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SPECIAL FEATURE:
HONORING CHARLES H. PETERSON, ECOLOGIST

Gulf fisheries supported resilience in the decade following unparalleled oiling

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Abstract. The 2010 *Deepwater Horizon* (*DwH*) disaster challenged the integrity of the Gulf of Mexico (GOM) large-marine ecosystem at unprecedented scales, prompting concerns of devastating injury for GOM fisheries in the post-spill decade. Following the catastrophe, projected economic losses for regional commercial, recreational, and mariculture sectors for the decade after oiling were US$3.7–8.7 billion overall, owing to the vulnerability of economically prized, primarily nearshore taxa that support fishing communities. State and federal fisheries data during 2000–2017 indicated that GOM fishery sectors appeared to serve as remarkable anchors of resilience following the largest accidental marine oil spill in human history. Evidence of post-disaster impacts on fisheries economies was negligible. Rather, GOM commercial sales during 2010–2017 were US$0.8–1.5 billion above forecasts derived using pre-spill (2000–2009) trajectories, while pre- and post-spill recreational fishery trends did not differ appreciably. No post-spill shifts in target species or effort distribution across states were apparent to explain these findings. Unraveling the mechanisms for this unforeseen stability represents an important avenue for understanding the vulnerability or resilience of human–natural systems to future disturbances. Following *DwH*, the causes for fishery responses are likely multifaceted and complex (including exogenous economic forces that typically affect fisheries-dependent data), but appear partially explained by the relative ecological stability of coastal fishery assemblages despite widespread oiling, which has been corroborated by multiple fishery-independent surveys across the northern GOM. Additionally, we hypothesize that damage payments to fishermen led to acquisition or retooling of commercial fisheries infrastructure, and subsequent rises in harvest effort. Combined, these social–ecological dynamics likely aided recovery of stressed coastal GOM communities in the years after *DwH*, although increased fishing pressure in the post-spill era may have consequences for future GOM ecosystem structure, function, and resilience.

Key words: creative destruction; disturbance; estuaries; fishery-dependent data; oil spill; social–ecological system; Special Feature: Honoring Charles H. Peterson, Ecologist.

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Introduction

Authors' Note: Dr. Charles Peterson, for whom this Special Feature is dedicated, was a global expert regarding the effects of marine oil spills and hydrocarbon pollution on benthic communities (Peterson et al. 2003, 2012). He was a major influence on our own interests in rigorously assessing the ecological impacts of human-driven perturbations, as well as our desire to employ holistic approaches for evaluating the acute and chronic impacts of oiling within estuarine and nearshore marine ecosystems. Notably, his most recent oil spill-focused publication examined the population-level impacts of the Deepwater Horizon (DwH) disaster on Gulf menhaden (*Brevoortia patronus*; Short et al. 2017). Much like our synthesis, that menhaden study evaluated the resilience or vulnerability of a fishery species to basin-scale oiling (determined by both direct and indirect effects) and highlighted the complex responses these systems may manifest following major pollution disturbance.

Resilience concepts have deep ecological roots, with parallels regarding the ability of socioeconomic systems to absorb external stressors or disturbances without shifting into alternative structural or dynamical states (Holling 1973). In coastal regions, ecological resilience and social resilience are inextricably linked as people depend heavily on marine ecosystem goods and services to underpin seafood, tourism, and energy sectors (Adger et al. 2005). Gauging vulnerability or resilience in these social–ecological systems is of global importance as humans are concentrated along coasts, which are subject to many natural (e.g., storms, flooding) and anthropogenic (e.g., climate change syndromes, oil spills) hazards. To guide predictive frameworks regarding the capacity of social–ecological systems to resist or adapt to coastal disasters, we must identify key ecosystem components and governance/recovery frameworks in terms of their sensitivity to disturbances and role in interaction webs (sensu McCann et al. 2017). This remains an elusive yet critical target unifying interdisciplinary research teams.

The *DwH* oil spill was an unprecedented disturbance for the Gulf of Mexico (GOM) ecosystem (Peterson et al. 2012). During and after the hemorrhaging of 4–5 million barrels of oil into the northern GOM between 20 April 2010 and 19 September 2010 (Camilli et al. 2012), there has remained broad concern regarding the impact of basin-scale pollution on potentially vulnerable commercial fishery, recreational fishery, and mariculture species and industries. Projections for overall economic damages to these sectors in the eight years following the spill (2010–2017) ranged between US$3.7 and US$8.7 billion (Sumaila et al. 2012). These anticipated losses were primarily due to feared ecotoxicological injury to GOM stocks, as well as 2010 fishery closures and negative consumer perceptions of Gulf seafood (McCrea-Strub et al. 2011; for further spatiotemporal details regarding these closures, see Ylitalo et al. 2012). Across diverse marine fauna, contact with fresh and weathered oil or dispersants can be toxic at low levels (e.g., 1-ppb polycyclic aromatic hydrocarbons), resulting in negative genetic, physiologic, morphologic, reproductive, behavioral, and survival responses (Whitehead et al. 2012, Incardona et al. 2014) that should depress populations (sensu Thorne and Thomas 2008). Yet, fishery-independent surveys in the northern GOM have documented few measurable changes in catch rates of coastal fishes in the post-spill decade (reviewed in Fodrie et al. 2014). These varied lines of evidence have complicated efforts to incorporate fisheries into holistic syntheses regarding the GOM-level consequences of unparalleled oiling.

To arbitrate among these alternative, data-supported scenarios: injury or no injury; and assess the vulnerability or resilience of GOM fishery sectors to basin-scale oiling, we leveraged publicly available state and federal fisheries data across the northern GOM (US controlled waters) during 2000–2017. We employed 2000–2009 fisheries data as a pre-spill baseline, from which 2010–2017 trends were forecast under a hypothetical no-spill scenario. For the response signal of GOM fisheries to the oiling disaster, we compared 2010–2017 fisheries statistics with the projections generated using pre-spill data and measured the direction and magnitude of deviations between observations and forecasts. Additionally, we considered a suite of biological and socioeconomic factors that may have been responsible for observed trends.

Methods

For each year and Gulf-bordering state, we collected 2000–2017 records of commercial ex-vessel sales, commercial landings, recreational expenditures, recreational catches, and mariculture farm-gate sales across ~200 species. All sales, landings, and catch data were indexed, separately, on a species-by-species basis, and then summed across species for each state. Additionally, we quantified state-level participation using commercial licenses and recreational angler surveys. Although licenses sold were one of the few GOM-wide proxies for commercial effort, there are notable limitations of this metric, such as latent capacity related to purchased-but-unused licenses. Therefore, we also extracted available effort data from GOM shrimp fisheries to further constrain fishing activity before and after *DwH*. From these data sources, we calculated per capita commercial sales (\$ license^{-1}) and per angler recreational expenditures (\$ angler^{-1}). To detrend data for inflation, sales and expenditure data were discounted to represent currency values during 2000 (Appendix S1: Table S1; United States Bureau of Labor Statistics).

Our analyses were bounded by several considerations regarding GOM fisheries. Firstly, this study extends to 2017 in accordance with forecasts made shortly after the disaster (McCrea-Strub et al. 2011, Sumaila et al. 2012), and do not account for lagged effects beyond this scope. Secondly, we based analyses on the GOM-facing (west) coast of Florida, and excluded Florida data that only reported whole-state figures that would have integrated information from Florida's Atlantic (east) coast. Otherwise, all data were recorded at the state level and then summed (appropriate for total landings, catches, sales, and values) or weight-averaged (appropriate for per capita metrics, accounting for numbers of licensees/anglers in each state) to reflect GOM-wide data. Thirdly, foreign fleet landings were not considered important as the United States has maintained an Exclusive Economic Zone in the northern GOM since 1991.

Commercial landings, as weight harvested and ex-vessel sales, were sourced for each GOM state from the National Oceanic and Atmospheric Administration National Marine Fisheries Service online search tool (NOAA Fisheries a). GOM commercial landings included total weights of all finfishes and shellfishes, except bivalve mollusks (e.g., clams, mussels, oysters, and scallops) that were reported as meat weights. Commercial ex-vessel sales represented total dockside values of annual commercial landings (Appendix S1: Fig. S1). Commercial licenses issued in the GOM were sourced from individual states' agencies responsible for wildlife, natural resources, and/or marine fisheries management and conservation (Appendix S1: Table S2). Two states (Mississippi and Texas) did not report commercial license sales for the complete 2000–2017 study period (Appendix S1: Fig. S2). Therefore, the number of commercial licenses reported in this study for the purposes of pre- vs. post-spill comparisons is for the three GOM states with complete 2000–2017 data sets (i.e., Alabama, Florida, and Louisiana). Annual commercial per capita sales in the GOM included data from all states that, in a given year, reported both total commercial ex-vessel sales and the number of commercial licenses issued during the same year in that state (see Appendix S1: Table S3 for a matrix of data availability across metrics, states, and time periods).

Given the comparatively complete and detailed records of shrimp-trawl harvests and effort in the GOM as part of the Gulf of Mexico Shrimp Fishery Management Plan, combined with the regional importance of the shrimp fishery, we also examined these records to further explore commercial fishing patterns between pre- and post-spill periods. Commercial harvest data for brown (*Farfantepenaeus aztecus*), white (*Litopenaeus setiferus*), and pink (*F. duorarum*) shrimp, reported as both harvest weights and ex-vessel sales in the GOM during 2000–2017 were sourced from the NOAA Fisheries online search tool (NOAA Fisheries a). Additionally, all shrimp-trawl vessels in the GOM are required to report detailed records of when trawl nets are actively fishing, which were summed into a total number of days fished each year across all vessels for 2000–2017. These effort data were obtained directly from NOAA's Southeast Fisheries Science Center (Galveston, Texas, USA). Annual catch per unit effort (CPUE) for the GOM shrimp-trawl fleet was then calculated using commercial harvest weight divided by total days fished.

Recreational catch data during 2000–2017 were sourced through NOAA Fisheries' Marine Recreational Information Program (MRIP) for each GOM state (NOAA Fisheries b). Recreational participation data reported as "number of recreational anglers" were also sourced primarily through MRIP for Alabama, Florida, Louisiana, and Mississippi (2017 data for Alabama and Mississippi were obtained from their respective state agencies responsible for wildlife, natural resources, and/or marine fisheries management and conservation, while Louisiana MRIP data were only available from 2000 to 2013; Appendix S1: Tables S2–S3). These recreational participation data were compiled by MRIP through angler surveys that were administered in person, over the phone, and through the mail, targeting anglers that fish from the shore, on personal vessels, and on for-hire vessels. Texas (2007–2017) and Louisiana (2014–2017), however, reported number of recreational licenses sold via their respective state agencies responsible for wildlife, natural resources, and/or marine fisheries management and conservation (Appendix S1: Tables S2–S3). Given the importance of Louisiana in *DwH* oiling impacts, we constrained our GOM-wide recreational participation and expenditures per angler analyses to 2000–2013 as "number of anglers" and "licensees" were not directly comparable.

The economic value of recreational fishing is reported as all impact expenditures associated with recreational fishing, including durable goods, fishing-associated travel, and charters (Lovell et al. 2016). Total impact expenditures during 2006–2012 were available from NOAA Fisheries Economic Impacts Tool (NOAA Fisheries c), while 2013 total impact expenditures were sourced from the Fisheries Economics of the United States (National Marine Fisheries Service 2015). Per capita impact expenditures were determined annually during 2006–2013 by dividing impact expenditures by recreational participation in each GOM state (Appendix S1: Fig. S3).

To extend the temporal scope of impact expenditure estimates beyond 2006–2013, and also help separate the economic effects of *DwH* on recreational fishing from the forces of the 2007–2009 great recession (sensu Eastern Research Group, Inc 2014), we leveraged the available record of state-by-state total impact expenditures (Appendix S1: Fig. S3) along with the complete 2000–2017 record of state-by-state recreational catch (Appendix S1: Fig. S4) to calculate estimated 2000–2017 impact expenditures. The value of each fish caught recreationally during 2006–2013 was determined (i.e., total impact expenditures divided by recreational catch; in year-2000 currency values: US\$41.49 fish^{-1} in AL, US\$48.50 fish^{-1} in FL, US\$74.30 fish^{-1} in LA, US\$823.34 fish^{-1} in TX, and US\$56.94 fish^{-1} in MS) and multiplied by the recreational catch in each state throughout 2000–2017 to approximate total recreational impact expenditures in each state (Appendix S1: Fig. S5). Despite potential uncertainties in these derivations (e.g., the marginal gain of added recreational harvests on expenditures is likely not constant), using this approach resulted in total impact expenditures (2000–2017) and per capita impact expenditures (2000–2013, calculated without TX, which reported "licenses" rather than "total anglers" as the unit of participation during this interval) that were directly linked to the number of recreationally harvested fish reported in the GOM as a social–ecological response metric following *DwH*. Furthermore, conclusions based on the 2006–2013 record (e.g., reported expenditures) and 2000–2017 record (e.g., calculated expenditures) were consistent regarding the response of the recreational sector to the oil disaster (Appendix S1: Figs. S3–S4).

We distinguished mariculture from aquaculture as the farming of fish and shellfish species in estuarine or marine waters, and as the enterprises that potentially experienced environmental impacts from *DwH*. Eastern oysters (*Crassostrea virginica*) comprise the largest component (11.2 million kg yr^{-1}) of GOM mariculture (National Marine Fisheries Service 2016) and were explored as a proxy of trends in GOM seafood farming. Oyster production data for GOM states were obtained through the United States Department of Agriculture Censuses of Aquaculture in 2005 and 2013 (number of farms and sales in millions of US dollars per year; National Agricultural Statistics Service 2006, 2014; Census of Agriculture 2002, 2005, 2012–2013), as well as from individual state agencies responsible for wildlife, natural resources, and/or marine fisheries management and conservation (Appendix S1: Table S2). Given the notably incomplete record and varied metrics of mariculture farmgate sales across GOM states (e.g., Alabama and Florida = pieces, Mississippi = sacks, Louisiana = mariculture and wild harvest aggregated; Appendix S1: Fig. S6), we could not pursue formal inferential analyses of pre- vs. post-spill patterns for this sector.

For each of twelve metrics: ex-vessel sales, commercial landings, commercial licenses, sales per license, shrimp ex-vessel sales, shrimp landings, shrimping effort, shrimping CPUE, recreational catch, angler participation, total impact expenditures, and impact expenditures per angler, we fitted separate linear regressions for pre- and post-spill data. Using the linear fit of pre-spill data, we forecasted trends for 2010–2017. We considered 2000–2009 to be the appropriate scope for a pre-spill baseline because this time period: (1) would be relatively buffered from fishery patterns that manifest over multi-decadal scales (e.g., long-term fishery declines due to historic overfishing); and (2) balanced the temporal scope of post-spill data. For commercial ex-vessel sales and shrimp ex-vessel sales, we excluded 2000–2001 data in linear fits of pre-spill patterns and subsequent forecasts for 2010–2017. Those two years were defined by notably high sales, and given the statistical leverage of end-members, would have depressed forecasted 2010–2017 ex-vessel sales toward notably (unreasonably) lower estimates. This represents a conservative omission for comparing pre-spill forecasts and post-spill observations given the relatively high ex-vessel sales observed during the post-spill period. We also calculated 95% confidence intervals for both pre- and post-spill linear regression fits using the Real Statistics Resource Pack Software (Zaiontz 2020). Subsequently, gauging the response of GOM fisheries to *DwH* was based on the magnitude and direction of differences, if any, between 2010 and 2017 forecasts (no-spill scenario) and observations (using 95% confidence intervals as a conservative approach). These approaches allowed for both year-by-year comparisons and 2010–2017 integrated assessments.

We also compared species composition of commercial harvests among years to evaluate potential shifts in target species in the periods before vs. after the spill. For this analysis, we included all taxa ranked in the top 30 of harvests in at least one year, resulting in 55 species that represented GOM fisheries assemblages (>99% of all landings by weight). Non-metric multidimensional scaling (nMDS) and cluster analyses, based on Bray-Curtis similarity indices of taxon-specific landings (fourth root-transformed weight data), were employed to evaluate pairwise similarity of annual harvests using PRIMER 5.2.2 software (Clark and Gorley 2001).

Results

In year-2000 dollars, cumulative commercial sales across 2010–2017 were US$0.8 billion (using lower bound of 95% confidence interval for 2010–2017 regression) to US$1.5 billion (using 2010–2017 observations) above forecasts informed by pre-spill trajectories. Additionally, 95% confidence intervals for the post-spill regression were above forecasts during every year except 2010 (Fig. 1A). Post-spill harvests mirrored sales trends, elevated by 10–20% over both pre-spill harvests and post-spill forecasts (95% confidence intervals for post-spill regression exceeded forecasts during 2012–2017; Fig. 1A). Commercial participation expanded in the post-spill period by 10–15% relative to the years immediately before the spill, halting a 2000–2009 decline in license sales (Fig. 1B). Participation correlated with increases in 2010–2017 cumulative harvests and ex-vessel sales, while per capita commercial sales in the post-spill period remained on par with pre-spill figures at approximately US$7,000–10,000 licensee^{-1} yr^{-1} (Fig. 1B). Elevated post-spill harvests did not result from large spatial shifts in participation among states (Appendix S1: Fig. S2), or landings by state (Fig. 1C) across 2000–2017. Similarly, the relative biomass and species composition of Gulf-wide harvests were consistent throughout 2000–2017: >93% similarity for all year-by-year comparisons (Fig. 1D, Appendix S1: Fig. S7), including the identity of the top five harvested species (Table 1).

In year-2000 dollars, GOM-wide shrimp sales during the post-spill period either matched or exceeded forecasts in every year (using lower bound of 95% confidence interval for 2010–2017 regression; Fig. 2A). During this interval, we do note that 2010 was the only sales value that fell below forecast if confidence intervals are excluded. In contrast, shrimp harvests fell 1–5% below forecasts during 2010–2013 using the upper bound of the 95% confidence interval of the post-spill regression, and 5–20% below forecasts during 2010–2013 if confidence intervals are excluded (Fig. 2A). Shrimping effort was consistently ~75,000 days fished during 2010–2017, while effort during the 2000–2009 period decreased from ~200,000 days fished to ~75,000 days fished (Fig. 2B). Based on shrimp harvest and effort data, shrimp CPUE was consistently 1250–1500 kg days-fished^{-1} during 2010–2017, which followed an increase in CPUE during the 2000–2009 interval from ~500 kg days-fished^{-1} in 2000 to ~1250 kg days-fished^{-1} in 2009 (Fig. 2B).

Recreational catches and estimated impact expenditures during 2010–2017 did not manifest the post-spill surges recorded in the commercial sector, and catches, participation, and total impact expenditures fell below forecasts by 5–15% during 2010–2011 (excluding statistical

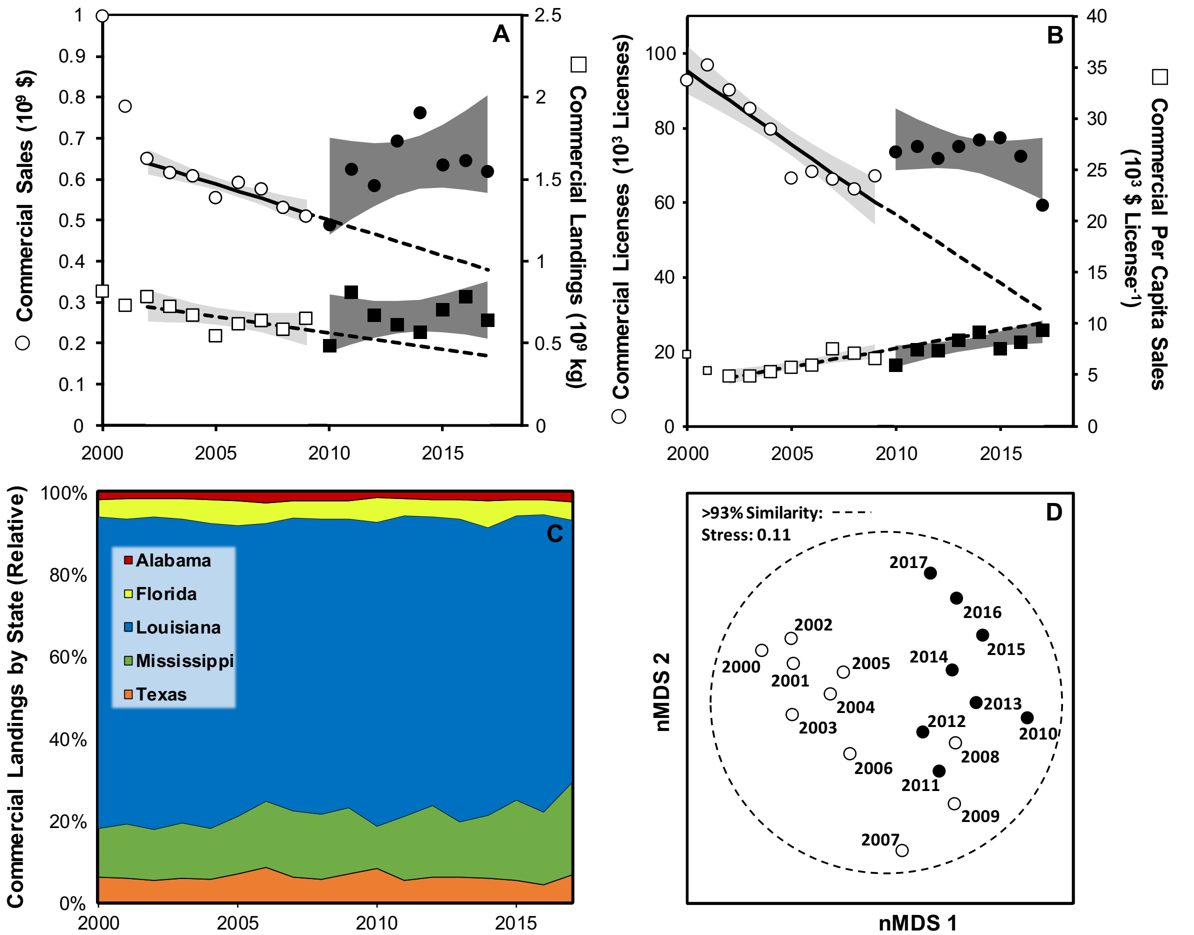

Fig. 1. Gulf of Mexico (GOM) commercial fisheries trends, 2000–2017. (A) GOM-wide total annual commercial ex-vessel sales and harvests. (B) Annual commercial license issued in Alabama, Florida, and Louisiana (Mississippi and Texas license data unavailable across complete study period) and per capita commercial sales among states with both sales and license data available. (C) Relative distribution of landings by state for GOM annual commercial harvests. (D) Spatial representation of relative biomass and composition of GOM annual commercial harvests using non-metric multidimensional scaling (nMDS). Open symbols represent 2000–2009 pre-spill data, while closed symbols represent 2010–2017 post-spill data. In A-B, solid lines represent the linear fit of pre-spill data, while dashed lines represent the linear interpolation for 2010–2017 using 2000–2009 pre-spill data (i.e., forecasted trajectory in the absence of 2010 oiling disaster). Light- and dark-gray saddles show 95% confidence intervals for pre- and post-spill regressions, respectively. Sales data represent year-2000 US dollars ($), while landings are in kilograms (kg).

confidence intervals). Over the complete post-spill period, however, confidence intervals for recreational catches (140–200 million fish yr^{-1}) and angler participation (4–7 million anglers yr^{-1}) consistently overlapped with forecasts (Fig. 3A). Correspondingly, post-spill annual total recreational impact expenditures (US$9.5–12.0 billion yr^{-1}) and per angler expenditures (US$1,450–1,700 $angler^{-1} \cdot yr^{-1}$) were well forecast by pre-spill data (Fig. 3B).

Discussion

Harvests and ex-vessel sales indicate that the commercial sector served as an anchor of post-spill economic stability and potential avenue of

Table 1. Species identity and harvest biomass (10^6 kg) of the top five commercial/mariculture fisheries in the Gulf of Mexico (GOM), 2000–2017.

Year	First	Second	Third	Fourth	Fifth
2000	*Bp*, 591	*Fa*, 71	*Ls*, 49	*Cs*, 31	*Cv*, 12
2001	*Bp*, 528	*Fa*, 65	*Ls*, 37	*Cs*, 31	*Cv*, 12
2002	*Bp*, 585	*Fa*, 55	*Ls*, 38	*Cs*, 30	*Cv*, 11
2003	*Bp*, 518	*Fa*, 61	*Ls*, 43	*Cs*, 29	*Cv*, 12
2004	*Bp*, 464	*Fa*, 54	*Ls*, 51	*Cs*, 27	*Cv*, 11
2005	*Bp*, 370	*Ls*, 46	*Fa*, 43	*Cs*, 23	*Cv*, 9
2006	*Bp*, 409	*Fa*, 64	*Ls*, 60	*Cs*, 30	*Cv*, 9
2007	*Bp*, 456	*Fa*, 52	*Ls*, 45	*Cs*, 26	*Cv*, 10
2008	*Bp*, 421	*Ls*, 44	*Fa*, 36	*Cs*, 22	*Cv*, 10
2009	*Bp*, 455	*Fa*, 56	*Ls*, 53	*Cs*, 28	*Cv*, 10
2010	*Bp*, 342	*Ls*, 42	*Fa*, 33	*Cs*, 19	*Cv*, 7
2011	*Bp*, 635	*Fa*, 54	*Ls*, 41	*Cs*, 25	*Cv*, 9
2012	*Bp*, 500	*Fa*, 48	*Ls*, 47	*Cs*, 25	*Cv*, 10
2013	*Bp*, 440	*Fa*, 49	*Ls*, 40	*Cs*, 21	*Pc*, 9
2014	*Bp*, 385	*Fa*, 48	*Ls*, 43	*Cs*, 23	*Cv*, 8
2015	*Bp*, 539	*Fa*, 50	*Ls*, 39	*Cs*, 24	*Cv*, 8
2016	*Bp*, 619	*Ls*, 50	*Fa*, 38	*Cs*, 23	*Cv*, 7
2017	*Bp*, 461	*Ls*, 49	*Fa*, 45	*Cs*, 24	*Cv*, 8

Notes: Species abbreviations: *Bp*, Gulf menhaden (*Brevoortia patronus*); *Fa*, brown shrimp (*Farfantepenaeus aztecus*); *Ls*, white shrimp (*Litopenaeus setiferus*); *Cs*, blue crab (*Callinectes sapidus*); *Cv*, eastern oyster (*Crassostrea virginica*); and *Pc*, crayfish (*Procambarus clarkii*).

social–ecological resilience for oil-stressed GOM coastal communities. Recreational data also indicate that GOM fisheries supported socioeconomic recovery in response to a basin-scale environmental perturbation. While seafood clearly continued to be caught and sold during 2010–2017 at levels comparable to—or exceeding—pre-spill trends, these fishery-dependent statistics, by themselves, must be used with caution to infer the ecological status of the GOM preceding and following *DwH* (sensu de Mutsert et al. 2008). Indeed, fisheries-dependent data integrate marine ecosystem dynamics, but also socioeconomic drivers such as fuel and equipment prices, species-level market values, management actions, and broader economic drivers. In particular, we do not conclude that higher commercial harvests and sales in the aftermath of *DwH* resulted from elevated abundances of GOM fishes, shrimps, and crabs during 2010–2017. Rather, we consider below how a combination of factors likely drove observed fisheries patterns, such as the relative stability of fishery stocks, increased commercial participation/effort (potentially impacted by spill-related damage payments), and fishery-specific market dynamics (e.g., shrimp).

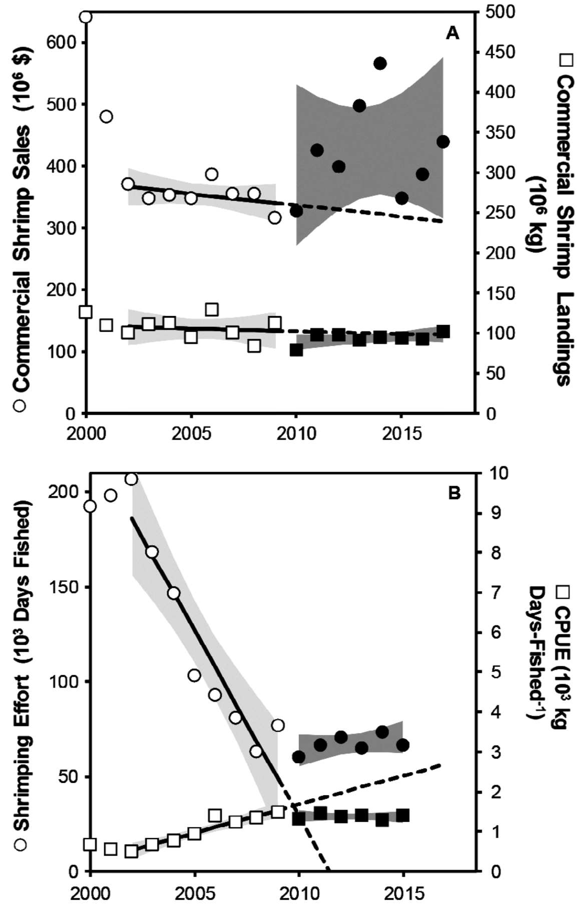

Fig. 2. Gulf of Mexico (GOM) commercial shrimping fisheries trends, 2000–2017. (A) GOM-wide total annual commercial ex-vessel sales and harvests of brown (*Farfantepenaeus aztecus*), white (*Litopenaeus setiferus*), and pink (*Farfantepenaeus duorarum*) shrimp, combined. (B) GOM-wide commercial effort and catch per unit effort (CPUE) for brown, white, and pink shrimp, together. Open symbols represent 2000–2009 pre-spill data, while closed symbols represent 2010–2017 post-spill data. Solid lines represent the linear fit of pre-spill data, while dashed lines represent the linear interpolation for 2010–2017 using 2000–2009 pre-spill data (i.e., forecasted trajectory in the absence of 2010 oiling disaster). Light- and dark-gray saddles show 95% confidence intervals for pre- and post-spill regressions, respectively. Sales data represent year-2000 US dollars (\$), while landings are in kilograms (kg).

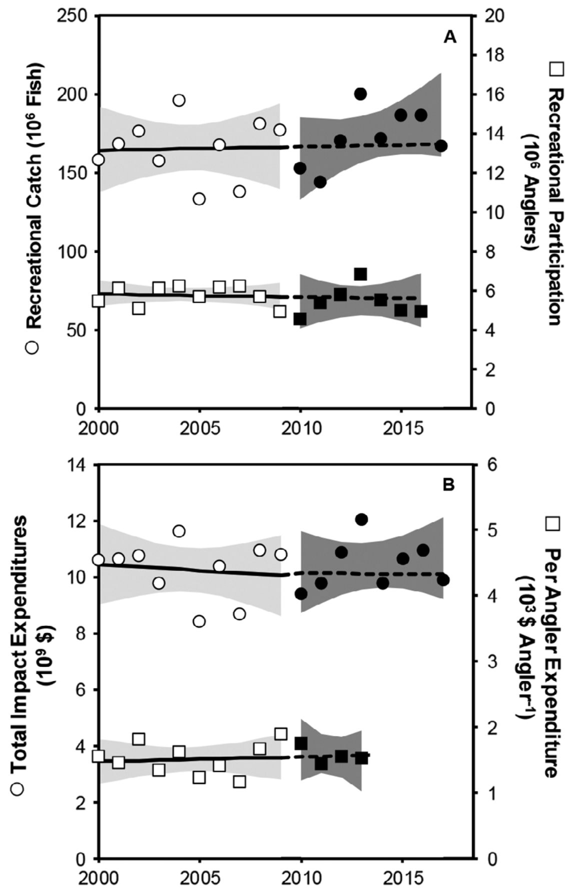

Fig. 3. Gulf of Mexico (GOM) recreational fisheries trends, 2000–2017. (A) Recreational catch and angler participation in the GOM (Texas participation data unavailable). (B) Total and per angler (excluding Texas) expenditures in the GOM. Expenditures calculated using 2006–2013 per fish value of recreational sector and recreational catch across the entire 2000–2017 study period. Open symbols represent 2000–2009 pre-spill data, while closed symbols represent 2010–2017 post-spill data. Solid lines represent the linear fit of pre-spill data, while dashed lines represent the linear interpolation for 2010–2017 using 2000–2009 pre-spill data (i.e., forecasted trend in the absence of 2010 oiling disaster). Light- and dark-gray saddles show 95% confidence intervals for pre- and post-spill regressions, respectively. Expenditure data represent year-2000 US dollars ($).

Responses in fishery sectors appear to have been underpinned by relative population-level stability among harvested taxa in the aftermath of the *DwH* oiling disaster. This stability among fishery species has been corroborated by several nearshore fishery-independent surveys following this unparalleled perturbation among both finfishes (Fodrie and Heck 2011, Able et al. 2015, Schaefer et al. 2016, Martin et al. 2020) and decapod crustaceans (Moody et al. 2013, Van der Ham and de Mutsert 2014, Grey et al. 2015). Multiple species of sciaenids, lutjanids, serranids, and penaeids comprise these outcomes, despite known harms for individuals exposed to oil among nekton (reviewed in Fodrie et al. 2014). While the collapse of Pacific herring (*Clupea pallasii*) five years after the Exxon Valdez spill highlights that oiling may have lagged or chronic effects that contribute to mounting ecosystem instabilities (sensu Thorne and Thomas 2008), Gulf menhaden (*Brevoortia patronus*) represent an analogous forage fish that has demonstrated little evidence of delayed population-level injuries (Short et al. 2017). Rather, 2011 and 2016 defined the two maximum commercial harvest years for Gulf menhaden during the 2000–2017 record (Table 1).

Several mechanisms likely contributed to the population-level stability of fishes and shellfishes that allowed fisheries to serve as a pathway of economic constancy and that inform models of coastal social–ecological resilience or vulnerability against future environmental disasters. Many Gulf fishes and crustaceans were capable of detecting and fleeing oil-affected areas, or were inoculated for hydrocarbon exposure via natural and anthropogenic seepage (Fodrie et al. 2014). Additionally, density-mediated compensatory responses potentially counterbalanced the impacts of oil exposure, dampening effects at population levels (Neubauer et al. 2013). Oil-related mortality of higher predators, including marine birds and mammals, decreased natural mortality on fishes and shellfishes, mitigating losses due to oil toxicity (Short et al. 2017). Similarly, food-safety fishery closures (Ylitalo et al. 2012) contributed toward seasonal (May–October) reductions in 2010 fishing mortality. These changes in summer–fall harvest pressure likely had positive effects on the reproductive output and subsequent abundances of fishes and shellfishes throughout 2010–2017 (Fodrie and Heck 2011). We do note, however, that overall GOM harvests in 2010 were remarkably high given the broad closures following the spill. This result is perhaps explained by the degree to which fishermen shifted effort to later in the year following the reopening of fishing grounds (sensu Chagaris et al. 2019). Beyond this ecological stability, fishing industries in the Gulf may have been further buffered by the shear diversity of target species on which commercial and recreational sectors depend (Bailey and Pomeroy 1996).

While these results indicate fisheries provided critical biological and economic "memory" (i.e., functional components of a system that persist following disturbance; sensu Adger et al. 2005) for recovery of the social–ecological system impacted by *DwH*, they do not negate the acute disruptions or subsequent increases in anxiety, stress, and depression that followed this major environmental disaster (Gill et al. 2012). Moreover, while collective fisheries appeared stable following widespread oiling, cases of concern exist. Blue crab (*Callinectes sapidus*) and eastern oyster (*Crassostrea virginica*) are renowned commercial fisheries in the GOM, yet harvests of these species were 17% and 23% depressed in post- vs. pre-spill periods, respectively (Table 1). Sessile oysters, specifically, suffered the double insult of oiling injury combined with damages related to mitigation efforts such as extensive freshwater diversions and shoreline boom deployment (Powers et al. 2017).

Patterns in GOM shrimp fisheries also highlight the complexities of dissecting the drivers and responses of perturbed social–ecological systems. For instance, the ability of the shrimp fishery to support economic resilience following *DwH* was likely driven, in part, by unrelated market forces. In particular, the per mass value of GOM shrimp increased by ~25% during the early 2010s, relative to the 2000s, due to pervasive early mortality syndrome of farmed shrimp in Thailand (which at the time accounted for one-third of imports to the United States; Gulf of Mexico Fishery Management Council 2019). Thus, while total commercial shrimp sales were relatively high during 2010–2017, those patterns did not correspond closely to trends in commercial shrimp harvests and trawling effort. Rather, shrimp harvest and effort were relatively stable during 2008–2017. Moreover, trends in shrimp effort and harvest during 2000–2017 were not chiefly driven by population-level abundances of shrimp in the pre- and post-spill eras, but rather permit moratoriums and effort caps enacted to reduce red snapper (*Lutjanus campechanus*) bycatch mortality by 74% in 2008 relative to 2001–2003 levels, and subsequently amended to a 67% reduction in 2011 relative to 2001–2003 levels (Gulf of Mexico Fishery Management Council 2019). Regardless of these uncertainties, however, it appears certain that the GOM shrimp fishery retained considerable value in the years immediately following the spill, which supported economies in many stressed coastal communities. We also note that shrimp CPUE, a potential indicator of shrimp population status within the fishery-dependent sector, also remained high in 2010–2017 relative to pre-spill data.

The macroeconomic effects of natural disasters appear varied across catastrophes, geographic locations, and socioeconomic strata (Strobl 2011). There are multiple competing hypotheses that describe how economic output might respond to environmental catastrophes in the long run beyond the null model of "no effect." These include the following: (1) "no recovery," in which disasters slow growth by destroying capital or goods that are replaced by funds moved away from more productive investments; (2) "recovery to baseline," in which economic output is initially slowed, but then accelerated by high-demand, low-supply forces until growth converges toward the pre-disaster trend; (3) "build back better," in which growth is initially slowed, but replacement and modernization of older/outdated assets has a gradual, positive effect on long-term growth; and (4) "creative destruction," in which economies are stimulated via increased demand for goods or services, inflowing aid, or stimulated innovation (Skidmore and Toya 2002, Field et al. 2012).

Following the *DwH* environmental disaster, total commercial ex-vessel sales mimicked a "creative destruction" economic response, while total recreational impact expenditures more likely reflected a "recovery to baseline" pattern by no later than 2012. While recreational patterns likely tracked regained confidence of GOM anglers in seafood safety, the commercial response is more complex. In contrast to creative destruction models (Cuaresma et al. 2008), replacement costs of destroyed goods in the commercial sector (i.e., fish), subsequently reported as economic growth, do not apply. Additionally, there is little evidence that commercial fishermen invested in human capital or technological advances following the spill that generated higher ex-vessel sales. There is also no indication that oiling triggered major investment shifts toward, or damages to, the mariculture industry, although inferences are restricted by sporadic records of Gulf mariculture farmgate sales throughout 2000–2017 (Appendix S1: Fig. S6).

Consistent with creative destruction models, however, commercial fishermen did receive external financial support via participation in clean-up operations, the Seafood Compensation Program, and business emergency claims that totaled US$9.1 billion (Cockrell et al. 2019). By comparison, total GOM ex-vessel sales during 2000–2017 totaled US$11.5 billion. Thus, damage payments likely increased the total income of many license holders by >50% during the 2010–2017 period. Privacy laws limit identification of aid recipients, but there is strong anecdotal evidence (e.g., many popular press articles, wide use of the term "spillionaires") that these payments supported retooling or expansion of commercial fishing infrastructure. Amendment 18 to the GOM Shrimp Fishery Management Plan also noted that permit holders for shrimping in federal waters benefited from oil spill-related payments (these fishermen contribute about two-thirds of shrimp landings and three-fourths of shrimp sales; Gulf of Mexico Fishery Management Council 2019). Indeed, 66% of shrimping permit holders in 2010 received revenues from damage claims or participation in the BP Vessel of Opportunity Program (VOOP) to clean up oil (28% of fleet served in VOOP). Amendment 18 concluded that these spill-related incomes, combined with low gas prices and reduced farmed shrimp imports, significantly increased profits for shrimpers in the years following the oiling disaster.

Notably, spill-related payments were not needed to replace infrastructure that was left principally undamaged by the spill. This distinguishes *DwH* from natural disasters such as major hurricanes and tsunamis that often devastate physical capital such as boats, gears, and shore-based support facilities. Combined, these forces provided a mechanism to activate latent interest and capacity within commercial fishing communities. Thus, "creative disturbance" rather than creative destruction potentially contributed toward 2010–2017 increases in participation and fishery-specific effort. This increase in effort/participation, rather than dramatic increases in biomass of fishery stocks, shifts in target species, or fishing locations (spatial stability of commercial fleets also noted by Cockrell et al. 2019), was likely an important driver of post-spill harvests, especially since income per licensee did not shift dramatically after *DwH*. Furthermore, entry into GOM commercial fisheries is relatively "open," with few requisites or participation caps compared with access frameworks in other regions. In this context, the adaptive capacity of GOM commercial fisheries could have been relatively high vis-à-vis responses to social–ecological conditions in the post-spill era. Recreational anglers, by contrast, did not receive damage payments despite significant concerns of non-market losses in 2010 (Alvarez et al. 2014, but see Train 2016), which could partially explain the different responses of these sectors in the post-spill period.

These findings indicate that coastal fisheries can be relatively insensitive to major pulse disturbance (Bender et al. 1984), although these events are sometimes very publicized (e.g., oiling). Instead, press disturbances such as climate change (Fodrie et al. 2010), pervasive habitat degradation (Gittman et al. 2015), and fishing (Powers et al. 2013) may force comparatively more significant shifts within coastal fishery assemblages over time. Thus, a lasting paradox of this pulse environmental disaster may be that fishery systems underpinned initial ecological and economic resilience. Subsequent bolstering of commercial fisheries infrastructure and effort in the post-spill era, however, may ultimately have profound press effects on GOM ecosystem structure, function, and future resilience capacity.

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Data Availability

Data are available from the Gulf of Mexico Research Initiative Information & Data Cooperative (GRIIDC): https://doi.org/10.7266/YJXPGGPZ

Supporting Information

Additional Supporting Information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/ecs2.3801/full