The ideas in this paper were presented at several workshops sponsored in the wake of the Deepwater Horizon oil spill that were convened in 2010. The concept of a Synthesis Center also was the focus of a grant submitted to FIO/BP in 2010 (but which was not funded). The following text was written and publicly distributed in November 2010 at a conference hosted by the Mote Marine Laboratory.

Beyond Deepwater Horizon:
Ecological Synthesis and Integration in a Changing Environment

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The world changes, and in so doing, ecosystems and the services they provide also change. Some drivers of ecological change are natural; others are anthropogenic (i.e., the result of human pressures brought on by the increasing use of coastal resources by human society). Despite recent technological advances and ground-breaking research, we still lack the basic knowledge needed to understand and predict the response of most ecosystems to change. The Deepwater Horizon oil spill in the Gulf of Mexico highlights this information gap. The Gulf of Mexico ecosystem provides valuable services, which shape not only the ecology, but also the aesthetics, culture and economics of the region. Oil from DWH may no longer be flowing, but the oil that was released, along with associated attempts to deal with the spill (e.g., the release of dispersants) continues to affect the ecology and socio-economics of the Gulf. Unfortunately, the DWH accident is not unique. Many natural and anthropogenic disturbances, in addition to oil spill(s), potentially impinge on the Gulf, including climate change, sea-level rise, hurricanes, eutrophication, anoxia, disease, invasive species and overfishing. No doubt, the future holds even more (but as of today, unknown) challenges. Here, we highlight several examples of ecological information gaps highlighted by the DWH oil spill but which are generic to a range of impacts (below, and Boxes 1-5). We then lay out a proposal for how to rectify these shortcomings using a combination of innovative approaches that will enhance scientific understanding of the Gulf's ecosystems.

Box 1. *Sea Turtles: a need for demographic data.* Five species of sea turtles inhabit the Gulf of Mexico, all of which are endangered or threatened, and all of which were important consumers before their populations were over-exploited by humans (Jackson et al. 2001). The entire breeding and nesting ranges and most of the foraging range of the Kemp's ridley (*Lepidochelys kempii*) are in the Gulf of Mexico., yet we lack the necessary data to determine the effects of the DWH oil spill on sea turtles, to develop effective management plans to mitigate these effects, or to devise effective approaches in response to another unplanned event. For example, sea turtle assessments in the Gulf have relied heavily on counts of nests deposited in beaches each year with little or no data on abundance of sea turtle stages in the water (National Research Council, 2010) or demographic parameters (e.g., growth, survival, reproduction). Demographic rates are required to understand the causes of trends in sea turtle populations, to predict future trends, and to design management plans. This goal is obtainable; these values have been estimated for sea turtle populations outside of US waters (e.g., Kendall and Bjorkland 2001; Bjorndal et al. 2003, 2005).

Assessment: or why inferring effects is difficult. One approach to understanding responses of

Box 2. *Oyster reefs: scaling from ecotoxicology to population dynamics*. Oyster reefs contain considerable biodiversity, provide critical habitat for juvenile fish, invertebrates, and birds, support economically important fisheries, filter huge volumes of water, and provide significant shoreline protection (Peterson 2003, Coen et al. 2007). Oyster reefs have declined by 85 – 90% globally, and are thought to be the most endangered marine habitat in the world (Beck et al. 2009). Over 75% of remaining functional oyster habitat is on U.S. shores, with the majority of that (>70%) located in the Gulf of Mexico. Oysters are particularly vulnerable to oiling because they are filter feeders, sessile, and lack efficient enzymes for metabolizing and detoxifying PAH compounds and metabolites (Law et al. 2002). In the Gulf of Mexico, other stressors (e.g., reduced freshwater flow; disease) will likely interact with effects of dispersed oil. Although challenging, there are approaches that can help understand the response of oysters to these stressors. For example, dynamic energy budget (DEB) models (Kooijman 2000) are powerful tools to extrapolate known effects of contaminants on an animal's physiology to its growth and reproduction (Muller et al. 2010a,b). By coupling DEBs with population dynamics and ocean circulation models (which influence larval dispersal) we can successfully extrapolate ecotoxicological studies with the ecological endpoints of interest to managers (e.g., oyster bed production).

systems to a perturbation is reactive: wait for the perturbation and then attempt to assess "what?" and "why?". This approach is exemplified by most of the research supported by "rapid" funds from BP and various federal agencies (e.g., NOAA and NSF). However, ecological systems are notoriously variable in space and time, changing stochastically and in response to natural phenomena as well as those induced by humans. As a result, assigning causation to an observed change is problematic: e.g., was an observed reduction in the density of grouper due to a deleterious effect of an oil spill or was it a response to other factors coincident in time and space with the spill? "Rapids" provide valuable data "today", but cannot fill in historical gaps on their own. As a result, "rapids" often fall short of their goal of determining "effects".

An alternative is proactive: synthesize existing data using innovative quantitative and conceptual tools, identify information gaps, design research to fill those gaps, and develop approaches that facilitate the quantification of future change. In the context of the Deepwater Horizon oil spill, a proactive approach would have facilitated an understanding of the DWH spill, but if adopted now, it can advance our understanding of *future* changes to the Gulf of Mexico ecosystem.

A successful proactive approach must overcome the challenge of isolating a "signal" (e.g., the effect of the oil spill) from the "noise" induced by other factors. Two general options exist: (1) the development of mechanistic models that take known or well-estimated impacts on other parameters (e.g., from toxicity studies or mortality estimates) and extrapolate them to endpoints of direct interest (e.g., population density and dynamics) and (2) field assessments of the variables of interest (e.g., density of an endangered species, or fisheries yield) using rigorous time series approaches (Box 1). The former requires synthetic approaches that link theory (e.g., from toxicology and population dynamics) with data (e.g., LC50s, feeding patterns, reproductive allocation) and integrates them across levels of biological organization (e.g., from cells to ecosystems): Box 2. The latter requires long-term data from multiple sites that can be used to develop predictive models of expected dynamics in the absence of the impact of interest (i.e., incorporating other drivers): Box 3. The challenge with both approaches is that they are data intensive and require synthesis. The former benefits from, and the latter requires, substantial pre-impact data, which are lacking from much of the Gulf. These data must include the myriad species involved in ecosystem processes (Box 4) and must also include the interactions between the ecological and social systems that impinge on the Gulf (Box 5).

Shortcomings. The above summaries point out several major shortcomings of existing research:

1. Lack of long-term coordinated study (even the best scientific studies are subject to limited spatial and temporal coverage).
2. Lack of synthesis and integration (most research is focused on single investigator-led studies, limited in scope and lacking in disciplinary integration).
3. Limited use of existing data (tremendous datasets exist, but are not readily accessible to the scientific community).
4. Limited knowledge about the biological systems that exist in the Gulf, and how they interact with the social systems.
5. Shifting information needs and topics strain the expertise of established Gulf coast scientists (scientific inquiry must be nimble, flexible and adaptive).

In response to these needs, we suggest a three-tiered and complementary approach is necessary to facilitate future understanding of the Gulf of Mexico ecosystems and their responses to environmental change and management. We build on the expertise of faculty and scientists at Gulf coast institutions and those from outside the region who can provide additional insight and collaboration. We model these suggestions on innovative national approaches developed elsewhere, drawing from their strengths, but adapting them to the specific needs of the Gulf.

REGIONAL LONG-TERM ECOLOGICAL RESEARCH NETWORK (R-LTERN). The National Science Foundation's LTER program supports long-term study of critical ecosystems and facilitates cross-system comparisons. The NSF LTER program includes 26 diverse sites (e.g., placed in a coral reef, the south pole, a temperate prairie, a tropical forest, an urban city) spread across the globe. Only one of these (the Florida Coastal Everglades LTER) is in close proximity to the the Gulf of Mexico. We call for a Regional LTER Network, modeled on the NSF program, consisting of 3-15 sites distributed throughout the Gulf (depending on funding). Each site would: 1) generate long-term ecological and environmental data desperately needed to assess changes in the Gulf ecosystem; 2) provide infrastructure for additional (externally funded) process-oriented field studies; 3) facilitate collaborative field research and student training. With such a network, the Gulf

BOX 3. *Seagrasses: a need for long-term monitoring of an essential habitat.* Seagrasses are one of the most productive ecosystems in the world (Hemminga and Duarte 2000), and provide refuge and foraging habitat for myriad of species in the Gulf of Mexico (including approximately 85% of the marine species supporting recreational and commercial fisheries in Florida). Seagrass meadows are important components of the marine carbon cycle (Duarte 2010) and much of their primary production is ultimately sequestered in sediments or exported to neighboring systems (Duarte et al. 2005). Seagrasses also improve water quality (by reducing the particle loads removing dissolved nutrients), stabilize sediments, and protect coastlines (by dissipating wave energy); thus, seagrasses provide tremendous ecological and economic value (Orth et al. 2006). Seagrasses in the Gulf are threatened by the Deepwater Horizon disaster but also are threatened by anthropogenic nutrient loading (Mattson et al. 2007) and other impacts. Any rigorous attempt to identify the effects of some perturbation (e.g., an oilspill) must distinguish those effects from the effects of other processes that also affect water quality and/or seagrasses. This requires well coordinated and integrated sampling programs (see Schmitt & Osenberg 1996). Such programs will provide a basis for development and implementation of monitoring that allows scientists and resource managers to detect and address undesirable changes in the ecological health and integrity of estuarine and nearshore coastal habitats and their associated fish and wildlife in the long-term and at the ecosystem level.

Box 4. *Biodiversity: what we don't know.* Marine resource management is undergoing a broad shift from focusing on exploited species (e.g., oysters) to ecosystem-based management, with a focus on marine biodiversity. A growing body of research demonstrates that the maintenance of marine biodiversity may be key for sustained ecosystem health and resilience against global change, suggesting that managing for marine biodiversity may help resolve conflicting management objectives (Naeem et al 2009). Thus, biodiversity might serve as a master variable in evaluating both the health of marine ecosystems and the success of management efforts (McLeod & Leslie 2009). Yet there is no rigorous, standardized, coordinated approach to monitoring marine biodiversity in a way that produces a coherent picture of status and trends. In the Gulf, we do not even know the biodiversity of most habitats. This is especially true for deepwater environments and for small organisms (invertebrates, protists, and microbes), which are not in the public eye, but are critical players in the dynamics of ecological systems. Recognizing this need, the National Oceanographic Partnership Program has recently organized a workshop on "Attaining an operational marine biodiversity observation network", sponsored by NOAA, NASA, MMC, ONR, NSF, BOEMRE (formerly MMS), and the Smithsonian. They call for a major increase in our national capacity to sample, process, and analyze marine biodiversity, at both the national and regional (e.g., Gulf) scales.

could become an exemplar for the regional study of large complex ecosystems that are jointly driven by natural and anthropogenic factors. The R-LTER would complement the developing network of data streams for the physical environment in the Gulf (e.g., through the various ocean observing systems: Gulf of Mexico Coastal Ocean Observing System, FL COOS, SECOOS) and existing long-term biological monitoring programs such as the Florida FWC's fisheries independent monitoring (FIM) of exploited fish populations Both the physical and biological data are critical to understanding the Gulf ecosystem, its dynamics, and the role played by various environmental phenomena.

CENTER FOR ECOLOGICAL SYNTHESIS AND APPLICATION. A Center for Ecological Synthesis and Application, emphasizing the compilation, synthesis and integration of ecological and environmental data and theory, will: 1) advance understanding of the ecosystems of Florida and the broader Gulf of Mexico/Caribbean region; 2) facilitate the management and conservation of biological resources and resolve pressing environmental issues; 3) invigorate collaborative research within the Gulf region; and 4) enhance the role of the Gulf universities in the development of policy central to management of the Gulf ecosystems.

Resolving environmental problems requires synthesis of data, quantitative modeling (e.g., involving mathematics, statistics, and computational informatics), and application that spans disciplines (including biology, chemistry, sociology, economics, engineering). Teams will be highly integrative and transcend the boundaries and ecological and social sciences where appropriate, e.g. in the study of ecological-social dynamics of fisheries restoration (Box 5). Because problems change, the expertise required to solve these issues also should be dynamic – rather than create a Center with defined personnel, we need a Center with dynamic collaborations that respond adaptively. The Center should create and support interdisciplinary, collaborative research teams, consisting of faculty mentors, post-doctoral fellows, graduate students and undergraduates. These teams would use the data generated by the R-LTERN, as well as existing data provided by federal and state monitoring programs (e.g. for fisheries) and by scientists throughout the world. The intellectual heart of the program would be the interdisciplinary post-doctoral fellows, cross-mentored by faculty from different institutions. Research teams would have a specific and defined set of goals with an approximate 2-4 year timeframe. For example, 2-4 groups, with staggered initiation dates, would address environmental problems defined in consultation with State and regional environmental institutions and agencies and an international advisory board.

This Center should be modeled on the transformative success of the National Center of Ecological Analysis and Synthesis (funded by NSF and the State of California). By partnering with NCEAS' and their EcoInformatics program the Center could immediately build on their years of experience in interdisciplinary working groups, post-doctoral mentorship and complex database compilation, management and distribution. Through NCEAS we also would gain immediate connections with DataONE (Data Observation Network for Earth), which is a new NSF initiative that currently has no Florida (or gulf coast) participants. DataONE is poised to become *the* central environmental distributed data network. This partnership would therefore jumpstart our Center and allow us to focus on synthesis (e.g., by avoiding the need to reinvent ecoinformatics and the required cyberstructure), and propel the Center into this emerging research arena. By also partnering with the Northern Gulf Institute's Ecosystem Data Assembly Center, the Center would enhance our ability to distribute data and facilitate collaborations with another gulf coast institution.

BIODIVERSITY CENTER. The diversity of life of Earth – millions of species, with over 30,000 already documented in the Gulf of Mexico (Felder et al 2009) – makes monitoring, modeling, and understanding ecosystems challenging. Great species diversity is the basis of most ecosystems, food webs, and a broad range of species have direct relevance to humans. We know that diversity is essential for ecosystem function, but have limited ability to identify, let alone monitor the vast majority of species. As species abundances and ranges change, novel species (including non-indigenous ones like lionfish) invade while others disappear, ecosystems alter with untold consequences.

Recognizing the importance of biodiversity for understanding the biosphere, together with emerging methods for large-scale assessments and monitoring of biodiversity, is leading to several large-scale synthetic efforts. Our ability to identify and track biodiversity has been increasing rapidly with conceptual advances in taxonomy, molecular biology, informatics, and ocean-technology, making synthetic approaches to biodiversity possible and timely. NSF is considering the establishment of a national center for biodiversity, modeled after the transformative National Center for Ecological Analysis & Synthesis (NCEAS). An interagency panel is working toward establishing a national Marine Biodiversity Observation program (see Box 4). Proactively, the Florida Museum of Natural at UF History has established a Biodiversity Center this year, with a mission to pursue large-scale, synthetic efforts on biodiversity. An initial objective of the UF center will be to develop Digital Florida, a portal to biodiversity information in the state, to bring together information on species occurring in the state, including images, distributional data, and relevant biological information, and allow users to query any area to understand what is known about species occurrences there. This newly

Box 5. *Restoration of exploited biological resources: understanding linked ecological-social systems is crucial.* Commercial and recreational fisheries in the Gulf of Mexico generate billions of dollars in economic benefits and are of great social and cultural importance. Direct effects of oil pollution on these resources may be severe (Mathews et al. 1991; Thorne & Thomas 2008). Area closures and changes in demand for seafood and for recreational fishing following the DWH oil spill are likely to confound, and may even outweigh direct effects of oil pollution on such populations. Restoration and management therefore require an integrative, interdisciplinary approach to understanding the ecological-social systems involved (Collins 1998, Ostrom 2009). As in the case of purely ecological aspects, a long-term perspective is crucial to understanding the dynamics of coupled ecological-social systems. In addition, close two-way interaction with management stakeholders (resources users, management agencies, NGOs) is likely to facilitate understanding and lead to better restoration plans and outcomes (Lorenzen 2008; Lorenzen et al. 2010).

established Biodiversity Center, together with emerging national initiatives and programs and other regional efforts, would provide the necessary power to handle essential species-level information for ecosystem studies and monitoring.

These three initiatives form a conceptual triad, with strong integration and synthesis among them. Together they will facilitate a deeper understanding of the Gulf of Mexico ecosystems and lead to more informed management of the marine resources vital to the long-term sustainability of the communities that rely on the Gulf.

Beck et al. 2009. *Shellfish Reefs at Risk: A Global Analysis of Problems and Solutions*. The Nature Conservancy, Arlington VA. 52 pp.

Bjorndal et al 2003. Marine Ecology Progress Series 252:273-281.

Bjorndal et al 2005. Ecological Applications 15:304-314.

Coen et al 2007. Marine Ecology-Progress Series 341:303-307

Collins et al. 1998. Mar. Poll. Bull. 36:211-221.

Duarte et al. 2005. Biogeosciences, 2: 1–8.

Hemminga & Duarte 2000. Seagrass Ecology. Cambridge Univ. Press, Cambridge.

Jackson et al. 2001. Science 293:629-638.

Kendall and Bjorkland. 2001. *Biometrics* 57:1113-1122.

Kooijman. 2000. Dynamic energy and mass budgets in biological systems. Cambridge University Press.

Law et al 2002. Journal of Environmental Monitoring 4:383-388

Lorenzen 2008. Reviews in Fish. Sci. 16:10-23

Lorenzen et al 2010. Bull Mar Sci 86:169-177.

Mathews et al. 1991. Mar Poll Bull 27: 251-271.

Mattson et al 2007. The Florida Big Bend. pp. 170–205. In: L. Handley, D. Altsman and R. DeMay (eds.), Seagrass status and trends in the northern Gulf of Mexico: 1940–2002: U.S. Geological Survey Scientific Investigations Report 2006–5287 and U.S. Environmental Protection Agency 855–R–04–003, 267 pp. [available online: http://pubs.usgs.gov/sir/2006/5287/]

McLeod & Leslie (editors) 2009. Ecosystem-Based Management for the Oceans. Island Press, Washington, DC.

Muller et al. 2010 Ecotoxicology, DOI 10.1007/s10646-009-0385-3.

Naeem et al (editors) 2009. Biodiversity, Ecosystem Functioning, and Human Wellbeing: An Ecological and Economic Perspective. Oxford University Press.

National Research Council. 2010. Assessment of sea turtle status and trends: integrating demography and abundance. The National Academies Press, Washington, DC.

Orth et al. 2006. Bioscience 56: 987-996.

Ostrom 2009. Science 325:419-422.

Peterson 2003. _Marine Ecology-Progress Series 264:249-264

Schmitt & Osenberg1996. *Detecting ecological impacts: Concepts and applications in coastal habitats*. Academic Press, San Diego.

Thorne & Thomas 2008. ICEAS J Mar Sci 65:44-50