Impacts of *Deepwater Horizon* on Fish and Fisheries: What Have we Learned about Resilience and Vulnerability in a Coupled Human-Natural System?

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The *Deepwater Horizon* (DWH) oil spill occurred in a region of the Gulf of Mexico (GoM) supporting abundant, diverse and valuable communities of fishes and fishers. The economy of the northern GoM is inextricably tied to the natural resource bases of the region (tourism, fishing, oil and gas, etc.) and thus the coupling between the human and ecological systems is tight and subject both feed-back and, to some extent, feed-forward controls. Management actions taken during the 87-day DWH spill incident included the closure of over 280,000 km^2 of productive fishing area (about 1/3 of USA federal waters in the GoM), resulting in significant declines in catches and revenues for some critical species for several months after the spill. As well, a variety of oil spill countermeasures including the use of chemical dispersants (at the well

head and the sea surface), releases of freshwater into marshes to staunch the progression of oil ashore, creation of sand berms, burning of oil at sea and mechanical pickup were employed. Because of the closures, fishers were compensated for lost fishing opportunities in a number of ways, including employment in oil spill response efforts (the VoO or Vessel of Opportunity program), accepting compensation payments from the Responsible Parties, and moving fishing areas and shifting to open areas of the GoM. Some fisheries were heavily impacted during 2010 (e.g., menhaden and inshore invertebrate fisheries), while for others, area shifting resulted in little change in GoM-wide fishery catches (e.g., red snapper, penaeid shrimps). In the 10 years since the DWH disaster, many fisheries have recovered, exhibiting patterns of inter-annual variability consistent with those seen prior to the spill, but other species have shown little to no recovery. One of the critical issues in understanding oil spill effects is that of causal inference given multiple simultaneous drivers and feedbacks, thus the appeal of viewing fish-fishery interactions as a coupled human and natural system.

Results of long-term monitoring studies document a variety of responses of various taxa occupying diverse habitats from estuarine/coastal to open ocean. These impacts resulted both from oil contamination and from various response countermeasures. Differential recovery trajectories are mediated by life history aspects contributing to resilience and to some extent the degree of ongoing contamination from pools of residual oil and other chronic sources. Relatively resilient species were those exhibiting low to moderate modularity (near ubiquitous species or populations) and those with relatively short life cycles. Fishing community resilience to the spill was related to a variety of employment alternatives during closures and facilitated by the capacity of fishers to adapt to non-traditional opportunities in fishing and by financial assistance programs. Overall, the level of business failures during and just after DWH was lower than historical averages for important reef fish fisheries of the Gulf.

Introduction

The Gulf of Mexico (GoM) Large Marine Ecosystem (LME, Fig. 1) is a highly complicated (many interacting components) and complex (non-linear and multi-order relationships among components) Coupled Human And Natural System (CHANS, Liu et al. 2007; Carter et al. 2014; Ainsworth et al. 2017; Ferraroa et al. 2019). The ecosystem supports a wide range of valuable provisioning services (e.g., petroleum, fisheries, fresh water extractions) as well as the full array of other critical ecosystem service categories (e.g., regulating, supporting and cultural, NASEM 2013; Davis 2017; Gracia et al. 2020; Murawski et al. 2020; 2021). Monitoring of fish stock abundance and recruitment was ongoing prior to DWH primarily in support of state and federal fisheries management. The five bordering U.S. states and several federal agencies (primarily NOAA/NMFS) conduct routine monitoring surveys in support of fisheries and environmental management. These surveys show a diversity of responses of fishery-supporting species consistent with their life history attributes, and the degree to which populations intersected the oil spill and/or were affected by response measures such as fresh water diversions in Louisiana's marshes (Peterson et al. 2017). New sampling programs instituted since the spill have provided a robust baseline of oil contamination (primarily sampling for polycyclic aromatic hydrocarbons – PAHs) and abundance changes that did not exist prior to DWH (Murawski et al. 2014; 2018; Pulster et al. 2020a; 2020b). Concerted efforts to catalog the biodiversity and measure the response of fish communities including the meso- to bathy-pelagic realms of the GoM (McClain et al. 2019; Sutton et al. 2020) have been supported by the Natural Resource Damage

Assessment (NRDA; *Deepwater Horizon* Natural Resource Damage Assessment Trustees 2016) and by the Gulf of Mexico Research Initiative (GoMRI), among other institutions.

The purpose of this paper is not to provide a comprehensive overview of the many, diverse impact trajectories of resources affected, and alternatively, those impervious to the effects of DWH. Rather, we report on the intersections between impacts on fishery resources and their coupling to human use outcomes for fisheries in the GoM. Additionally, we provide a conceptual model of how a CHANS approach can be structured for the GoM to help elucidate causal relationships among system components, given the wealth of ecological, economic and anthropological information available for the LME and useful in the context of oil spill impact assessment.

Vulnerability and Resilience of Gulf Fish and Fisheries

The coupling of ecological and human-centric systems provides a rich format for understanding the causal relationships between a particular driver (e.g., the DWH oil spill and associated mitigation measures) and their impacts on ecosystems and people, in the context of other multiple, significant, and synergistic factors affecting those outcomes (Adger et al. 2005; Liu et al. 2007; Carter et al. 2014). In contrast to an approach to causality focused on a single cause-effect relationship (e.g., changes in a population affected by a single, dominant driver, such as DWH), the CHANS approach offers three important distinctions: (1) the approach provides a context for multiple simultaneous drivers, (2) it emphasizes two-way (e.g., reciprocal) interactions between natural and human components of systems as well as multiple cascading interactions, and (3) it is scalable across the range of habitat complexity, human and animal population modularity and mobility, and human drivers (e.g., local fishing effects to global change effects; Levin et al. 2006; Carter et al. 2014; Ferraroa et al. 2019).

Case in point, long time series data document a continuous decline is population abundance of blue crab (*Callinectes sapidus*) in coastal waters of Alabama dating decades prior to DWH (Fig. 2). How do we interpret the impacts of the DWH spill given that the proximal drivers of long-term decline in this species are likely overfishing and habitat degradation? As well, does the closure of the fishery during late spring to late autumn of 2010 tell us anything about the strength of the fishery effect on abundance? In this case, there appeared to be a slight (but statistically insignificant) uptick in mean abundance the following year (and thus little positive impact from a short-term MPA; Fiore et al. 2020) which apparently did not arrest the longer-tern declining trend (Fig. 2). A similar, but perhaps more compelling example of coastal resource response is that of white shrimp (*Litopenaeus setiferus*) and brown shrimp (*Farfantepenaeus aztecus*) in the Barataria Bay region of coastal Louisiana (Fig. 3). These two species provide the bulk of commercial shrimp landings not only in Louisiana but the GoM as a whole (Fiore et al. 2017). This region was heavily impacted by both oil transport to the coast originating from DWH and large-scale releases of freshwater as an oil spill countermeasure (Peterson et al. 2017; Murawski et al. 2021). Closure of the fishery for most of the spring, summer and autumn likely resulted in the strong in-year increase observed in 2010 for white shrimp and the spike in abundance in the following year (2011) for brown shrimp. Both stocks had been increasing prior to the spill due to long-term, significant declines in shrimp fishing effort (Fiore et al. 2017), in part associated with destruction of many shrimp vessels due to hurricanes in 2005 and the overall economics of shrimp fishing (and economics of competing shrimp imports). That the increases in 2010 and 2011 could not be sustained is likely due to the longer-term fishery effect (Fiore et al. 2017) and the short-term expectations of higher shrimp volume which may have attracted effort to the re-opened area following the closures. Thus, while the general perception for most inshore populations was significant declines due to the impacts of contamination and countermeasures (Peterson et al. 2017) in some cases the closures actually may have resulted in substituting one significant driver for another.

The literally thousands of resource species and sub-populations in the vicinity of the DWH accident exhibited a wide range of population trajectories from 2010 onward, likely reflecting their relative vulnerabilities to contamination from the spill, the degree of population resilience inherent in the various life histories of animals, and other attributes of the LME system (Murawski et al. 2016; 2021; Schwing et al. 2020). To the last point, resource populations are either semi-distinct population segments, linked in geographically dispersed meta-populations, or represent homogeneous populations throughout the Gulf, reflecting a continuum of population modularity vs. connectivity (Paris et al. 2020). There are many examples of sub-populations of a species contributing to the resiliency of the larger meta-population (e.g., Schindler et al. 2010). If there are significant adult movements or larval exchange among sub-populations, this "portfolio effect" may contribute to overall resource resilience. The portfolio effect can work at the meta-population level and also represents a significant factor buffering multispecies fisheries from the vagaries of individual species changes (Cline et al. 2017). In the case of Gulf fisheries, the multispecies nature of the resource and the flexibility of Gulf fishers to target multiple fisheries (particularly seasonally and in nearshore regions) and different areas (Cockrell et al. 2019) is likely an important factor contributing to the apparent resilience of Gulf-wide fishery landings following DWH (Fig. 4).

Total fishery landings and first-sale value (e.g., prices paid to fishers) from the USA GoM have varied considerably over time (Fig. 4). Total landings (tons) peaked in the mid-1980s at about 1.2 million metric tons, whereas total (non-deflated) value peaked in 2014 at nearly $1.1 billion

(Fig. 4). The volume of GoM landings is generally dominated by catches of Gulf menhaden (*Brevoortia patronus*), a low value industrial fish, whereas the overall value of the fishery is dominated by white and brown shrimp catches. Landings declined sharply in 2010, to the lowest level since the late 1950s, (Fig. 4) doubtlessly due to the closure of prime Gulf menhaden fishing areas off Louisiana and Mississippi. However, overall landings value declined only slightly primarily due to shrimp fishing vessels re-locating to productive fishing grounds off Texas (and to some extent Florida) and reef fish fishing vessels (targeting primarily snappers and groupers) transferring effort primarily to the west Florida shelf (Cockrell et al. 2019).

Fishers confronted with the large scale fishery closures, and perceptions of oil-tainted seafood, exhibited a range of compensatory behaviors. For those fishers used to exploring fishing grounds beyond areas subject to closures, re-location west or east resulted in preserving revenue and in some cases, increased revenues from open areas (Cockrell et al. 2019). Their success in adapting to the abrupt closure of grounds was primarily tied to either to their experience with the "explore vs. exploit" trade-off (O'Farrell et al. 2019) or the ability to form or use existing networks to rapidly gain knowledge of new fishing opportunities in unfamiliar regions.

Fishers were also afforded income from several compensation programs (Mayer et al. 2015) contributing to their economic viability. During the fishery closures, the Responsible Party (BP) chartered about 3,000 fishing vessels to perform various clean-up and monitoring activities as part of the Vessel of Opportunity (VoO) program. Overall the VoO dispersed $594 million to qualifying fishers in the impacted region (Mayer et al. 2015), a total nearly equal to the cumulative first-sale revenue of all USA Gulf fisheries in 2010 (Fig. 4). In addition to the VoO, compensatory payments to businesses affected by the spill totaled about $10.5 billion (Mayer et al. 2015). While only a fraction of affected businesses were fishers, these payments also were made to various fishing support businesses (maintenance, supply, wholesale fishmongers, etc.) in coastal communities. The ability to qualify for compensatory payments or participate in the VoO may explain the lower than customary business failure rate documented for the reef fish fishery coincident with the DWH accident (Cockrell et al. 2019).

The longer-term resilience of the fishing industry to the DWH spill and ensuing management decisions is thus partly a function of the population-level consequences of the spill for marine resources, the inherent coping mechanisms of fishers (e.g., managed portfolios of targeted fisheries, ability to adapt to abrupt change) and mechanisms set up during the spill to compensate fishers for lost income. However, the resilience potential of fishers may come at a cost of both disassociating fishery catches from traditional ports and communities (in the cases where landings ports changed) or perceived unfairness of the disbursement of compensation payments among community members (Mayer et al. 2015).

The considerable literature on population resilience and vulnerability often conflates the two concepts (Adger et al. 2005; Adger et al. 2006; De Lange et al. 2010a; 2010b). However, in our estimation these concepts are separable since the vulnerability of a species or human community is to a specific threat and not to threats generally (Murawski et al. 2021). Thus, for example, a coastal community may not be particularly vulnerable oil spills generally, but highly vulnerable to one emanating in the trajectory path from a particular site. Likewise, resilience (e.g., the capacity to either resist a population insult or recover quickly from it) is primarily related to a variety of endogenous population traits (longevity, reproductive strategy, ability to metabolize and excrete xenobiotic chemicals, etc.) or related to the degree of connectivity with adjacent populations in its “portfolio”. Thus, we may classify various Gulf resources in terms of a bivariate matrix of vulnerability scores on one axis and species resiliency on the other. While not a focus of this paper, the extrema of population resilience include deep corals (long-lived and slow growing this with low resilience to xenobiotics such as oil contamination, and were highly vulnerable because of oil transport to the sea floor during DWH (Schwing et al. 2020). At the other extreme, Gulf menhaden appear highly resilient because of their short life span, high relative fecundity and high degree of population connectivity. As well, because of the timing and transport of DWH oil to the coast, vulnerable menhaden life stages were not particularly vulnerable to the DWH spill (Murawski et al. 2021).

A Coupled Systems View of Gulf Fisheries and Fishes

The CHANS approach appears to be highly suited to evaluating the resilience of fishes and their co-dependent human systems in the GoM to shocks such as DWH (Fig. 5). The literature defines several concepts that are essentially tests of the veracity of the CHANS designation and whether causal inferences can be drawn that explain the various states of the system (Ferraroa et al. 2019). The term *excludability* is used to characterize the degree to which outcomes have no causal link other than the treatment variable of interest; *no interference*, describes the assumption that a causal effect link is not is not in turn affected by changes in the spatial domain adjacent to area of interest. Violations of the assumptions of *excludability* or *no interference* complicate the direct interpretation of causal inference (Ferraroa et al. 2019). In particular, human capital mobility (such as was exhibited for fishers during DWH) can bias causal inferences about the strength of human drivers because of the *no interference* assumption (Ferraroa et al. 2019). However, as can be seen from the example of white and brown shrimp (Fig. 3), the exclusion of fishing from that area for a full life span of one generation of the species reveals the strength of the causal relationship between fishing mortality extant before and after closures, despite the fact that effort flowed out of the spatial domain of Barataria Bay during the closures and was likely differentially attracted to it after the closures were lifted. One cannot, however, discount other simultaneous drivers that were manipulated during the spill (such as the toxic effects of the oil and dispersing chemicals and the flooding of the habitat with freshwater). The DWH scenario involving significant fishery closures (Fig. 1) represents a massive, short-term MPA 'experiment' that would have been impossible to conduct otherwise, and has revealed the importance of fishing (and other environmental drivers) as having important causal links between human activities and the state of the natural system. It also emphasizes the importance of both direct and indirect interactions and the overlay of geographically scalable environmental co-stressors such as sea level rise (Fig. 5).

The systems diagram (Fig. 5) documents structural associations between the variety of environmental co-stressors, most of which are under varying degrees of human control. The separability or confounding effects of these stressors is difficult to experimentally define and is more likely the domain for ecosystem models (e.g., Ainsworth et al. 2017). The scenario of an oil spill (e.g., DWH) affects the vulnerability of particular resources to exposure, and, along with the pre-spill resilience capacity (also affected by the non-spill co-stressors) influences resource trajectories during and post-spill. Given the varying effects of the spill on marine populations (no effect, decline, beneficial effect) resources will be defined by their post-spill trajectories. For those resources (and their habitats) negatively affected by the oil or associated counter-measures, "recovery" will be dependent on "natural" processes (e.g., recruitment, natural mortality, fishing effort, etc.) as influenced by directed restoration activities. Restoration may include direct habitat manipulation, cultivation and stocking of affected species, or "compensatory" conservation efforts to reduce other stressors either for a pre-determined time period or permanently. Clearly human interference in this process can consequentially affect the trajectories of population recovery. However, as has been demonstrated in other environmental management domains, the assumption that resource recovery will be symmetric in timing or degree with resource decline may be seriously flawed (Duarte et al. 2009). Not only is the 'shifting baseline' syndrome an important consideration in setting restoration goals (recover to where?), but restoration efforts may fundamentally change the structure of the CHANS system being considered.

Summary

The *Deepwater Horizon* oil spill had consequential and, at this point, ongoing impacts on the coupled human and environmental system supporting fish and fisheries of the northern Gulf of Mexico. Nearshore resources, in particular, were significantly impacted by a combination of the oil spill and *various spill countermeasures* that were deployed, some of which may have had more consequential negative impacts than the oil contamination itself. The 280,000 km^2 fishery closure (from April 2010 to well into 2011) was the largest fishery closure ever enacted for a marine oil spill in the USA, and had significant, observable impacts on some resource species. However, other simultaneous impacts to resources (e.g., from toxic contamination) complicate the evaluation of causal inference from all of the impacts of the spill and associated countermeasures.

The development of the CHANS approach to the human-natural fishery system in the Gulf affords new insights into the interplay of various co-stressors and in particular may provide an important framework to understand impacts of massive restoration projects ongoing in coastal and nearshore regions. The area is subject to significant and ongoing habitat loss as well as increased freshwater inputs from natural sources as well as directed river diversions. The system also provides a virtually unique testbed to better define direct and indirect causal links between human and natural components of the system and for making predictions regarding the long-term consequences for Gulf fisheries not only for DWH but other environmental catastrophes (Berenshtein et al. 2019).

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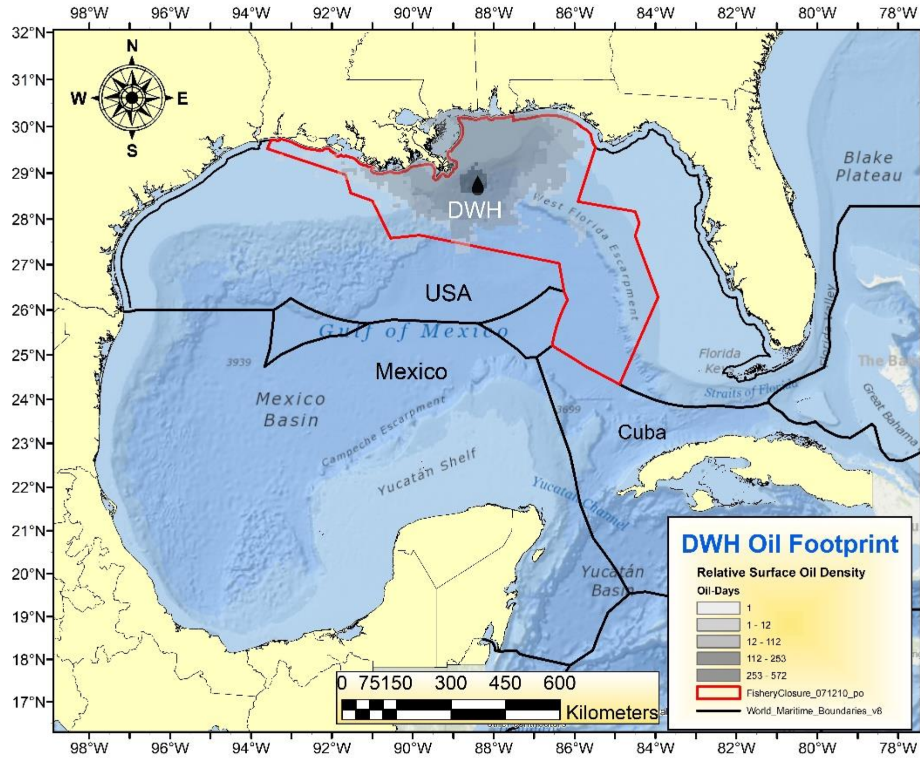

Figure 1. Spatial extent of surface expression of the *Deepwater Horizon* oil spill (gray shaded areas, Murawski et al. 2014) and maximum extent of fishery closures (red polygon, July 12, 2010).

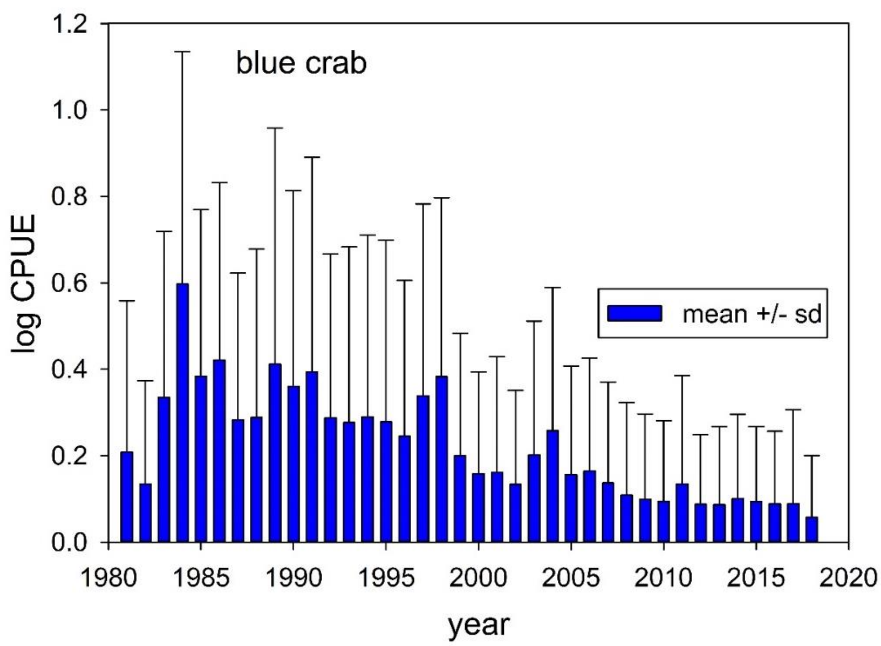

Figure 2. Relative abundance (catch per unit if effort – CPUE) from the Alabama Trawl Survey (Alabama Marine Resources Division), 1981-2018. Blue bars are the mean +/- 1 SD (error bars).

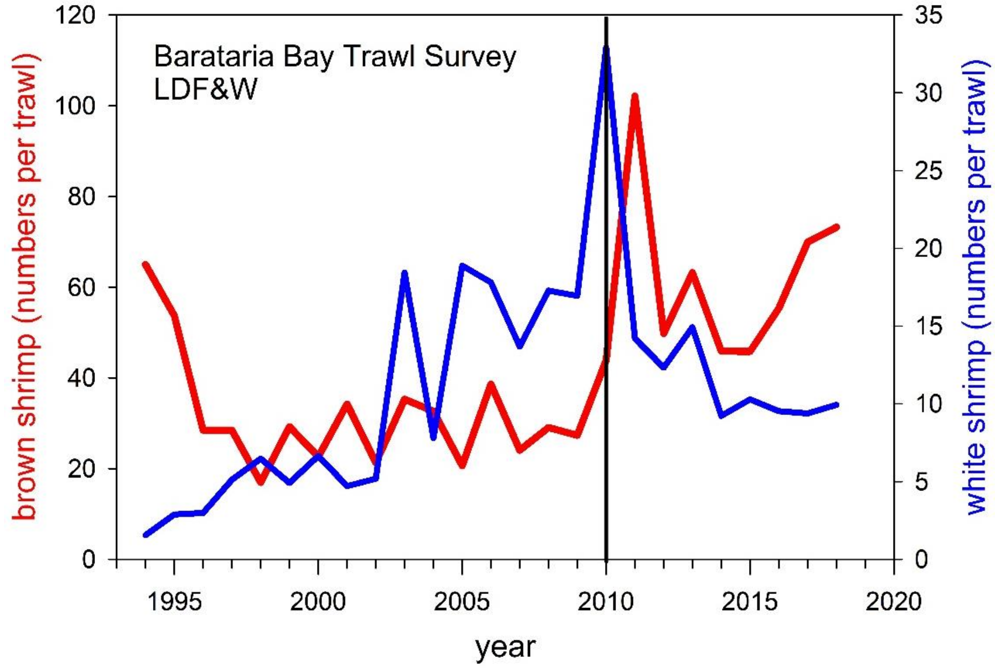

Figure 3. Relative abundance (numbers per standardized trawl haul) of two species of shrimp from the Louisiana Department of Fisheries and Wildlife's trawl survey in Barataria Bay, 1994-2018.

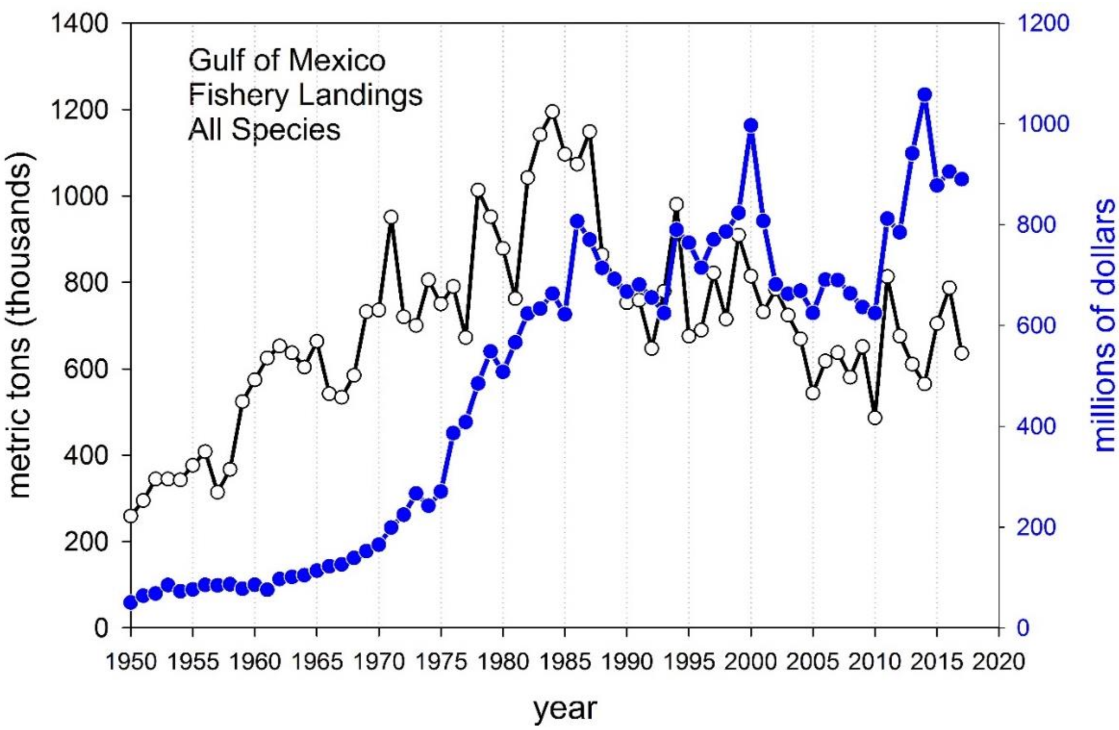

Figure 4. Total fishery landings (metric tons) and first sale value ($ millions) of commercial fishery landings in the USA portion of the Gulf of Mexico, 1950-2017.

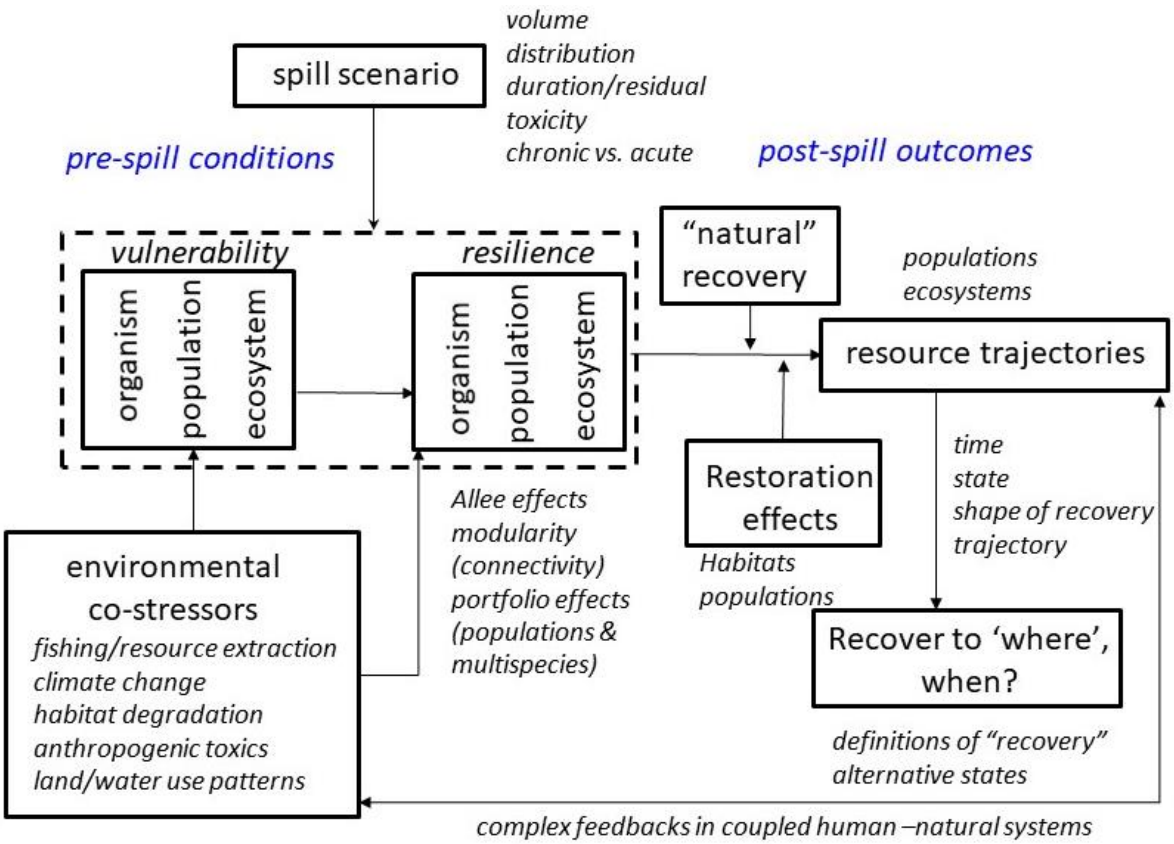

Figure 5. The cycle of pre-spill, post-spill and recovery sequences of resources affected by large-scale contaminant events such as *Deepwater Horizon*.