from being overfished. Thus, ecosystem information coupled with flexible management strategies is needed to effectively manage fisheries, especially in response to extreme environmental conditions (Harford et al. 2018, Huynh et al. 2020; Free et al. 2023). It is useful to examine past responses to extreme events for lessons learned and to develop an iterative portfolio of management strategies to cope with the dynamic nature of marine ecosystems and fisheries in a changing context.

Ecosystem-based fisheries management (EBFM) is a process to apply whole systems thinking to decision-making in fisheries management by prioritizing the larger ecosystem (Pikitch et al. 2004). Implementing EBFM requires a clear articulation of the issues, actionable objectives within the statutory framework of regional Fishery Management Councils (hereafter referred to as regional councils), and the evaluation of progress with specific, measurable, achievable, relevant, and time-bound performance metrics. To overcome these challenges, the United States (U.S.) National Oceanic and Atmospheric Administration (NOAA) Fisheries instituted a policy in 2016 to incorporate EBFM where practicable into the fisheries management process (Link 2016)., This EBFM policy directed the eight U.S. regional councils to develop Fishery Ecosystem Plans to address regional needs (Levin et al. 2018; LGL, 2021). The Gulf Council (formerly the Gulf of Mexico Fishery Management Council) approved a draft Fishery Ecosystem Plan (LGL 2022; Gulf Council 2025) outlining an iterative and modular process, the Fishery Ecosystem Issue (FEI) loop (Fig. 1). The FEI loop's purpose is to implement regional EBFM and address specific ecosystem challenges to fisheries management in the Gulf of America (formerly the Gulf of Mexico). To implement EBFM as outlined by the FEP, the FEIs must have several general characteristics. First, managers, scientists, and fishermen need to co-develop a conceptual model of the issue, including broader linkages to the ecosystem using inputs from experienced and active fishermen in addition to managers and scientists. Some of the advantages of broad participation in developing the conceptual model are incorporating local ecological knowledge (LEK) and forming meaningful policy recommendations relevant to stakeholders. Second, an issue that needs management action should be bounded in space and time within the co-developed conceptual model of the fishery ecosystem. The fishery ecosystem is defined here, following the Gulf Council's Fishery Ecosystem Plan (LGL 2022; Gulf Council 2025), to include all the interrelated ecological, economic, and social components relevant to the fishery (also referred to as "the triple bottom line", Marshall et al. 2018); boundaries must be defined to exclude unnecessary information. Finally, the process should result in actionable management

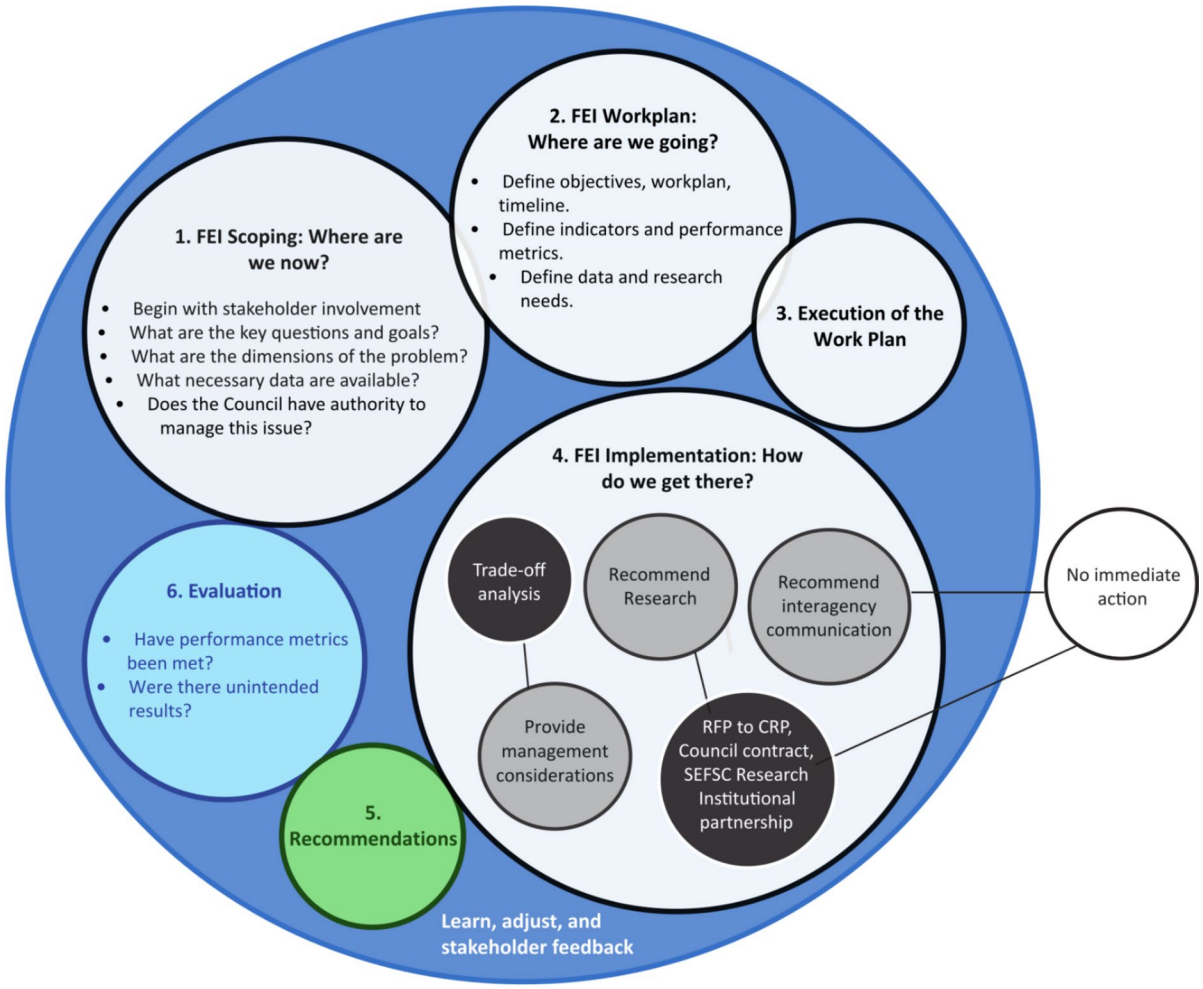


Fig. 1 The fishery ecosystem loop proposed by the Gulf council and modified from LGL (2022) and Levin et al. (2018). The loop is designed to systematically address proposed fishery ecosystem issues (FEIs) that may impact federal fisheries in the Gulf. Image courtesy of the Gulf council

guidance, identify pathways to address knowledge gaps, evaluate the success of the management action, and seek interjurisdictional partnerships if needed. Intentional framing ensures that regional councils can use the FEI loop, or a similar process, to alter fishery outcomes in a material way.

This paper details the progress towards EBFM with an emphasis on HABs of the dinoflagellate *Karenia brevis*, referred to as red tides, on the West Florida continental shelf (WFS) in the Gulf of America. The WFS spans a total area of ~ 392,000 km^2 (~ 170 km from the shore to the shelf break), has a median depth of 38 m, and is dominated by sand mixed with hard bottom structure including natural and artificial reefs. Extensive collaboration between fishermen, managers, and scientists on the impacts of red tides on WFS fisheries (Blake et al. 2022) serves as a case study for the implementation of the FEI process. Despite a 15 + year history of including red tides in single-species fisheries management, red tides have yet to be addressed from a proactive and holistic ecosystem perspective that includes additional affected species, socio-economic tradeoffs, and interjurisdictional collaborations. Red tides can cause episodic mass mortality events affecting managed (Driggers et al. 2016; Sagarese et al. 2021; Vilas et al. 2023), unmanaged (Smith 1975; Tiffany

and Heyl 1978), and protected species (Landsburg et al. 2009). This prompted the explicit inclusion of episodic mortality in stock assessments (since SEDAR 2009a, 2009b) and catch advice (Sagarese et al. 2021) for federally managed gag (*Mycteroperca microlepis*) and red grouper (*Epinephelus morio*). Herein, we make significant progress towards step 1 of the FEI loop (Fig. 1) by defining red tides and assessing their ecological, economic, and sociocultural impacts relevant to federal fisheries management. We then review the history of integrating red tides into stock assessment and synthesize previous single-species actions into a more coherent strategy with an emphasis on EBFM (retrospective on steps 2–6 of the FEI loop). We also explore the Federal fisheries management options to improve the incorporation of red tide in the fishery management process (step 4). Lastly, we highlight knowledge gaps (step 2) and discuss how this case study can assist other regions working to formalize EBFM around regionally specific issues. We intend for this paper to support future applications of the FEI loop pertaining to red tides on the WFS.

FEI case study: Florida red tides

What are red tides?

HABs of *K. brevis*, also known as red tides, have been documented in the Gulf of America in both Mexican and U.S. coastal waters since the 1800 s (Magaña et al. 2003). On the WFS, red tides tend to occur in late summer and last until late fall, sometimes extending into the winter months, on a nearly annual basis (Fig. 2a, Stumpf et al. 2008). The blooms can be patchy and occur anywhere along Florida's Gulf coast, but the core region of red tide occurrence is typically nearshore (less than 18 m in depth) between Clearwater and Naples, Florida (Fig. 2b–g). A combination of physical oceanography and land-based nutrient inputs contribute to *K.brevis* bloom initiation, maintenance, and termination (Hu et al. 2006; Stumpf et al. 2008; Walsh et al. 2003, 2006; Maze et al. 2015; Weisberg et al. 2019; Medina et al 2022). Red tides cause a wide range of ecological, economic, and socio-cultural impacts on the WFS, primarily through the production of a suite of neurotoxins called brevetoxins. These impacts are discussed below.

Ecological impacts

The federally managed species determined to be most impacted by red tides are red and gag groupers (Smith 1975; Walter et al. 2013; SEDAR 2019; Driggers et al. 2016), although impacts likely extend to a broader suite of species (managed or not).Red grouper are mostly targeted by commercial fisheries (longline, vertical line, and trap gears), whereas gag grouper are predominantly targeted by hook-and-line recreational fisheries. These groupers represented ~ 22% (~ 2.5 milllion pounds or ~ 1.1 million kg) and ~ 3% (~ 360,000 pounds or ~ 160,000 kg), respectively, of the commercial landed weight for federally-managed reef fish species averaged over a 3 year period in the Gulf (2022–2024; https://www.fisheries.noaa.gov/southeast/commercial-fishing/gulf-america-historical-commercial-landings-and-annual-catch-limit, accessed 2025-03-11). The recreational sector's landings are similar in magnitude to the commerical sector (Sagarese et al. 2025). These groupers are typically associated with hard bottom habitats from nearshore out to the shelf break, and juveniles of both species are found nearshore and inshore making them vulnerable to red tides.

Brevetoxins can readily be absorbed through the skin and gills, inhaled via aerosols into the lungs, or ingested via prey species (Landsberg 2002). This can lead to mortality (Landsberg et al. 2009), reduced mobility (Gravinese et al. 2018, 2019, 2020), and decreased growth and reproductive output (Flewelling et al. 2010; Griffin et al. 2023; Walters et al. 2013). In addition, brevetoxins can bioaccumulate in the food web leading to a delayed ecosystem expression (Tester et al. 2000; Naar et al. 2007; Flewelling et al. 2010; Landsberg et al. 2009), and blooms can spatially displace mobile species (Griffin et al. 2023). The cumulative effects of dense algal biomass decomposition and water column stratification can deplete dissolved oxygen, further contributing to the mass mortality of benthic fauna and demersal fishes (Smith 1975, 1976; Driggers et al. 2016; Turley et al. 2022). Widespread instances of hypoxia/anoxia coupled with long-lasting red tides contribute to mass mortality events, benthic habitat destruction, and community reorganization, emphasizing the long-lasting and

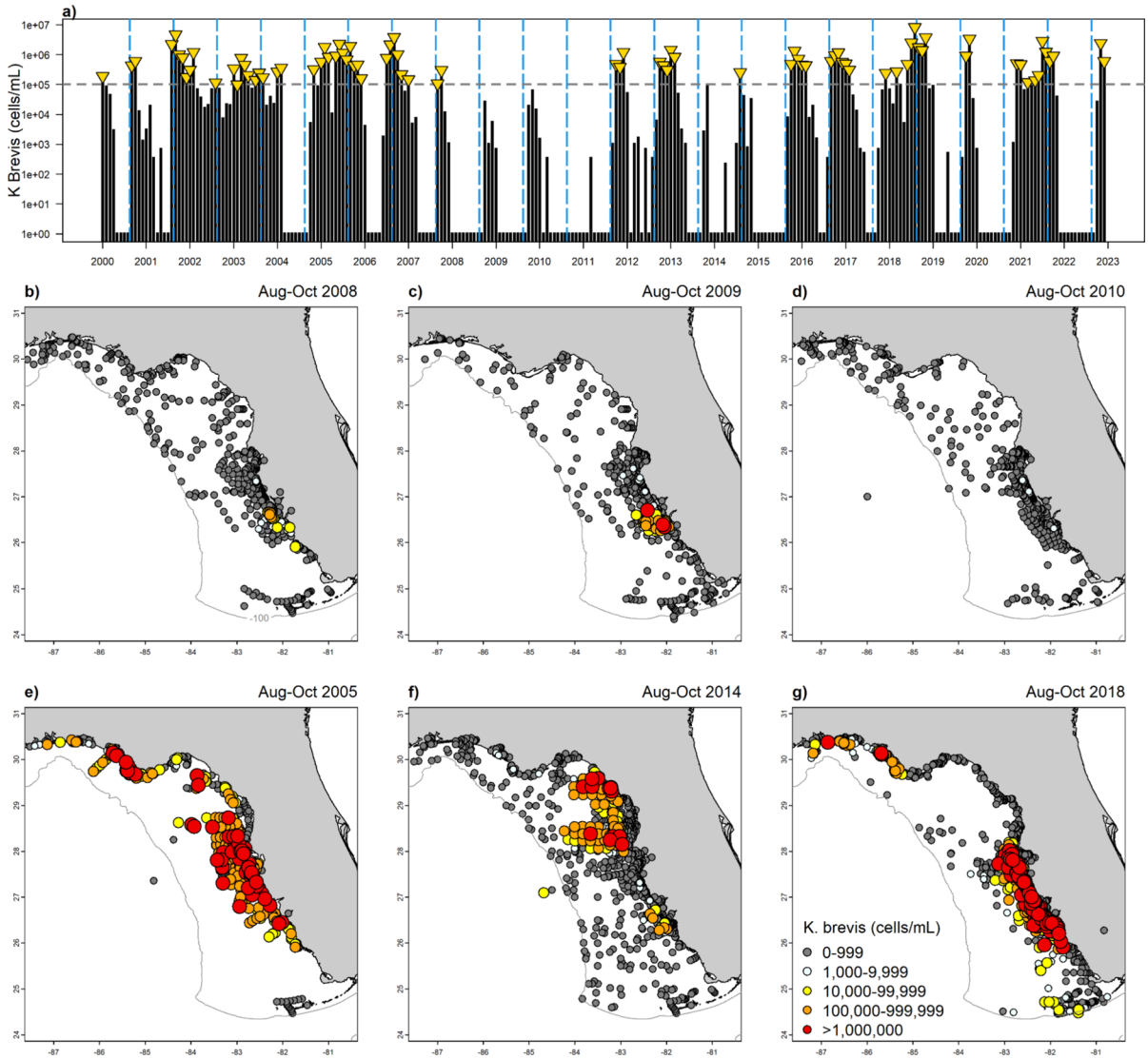


Fig. 2 Spatiotemporal distribution of *Karenia brevis* observations on the West Florida Shelf 2000–2022. **a** Timeseries of the 95 percentile of *K. brevis* cell density per month. The y-axis is on a logarithm (base 10) scale. The gold triangles indicate months above the bloom threshold (> 100,000 cells mL^{-1} horizontal dashed line), and the vertical dashed blue lines are September. **b–g** K. brevis cell densities (August–October) for select years. The middle row plots **b–f** are 2008–2010, which was three years without major blooms. The bottom row plots **e–g** are 2005, 2014, and 2018, which were the worst red tide years since 2000 and included in the stock assessments for gag and red groupers. The gray contour is the 100 m isobath, which is the approximate limit of the continental shelf

widespread impacts on the ecosystems and associated fisheries (Smith 1975; Dupont et al. 2010; Driggers et al. 2016; Turley et al. 2022). These ecological pathways for brevetoxins and the fate of bloom biomass underscore the complexity of the impacts of red tides on the fishery ecosystem and the necessity for integrated management strategies.

The impacts of red tide extend beyond individual mortality to significant population-level consequences. Zooplankton, including the larvae of invertebrates and fishes, decline during red tides, potentially leading to a trophic cascade (Lester et al. 2008; Warlen et al. 1998). Mortality rates across ecological functional groups in nearshore habitats can be high

(Smith 1976), with significant decreases in fish species abundance and species richness (Gannon et al. 2009) affecting community composition and ecological functioning (Flaherty and Landsberg 2011). Furthermore, red tides have been associated with reduced annual recruitment following severe events (Flaherty and Landsberg 2011) and differential recovery times, with some species returning immediately after red tide conditions cease, while others take longer (a year or more) after the initial disturbance (Smith 1975, 1976; Flaherty and Landsberg 2011; Berens et al. 2021). Compensatory dynamics within and among species are not well understood and likely contribute to ecological succession and exclusionary processes. Generally, red tides are disturbance events that favor opportunistic species with high turnover and disfavor climax species that tend to be slower growing.

The broader impacts of red tides on WFS ecosystems introduce complexities in defining overall population-level effects. Red tides may have a delayed top-down positive effect on forage species and juveniles of many species by removing larger predators and competitors, potentially offsetting direct brevetoxin impacts and contributing to resiliency at the base of the food web after red tide events (Vilas et al. 2023). Young gag tend to be found in nearshore areas where red tides are most severe, making them particularly vulnerable, depressing future gag population trends. When red tides occur offshore, they can cause adult red grouper mortality, which in turn causes cascading ecosystem effects by reducing competition and predation on other species (Grüss et al. 2016b). The ecological complexity of the WFS contributes to some ecological resiliency to disturbances; however, the combination of anthropogenic factors (e.g., fishing and coastal development) and natural stressors (e.g., cold snaps, heatwaves, hurricanes, and red tides) erodes resilience over time (Sagarese et al. 2017; Lugo et al. 2000; Vilas et al. 2023). Conceptual models developed by stakeholders from fishing communities along the Florida Gulf Coast (Spooner et al. 2021) assisted in defining the complex and interconnected impacts of red tide on ecosystems as well as social and economic aspects of the fishery system (Fig. 3). Stakeholders conceptualized that water quality, water temperatures, and hurricanes contributed to the emergence of red tides, and as a result nearshore habitat declined, fish mortality increased, fishing effort changed, and tourism was negatively affected. Stakeholder input confirmed some known impacts and identified causal relationships previously unknown to fishery scientists and managers.

Economic impacts

Red tides have long disrupted Florida's fisheries, but studies on recent severe blooms reveal how widespread the economic effects can be. On a macro-level, red tides have measurable impacts to county and state revenues. During months with active blooms, Pinellas County, Florida experienced a 15% decrease in taxable sales concentrated in the fishery and seafood industries (Bechard 2020). More broadly, counties affected by red tides experienced substantial reductions in taxable revenues during months when red tides occurred (Alvarez et al. 2024). For example, Florida lost 2.7 billion USD in tourism-related statewide revenues in 2018 due to the 2017–2019 severe red tide. Large scale economic analyses demonstrate the aggregated impacts of red tides (Alvarez et al. 2024); however, finer-scale analyses reveal more nuanced economic impacts (Bechard 2020).

Economic assessments often focus on direct losses, but red tides alter fishing behavior causing cascading impacts on businesses, supply chains, and coastal communities (i.e., dependent on tourism and commercial fishing), and these aspects can be difficult to assess. For example, red tides do not appear to influence the size of the commercial fleet or the amount of fishing effort, but do influence individual vessel behavior, as reef fish fishermen actively avoid blooms (Perruso et al. 2023; see Perruso et al. and Chollett et al. 2026 for more about fleet dynamics). For inshore fisheries, some fishing entities (i.e., individual vessels or fishing businesses) have been able to mitigate losses by moving to less affected areas and diversifying species targeted (e.g., blue crab; Court et al. 2025a), which may increase revenues in some instances (NOAA-NMFS unpublished report). While these adaptive strategies can help lessen revenue losses, they may increase operational expenses such as higher fuel costs, additional gear purchases, leasing additional quota, or increased healthcare costs due to complications from aerosolized toxins, which can offset revenue gains (Shane Dooley, pers. comm, July 21, 2021).

Recreational fishing can also be greatly affected by red tides. Counties close to active blooms during

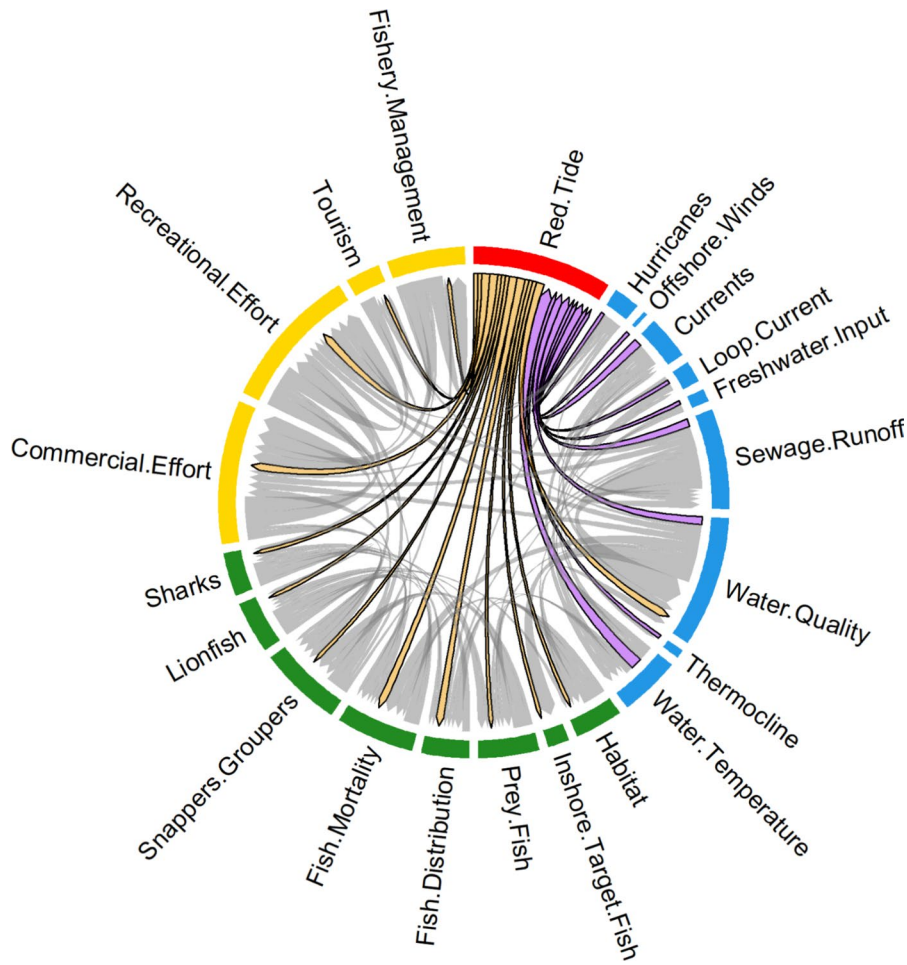


Fig. 3 Chord diagram of consolidated conceptual models developed in participatory workshops as part of marine resource education program-supported work in 2019. The models were simplified by standardizing terms and removing all links that were not directly linked to red tide. This shows the diversity of nodes that either affect or are affected by red tides. Green arrows are links directed into red tides and red arrows are links directed out of red tide

the 2017–2019 red tide experienced a 14% drop in offshore recreational fishing trips overall (i.e., private, charter, and head boats) although the impacts to shoreline fishing were less clear (Court et al. 2025a). Charter fishing operators during the 2017–2019 red tide reported a 63% revenue decrease when blooms were locally present and a 20% decrease after the event had ended (Court et al. 2021). Fishing supply businesses (bait, tackle, rods, and reel retailers) also reported a 60% revenue decrease when a bloom was locally present, a 50% revenue decrease when the bloom was not present locally, and a 17% decrease after the event had ended (all percentages are relative to baseline revenues without red tides; Court et al. 2021). Red tides appear to not only reduce recreational effort, but cause a spatial shift as anglers avoid bloom areas entirely, redistributing effort to unaffected sites potentially altering local economies (Botta 2017). Overall, red tides can have geographically wide-spread and prolonged economic impacts for recreational fishing businesses, with a full recovery often delayed until many months after the bloom dissipates.

The economic impacts of red tides are inextricably linked by feedback loops within and between business sectors. For example, red tides affect tourism, which drives demand for charter-for-hire trips, private recreational sector expenditures, seafood demand, and restaurant patronage. Repeated red tides can weaken visitor perception of the affected area as a tourist destination and further exacerbate economic impacts (Adegbola et al. 2025). In 2018, significant reductions in Airbnb reservations were associated with the ongoing red tide (Ferreira et al. 2023); meaning fewer tourists, fewer anglers, and slower economic recovery. In some fishing communities, the feedback was not

short term because the recovery from the 2017–2019 red tide lasted into 2021 complicated by the COVID-19 pandemic. While many fishing (both commercial and recreational fishing-related) businesses survived past 2021, the industry experienced a significant loss of personnel who either switched employment sectors or migrated away from the coastal areas (decisions to leave the industry are complex and include factors beyond red tides; for example see Cockrell et al. 2019). This puts additional pressure on fishermen to find reliable deckhands and on fish houses that were dealing with fewer vessels (Roy Kibble, pers. comm, July 21 st, 2021). The broad-scale economic impacts of red tides have profound implications and are directly linked to the socio-cultural identities of fishing communities in the region.

Socio-cultural impacts in fishing communities

Economic losses from red tides tend to overshadow the socio-cultural aspects, yet these represent a critical dimension of the impacts to fishing communities. National Standard 8 of the Magnuson-Stevens Fishery Conservation and Management Act (MSA, 2007) requires fishery management plans to ensure the continued participation of communities in fisheries and minimize economic impacts from management actions. Such impacts are difficult to assess using existing data sources; thus, a local knowledge approach is often critical for revealing these impacts. In Florida, oral histories conducted with fishermen (a group that included commercial, recreational, and for-hire; with some participants engaged in multiple categories) reveal a number of concerns regarding social and cultural impacts of red tides and associated management actions (McPherson, Karnauskas, and Blake 2018). Some fishermen expressed that red tides have negatively affected populations of mullet (McPherson, Karnauskas, and Blake 2018), which have historically been a significant part of the cultural identity of Florida's Gulf Coast (Zacks 2019), and red tides may be contributing to a decreasing cultural preference for mullets in Central Florida. Additionally, the impacts of red tides have exacerbated fishermen stress and mental health issues, which trickles down affecting associated families and communities (McPherson, Karnauskas, and Blake 2018). Similarly, members of coastal communities with strong ties to the marine occupational sector reported elevated levels of stress and anxiety related to income loss, fear for personal and family health, and disruption of everyday routines (Lindsey & Anderson 2021). Although erosion of community identity is difficult to measure, compounding stressors over the past two decades, including red tides, hurricanes, the Deepwater Horizon disaster, and market and regulatory changes (Cockrell et al. 2019), have driven many fishermen to alternative employment, decreased opportunities for younger generations, and further eroded trust in government through perceived lack of or ineffective action. In tightly-knit fishing communities, such shifts are disruptive to traditional ways of life affecting the passing of marine cultural heritage to future generations (McKinley et al. 2024).

Public perception further compounds the localized socio-cultural impacts of red tides where risk comes from direct exposure and is also shaped by media coverage. Widespread media coverage, including social media, can unintentionally perpetuate negative public perceptions of red tides (Kuhar et al. 2009; Skripnikov et al. 2021), including erroneous beliefs that seafood is unsafe to eat during red tides In fact, regional seafood tends to be caught in areas not affected by blooms (Larkin and Adams 2008), which is different from shellfish advisories that are designed to protect consumers from bloom-contaminated shellfish (FDACS 2023). However, well-framed, accurate messaging, especially when it addresses specific concerns, such as the safety of commercially caught red grouper, increases the willingness to consume such seafood during a bloom (Bechard & Lang 2023). Prior individual experience also plays a role in perceptions and decision making as red tide presence was the second-most important factor in determining travel plans to an affected coast for Florida residents (Adegbola et al. 2025). Out-of-state residents tend to have less flexibility to alter plans in response to a red tide, and as a result, severe blooms may decrease future visitation rates. The cumulative socio-cultural impacts of red tides on the west coast of Florida underscore the complexities (i.e., ecological, economic, or socio-cultural) that fishermen face and the challenges present in recommending or implementing policies in response to severely disruptive events.

Where have we been?

Red tide mortality within stock assessments

Accounting for ecosystem processes within single-species catch advice has been challenging and complex, contributing to a perceived lack of progress from stakeholder and ecosystem-based fishery management perspectives. The first set of challenges for a stock assessment analyst to quantitatively include ecosystem considerations has been identification of the mechanisms that affect the species' population dynamics and how exactly to link this impact to the relevant model parameters. Local ecological knowledge (LEK) has been instrumental in guiding the inclusion of red tide impacts in stock assessment models. Initially, public comments by fishermen identified red tides as a threat to managed species in the region and prompted the information to be included in stock assessments (SEDAR 2006). Ample scientific evidence also exists documenting kills of grouper due to red tides (Smith 1975; Walter et al. 2013; SEDAR 2019; Driggers et al. 2016), and logically many assessment modeling efforts to date have focused on estimating episodic mortality in years of severe red tide. However, in addition to causing mortality, red tide blooms impact stock movement, catchability, and/or recruitment—processes that are difficult to disentangle as they may present confounding signals in data streams. For example, in oral history interviews conducted in 2019 (Blake et al. 2022), several fishermen gave accounts of fishing trips with high catchability in the summer of 2014 when grouper had apparently aggregated on the edges of a red tide occurring over the Middle Grounds. Following this red tide event, many fishermen noted a shift in fishing effort further south along the West Florida Shelf due to a paucity of grouper in this region until the area recovered several years later. Gulf-wide assessment frameworks are not suited to model such dynamics at sub-annual or sub-regional scales—nor is it clear that modeling these dynamics explicitly would result in improved catch advice—but these dynamics do introduce the potential for model misspecification and bias in catch advice.

A second challenge in quantitatively including red tide impacts in a stock assessment involves defining the severity of red tide mortality, given that red tide blooms are usually present to some extent along the West Florida Shelf on an annual basis. Once it was established based on LEK that red tide blooms likely warranted the estimation of extra mortality in stock assessments for both gag and red groupers (SEDAR 2009a, 2009b), a collaborative team of stock assessment and remote sensing scientists developed a quantitative, spatiotemporally explicit index of red tides based on satellite data to drive red tide mortality in stock assessments (Walter et al. 2013, 2015; Sagarese et al. 2018); however, cloud cover, sun glint, satellite sensor inconsistencies, and limited ground-truthing samples hindered the accuracy and utility of these indices. After extensive sensitivity analysis of ways to incorporate red tide mortality during assessments (Fig. 4), the Assessment Panels concluded that the most robust way to estimate red tide mortality within the stock assessment was for analysts to specify which "severe" red tide years to include in consultation with ecosystem information (e.g., LEK, cell count data, fish kill reports, and remote sensing) and the model estimated the additional mortality from other integrated data sources (Sagarese et al. 2021; Sagarese & Harford 2022). Still, providing a clear definition of "severe" red tide is not straightforward; for example, analyses in 2014 utilizing satellite data (Walter et al. 2015; Sagarese et al. 2018) and species distribution models (Chagaris and Sinnickson 2018) indicated minimal red tide impacts on grouper, conflicting with input from fishermen who regularly fished the affected areas (Karnauskas et al. 2019; SEDAR, 2019b). Part of this discrepancy was thought to be due to subsurface impacts not detected by satellite; Turley et al. (2021) discovered an association between certain red tide blooms and large hypoxic areas, with these hypoxic red tide events perceived as having much more severe impacts on offshore fisheries (Blake et al. 2022). Finally, once it has been established that a red tide event is significant enough to warrant inclusion, there is the question of how severity varies by life stage. Insights on age-specific effects have been gained from a spatial ecosystem model of the WFS (Ecopath with Ecosim; hereafter WFS ecosystem model) which has been employed to derive species- and age-specific red tide mortality indices to inform grouper assessments (Vilas et al. 2020, 2023; SEDAR 2021a). A combination of insights from these ecosystem models and LEK were also used to determine that red tide impacts were not of sufficient significance to support the estimation of red tide

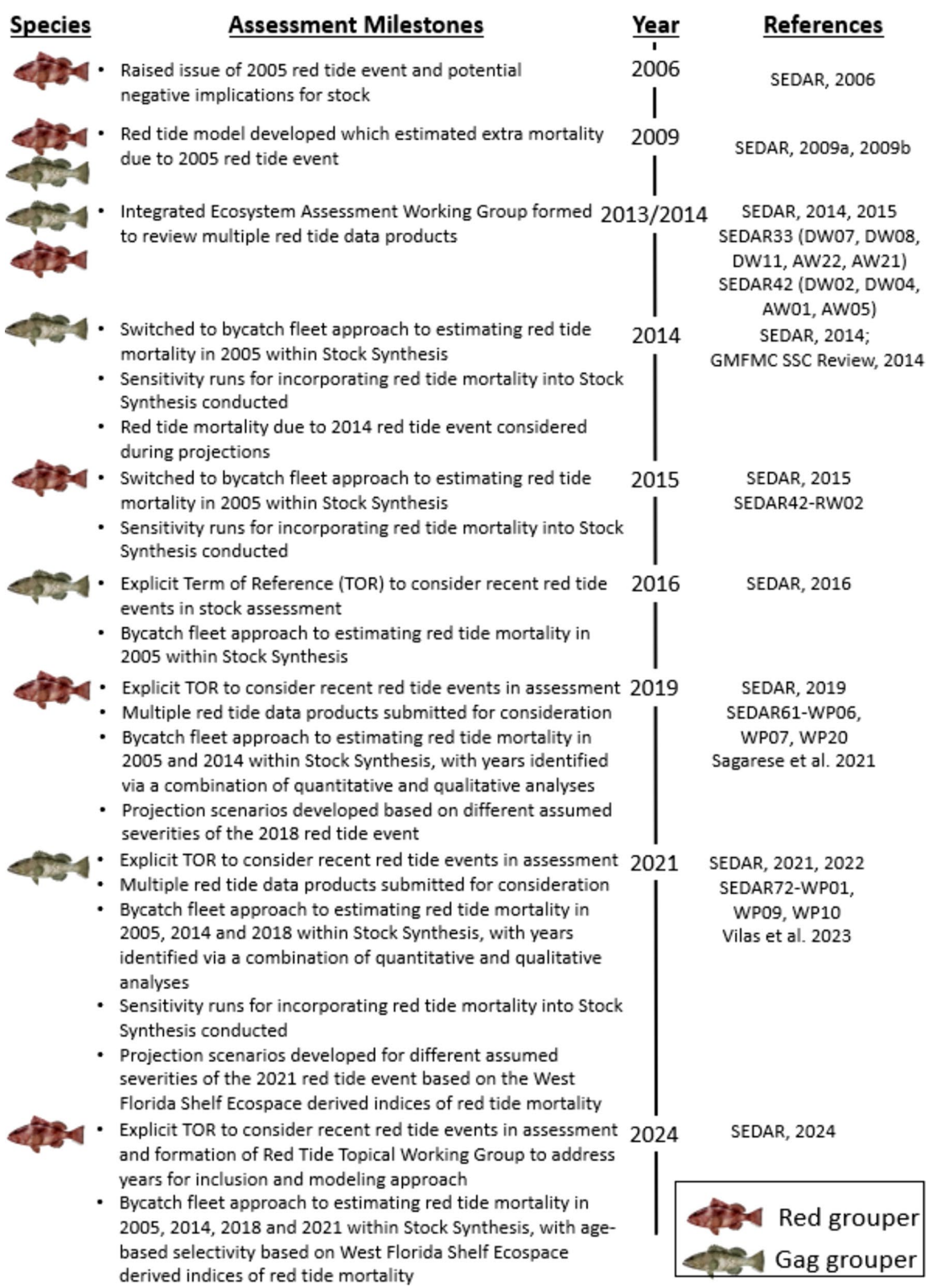


Fig. 4 Timeline of red tide considerations and major milestones from Gulf stock assessments. References are provided for additional information

mortality within stock assessments for scamp grouper (*Mycteroperca phenax*) and yellowedge grouper (*Hyporthodus flavolimbatus*) (SEDAR 2021b, 2024).

Ultimately, the choice of explicitly accounting for red tide mortality in the model framework has had varied outcomes on catch advice. While integrating ecosystem information can reduce scientific uncertainty in stock assessments, the setting of catch limits by the Gulf Council also benefits from such information. When red tide occurs in the most recent years of the assessment or in the projection period, assumptions regarding red tide severity are highly influential on the catch advice. For example, the 2018 red grouper assessment took place during an extended red tide bloom that caused much concern in the fishing community (Sagarese et al. 2021), but analysts lacked knowledge on how to characterize the event. Stock assessment analysts performed several projection scenarios to provide a range of forecasted catch advice, allowing the Gulf Council's Scientific and Statistical Committee (hereafter SSC) to select a probable scenario based on LEK and available data (Sagarese et al. 2021). Similarly, during the 2021 gag grouper assessment, a mortality index derived from the WFS ecosystem model served as a foundation for developing two sensitivity runs (i.e., not implemented in the base assessment model), where age-specific selectivity and time blocks on mortality were created (SEDAR 2021a). Several projection scenarios were conducted for gag grouper, incorporating varying levels of 2021 red tide mortality based directly on the mortality estimates obtained from the WFS ecosystem model (Table 1), which impacted the catch advice because the SSC selected the medium scenario and avoided longer rebuilding times (SEDAR72 determined gag were overfished necessitating a rebuilding plan). Notably, the explicit inclusion of red tide in the assessment terms of reference, which are defined prior to a stock assessment, has helped contribute to the successful operationalization of estimating red tide mortality for Gulf grouper stocks. This is a good example of how taking the EBFM approach can improve assessments by taking a broader, ecosystem-wide, perspective.

Gulf council management actions

The traditional fisheries management process uses the stock assessment results to justify changing catch limits. This results in a reactive approach to addressing the impacts of red tides in which the time scales of the red tide and management are not aligned. In the Gulf, amendments to the Reef Fish management plan explicitly addressed the impacts of red tide beginning in 2008 (GMFMC 2008; Table 2), and since then red grouper catch limits have been adjusted frequently by the Gulf Council, partly informed by LEK on the impacts of red tides and the explicit inclusion of red tide mortality in stock assessments. Amendment 30B, implemented in May 2009, considered that the declines in grouper abundance after the 2005 red tide were due to redistribution rather than episodic mortality. As a result, the acceptable biological catch (ABC) for red grouper was increased, leading to larger commercial quotas and higher recreational bag limits (GMFMC 2008). The 2009 red grouper stock assessment results, unavailable during the rule-making for Amendment 30B, estimated that the red tide killed approximately 20% of the stock in 2005 (SEDAR 2009b; Table 1). After the SSC deliberated the implications of the mortality in the stock assessment, a regulatory amendment decreased the red grouper ABC (GMFMC 2010). In 2016, the Gulf Council approved increases in red grouper ABC based on the 2015 stock assessment, assuming that the effects of the 2014 red tide were minimal (SEDAR 2015; GMFMC 2016b) despite conflicting information between the satellite data (Walter et al. 2015; Sagarese et al. 2018) and public comments. An emergency rule and management action later lowered the red grouper ABC in response to record low landings in 2017 and concerns expressed by stakeholders about the effects of the ongoing red tide in 2018, while the results of the 2018 red grouper stock assessment were pending (GMFMC 2019). Gulf red grouper has largely been resilient to red tide events, where pulses of biomass and recruitment can be seen in the years following red tides (Fig. 5c, d).

Gag grouper management has also been responsive to red tides over the years. Amendment 32 established a rebuilding plan for gag grouper (GMFMC 2011) based on the results of the 2009 assessment that indicated the stock was overfished and undergoing overfishing (SEDAR 2009a). The decline in gag biomass was partially attributed to increased mortality due to the 2005 red tide (GMFMC 2011; SEDAR 2009a), although the proportion killed has varied across assessments (Table 1). The 2014 red tide was

Table 1 Summary of assessment outcomes related to red tide from Gulf stock assessments. RTM refers to instantaneous red tide mortality estimates from the assessment model

Assessment	Outcome
Red grouper (SEDAR 2009a, b)	Improved fits to indices of abundance 2005 RTM = 0.32 year^{-1}, killed 21% of population
Gag grouper (SEDAR 2009a, b)	Improved fits to indices of abundance 2005 RTM = 0.35 year^{-1}, killed 1.8 million fish (23% of population)
Gag grouper (SEDAR 2014)	2005 RTM = 0.71 year^{-1} (CV = 0.088), killed 3.4 million fish (41% of numbers, 40% of biomass) Index of red tide mortality produced with satellite and species distribution data were used as support for assuming no impact of 2014 red tide on gag due to limited spatial overlap (GMFMC SSC Review 2014)
Red grouper (SEDAR 2015)	2005 RTM = 0.55 year^{-1} (CV = 0.109), killed 53.3 million fish (34% of numbers; 44% of biomass)
Gag grouper (SEDAR 2016)	2005 RTM = 0.73 year^{-1} (CV = 0.084), killed 3.2 million fish (42% of numbers; 39% of biomass)
Red grouper (SEDAR 2019)	2005 RTM = 0.34 year^{-1} (CV = 0.309), killed 35.9 million fish (23% of numbers; 30% of biomass) 2014 RTM = 0.26 year^{-1} (CV = 0.429), killed 13 million fish (19% of numbers, 21% of biomass) SSC supported treating 2018 red tide similar to 2005 additional analyses provided in Sagarese et al., (2021)
Gag grouper (SEDAR 2021a, 2022)	2005 RTM = 0.74 year^{-1} (CV = 0.16), killed 7.78 million fish (41% of numbers; 52% of biomass) 2014 RTM = 0.91 year^{-1} (CV = 0.22), killed 4.78 million fish (48% of numbers; 63% of biomass) 2018 RTM = 0.07 year^{-1} (CV = 3.30), killed 0.28 million fish (6% of numbers; 7% of biomass) Index of red tide mortality produced with West Florida Shelf Ecospace model was used to parameterize 2021 red tide mortality in projections, with the medium scenario selected by the SSC (updated analyses presented in Vilas et al. 2020)
Scamp grouper (SEDAR 2021b)	RTM discussed during data workshop but deemed not important based on limited spatial overlap
Yellowedge grouper (SEDAR 2024)	RTM discussed during data updates Topical working group but deemed not important based on limited spatial overlap
Red grouper (SEDAR 2025)	2005 RTM = 0.17 year^{-1} (CV = 0.53), killed 5.9 million fish (12% of numbers; 14% of biomass) 2014 RTM = 0.20 year^{-1} (CV = 0.46), killed 5.0 million fish (6% of numbers; 13% of biomass) 2018 RTM = 0.04 year^{-1} (CV = 2.0), killed 2.1 million fish (3% of numbers; 3% of biomass) 2021 RTM = 0.10 year^{-1} (CV = 1.6), killed 6.7 million fish (6% of numbers; 5% of biomass)

challenging because a benchmark assessment had just been completed and determined that the gag stock was not overfished nor undergoing overfishing. The bloom, however, occurred offshore in an area of greatest gag abundance and there was uncertainty about the extent and impact of the bloom. The SSC recommended a one year ABC that assumed the ongoing red tide was similar to the 2005 red tide (GMFMC-SSC 2014). The ABC was later revised upward assuming no significant impacts based upon an assessment of the 2014 bloom by Florida Fish and Wildlife Research Institute. In subsequent years, the Gulf Council did not increase gag catch levels in response to additional input from the SSC, the Reef Fish Advisory Panel, and public comments, which emphasized a lack of evidence for gag recovery (GMFMC 2016a). More recently, the SSC recommended using a spawning potential ratio of 40% as the preferred reference point for calculating the overfishing limit and ABC after reviewing the 2022 stock assessment (GMFMC 2022c) justified mainly due to life history, but also their susceptibility to red tide mortality. The change in reference point coincided with a stock assessment indicating that the stock

Table 2 Summary of major Gulf council actions to the reef fish fishery management plan in the context of red tides. OFL = Overfishing limit; AP = Advisory panel; ACL = Annual catch limits

Council action	Species	Action taken	Initiated	Effective	Red tide context
Amendment 30B	gag	set thresholds and benchmarks; set ACL (previously none)	mid 2007	5/18/2009	
Amendment 30B	red grouper	increase ACL	mid 2007	5/18/2009	assumed declines in indices of red grouper from fish movement due to red tide in 2005
2010 regulatory amendment	red grouper	decrease ACL	mid 2010	1/1/2011	2009 stock assessment found ~ 20% of stock died due to episodic mortality from red tide
2011 regulatory amendment	red grouper	increase ACL	early 2011	11/2/2011	SSC cautioned that greater uncertainty in projections further from last assessment in 2009
Amendment 32	gag	set 10 yr rebuilding plan; reduce quota to account for dead discards; modifies multi-use to formula based on buffer	early 2011	3/12/2012	overfished/overfishing status based upon assessment with red tide mortality
Amendment 32	red grouper	increase ACL	early 2011	3/12/2012	update assessment including red tide indicated increase could occur
Framework action to modify gag minimum size limits and recreational season, and black grouper minimum size limits	gag	no changes to ACL	early 2015	5/25/2016	FL-FWRI indicated that impacts of 2014 red tide was minimal, 4–7% of 2005; SSC, reef AP and public testimony did not support increase of ACL
Framework action to the fishery management plan for reef fish resources of the Gulf of Mexico	red grouper	increase OFL, ABC, ACL	mid 2014	10/12/2016	The red tide event in 2014 was concluded to be negligible in SEDAR 42 (2015)
Amendment 44: Minimum stock size threshold revision for reef fish stocks with existing status determination criteria	reef fish	Defining Minimum Stock Size Threshold	early 2016	12/21/2017	large buffer requires harsher management actions in the face of red tides
Modification of Gulf of Mexico red grouper annual catch limits and annual catch targets	red grouper	reduces ACL	late 2018	10/31/2019	2017 landings second lowest; not clear if red tide event affected red grouper in 2018; SEDAR 61 red grouper stock assessment underway; Stakeholders indicate that 2018 red tide may have had negative impact on red grouper
Amendment 53	red grouper	reduces OFL, ABC, ACL	late 2019	6/1/2022	SEDAR61 indicated maintaining landings at 2017 landings (and in the 2019 emergency action) resulted in a low probability of overfishing in 2020–2024 under all red tide scenarios with the exception of the most severe simulation of double 2005 red tide mortality; SSC decided to assume 2018 = 2005; council requested reallocation based upon MRIP-FES

Table 2 (continued)

Council action	Species	Action taken	Initiated	Effective	Red tide context
Modification of Gulf of Mexico Red Grouper Catch Limits	red grouper	increases OFL, ABC, ACL	early 2019	8/8/2022	Alternative 2 was preferred based upon 3 year moving average, which is more representative of population trends due to uncertainty around 2021 red tide compared to 5 year moving average; An accounting of the potential additional episodic natural mortality from this red tide event is not included in the SSC's recommended catch limits under Preferred Alternative 2, nor in the catch limits demonstrated in Alternative 1. Therefore, depending on the spatial extent, duration, and severity of the 2021 red tide event, either alternative may represent a harvest level that could result in negative biological effects for the red grouper stock

was overfished and that overfishing was occurring (SEDAR 2021a), assuming a medium-severity red tide occurred in 2021 during projections. Red tide-related management actions for gag and red groupers have been reactive, and frequent reversals of catch advice highlight the complexity of red tide impacts and the need for including accurate ecosystem information and continued robust stakeholder engagement.

Where can we go? possible management pathways

Within this section, we address step 4 of the FEI loop by providing some management considerations. With the single-species stock assessment framework, the primary mechanism for managing in response to red tides is adjusting fishing mortality to remain sustainable in light of additional mortality. As described in the sections above, a large body of work has been dedicated to how red tide is incorporated into stock assessments and how the catch limits are appropriately derived given this additional source of non-fishing mortality. The benefit of an FEI-like process is that it allows for additional scoping in the development of tactical advice; i.e., the regulations developed to achieve the desired fishing mortality level. Here, the Council has several options to control fishing mortality, via input or output controls, along various dimensions (e.g., time, space, gear), and through different forms of management (e.g., regulated open access versus rights-based access like individual fishing quotas). Consideration of how fishing mortality is constrained in addition to other management options, while meeting the basic legal mandates of preventing overfishing and managing for a biomass that achieves optimum yield, can help address the ecological, economic, and socio-cultural effects of red tides on the fishery ecosystem laid out in the sections above. The FEI loop is an iterative framework to define the parameters of the problem and thoughtfully recommend research to inform new or adjusted management approaches (Levin et al. 2018). The following sections outline possible management strategies that serve as a starting point for discussion.

Developing management options robust to episodic mortality events

Much of the history of incorporating red tides into stock assessment has focused on how to adjust fishing

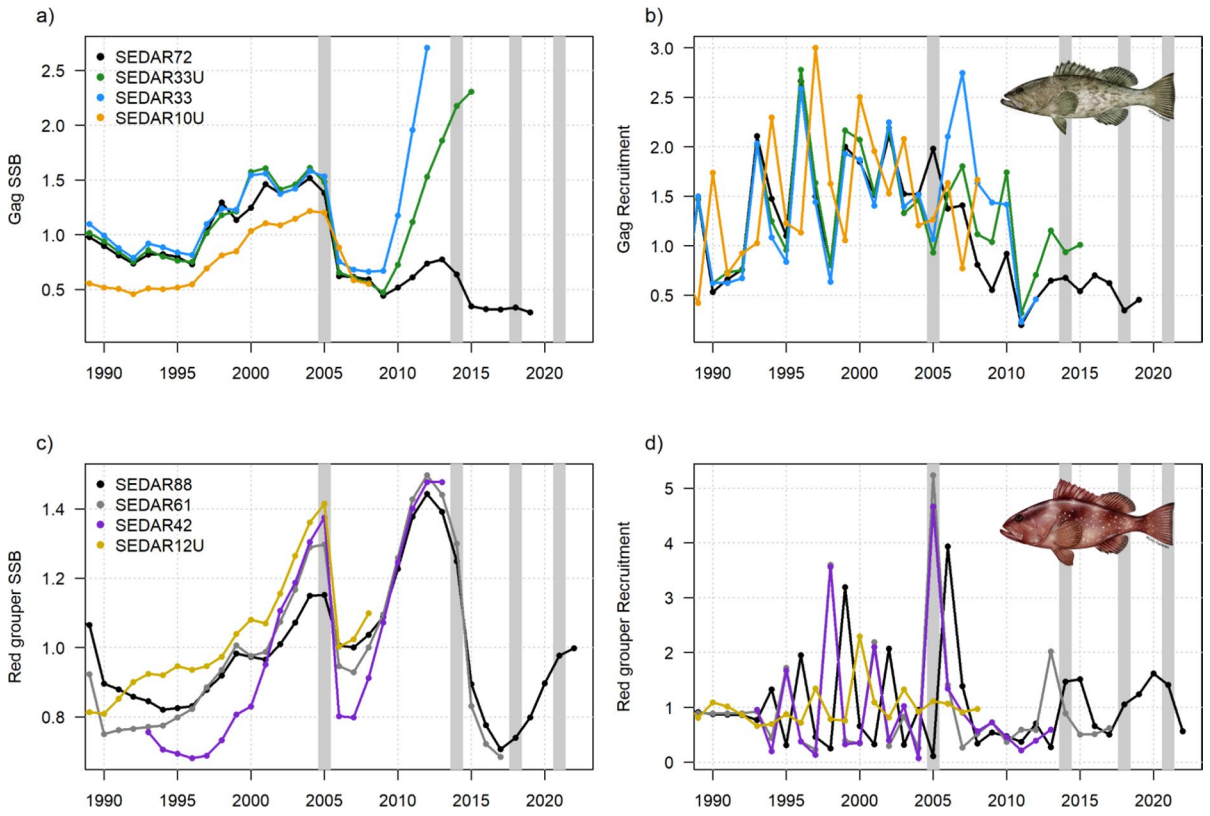


Fig. 5 Population estimates of spawning stock biomass (SSB; left column) and recruitment (age-0s; right column) for gag (top row) and red groupers (bottom row). Both SSB and recruitment are normalized to a mean of 1. Gray vertical lines represent red tide events (2005, 2014, 2018, and 2021) that were incorporated into the stock assessments

mortality, with the predictable response of reducing catches in light of or in anticipation of a red tide. While such an approach manages fishing mortality, it does not address many of the other key elements of fisheries management, particularly the needs of the fishery. Management strategy evaluation represents an opportunity to explicitly consider multiple, sometimes competing objectives. In a recent application, Harford et al. (2018) considered two assessment-management scenarios: a fixed decision interval (the current Gulf Council strategy) and a reactive decision interval (assessed immediately after an episodic event). While both managed fishing mortality, reactively updating ACLs after a red tide imposed a significant scientific and regulatory burden, requiring timeliness of event detection and the accurate assessment of event severity for little gain in yield (Grüss et al. 2016a; Harford et al. 2018). Critically we have also found that frequent changes in catch limits create financial strain particularly for fisheries with an ITQ market. Hence, fishermen may prefer strategies that provide greater stability over overall yield. Greater use of MSE to explicitly consider social and economic objectives in developing management options both from a single species (Harford et al. 2018) and multi-species (Gruss et al. 2016a) perspective will identify management options that provide improved outcomes for the fishery while meeting the need to manage fishing mortality.

Fostering adaptive capacity within the fishery management system

Episodic mortality driven by red tide is an external stressor that has major reverberations within the fishery system and adaptive management can lessen the impacts of these types of events (Seara et al. 2016; Golden et al. 2024b; Stelzenmüller et al. 2024;

Drexler et al. 2025; Reimer et al. 2025, and references within). The potential of individual fishermen to adapt to shocks such as severe red tides depends on the availability of alternatives given the current set of regulations (Reimer et al. 2025). Discussions during recent stakeholder meetings have outlined possible pathways to foster the fishing industry's capacity for adaptation. For example, red tides can kill significant proportions of gag and red grouper stocks in a single year (Table 1) and commercial fishermen may find themselves in a situation with lots of quota and no fish to catch. When nearshore red tides displace the fishing fleets offshore (Perruso et al. 2023) into areas of high red snapper abundance (Karnauskas et al. 2017), fishermen targeting grouper are likely to encounter elevated abundances of red snapper and may lack quota to land these fish, increasing regulatory discards. In such situations, managers could develop emergency rules to remove barriers to quota leasing, introduce leasing alternatives (e.g., pay a fee), or allow 1:1 trading of quota across species (as is currently allowed for gag and red grouper under multi-use allocation rules), which would encourage the conversion of discards into landings. Indeed, some increased-flexibility approaches already exist that could be implemented for red tides; the Gulf Reef Fish Shareholders' Alliance has a red snapper quota bank for its members that allows participants to buy quota to convert discards into landings (GRFSA 2025). In the for-hire recreational industry, charter captains exposed to an extended, severe red tide event may be unable to make use of a charter permit purchased for that year. Various options exist for providing more flexibility and maintaining economic viability in light of the red tide; managers could allow for the permit to be leased to other captains or boats in unaffected areas, which would provide revenue to the captain in the affected area and accommodate the increased "spillover" tourism in red-tide-adjacent areas. Another option, for fishermen owning multiple vessels with different types of permits, could be a provision for a temporary switch in permits to a more fuel-efficient vessel to help maintain profitability in periods where captains may have to fish further offshore to avoid red-tide-affected areas (based upon personal communication with charter captains). Permits are tied to specific vessels and giving captains the ability, under limited circumstances, to switch permits between vessels may confer some adaptability. Methodically cycling through the FEI loop may uncover other red tide-related "pinch points" encountered by commercial and recreational fishermen that might be mitigated by adaptability-focused management interventions.

Fostering adaptive capacity within the fishing industry

Adaptive capacity can result from targeted management actions implemented to increase flexibility during shock events, but managers can also create the conditions for the emergence of "bottom-up" approaches for increased flexibility (Reimer et al. 2025). Industry-driven (aka "bottom-up") adaptive capacity, such as the formation of cooperatives, risk pools, and quota banks, may allow fishermen to respond on faster time scales than would be possible through the existing regional council processes (Reimer et al. 2025). For example, existing state and federal disaster response and financial support mechanisms (e.g., federal Fishery Resource Disaster Determination process) are ill-equipped to assess and address the localized and differentiated impacts faced by the fishing industry sectors (See Sect. "Economic Impacts"; Alvarez et al. 2024), as fishermen lack ways to cope financially in the short term. The current support systems fall short of addressing immediate needs because relief funds can take years to be disbursed. Marine insurance mechanisms could provide quicker, more predictable, and more scalable financial support to small-scale fishermen (Watson et al. 2023). Some fishermen have called for alternative insurance models similar to the USDA's Federal Crop Insurance Program, which offers a range of products to protect farmers from yield and revenue losses due to natural disasters and market fluctuations, and is publicly subsidized but administered through private insurers. Developing a comparable insurance framework for fisheries, potentially covering revenue losses, disaster-related closures, or effort disruptions, could provide a much more timely and reliable safety net for the fishing industry in the face of increasingly frequent environmental and economic shocks such as major red tide events. Fishermen are adept at adapting to changing conditions, and a key role of fishery managers is to support the innate fishermen's adaptability with

flexible management mechanisms (Golden et al. 2024a). Finally, increased communication among industry participants and collaborative monitoring networks to share on-the-water conditions may help fishermen reduce the impacts of a major red tide (see Court et al. 2025b).

Interjurisdictional partnerships

Fishery managers encounter significant challenges when addressing red tides partially because the root causes are beyond the fisheries management jurisdiction. Red tides are triggered by large-scale oceanographic and atmospheric processes outside the scope of management action; however, research indicates that nutrient loading from land-based sources can sustain red tides (Medina et al. 2022). Furthermore, red tides typically occur inshore and nearshore, making the land–ocean interface a critical area to focus attention as nearshore habitats are important for forage species and nursery grounds for federally-managed species. A good example of the land-use policies benefiting fisheries comes from Hawaii, where a combination of land-based and fishery-based actions was most effective in achieving fishery management objectives and contributed to increased ecosystem resilience to marine heatwaves (Gove et al. 2023). In Florida, an opportunity may exist to engage with the Florida Harmful Algal Bloom Task Force, an interjurisdictional group that advises on strategies and make recommendations to research, monitor, control, and mitigate HABs in Florida waters (Florida Harmful Algal Bloom Task Force 2021). Coordination between the task force and the Gulf Council may help achieve federal fishery management objectives by elevating the impacts on fisheries and the fishing industry. Because red tide events cross multiple jurisdictions (i.e., federal, state, county, and municipal), a comprehensive action plan to address red tides may require fisheries managers to seek additional interjurisdictional partners. While better coordination amongst groups may lead to better fisheries outcomes, it is important to realize that the levers fishery managers have to pull within inter-jurisdictional partnerships are limited and more direct management actions as outlined in previous sections are more likely to lead to tangible outcomes.

Research gaps and recommendations

In this section, we address step 2 of the FEI loop by highlighting gaps in our understanding of how red tide impacts the fishery ecosystem. While red tides can cause fish mortality, the lethal and sublethal thresholds are poorly understood and generally not species-specific. Mortality is also likely affected by the co-occurrence of other synergistic stressors during severe red tides, such as hypoxia (Turley et al. 2022). Assuming a uniform mortality rate across species or life stages is unrealistic, but little data exist to adjust our assumptions or parameterize ecosystem models or age-structured population models. We know from LEK that certain species aggregate at the edges of dense blooms and hypoxic areas, suggesting a behavioral response (Turley et al. 2021); however, the functional form of the response and how it varies between species or life stages is unknown. Given the observed behavioral response to red tides, sublethal effects on feeding, growth, and reproduction are likely but not understood. Previous work has focused mostly on estimating acute mortality, but there has not been a focus on understanding recovery times. Further research that combines observational data and modeling would assist in refining assumptions on the individual, population, and ecosystem-level effects, and thereby would enhance stock assessments and catch advice for affected populations. Furthermore, any management action on a stock under a rebuilding plan would benefit from a better understanding of recovery time after a red tide. Additional process-oriented research into the mechanisms by which red tides impact fish populations would improve stock assessment models and resulting catch advice; however, this research does not address a central concern that episodic mortality events cause major swings in stock biomass and can lead to wildly fluctuating annual catch limits, particularly when stock assessments are conducted infrequently.

Enhanced data collection to better assess the impacts of red tides could be achieved with cooperative research and citizen science initiatives. Increased citizen science engagement through outreach, educating fishermen and other Gulf patrons on their ability to improve fish kill reporting, would improve impact assessments. Enhanced fish kill reporting and sampling, in which trained scientists process the samples including species identification through

environmental DNA and age with otoliths or length, may assist in characterizing mortality across species and age/size classes. Greater investment in cooperative research programs, in which industry partnerships are developed, would address current data limitations frequently encountered in research on red tide impacts to fisheries, particularly for more offshore species. Cooperative research expands the pool of data to inform the decision-making process and builds trust between groups of stakeholders (Van Vranken et al. 2020; Neidig et al. 2024**).** Research set-aside programs, which are funded by the sale of a portion of the quota set aside, are used by the New England and Mid-Atlantic Fishery Management Councils to cost-effectively fill critical research gaps in collaboration with fishermen (https://www.fisheries.noaa.gov/new-england-mid-atlantic/funding-financial-services/greater-atlantic-research-set-aside-program, accessed 2026-03-06). Such programs could be used to incentivize increased monitoring on the impacts of red tide on the fishery ecosystem; however, the quota set aside must come from the fishery targeted for additional research. Funding from research set-asides could also be used to support comprehensive, multi-trophic, event-response sampling that can be combined with routine monitoring programs to assess ecosystem impacts over space and time. Other short term funding sources include NOAA National Centers for Coastal Ocean Science's HAB Event Response Program, which could be used to fill in data gaps. Funds from this program were applied in the wake of the 2017–2019 red tide and helped to fund research that identified the association of hypoxia with several devastating red tides in the region (Turley et al. 2022). Finally, long-term monitoring programs conducted by federal, state, and academic partners could be more adaptive to episodic mortality events (e.g., red tide) to better quantify localized impacts and to compare with ecosystem models and LEK.

The current stock assessment-management enterprise and associated harvest control rules have resulted in major year-to-year fluctuations in the ACLs. For example, the red grouper quota decreased 61% from 2017 to 2018, and the gag quota decreased 79% from 2022 to 2023. Such drastic changes in the ACL present challenges for both sectors; catch limit stability benefits commercial fishermen by reducing risk and optimizing resource allocation, and benefits recreational fishermen by ensuring there are opportunities to catch desirable species at predictable times throughout the year. Thus, research is needed to understand whether the current mechanisms for setting ACLs (i.e., harvest control rules) are functioning well to meet industry needs. Alternative control rules – that might better meet the objectives of industry—could be used to buffer the ACL to reduce the risk of overfishing in the long term and create more stability in catch limits (e.g., Harford et al. 2018). These harvest control rules have been explored in other regions; for example, the Mid-Atlantic Fishery Management Council recently approved a framework action for a "percent change approach" that addresses previous angler frustrations regarding volatility in recreational fishing regulations and lost fishing opportunities (MAFMC 2022). In the Gulf, a similar approach known as the "interim analysis" is used to recommend catch level adjustments based on recent relative abundance trends, and has also been simulation tested to understand performance outcomes (Klibansky et al. 2022). Such simulation exercises, if carried out as part of a red tide FEI process with an evaluation of how well they meet predefined stakeholder objectives, may improve outcomes and reduce stakeholder frustration stemming from volatile fishing regulations in the Gulf.

Socioeconomic research is needed to characterize the extent of red tide impacts on people and businesses involved in the affected fishing communities and evaluate the effectiveness of adaptive strategies. For example, the number of lost fishing days due to blooms relative to the number of days fished in a non-red tide season could serve as an index of lost fishing opportunities (Moore et al. 2019). Similarly, red tides may cause fishermen to transit further to fishing areas to avoid blooms, which incurs more costs and may lead to shifted target species, bycatch, or discards. While some work has been done to test fishermen's behavior in response to red tide via Vessel Monitoring System data (Perruso et al. 2023), analysis pairing these data with spatially explicit catch would help assess edge effects and changing catch composition during these events. The synergetic effects of devastating events (e.g., red tides, hurricanes) on community resilience and industry consolidation are not understood. Additional research analyzing existing data in the context of red tides is needed to determine the number of businesses lost, a measure of industry consolidation (e.g., Individual Fishing Quota),

revenue loss, and changes to allocation prices. Few data exist on fishing-associated businesses (e.g., ice houses, tackle shops, boat yards) that are also impacted by these events. These data may be required to successfully petition for a HAB Events of National Significance designation. Repeated events in rapid succession may erode resiliency, forcing fishermen to sell capital investments, including permits, quotas, boats, or working waterfronts, exacerbating industry consolidation and real estate gentrification. Red tides do more than disrupt economies; they challenge the cultural rhythms, identities, and emotional resilience of Florida's fishing communities (Blake et al. 2022). These socio-cultural effects may not always appear in landings data or disaster declarations, making it difficult to mediate them directly, but they shape how communities experience, adapt to, and ultimately survive these recurring environmental stressors. Addressing these hidden dimensions of red tide impacts is essential for developing a more effective response to HABs—one that considers the cultural and social well-being of coastal communities alongside ecological and economic metrics.

Discussion

Engaging with stakeholders to understand the interconnectedness of the fishery ecosystem is a prerequisite for EBFM. In our region, the inclusion of red tides in fishery management within the Gulf Council has been primarily driven by stakeholders. When the Gulf Council reduced catch limits in response to red tide-informed stock assessments, some fishermen have the perception that they are being penalized for something beyond their control. The reality is that integrating ecosystem information in stock assessments has helped explain stock declines that would otherwise have been assigned as fishing mortality, which would in fact penalize the fishery and could drive the stock into an overfishing status (Sagarese et al. 2021; Sagarese and Harford 2022). Whether catch advice was less or more precautionary due to incorporating ecosystem information depends upon the specific situation, as the availability of complementary ecosystem and LEK analyses has also influenced fisheries decision-making.

The disconnect between stakeholder perspectives and EBFM success highlights a communication opportunity to re-engage with stakeholders in the process. Overall, it is commendable how responsive the Gulf Council process has been to stakeholder concerns, but the bottom-up and reactive approach has resulted in "red tide fatigue". The term "red tide fatigue" comes from Gulf Council public comments and describes stakeholder sentiment to the ad hoc and reactive nature of how regional fishery management has dealt with red tides. Identifying target objectives and metrics for measuring progress and, crucially, communicating successes could help alleviate fatigue. Moreover, without clear metrics to gauge or track success, there is little incentive for future engagement from fishermen, further exacerbating engagement fatigue. A straightforward, albeit narrow, measure of success has been derived from the stock assessments; modeled abundance indices in stock assessments better fit the observations when extra mortality from red tides is included (Sagarese et al. 2021). Additional success metrics are needed before new actions are considered, and any progress, particularly successes, needs to be communicated to stakeholders to reinforce engagement. Setting clear objectives (step 2 of the FEI loop) and evaluating progress by predefined metrics (step 6) may help to alleviate stakeholder frustration.

No other nation or U.S. region explicitly integrates HABs into stock assessments or catch limits, aside from closures due to possible contamination. The response to HABs in fisheries management across different regions is limited and varies based on species and regional characteristics. Along the U.S. West Coast (Washington, Oregon, and California), shellfish fisheries are significantly affected by HABs, differing considerably from the finfish fisheries of the WFS. The species impacted include bivalves harvested along the shoreline and Dungeness crabs managed by the states (Moore et al. 2009). The primary concern of state fisheries management in the U.S. Pacific Northwest is the contamination of domoic acid and the potential health risks to humans resulting from consumption. Consequently, fisheries are shut down if routine monitoring reveals that a domoic acid threshold has been exceeded. A key difference here is that HABs of Pseudo-nitzschia do not appear to significantly affect the populations of managed species, but shifts the timing of when they can be harvested (Holland & Leonard 2020). The issue of HABs is relevant to

the Pacific Fishery Management Council because the Dungeness crab fishery is a keystone fishery that many fishermen participate in (Fisher et al. 2021). On a global scale, HABs are recognized as harmful to wild capture fisheries; however, their effects appear mainly confined to isolated instances or potential recruitment impacts, neither of which seems to trigger management interventions (Brown et al. 2020). The key policy options used by other regions include education and outreach, monitoring combined with closures, short-term forecasting for stakeholder awareness, and mitigation strategies that necessitate expanding policy collaborations (Brown et al. 2020; Ekstrom et al. 2020).

There are many challenges to successfully implementing FEIs, or similar EBFM. Regulatory nimbleness is needed, particularly if an issue (like a red tide or other episodic mortality event) has an acute expression demanding a timely management response; however, stakeholder engagement is needed, which tends to slow the process down (Mikalsen & Jentoft 2001; NSGLC 2022). The tradeoff between timely response and stakeholder engagement can come in the FEI process, where conversations can address the various concerns, and management strategies can be proposed outside an event response when timely decisions may be critical. This proactive process front-loads the engagement to develop a suite of tools to use when circumstances dictate a response (e.g., harvest control rules), and thus reduce time between event and response. Critical engagement can be revisited via the FEI loop to assess the effectiveness of management actions after implementation, and peer review of outcomes can further inform any changes to the suite of management actions to be used in the future. An additional challenge to applying EBFM is that factors external to fishery management jurisdiction may impact fishery productivity or participation, adding complexity to existing internal factors (e.g., competition between commercial and recreational sectors, discards, bycatch). Policies addressing external factors are underdeveloped and may require interjurisdictional partnerships to achieve objectives that satisfy common interests (Cormier et al. 2017; Dolan et al. 2016). Finally, the Council may need to formally recognize that some ecosystem issues may have no immediate fishery management response due to insufficient information or a gap in the Council's statutory authority, which shifts possible actions to communication strategies, interjurisdictional engagement, or recommending additional research.

Conclusions

In the present work, we have focused on reviewing the history of red tides as a fishery ecosystem issue on the WFS. The information presented here can inform discussions in developing a red tide FEI and further refine the nascent FEI process in the Gulf region. We stress that future work on a red tide FEI will require broad stakeholder engagement to effectively define objectives, work plans, and metrics to determine what constitutes success. The diverse ecosystem issues that affect fisheries, such as HABs, are complex, thus requiring a transdisciplinary approach and participation from a multi-stakeholder group to account for unintended effects and tradeoffs from management actions. This necessitates thorough scoping to define the species directly and indirectly affected and set relevant bounds (e.g., temporal, spatial, fisheries, and sectors affected). Implementing EBFM (e.g., Fishery Ecosystem Plans and FEIs or similar processes) does not require a completely new set of management options or non-management actions (e.g., communication strategies, recommended research, interjurisdictional cooperation). For example, the U.S. fishery management plan amendment process requires an assessment of the cumulative impacts of any management action on the ecological, economic, and social sectors (MSA 2007). Thus a small step towards EBFM would be for the U.S. regional councils to encourage council members to explicitly discuss the implications of proposed management actions to all the sectors in the triple bottom line. Given that the ability of regional councils to manage larger ecological issues is limited, there is a need for additional interjurisdictional partnerships and strengthened connections within existing partnerships. Nevertheless, FEIs provide regional councils with an opportunity to reframe ecosystem-level challenges and develop novel strategies to address them, moving beyond single species stock assessment to advance EBFM.

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Data availability Red tide monitoring data used to create Figure 2 is publicly available from Florida Fish and Wildlife Research Institute's HAB Monitoring Database (https://myfwc.com/research/redtide/monitoring/database/).

Declarations

Conflict of interest The authors declare no conflict of interest.

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