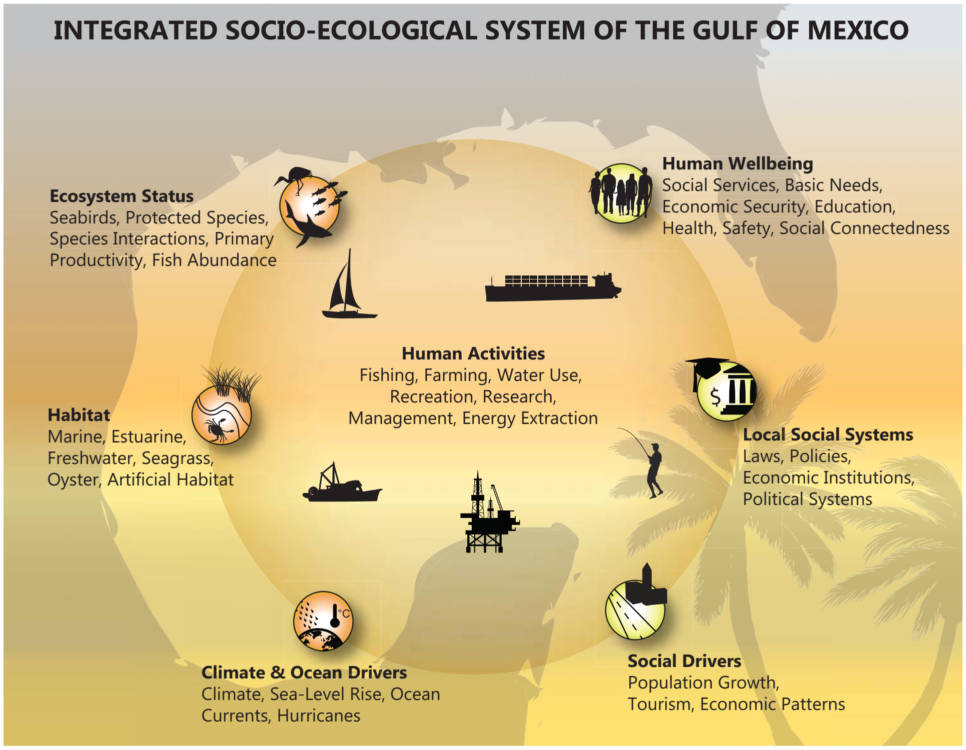
NOAA Technical Memorandum NMFS-SEFSC-706

2017 ECOSYSTEM STATUS REPORT UPDATE FOR THE GULF OF MEXICO

Mandy Karnauskas, Christopher R. Kelble, Seann Regan, Charline Quenée, Rebecca Allee, Michael Jepson, Amy Freitag, J. Kevin Craig, Cristina Carollo, Leticia Barbero, Neda Trifonova, David Hanisko, and Glenn Zapfe



U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Southeast Fisheries Science Center
75 Virginia Beach Drive
Miami, Florida 33149

March 2017

NOAA Technical Memorandum NMFS-SEFSC-706

2017 ECOSYSTEM STATUS REPORT UPDATE FOR THE GULF OF MEXICO

Mandy Karnauskas, Christopher R. Kelble, Seann Regan, Charline Quenee, Rebecca Allee, Michael Jepson, Amy Freitag, J. Kevin Craig, Cristina Carollo, Leticia Barbero, Neda Trifonova, David Hanisko, and Glenn Zapfe

National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Southeast Fisheries Science Center
75 Virginia Beach Drive
Miami, Florida 33149

U.S. DEPARTMENT OF COMMERCE
Wilbur L. Ross, Jr., Secretary

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
Benjamin P. Friedman, Under Secretary for Oceans and Atmosphere (Acting)

NATIONAL MARINE FISHERIES SERVICE
Samuel D. Rauch, III, Assistant Administrator for Fisheries (Acting)

March 2017

NOTICE

This report should be cited as follows:

Karnauskas, M., Kelble, C. R., Regan, S., Quenée, C., Allee, R., Jepson, M., Freitag, A., Craig, J. K., Carollo, C., Barbero, L., Trifonova, N., Hanisko, D., Zapfe, G. 2017. 2017 Ecosystem status report update for the Gulf of Mexico. NOAA Technical Memorandum NMFS-SEFSC-706, 51 p.

Authors and affiliations:

Mandy Karnauskas, National Marine Fisheries Service, Southeast Fisheries Science Center, 75 Virginia Beach Drive, Miami, FL 33149

J. Kevin Craig, National Marine Fisheries Service, Southeast Fisheries Science Center, Beaufort Laboratory, 101 Pivers Island Road, Beaufort, NC 28516

David Hanisko, Glenn Zapfe, National Marine Fisheries Service, Southeast Fisheries Science Center, Pascagoula Laboratory, 3209 Frederic Street, Pascagoula, MS 39567

Michael Jepson, National Marine Fisheries Service, Southeast Regional Office, 263 13th Avenue South, St. Petersburg, FL 33701

Christopher R. Kelble, Office of Oceanic and Atmospheric Research, Atlantic Oceanographic and Meteorological Laboratory, 4301 Rickenbacker Causeway, Miami, FL 33149

Rebecca Allee, National Ocean Service, Office for Coastal Management – Gulf Region, 1021 Balch Boulevard, Suite 1003, Stennis Space Center, MS 39529

Charline Quenée, Cristina Carollo, Leticia Barbero, Neda Trifonova, Cooperative Institute for Marine and Atmospheric Studies, Rosenstiel School for Marine and Atmospheric Science, University of Miami, 4600 Rickenbacker Causeway, Miami FL 33149

Seann Regan, National Ocean Service, National Centers for Coastal Ocean Science, Hollings Marine Lab, 331 Ft. Johnson Road, Charleston, SC 29412

Amy Freitag, National Ocean Service, National Centers for Coastal Ocean Science Cooperative Oxford Lab, 904 South Morris Street, Oxford, MD 21654

Questions, comments, or feedback on this report? Please contact:

Mandy Karnauskas
Mandy.Karnauskas@noaa.gov
NOAA Fisheries
75 Virginia Beach Drive
Miami, Florida 33149

Table of Contents

1. HIGHLIGHTS

- The Atlantic Multidecadal Oscillation, which was consistently on an increasing trend from the 1980s to 2010, has begun to slightly decline in recent years but is still in its positive phase.
- Several important ecosystem pressures have experienced changes in rates over recent years relative to long-term trends. Sea surface temperature and sea level rise, which have consistently increased over the past three decades, are now increasing at even faster rates in some areas. Ocean acidification, the result of increasing atmospheric CO_2, has also increased over time. Hypoxia has recently become more severe off the coasts of Texas, but less severe in waters off the Louisiana coast.
- Areal coverage of natural habitats, such as seagrasses and wetlands, are generally on the decline in the region. On the contrary, numbers of artificial habitats, such as artificial reefs and oil platforms, have generally increased over time.
- Primary productivity measures and zooplankton biovolume estimates are highly variable, but generally stable over time. Primary productivity has increased slightly in recent years relative to the long-term average.
- Mean trophic level of the commercial catch has remained stable in recent years. Nearly all fish species of primary or secondary economic importance are at biomass levels at or above the mean biomass over the last three decades. The proportion of stocks undergoing overfishing is at an all-time low.
- Total fish and invertebrate commercial landings and revenues, which were generally declining or stable in past decades, have increased in recent years. Employment in the ocean economy and ocean-related GDP have also increased during this period, and have become more stable from year to year. Recreational fishing effort has also recently increased substantially after having decreased from 1980 to 2010.
- The conversion of other land cover types into developed land has continued across the region. However, this process has progressed at a much faster rate in urban centers such as Houston, Texas and Tampa, Florida.
- Indicators of human dimensions throughout the Gulf counties parallel wider trends that show an increase in urbanization and migration to urban areas. External shocks to the system, such as Hurricane Katrina, show how populations in low-lying areas may be more susceptible and less resilient to environmental change. Some of these same areas also show a higher rate of fishing engagement and reliance.

2. INTRODUCTION

With the aim of supporting Ecosystem-Based Management, the Gulf of Mexico NOAA Integrated Ecosystem Assessment Program seeks to provide scientific knowledge of the Gulf of Mexico integrated ecosystem, and transfer that knowledge to scientists and managers. The purpose of this report is to provide a broad-level overview of the current state of the Gulf of Mexico (GoM), with respect to recent and historical trends. Management of the GoM Large Marine Ecosystem is a challenging task, not only due to the wide range of anthropogenic impacts affecting the ecosystem, but also because of the range of services extracted from the ecosystem and the diverse user groups with numerous and sometimes conflicting objectives. Monitoring the ecosystem state is accomplished through the development of indicators, which are specific, well-defined and measurable variables that have been proven to reflect the status of some component of the ecosystem. A suite of indicators was developed to represent key components of the GoM, and are presented in this report. To aid in the selection of appropriate indicators, a conceptual modeling framework is used to identify focal ecosystem components. The conceptual framework, as well as other statistical considerations and criteria used to select indicators presented in this report, are described below. This is the first Update Report for the Gulf of Mexico, and builds on the original Ecosystem Status Report for the Gulf of Mexico published in 2013 [1]. The Ecosystem Status Reports are compiled by NOAA's Gulf of Mexico Integrated Ecosystem Assessment Program, in collaboration with academic partners, conservation organizations, and other government and state agencies.

2.1 Indicator selection

The original 2013 Ecosystem Status Report for the Gulf of Mexico included over 100 indicators representing various physical forces, ecosystem pressures, biological states, ecosystem impacts, and community responses in the region. For the 2017 Update Report, we carried out steps to refine the original list into a more robust and easily interpretable suite of indicators. Firstly, we engaged in informal feedback requests with regional managers and users of the report, with an eye toward identifying deficiencies and understanding which indicators had most direct linkages to management. Secondly, we took into account data accessibility and reliability issues, preferentially developing indicators based on long-standing data collection programs such that they can be routinely updated in future reports. Thirdly, we took into consideration statistical issues, such as redundancy and sensitivity. A multivariate analysis of the indicator suite from the 2013 report revealed that a large number of indicators changed in response to what was hypothesized to be a climate-driven ecosystem shift [2]. The statistical analysis showed that many indicators were immediately responsive to this shift, and were thus sometimes highly correlated; in these cases, a single indicator can then be representative of a wide range of processes. Finally, we reviewed the existing indicators for other common selection criteria (e.g., [3]), particularly regarding: i) a strong conceptual basis, ii) representation of the appropriate spatial and temporal scales, iii) track records of use in other regions, and iv) direct linkages to important societal dimensions. With respect to this latter attribute, it was recognized that the original Status Report lacked robust representation of human dimensions ecosystem components, and this update contains a much more focused representation of this sector. In sum, the indicators reported within this document were selected by carefully balancing considerations regarding management linkages, data availability, statistical robustness, and representation in spatial, temporal, and societal dimensions.

2.2 Notes on interpreting time series figures

Time series data are plotted in a standardized format for ease of interpretation (e.g., Fig. 2.1). The x-axis represents the temporal dimension, which may be monthly, yearly, or irregular time steps, and the y-axis represents the indicator value in units specified in the axis label. The dashed horizontal line represents the mean indicator value across the entire time series, and the solid horizontal lines denote the mean plus or minus one standard deviation. Red shaded areas and green shaded areas show years for which the indicator value is below or above one standard deviation from the mean, respectively. The blue vertical shaded box highlights the last five years of indicator values, over which additional metrics are calculated. Black circles to the right of each figure indicate whether the indicator values over the last five years are greater (plus sign), less than (minus sign), or within (solid circle) one standard deviation from the mean of the overall time series. Arrows to the right of each figure indicate whether the least squares linear fit through the last five years of data produces a positive or negative slope that is greater than one standard deviation (upward or downward arrows respectively), or less than one standard deviation (left-right arrow). Multi-panel plots are used to show trends in the same indicator, calculated for different species or over different spatial domains.

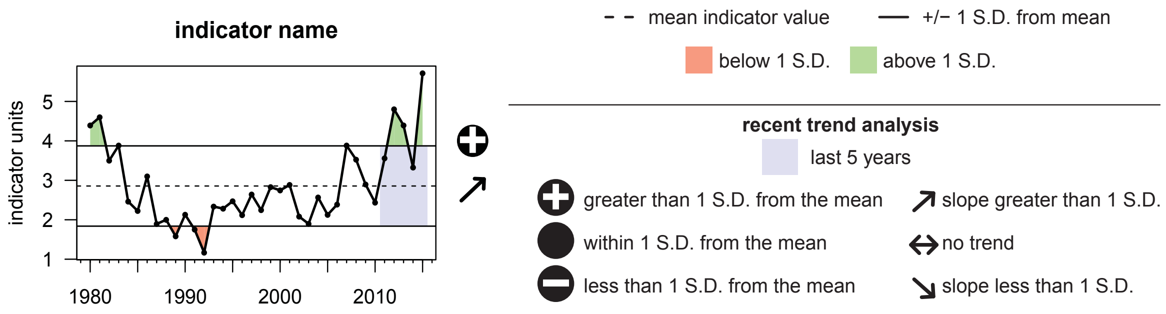


Figure 2.1. Example time series plot, showing an indicator plotted with its mean and standard deviation, and trend analysis for the most recent 5 years of data. See text for more detailed description of specific calculations.

3. CONCEPTUAL MODELS

In selecting indicators for the purpose of ecosystem monitoring, conceptualizing the ecosystem and its focal components, drivers, pressures, states, services, and responses is crucial. The Gulf of Mexico Integrated Ecosystem Assessment (IEA) team has undertaken several conceptual modeling efforts to elicit subject matter expert opinion and engage stakeholders in conceptualizing the integrated systems of the GoM, in order to develop indicators for this report. The team utilizes a holistic approach for conceptualizing the integrated socio-ecological system in the GoM by incorporating metrics from all areas of the Driver-Pressure-State-Ecosystem Service-Response (EBM-DPSER) framework [4].

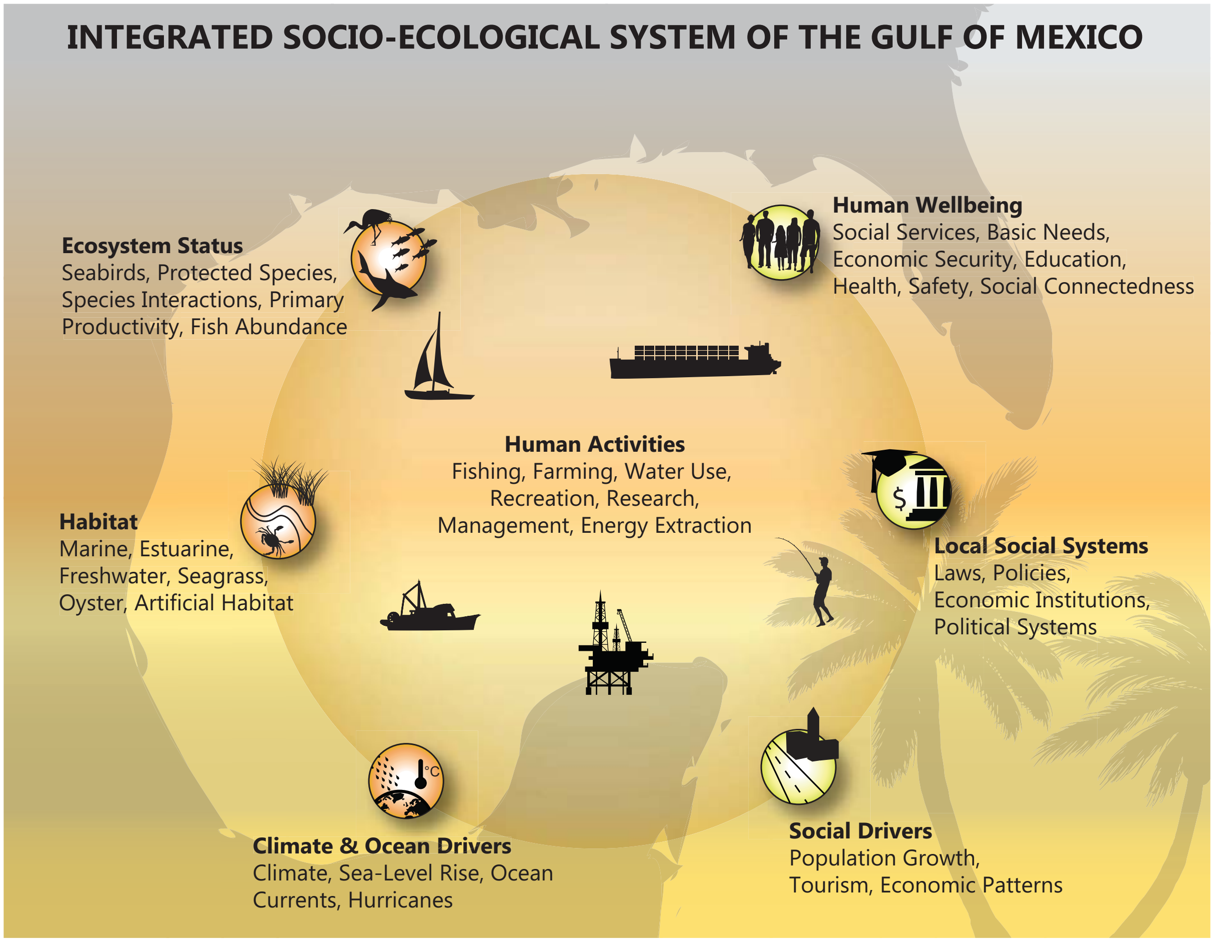


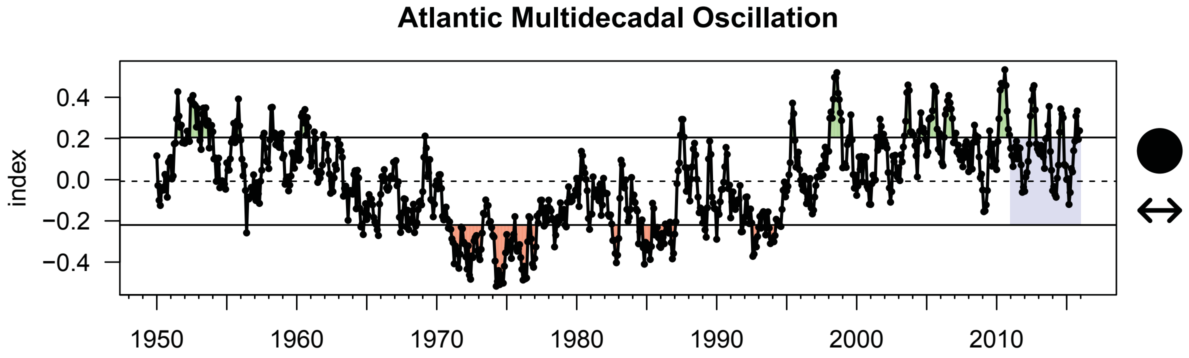
Figure 3.1. The socio-ecological conceptual framework used to guide indicator development for the Gulf of Mexico

Conceptual modeling efforts with the Gulf of Mexico IEA team have included in-person efforts to support group decision-making, web-based platforms that allow for real time collaborative thinking, and computer based systems that support Fuzzy-logic Cognitive Mapping and allow for the testing of statistical significance of connections in the various systems and subsystems. These efforts have resulted in a series of conceptual models pertaining to various sectors of the ecosystem and the connections to human processes. One overarching result from this work is the integrated Socioecological conceptual framework used to guide indicator development for the GoM (Fig. 3.1). Important to the framing of the Gulf of Mexico Socioecological conceptual framework are the links between humans, the coastal environments, and the species that inhabit these places.

4. CLIMATE DRIVERS

4.1 Atlantic Multidecadal Oscillation

The Atlantic Multidecadal Oscillation (AMO) is a climate mode in the North Atlantic, occurring on multidecadal time scales. The AMO index is a measure of basinwide sea surface temperature variation in the North Atlantic, adjusted to remove trends in anthropogenically forced warming [5, 6]. Like other modes of variability (e.g., El Niño Southern Oscillation), the AMO has impacts on a large geographic scale via atmospheric teleconnections, and has been hypothesized to have an influence on a range of North Atlantic fisheries and ecosystems [7, 8]. In the GoM, the AMO has been associated with changes in the strength of the Yucatan Current and Loop Current [9], precipitation in the Mississippi River watershed [5], and depth of the mixed layer [10]. Through these relationships, the AMO may affect GoM ocean temperatures, stratification, surface plankton productivity, and the development of hypoxia at the outflow of the Mississippi River – processes that can in turn influence the dynamics of biological and human communities.



Atlantic Multidecadal Oscillation

Figure 4.1. Monthly values of the Atlantic Multidecadal Oscillation index.

Several independent analyses of the indicator suite presented in the original Gulf of Mexico Ecosystem Status Report indicate that the AMO has a major influence on many components of the GoM ecosystem. Karnauskas et al. [2] found evidence of an ecosystem-wide reorganization in the GoM, coincident with changes in the phase of the AMO. They suggest that the AMO influences the physical environment of the GoM, particularly temperature and hypoxia, which then impacts higher trophic level and socioeconomic components of the ecosystem. A separate, independent analysis of the same indicator suite also found the AMO to be a significant predictor of ecosystem responses (M. Drexler, pers. comm.) Finally, in a cross-regional comparative study, Tam et al. [11] found the AMO to be the most important factor in the GoM driving a suite of ecological indicators, whereas in other regions anthropogenic factors (e.g., exploitation level) were more influential than climate drivers. Multiple lines of evidence thus suggest that the AMO may be the underlying driving force for many observed changes in the GoM.

We use the monthly unsmoothed AMO index, reported by NOAA's Earth System Research Laboratory [12]. The AMO index was in a warm phase from the 1920s to the 1960s, a cold phase from 1970s to the early 1990s, and then changed back to a warm phase in the mid-1990s. Although the index remains in the warm phase at present, it shows a slight decrease in the past 5 years, with the index dropping below average more frequently than in the decade 2000 - 2010 (Fig. 4.1).

4.2 Sea surface temperature

Ocean temperatures can have both direct and indirect effects on a wide range of ecosystem components. Temperature has already appeared to be a factor in preference-driven shifts in fish distributions in the GoM over recent decades [13, 14]. Species that are immobile such as corals may be subject to mortality when exposed to long-duration changes in temperature with rapid onset; indeed, Gulf corals have experienced bleaching and death in recent years in response to rising ocean temperatures [15]. Temperature shifts may also have indirect effects on human communities; for example, by inducing disease outbreaks in commercially important shellfish species [16].

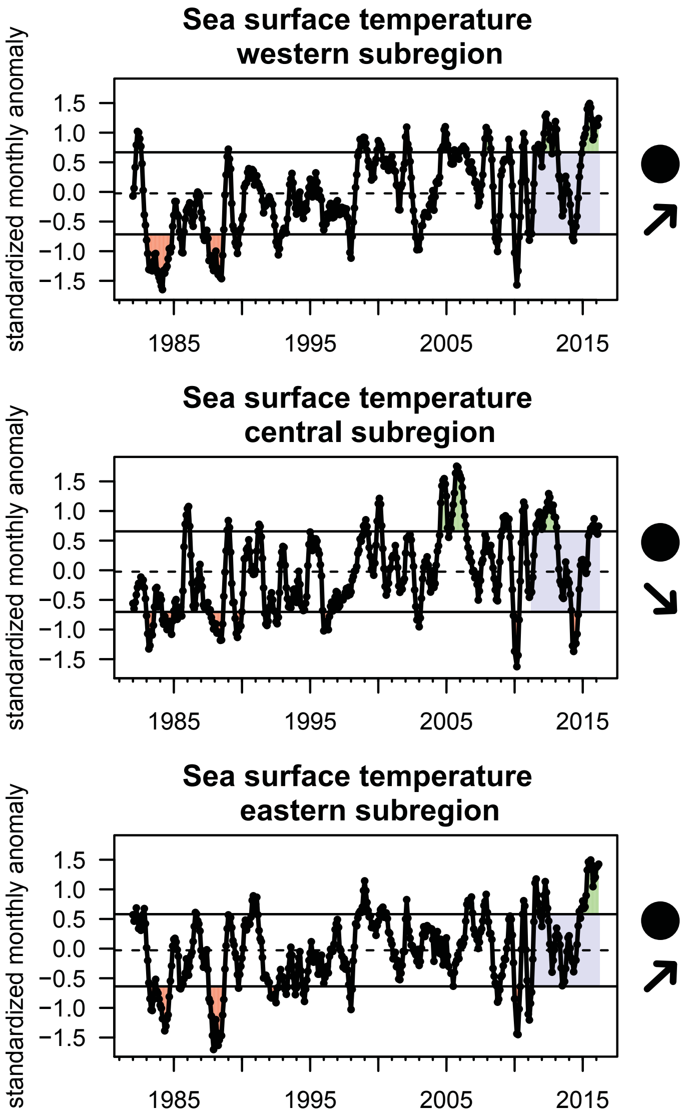


Figure 4.2. Moving average of standardized monthly anomalies of sea surface temperatures, averaged over western (top), central (middle) and eastern (bottom) subregions.

A number of temperature-derived indicators were calculated in the first Ecosystem Status Report, and these measures were found to be highly correlated. The mean offshore sea surface temperature was found to be one of the most significant indicators in terms of the mid-1990s ecosystem reorganization, and is available at fine spatial and temporal scales likely most relevant at the scale of marine organisms. We therefore chose to report monthly SST indices, calculated for select regions within the GoM, using the one-quarter degree Daily High-Resolution Blended SST Analysis product [17]. A principal components analysis was used to analyze spatial patterns in SST variability across time, and formed the basis of defining subregions. This ensures that, for example, areas of coinciding increases and decreases in temperature were not averaged out into a flat time series. We identified three distinct regions: waters of the Southern Texas shelf (western subregion), nearshore waters along the Louisiana shelf (central subregion), and an area roughly encompassing the West Florida Shelf (eastern subregion).

We report a 6-month moving average of standardized monthly anomalies for each region, which allows visualization of SST trends isolated from the annual temperature cycle (Fig. 4.2). In all three regions, temperatures have increased gradually over three decades, although the West has warmed more rapidly than the East. The Texas subregion has increased at a linear rate of 0.31 degrees Celsius per decade, whereas the rate of increase has been slightly lower for the Louisiana shelf and West Florida shelf subregions (0.22 and 0.20 degrees Celsius per decade, respectively). In general, the three time series are highly correlated, with high and low anomalies apparent in all regions. For example, extreme cold anomalies were observed in January of 2010, an event which produced cold-stunning in sea turtles [18] and mass mortality in manatees [19] and fish such as snook [20]. At certain periods, the time series are decoupled, most notably in 2005 when a major warm anomaly was present off the coast of Louisiana while temperatures were below average in the West Florida Shelf. In the recent five-year period, rates of increase have been higher off the coast of Texas and on the West Florida Shelf, while the Louisiana shelf has generally been subject to cooling. In all three subregions, the mean recent temperatures remain within one standard deviation from the mean.

4.3 Sea level rise

Sea level rise can have direct impacts on coastal communities and the surrounding ecosystems. To develop indicators of sea level rise we used the NOAA Tides and Currents webpage [21], which contains data from the Center for Operational Oceanographic Products and Services. The stations are operated by the National Water Level Observation Network (NWLON) and are distributed around the globe to collect detailed information on tides and local sea levels. For the GoM, we used the existing NWLON reporting stations, with the exception of Freeport and Galveston, TX; Eugene Island, LA; and Mobile State Docks, AL due to breaks in the data. The stations are spread throughout the study area, and report the mean sea level (MSL) trends at each point. Data from these stations all date back at least 30 years and, in some cases, back to the early 20th century.

The MSL trends reported are local rather than global trends with seasonal trends removed, and there is noticeable variation between sites. The data were averaged by year at each station and then averaged by state (Fig. 4.3). Alabama and Mississippi were combined due to the low number of stations. The station in Grand Isle, Louisiana recorded the greatest rate of sea level rise over the past seven decades, with a mean increase of 9.05mm/year or approximately 1 m of sea level rise per century. Port Mansfield, TX reported the lowest rate of sea-level rise in the northern GoM, at 1.93mm/year over the past four decades. The remaining stations around the GoM also showed significant increases in sea level, but at slower rates. All states show a positive trend, but Texas and Louisiana exhibit the steepest rise in mean sea level over time. Changes in sea level can affect the stability and safety of coastal communities and can also have impacts on coastal ecosystems by affecting the extent of various habitat types.

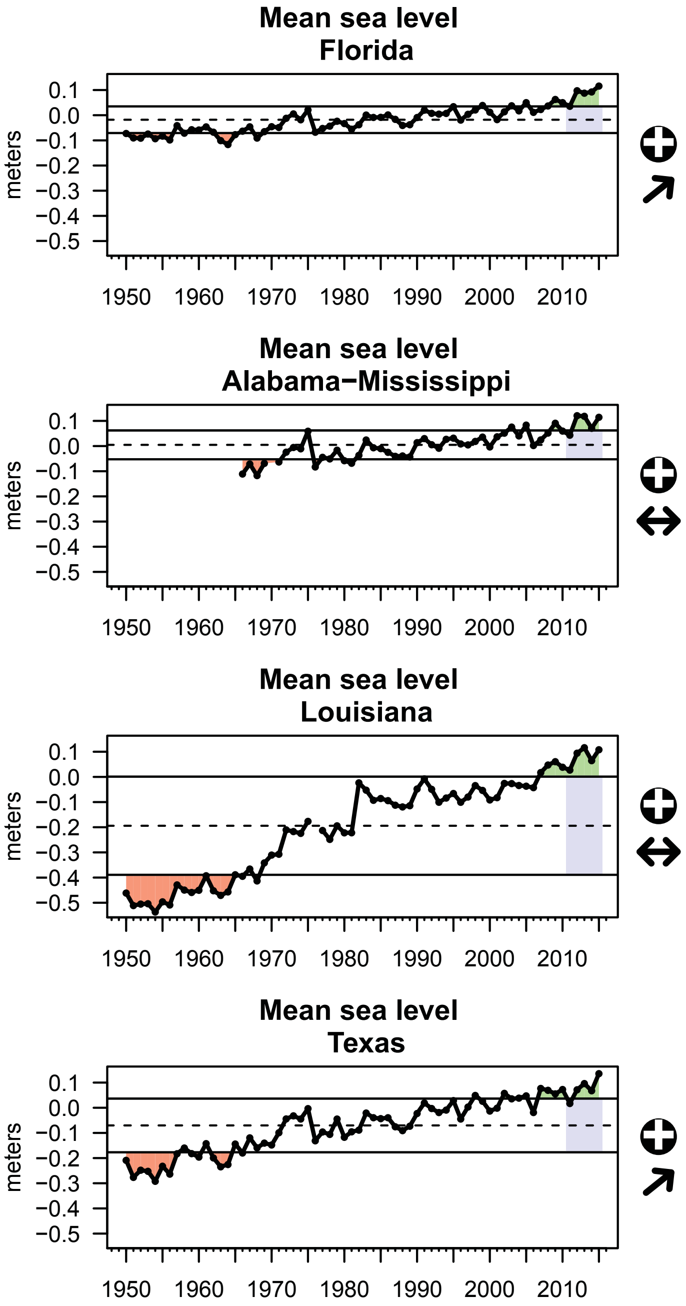


Figure 4.3. Mean yearly sea level rise by state of the Gulf of Mexico.

5. PHYSICAL AND CHEMICAL PRESSURES

5.1 Eutrophication

The GoM water column is significantly influenced by runoff from several major rivers, including the Mississippi, Mobile, Apalachicola and Rio Grande. As these rivers flow through agricultural lands, they collect fertilizers and other organic compounds that they then transport to the coast [22]. Maintaining the proper balance of nutrients is important to support ecosystem productivity, function and health. An excess of nutrients can be detrimental as it can cause eutrophication. Eutrophication results in an imbalance in productivity and overall ecosystem function, causing shifts from benthic primary producers, such as seagrass beds, to phytoplankton, and resulting in hypoxia when the increased organic material is consumed by bacteria. Some of the major nutrient species leading to eutrophication are nitrogen oxides (NOx), total nitrogen (TN) and total phosphorus (TP) in a system.

For the GoM, we examined the five coastal rivers with nutrient loading values available from the USGS [23]. For TN, the Mobile River reported increases in loading, while the other four sites reported decreasing trends (Fig. 5.1). The TP levels were found to be increasing in the Mobile River and the Mississippi-Atchafalaya River Basin (MARB), but the remaining three locations show decreasing or steady levels. Lastly, the NOx measurements showed decreasing trends in the MARB, Mobile River, and Apalachicola River, however, no data were found for Rio Grande or Brazos River. Looking at short term trends however, it appears that most are decreasing within the last 2-5 years. The watershed feeding into the MARB is the third largest in the world and its waters pass through 31 states comprising the heart of the United States' agricultural lands. The MARB output has the highest measurements for all nutrients, reporting numbers at least two orders of magnitude larger than some of the other four sites.

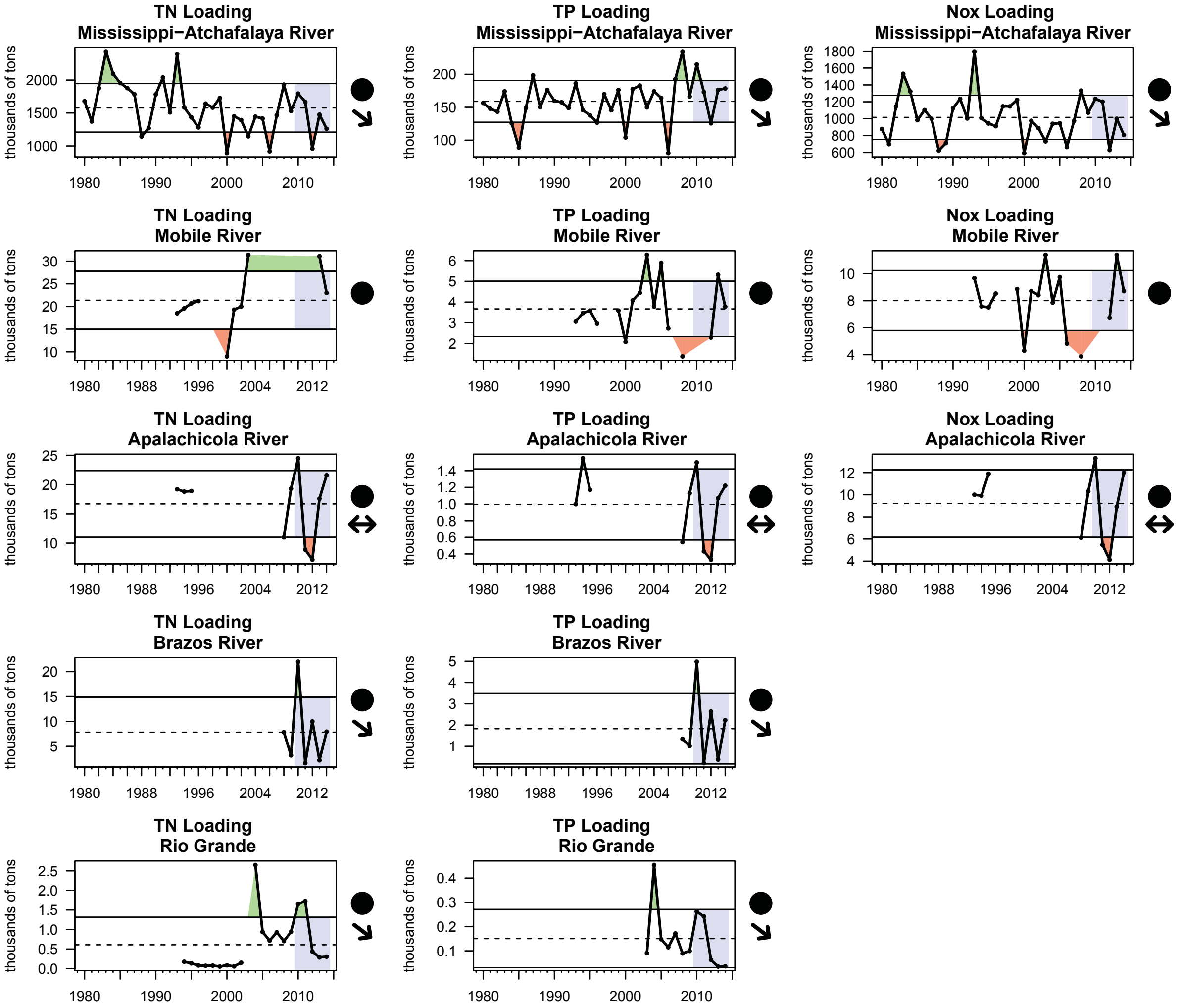
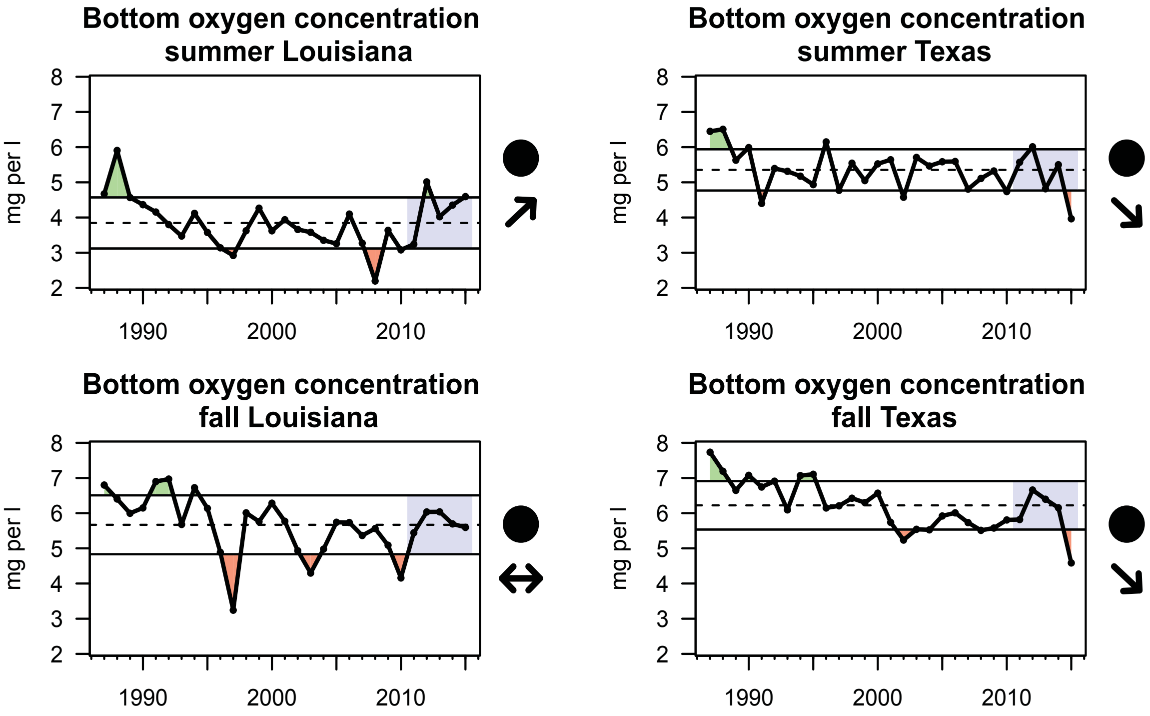


Figure 5.1. Nutrient loading plots for five river sites around the Gulf of Mexico, reported in thousands of tons per year. Note different y-axis scales.

5.2 Hypoxia

Hypoxia, or low dissolved oxygen, is defined as oxygen levels less than two milligrams per liter. The northern Gulf shelf experiences one of the largest seasonal hypoxia zones in the world, primarily resulting from riverine-derived nutrients from the Mississippi-Atchafalaya River watershed described above, as well as salinity stratification of oceanic waters which inhibits re-aeration of bottom waters. Sufficient concentrations of dissolved oxygen in the subsurface depths of the ocean are critical to maintaining ecosystem function. Benthic organisms may die when exposed to extended hypoxic conditions, and mobile organisms may experience sublethal effects on growth and reproduction or move out of the area, potentially altering fishery harvest and bycatch rates. In the GoM, hypoxic events are most common during the summer months (June-August) and in the shelf waters off of the Louisiana coast, but have been documented on the Texas shelf as well as further east off Mississippi and Alabama.



Bottom oxygen concentration summer Louisiana

Bottom oxygen concentration summer Texas

Bottom oxygen concentration fall Louisiana

Bottom oxygen concentration fall Texas

Figure 5.2. Average annual dissolved oxygen concentration values for the Louisiana (left) and Texas (right) coastal shelf, in summer (top) and fall (bottom).

Bottom water dissolved oxygen is measured regularly as part of the fishery-independent Southeast Area Monitoring and Assessment Program (SEAMAP) trawl and hydrographic survey which has been conducted bi-annually since 1987. Estimates of average bottom dissolved oxygen concentrations on the shelf (5-110 m depth) are variable across years but show an overall decreasing trend over time, although in recent years concentrations have increased off the coast of Louisiana in both summer and fall (Fig. 5.2). Hypoxia off the coast of Texas is typically less severe, although bottom oxygen concentrations have decreased more dramatically in recent years. The severity and spatial extent of the hypoxic zone varies greatly from year to year due to a number of factors such as nutrient loading, wind stress, freshwater discharge, hurricane activity, coastal circulation, and atmospheric warming [24]. Interestingly, the recent increase in bottom dissolved oxygen off the coast of Louisiana coincides with a decrease in sea surface temperature in that region, whereas the decrease in dissolved oxygen off the coast of Texas coincides with a recent increase in sea surface temperature in that region (Section 4.2). Increased stratification reduces vertical mixing and prevents oxygen from diffusing below the pycnocline [25], and the observed recent trends in hypoxia may be partially explained by changes in temperatures.

5.3 Carbon fluxes and ocean acidification

The ocean absorbs atmospheric CO_2 thus contributing to decreasing the impact of anthropogenic carbon emissions as a result of the burning of fossil fuels, cement production, and other factors [26]. Current estimates suggest that global oceans absorb 26% of these emissions. However, until a decade ago, little was known about the behavior of the waters of the GoM, and few measurements had been carried out in the area. Initial estimates based on data gathered from two summer cruises appeared to indicate that the area was a source of CO_2 into the atmosphere [27]. Over the last decade, there has been a significant effort to increase measurements of carbon fluxes to determine the contribution of the GoM to the global carbon sink. Over half a million data points have been gathered and made publicly available [28]. With these data, new estimates suggest that the GoM is actually a weak sink for atmospheric carbon on an annual scale, acting as a source during the summer season and as a sink during the winter season. The carbon exchange dynamics in the northern GoM are heavily impacted by the fresh water and nutrient inputs from the Mississippi River, which can change from year to year, but data-based estimates suggest that this area of the Gulf is also a net sink for atmospheric carbon, absorbing 0.96 ± 3.7 mol m^{-2} yr^{-1} [29].

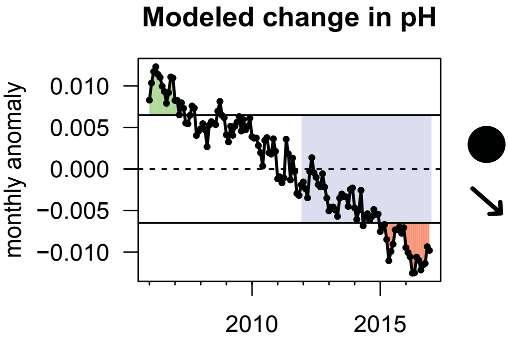


Figure 5.3. Monthly anomalies of average northern GoM pH model estimates.

While the absorption of atmospheric CO_2 by the oceans has a beneficial impact because it contributes to decreasing atmospheric CO_2 concentrations by sequestering carbon, there are also negative impacts to the ecosystem. Ocean acidification refers to the lowering of seawater pH over an extended period of time, which makes the water more acidic. When the CO_2 enters the ocean, some of it reacts with water to form carbonic acid and release protons, which reduces the pH. This increased seawater CO_2 also decreases the carbonate ion concentration, and the saturation states of calcium carbonate minerals that are biologically important. The precise impacts of ocean acidification in the GoM are not well understood, and coastal ocean acidification is further complicated by the fact that the GoM is a riverine-dominated shelf system, particularly in the north, with naturally lowered pH due to the breakdown of terrestrial organic matter entering via river runoff. Additionally, there are very few and scattered quality pH measurements available in the GoM. Thus, we examined historic pH calculations from the CMIP 5 modeling suite [30]. Modeled changes in pH were calculated based on surface pH estimates, averaged over the northern GoM in areas where the water depth was greater than 1000 feet, to remove uncertainties associated with coastal pH calculation using this method. The specification of this spatial domain is consistent with the procedure used to calculate the net primary productivity indicator (Section 7.1). Modeled pH shows a significant downward trend over the past decade, with a distinct seasonal cycle of lower pH in the summer and higher pH in the winter. To analyze trends not due to the seasonal cycle, we present the index in terms of unstandardized monthly anomalies (Fig. 5.3).

6. HABITAT STATE

6.1 Areal extent of estuarine habitats

The habitat extent data for several sites of interest throughout the GoM are limited both spatially and temporally. A lack of robust data for each habitat type, spanning multiple decades, makes it challenging to properly analyze trends. We combined data from several sources, including the USGS Seagrass Status and Trends report [31], the Emergent Wetlands Status and Trends report [32], the Tampa Bay National Estuarine Program, the

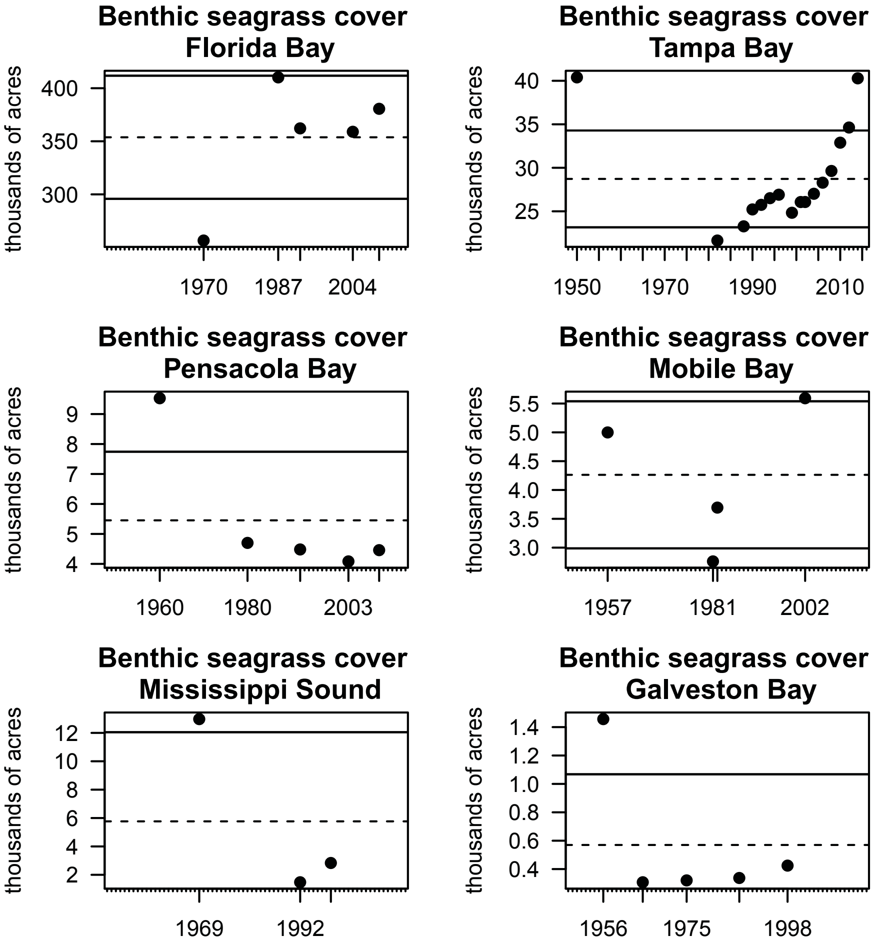


Figure 6.1. Benthic seagrass cover for six estuarine bays around the Gulf of Mexico. Note different y-axis scales.

Alabama Department of Conservation and Natural Resources oyster reef data, Southwest Florida Water Management District seagrass data, and the Florida Fish and Wildlife Conservation Commission's Florida Fish and Wildlife Research Institute. Currently, a central and updated repository of Gulf coastal habitats is lacking. Seagrass data were more readily available than other habitats. The available data indicate that coverage is declining in the Pensacola Bay, Mississippi Sound, and Galveston areas, while Florida Bay and Mobile Bay have reported increases in seagrass coverage (Fig. 6.1). Tampa Bay has shown increases in seagrass coverage in recent years due to restoration and management efforts, following a massive die-off in the late 1950's [33].

Some data on wetlands are available for historical periods, but in the past decade few measurements have been made to estimate overall extent of wetland areas in the GoM. The available data show a net decline throughout all study areas, with the most pronounced changes reported in the Mississippi Sound area. Data from only one monitoring project for oysters was found and thus was not included in this report. No specific data on mangrove habitat, another key habitat type, were found at this time for the northern GoM.

6.2 Artificial structures

The GoM is home to a large number of artificial structures, resulting from oil extraction industry, or intentional installation of materials for the purpose of attracting fish and other organisms. Oil rigs, by virtue of their three-dimensional structure, are known to harbor significant densities of important commercial species such as red snapper [34], and may increase productivity by augmenting rates of recruitment and growth [35]. Because of the positive benefits to fishing and scuba diving industries that have been observed to result from installation of these structures, a number of decommissioned rigs have been converted to artificial reefs, which then become managed by the various state agencies. Various Gulf states have also been involved in the deployment of artificial reef structures for over a century, but did not begin reef-building programs in earnest until the 1980s, when various artificial reef management plans and funded programs were formed. The purpose of these plans was largely to create reef habitat in areas that were typically devoid, and thus improve local economies through increased opportunities for recreation.

While the construction of oil rigs in the Gulf predated the deployment of artificial structures by nearly three decades, the growth in artificial reef programs has been explosive and their numbers now far exceed numbers of extant oil rigs almost six-fold (Fig. 6.2). Artificial reefs can be composed of a large variety of materials, including various metal, limestone, or concrete structures, sunken vessels or army tanks, and a range of repurposed materials. The most significant hotspot of artificial reef activity has occurred in the Alabama Artificial Reef Zone, where public deployments have been permissible since the 1980s. According to a survey using side-scan sonar, the Reef Zone is now thought to house over 10,000 artificial structures, approximately 78% of which are unpublished public deployments (S. Powers, pers. comm.). The majority of these deployments are composed of steel structures such as steel poultry transport cages that have been welded together, although specially fabricated concrete pyramid reef modules and repurposed concrete culverts contribute to a significant portion of Alabama's artificial reef construction material (C. Newton, pers. comm.). The index reported here represents the best available estimate for the number of artificial reefs, but because deployments vary dramatically in size and three-dimensional complexity, it may not be fully representative of the total amount of artificial substrate in the region.

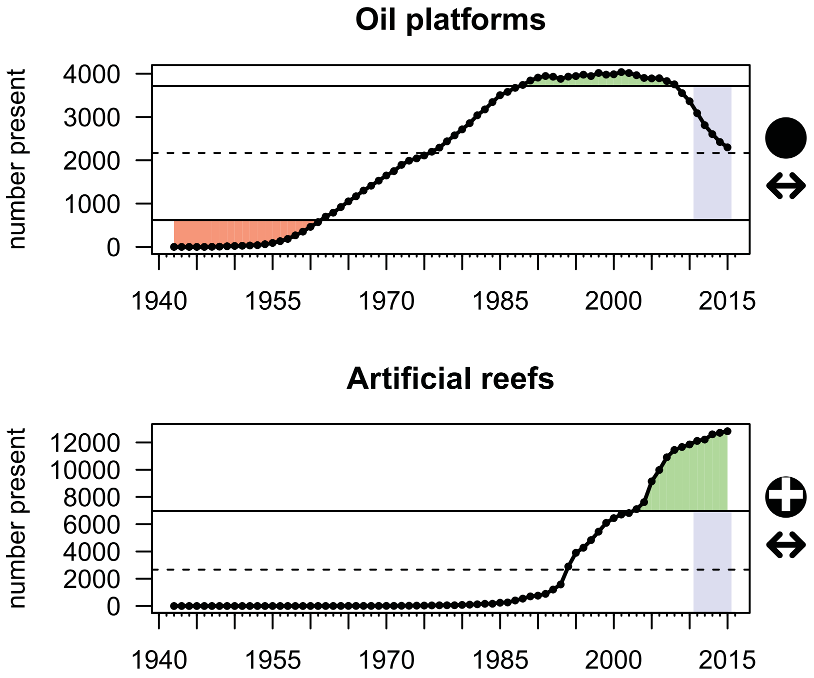


Figure 6.2. Total number of oil platforms (top) and artificial reefs (bottom) present in the northern GoM.

Growth in oil rigs was approximately linear from the late 1950s until the 1990s, at which point installations leveled off; removals began to consistently exceed installations in the early 2000s and thus the total number of rigs has declined in the past decade (Fig. 6.2, top). Artificial reef building began in the mid-1980s and the rate of increase has been relatively constant since this time, with approximately 400 new reefs added to the GoM each year (Fig. 6.2, bottom). Note that while most artificial reefs are not purposely removed, they will eventually break down due to corrosion or be swept away by storm activity. Also, certain states routinely maintain artificial reef sites via replenishment (i.e., deploying additional materials at existing sites). The index reported here does not include any estimates of artificial reef removal or replenishment, as these are largely unknown. Artificial reef deployments in Texas are also excluded as these dates were not available. The index does include the best available estimates for the numerous unpublished public reef deployments in the Alabama Artificial Reef Zone, based on an extrapolation from side-scan sonar surveys and permitting information from the Dauphin Island Alabama Marine Resources Division.

6.3 Wetland land use and land cover

Land use and land cover change is derived from the Coastal Change Analysis Program (C-CAP) within the National Oceanic and Atmospheric Administration (NOAA) Office for Coastal Management.

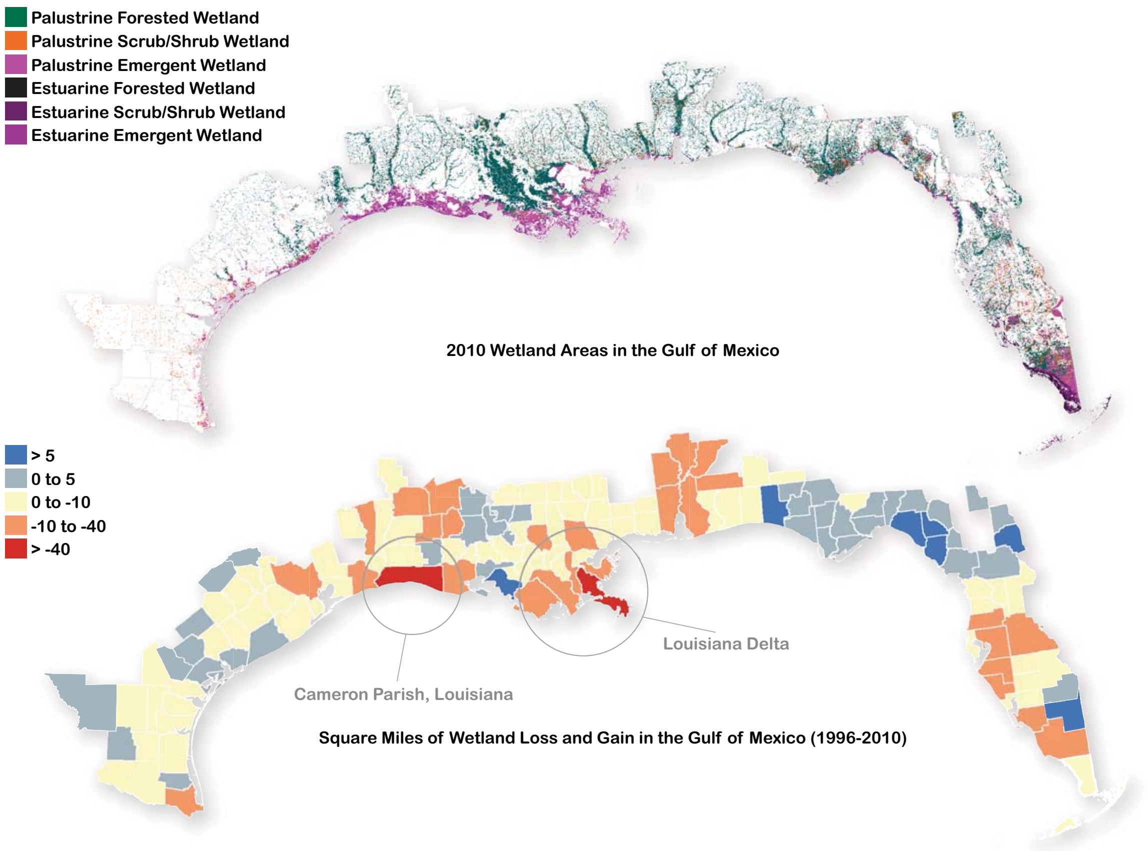


Figure 6.3. Wetland coverage across the U.S. coastal watershed counties in the Gulf of Mexico in 2010 (top), and square miles of wetland loss and gain by county from 1996-2010 (bottom).

Wetland land cover change in the GoM represents a relatively large proportion of total land area in the GoM coastal environment, making up approximately 20% of the total land cover (Fig. 6.3). This includes Palustrine Forested, Palustrine Emergent, Palustrine Shrub/Scrub, Estuarine Forest, Estuarine Shrub/Scrub, Estuarine Emergent, and Unconsolidated Shore land cover types. Wetlands are especially dynamic and change from year to year, with both gains in some areas and losses in others; however, the general trend across the GoM is wetlands loss. Approximately 1000 square miles of wetland have been lost between 1996 and 2010 – primarily due to conversion to open water, and to a lesser extent from development and urbanization. Similarly to urban development, the extremes in wetland land cover change are highly localized and vary geographically, with the most wetland loss occurring along coastal Louisiana in the Louisiana Delta, as well as in Cameron Parish Louisiana, which is home to both the Sabine National Wildlife Refuge, and the Rockefeller Wildlife Refuge. Wetland loss is primarily attributed to impact from storms, subsidence, erosion, saltwater intrusion, and the lack of sediment replenishment for marsh habitat [36, 37, 38].

7. LOWER TROPHIC STATES

7.1 Net primary productivity

Net Primary Productivity (NPP) is the net production of carbon by primary level producers such as phytoplankton. Another source of carbon in the Gulf is from photosynthesis by the brown algae *Sargassum* that creates large mats along the surface waters. NPP is usually expressed as the biomass (in units of weight of carbon) under a square meter of the ocean per unit time [39]. NPP is a complex function of the physiology of phytoplankton, growth rate, carbon-to-chlorophyll a ratios, temperature, nutrient, and sunlight and nutrient history and availability [40, 41]. Primary production can be altered due to changes in the physical and chemical environment, and thus these dynamics can influence fisheries production via thir effects on primary production [42]. NPP provides proxy information on trophic dynamics of surface ocean waters, which is helpful when looking at the impact of variations in near-surface water column thermal structure and mixing [39].

In the GoM, the NPP is an example of a biological parameter that serves as an index to the biological state of the GoM. It has been associated with changes in wind speed, cold temperature events, and is directly affected by the depth of the mixed layer [39]. The coastal waters of the Gulf are characterized by an enhanced primary production due to influence from the Mississippi River [43]. In addition, the estuaries of the northern GoM region, all located at approximately 30° N, have high solar insolation, which can support relatively high primary production throughout the year [44]. Benthic primary production is significant [45], owing to the shallow nature of these systems. Certain parts of the year tend to be more productive than others (e.g. March and April), due to the organisms that produce the carbon. These organisms have large population increases during the spring months, after which their populations crash as vertical stratification increases and nutrients in the surface ocean become limiting.

We report monthly averages of NPP (1998-2015) within the northern Gulf area above 25° N latitude, plotted as standardized monthly anomalies to remove the strong seasonal effect (Fig. 7.1). We note that there are strong individual year effects in the time series. The NPP ranges from 528 to 608 mg C m^{-2} d^{-1} during the late 1990s. However, we see a rise in the production from 2008 that is

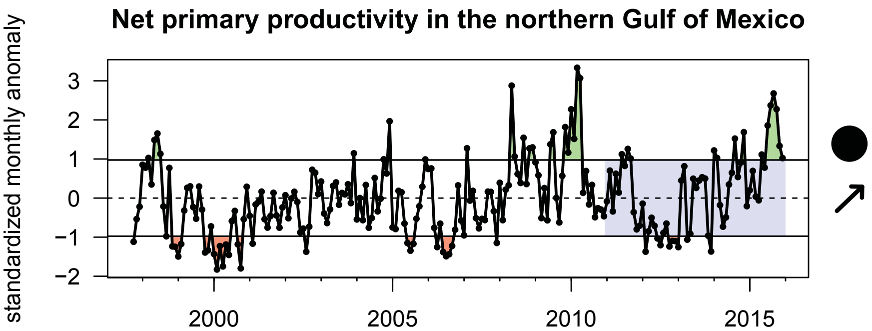


Figure 7.1. Standardized monthly anomalies of net primary productivity for the Northern GoM, derived from Moderate Resolution Imaging Spectrometer (MODIS) observations. Adapted from Muller-Karger et al. [39].

relatively stable until 2011 and it is in the range of 530-675 mg C m^{-2} d^{-1}. Similarly, an increasing trend is observed after 2012. The lowest value of 528 mg C m^{-2} d^{-1} was reported during 2006. Peaks in NPP occur during periods of the strongest winds and SST minima, while the NPP minimum occurs when the MLD reaches its lowest values [39].

7.2 Zooplankton biomass

Zooplankton are a fundamental link in the marine food web with a crucial role as both predator and prey to a wide range of trophic levels. Therefore, any changes in the zooplankton community are reflected throughout the marine ecosystem due to this strong linkage [46]. The Southeast Area Monitoring and Assessment Program (SEAMAP) has conducted plankton surveys throughout the GoM since 1982. Although taxonomic specific zooplankton biomass is not directly measured, displacement volume from samples collected during SEAMAP ichthyoplankton surveys can act as a proxy measurement [47].

Data from spring and fall plankton surveys were standardized to develop an index of zooplankton biovolume (ml m^{-3}). The two surveys are spatially distinct, with the spring survey sampling the open ocean from the shelf break to the extent of the U.S Exclusive Economic Zone, and the fall survey sampling from nearshore to outer continental shelf. Both surveys target a set of core stations arranged in a fixed systematic grid. The spring surveys call for two complete passes of the core stations during the survey and the fall a single pass. During the spring survey two complete passes were rarely achieved, resulting in variable spatial coverage within and among years of the survey. Therefore to develop the index of zooplankton from the spring survey, we selected only samples from each year that represented the most consistent spatial and temporal single pass of core stations from all years. For the fall survey, we limited samples to those taken from stations that had been sampled during at least 66% of the survey years [48]. Years with incomplete spatial coverage respective to each survey were dropped from the indices.

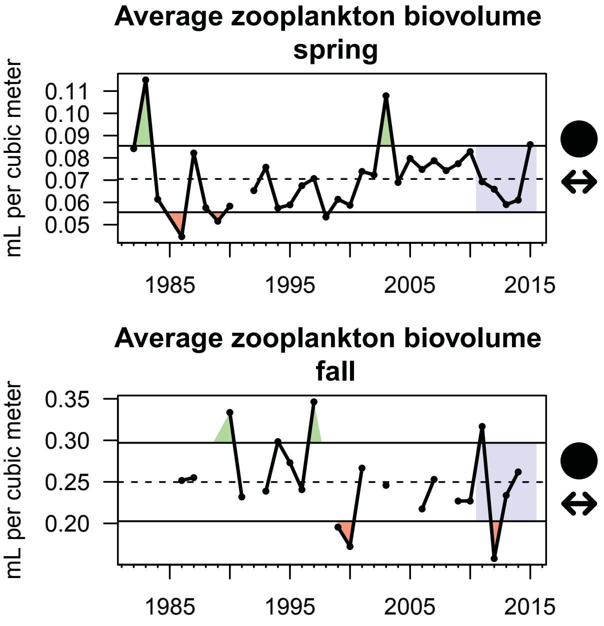


Figure 7.2. Average zooplankton biovolume calculated for the SEAMAP spring and fall surveys using methods from Hanisko et al. [48]. Note different y-axis scales.

Zooplankton biomasses from the spring surveys are approximately 28% of those from the fall survey, and reflect the spatial differences between their open ocean and continental shelf environments. The spring zooplankton index shows no trend, but there appears to be a quasi-decadal oscillation where annual biomass is less/greater than the time series mean (Fig. 7.2). In contrast, the fall zooplankton index indicates that biovolumes tended to be greater in earlier years (1985 - 1997) relative to the more recent period.

7.3 Forage fish abundance

Menhaden are an important forage species in the GoM, supplying a massive industrial fishery as well as contributing to the diets of a wide number of species in the ecosystem [49]. The reduction fishery for Gulf menhaden, *Brevoortia patronus*, is by far the largest fishery in the GoM, with removals on the order of half a million metric tons per year. The species is thought to play a substantial role in ecosystem structure and function [50], and an index of menhaden biomass derived from the stock assessment thus serves as a potential indicator of the amount of forage available in the ecosystem. Menhaden are currently assessed using an age-structured model, and stock biomass is reported for age-1 fish and above [51].

Fishing pressure on the menhaden stock has changed dramatically in past decades, largely in response to market forces. The first menhaden plants were opened in the 1940s in response to an increased demand for fish meal for agricultural purposes [52]. During the 1960s and 1970s, the fishery expanded and fleet size reached about 80 vessels, but beginning in the 1980s the fishery began consolidating due to a decline in market prices. In the last decade, additional declines in effort have resulted from loss of infrastructure due to hurricanes, and fleet size has remained around 40 vessels for the past decade [51]. Menhaden landings closely track fishing effort, with maximum extraction peaking at nearly 1 million metric tons in 1984, followed by a gradual decline throughout the following decades. Accordingly, the stock assessment estimates that population biomass reached a low period in the late 1980s to early 1990s, and is estimated to have generally increased in the past three decades (Fig. 7.3). The current stock assessment estimates that the population has not been overfished and has not undergone overfishing for the last several decades [51]. Current fishing mortality is estimated to be lower than proposed management benchmarks for sustainability, and thus while effort has remained relatively stable since 2000, the population biomass has continued to increase.

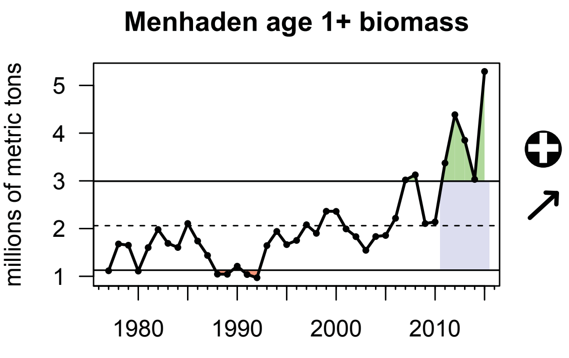


Figure 7.3. Estimate of total Gulf menhaden biomass excluding recruits from the most recent stock assessment.

A recent review of the ecosystem role of menhaden indicates that the species may have a lesser contribution to predator species diets compared to forage species in other ecosystems, perhaps due to the greater diversity of both predator and forage species in the sub-tropics [49]. Specifically, Sagarese et al. [49] found that Gulf menhaden contribute between 2-3% of the diets of most predator species; in comparison, all forage fishes (including menhaden, 16 clupeids, and 10 engraulids) contributed approximately 11% to predator diets. Therefore, considering the abundance of menhaden in the ecosystem alone may be misrepresentative of the total forage base in the ecosystem. However, developing abundance estimates for the variety of other forage species in the system would be challenging, as none of these species are subject to fisheries on the same scale as the Gulf menhaden and therefore are not routinely assessed.

8. UPPER TROPHIC STATES

8.1 Upper trophic level biodiversity

Biodiversity plays an important role in maintaining the productivity and functionality of marine ecosystems. Biodiversity is important for maintaining the adaptive capacity of marine ecosystems to changing environmental conditions, mediating biogeochemical cycles that influence the flow of energy through ecosystems, and as a current and future source of food, medicinal products, and other materials. Changes in biodiversity of upper trophic levels, such as fish and macroinvertebrates, can signify important changes occurring in other aspects of the ecosystem that are not readily observable.

Biodiversity indices are calculated based on samples from the Southeast Area Monitoring and Assessment Program (SEAMAP) bottom trawl survey, and are reported separately for summer

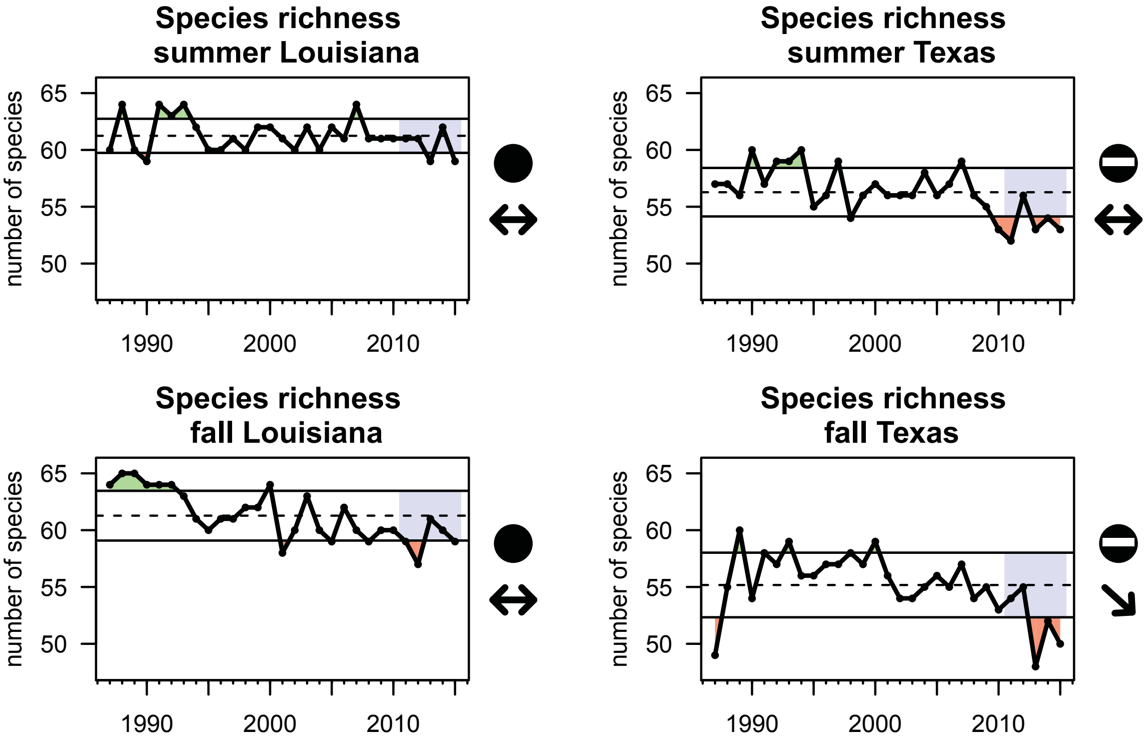


Figure 8.1. Species richness metrics calculated from the SEAMAP survey. Metrics are reported separately for Louisiana (left) and Texas (right) waters and for summer (top) and fall (bottom) surveys.

and fall surveys and for coastal waters of Louisiana and Texas (Figs. 8.1, 8.2). Two indices – species richness and the Shannon-Weiner diversity index – are calculated based on 65 of the most abundant species in the survey, which includes mobile finfish and some macroinvertebrates such as shrimp and crabs. In Louisiana waters, the number of species present in the surveys has ranged from 57 to the full 65; species richness in Texas waters is slightly lower with numbers ranging from 48 to 60. The indices sometimes fluctuate dramatically from year to year, which may represent artifacts of the SEAMAP survey rather than true changes in richness. Survey methods, spatial coverage, and timing of cruises have all varied throughout the three decades of data collection. In general, slight declining trends are observed in species richness, with the exception of the summer survey in Louisiana waters. These trends are driven by absences of different species in different years, seasons, and regions. However, on both the Texas and Louisiana shelf, downward trends appear related to the absence of several relatively infrequent pelagic species in the survey including bay anchovy, Atlantic threadfin herring, and Spanish mackerel, suggesting a common cause perhaps related to recruitment patterns of pelagic fishes, spatial distribution, or availability to the survey.

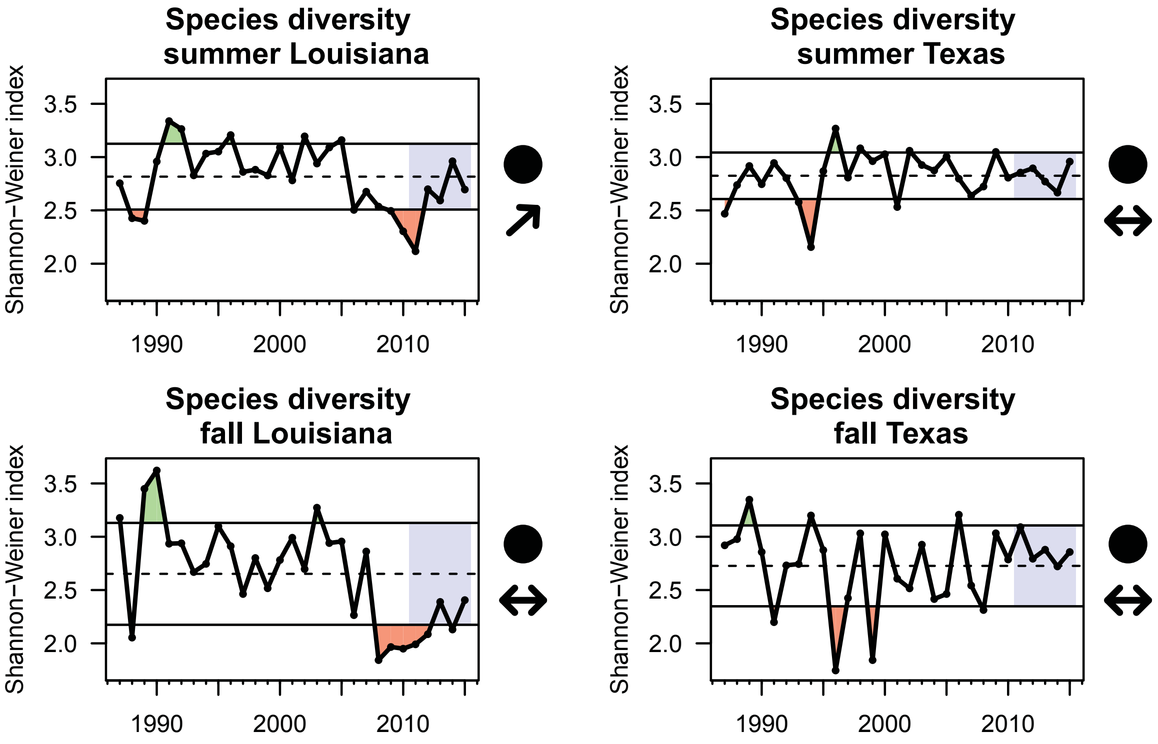


Figure 8.2. Species diversity metrics calculated from the SEAMAP survey. Metrics are reported separately for Louisiana (left) and Texas (right) waters and for summer (top) and fall (bottom) surveys.

Similar trends are observed for species diversity, with the historical period typically having higher diversity than the recent period, particularly for Louisiana waters in summer and fall. Marked declines in diversity occur in Louisiana waters, starting in the year 2005. This can be attributed mostly to large declines in shrimping effort since the early 2000s associated with increases in imported shrimp. Shrimping activity tends to produce large amounts of bycatch, particularly of scianeid fishes, such as spot and croaker. In the absence of shrimping, these species increase in abundance and dominate the demersal fish community in the region, leading to lower apparent species diversity. Shrimping effort is typically lower in Texas waters and occurs later in the summer due to management regulations; thus, the effect of shrimping on biodiversity indices in Texas waters is less notable. In recent years, both species richness and diversity have been stable, with the exception of a further decrease in richness in Texas waters in the fall survey, and an increase in species diversity in Louisiana waters during the summer survey.

8.2 Mean trophic level

Mean trophic level (MTL) is calculated on the basis of catch data and survey data, to elucidate trends in what is being fished versus what is present in the ecosystem. The MTL index is calculated as an average of the assigned trophic level for individual species or species groups, weighted by the total poundage of each group, per year. The MTL indicator can be used to make inferences concerning the impacts of fishing on an ecosystem [53], and a decrease in MTL over time can be representative of "fishing down the food web," which can indicate unsustainable patterns with potentially negative impacts on ecosystem function. In the GoM, trends in the MTL are driven mainly by two large-volume, low-trophic level fisheries: menhaden and penaeid shrimp. Menhaden is a historically important reduction fishery and is by far the largest fishery in the GoM in terms of biomass, with total landings almost three times that of all other commercial species landings combined. Shrimp fisheries, although much lower in total poundage, are much higher in value, making up approximately 60% of the overall ex-vessel revenues from all commercial fisheries in the GoM. Shrimp and menhaden fisheries are driven largely by external market forces, and therefore the MTL of the catch may not be representative of species abundances or the state of the biological ecosystem. We present the MTL calculated for different sets of species groups, from NOAA Fisheries commercial landings statistics from the Southeast Fisheries Science Center. Note that trends prior to 1980 should be interpreted with caution, as landings were reported at coarser taxonomic levels and often include sizeable percentages of unclassified or unknown groupings.

The MTL of all commercial finfish (Fig. 8.3, top) largely reflects patterns in menhaden landings. The Gulf menhaden fishery began in the 1940s in response to demand in fish meal and fish oil and quickly expanded for the next several decades. A peak in landings occurred in 1984, after which time the fishery experienced gradual consolidation and a steady decrease in landings occurred. The MTL calculated for all commercial finfish landings except menhaden (Fig. 8.3, second panel) represents changes in other targeted species. The MTL is initially lower than the long-term average, due to the dominance of the commercial mullet fishery which has targeted these low trophic-level species for bait, meat, and roe since the early 1900s. Landings of mullet were an important component of the overall commercial landings up until the late 1970s, when landings declined in response to overfishing, habitat loss, or other environmental factors [54].

The late 1970s was also a time of rapid expansion of offshore fishing fleets, prompted by the Fishery Conservation and Management Act of 1976 and subsequent legislation to foster development of commercial fisheries. Increases in shark and tuna catches during the 1980s contribute to a rapid increase in the MTL during this time. Since the 1990s, the MTL has remained relatively stable through a mix of higher trophic level species catches.

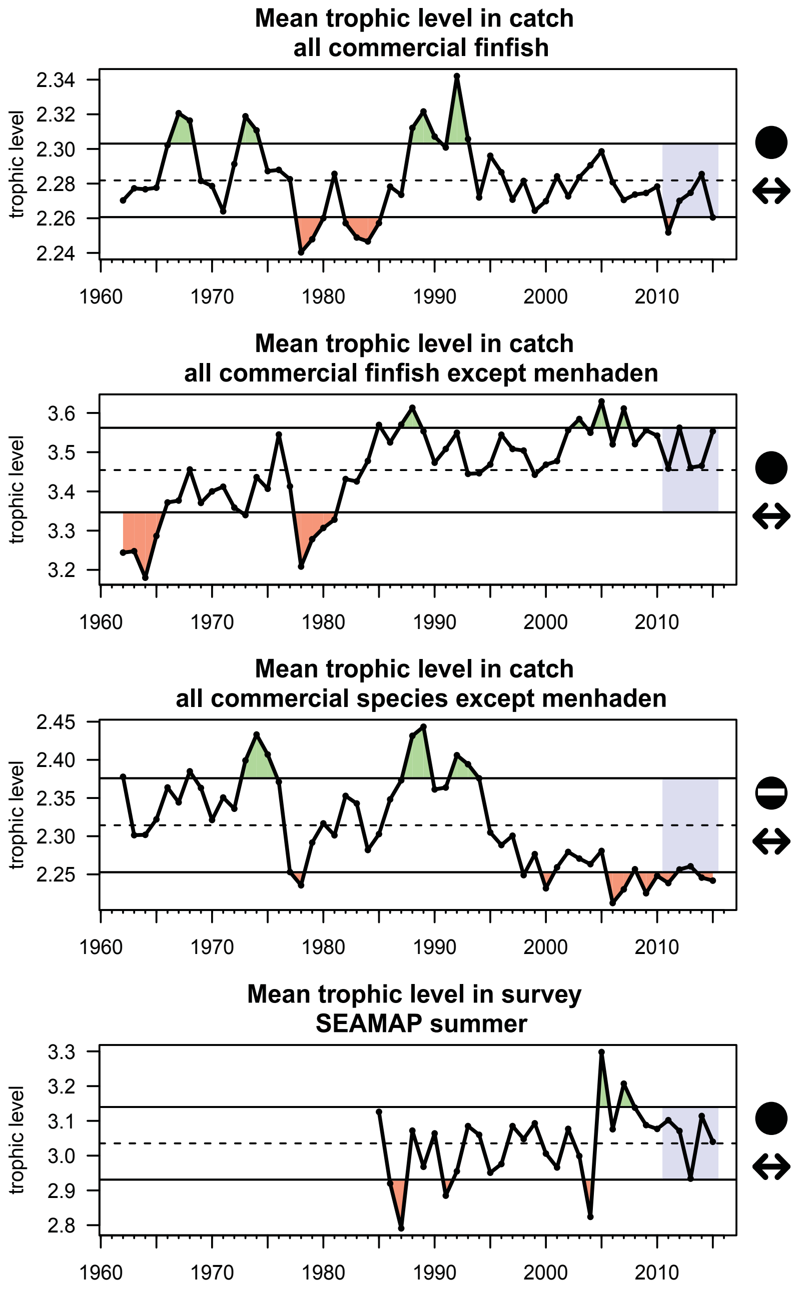


Figure 8.3. Mean trophic level index calculated from the commercial landings data (top three panels) and from the SEAMAP survey (bottom). The catch-based index is calculated separately for all commercial finfish, all finfish except menhaden, and all commercial species except menhaden. Note different y-axis scales in each panel.

The MTL of commercial species catch except menhaden is driven mainly by trends in the ratio of finfish to invertebrate catch. Finfish landings increased slightly in the 1970s and 80s and then decreased starting in the 1990s, coincident with the implementation of a variety of management regulations designed to rebuild declining stocks. The Gulf of Mexico Fisheries Management Council implemented a number of Fishery Management Plans in the 1980s, and major Amendments restricting fishing effort were passed in the 1990s. Management actions at the state level also contributed to steep declines in landings for inshore fisheries; for example, a gill net ban in Florida in the mid-90s led to drastic reductions in effort for spotted seatrout and bluefish [55, 56]. Invertebrate landings, which are dominated by shrimp species, were mostly level through the

1990s, and began to decline in the 2000s, primarily in response to the explosion of low-cost shrimp imports. Growth in the production of farmed shrimp was particularly pronounced in the late 1990s, with culture quadrupling from 1997 to 2005 and prices coincidently declining over the same period [57]. Additional declines in the shrimp industry have occurred as a result of rising fuel prices and loss of vessels and infrastructure during major events such as Hurricane Katrina. Since 2005, invertebrate landings have thus continued to decline while finfish landings have stabilized, and the MTL for all commercial species has remained below average but stable for the past decade.

The MTL of species present in the ecosystem was calculated based on samples from the Southeast Area Monitoring and Assessment Program (SEAMAP) trawl survey, based on the 65 most abundant species in the survey (Fig. 8.3, bottom). The survey uses a small mesh bottom trawl that is similar to gear used in the shrimp trawl fishery. The index shows little trend, with fluctuations from 2.8 to 3.3 over the 30 years of survey data analyzed – similar to the pattern in MTL of the catch. While the catch includes species from both higher and lower trophic levels, the relative stability of this index is partly due to the survey capturing a number of small-bodied fishes and invertebrates that feed at a similar trophic level. The decrease in MTL in 2004 was due to declines in abundance of a few low-trophic level pelagic species that are abundant in the survey in some years (e.g., bay anchovy), while the increase in 2005 was due mostly to increases in abundance of higher trophic-level demersal species, particularly Atlantic croaker. Trends in MTL from these data should be interpreted with caution, however, because trophic level assignments are typically based on feeding studies of adults, while the survey mostly captures smaller juveniles that may feed at lower trophic levels.

8.3 Overfishing status

Gulf of Mexico stocks in federal waters are managed by the Gulf of Mexico Fisheries Management Council, or jointly with the South Atlantic Fisheries Management Council. In the case of highly migratory species that must be managed both domestically and internationally, species are managed under the authority of the Atlantic Tunas Convention Act with recommendations from the International Commission for the Conservation of Atlantic Tunas. The number of GoM stocks contained within the various Fishery Management Plans (FMPs) of these management bodies has ranged from over 60 in the early 2000s to approximately 40 in recent years. While the number of managed species has decreased slightly, stock assessment efforts have increased dramatically; stock status was only known for about one-quarter of all managed species in the early 2000s whereas status is currently available for over 90% of the species included in management plans.

The assessment and identification of overfished stocks, implementation of rebuilding plans, and increased regulations over the past several decades have all led to a general decrease in the number of managed stocks that are overfished (i.e., stock size is below that which produces maximum yield on a continuing basis) or experiencing overfishing (i.e., subject to fishing rate

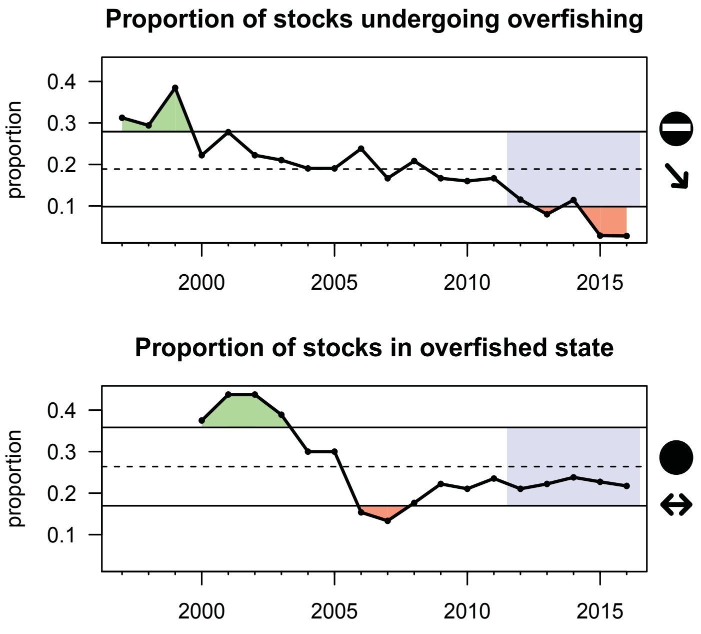


Figure 8.4. Proportion of assessed U.S. stocks estimated to undergoing overfishing (top) and proportion of stocks estimated to be in overfished state (bottom).

that does not produce maximum sustainable yield over the long term). Changes in stock status nationally are compiled in annual reports to U.S. Congress [58]. In the GoM, management regulations implemented largely in the 1990s led to positive changes during the decades that followed. Vermilion snapper, red grouper and king mackerel were rebuilt to sustainable levels in 2006, 2007 and 2008 respectively. Red snapper, a species which has historically undergone intense overexploitation, was no longer subject to overfishing in 2012. In 2014, gag grouper was declared rebuilt, and in 2015, Hogfish, greater amberjack, and gray triggerfish were all removed from overfishing lists. Overall, the proportion of stocks undergoing overfishing has steadily decreased from over one-third to less than five percent, and as of 2016 only a single stock (dusky shark, managed through the Consolidated Atlantic Highly Migratory Species FMP) is subject to overfishing (Fig. 8.4; top). As expected, stocks responded to decreases in fishing pressure by rebuilding, with the proportion of stocks in an overfished state decreasing from nearly half in the early 2000s to less than one-fifth within the same decade (Fig. 8.4; bottom). Since 2007, however, the proportion of stocks in overfished status actually increased slightly and remained level around one-fifth. A reduction in fishing pressure, in the absence of subsequent recovery, may indicate that forces external to stock dynamics have prevented stocks from rebuilding as expected. Such forces could include management implementation error, environmental drivers, and alterations in predator-prey dynamics – or a combination of the above.

It is important to note that hundreds of species of commercial and recreational importance in the GoM do not fall under any Fishery Management Plan, and the proportions reported here are not necessarily representative of all fished species in the region. However, those species not regularly assessed generally make up a small portion of the total landings and have lesser economic importance.

9. ECOSYSTEM SERVICES

9.2 Abundance of economically important species

Stock assessment models incorporate a wide range of data sources, such as landings, catch-per-unit-effort trends, and life history characteristics, in order to produce estimates of stock status. Estimates of abundance or biomass from stock assessments can serve as indicators of stock size, although as model outputs they are subject to a number of uncertainties related to data inputs, model specification, and parameter estimation [59]. For a broad understanding of stock trends, model-derived estimates are preferable to standardized abundance indices which, while potentially subject to fewer sources of error, can have a high noise-to-signal ratio and may be representative of certain age classes or subsectors of the stock. We report biomass estimates (or abundance when biomass is not available) for all species with stock units exclusive to the GoM

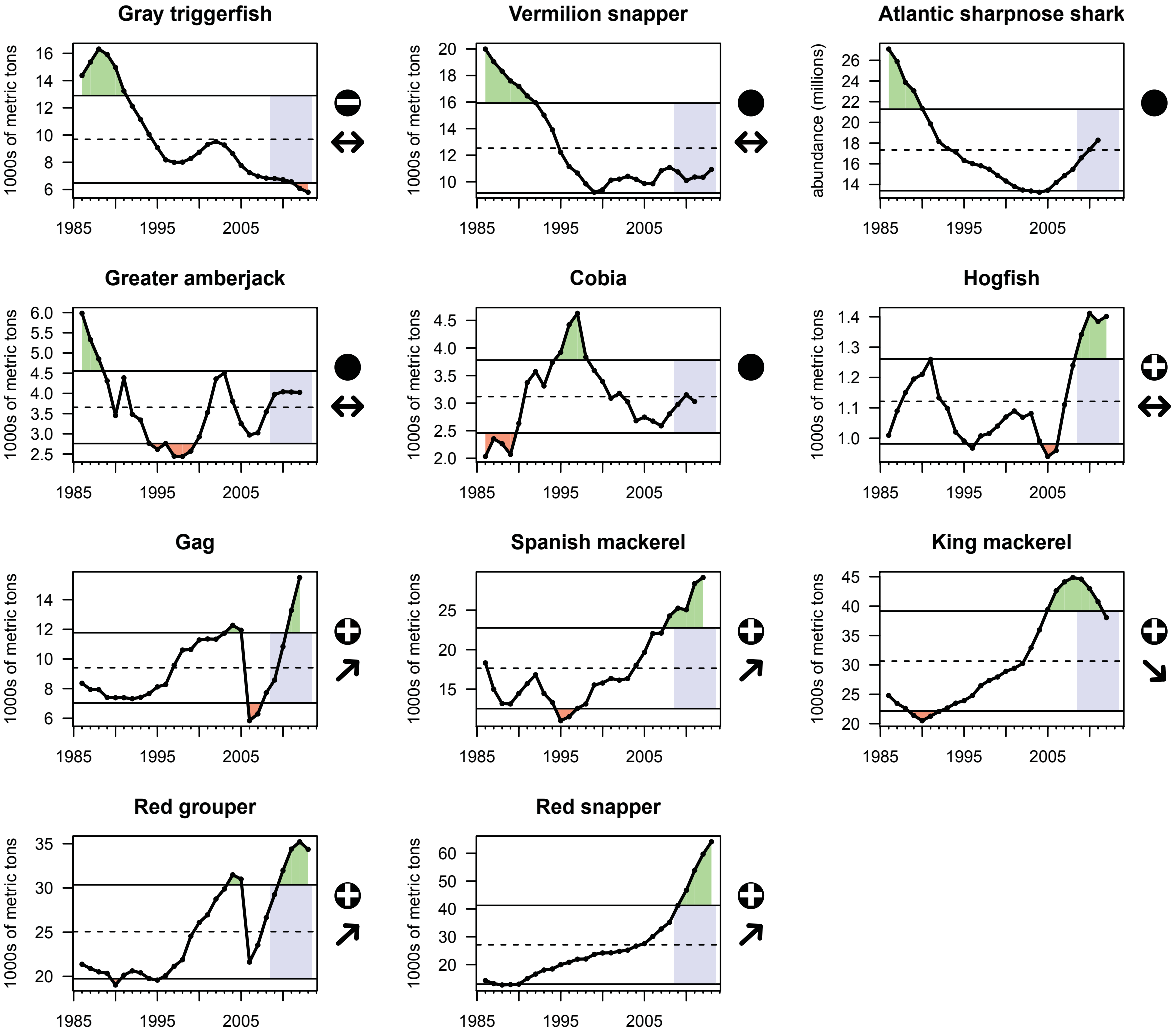


Figure 9.1. Estimated abundances of major assessed commercial species in the northern GoM, derived from recent stock assessments. Note different y-axis scales.

with available update stock assessments since 2011 (Fig. 9.1). Stock assessments for the GoM are carried out through the Southeast Data, Assessment, and Review (SEDAR) process.

Many species of primary commercial and recreational importance, such as snapper, grouper and mackerels, were historically overfished and have shown recovery trajectories in the past two decades. At the same time, species of secondary importance are decreasing in abundance, which may indicate a shift in fishing effort as tighter restrictions were put in place to control overfishing of primary targets. Over the recent five year-period, stock sizes have remained within one standard deviation of the mean, or well above average, for all species except gray triggerfish. Additionally, none of the species have exhibited significant declines in recent years, with the exception of king mackerel. Gray triggerfish is a particular case as it has almost consistently decreased in abundance over the past decades, despite an implemented rebuilding plan and regulations to reduce fishing pressure; decreases in recent years are also due to particularly low recruitment during this period [60]. King mackerel, while not overfished or undergoing overfishing, has also exhibited reduced recruitment in recent years for reasons thought to be related to environmental effects [61].

A principal components analysis of the matrix of species abundance estimates over time is used to find common linear trends among species, and the yearly scores from the first principal component can be indicative of shared external influences on the suite of species as a whole. For the time period analyzed here, the first principal component explains over half the variation in trends among all 11 species, and is thus potentially a useful indicator for quantifying management effects and environmental processes (Fig. 9.2). For example, the effect of the 2005 red tide event is apparent by the significant change in trajectory of the indicator, as the biomasses of several grouper species were severely reduced in that year. Over the entire time series, the rate of change of the indicator generally increases, indicative of greater rates of change (either positive or negative) among the set of species as a whole.

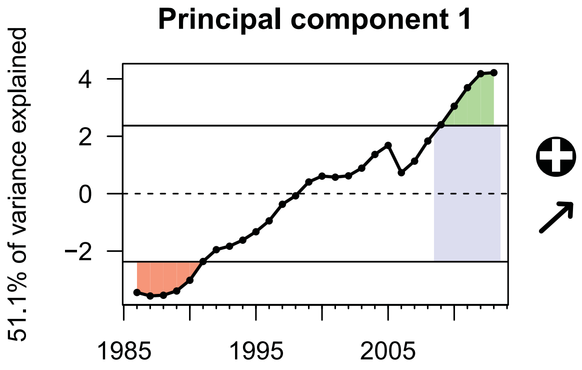


Figure 9.2. First principal component calculated from the matrix of commercial species abundances. The unitless index is a representation of the overall rate change in abundances across the entire suite of species.

Short-term trends in stock sizes should be interpreted cautiously because the most recent years of data from the stock assessment typically are the most uncertain, as the signal of recent cohorts of fish are not fully captured in all of the data streams. Additionally, not all stock assessments were updated in 2013, and due to these missing values the last two years of the principal component indicator should be interpreted with caution.

9.3 Bird abundance

Birds are commonly used as indicator species as they are important functional components of the ecosystem from the perspective of both trophic ecology and tourism value [62]. Waterbirds in particular are useful because they often occupy higher trophic levels, are highly mobile and can respond quickly to environmental change, and are conspicuous and easy to monitor [63] . In practice, the use of birds as bioindicators has been met with both successes and failures, and it is generally recommended to: use a suite of species, look at trends over a large spatial extent, and to tailor the indicator species to specific ecosystem attributes [64]. We chose a suite of five waterbird species for the purpose of tracking trends in occurrence rates in the GoM. Three species: white ibis (*Eudocimus albus*), wood stork (*Mycteria americana*), and roseate spoonbill (*Platalea ajaja*), have been used extensively in local monitoring efforts within the region and are well-known to respond to changes in prey abundance induced by hydrological alterations [65]. The brown pelican (*Pelecanus occidentalis*) was chosen as it has been documented to be impacted by human activities, both via competition from human fishing pressure, and also via mortality from entanglement and consumption of marine debris [63]. This species was listed under the Endangered Species Act until 2009, when it was removed from the Threatened and Endangered list, due to bans on contaminants that had historically

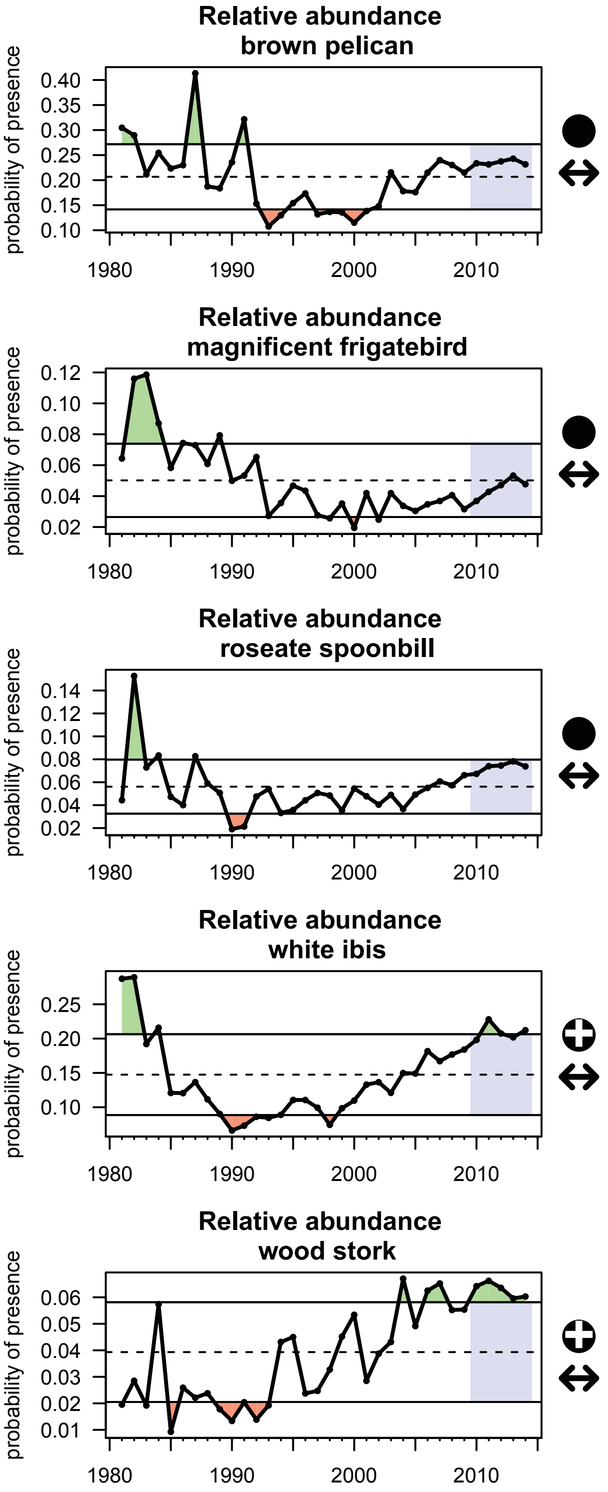


Figure 9.3. Relative indices of abundance for five bird species in the coastal GoM. Note different scales on y-axis; the relative magnitude applies only over the particular habitats sampled in the database, and thus differences among species do not reflect differences in total population abundance.

impacted the population. Finally, the magnificent frigatebird (*Fregata magnificens*) was chosen because its residency is generally restricted to coastal areas of the GoM and it is dependent on coastal habitats such as mangroves for nesting; also, it has a slower reproductive rate than other species considered and therefore, its trends in abundance will integrate a wider spectrum of factors.

We used the Cornell Lab of Ornithology's eBird database [66], an extensive, standardized compilation of volunteer and professional bird sighting observations. To construct relative indices of abundance, we used the eBird Reference Dataset [67]; only observations from GoM coastal watershed counties were included, and data were filtered to restrict to certain standardized count types and levels of observation effort. For the selected subset of the data, numbers of counts averaged about 100 per year in the 1980s and increased exponentially to nearly 60,000 counts in 2014 alone; counts prior to 1980 were sparse and therefore were not included. A generalized linear modeling framework was used to standardize the indices with respect to time of year, habitats, areas surveyed, sample method, and effort. The purpose of this approach was to remove the influence of the artifacts of the data set, such as variable observation effort in space and time, and differences in sampling over time.

The two open-water foraging species, brown pelican and magnificent frigatebird, demonstrate low relative abundance around the year 2000, and increase to above average in the last decade (Fig. 9.3). The two species in the ibis and spoonbill family demonstrate low abundances in the mid-1990s, with more recent increases to above average levels. The wood stork, known to have undergone drastic reductions in abundances due to hydrological alterations, was at below average abundances in the early years, and showed increases in relative abundance in the 1990s [68]. The index has been stable at levels well above average for approximately a decade (Fig. 9.3). A principal components analysis of the matrix of species abundances over time is used to find common linear trends among species, and the yearly scores from the first principal component can be indicative of shared external influences on the suite of species as a whole (Fig. 9.4). For the time period analyzed here, the first principal component explains over half the variation in trends among all 5 species, and is thus potentially a useful indicator for quantifying the factors influencing bird populations.

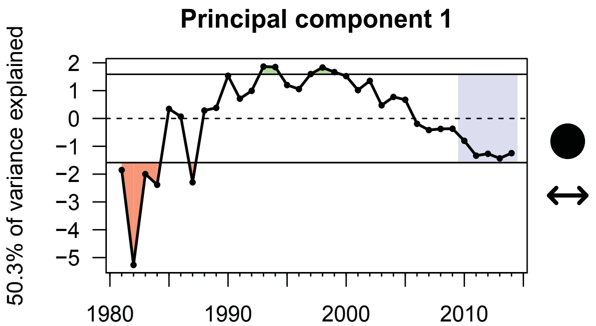


Figure 9.4. First principal component calculated from the matrix of bird species abundances. The unitless index is a representation of the overall rate change in abundances across the entire suite of species.

Ideally, abundance indices for true pelagic seabirds would be presented, as they would be more representative of the state of the pelagic ecosystem and the quality of the larger-scale forage base in the GoM. However, observations for such species are exceedingly rare in the eBird database, and other long-term monitoring data for these species are severely lacking [69]. A number of monitoring efforts have recently been initiated, including the Gulf of Mexico Avian Monitoring Network and the Gulf of Mexico Marine Assessment Program for Protected Species (GoMMAPPS); the latter is funded by the Bureau of Ocean Energy Management. Identification of priority species for monitoring is underway, and will include a suite of pelagic species such as terns, gulls, petrels, gannets, and shearwaters (J. Gleason, pers. comm.).

10. HUMAN DIMENSIONS

The human dimensions indicators collectively take a snapshot of the human condition across the Gulf Region. Working at such a large scale requires large data collection efforts such as the U.S. Census or regional fisheries management. Therefore, these indicators are likely familiar to a wide variety of stakeholders as they are used in many different contexts. The selected indicators are designed to give a general overview of the status and trends related to human dimensions, and can be tracked through time. For the GoM, maps of the indicators across the region also provide good insight into the dynamics and potential inequalities in coastal communities tied to Gulf-wide resources.

10.1 Human population

As of the 2010 Census, there were 24.4 million people living in the coastal watershed counties of the Gulf Coast (Fig. 10.1). The coastal watershed counties are intended to delineate those areas in which land use practices most directly affect coastal ecosystems, and are defined as counties where at least 15 percent of the total land area is

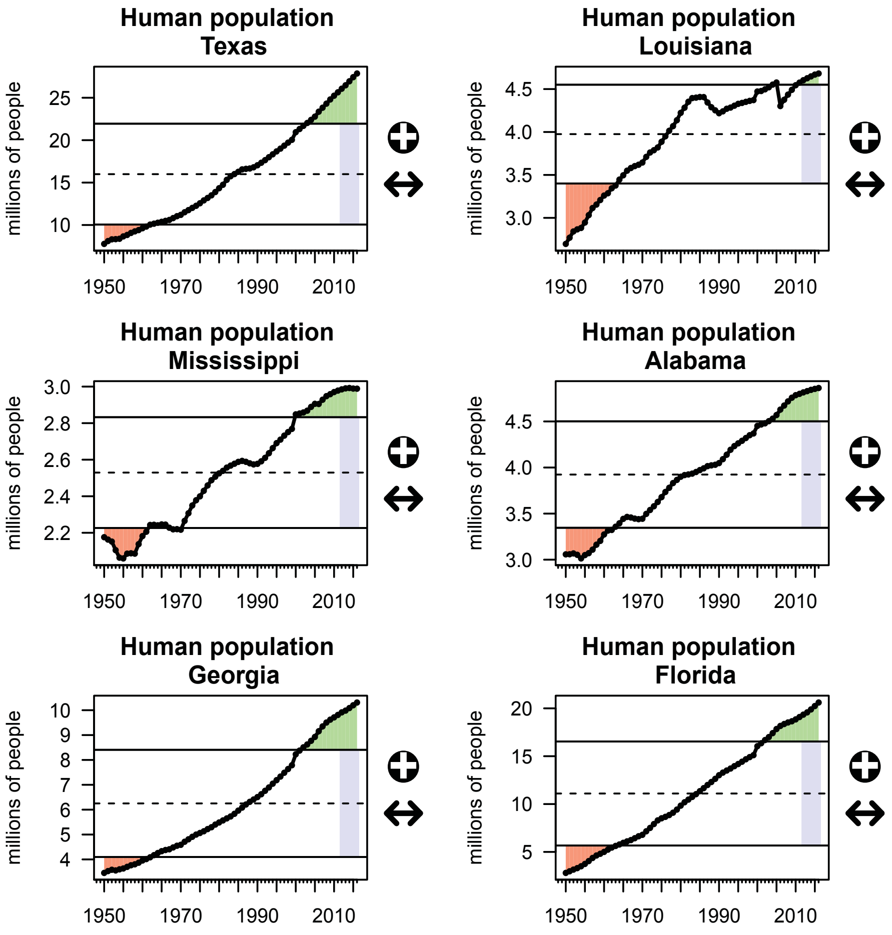
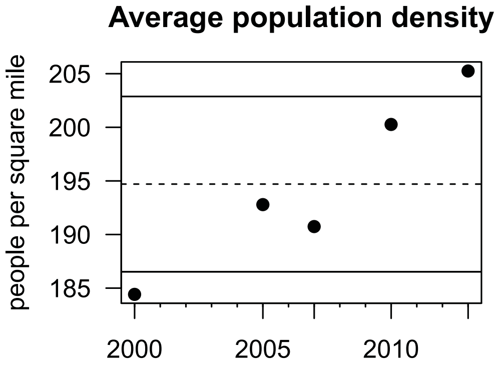


Figure 10.1. Total population across the coastal communities of the Gulf of Mexico by state. Note different y-axis scales.

located within a coastal watershed. For the Gulf of Mexico, the coastal watershed counties include several metropolitan areas with more than 1 million people: Houston, TX; St. Petersburg/Clearwater, FL; and Tampa, FL. Eighty percent of the counties gained population from 2000-2010, with Sumter County, FL and Fort Bend County, TX gaining more than 150%. The remaining 20% mostly showed small losses, with the exception of Orleans and Cameron Parishes in Louisiana, both of which lost more than 30% of their population. Data are from the American Community Survey 3-year estimates and decadal Census. Population is closely tied to economic opportunity and available resources to support that economic activity [70].

10.2 Population density



10.2. Average population density averaged across the coastal communities of the Northern Gulf of Mexico.

The 148 coastal watershed counties of the Gulf encompass a total of 119,183 square miles of land. Population density is generally low, with an average of 200 people per square mile in 2010 (Fig. 10.2). This includes five urban areas, as defined by a population density of over 1000 people per square mile: Hillsborough County, FL (Tampa), Pinellas County, FL (St. Petersburg/Clearwater), Jefferson Parish, LA (western New Orleans), Orleans Parish, LA (eastern New Orleans), and Harris County, TX (Houston) (Fig. 10.3). Population density is growing in accordance with the population growth in the region, increasing from an average of 184 people per square mile in 2000 to approximately 205 people per square mile as of 2013 (Fig. 10.2). Data are from the American Community Survey 3-year estimates and decadal Census. Population density is largely driven by urbanization, which is increasing globally, and by people concentrating around available resources [70]. The urban areas in the Gulf region both grew and

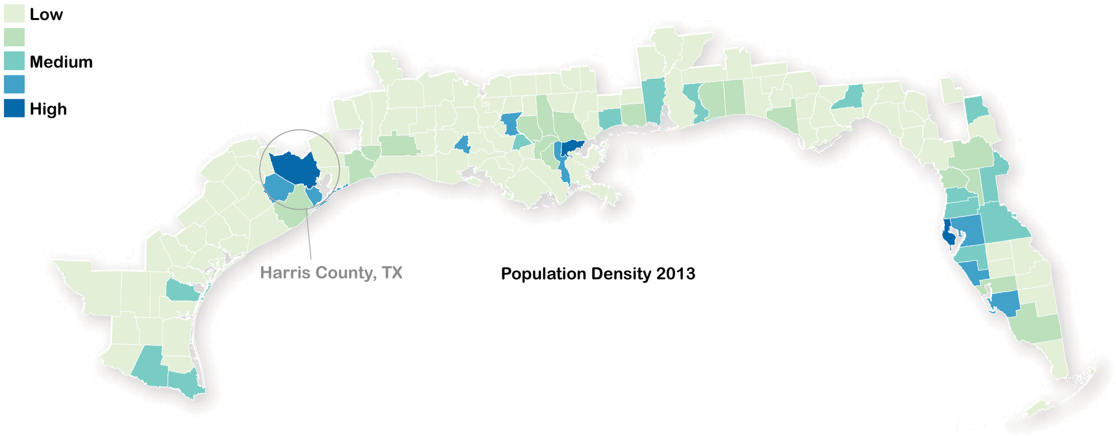


Figure 10.3. Levels of population density by county in 2013.

became more dense since 2000, suggesting that urbanization and human migration are important social forces in the region.

10.3 Coastal urban land use

Land cover and land cover change data obtained from satellite imagery can give an overall picture of environmental change, and may be an important indicator of pressures on various ecosystems within the GoM coastal environment. Land cover change data have also been shown to provide a useful indicator of ecosystem services provided in the region [71]. The data used in these analyses are derived from the Coastal Change Analysis Program (C-CAP) within the National Oceanic and Atmospheric Administration (NOAA) Office for Coastal Management.

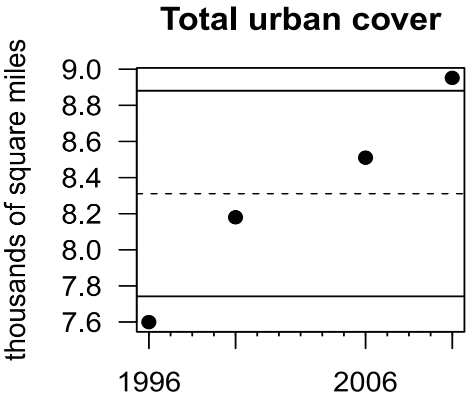


Figure 10.4. Total area described as urban cover across the Gulf of Mexico coastal watershed counties.

Urban land cover represents a relatively small amount of the total land cover, totaling

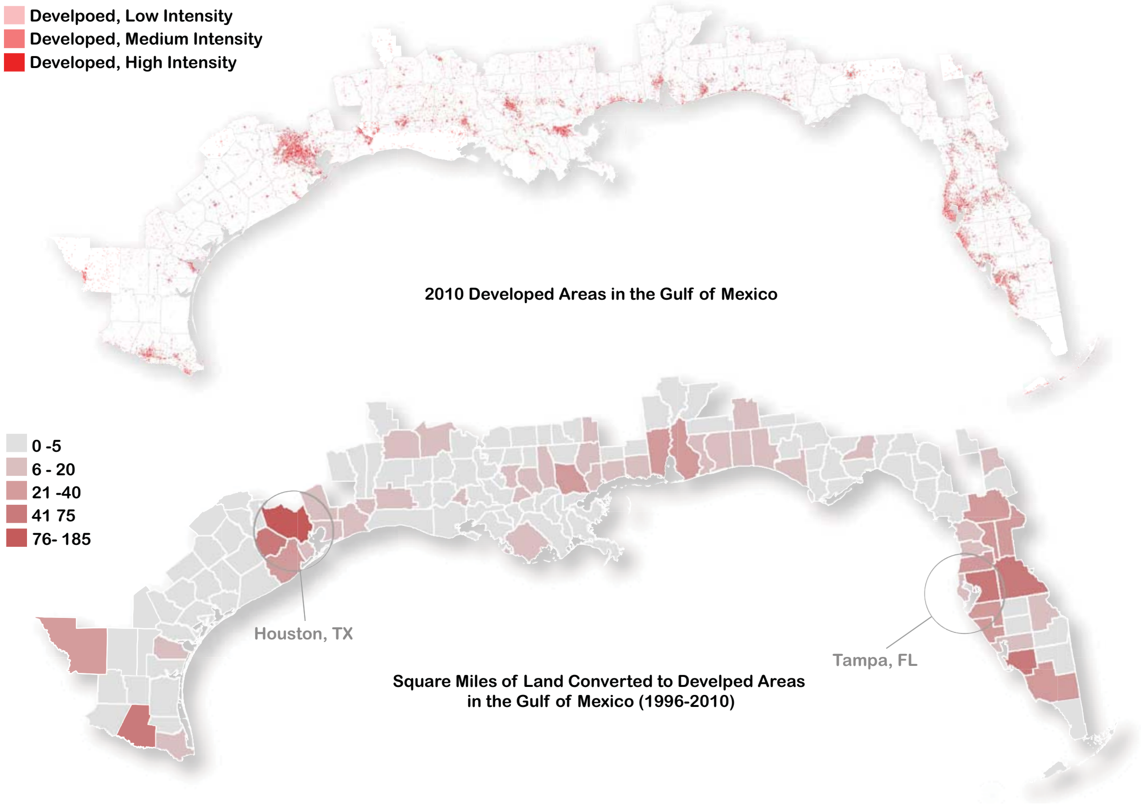


Figure 10.5. Level of development in coastal watershed counties of the Gulf of Mexico region (top) and total area of land converted to developed area by county from 1996-2010 (bottom).

approximately 5% of the GoM region. This land use type, while covering a spatially small area, represents a significant strain on the environment due to the influence on ecosystems, high degree of impervious surfaces, amount of pollutants discharged, and the fact that these areas contain the vast majority of the regional human population. Urban land cover classes which include low-intensity development (21 to 49 percent impervious surfaces), medium-intensity development (50 to 79 percent impervious surfaces), high-intensity (80 to 100 percent impervious surfaces), and developed open spaces increased in the GoM between 1996 to 2010, at a rate of more than 15% (Fig. 10.4). While this urban expansion is significant across the region as a whole, this increase in development occurred at a much higher pace in certain geographic areas (Fig. 10.5). For example, in Harris County and Fort Bend County, Texas, which contain the city of Houston, approximately 240 miles of land were converted into developed land. This represents a rate of change of more than 80% in these counties between 1996 and 2010.

10.4 Total ocean economy

The 72 coastal shoreline counties of the GoM collectively contribute around 600,000 jobs and close to 100 billion dollars in gross domestic product (GDP; Figs. 10.6 and 10.7). For the coastal counties, employment fluctuates but is relatively stable, and GDP has increased 60% since 2000; this is in contrast to a 35% decline since 2000 in ocean-related GDP for the Gulf states as a whole (in 2013 inflation-adjusted dollars). The top ocean-related GDP contributing coastal counties in 2013 were: Pinellas County (FL), Lafourche Parish (LA), Orleans Parish (LA), St. Tammany Parish (LA), Terrebonne Parish (LA), Harris County (TX), and Nueces County (TX). These data are collected annually by the Bureau of Labor Statistics and summarized for coastal counties as part of the National Oceanic and Atmospheric Administration's Office for Coastal Management Economics: National Ocean Watch (ENOW) program. The total ocean economy includes six categories: living resources, marine construction, marine transportation, offshore mineral resources, ship and boat building, and tourism and recreation. The coastal counties vary in the main source of their GDP across these categories; this economic diversity for the region as a whole is considered beneficial, as it provides resilience to dynamics

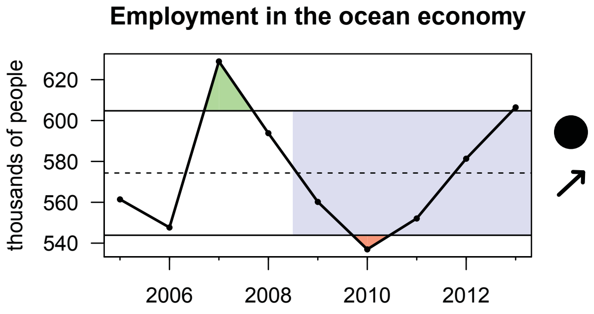


Figure 10.6. Total employment across the Gulf of Mexico region.

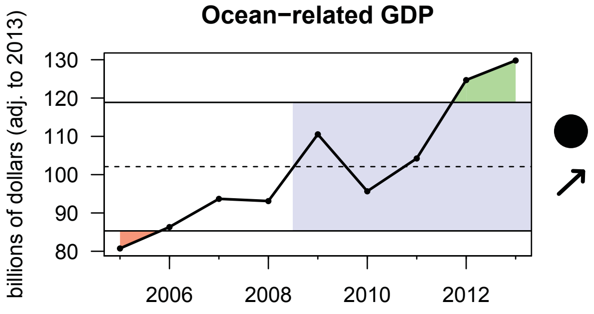


Figure 10.7. Total ocean-related gross domestic product (adjusted to 2013 inflation levels) across the Gulf of Mexico region.

within a single industry. While GDP indicates the overall size of the economy, employment numbers are a better indicator of how well economic growth is distributed among the population, and both should be considered when evaluating the health of the economy.

10.5 Landings and revenue from commercial fishing

Gulf-wide commercial landings and inflation-adjusted revenues are provided from 1950 through 2015. Commercial landings in the Gulf peaked in the mid-1980s and have seen a downward trend, with a marked decline in 2010 (Fig. 10.8). Revenues peaked in the late 1970s and again in the mid-1980s, and have generally declined up until 2010. Since 2010, landings and revenues have rebounded close to the time series average.

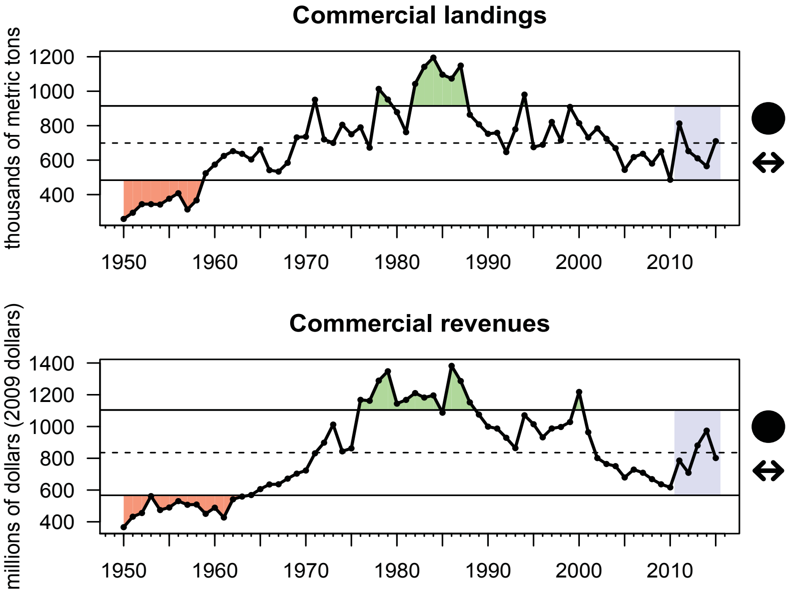


Figure 10.8. Yearly commercial landings for the Gulf of Mexico (top) and the associated inflation-adjusted commercial revenues (bottom).

Commercial landings in pounds and value at the county level come from the Accumulated Landing System database, which contains dealer addresses. Gulf coastal counties with the highest volume of landings in pounds are concentrated in Louisiana and Mississippi (Fig. 10.9). Both of these states have menhaden processing plants that contribute a large amount of pounds to landings. In terms of landings values, there is a concentration of counties in the state of Louisiana, with exceedingly high landings values. However, all Gulf states have counties with high landings values, which is driven in many areas by the shrimp industry. Lobster and stone crab fisheries are important to South Florida, with Monroe and Pinellas as the leading counties in the state. Texas has significant landings values in Galveston and Cameron counties, with Jefferson and Matagorda counties also contributing. In Louisiana, the parishes of Plaquemines and Terrebonne lead in landings value, with Jefferson, Lafourche and Vermilion parishes also contributing substantially.

10.6 Social connectedness

The social capital of a location is an aspect of coastal community well-being that is challenging to quantify. Social connectedness is a composite index of factors which indicate, at the community level, the social support present as well as residents' place attachment. These

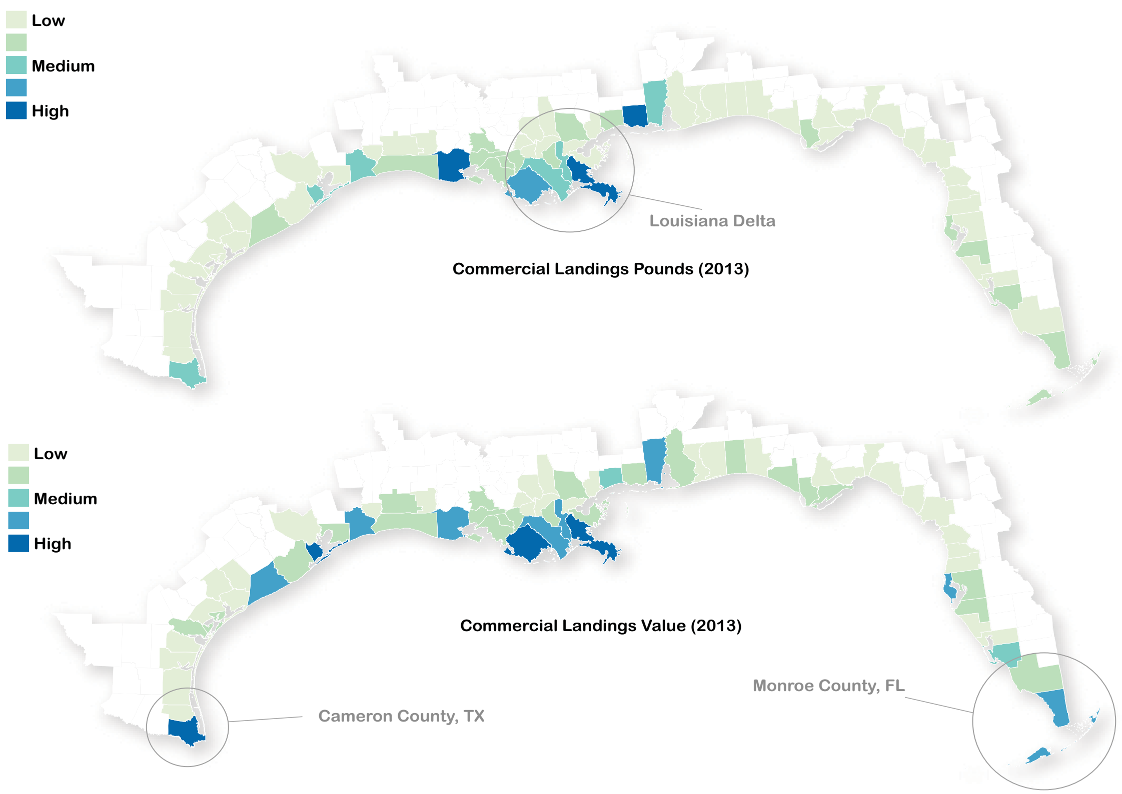


Figure 10.9. Commercial landings levels by county in 2013 (top) and the values of those landings for the same year (bottom).

concepts help describe factors such as residents' ability to rely on social capital in difficult times, and how they place value on the natural and cultural landscape of the region.

The social connectedness indicator was developed as part of a well-being measure of coastal communities [72] and is based on data derived from the decadal Census, the National Center for Charitable Statistics, and voter participation rates [73]. The average social connectedness fluctuates but shows a slight decline over time, with the average in 2012 of 38.2% of possible social connectedness attributes examined (Fig. 10.10). Some counties consistently score in the top 10% of the range of social connectedness (St. James Parish, LA; Amite County, MS; Wilkinson County, MS; Fayette County, TX) while others consistently score in the bottom 10% (Desoto County, FL; the Rio Grande Valley, TX; Cameron County, TX; Hidalgo County, TX; and Webb County, TX) (Fig. 10.11).

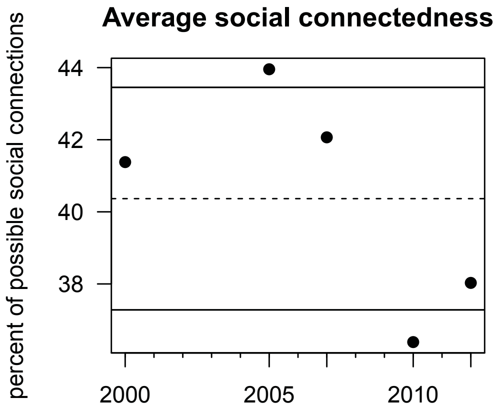


Figure 10.10. The average social connectedness indicator averaged across the Gulf of Mexico region.

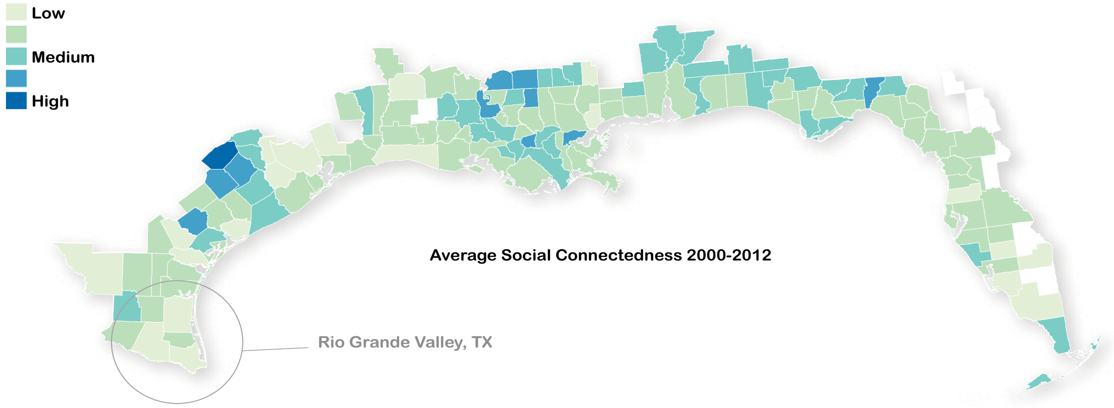


Figure 10.11. Average social connectedness levels by county from 2000-2012.

10.7 Commercial and recreational fishing engagement

Commercial and recreational fishing engagement and reliance are measures of sector fishing activity at the county level from federal fisheries datasets. Commercial and recreational fishing engagement is measured by the absolute numbers of the respective activity. For example, for

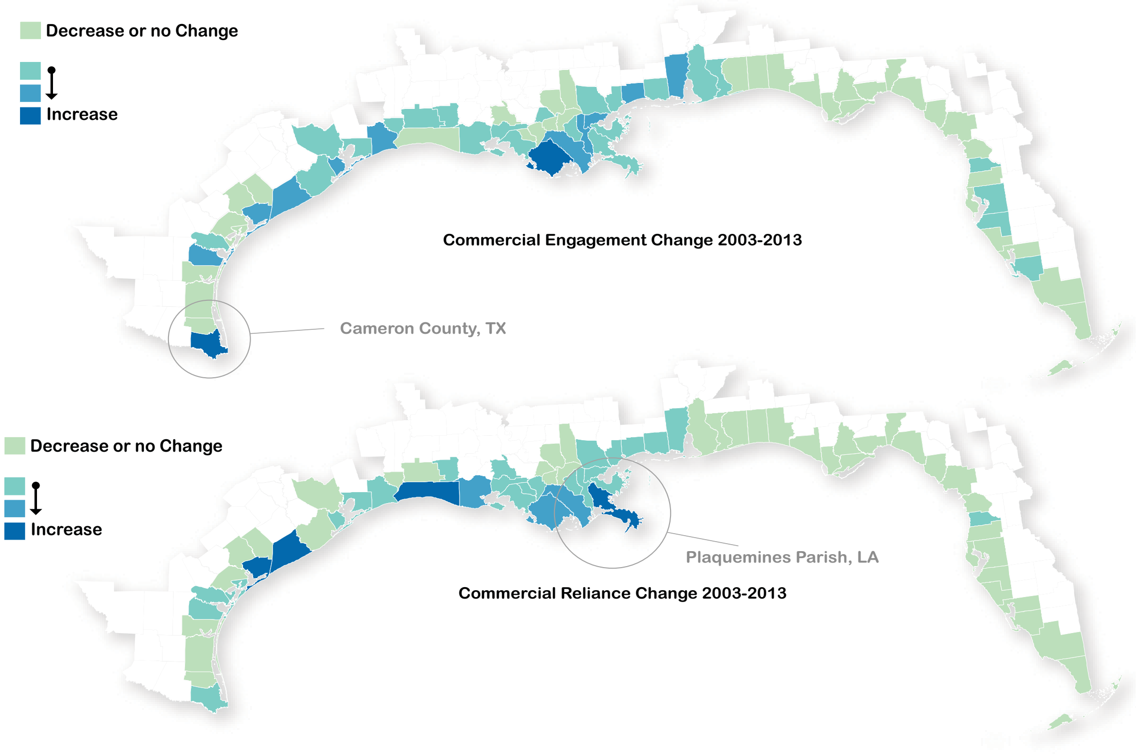


Figure 10.12. Level of commercial engagement change by county from 2003-2013 (top) and level of commercial reliance change by county from 2003-2013 (bottom).

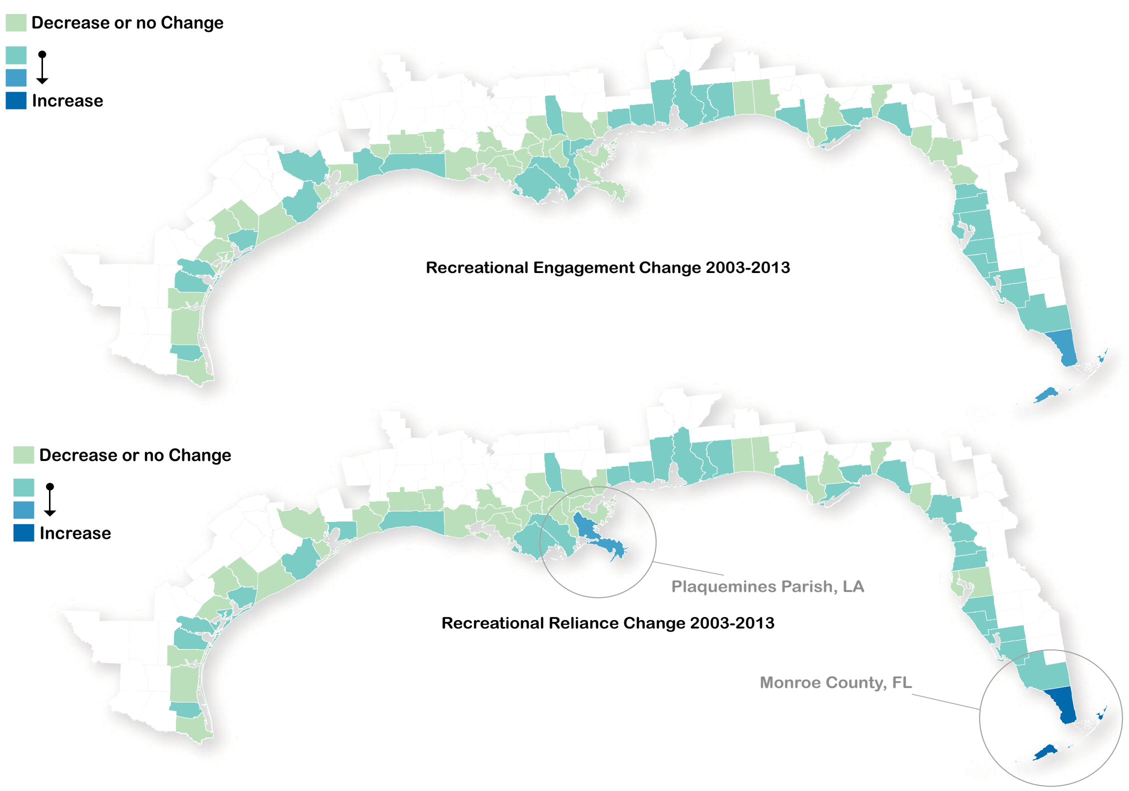


Figure 10.13. Level of recreational engagement change by county from 2003-2013 (top) and level of recreational reliance change by county from 2003-2013 (bottom).

commercial fishing engagement the index is derived from the actual pounds of landings, the number of commercial vessels by homeport address, the number of commercial vessels by owner's address, and the number of dealers with landings. The recreational engagement index is derived from the number of recreational vessels by homeport address, number of recreational vessels by owner's address, and number of recreational infrastructures (boat ramps associated with community). The commercial and recreational reliance indices are relative measures consisting of the same variables related to commercial or recreational fishing activity, but divided by the population of the community. These variables are then put into a principal component analysis with a single factor solution [74]. The factor score becomes the engagement or reliance index score for the community. These factor scores were then compared from 2003 to 2013 and the amount of change was calculated. Values below the mean denote a decrease, while values above the mean denote an increase in either engagement or reliance.

Most Gulf coast counties have seen a decrease or slight increase in their commercial fishing engagement and reliance (Fig. 10.12). Coastal counties in Louisiana and Texas have seen large increases in both their engagement and reliance on commercial fisheries. However, Cameron and Vermilion Parishes have seen decreases in their commercial fishing engagement and an increase in their commercial fishing reliance. For recreational fishing engagement and reliance, most counties have again seen a decrease or very slight increase in both engagement and reliance (Fig.

10.13). Monroe County, Florida has seen a large increase in its recreational fishing engagement and an even larger increase in its recreational fishing reliance. Plaquemines Parish, Louisiana has seen a slightly larger increase in its recreational fishing reliance.

10.8 Recreational fishing effort

Recreational fisheries are of great importance to the Gulf region; the GoM alone accounts for nearly half of all of the marine recreational harvest in the United States [75]. Recreational effort in terms of angler trips is measured by NMFS via the Marine Recreational Fishery Statistics Survey (MRFSS), recently updated to the Marine Recreational Information Program (MRIP), and in Texas by the Texas Parks and Wildlife Department. The reported index includes effort for shore, private, charter, and headboat sectors of the recreational fishery (with the exception of Texas, which includes only private and charter sectors). Charter vessels and headboats (or party boats) are both part of the for-hire sector; charter vessels tend to be smaller and charge on a vessel basis, whereas headboats carry a greater number of passengers and charge on a per passenger basis. Angler days are reported from the NMFS Headboat Survey and are stated in terms of normalized 12-hour trips (e.g., two 6-hour trips would equal a single angler day).

The two indicators of recreational effort are not well correlated, as a result of the variety of economic, biological and societal issues affecting the frequency and nature of fishing trips (Fig. 10.14). Angler trips were generally below average in the 1980s and 1990s, and remained above average after the year 2000. On the contrary, angler days were above average prior to 2000 and below average thereafter. Based on conversations with headboat industry captains and staff and port agents, one of the major factors driving effort is fuel prices (K. Brennan pers. comm.), which peaked during the 2008 main fishing season, crashed in 2009, increased through 2010 and 2011, and have generally decreased since. To maintain revenues, headboat owners are therefore more likely to take more frequent, but shorter, fishing trips. Private and charter boat modes, which are generally composed of smaller boats with fewer passengers, may have more flexibility in the decision to go fishing than headboats, which may need a higher minimum number of customers to warrant the costs of a trip. Other influential drivers of effort in the GoM are related to regulatory factors (e.g., length of

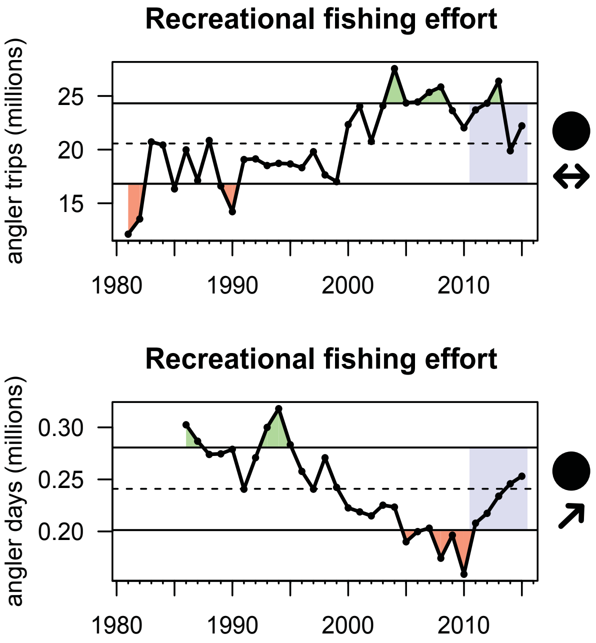


Figure 10.14. Gulf-wide recreational fishing effort expressed in terms of angler trips (top) and angler days (bottom).

closed season), tourism levels, and environmental factors [76]. The year 2008 was notable in terms of hurricane activity, with two named tropical storms and two major hurricanes, the latter of which caused significant damage and disruptions to areas of Texas and Louisiana (K. Brennan pers. comm.). In the past five years, angler days have increased significantly while angler trips have remained relatively stable. Notably, 2015 was the first year in the entire time series where both angler trips and angler days were both above average, indicating that the sector as a whole is making more frequent and longer trips.

10.9 Integrated human dimensions perspectives

Considering the full suite of human dimensions indicators, it can be observed that certain regions have changed significantly since 2000 (the first available year of data for most indicators). Some of these changes are related to national trends in urbanization, land cover changes, and population growth, overlaid with local events like Hurricane Katrina and Deepwater Horizon. For example, population density increased rapidly around Houston after Hurricane Katrina, while population in low-lying areas decreased; this suggests that natural disasters may concentrate population growth and resettlement around urban areas and intensify the effects of urbanization. The Gulf-wide trends also make apparent the need for smaller-scale, community-level analysis. For example, the loss of wetland area in coastal Louisiana, (Cameron Parish, and in the Delta) and the reliance on commercial fishing engagement in the same region suggest a stronger need for social connectedness and other measures of resilience that are best measured at a community scale. The Gulf-wide status report underscores a need to look more carefully at these communities in particular (i.e. Cameron Parish, LA, or the communities directly hit by Katrina), as broad trends across the region are likely more pronounced at the community scale. It is also important to note that the interaction of these social trends with changes in the natural environment create a feedback loop: changes in the environment cause changes in the human community, which in turn cause societies to make decisions that affect that natural environment.

11. INTEGRATED ECOSYSTEM PERSPECTIVES

For the purpose of synthesizing the information contained in the full suite of indicators presented here, we categorize indicators broadly as drivers, states, and responses. Drivers may include everything from global climate effects to changes in local habitats, but generally are indicators that are thought to be responsible for producing change in the ecosystem. States include largely biological components of the ecosystem that respond to the underlying physical drivers. Responses can be biological, social, or economic in nature and can include ecosystem services [4] or other processes that respond to changes in the biological ecosystem. Some responses, such as human population or fishing effort, can in turn be drivers as they also produce changes in the biological ecosystem. The categorization is used to highlight broad trends; however in reality these categorizations can be somewhat fuzzy in nature.

A traffic light plot of the indicator suite is presented for the purpose of comprehensively viewing changes in the different parts of the ecosystem over time (Fig. 11.1). The traffic light plot is created by color-coding the value of the indicator each year according to quintiles; colors from red to yellow to blue show that the indicator moving between below, at, and above average, respectively (see legend). Indicators are grouped by category, and appear on the plot sorted by their loading (i.e., their influence) from a principal components analysis. In this way, indicators showing similar patterns across time are grouped more closely together. Synthesis of indicators presented in the first 2013 Ecosystem Status Report revealed the presence of an ecosystem-wide reorganization occurring around the mid-1990s, potentially driven by a regime change in the Atlantic Multidecadal Oscillation (AMO) [2]. In the process of selecting indicators for this report, we purposefully cut down on indicators that were

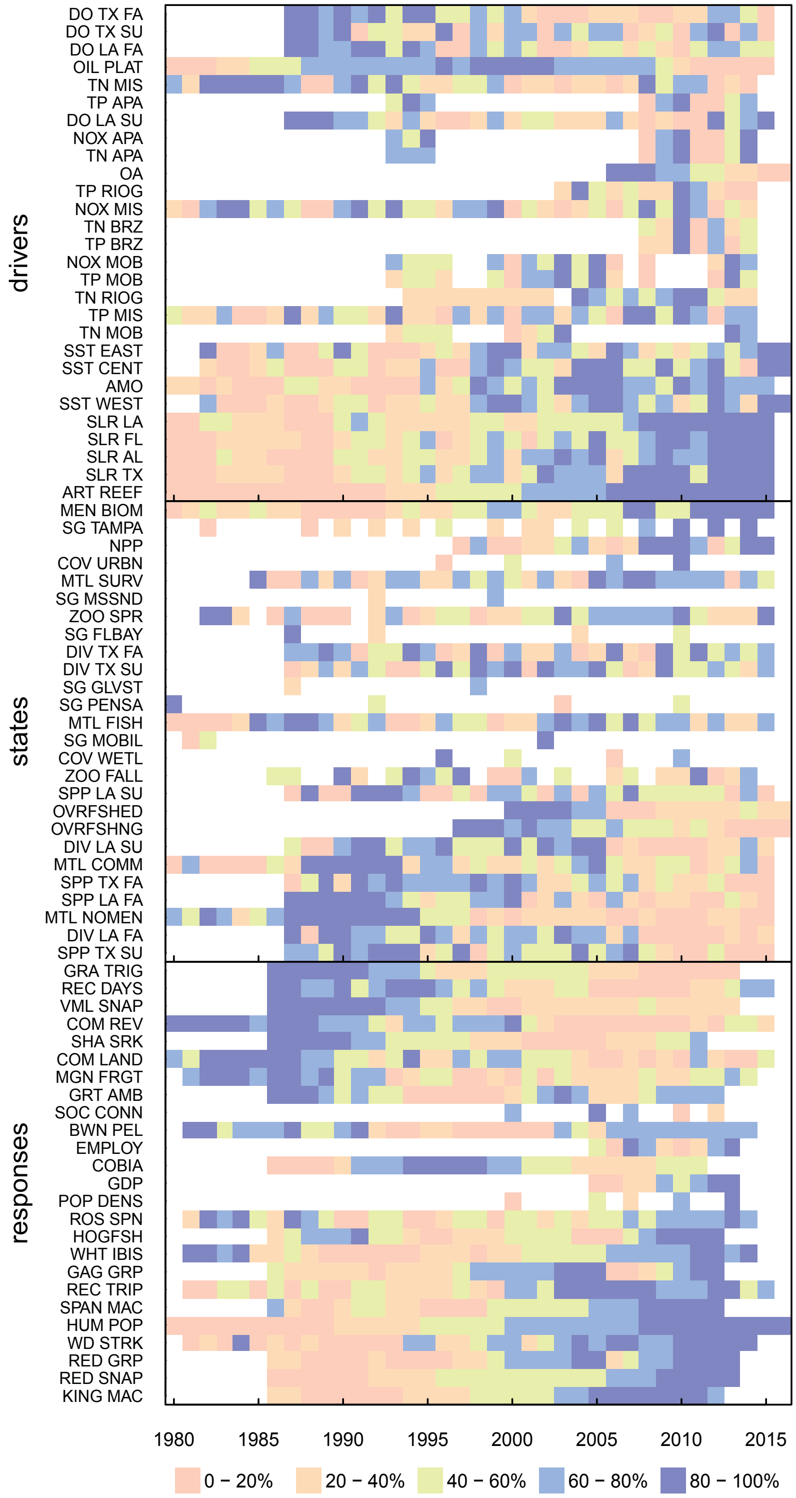


Figure 11.1. Traffic plot of all indicators presented in this Update Report. The indicators are sorted by category and appear in order of their first principal loading from a principal components analysis, which groups indicators with similar trends more closely together.

redundant, which included a number of physical and biological factors that were correlated with the AMO, and thus the shift should be less pronounced. Still, a visual analysis of the traffic plot indicates a time period of rapid change in most indicators occurring around the mid-1990s.

Plots of historical trends versus recent trends and historical variability versus recent variability allow for a composite view of the relative changes in the entire ecosystem over the last five years. The historical period is defined as 1980 (or the first year of data availability) to 2011, and the recent period is defined as 2011 to the last year of data availability. The trend plot is produced by fitting a linear regression through the historical period and the recent period, and plotting the slopes on the two axes. Points falling within the shaded region denote indicators where the trends have recently decreased in comparison to historical trends, whereas points in the unshaded region are indicators with trends that have increased compared to the historical trend (Fig. 11.2). The variability plot is produced by calculating the absolute scaled year-to-year changes in indicator values for the historical period and recent period, and again plotting their means on the two axes. Points falling within the shaded region denote indicators that have stabilized in the recent period, whereas indicators in the unshaded region show more year-to-year variability in the recent period (Fig. 11.3). In both plots, indicators are color-coded by broad categories.

A number of important physical drivers have undergone significant changes in the recent period. The AMO has been increasing steadily from 1980 - 2011 and shifted from a negative to positive state in the mid-1990s. Since 2011, however, the trend in the AMO index has been slightly decreasing. Sea surface temperature monthly anomalies, which have increased at moderate rates from 1980 - 2011, have seen more dramatic increases in the recent period (2011 – 2016) in the eastern and western subregions. On the contrary, temperature anomalies in the central subregion have increased more slowly in the recent period. A recent review of climate-driven species migrations indicated movement occurring roughly between the western and central subregions [13] and it is plausible to suspect that different warming patterns in these areas could be driving these migrations. Sea level rise, also on the increase in the historical period, has increased more rapidly in the recent period across the entire GoM. In reference to modification of habitat via the installation of artificial structures, the growth in artificial reef installations has remained stable, while dramatic decreases have occurred in the number of oil platforms installed. In the recent period, platform installations have dropped dramatically and the total numbers of structures has declined – note however, that some rigs are converted to artificial reefs. Total nutrient inputs from several major watersheds have also declined in the recent period, with the exception of the Apalachicola River where inputs have increased; however these results are based on a short and highly variable time series. Summer and fall dissolved oxygen concentrations have decreased in Texas, but increased in Louisiana coastal waters in recent years.

Recent trends in ecosystem states have remained somewhat similar to those seen in the historical period, with the exception of menhaden biomass and the biodiversity measures. The recent rapid increase in menhaden biomass is due to a reduction in fishing pressure driven by market forces, as described above. The large increase in year-to-year variability in menhaden biomass should be interpreted with caution as the index is a stock assessment output; typically, the most recent years of the assessment are the most poorly informed and this may lead to more noise in the biomass estimates. Some of the species diversity indices have stabilized in the recent period, which may reflect a true stabilization of the species composition in the ecosystem, or could be the result of standardization of the SEAMAP survey methods. The trend in number of overfished stocks has become more positive; however, this is as a result of recent stabilization at

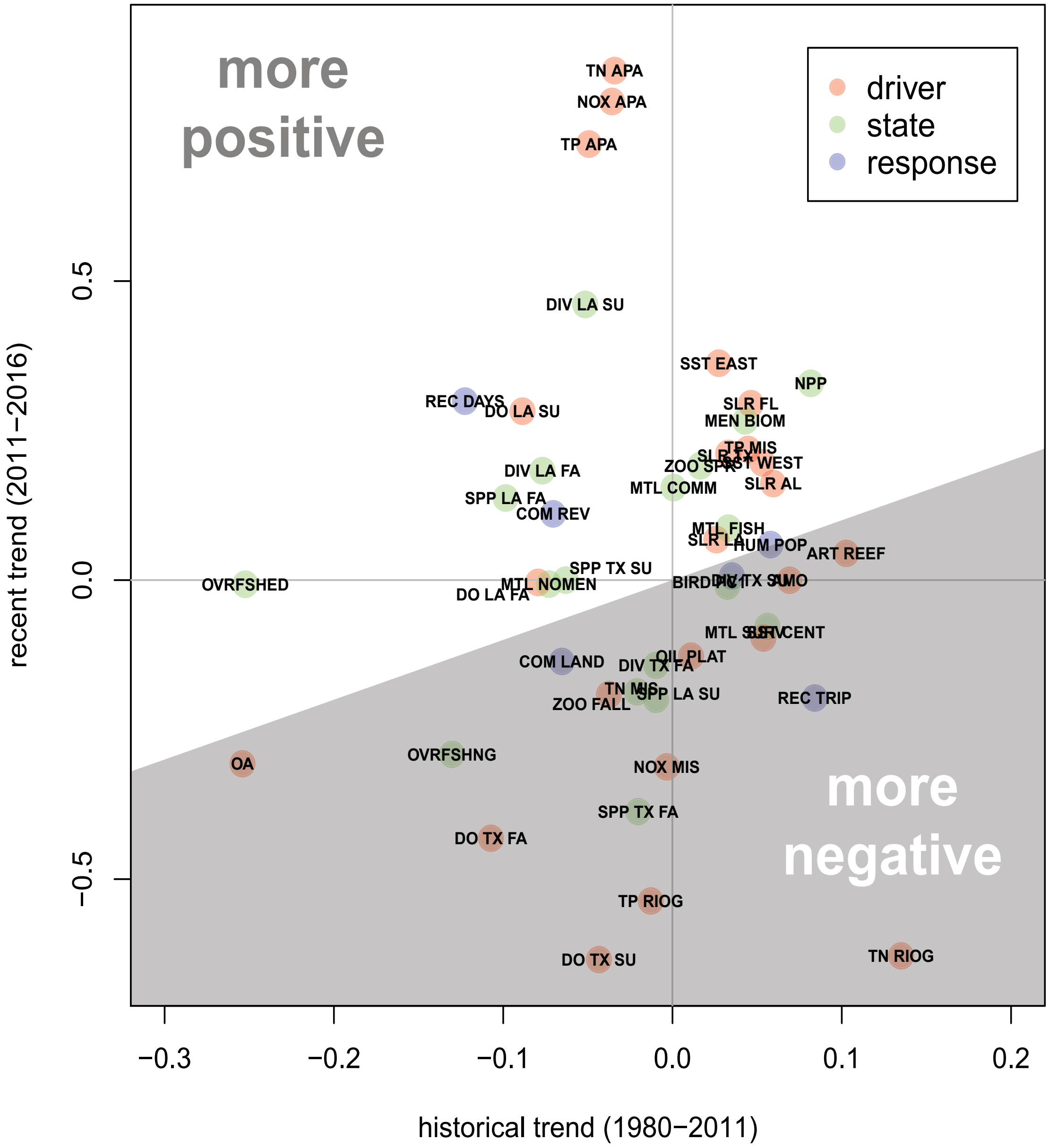


Figure 11.2. The least-squares linear trend through the indicators during the historical period plotted against the linear trend through the recent period.

low levels after having experienced a decline from nearly half of stocks overfished to less than one-fifth, during the historical period. On the other hand, the number of stocks undergoing overfishing was decreasing historically, and has decreased even more rapidly in the recent period. Mean trophic level of all commercial finfish except menhaden has become less stable in the recent period, largely due to high variability in snapper and grouper catches. On the contrary, mean trophic level of all commercial species except menhaden has become more stable, due to a leveling in landings of both total finfish and invertebrate landings in recent years.

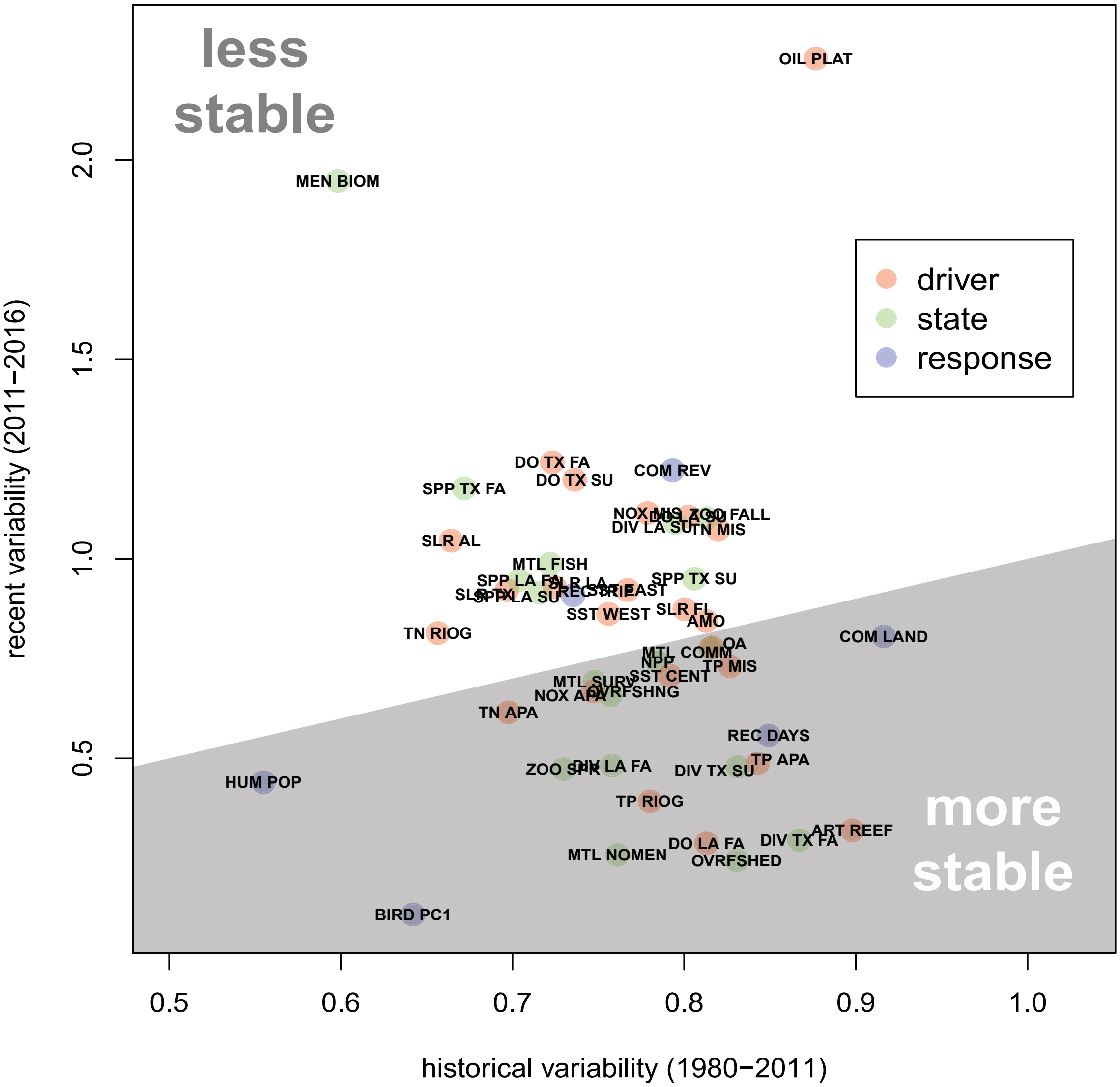


Figure 11.3. Absolute scaled year-to-year differences during the historical period plotted against differences during the recent period.

A number of ecosystem responses have become increasingly positive and stable in the recent period, although most of these indicators lack sufficient time series length with which to analyze trends. Recreational fishing effort and commercial revenues have both recently increased after having decreased during the historical period. The first principal component of the suite of bird species has shown increased stability in the recent period, although this may be due to statistical artifacts. Observer coverage in the eBird database has increased dramatically in recent years, which should lead to more precise estimates and decreased noise in the index.

The specification of the “short-term period” as the five most recent years of data is a standard that has been used in other NOAA Fisheries ecosystem assessments [77, 78]. In the GoM, the five-year cutoff coincides roughly with a major event: the Deepwater Horizon oil spill, which occurred in April and May of 2010. It is important to note that the indicators in this report, and the spatial scales over which they were calculated, were not selected for the purpose of understanding this event. Therefore, any short-term trends reported here should not be interpreted as resulting from oil spill impacts. Furthermore, different ecosystem processes have different lag times in responding to such an event, which may or may not coincide with the recent five year period. A careful consideration of the indicators presented here, at the appropriate temporal and spatial scales, is needed to perform a more robust assessment of the ecosystem impacts of the DWH event. Such an analysis is currently underway and will be published separately from this 2017 Update report.

12. RESEARCH RECOMMENDATIONS

This report is designed to assess the state of the GoM using indicators at a single spatial scale; Gulf of Mexico-wide, or at broad subregional scales. Further work needs to be done to analyze indicators at the appropriate spatial scales for the investigation being undertaken. Relevant signals are often “hidden” when indicators are considered at the Gulf-wide scale, because they are being averaged over such a large spatial scale. For example, sea surface temperatures are relatively stable across the northern Gulf as a whole in recent years, but coincident patterns of warming and cooling are apparent at regional scales. The appropriate scales to be considered may vary by process and by the management question at hand. At minimum, select indicators could be recalculated across varying domains, to determine the scales at which processes and pressures affect the GoM.

Several of the indicators could potentially be improved through enhanced data discovery, standardization, and analysis. The eBird database contains an extensive amount of information and could be used to develop a variety of indicators representing different processes in addition to the five indicators on birds used in this report. This could include developing indicators regarding the activity of the birders, themselves, rather than just the birds they are observing. For example, one could use the database to better understand the tourism value of birds to the region. The bird indices of abundance presented in this report are a preliminary effort, and warrant further refinement and development. The selected suite of indicator species should be refined in future updates. Also, true pelagic bird species are not well represented due to low occurrence rates in the database. Alternative statistical methods or data sources should be explored to create abundance indices for pelagic species.

Zooplankton species and population distribution have proven to be a valuable indicator of whole ecosystem processes and shifts in many other coastal and marine ecosystems [79, 80]. In the GoM, zooplankton observations are collected routinely; however, the biovolume as a proxy for biomass of the total zooplankton community is the only aspect of the zooplankton community routinely quantified. Variability is observed in zooplankton biovolume (Fig. 7.2); however, the sensitivity of this indicator would be dramatically improved and the insights gained increased by orders of magnitude if these samples were analyzed to give us information on zooplankton species distributions and shifts. By knowing which species are present and dominant, a better understanding can be gained on how the trophic web is shifting to favor specific upper trophic level species, including economically and socially important species.

The eutrophication indicator is currently based upon nutrient loading from rivers that flow into the GoM, with the data dominated by routine, long-term measurements of the Mississippi River only. This does not give an accurate representation of whether nearshore coastal systems are experiencing the socially and ecologically undesirable effects of eutrophication. There is a technique already developed and applied in estuaries and embayments in the GoM to determine the degree of eutrophication [81, 82]. This National Estuarine Eutrophication Assessment determined the status of these estuaries in 1999 and 2007. This method should be re-applied using the more available data in these estuaries to understand the current status of eutrophication in these estuaries and quantify how eutrophication in GoM estuaries has changed over time. If this is accomplished, we can then examine the eutrophication status of estuaries in conjunction with the other indicators presented here to determine and quantify the degree to which eutrophication in estuaries affects estuarine-dependent fishery species and fisheries in the GoM.

This Update Report lacks information on protected species such as corals, sea turtles, and marine mammals. Overall, monitoring programs for these species are fragmented and sporadic, which limits the development of indicators to describe their status and trends [69]. Corals comprise a relatively small proportion of benthic habitat within the Gulf of Mexico, particularly if the well-studied Florida Reef Tract, located at the boundary of the Gulf of Mexico and the southeastern United States, is excluded. The best-studied coral reefs in the northern Gulf of Mexico are located within the Flower Garden Banks National Marine Sanctuary, which covers approximately 146 square km. This site is monitored by the NOAA Coral Reef Conservation Program's National Coral Reef Monitoring Plan [83] which has been implemented for the past five years, and the data generated from this program could provide a basis for future indicator development. For marine mammals, the expansion of existing research and monitoring programs and standardization of data collection and archiving are needed to provide information on status of these species [84].

The standardization and centrality of data collection, archiving, and access would improve our ability to accurately assess the status of the GoM ecosystem. For example, the estuarine habitat indicator, section 6.1, could only consider areal extent of seagrass habitats in six estuarine bays. This data had to be discovered, standardized, and collated specifically for this Report. This indicator currently ignores many other important estuarine habitats, including salt marshes, oysters, and mangroves. By standardizing the collection of data across the GoM, and improving its accessibility, we could likely investigate all of these habitat types across a larger number of estuarine bays and better understand estuarine habitat dynamics and change across the GoM.

Finally, the information contained in the indicators presented here would be more meaningful if accompanied by associated measures of uncertainty. All indicators, as measurements of processes in the ecosystem, have some measure of uncertainty associated with them. Calculating measures of variance and including these measures within each figure would allow for visualization of the amount of signal versus noise in each indicator. Additionally, it would be more useful to consider the significance of recent trends not only in light of the rate of change of the indicator, but also whether the change exceeds variability expected due to the uncertainty inherent in the measure. Quantification of indicator variance, as well as improved methods for considering the significance of recent trends, should be explored in future updates of the report.

While the current ESR explores a host of indicators across both ecological and human dimensions, there is need for increased transdicsciplinary analyses. Further integration and synthesis across biophysical or ecological indicators and indicators of human dimensions should be undertaken at various spatial and temporal scales. Thus, the improved standardization of data collection, archiving, and access needs to include the human dimensions indicators. Moreover, both human dimensions and biophysical indicators need to be developed, and the data collected with integration between the two disciplines as a primary purpose. These data could include analysis on more in-depth indicators related to the economy, and human health, as well as potential migration patterns after large scale events (such as hurricane Katrina and the DWH). Another line of inquiry might be the question of spatial and temporal scale, specifically focusing on how these relationships might change or decay with distance and time. For example, how far does a decline in shrimp productivity in the Louisiana delta influence shrimp fishers and how far do market impacts extend? In other words, is the effect only observed within Louisiana, or is it measurable across several states or the entire region? Similarly, do the impacts form a single year decline, or do they last for multiple years due to lags and produce non-linear changes? These potential impacts could include forced diversification into other industries, loss of employment, mental and human health impacts, and even migration.

13. ACKNOWLEDGMENTS

We thank Matt McPherson, Michael Schirripa, Pamela Fletcher, Scott Cross, and Steve Giordano for their input in the planning stages of this document. We acknowledge Bonnie Ponwith, Alex Chester, Randy Clark and Shannon Martin for reviewing the document and providing helpful comments. We acknowledge Ruben van Hooidonk for providing data on ocean acidification, Frank Muller-Karger for data on net primary productivity, Amy Schuller for data on menhaden abundance, and Penny Hall for providing data on seagrass. David Gloeckner and Steve Turner assisted with NOAA Fisheries commercial landings statistics, Vivian Matter and Kenneth

Brennan assisted with NOAA Fisheries recreational effort statistics and interpretation, and Shannon Cass-Calay assisted with stock assessment data. Craig Newton, James Sanders, and Mike McDonough provided assistance with data on artificial reef structures installed by state agencies. We thank Wesley M. Hochachka for guidance in using the Cornell University Lab of Ornithology's eBird dataset. We also thank Jeffrey Gleason for a helpful review of the bird abundance section. Finally, we thank the science and management community that provided feedback on the original Ecosystem Status Report. This research was carried out in part under the auspices of the Cooperative Institute for Marine and Atmospheric Studies (CIMAS), a Cooperative Institute of the University of Miami and the National Oceanic and Atmospheric Administration, cooperative agreement #NA10OAR4320143.

14. REFERENCES

[1] Karnauskas, M., M. Schirripa, C. Kelble, G. Cook and J. Craig. 2013. Ecosystem status report for the Gulf of Mexico. NOAA Technical Memorandum NMFS-SEFSC-653.

[2] Karnauskas, M., M. Schirripa, J. Craig, G. Cook, C. Kelble, J. Agar, B. Black, D. Enfield, D. Lindo-Atichati, B. Muhling, K. Purcell, P. Richards and C. Wang. 2015. Evidence of climate-driven ecosystem reorganization in the Gulf of Mexico. Global Change Biology, 21, 2554–2568.

[3] Niemeijer D. and R. S. de Groot. 2008. A conceptual framework for selecting environmental indicator sets. Ecological Indicators, 8, 14-25.

[4] Kelble, C. R., D. K. Loomis, S. Lovelace, W. K. Nuttle, P. B. Ortner, P. Fletcher, G. S. Cook, J. L. Lorenz and J. N. Boyer. 2013. The EMB-DPSER conceptual model: Integrating ecosystem services into the DPSIR framework. PLoS ONE, 8(8), e70766.

[5] Enfield, D., A. Mestas-Nunez and P. Trimble. 2001. The Atlantic Multidecadal Oscillation and its relationship to rainfall and river flows in the continental U.S. Geophysical Research Letters, 28, 2077-2080.

[6] McCabe, G. J., M. A. Palecki and J. L. Betancourt. 2004. Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States. Proceedings of the National Academy of Science, 101, 4136-4141.

[7] Shackell, N., A. Bundy, J. Nye and J. Link. 2012. Common large-scale responses to climate and fishing across Northwest Atlantic ecosystems. ICES Journal of Marine Science, 69, 151–162.

[8] Edwards, M., G. Beaugrand, P. Helaouet, J. Alheit and S. Coombs. 2013. Marine ecosystem response to the Atlantic Multidecadal Oscillation. PLoS ONE, 8(2), e57212.

[9] Liu, Y., S.-K. Lee, B. A. Muhling, J. T. Lamkin and D. B. Enfield. 2012. Significant reduction of the Loop Current in the 21st century and its impact on the Gulf of Mexico. Journal of Geophysical Research, 117, C05039.

[10] Zhang, L., C. Wang and L. Wu. 2012. Low-frequency modulation of the Atlantic warm pool by the Atlantic Multidecadal Oscillation. Climate Dynamics, 39, 1661–1671.

[11] Tam, J., J. Link, S. Large, K. Andrews, K. Friedland, J. Gove, E. Hazen, K. Holsman, M. Karnauskas, J. Samhouri, R. Shuford, N. Tolimieri and S. Zador. In review. Comparing apples to oranges: common trends in anthropogenic and environmental pressures across multiple marine ecosystems. Ecological Applications.

[12] Earth System Research Laboratory. Climate Indices: Monthly Atmospheric and Ocean Time Series. [Online]. Available: http://www.esrl.noaa.gov/psd/data/climateindices/. [Accessed 15 July 2013].

[13] Pinsky, M. L., B. Worm, M. J. Fogarty, J. L. Sarmiento and S. A. Levin. 2013. Marine taxa track local climate velocities. Science, 341, 1239-124.

[14] Fodrie, F., K. Heck, S. Powers, W. Graham and K. Robinson. 2010. Climate-related, decadal-scale assemblage changes of seagrass-associated fishes in the northern Gulf of Mexico. Global Change Biology, 16, 48-59.

[15] Coles, S. L. and B. Riegl. 2012. Thermal tolerances of reef corals in the Gulf: a review of the potential for increasing coral survival and adaptation to climate change through assisted translocation. Marine Pollution Bulletin, 72(2), 323-332.

[16] Harvell, C. D., K. Kim, J. M. Burkholder, R. R. Colwell, P. R. Epstein, D. J. Grimes, E. E. Hofmann, E. K. Lipp, A. D. M. E. Osterhaus, R. M. Overstreet, J. W. Porter, G. W. Smith and G. R. Vasta. 1999. Emerging marine diseases - climate links and anthropogenic factors. Science, 285(5433), 1505-1510.

[17] Reynolds, R. W., T. M. Smith, C. Liu, D. B. Chelton, K. S. Casey and M. G. Schlax. 2007. Daily high-resolution-blended analyses for sea surface temperature. Journal of Climate, 20, 5473-5496.

[18] Roberts, K., J. Collins, C. H. Paxton, R. Hardy and J. Downs. 2014. Weather patterns associated with green turtle hypothermic stunning events in St. Joseph Bay and Mosquito Lagoon, Florida. Physical Geography, 35(2), 135-150.

[19] Barlas, M. E., C. J. Deutsch, M. de Wit and L. I. Ward-Geiger, eds. 2011. Florida manatee cold-related unusual mortality event, January-April 2010. Final report to USFWS (grant 40181AG037). Florida Fish and Wildlife Conservation Commission, St. Petersburg, Florida.

[20] Adams, A. J., J. E. Hill, B. N. Kurth and A. B. Barbour. 2012. Effects of a severe cold event on the subtropical, estuarine-dependent common snook, *Centropomus undecimalis*. Gulf and Caribbean Research, 24(1), 13-21.

[21] NOAA Center for Operational Oceanographic Products and Services. NOAA Tides and Currents. 2016. [Online]. Available: https://tidesandcurrents.noaa.gov/sltrends/sltrends.html.

[22] National Science and Technology Council. 2000. Integrated assessment of hypoxia in the northern Gulf of Mexico. National Science and Technology Council, Committee on Environment and Natural Resources.

[23] U.S. Geological Survey. Coastal Rivers - Nitrate Loads and Yields. 2016. [Online]. Available: https://cida.usgs.gov/quality/rivers/coastal.

[24] Bianchi, T. D. S., J. Cowan Jr., R. Hetland, P. Chapman, J. Day and M. Allison. 2010. The science of hypoxia in the northern Gulf of Mexico: A review. Science of the Total Environment, 408, 1471-1484.

[25] Scavia, D., N. Rabalais, R. Turner, D. Justic and W. J. Wiseman. 2003. Predicting the response of Gulf of Mexico hypoxia to variations in Mississippi River nitrogen load. Limnology and Oceanography, 48(3): 951–956.

[26] Le Quéré, C., R. M. Andrew, J. G. Canadell, S. Sitch, J. I. Korsbakken, G. P. Peters, A. C. Manning, T. A. Boden, P. P. Tans, R. A. Houghton, et. al. 2016. Global Carbon Budget 2016. Earth System Science Data, 8(2), 605-649.

[27] Takahashi, T., S. Sutherland, R. Wanninkhof, C. Sweeney, R. Feely, D. Chipman, B. Hales, G. Friederich, F. Chavez, C. Sabine and A. Watson. 2009. Climatological mean and decadal change in surface ocean pCO2, and net sea–air CO2 flux over the global oceans. Deep Sea Research Part II: Topical Studies in Oceanography, 56(8), 554-577.

[28] Bakker, D., B. Pfeil, C. Landa, N. Metzl, K. O'Brien, A. Olsen, K. Smith, C. Cosca, S. Harasawa, S. D. Jones, et al. 2016. A multi-decade record of high-quality fCO2 data in version 3 of the Surface Ocean CO2 Atlas (SOCAT). Earth System Science Data, 8, 383-413.

[29] Huang, W.-J., W.-J. Cai, Y. Wang, S. E. Lohrenz and M. C. Murrell. 2015. The carbon dioxide system on the Mississippi River-dominated continental shelf in the northern Gulf of Mexico: 1. Distribution and air-sea CO2 flux. Journal of Geophysical Research: Oceans, 120(3), 1429 - 1445.

[30] van Hooidonk, R., J. Maynard, D. Manzello and S. Planes. 2014. Opposite latitudinal gradients in projected ocean acidification and bleaching impacts on coral reefs. Global Change Biology, 20, 103–112.

[31] Handley, L., D. Altsman and R. DeMay, eds. 2007. Seagrass status and trends in the northern Gulf of Mexico: 1940-2002. U.S. Geological Survey Investigations Report 2006-5287 and U.S. Environmental Protection Agency 855-R-04-003.

[32] Handley, L., K. Spear, C. Thatcher and S. Wilson, eds. 2016. Emergent wetlands status and trends in the northern Gulf of Mexico: 1950-2010. U.S. Geological Survey and the U.S. Environmental Protection Agency, https://gom.usgs.gov/web/Site/EmWetStatusTrends.

[33] Cicchetti, G. and H. Greening. 2011. Estuarine biotope mosaics and habitat management goals: an application in Tampa Bay, FL, USA. Estuaries and Coasts, 34, 1278–1292.

[34] Gallaway, B. J., S. T. Szedlmayer and W. J. Gazey. 2009. A life history review for Red snapper in the Gulf of Mexico with an evaluation of the importance of offshore petroleum platforms and other artificial reefs. Reviews in Fisheries Science, 17(1), 48-67.

[35] Claisse, J. T., D. J. Pondella II, M. Love, L. A. Zahn, C. M. Williams, J. P. Williams and A. S. Bull. 2014. Oil platforms off California are among the most productive marine fish habitats globally. Proceedings of the National Academy of Sciences, USA, 111(43), 15462-15467.

[36] Kirwan, M. L. and J. P. Megonigal. 2013. Tidal wetland stability in the face of human impacts and sea-level rise. Nature, 504, 53-60.

[37] Blum, M. D. and H. H. Roberts. 2009. Drowning of the Mississippi Delta due to insufficient sediment supply and global sea-level rise. Nature Geoscience, 2, 488-491.

[38] Kolker, A. S., M. A. Allison and S. Hameed. 2011. An evaluation of subsidence rates and sea-level variability in the northern Gulf of Mexico. Geophysical Research Letters, 38, L21404.

[39] Muller-Karger, F. E., J. P. Smith, S. Werner, R. Chen, M. Roffer, Y. Liu, B. Muhling, D. Lindo-Atichati, J. Lamkin, S. Cerdeira-Estrada and D. B. Enfield. 2015. Natural variability of surface oceanographic conditions in the offshore Gulf of Mexico. Progress in Oceanography, 134, 54-76.

[40] Cloern, J. E., C. Grenz and L. Vidergar-Lucas. 1995. An empirical model of the phytoplankton chlorophyll : carbon ratio-the conversion factor between productivity and growth rate. Limnology and Oceanography, 40(7), 1313 - 1321.

[41] Li, Q. P., P. J. S. Franks, M. R. Landry, R. Goericke and A. G. Taylor. 2010. Modeling phytoplankton growth rates and chlorophyll to carbon ratios in California coastal and pelagic ecosystems. Journal of Geophysical Research: Biogeosciences, 115, G4003.

[42] Blanchard, J. L., S. Jennings, R. Holmes, J. Harle, G. Merino, J. I. Allen, J. Holt, N. K. Dulvy and M. Barange. 2012. Potential consequences of climate change for primary production and fish production in large marine ecosystems. Philosophical Transactions of the Royal Society B, 367, 2979-2989.

[43] Lohrenz, S. E., G. L. Fahnenstiel, D. G. Redalje, G. A. Lang, X. Chen and M. J. Dagg. 1997. Variations in primary production of northern Gulf of Mexico continental shelf waters linked to nutrient inputs from the Mississippi River. Marine Ecology Progress Series, 155, 45-54.

[44] Bianchi, T. S., J. R. Pennock and R. R. Twilley, eds. 1998. Nutrient behavior and phytoplankton production in Gulf of Mexico estuaries. In: Biogeochemistry of Gulf of Mexico Estuaries, New York, John Wiley & Sons, Inc., 448 pp.

[45] Murrell, M. C., J. G. Campbell, J. D. Hagy III and J. M. Caffrey. 2009. Effects of irradiance on benthic and water column processes in a Gulf of Mexico estuary: Pensacola Bay, Florida, USA. Estuarine Coastal and Shelf Science, 81, 501-512.

[46] Keister, J. E., D. Bonnet, S. Chiba, C. L. Johnson, D. L. Mackas and R. Escribano. 2012. Zooplankton population connections, community dynamics, and climate variability. ICES Journal of Marine Science, 69, 347–350.

[47] Postel, L., H. Fock and W. Hagen. 2000. Biomass and abundance. ICES Zooplankton Methodology Manual.

[48] Hanisko, D., A. Pollack and G. Zapfe. 2015. Vermilion snapper (*Rhomboplites aurorubens*) larval indices of relative abundance from SEAMAP Fall Plankton Surveys, 1986 to 2012 SEDAR45-WP-05. SEDAR, North Charleston, SC.

[49] Sagarese, S. R., M. A. Nuttall, T. M. Geers, M. V. Lauretta, J. F. Walter III and J. E. Serafy. 2016. Quantifying the trophic importance of Gulf menhaden within the northern Gulf of Mexico ecosystem. Marine and Coastal Fisheries, 8(1), 23-45.

[50] Geers, T., E. Pikitch and M. Frisk. 2016. An original model of the northern Gulf of Mexico using Ecopath with Ecosim and its implications for the effects of fishing on ecosystem structure and maturity. Deep Sea Research Part II: Topical Studies in Oceanography, 129, 319-331.

[51] SEDAR 2013. SEDAR 32A stock assessment report - Gulf of Mexico menhaden. Southeast Data, Assessment, and Review, North Charleston, SC.

[52] Smith, J. W. 1991. The Atlantic and Gulf menhaden purse seine fisheries: origins, harvesting technologies, biostatistical monitoring, recent trends in fisheries statistics, and forecasting. Marine Fisheries Review, 53, 28–41.

[53] Rochet, M. J. and V. M. Trenkel. 2003. Which community indicators can measure the impact of fishing? A review and proposal. Canadian Journal of Fisheries and Aquatic Sciences, 60(1): 86-99.

[54] Gulf States Marine Fisheries Commission. 1995. The striped mullet fishery of the Gulf of Mexico, United States: a regional management plan. Gulf States Marine Fisheries Commission, Ocean Springs, Mississippi.

[55] Murphy, M. D., D. Chagaris and D. Addis. 2011. An assessment of the status of spotted seatrout in Florida waters through 2009. Florida Fish and Wildlife Conservation Commission, St. Petersburg, Florida.

[56] Muller, R. G. 2001. The 2000 update of the quota and stock assessment of bluefish, *Pomatomus saltatrix*, on Florida's Atlantic coast. Florida Fish and Wildlife Conservation Commission, St. Petersburg, Florida.

[57] Keithly, W. R. J. and P. Poudel. 2008. The Southeast USA Shrimp Industry: Issues Related to Trade and Antidumping Duties. Marine Resource Economics, 23: 459-483.

[58] NOAA Fisheries Office of Sustainable Fisheries. Status of U.S. Fisheries. [Online]. Available: http://www.nmfs.noaa.gov/sfa/fisheries_eco/status_of_fisheries/status_updates.html. [Accessed 1 Nov 2016].

[59] Brooks, E. N. and J. J. Deroba. 2015. When "data" are not data: the pitfalls of post hoc analyses that use stock assessment model output. Canadian Journal of Fisheries and Aquatic Sciences, 72, 634–641.

[60] SEDAR 2015. SEDAR 43 stock assessment report - Gulf of Mexico gray triggerfish. Southeast Data, Assessment, and Review, North Charleston, SC.

[61] SEDAR 2014. SEDAR 38 stock assessment report - Gulf of Mexico king mackerel. Southeast Data, Assessment, and Review, North Charleston, SC.

[62] Furness, R. W. and J. Greenwood, eds. 1995. Birds as Monitors of Environmental Change, London: Chapman & Hall, 356 pp.

[63] Ogden, J. C., J. D. Baldwin, O. L. Bass, J. A. Browder, M. I. Cook, P. C. Frederick, P. E. Frezza, R. A. Galvez, A. B. Hodgson, K. D. Meyer, L. D. Oberhofer, A. F. Paul, P. J. Fletcher, S. M. Davis and J.J. Lorenz. 2014. Waterbirds as indicators of ecosystem health in the coastal marine habitats of Southern Florida: 2. Conceptual ecological models. Ecological Indicators, 44, 128-147.

[64] Stolen, E. D., D. R. Breininger and P. C. Frederick. 2005. Using waterbirds as indicators in estuarine systems: successes and perils. In: Estuarine Indicators, Boca Raton, Florida, CRC Press.

[65] Brandt, L., J. Beauchamp, J. Browder, M. Cherkiss, A. Clarke, R. Doren, P. Frederick, E. Gaiser, D. Gawlik, L. Glenn, E. Hardy, A. L. Haynes, A. Huebner, K. Hart, C. Kelble, S. Kelly, J. Kline, K. Kotun, G. Liehr, J. Lorenz, et al. 2014. System-wide Indicators for Everglades Restoration. Unpublished Technical Report.

[66] Cornell Lab of Ornithology. eBird. [Online]. Available: www.ebird.org. [Accessed 7 Dec 2016].

[67] Munson, M. A., K. Webb, D. Sheldon, D. Fink, W. M. Hochachka, M. Iliff, M. Riedewald, D. Sorokina, B. Sullivan, C. Wood and S. Kelling. 2014. The eBird Reference Dataset, Version 4.0. Cornell Lab of Ornithology and National Audubon Society, Ithaca, NY.

[68] U.S. Fish and Wildlife Service. 2007. Wood stork (Mycteria americana) 5-year review: summary and evaluation. U.S. Fish and Wildlife Service, Southeast Region, Jacksonville, Florida.

[69] Love, M., A. Baldera, C. Robbins, R. B. Spies and J. R. Allen. 2015. Charting the Gulf: Analyzing the gaps in long-term monitoring of the Gulf of Mexico. Ocean Conservancy, New Orleans, LA.

[70] OECD 2008. OECD Annual Report 2008. Organisation for Economic Co-operation and Development, Paris, France.

[71] Burkhard, B., F. Kroll, F. Müller and W. Windhorst. 2009. Landscapes' capacities to provide ecosystem services – a concept for land-cover based assessments. Landscape Online, 15, 1-22.

[72] Dillard, M. K., T. L. Goedeke, S. Lovelace and A. Orthmeyer. 2013. Monitoring well-being and changing environmental conditions in coastal communities: development of an assessment method. NOAA Technical Memorandum NOS NCCOS 174, Silver Spring, MD.

[73] Leip, D. Atlas of U.S. Presidential Elections. [Online]. Available: http://uselectionatlas.org/.

[74] Jepson, M. and L. Colburn. 2013. Development of social indicators of fishing community vulnerability and resilience in the U.S. Southeast and Northeast regions. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-F/SPO-129.

[75] National Ocean Service 2011. The Gulf of Mexico at a Glance: A Second Glance. U.S. Department of Commerce, Washington, D.C.

[76] Carter, D. and D. Letson. 2009. Structural vector error correction modeling of integrated sportfishery data. Marine Resource Economics, 24, 19-41.

[77] Garfield, T. and C. Harvey, eds. 2016. California Current integrated ecosystem assessment state of the California Current Report, 2016. National Marine Fisheries Service.

[78] Zador, S. G., K. K. Holsman, K. Y. Aydin and S. K. Gaichas. 2016. Ecosystem considerations in Alaska: the value of qualitative assessments. ICES Journal of Marine Science, 74(1), 421-430.

[79] Hooff, R. C. and W. T. Peterson. 2006. Copepod biodiversity as an indicator of changes in ocean and climate conditions of the northern California current ecosystem. Limnology and Oceanography, 51(6), 2607-2620.

[80] Morse, R. E., K. D. Friedland, D. Tommasi, C. Stock and J. Nye. 2017. Distinct zooplankton regime shift patterns across ecoregions of the US Northeast continental shelf Large Marine Ecosystem. Journal of Marine Systems, 165, 77-91.

[81] Bricker, S., J. Ferreira and T. Simas. 2003. An integrated methodology for assessment of estuarine trophic status. Ecological Modelling, 169, 39–60.

[82] Bricker, S., C. Clement, D. Pirhalla, S. Orlando and D. Farrow. 1999. National Estuarine Eutrophication Assessment. Effects of nutrient enrichment in the nation’s estuaries. NOAA—NOS Special Projects Office.

[83] NOAA Coral Program 2014. National Coral Reef Monitoring Plan. NOAA Coral Reef Conservation Program, Silver Spring, MD.

[84] Cornish, V., ed. 2015. Gulf of Mexico Marine Mammal Research and Monitoring Meeting: Summary Report. Marine Mammal Commission, Bethesda, MD.