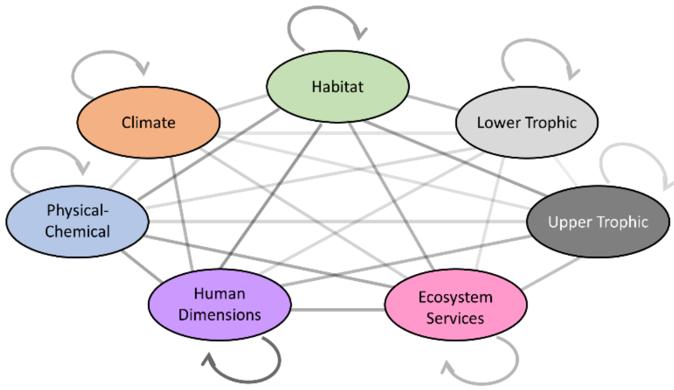
Tab Q, No. 4(e)

**11/01/2021**

# Indicator Development for Fishery Ecosystem Planning: Summary Report




## White Paper

**November 2021**

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# ABBREVIATIONS USED IN THIS DOCUMENT

| | |
|---|---|
| ACL | annual catch limit |
| BOEM | Bureau of Ocean Energy Management |
| C-CAP | Coastal Change Analysis Program |
| ENOW | Economics: National Ocean Watch |
| ESI | Environmental Sensitivity Index |
| FEP | Fisheries Ecosystem Plan |
| GDP | Gross Domestic Product |
| Gulf Council | Gulf of Mexico Fishery Management Council |
| MODIS | Moderate Resolution Imaging Spectrometer |
| MTL | mean trophic level |
| NMFS | National Marine Fisheries Service |
| NOAA | National Oceanic and Atmospheric Administration |
| NPP | Net Primary Productivity |
| SEAMAP | Southeast Area Monitoring and Assessment Program |
| SEDAR | Southeast Data Assessment and Review |

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# CHAPTER 1. INTRODUCTION

Managing fisheries from an ecosystem-based perspective requires an understanding of the complex interactions among the many biotic and abiotic components that constitute the ecosystem (Kilborn et al. 2018; Chagaris et al. 2019). A particular challenge is that these components and interactions are not static and, thus, decisions to facilitate the sustainable use of marine resources may need to be modified in response to changing conditions (Spooner et al. 2021). A widely adopted approach to quantify such changes has been to identify "indicators" that serve to communicate shifts in the state and function of the ecosystem that may have implications for fisheries. An indicator is a variable that provides an "indication" (in contrast to a complete picture) of the present state or trend of some aspect of the ecosystem. A suite of indicators are typically needed to collectively reflect the condition and trajectory of the relevant physical, ecological, and human dimensions of the ecosystem (Karnauskas et al. 2017).

As part of our broader aim to guide the Gulf of Mexico Fisheries Management Council (Gulf Council) toward a Fisheries Ecosystem Plan (FEP), we have worked toward the following goals with respect to indicators:

I. Suggest indicators that would be most useful to the Gulf Council when considering potential ecosystem impacts resulting from management decisions
II. Provide a framework for how to incorporate indicator information into decision making
III. Provide tools that contribute toward the utility and interpretability of indicator information.

In the sections that follow, we discuss our process for meeting these goals and offering guidance to the Gulf Council. We review the indicators for the Gulf of Mexico (Gulf) that were developed for the Ecosystem Status Reports (Karnauskas et al. 2013; 2017), discussing how they could be used by the Gulf Council and the challenges identified during the process. We then provide guidance on what indicators are most helpful to consider, from the perspective of fisheries management and how to use indicators effectively. We then discuss the value and present status of an online dashboard that would allow users to interact with and visualize fisheries indicators and their relationships. We complete the report with a bulleted summary of recommendations to the Gulf Council regarding indicators.

# CHAPTER 2. REVIEW OF PREVIOUSLY CONSIDERED INDICATORS

The National Oceanic and Atmospheric Administration's (NOAA) Integrated Ecosystem Assessment program was designed to support ecosystem-based management. The primary product of this program has been the development of regional Ecosystem Status Reports which select, prioritize and plot the data from a suite of indicators that provide information on the state and trends of a given region. We began our work to identify relevant indicators to the Gulf Council by examining the Ecosystem Status Reports produced for the Gulf of Mexico (Karnauskas et al. 2013; Karnauskas et al. 2017). The initial Ecosystem Status Report for the Gulf of Mexico was an impressive compilation of data with the goal to "summarize the various focal ecosystem components in the Gulf necessary to consider from an ecosystem perspective" (Karnauskas et al. 2013). The report considered more than 100 indicators within the broad categories of climate drivers, physical pressures, state of benthic habitats, state of lower trophic levels, state of upper trophic levels, fishing indicators, and socioeconomic indicators. The report has been influential, having been cited in more than 75 publications to-date (peer-reviewed articles in scientific journals, technical reports, dissertations, and theses). The scientific community recognized the value in this report as descriptively showing changes within a suite of variables across the Gulf. Five years later, the Ecosystem Status Report streamlined the indicators presented, aiming to make the report more robust and easily interpretable (Karnauskas et al. 2017). The streamlined report used indicators that were drawn from 7 broad categories: climate drivers, physical and chemical pressures, habitat state, lower trophic states, upper trophic states, ecosystem services, and human dimensions. Given that our aim was to further refine the indicators recommended to the Gulf Council, we started our work from the indicators that were included in the 2017 Ecosystem Status Report.

We first compiled these indicators into a table in which information on spatial resolution, temporal resolution, frequency of updates, data source, and potential relevance to fisheries was recorded. This was shared with Gulf Council staff on Google Drive (https://docs.google.com/document/d/1SG5QkhE3vNKhPf5IP4zzYl8au2kK0nLP/edit; see also Appendix A). We then conducted analyses to explore how these indicators were related to each other and which were likely to be most relevant in the context of fisheries (Figure 2.1). For these analyses, only indicators with 10 or more annual data points were used. The climate category consisted of 15 indicators associated with sea surface temperatures and sea level. The physical-chemical category consisted of 25 indicators associated with eutrophication (river runoff), hypoxia (oxygen concentration), and carbon fluxes (pH). The habitat category consisted of 5 indicators associated with artificial reef structures and sea grass cover. Lower trophic level consisted of 9 indicators associated with primary productivity, zooplankton, and menhaden abundance. Upper trophic level consisted of 9 indicators associated with species richness and diversity metrics, and the proportion of assessed stocks that are overfished or undergoing overfishing. Ecosystem services consisted of 18 indicators associated with the abundance of bird and fish species. Human dimensions consisted of 12 indicators associated with human population, commercial fisheries landings and revenue, and recreational fishing effort. For each indicator, the linear correlation coefficient was computed and squared between it and every other indicator (i.e., $R^2$). These $R^2$ values were then grouped by pairs of category types (e.g., climate and physical-chemical indicators) and averaged so that the strength of the relationships between categories could be compared (Figure 2.1).

Of the categories of indicators listed in the 2017 Ecosystem Status Report, the Gulf Council is most often responsible for managing certain aspects of "human dimensions" (which include indicators of landings and fishing effort) and "ecosystem services" (which includes abundance estimates for fished species and protected species). The indicators associated with human dimensions tended to correlate most strongly with other human dimensions indicators (mean $R^2$ = 0.59), followed by habitat indicators (mean $R^2$ = 0.40), physical-chemical indicators (mean $R^2$ = 0.35), ecosystem services indicators (mean $R^2$ = 0.32), upper trophic level and climate indicators (mean $R^2$ = 0.29, for both) and lower trophic-level indicators (mean $R^2$ = 0.15). Indicators associated with ecosystem services were most closely related to physical-chemical and human dimensions indicators (mean $R^2$ = 0.32, for both), followed closely by habitat indicators (mean $R^2$ = 0.31), and other ecosystem services indicators (mean $R^2$ = 0.29). Upper trophic level indicators were less related (mean $R^2$ = 0.25), followed by climate indicators (mean $R^2$ =0.18) and lower trophic level indicators (mean $R^2$ = 0.12).

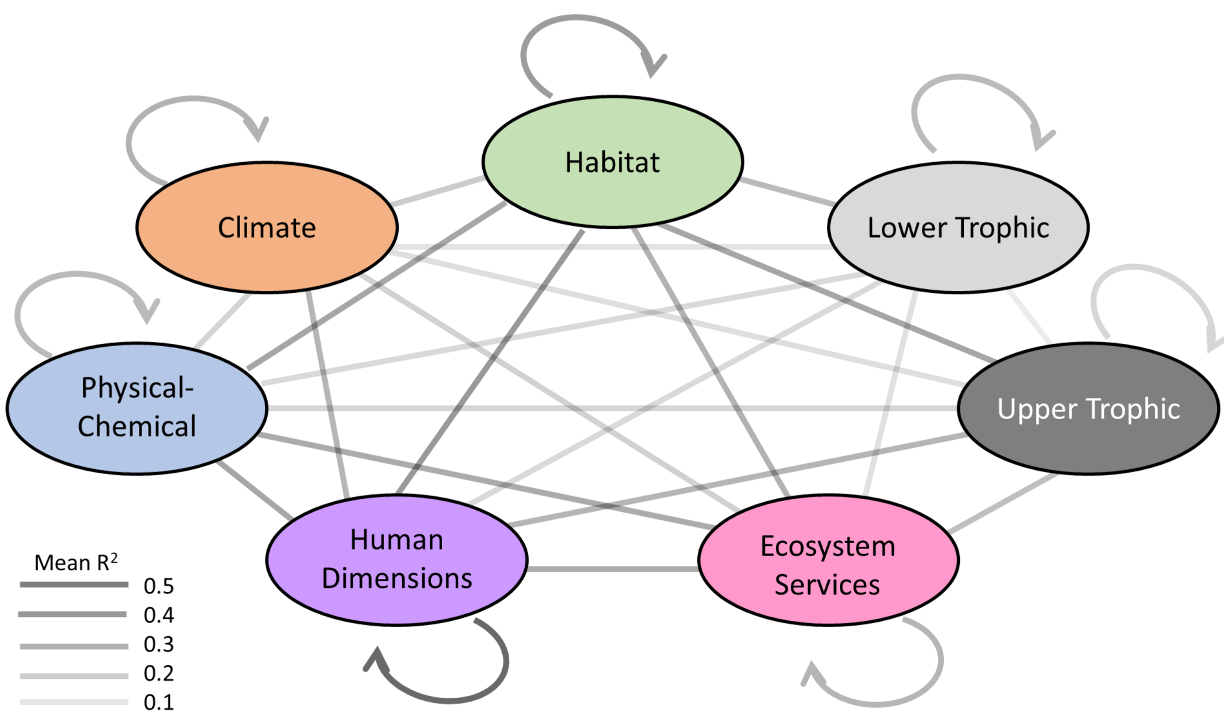


**Figure 2.1.** Relationships among categories of indicators. Colored ovals represent the different categories, connecting lines show the mean relationship between indicators of each category (linear correlation, $R^2$), darker colors imply stronger relationships, on average.

The indicators most closely associated with fisheries are the metrics of fish biomass (Gulf-wide abundance for cobia, gag, gray triggerfish, greater amberjack, hogfish, king mackerel, red grouper, red snapper, and vermillion snapper), total commercial fisheries landings, and the proportion of assessed stocks overfished or undergoing overfishing. The observed relationships between indicator categories are not, necessarily, causal. Nonetheless, they may provide useful insight into the Gulf fisheries ecosystem (Figure 2.2). For instance, decreases in proportion of stocks that are overfished or experiencing overfishing correlates strongly with increases in bird abundance and increases in the number of artificial reefs (habitat). The comparatively weak correlations between stock status and climate, lower trophic level, or upper trophic level indicators suggest that the reason for decreases in the overfishing/overfished status of stocks are not due to bottom-up forcing or foodweb dynamics. Instead, management decisions or economic forces that have changed how humans interact with the upper tiers of foodwebs (e.g., fishes and birds) may be more important. Further support for this hypothesis is that even fish biomass is more strongly related to indicators associated with human dimensions than climate or lower trophic level indicators (Figure 2.2). What's more, in looking at the overall "strength of connections" among the indicator groups (Figure 2.1), human dimensions indicators had the highest mean correlations to other indicators (mean $R^2 = 0.30$, excluding within group indicators) whereas lower trophic level indicators had the lowest mean correlations (mean $R^2 = 0.13$, excluding within group indicators), followed by climate (mean $R^2 = 0.18$, excluding within group indicators).

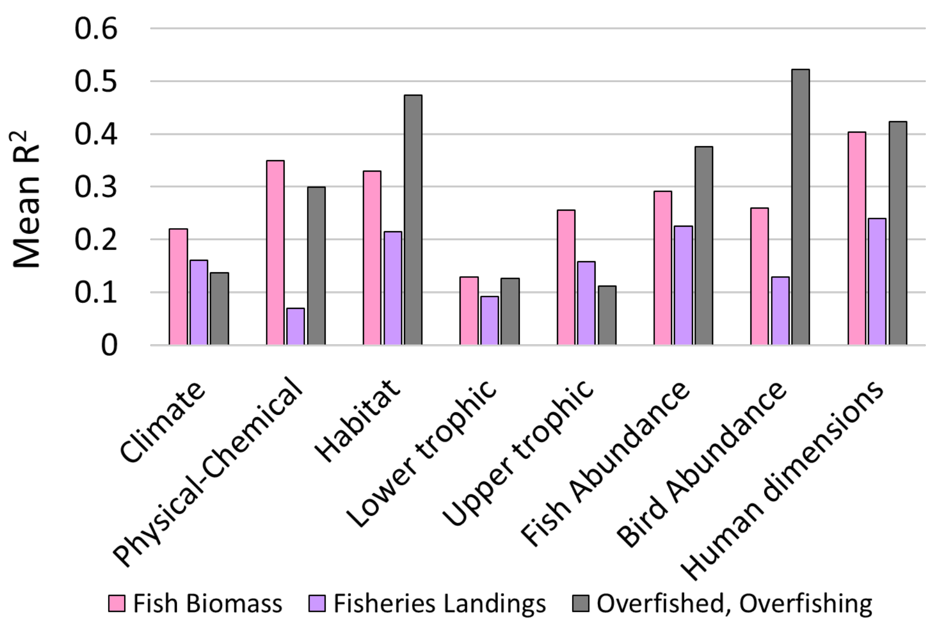


**Figure 2.2.** Relationships between fisheries-relevant metrics and different categories of indicators. Fish biomass (pink bars), fisheries landings (purple bars), and the proportion of assessed stocks that are overfished or are undergoing overfishing (grey bars).

From these analyses, we can conclude, at minimum, indicators associated with human dimensions need to be prioritized by the Gulf Council. Indeed, even the indicators associated with "habitat" (which was the category with the second highest "strength of correlations" with a mean $R^2 = 0.28$) are probably better ascribed to human dimensions. Of the 5 habitat indicators included in this analysis, 4 were based on the number of oil and gas platforms and artificial reefs in the Gulf.  Thus, even from a purely academic perspective, it appears that further work to examine the role of human dimensions in ecosystem processes would be highly informative (Kelble et al. 2013).

# CHAPTER 3. CHALLENGES ASSOCIATED WITH IDENTIFYING ECOSYSTEM INDICATORS

Several challenges to providing the Gulf Council recommendations were identified in the process of reviewing and synthesizing indicators from the 2017 Ecosystem Status Report. The challenges are associated with the fundamental complexities of understanding an ecosystem (Figure 3.1) and ensuring relevance to fisheries management. For indicators to provide adequate representation of an ecosystem, consideration of at least three dimensions is required: (1) spatial heterogeneity, (2) organizational connectivity, and (3) temporal contingency (Figure 3.1) (Cadenasso et al. 2006).

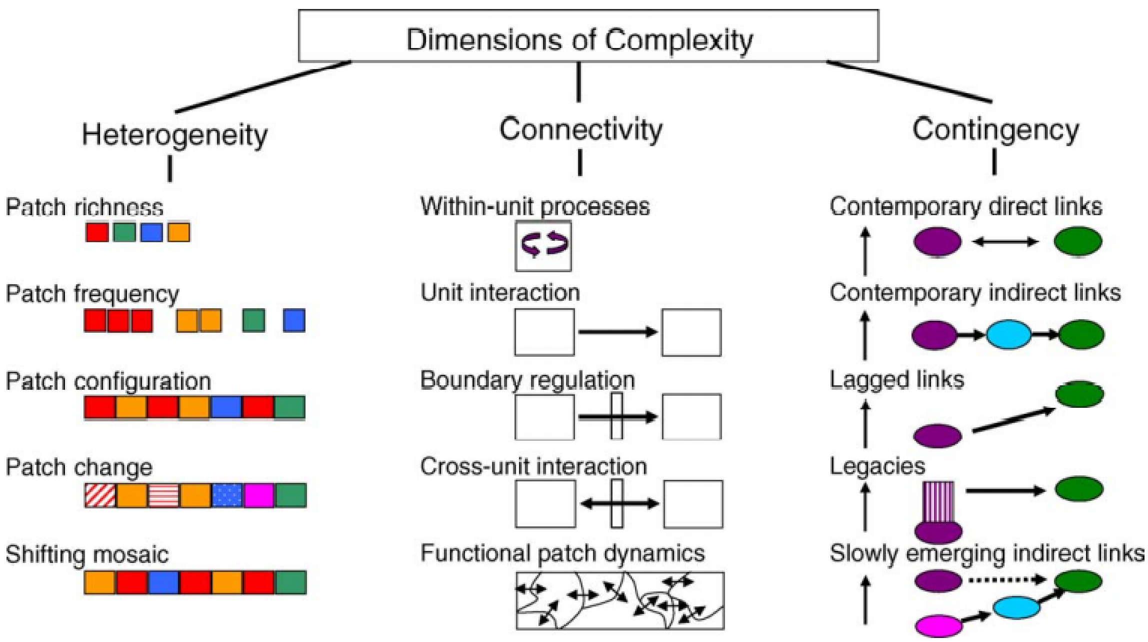


**Figure 3.1.** Figure from Cadenasso et al. (2006). Framework for ecosystem complexity. The three dimensions of ecosystem are spatial heterogeneity, organizational connectivity, and temporal contingencies. Components of the framework are arrayed along each axis increasing in complexity. For example, a more complex understanding of spatial heterogeneity is achieved as quantification moves from patch richness, frequency and configuration to patch change and the shift in the patch mosaic. Complexity in organizational connectivity increases from with-in unit process to the interaction of units and the regulation of that interaction to functional patch dynamics. Finally, historical contingencies increase in complexity from contemporary direct effect through lags and legacies to slowly emerging indirect effects. The arrows on the left of each illustration of contingency represent time.

Spatial heterogeneity considers the elements and components of the ecosystem and how they are arranged. Aside from indicators associated with climatic forcing, most other indicators are likely to vary at sub-regional scales within the Gulf. Accounting for spatial heterogeneity can be accomplished if indicator data are available at sufficiently high spatial resolution. Organizational connectivity considers the relationships and interactions of ecosystem components. To account for organizational connectivity, indicators that are sensitive to impacts from outside of the measured area or that explicitly track movements across boundaries are required. Such indicators do not exist in the Ecosystem Status Report (Karnauskas et al. 2017). We therefore discuss options for producing connectivity indicators in section 2.3. Temporal contingency considers how those components change through time including slowly emerging indirect effects, lagged linkages and historical processes. This complexity inherent to ecosystems results in self-organization, as well as emergent properties and non-linear behavior of its components (Cadenasso et al. 2006). Temporal contingency can be accounted for if indicator data has a sufficiently long duration. Of the indicators in the 2017 Ecosystem Status Report, 54 have three decades or more of data and could be prioritized to investigate for potential lagged effects.

The following example demonstrates the need for indicators at the appropriate spatial scale to be useful and that Gulf-wide data may not give a complete picture. From the 1990s and mid-2000s to present, Gulf-wide effort in the bottom longline fisheries have declined by ~50% (Figure 3.2). However, when examined by statistical zone, the drop in effort is primarily associated with the central West Florida Shelf (statistical zone 5). Most other areas have either seen marginal decreases in effort or no change in effort; off the coast of Louisiana there is even an increase in effort (statistical zone 13) (Figure 3.2). While this level of spatial detail is more useful than a Gulf-wide summary, further context is still needed to understand changes in fishing effort. Were they economically driven, required by management, in response to the changing distribution of target species? Did fishers formerly targeting the West Florida Shelf shift to Louisiana? Overlaying additional information introduces a challenge for understanding trends and relationships - graphs and maps presenting data that vary through time across multiple spatial scales can be difficult to visualize and digest (see Chapter 5 for our suggested solution).

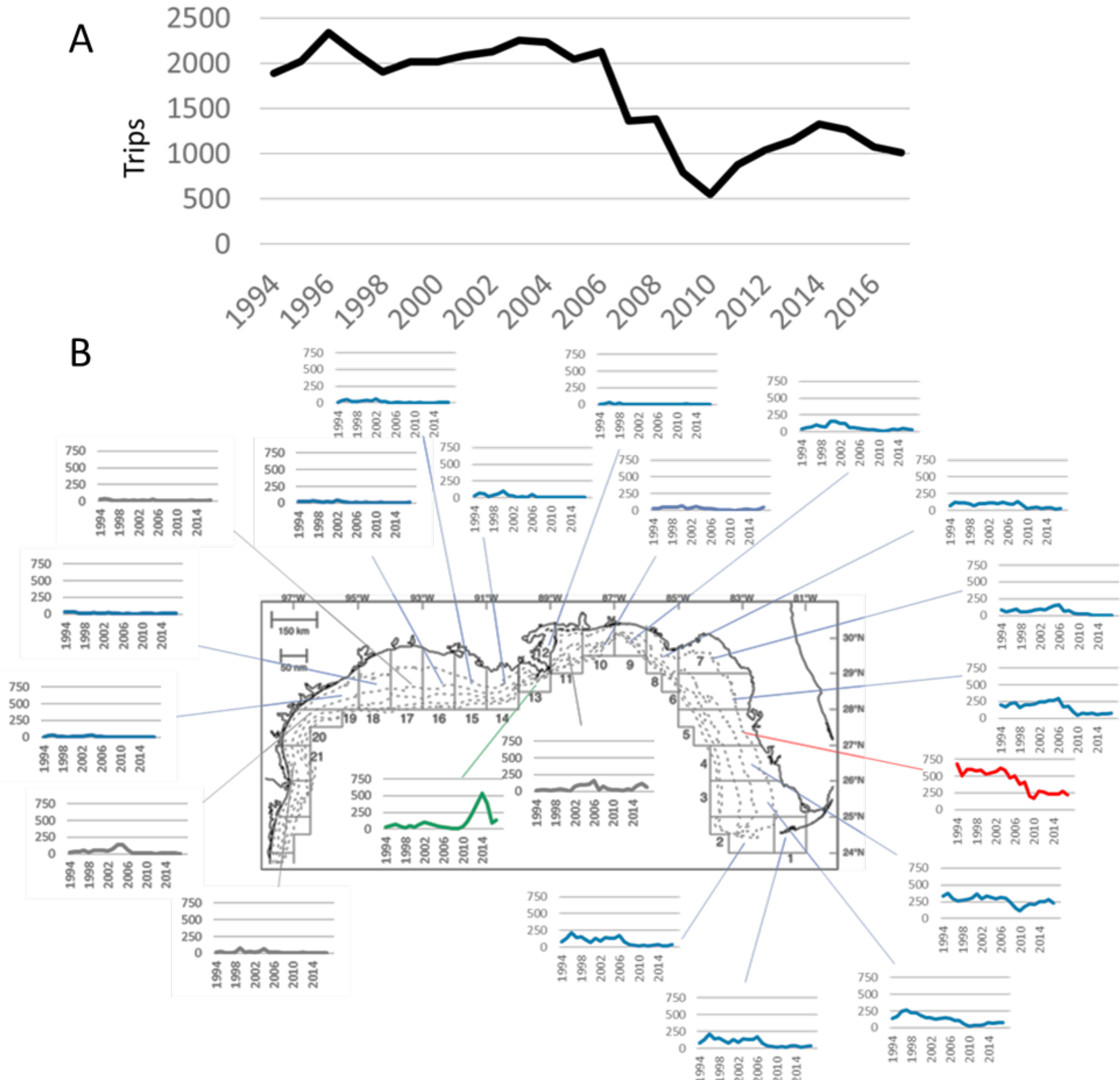


**Figure 3.2.** (A) Annual Gulf-wide bottom longline effort by commercial fisheries each year. From 2010 forward, the number of trips taken across the Gulf has decreased by ~50% from the 1990s and mid-2000s. (B) Bottom longline effort shown by statistical zone. Statistical zones in which effort has significantly decreased during from 1994 to 2016 are shown with blue lines (the stat zone with the largest decrease in effort is shown in red), no change is shown in grey lines, an increase in effort is shown in green.

Another challenge that was apparent during our synthesis of data from the Gulf of Mexico Ecosystem Status Report (Karnauskas et al. 2017) was that several additional research steps are required before indicators can be "operationalized" for fisheries management. While the status of indicators and their trends through time were documented and discussed in detail, a clear linkage between those indicators and key aspects of fisheries have not been established. In part the issue is that the Ecosystem Status Report is aimed at providing a better understanding of the state of the Gulf (descriptive science), whereas management issues are often articulated in the form of a particular question to answer (hypothesis-driven science). For instance, it is not apparent whether the phase of Atlantic Multidecadal Oscillation (a climate index of sea surface temperatures that has been shown to correlate with ecosystem level changes in the Gulf (Tam et al. 2017)) would influence the abundance or distribution of red snapper in a way that should be taken into account by the Gulf Council when setting harvest limits. Thus, future work will require some level of hypothesis testing, based on common questions faced by the Gulf Council, for indicator selection. Indeed, other Regional Fishery Management Councils heavily invested in indicator research, development and use. For instance, the North Pacific and New England Councils produce an annual Ecosystem Status Report on indicators that have provided useful guidance for managing these regions. These status reports are particularly valuable in these regions where explicit links between physical drivers is directly tied to multiple species fishery availability. For example, the timing of sea ice melt in Alaskan waters determine much of the season's fishing effort and landings. Generating such intensive reports for the Gulf may not be possible with the present resources available. It may not even be practical without understanding the explicit links like in Alaska. The main, initial hurdle is to use research to establish linkages between ecosystem indicators and fisheries and to measure these indicators over time (Link & Marshak 2019).

# CHAPTER 4. FRAMEWORK FOR SELECTION AND USE OF INDICATORS

In the context of fisheries management, indicators should provide timely information regarding the state of the ecosystem, be easily understood and accepted by scientists, managers, politicians, and stakeholders, and provide context for choosing among actions that decision-making bodies are presented with. Given the Gulf Council's need to work toward actionable results, indicators are also only valuable as they relate to answering specific management questions (Marshall et al. 2018). To this last point, continued research will be needed to assess how ecosystem indicators relate to specific fisheries questions.

In selecting indicators, we suggest that the Gulf Council consider "base" indicators and "auxiliary" indicators. Essential base indicators for the fisheries ecosystem include those associated with catch, effort, and participation in the federally managed fisheries of the Gulf. Auxiliary indicators are those that either impact base indicators or are impacted by base indicators. Base indicators need to include commercial and recreational fisheries data and should be obtained at high spatial specificity (e.g., by National Marine Fisheries Service (NMFS) statistical zone for commercial fisheries), account for connections between the areas fished and the ports of landings, and have data that extend sufficiently far back to gauge the factors that drive variability and trends through time. Base indicators would likely be useful in providing context for nearly any management question (or FEI) faced by the Gulf Council. The availability of synthesized, digestible information on trends in catch/effort/participation indicators, in conjunction with trends in environmental drivers (auxiliary indicators), to Gulf Council members prior to taking action (e.g., setting stock annual catch limits (ACLs) under variable environmental conditions), would be beneficial for fostering better informed decisions (Marshall et al. 2018). While the base indicators are fairly clear, identifying the appropriate auxiliary indicators will require further research to determine the relationships within the Gulf Ecosystem.

With the present resources available, what is likely to be immediately beneficial for the Gulf Council is to use indicators to provide broader ecosystem context for decisions on specific, subregional ecosystem issues. For instance, consider that the Gulf Council wanted to manage a specific forage fish that had not previously been assessed or managed, and it was determined that some other managed stock rely on the forage fish for a significant portion of their diet. Using the base indicators described above, it would be possible to illustrate the spatial and temporal overlap in effort and landings for the managed stock, with the forage species. Such information would provide a backdrop and contribute to a conceptual model of the relative impacts of this and other stressors (social, physical, biological) on forage fish biomass, in space and time and how these might be affected by a change in ACL of the managed predator species (Marshall et al. 2018). It may not be possible, however, without detailed ecosystem models, to determine accurately how increasing the ACL for the predator stock would influence the biomass of forage fish (Chagaris et al. 2020).

There are several ways that indicators could function in the framework of a Gulf FEP. Guidance for 'Next Gen' FEPs uses the framework of the "FEP Loop" (Essington et al. 2016; Levin et al.

2018; Figure 4.1). The FEP Loop is a structured process for establishing goals and transforming them into action. Our initial analysis suggests, however, that using the FEP Loop process at the scale of the entire Gulf Ecosystem has not led to actionable guidance. We have suggested adapting the FEP Loop to address specific issues in subregional areas of the Gulf, to address Fisheries Ecosystem Issues (FEI). At the first step (Where are we now?), the base indicators should be used to understand the current status and trends of the fisheries system, as a conceptual model is being developed. At this stage, it should be determined whether additional indicators should be selected to provide insight into the particular issue at hand. The second step (Where are we going), uses that information to guide the design of strategic and operational objectives. In the third step, (How will we get there?), relevant indicators may be selected as performance measures and for conceptual scenario modeling to evaluate the consequences of alternative management actions. In the fourth step (Implementation of the plan.), the actions are initiated and carried out. In the fifth step (Did we make it?), changes in the performance measure indicators are consulted to assess whether management decisions had their intended/predicted impacts. Depending on outcomes, management decisions either can be revised, or the course can be kept.


**Figure 4.1.** The FEP Loop, shown in white boxes, as adapted from Essington et al. (2016) and Levin et al. (2018). Blue boxes show at what points indicators would provide information to guide the process.

As an example, assume that the Gulf Council wished to consider the effects of removing oil and gas platforms on recreational red snapper fishing in Louisiana. This question could be addressed using the FEI Framework. At step 1, angler effort (e.g., saltwater recreational fishing licenses and trips taken during red snapper season) and catch of red snapper in Louisiana would be examined to see the overall magnitude of this issue and the trends through time. Additional indicators might be selected that include platform locations, the number of standing platforms from 1920 to today, and the length of red snapper season by year. These could be paired with published data from studies quantifying the abundance of red snapper on platforms in Louisiana (Gallaway et al. 2021). With these indicators, scenario modeling could be conducted to predict how decreasing locations for fishing opportunities (i.e., platform removal) for recreational anglers might have consequent effects on indicators. Such information could then guide the prioritization of “rigs to reefs” initiatives and placement of decommissioned platforms in places that could be accessed by fishers and were well suited to recruit red snapper. The success of such efforts could be measured and informed by monitoring base indicators associated with recreational fishing participation, catch, and effort.

# CHAPTER 5. TOOLS TO FACILITATE USE OF INDICATORS

A key aspect of making indicator data useful is to provide ways for the Gulf Council to visualize and explore relationship among different variables. As part of a solution for helping the Gulf Council make use of indicator data, we are working to produce an online data visualization dashboard that will allow the Gulf Council and other stakeholders to interact with and visualize relationships between various data sets in space and time. The aim is to populate the dashboard with example data on fisheries catch, effort, and connectivity at spatial and temporal scales meaningful for management decisions. The Gulf Council will be able to provide input on the design and datasets included for this tool, should this be of interest for further development. This portion of our work is being conducted in collaboration with THEI Consulting, who is responsible for producing the dashboard. At present, the IT infrastructure for the dashboard has been built, and the preliminary design phase is complete. A prototype of the dashboard has been developed and is housed on an LGL server with the relevant spatial domains defined. Initial base indicator datasets are being organized and curated to be uploaded to the dashboard (Table 5.1), and functionality/system testing will follow. Input from potential users will be sought, revisions to the dashboard will be made, and the beta version will be deployed online at the close of this project (Figure 5.1).

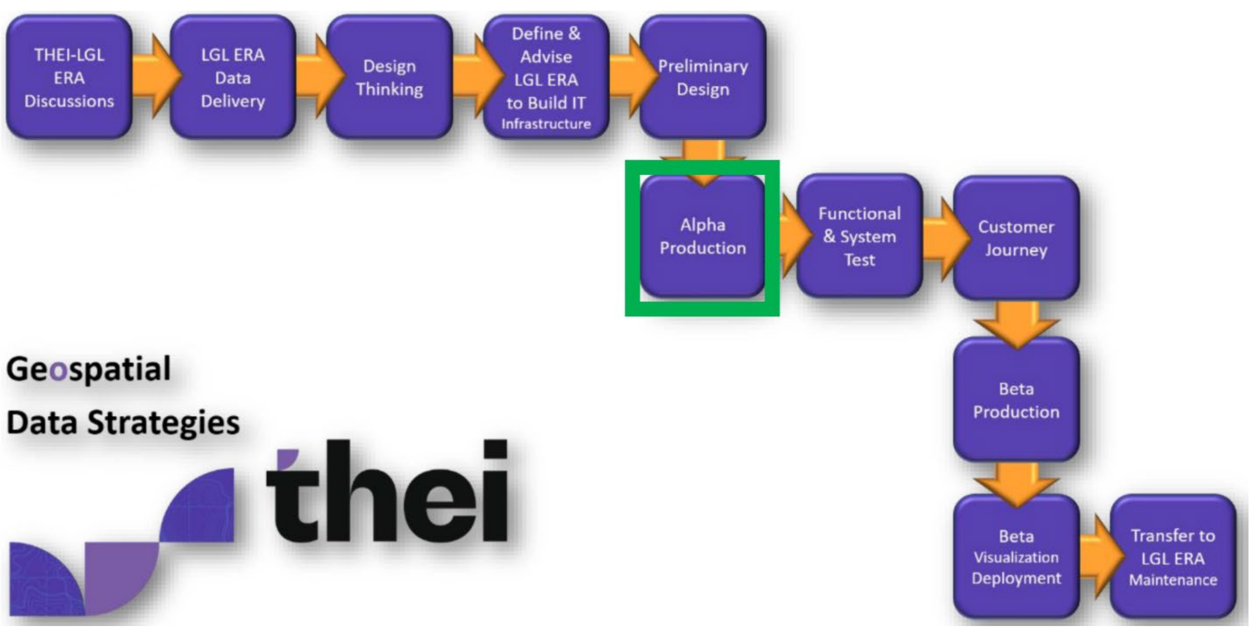


**Figure 5.1.** Road map to the development of the Indicator Visualization Dashboard. This tool for the Gulf Council is being produced in collaboration with THEI Consulting, the green square shows the current status of dashboard development. Completion of this road map is anticipated by January 2022.

**Table 5.1.** Initial datasets to be uploaded to the indicator visualization dashboard.

| Base Indicators | | |
|---|---|---|
| **Indicator Name** | **Temporal Scale** | **Spatial Scale** |
| Buoy effort (commercial trips) | Annual (1994-2016) | NMFS Stat Zone |
| Cast net effort (commercial trips) | Annual (1994-2016) | NMFS Stat Zone |
| Bandit effort (commercial trips) | Annual (1994-2016) | NMFS Stat Zone |
| Hook and line (commercial trips) | Annual (1994-2016) | NMFS Stat Zone |
| Powerheads / bangsticks (commercial trips) | Annual (1994-2016) | NMFS Stat Zone |
| Spear (commercial trips) | Annual (1994-2016) | NMFS Stat Zone |
| Bottom longline (commercial trips) | Annual (1994-2016) | NMFS Stat Zone |
| Gillnets (commercial trips) | Annual (1994-2016) | NMFS Stat Zone |
| Traps (commercial trips) | Annual (1994-2016) | NMFS Stat Zone |
| Other gear (commercial trips) | Annual (1994-2016) | NMFS Stat Zone |
| Cobia commercial landings (lbs.) | Monthly (1994-2016) | County landed, NMFS Stat Zone |
| Gag commercial landings (lbs.) | Monthly (1994-2016) | County landed, NMFS Stat Zone |
| Gray Triggerfish commercial landings (lbs.) | Monthly (1994-2016) | County landed, NMFS Stat Zone |
| Greater Amberjack commercial landings (lbs.) | Monthly (1994-2016) | County landed, NMFS Stat Zone |
| Red Grouper commercial landings (lbs.) | Monthly (1994-2016) | County landed, NMFS Stat Zone |
| Red Snapper commercial landings (lbs.) | Monthly (1994-2016) | County landed, NMFS Stat Zone |
| Vermillion Snapper commercial landings (lbs.) | Monthly (1994-2016) | County landed, NMFS Stat Zone |
| Private Recreational Angler Trips | 2 x yearly, high/low season* (1994-2016) | State |
| Charter Recreational Angler Trips | 2 x yearly, high/low season* (1994-2016) | State |
| Cobia recreational landings (lbs.) | 2 x yearly, high/low season (1994-2016) | State |
| Gag commercial landings (lbs.) | 2 x yearly, high/low season* (1994-2016) | State |
| Gray Triggerfish recreational landings (lbs.) | 2 x yearly, high/low season* (1994-2016) | State |
| Greater Amberjack recreational landings (lbs.) | 2 x yearly, high/low season* (1994-2016) | State |
| Red Grouper recreational landings (lbs.) | 2 x yearly, high/low season* (1994-2016) | State |
| Red Snapper recreational landings (lbs.) | 2 x yearly, high/low season* (1994-2016) | State |
| Vermillion Snapper recreational landings (lbs.) | 2 x yearly, high/low season* (1994-2016) | State |

*The designation of "high" or "low" season corresponds to how the state of Texas collects recreational data. For Texas low season = January 1 - May 14 and November 15 - December 31; high season = May 15 - November 14. To approximate this for other states (West Florida, Alabama, Mississippi, and Louisiana) we assumed low season = January-April and November-December; high season = May-November.

# CHAPTER 6. SUMMARY RECOMMENDATIONS

Based on our analyses and review of the literature presented in this report, we provide the following recommendations to the Gulf Council with regard to the development and use of ecosystem indicators for fisheries management. First and foremost, we recommend further investment in indicator research, development, and reporting to support and accompany expanding Fishery Ecosystem Planning. The recommendations to the Gulf Council are organized according to the three goals outlined at the beginning of this document.

I. Suggest indicators that would be most useful to the Gulf Council when considering potential ecosystem impacts resulting from management decisions
II. Provide a framework for how to incorporate indicator information into decision making
III. Provide tools that contribute toward the utility and interpretability of indicator information.

*Suggested Indicators*

1. Base indicators should include annual metrics of fisheries catch, effort, and participation
    a. Commercial fisheries - subsets by NMFS statistical zone, subsets by gear type
    b. Recreational fisheries - subsets by inshore, state, and federal waters
2. Auxiliary indicators should be selected to understand drivers of and impacts from base indicators
    a. Given the apparent importance of human dimensions indicators, these should be prioritized for consideration
    b. Given the lack of information on indicators that relay information about connectivity across the Gulf, these should be developed

*Suggested Framework for Incorporating Indicators into Decision Making*

1. An indicator task force (comprised perhaps of the Ecosystem Technical Committee) should be recruited to advise the Gulf Council on indicator development, selection and use.
    a. Establish relationships of indicators to key fisheries metrics
    b. Provide conceptual scenario models of future trends for the Gulf Council to consider within the FEP Loop
2. Indicators should be used throughout the FEI process
    a. At the outset indicators provide context for the current status of the Gulf ecosystems and inform strategic objectives.
    b. Within FEI loops addressing specific issues, indicators can be selected as performance measures for conceptual scenario modeling to evaluate possible consequences of management alternatives.
    c. Upon implementation of decisions, indicators can be monitored to determine whether intended impacts have occurred and whether that decision should be maintained or revised.

3. We suggest that future indicator work be primarily focused on specific sub-regional issues (FEIs). Nonetheless, some resources should be allocated to continue production of regular Ecosystem Status Reports (e.g., Karnauskas et al. 2017) at a frequency of 3-5 year intervals, to provide the Council with general information on the status of the Gulf Ecosystem.

*Tools to Contribute Toward the Utility and Interpretability of Indicators*

1. An indicator visualization dashboard should be developed and maintained for the Gulf Council and publicly available for stakeholders
    a. Populated with base indicators initially
    b. Designed so that auxiliary indicators can be easily searched (and added) for specific management questions
    c. Designed so that indicator relationships and relevant ecosystem processes can be explored and contextualized with an interactive map and graphs
    d. Data can be downloaded for offline analyses

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# APPENDIX A.   PRELIMINARY INDICATOR TABLE

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The table below summarizes parameters of the main indicators used in the 2017 Gulf of Mexico Ecosystem Status Report & https://ecowatch.noaa.gov/regions/gulf-of-mexico. At the end of the larger categories, we have also included some additional indicators to consider (*in italics*). These additions are not necessarily exhaustive nor systematically considered but serve as a repository for some of the ideas being discussed and are based on what (1) might be straightforward to obtain in time-series form and (2) may be an important part of the ecosystem to consider, either as an ecosystem driver or response variable. Our goal for this list is to identify examples of what has been considered indicative of Gulf ecosystem health.

Our next step is to map the relationships among these indicators in a matrix format (https://docs.google.com/spreadsheets/d/1PODO14IL1GgkrA2tnnULKx_C8OwlHJ6wRgSQX-Sbl9o/edit#gid=662250155).
As part of this process we will prioritize indicators based on the following criteria:

- be relevant to fishery management
- create actionable information
- be understood by a broad audience of stakeholders: i.e. “What do they indicate”
- scientifically valid
- measurable and being measured at relevant time and spatial granularity
- available, downloadable, regularly updated

Furthermore, in accounting for relationships among indicators we will also identify which ones are redundant or too narrow in scope to be of value and, conversely, where additional indicators may be needed to fill gaps in measuring ecosystem health.

| Indicator | Spatial Resolution | Temporal Resolution | Updated | Data Source | Indicative of what? |
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| **Climatological** | | | | | |
| North Atlantic Oscillation | Basin | Yearly | Yearly | https://www.cpc.ncep.noaa.gov/data/teledoc/nao.shtml | Relative position and strengths of low atmospheric pressure over Iceland and high atmospheric pressure over the Azores. This aspect of climate may alter hurricane tracks and precipitation, which broadly influence fisheries ecology (see, e.g., https://aquila.usm.edu/cgi/viewcontent.cgi?article=1578&context=fac_pubs) |
| Atlantic Multidecadal Oscillation | Basin | Yearly | Yearly | https://psl.noaa.gov/data/climateindices/ | Basin-wide temperature variability: related to precipitation, hypoxia, water column stratification which broadly influence fisheries ecology (see, e.g., https://www.frontiersin.org/articles/10.3389/fmars.2017.00282/full) |
| **Physical - Chemical** | | | | | |
| Sea Surface Temperature | Western / Central/ Eastern Gulf | 6 month moving average | ? | https://www.ncdc.noaa.gov/oisst | Ocean temperature impacts the rate of all physical, chemical, and most biological processes occurring in the ocean. |
| Sea Level | State | ? | ? | NA | Sea level has direct impacts on coastal communities and certain habitats (e.g., marsh vs. mangrove) in terms of susceptibility to extreme weather, erosion, and a variety of coastal processes. |

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| Hypoxia | LA / TX | Summer / Fall | | Southeast Area Monitoring and Assessment Program (SEAMAP) trawl and hydrographic survey | Hypoxia is low dissolved oxygen (<2 mg per L), may result in die-offs, reduced growth/reproduction, or movement out of an area by mobile species. |
| Carbon fluxes – ocean acidification | NA | monthly | | CMIP 5 | When CO2 enters the ocean, pH is reduced (more acidic) which might have negative impacts on calcification of calcium-carbonate shells or even alter fish behavior by disrupting neurotransmitters. Actual effects in the Gulf are not well-established. |
| Eutrophication (Nitrogen oxides, total nitrogen, total phosphorus) | 5 river systems | Yearly | | U.S. Geological Survey. Coastal Rivers - Nitrate Loads and Yields. 2016. [Online]. Available: https://nrtwq.usgs.gov/nwqn/#/ | Eutrophication results from excess nutrients, i.e., an imbalance in productivity. This can cause shifts from benthic primary producers (seagrasses) to phytoplankton and contributing to hypoxia when increased organic material is consumed by bacteria. |
| ***Additional Indicators for consideration (not part of EcoWatch or the 2017 Gulf Ecosystem Status Report)*** | | | | | |
| *Upland Sources of Pesticides?* | | | | | In addition to nitrogen and phosphorus, pesticides from agriculture may have negative impacts on marine organisms. This may be related to eutrophication and hypoxia in some circumstances, but could act independently in others. |
| *Wave height* | Gulf-wide, gridded <0.1 deg lat/lon | | | https://polar.ncep.noaa.gov/waves/viewer.shtml?-multi_1-latest-gmex-hs- | Wave height is related to wind conditions, and may be an important consideration for fishing activity (particularly recreational). Fewer trips or less time on the water may be expected when wave height is larger. |

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| | | | | | Units to consider might by # of days with mean wave height > 4 ft for a given state? |
| *Tropical Storms* | | | | https://www.nhc.noaa.gov/data/ | Tropical storms typically act as stressors to human coastal communities. Storms can have a variety of impacts on the ecosystem (e.g., mixing the water column can minimize hypoxic condition or reduce thermal stress on corals; changes to surface circulation can influence the dispersal of marine organisms). Annual counts easily obtained. |
| **Biological** | | | | | |
| Benthic seagrass cover | Florida, Tampa, Pensacola, Mobile, MS Sound, and Galveston Bays | Annual | Rarely | USGS Seagrass Status and Trends report, Emergent Wetlands Status and Trends report, the Tampa Bay National Estuarine Program, Alabama Department of Conservation and Natural Resources oyster reef data, Southwest Florida Water Management District seagrass data, and the Florida Fish and Wildlife Conservation | A variety of species depend upon seagrass habitats to complete some elements of their life-cycle, either as spawning, nursery, or foraging grounds including economically valuable species and protected species. Increases in this habitat provides more resources to those species. Decreases in this habitat may also be indicative of ecosystem disturbances. |

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| | | | | Commission's Florida Fish and Wildlife Research Institute | |
| Wetland use and land cover | Gulf-wide | | | Coastal Change Analysis Program (C-CAP) | Wetlands provide a variety of ecosystem services in terms of buffering coastal areas from storm damage, erosion, improving water quality, and providing wildlife habitats. Decreases in this indicator imply greater coastal vulnerability. |
| Net Primary Productivity (NPP) | Northern Gulf | | | Moderate Resolution Imaging Spectrometer (MODIS) observations. Adapted from Muller-Karger et al. (2015). Progress in Oceanography, 134, 54-76. | NPP is the net production of carbon by organisms at the base of the foodweb (primary producers), such as phytoplankton. NPP gives an indication of food availability to higher trophic levels, with higher NPP typically translating to more food and the potential to support higher species abundances. This is often related to insolation, ocean mixing, winds, and riverine inputs. |
| Zooplankton biomass | Northern Gulf | Spring / Fall | | Southeast Area Monitoring and Assessment Program (SEAMAP) | Zooplankton are an important part of marine foodwebs serving as predators and prey for a variety of species. Higher abundances tend to indicate larger abundances and diversity of fish can be supported. |
| Menhaden (age 1+) biomass | Northern Gulf | | | NMFS Stock Assessment | Mendhanden are a forage fish that contribute to the diets of a wide number of species and supply a massive industrial fishery. Biomass may indicate the potential available forage within the Gulf, |

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| | | | | | but since it only contributes to 2-3% of most species diets a direct correspondence may not exist. |
| Species Richness | LA / TX | Summer / Fall | | Southeast Area Monitoring and Assessment Program (SEAMAP) | Species richness is the number of species observed and indicates ecosystem health in that more resilient ecosystems tend to have more species. |
| Species Diversity | LA / TX | Summer / Fall | | Southeast Area Monitoring and Assessment Program (SEAMAP) | Shannon-Wiener diversity index combines species richness and relative abundance and is a metric of biodiversity, higher indices indicate more species that are more even in terms of relative abundance. |
| Mean trophic level (MTL) of commercial finfish landings | Northern Gulf | | | NOAA Fisheries commercial landings statistics from the Southeast Fisheries Science Center | MTL is an average of the assigned trophic level for species (or groups of species) weighted by total poundage of each group. Decreases in MTL may indicate “fishing down the foodweb” or changes driven by market force / regulation for commercial fisheries. |
| Mean trophic level (MTL) of finfish in survey | Northern Gulf | Summer | | Southeast Area Monitoring and Assessment Program (SEAMAP) | MTL is an average of the assigned trophic level for species (or groups of species) weighted by total poundage of each group. Because SEAMAP mainly targets smaller, juvenile fish and trophic levels are assigned by adult diet, this index may be slightly misleading taken at face-values. |

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| Proportion of stocks undergoing overfishing | Gulf-wide | | | https://www.fisheries.noaa.gov/national/population-assessments/fishery-stock-status-updates | Stocks subject to a fishing rate that does not produce maximum sustainable yeild over the long term. A decrease in this index is indicative of improved management that corresponds to the ecological status of a species. |
| Proportion of stock in overfished state | Gulf-wide | | | https://www.fisheries.noaa.gov/national/population-assessments/fishery-stock-status-updates | Stock size is below that which produces maximum yeild on a continuing basis. A decrease in this index is indicative of improved management that has contributed to a population increase. |
| Estimated abundances / biomass of economically important fish | Gulf-wide | Annual | | SEDAR: Gray triggerfish, greater amberjack, gag, red grouper, vermillion snapper, cobia, Spanish mackerel, red snapper, Atlantic sharpnose shark, hogfish, king mackerel | Stock size (biomass or abundance) of these fish species are indicative of both ecosystem health and opportunity for commercial and recreational fisheries. |
| Bird relative abundance (probability of presence) | Northern Gulf | | | Cornell Lab of Ornithology eBird Reference Dataset: brown pelican, magnificent frigatebird, roseate spoonbill, white ibis, wood stork | 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. They also have value for tourism. Pelagic seabirds are not well represented, but these 5 species are likely of value for coastal habitats. |
| ***Additional Indicators for consideration (not part of EcoWatch or the 2017 Gulf Ecosystem Status Report)*** | | | | | |

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| *Sargassum coverage* | | | | https://www.aoml.noaa.gov/phod/sargassum_inundation_report/ | Role as habitat to ecologically valuable species (tunas, amberjack, mahi, sea turtles); Negative impacts to coastal human communities via beaching; Can be highly variable among years; relatively easily monitored |
| *Sea Turtle Nesting (W. Florida, Texas, Tamaulipas MX)* | | | | [a] annual nest counts of loggerheads, green, leatherback in Florida (https://myfwc.com/research/wildlife/sea-turtles/nesting/beach-survey-totals/); [b] annual nest counts in Kemp's ridley in Texas (https://seaturtles.org/turtle-count-texas-coast/); [c] annual nest counts of Kemp's ridley in Tamaulipas; | Sea turtles drive many of the management decisions related to fisheries in the Gulf. Specifically considering the reproductive output of Kemp's ridley, green turtles, and loggerhead turtles in different areas of the Gulf (W. Florida, Texas, and Tamaulipas MX) could be useful for the Gulf Council to consider. For the noted species/regions, annual counts should be easily obtained. |
| *Protected Species Strandings (marine mammals, sea turtles)* | | | | [a] annual number of marine mammal Unusual Mortality Events (https://www.fisheries.noaa.gov/national/marine-life-distress/active-and-closed-unusual-mortality-events); [b] annual bottlenose dolphin strandings; [c] | Sea turtles and marine mammals contribute to many of the management decisions related to fisheries in the Gulf. Strandings of marine mammals and sea turtles can be indicative of both natural and anthropogenic stressors to the ecosystem (e.g., cold snaps, boat strikes) as well as provide information on the distribution and abundance of these protected species. Data are recorded across the Gulf and could provide useful |

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| | | | | annual manatee counts (https://myfwc.com/research/manatee/research/population-monitoring/synoptic-surveys/); | context for certain Gulf Council decisions. |
| **Human Dimensions** | | | | | |
| Oil Platforms | Northern Gulf | | | Bureau of Ocean Energy Management (BOEM) | Representative of fishing opportunity, particularly for recreational anglers. |
| Intentional artificial reefs | (excluding TX) | | | | Representative of fishing opportunity. |
| Human population abundance in coastal watershed counties | States | | | American Community Survey 3-year estimates and decadal Census | Representative of resource use; strain on ecosystems via pollution and extraction |
| Human population density in coastal watershed counties | Gulf-wide | | | American Community Survey 3-year estimates and decadal Census | Representative of resource use; strain on ecosystems via pollution and extraction |
| Coastal Urban Land use | Gulf-wide | | | American Community Survey 3-year estimates and decadal Census | Representative of strain on ecosystems via pollution and extraction |
| Shoreline condition | Gulf-wide | | | NOAA Environmental Sensitivity Index (ESI) | Representative of coastal habitats (marshes, mangroves, beaches) and artificial structures (bulkheads, seawalls,revetments) |

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| Employment in the ocean economy | Gulf-wide, by state and county | Annual | | NOAA Office for Coastal Management Economics: National Ocean Watch (ENOW) program | Representative of contributions of Gulf ecosystem to coastal economies |
| Ocean-related Gross Domestic Product (GDP) | Gulf-wide | Annual | | NOAA Office for Coastal Management Economics: National Ocean Watch (ENOW) program | Representative of contributions of Gulf ecosystem to national economy |
| Revenue from commercial fishery landings ($) | Gulf-wide | | | | Representative of contributions of Gulf ecosystem to national economy |
| Amount of commercial fishery landings (tons) | Gulf-wide but with granularity that goes down to level of state, port, county, species? | | | | Representative of contributions of Gulf ecosystem to national economy |
| Social Connectedness | Gulf-wide | | | Decadal Census; National Center for Charitable Statistics; voter participation rates | |

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| Commercial Fishing Engagement | Gulf-wide | | | NOAA Fisheries Social Indicators<br><br>https://www.st.nmfs.noaa.gov/data-and-tools/social-indicators/ | Commercial and recreational fishing engagement are absolute measures of fishing activity as measured by the absolute numbers of that activity. For commercial fishing we used permits, pounds and value of landings and number of dealers for commercial fishing. |
| Commercial Fishing Effort | Gulf-wide | | | | |
| Recreational Fishing Effort | Gulf-wide | | | | |
| ***Additional Indicators for consideration (not part of EcoWatch or the 2017 Gulf Ecosystem Status Report)*** | | | | | |
| *Political Connectedness ($ lobbying congress)* | | | | | *How much political "clout" certain groups and/or regions have within the Gulf may influence a variety of ecosystem processes Perhaps this could be based on the number of lobbyists or amount of money spent lobbying.*<br><br>*These may include recreational anglers, different commercial fisheries, coastal developers; states, counties* |
| *Population composition* | | | | *https://spo.nmfs.noaa.gov/sites/default/files/TM129.pdf* | *Population composition is comprised of variables that correspond to the demographic makeup of the population. These variables, which measure the percentage of minorities, the percent of young children and female-headed households and the ability to speak English well are all common components identified as indicators of socially* |

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| | | | | | *vulnerable populations. Higher factor scores equal higher levels of vulnerability for this index.* |
| *Poverty Index* | | | | *NOAA Fisheries Social Indicators*<br><br>*https://spo.nmfs.noaa.gov/sites/default/files/TM129.pdf* | *Our poverty index contains several different poverty variables that cover all facets of the concept including the elderly, young and families in poverty along with the general percent of population receiving assistance. Higher factor scores equal higher levels of vulnerability for this index, as well.* |
| *Labor force composition* | | | | *NOAA Fisheries Social Indicators*<br><br>*https://spo.nmfs.noaa.gov/sites/default/files/TM129.pdf* | *Labor force structure includes variables that are indicative of the types of engagement within the labor force by examining the percent of the total population and the number of females that are in the labor force, the percent of those who may be retired and those who are self-employed. These variables combined lend themselves to a characterization that provides an indication of the strength and stability of the labor force* |
| *Recreational Access Points* | *Gulf-wide (except TX)* | | | *https://www.fisheries.noaa.gov/recreational-fishing-data/public-fishing-access-site-register* | *MRIP - APAIS fishing site registry. Includes details on fishing sites, infrastructure, amenities.* |
| *Environmental Justice Communities* | *Gulf-wide* | | | *https://www.epa.gov/ejscreen* | *EPA mapping program that includes social and environmental indicators.* |

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| *Recreational activity patterns* | *Gulf-wide* | | | [*http://releases.naturalcapitalproject.org/invest-userguide/latest/recreation.html*](http://releases.naturalcapitalproject.org/invest-userguide/latest/recreation.html) | *Natural Capital Project InVEST recreation tool has been used to map spatial patterns of recreational use in coastal and marine environments based on geotagged photos posted to social media.* |
| *Recreational and Commercial angler opinions* | *Gulf-wide* | | | *Gulf Council Something's Fishy Tool* | *Gulf Council's Something's Fishy tool. The positive or negative sentiment of angler comments could be tracked through time.* |
| *Recreational Angler Satisfaction* | *?* | | | *Academic studies* | |