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I. INTRODUCTION

The explosion of the Deepwater Horizon offshore drilling rig on April 20, 2010 initiated the world's largest known oil spill in the Gulf of Mexico Large Marine Ecosystem (LME).[1] Characterized by an extensive continental shelf and substantial nutrient input from rivers and Loop Current-induced upwelling, this region is valued for its high productivity and lucrative fisheries.[2] According to the United States National Marine Fisheries Service, approximately 18% of the U.S. domestic commercial fisheries landings reported in 2009 originated in the Gulf of Mexico.[3]

Estimates of the quantity of oil, natural gas and associated methane, and chemical dispersants released as a result of this calamity have been plagued by uncertainty. The U.S. Government-appointed team of scientists, the Flow Rate Technical Group, estimated that a total of 4.9

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1. Large Marine Ecosystems (LME) are ecologically defined geographic regions often used in the assessment and management of marine resources and the environment. LME boundaries have been determined according to characteristic bathymetry, hydrography, productivity, and trophic relationships. U.N. ENV'T PROGRAMME, THE UNEP LARGE MARINE ECOSYSTEM REPORT: A PERSPECTIVE ON CHANGING CONDITIONS IN LMES OF THE WORLD'S REGIONAL SEAS 3 (K. Sherman & G. Hempel, eds., 2008).

2. *See* Charles M. Adams, Emilio Hernandez & James C. Cato, *The Economic Significance of the Gulf of Mexico Related to Population Income, Employment, Minerals, Fisheries and Shipping*, 47 OCEAN & COASTAL MGMT. 565 (2004).

3. U.S. NAT'L MARINE FISHERIES SERV., FISHERIES OF THE UNITED STATES 2009, 6 (2010) (out of a total 7,867,333 thousand pounds landed, 1,419,747 thousand pounds landed in the Gulf of Mexico).

million barrels of oil were released from BP's Macondo well,[4] while the results of an independent study suggest that between 4.16 and 6.24 million barrels leaked from the well.[5] Additionally, according to BP's records, approximately 1.8 million gallons of dispersant were applied at the site of the leak as well as the sea surface.[6] Complex oceanographic processes have made it difficult to determine the current and future distribution of these substances from the surface to the sea floor and their persistence in the marine environment. Most importantly, there is no immediate answer to questions concerning short-term and long-term impacts on habitats and marine organisms in the path of this disaster.

The capacity of habitats and species to recover from the effects of oil, methane, and dispersants may have already been compromised due to pre-existing sources of stress. Since the 1950s, heavy fertilizer use within the Mississippi River drainage basin, encompassing 41% of the contiguous United States, has led to increased nitrate loading in the northern Gulf of Mexico.[7] This nutrient-laden, freshwater discharge ultimately results in the formation of periodic, oxygen-depleted "dead zones" devoid of fish, shrimp, and most other invertebrates in shelf waters off the coasts of Mississippi, Louisiana, and eastern Texas.[8] Also,

4. *U.S. Scientific Teams Refine Estimates of Oil Flow From BPs Well Prior to Capping*, RESTORETHEGULF.GOV (Aug. 2, 2010 1:18 PM), http://www.restorethegulf.gov/release/2010/08/02/us-scientific-teams-refine-estimates-oil-flow-bps-well-prior-capping.

5. *See* Timothy J. Crone & Maya Tolstoy, *Magnitude of the 2010 Gulf of Mexico Oil Leak*, 330 SCI. 634, 634 (2010).

6. *Operations and Ongoing Response*, RESTORETHEGULF.GOV (Jan. 20, 2011, 9:09 AM), http://www.restorethegulf.gov/release/2011/01/20/operations-and-ongoing-response-january-20-2011.

7. Nancy N. Rabalais, R. Eugene Turner & Donald Scavia, *Beyond Science into Policy: Gulf of Mexico Hypoxia and the Mississippi River*, 52 BIOSCIENCE 129, 135-136 (2002).

8. Thomas O'Connor & David Whitall, *Linking Hypoxia to Shrimp Catch in the Northern Gulf of Mexico*, MARINE POLLUTION BULL., 2007, at 1-3. The hypoxic zone in the northern Gulf of Mexico typically forms seasonally in mid-summer, and covers an area of approximately 20,000 km2. *Id.* at 1. It is the largest such zone in the coastal United States and the second largest in the world. N. N. Rabalais, R. E. Turner, B. K. Sen Gupta, D. F. Boesch, P. Chapman & M. C. Murrell, *Hypoxia in the Northern Gulf of Mexico: Does the Science Support the Plan to Reduce, Mitigate, and Control Hypoxia?*, 30 ESTUARIES AND COASTS, 753, 754 (2007). High concentrations of nitrogen in freshwater discharge, primarily from the Mississippi and Atchafalaya Rivers, spur phytoplankton blooms in the warm water over the continental shelf. *Id.* Excess phytoplankton not consumed by zooplankton predators sinks to the sea floor where they are decomposed by bacteria. *Id.* at 763. The chemical process of decomposition uses available dissolved oxygen at a faster rate than it is replenished at the sea surface,

the extensive shrimp trawl fishery in the Gulf of Mexico directly impacts many species of fish and invertebrates due to habitat destruction and bycatch mortality.[9]

This uncertainty is particularly troubling for commercial fisheries. While it is difficult to predict the impacts of an oil spill of this magnitude on the future of fisheries in the region, we can infer possible effects by investigating broader patterns. This study presents an analysis of the pre-spill spatial distribution of commercial fisheries catch and landed value in the Gulf of Mexico LME relative to the post-spill fisheries closure in an effort to evaluate potential economic losses.

II. METHODS

To understand the ecological and economic implications of fisheries on a global scale, the *Sea Around Us* Project[10] at the Fisheries Centre of the University of British Columbia developed and maintains global databases of spatially allocated fisheries data, including databases of catch[11] and corresponding landed value[12] used in this study. Commercial landings statistics, reported annually since 1950 to the United Nations Food and Agriculture Organization (FAO) by national fisheries management entities (for example, the U.S. National Marine Fisheries Service), include the taxonomic identity of the catch, the reporting year, the country reporting the catch, as well as the FAO statistical area from which the catch was taken.[13] These catch data were allocated to a

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creating a hostile, oxygen-depleted environment. *Id.* at 754. Stratification within the water column exacerbates this by preventing mixing with oxygen-rich surface water. *Id.*

9. *See* Laura Vidal & Daniel Pauly, *Integration of Subsystem Models as a Tool Toward Describing Feeding Interactions and Fisheries Impacts in a Large Marine Ecosystem, the Gulf of Mexico*, 47 OCEAN AND COASTAL MGMT. 709, 712 fig. 2, 722 (2007); *see also* R. J. David Wells, James H. Cowan Jr. & William Patterson III, *Habitat Use and the Effect of Shrimp Trawling on Fish and Invertebrate Communities Over the Northern Gulf of Mexico Continental Shelf*, 65 INT'L COUNCIL FOR THE EXPLORATION OF THE SEA J. OF MARINE SCI. 1610 (2008).

10. Daniel Pauly, *The* Sea Around Us *Project: Documenting and Communicating Global Fisheries Impacts on Marine Ecosystems*, 36(4) AMBIO: A J. OF THE HUMAN ENV'T 290 (2007).

11. Reg Watson, Adrian Kitchingman, Ahmed Gelchu & Daniel Pauly, *Mapping Global Fisheries: Sharpening Our Focus*, 5 FISH AND FISHERIES 168 (2004) (discussion of catch database designed and used by the *Sea Around Us* Project).

12. *See* U. Rashid Sumaila, A. Dale Marsden, Reg Watson & Daniel Pauly, *A Global Ex-vessel Fish Price Database: Construction and Applications*, 9 J. OF BIOECONOMICS 39 (2007) (discussion of the *Sea Around Us* Project's effort to attach landed values of fish to a catch database).

13. *See generally* FISHBASE, http://www.fishbase.org (last visited Mar. 21, 2011).

system of spatial cells measuring 0.5° latitude by 0.5° longitude[14] according to a rule-based procedure. Information regarding the biological distribution of the reported taxa (including depth and latitudinal limits, proximity to critical habitat, and primary productivity) as well as the fishing patterns and access agreements of the reporting country was used to restrict and prioritize those cells from which the catch was most likely to have originated. This process enables the production of maps illustrating the annual catch rate (tonnes per km^2) by taxonomic group and region (e.g., Exclusive Economic Zone (EEZ), LME, High Seas Area) from 1950 to 2005.

Ex-vessel price information[15] has been compiled according to taxa, year and country, and assigned to all landings records in the global catch database. To allow comparisons across countries, prices were converted to U.S. currency for all years using official currency exchange rates and converted to real values using consumer price index (CPI) data. Prices were then multiplied by spatially allocated landings data to facilitate the visualization of spatial and temporal trends in landed value.

For the purpose of this study, the catch and landed value databases were queried to investigate recent patterns in the Gulf of Mexico LME. For each of the 606 spatial cells within this LME, average annual taxon-specific total catch and landed value was computed for the period extending from 2000 to 2005. The location of the fisheries closure, as of July 22, 2010, in relation to georeferenced mean annual catch and landed value was mapped to provide clues regarding potential economic losses to commercial fisheries in the region (Figure 1). Spatial cells were proportionally allocated to six zones (i.e., the commercial fisheries closure within the U.S. EEZ, the remaining portion of the U.S. EEZ open to commercial fishing, the Mexican EEZ, the Cuban EEZ, and two High Seas Areas), and total catch and landed value statistics were computed for each. Additionally, the average annual catch and landed value of the five most valuable species in the U.S. EEZ during 2000-2005 (i.e., brown shrimp (*Farfantepenaeus aztecus*), white shrimp (*Litopenaeus setiferus*), blue crab (*Callinectes sapidus*), Gulf menhaden (*Brevoortia patronus*), and Eastern oyster (*Crassostrea virginica*)) was calculated for each zone (Table 1). Detailed data for each spatial cell used in this analysis are

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14. At this spatial scale more than 258,000 spatial cells are defined for the world as a whole, including approximately 180,000 spatial cells with at least some marine area. Watson et al, *supra* note 11, at 170.

15. Ex-vessel price information is the price that fishers receive when they sell their catch.

available on the *Sea Around Us* Project website.[16] Discrepancies between annual catch and landed value statistics reported here and those reported by national fisheries management entities likely result from over-allocation or under-allocation to spatial cells as well as differences in pricing methodologies.

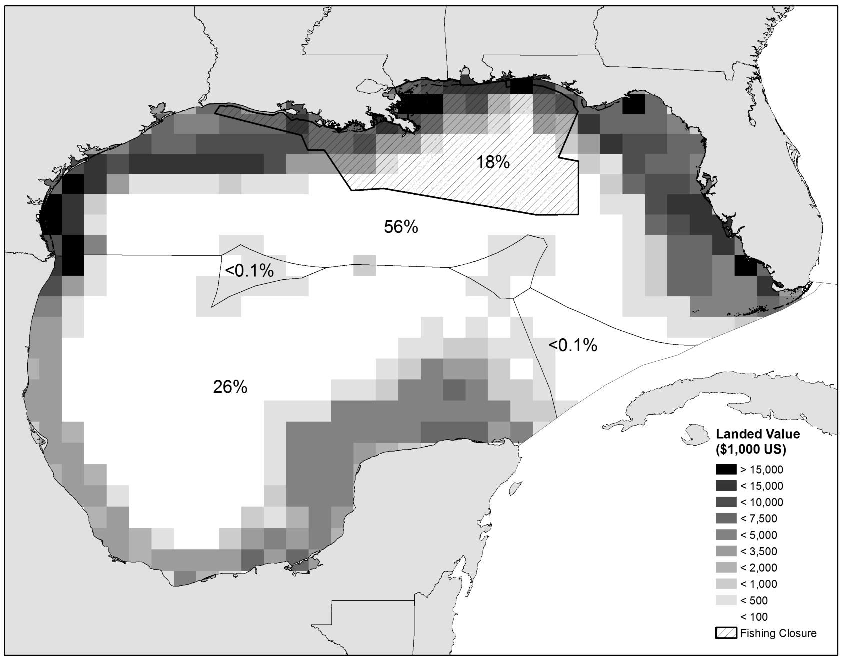

FIGURE 1. Spatial distribution of the mean (2000-2005) annual landed value of reported commercial fisheries catches in the Gulf of Mexico LME. The area closed to commercial fishing (including both federal and state within the U.S. EEZ as of July 22, 2010) accounts for approximately 18% of the total value of landings within the LME. The remainder of the U.S. EEZ still open to fishing accounts for 56%, while Mexican waters account for 26% of total landed value. Less than 0.1% of the annual landed value is derived from the two High Seas areas and Cuban waters.

III. RESULTS AND DISCUSSION

Over 100 species of fish, crustaceans, molluscs and other invertebrates, primarily inhabiting the highly productive continental shelf area, are commercially fished in the Gulf of Mexico. During 2000 to 2005, total annual reported commercial landings within the entire LME averaged 850,000 tonnes, generating approximately U.S. $1.38 billion in

16. *See* SEA AROUND US, http://www.seaaroundus.org (last visited Mar. 21, 2011).

annual landed value (Table 1). Commercial fisheries operating within the 200 nautical mile limit of the U.S. EEZ accounted for the majority of this catch and landed value (77% and 74%, respectively) followed by fisheries operating within Mexican waters (22% of total landings and 26% of total landed value) (Figure 1). The composition of the total annual catch within the LME was dominated by Gulf menhaden (52%), as well as Eastern oysters (13%), brown shrimp (5%), white shrimp (4%), and blue crab (4%). Due to high consumer demand and associated prices, landings of brown and white shrimp generated the greatest landed value (17% and 16% of the annual total within the LME, respectively), followed by blue crab (15%), Gulf menhaden (12%), and Eastern oysters (8%) (Table 1).

	Area	Catch (1,000 tonnes)						Landed Value ($1,000,000 US)					
Zone	**(1,000 km^2)**	**Total**	**BS**	**WS**	**BC**	**GM**	**EO**	**Total**	**BS**	**WS**	**BC**	**GM**	**EO**
US-open	550	513	29	25	20	343	51	767	175	152	134	126	47
US-closed	167	147	10	10	6	93	16	247	57	64	39	34	15
Mexico	741	191	1	1	6	9	45	358	5	3	29	3	45
Cuba	57	0	0	0	0	0	0	1	0	0	0	0	0
High Seas	36	1	0	0	0	0	0	1	0	0	0	0	0
Total LME	1,550	852	40	35	32	445	111	1,376	237	219	202	163	106

BS = Brown Shrimp
WS = White Shrimp
BC = Blue Crab
GM = Gulf Menhaden
EO = Eastern Oyster

TABLE 1. Average (2000-2005) annual commercial fisheries catch and landed value by zone within the Gulf of Mexico LME, including total and taxa-specific estimates, (BS = Brown Shrimp, WS = White Shrimp, BC = Blue Crab, GM = Gulf Menhaden, EC = Eastern Oyster).

Twelve days following the explosion of the Deepwater Horizon oil rig, the U.S. National Oceanographic and Atmospheric Administration (NOAA), as well as the States of Florida, Alabama, Mississippi, and Louisiana, began to declare portions of federal and state waters closed to commercial fishing in an effort to protect seafood safety and ensure consumer confidence.[17] As of July 22, 2010, over 10% of the total surface area of the Gulf of Mexico LME and approximately 24% of the U.S. Gulf EEZ and territorial waters was closed to commercial fishing operations.[18] During 2000 to 2005, habitats located within the boundaries of the closed area yielded commercial catches comprising approximately 17% of the total annual tonnage and 18% of the total annual value of reported landings within the Gulf of Mexico LME (Figure 1). The visible extent of the oil spill and resultant closures indicates that consequences will be greatest for U.S. fisheries. On average, 22% of the annual U.S. commercial catch in the Gulf and 24% of the corresponding annual landed value was derived from the area now closed to fishing, representing a potential, minimum annual loss of $247 million. While the majority of U.S. catch within the boundaries of the fisheries closure was composed of Gulf menhaden, landings of brown and white shrimp were most valuable (12% of the annual U.S. total in the Gulf), followed by blue crabs (4%), Gulf menhaden (3%), and Eastern oysters (1%) (Table 1). Economically important invertebrate fisheries may be most at risk due to the fact that relatively sessile, benthic organisms are likely to suffer higher rates of mortality as a result of the toxic effects of the oil spill compared to more mobile fish species.[19]

This study does not pretend to address the full range of biological and economic consequences of the Deepwater Horizon oil spill on fisheries in the Gulf of Mexico. The boundaries of the closed area have been largely based on the visible extent of oil slicks on the sea surface. Therefore, this study assumes that the economic impact of the oil spill will be limited by the spatial extent of the closed area. As foreign fishing vessels have been prohibited from operating within the U.S. EEZ since 1991, fisheries closures are also assumed only to impact U.S. fisheries operating within the closed area. However, the Gulf of Mexico is a dynamic system, and oil and dispersant has not been confined to the sea surface.[20] Most marine organisms, including those mentioned here,

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17. U.S. Nat'l Marine Fisheries Serv., *Information About the Federal Fishing Closure in Oil-Affected Portions of the Gulf of Mexico*, SOUTHEAST FISHERY BULL. July 2010, *available at* http://sero.nmfs.noaa.gov/sf/deepwater_horizon/FB_Closure_ info_Eng.pdf.

18. *Deepwater Horizon/BP Oil Spill Information,* NOAA FISHERIES SERVICE, *http*://sero.nmfs.noaa.gov/deepwater_horizon_oil_spill.htm (last modified May 20, 2011).

19. John M. Teal & Robert W. Howarth, *Oil Spill Studies: A Review of Ecological Effects*, 8 ENVTL. MGMT. 27, 31 (1984).

20. A continuous subsurface plume of oil exists over 35 km in length between 1,000 and 1,200 m depth as well as a more diffuse plume between 50 and 500 m depth. Richard Camilli et al., *Tracking hydrocarbon plume transport and biodegradation at* Deepwater Horizon, 10 SCI. 201, 201, 202 (2010).

exhibit daily and seasonal, small and large-scale migrations both laterally and vertically. Marine organisms may be directly impacted by physical contact with contaminants as well as indirectly affected via the fouling of important nursery and spawning habitats. Therefore, it is unlikely that the effects of the spill will be restricted spatially to closed area boundaries and temporally to the duration of fisheries closures. The possible future loss to U.S. commercial fisheries calculated in this study is suggested as a minimum estimate, and provides a preliminary perspective given pre-oil spill trends. Additionally, this analysis includes only reported commercial landings; illegal, unreported, and unregulated (IUU) fishing as well as lucrative recreational fishing are not considered. Despite limitations associated with the spatial resolution of the databases, this study indicates that the oil spill is clearly impacting an area of crucial economic importance within the Gulf of Mexico. Continued analyses, such as those presented here, should shed light on an uncertain future.