Building a fisheries trophic interaction database for management and modeling research in the Gulf of Mexico large marine ecosystem

Running title: Gulf of Mexico Trophic Interaction Database

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Abstract

Development of ecosystem-based fisheries management models depends, to a large extent, on the availability of trophic interaction data. These models could attend to ecological questions, examine ecosystem trophic structure, and be used in placement analysis for marine protected areas, among other uses. Collection of trophic interaction data requires extensive field and ship time, and is becoming prohibitively expensive, particularly at large marine ecosystem scales. Many studies on fish trophic interactions, at varying scales, have been conducted in the Gulf of Mexico over the past 120 years, and we are currently compiling data from these studies into a database. In this paper, we report on a collection of 747 references on trophic data for fishes in the Gulf, investigate spatial and taxonomic distributions of the fish species examined, and identify data gaps. Metadata lite, a condensed version of customary metadata that answers the who, what, where, when, and why, has been collected on all studies, all references have been geo-coded, and habitat characterizations have been standardized using the Coastal and Marine Ecological Classification Standard for about 60% of the references. Visualization tools and products to assist in the synthesis, analysis, and interpretation of the data, including maps, network depictions, and dynamic interactions, are discussed. A survey of trophic data available for fisheries management models for managed species in US Gulf waters appear to be adequate for at least 23 of 50 of managed species, while data for at least 14 species remain insufficient for model development assessment.

Food relations between predator and prey have long been recognized as a key ecological relationship (Fabre 1918, Elton 1927, Hutchinson 1959). Early marine food web studies investigated the relationship of benthic production to fish production and inter-relationships of the food web (Petersen 1918), and food and feeding habits of herring (Hardy 1924). Lotka (1925) and Volterra (1926) investigated relative roles of predation and fishing in European seas and conducted some of the first attempts to characterize food-web interactions. Lindeman (1942) introduced the concept of trophic dynamics to characterize the flow of nutrients and energy between organisms and the environment and through food webs. The concept was later encapsulated in a food-web developed for Georges Bank in which ecosystems were depicted as machines, with gear-like mechanisms representing how energy flowed through a food-web (Clarke 1946).

Fish ecologists have been proactive in trophic dynamics research. Workshops focused on food habits of fishes (Simenstad and Lipovsky 1976, Lipovsky and Simenstad 1978, Cailliet and Simenstad 1982, Simenstad and Cailliet 1984) examined trophic structure, competition, modeling, and simulation of fish bioenergetics and feeding behavior, competition and resource partitioning, and fish feeding as a structuring force on prey communities. Furthermore, the past two decades has witnessed a resurgence of interest in and study of food webs (Ings et al. 2009), be it in response to the needs of trophic models (McCann 2007, Bascompte et al. 2005, Allesina et al. 2008), in development and use of ecosystem indicators (Nichson and Jennings 2004, Bandy et al. 2010, Blanchard et al. 2010, Coll et al. 2010, Libralato et al. 2010), as a guiding concept in ecosystem-based fisheries management (EBFM) (Hall and Manprize 2004, Babcock et al 2005, Samhouri et al 2010), or in network topology research (Dunne et al. 2004, Srinivasan et al. 2007, Dunne and Williams 2009, Roopnarine 2010).

Software such as Ecopath (Polovina 1984, Christensen et al. 2004), ecological network analysis (ENA) (Ulanowicz and Kay 1991; Christian et al. 2005), and Atlantis (Fulton et al. 2011) are ecological modeling tools highly dependent on high quality trophic data. Currently, over 300 Ecopath models have been developed worldwide, 15 for the Gulf of Mexico, from which Vidal and Pauly (2004) combined the results of ten regional Ecopath models (Abarca-Arenas and Valero-Pacheco 1993, Arreguin-Sanchez et al., 1993a, Arreguin-Sanchez et al. 1993b, Browder 1993, Chavez et al. 1993, De la Cruz-Aguero 1993; Pauly and Christensen 1993; Vega-Cendejas et al. 1993,Venier 1997; Venier and Pauly 1997, Manickchand-Heileman et al. 1998) into a single Gulf-wide model. ENA has been used to model the effect of over-harvesting of oysters on a Chesapeake Bay food web (Ulanowicz and Tuttle 1992), the effects of reduced freshwater inflow on trophic dynamics of a South African estuary (Baird and Heymans, 1996), and food webs in the Florida Everglades (Heymans et al. 2002). Fulton (2011) cites 13 Atlantis models have been developed (or are under development) for marine ecosystems in Australia and the United States. Atlantis models are being used to explore marine ecosystem dynamics in a living marine resource management context for the NE US continental shelf LME (Link et al. 2010), and to explore the estimation of fish diet composition from multiple data sources in the Gulf of California, Mexico (Ainsworth et al. 2010). A critical concern for all the above cited trophic models is the lack of detailed food habits data.

We argue that historical marine fisheries trophic interaction data must be preserved in perpetuity for the purposes of scientific research, development of fisheries management metrics, and our intellectual heritage. In this light, we review and compare the status and structure of extant regional marine trophic fisheries databases around the world. We review the recent move toward ecosystem-based fisheries management and the important role that trophic data play in that movement. We describe the structure and status of the Gulf of Mexico trophic database, including the results from a pilot study using the Coastal and Marine Ecological Classification Standard (CMECS) to standardize habitat information, and a GulfGAME metadata project. Finally, we present results from an examination of the taxonomic gaps in the fish species with trophic data compared to the overall taxonomic structure of fishes in the Gulf, provide examples of our first attempts to visualize the data, and examine the status of integrating trophic data from the Gulf trophic database into the fisheries management structure of the Gulf of Mexico. Our overarching goal is to address the integration of trophic data into fisheries models and management through preservation, visualization, and interpretation.

Preservation of Historical Data

Understanding marine ecosystem phenomena such as the shifting baselines syndrome (Pauly 1995, Pauly et al.1998, Dayton 2004, Jackson et al. 2001, 2011), trophic cascades (Myers et al. 2007), and the effects of climate change on species diversity (Jackson et al. 2001) requires long-term historical data (Myers 2000, Zeller et al. 2005). Historical trophic data sets provide: (1) time series and spatial data used in ecosystem modeling; (2) diet composition and diversity data; and, (3) historical food web structure and trophic relationships in ecosystems altered long ago. But these data are very scattered and difficult to find and access, making it challenging to arrive at broad, scientifically supportable conclusions. Thus, there is a pressing need to archive, disseminate, and synthesize data on the diets of marine organisms to understand and deal with massive anthropogenic perturbations (i.e., overfishing, habitat destruction, invasive species, pollution, climate change) that are currently occurring in the world’s marine ecosystems. Data recovery and distribution are valuable contributions to ensure long-term returns on funds invested in data gathering. Data loss occurs for many reasons, from poor planning to major political and social disruptions, to catastrophic events (Matthews 1993). Many do not appreciate that data that appear uninteresting or unimportant today may be a gold mine for future scientists (Pauly 1992, Janzen 1986), and that the owners of marine trophic data, which are largely collected using state and Federal funds, are erroneously perceived to be entities other than the general public, despite marine resources being the ‘common heritage of mankind’ (Russ 2003).

Marine Trophic Interaction Databases

We have located six extant regional trophic databases (Table 1) throughout the world, three in the US, two in Europe, and one in Antarctica. In the US two large databases are collected by NOAA NMFS science centers at Woods Hole, MA and Seattle, WA. The Food Web Dynamics Program (FWDP) (<http://www.nefsc.noaa.gov/pbio/fwdp/FWDP.htm>) in Woods Hole documents predator-prey and competitive interactions, and has more than 100 fish species, over 500,000 stomach samples, while the Resource Ecology and Ecosystem Modeling (REEM) (http://www.afsc.noaa.gov/REFM/REEM/) program in Seattle, which focuses on the collection and analysis of data relating to trophic interactions in the North Pacific, has a food habits database including 106 fish species and 191,474 stomachs analyzed. A much smaller effort, the Chesapeake Bay Trophic Interactions Laboratory Services (CTILS), collected food habits data on commercially, recreationally, and ecologically important species in Chesapeake Bay and processed 14,302 stomachs from 47 species of fishes (Parthree et al. 2006). In Europe, there are two food habits database efforts in and around the North Sea. The DAPSTOM (An Integrated Database & Portal for Fish Stomach Records) (http://www.cefas.defra.gov.uk/our-science/fisheries-information/fish-stomach-records.aspx) food habits database (Pinnegar and Platts 2011), which contains data from the North, Irish, and Celtic Seas, has records dating back to 1893, and currently has data for 82 species of fish and a total of 59,181 stomachs analyzed. In addition, the International Council on the Exploration of the Sea (ICES) food habits database is collected from the North Sea, and has 35 fish species and 37,324 stomachs analyzed. In the Southern Ocean, the Australian Antarctic Data Center manages a trophic database which includes fishes, sea and shore birds, marine mammals, and squids. These data are extracted from 655, mostly peer reviewed, articles and reports. The British Antarctic Survey manages the Scotia Sea FOODWEBS project in Antarctica, which is synthesizing diet data from previously published studies. They have many datasets on diet but have not yet organized the data into a database (Personal communication with H. Peat, British Antarctic Survey).

An examination of Table 1 reveals a great heterogeneity in the reporting of trophic data and associated environmental and habitat data in the abovementioned databases. In general, most of the databases report similar cruise and sampling information, while data on predator and prey is more varied. Environmental and habitat data are generally not reported, or only a very few parameters are reported. All but one of the databases indicates that their data are publically accessible, and about half of them are still actively collecting new data.

FishBase (Froese and Pauly 2008) currently has a wide array of published information on more than 30,000 fishes, including diet and feeding habits data. While the trophic level is provided for over 8,100 species, only a minimum amount of data on food habits of fishes in the Gulf of Mexico ecosystem is provided. A survey of 17 fishes, for which there are 30 or more food habits references reported from the Gulf (Simons et al. unpublished data), reveals a wide disparity in the number of food habits source studies in the Gulf as compared to FishBase (Table 2). The food habits data available in FishBase are adequate for general assessments and predictions of diet, predators or trophic levels of a particular species based on diets of fishes in the same genus, order or family, but are insufficient for analysis of spatio-temporal trends in food webs. The disparity in numbers of references between FishBase and our effort is due in part to collections of grey literature including government reports, dissertations, and theses included in the Gulf trophic database which are generally difficult to find and obtain.

Ecosystem-Based Fisheries Management

As knowledge of fisheries ecosystems and food webs grew, and single species fisheries models and management strategies were failing, an increased call for multi-species fisheries management models developed in the late 1980’s (Browder et al. 1990, Sissenwine 1986), and finally many called for ecosystem-based management in the late 1990’s and the new millennium (NMFS 1999, Sherman and Duda 1999, Rogers-Bennett 2001, Busch et al. 2003, Garcia et al. 2003, Pew Oceans Commission 2003, Christensen and Pauly 2004, US Commission on Ocean Policy 2004, Pikitch et al. 2004, NRC 2006). Common to these reports is the stated need to better understand the food and predators of commercial fish species and their prey items as part of an ecosystem-based approach to fisheries management.

Over the past five years, the pace of movement towards ecosystem-based fisheries management (EBFM) has increased dramatically as the pace of literature published indicates (Leslie and McLeod 2007, Crowder et al. 2008, Ruckelshaus et al. 2008, Curtin and Prellezo 2010, Fletcher et al. 2010, Samhouri et al. 2010, Tallis et al. 2010). In addition, the US has funded four of its regional management councils to establish Ecosystem Science and Statistical Committees (ESSC) to aid in the move toward EBFM. Some of these efforts have used ecosystem models such as Ecopath (Pauly et al. 2000, Walters et al. 2008) or Atlantis (Smith et al. 2007) to assist in unraveling the complexity of the science and social aspects of the ecosystem. Other studies have used different approaches, but a common denominator appears to be the importance of thorough knowledge of the trophic web of interactions, thus indicating how robust a system might be against trophic cascades (Salomon et al. 2010), drastic regime shifts (deYoung et al 2008, Osterblom et al 2010) or total collapse of the system (Carpenter and Gunderson 2001).

The Gulf of Mexico Trophic Interaction Database

Database Architecture Development

A database architecture includes two components: (1) representation of reality, and (2) organization of data. The first component concerns what concepts or objects need to be represented in the database and how to most effectively represent these concepts or objects in database models. Because our proposed database aims to integrate spatial and temporal information for ecological interactions, we need to represent spatial and temporal characteristics of the identified concepts or objects. For example, the foraging range of a species can be represented as a polygon feature in a database. However, when we need to analyze the variation in foraging ranges over space and time and compare how the change relates to changes in other species, we will need to represent geo-spatial foraging traits in the database, so that such information can be queried and retrieved for analysis. The second component addresses how different sets of data, such as species data, habitat data, sea surface temperature, management zones, etc*.*, should be organized in the database to support modeling efforts that relate multiple variables to derive new understanding or forecasting. Both components of data representation and organization need to account for complexity and diversity of ecological systems and the nature of potential data sources.

A spatio-temporal database architecture for ecological interactions is being designed to account for the trophic data set outlined in the section above. The complexity and diversity of data to be included in the database amounts to general challenges in building databases. Because our approaches to data representation and organization centers on complex system processes and ecological interactions, and account for data heterogeneity at multiple resolutions, the database architecture is general and transferable to other ecological domains.

Specifically, we adopt Hierarchy Theory (Allen and Starr 1982, O’Neill et al. 1986, Ahl and Allen 1996) for the database architecture development that addresses common ecological issues, such as grain and scale, identification of entities (e.g. predators and prey), levels of dynamics, and disturbances. Hierarchy by definition imposes ordinations, as from smaller to larger, or from simpler to more complex. In a hierarchy, levels of organization are canonical. Salthe (1991) argued that distinction of levels in science related discourses can be based on either scale (extension), i.e. scalar hierarchy, or descriptive complexity (intension), i.e. specification hierarchy. The scalar hierarchy is built upon constraint relations among sub-systems (or parts) and super-systems (or wholes). Extension complexity in scalar hierarchy arises as dynamics of parts and wholes at different scales contextualizes each other at one locale. Such non-linear complexity makes simple aggregation of lower levels insufficient to explain what is going on at a higher level. Specification hierarchy, in contrast, is a nested system in which higher levels transitively integrate dynamics and phenomena at a lower level so that behavior at the higher level is determinable from knowledge of its component levels (Ahl and Allen 1996).

These concepts from Hierarchy Theory are central to many complex systems, including ecological systems and weather systems (Yuan 1999). Database architectures built upon these concepts will provide rich grounds for data mining and knowledge discovery of higher level concepts (Goodchild et al. 2007, Yuan 2008). In designing the database architecture with Hierarchy Theory principles, we include levels of trophic dynamics as determined by foraging ranges or ecospaces that correspond to different levels of spatial and temporal scales. For example, we may have local, zonal, and regional food webs. The database architecture will explicitly connect all the food webs through data representing nutrients and energy flows (i.e. predator-prey interactions).

Geographical Boundaries and Taxonomic Constraints

The food habits data encompass all marine and estuarine waters of the Gulf, along the United States, Mexico, and Cuba. The taxa to be considered for the database are those that inhabit the Gulf region and its waters for at least part of their life cycle. Table 3 lists the major taxonomic groups planned for inclusion in the database and the current status of the data search. Fishes that occur both in brackish/marine and freshwaters are reported during the brackish and marine portions of their life cycle. Sea birds and shore birds that migrate into and out of the area will only have the portion of diets reported from the Gulf region included in the database. In rare cases where diet data are from both the Gulf of Mexico and other areas (i.e. the Atlantic or Caribbean Sea), and cannot be separated, the data will be tagged so as to indicate this to the user. The current focus of the project is on fishes, but all taxa listed in Table 3 will be included as time and funding allow, and other taxa not presently in Table 3 (e.g. chaetognaths, sponges, echinoderms, etc.) will be considered for inclusion in the database at a later date.

Data Sources, Acquisition, and Quality Assurance

The reporting of trophic data in the Gulf of Mexico is very disparate and non-standard in format. We are to the extent possible attempting to standardize the data (i.e. we are converting all measures to common units, converting names to a common usage, etc.), but this will not be possible in many cases. In an attempt to preserve as much data as possible, we are including a large number of parameters for both the predators and prey. All organisms will be recorded to the lowest taxonomic rank reported, and while this may not be useful to a fisheries modeler who uses aggregated data, these data may suit the network researcher who wants to analyze large datasets of very specific directed interactions. This level of detail in the data preservation will allow users to customize their output data for analyses by size, season, location, or other parameters.

Data are being extracted from peer reviewed articles from primary literature, government reports, dissertations and theses, abstracts, proceedings of meetings/conferences, electronic databases, and unpublished material. Intellectual property rights of author’s copyrighted material will be preserved through permission from the author, when necessary. Detailed spatial context of the data has been preserved, through maps, names, coordinates or descriptions of sampling locations. A number of electronic datasets have been identified for inclusion in the Gulf trophic database (Table 4). Locating and obtaining access to additional digital databases will be an ongoing process and a priority for the foreseeable future.

Spatial data are documented with the Federal Geographic Data Committee (FGDC) (http://www.fgdc.gov/) Biological Profile, while habitat data follow the Coastal and Marine Ecological Classification Standard (CMECS), and metadata made available with the FGDC Clearinghouse mechanism. (the CMECS documentation can be found at http://www.cmecscatalogue.org/docs/CMECS\_doc.pdf). The database schema will follow the Ecological Metadata Language (EML), an XML-based metadata specification, and OBIS schema (Fig. 1). As part of this process, we will contribute metadata standards for data from trophic studies. We are using Darwin Core (<http://www.tdwg.org/activities/darwincore/>) to define as many of the fields as possible to maintain compatibility with other databases currently using Darwin Core (e.g. FishBase and OBIS), and we expect to define new Darwin Core fields for trophic data.

The following information, including metadata, is being extracted from each data source, when provided:

* Geopolitical places – country, state, region, etc.
* Geospatial areas – tidal river, estuary, continental shelf and slope, abyssal realm, etc*.*
* Geographic coordinates – latitude, longitude.
* DateTime – year, season, month, date, hour.
* Habitat – ecoregion, system, water column, geo-forms, substrate, biotic communities, etc*.*
* Collection method – trawl, bag seine, gill net, hook and line, bait type, etc.
* Taxonomy – species name, common name, phylum, class, order, family, etc.
* Predator – number of predators, predator weight, predator length, number of stomachs examined, number with food, percent fullness, etc.
* Prey – presence/absence, number, percent number, volume, percent volume, biomass, percent biomass, frequency of occurrence, percent frequency of occurrence, etc.
* Stable isotopes – isotope name, δ value, standard value.
* Source – author, date, title, publisher, book title, journal article title, etc.

The Gulf of Mexico trophic interaction database will be compatible and extensible to extant database projects and programs. Coordination and collaborative promises have already been achieved with FishBase (www.fishbase.org), SeaLifeBase (http://www.sealifebase.org/), EOL (http://www.eol.org/), Data Conservancy (http://dataconservancy.org/), and the Gulf of Mexico Digital Atlas (<http://www.ncddc.noaa.gov/activities/science-technology/digital-atlas/>). In addition, we will seek to link our database to INCOFISH (http://www.incofish.org/), FishNET2 (http://fishnet2.net/), EPOMEX (http://etzna.uacam.mx/epomex/index.html), ORNIS (<http://www.ornisnet.org/>), MaNIS (<http://manisnet.org/>), and other relevant ecological, fisheries or biodiversity webpages. This will allow for data and format sharing to achieve the maximum accessibility and usefulness of the trophic data, and add value to the existing databases through pre-planned links. The vision is that the structure, methods, and tools will be extensible to other large marine ecosystems. The extensibility and transportability of the database model is important to support the development of similar databases globally.

The data will be freely accessed through a graphical user interface, and a map based interface on a publicly accessible website that will be announced in the summer of 2012. A beta test version of the database will be launched in the summer of 2012 for input and testing by a small group of volunteers. Database users will be able to query the database by prey, predator or location, and will have a choice of including downloads of differing categories of data (e.g. predator data, prey data, location information, collection methods, sample preservation methods, and the reference citation information). File formats for data downloads are expected to include csv, Excel, and shape files.

Coding the Coastal and Marine Ecological Classification Standard (CMECS)

The diet of an organism is in large part influenced by the habitat in which the organism resides or that of its feeding grounds. For fishes, under provision of the Magnuson-Steven Fishery Conservation and Management Act, it has been mandated that these areas be classified as essential fish habitat (EFH). In addition, it has been suggested that important food web relationships be considered EFH (Thrush and Dayton 2010). Until recently, there were no comprehensive and standardized classification for estuarine and marine habitats, but this will soon be remedied by the Coastal and Marine Ecological Classification Standard (CMECS).

The CMECS system provides a uniform protocol for identifying, characterizing, and naming ecological units to support activities such as monitoring, protection, and restoration of biotic assemblages, protected species, critical habitat, and important ecosystem components. CMECS at its highest level classifies a habitat into an ecoregional context (Spaulding et al. 2007) and into one of three systems, Marine, Estuarine, and Lacustrine. There are up to four components (Water Column Component, Biotic Component, Substrate Component, GeoForm Component) used to provide further detailed information.

We conducted a pilot study to unify codification of habitat data in the numerous trophic references using CMECS (Yuan et al. 2010). Approximately 60% of the references in hand at the time the project was undertaken were coded. In many cases, habitat information is included in the reference material or it can be inferred from the study, or from a reference cited therein. However, these data are in varying degrees of detail, clarity, and consistency. The inconsistency issue entailed extracting all relevant habitat information reported in the document and adapting those descriptions to the CMECS terminology. Queries have produced lists and maps of trophic studies that include a particular habitat types (Fig. 2).

Metadata and Gulf Geospatial Assessment of Marine Ecosystems (GAME)

Metadata records have been created for 747 references from a bibliography of food habits of fishes for estuarine and marine environments of the Gulf of Mexico (Simons et al. unpublished data). Metadata were generated using the Gulf GAME survey tool that allows records to be entered through a user friendly interface (http://research.myfwc.com/game/survey.aspx). These records were incorporated into the Gulf GAME catalog and are available online for search and retrieval (http://research.myfwc.com/game/search.aspx). The catalog stores metadata “lite” (i.e. only the minimal mandatory FGDC elements are captured) and records are FGDC concurrent. The efforts allow archiving for long-term persistence of information that previously had no attendant metadata. Also, it makes information easier to discover since the majority of the bibliographic references upon which the database will be built are not available online.

Analyses

Taxonomic Gap Analysis

As most of the effort to date has focused on trophic data of fishes, this gap analysis only accounts for fishes. The taxonomic coverage of fishes in the Gulf trophic interaction database was compared to the Gulf of Mexico biodiversity database (McEachran 2009) located on the Gulfbase website (http://www.gulfbase.org/). There are 1,541 species of fishes reported in the Gulf biodiversity database compared to ~762 fish species in the Gulf trophic interaction database, of which 143 do not appear in the Gulf biodiversity listing. These missing species are primarily fresh and brackish water species that were collected in upper reaches of estuaries.

There are four classes of fishes (Myxini – hagfishes, Petromyzontida – lampreys, Chondrichthyes – sharks, skates, and rays, Actinopterygii – ray-finned fishes) in the Gulf of Mexico. The Myxini and Petromyzontida are not represented among the food habits studies compiled to date for the Gulf, while both the Chondrichthyes and Actinopterygii are well represented in the database.

There are 44 orders of fishes in the Gulf (McEachran 2009), of which seven (Myxiniformes (3 species), Petrozontiformes (1 species), Saccapharyngiformes (1 species), Ateleopodiformes (2 species), Polymixiiformes (2 species), Stephanoberyciformes (22 species), and Zeiformes (8 species)) are not represented in the Gulf trophic database. These orders are generally not very species rich and except for the Myxiniformes and Petrozontiformes tend to be deep-sea inhabitants. None of these orders include commercially or recreationally important fish species.

McEachran (2009) lists 236 families of fishes in the Gulf of Mexico, 100 of which are presently not represented in the Gulf trophic database. Four families of fish in the Gulf trophic database are represented by more than 20 species (number of species in the database is given in parentheses): Serranidae – sea basses and groupers (44), Melanstomiidae – scaleless dragonfishes (27), Carangidae -- jacks (22), and Sciaenidae -- drums (22). There are an additional 13 families that are represented by 10 to 19 species.

Exploring Gulf Trophic Data Through Visualizations

A function of ecoinformatics is to extract information from large ecological databases (Jones et al. 2006). A chief mechanism toward this end is through visualization (Kelling et al. 2009). This can be accomplished for species occurrence data by web services such as Lifemapper (http://www.lifemapper.org/), Aquamaps (http://www.aquamaps.org/), and OBIS (<http://www.iobis.org/>) where users can identify biodiversity hotspots and large-scale ecological patterns, analyze dispersions of species over time and space, and predict species' locations using environmental correlates such as temperature, salinity, and depth. At larger scales, visualization of food web topology in three dimensions using Network3D (Yoon et al. 2005) provides a better appreciation of the web’s complexity although not necessarily an understanding of trophic interactions and structure.

*Location of Studies*. – When provided by map or geo-coordinates, the sampling locations for food habits studies in the Gulf have been digitized into the database, while those with general descriptions are defined by “fuzzy” polygons. The map in Fig. 3A shows the location of all of the individual sampling stations from the 419 references that provided them, either by geo-coordinate lists or maps. A total of 747 of the studies are represented by a centroid (some widely dispersed studies are represented by multiple centroids) (Fig. 3B). Each study examined a widely varying number of fish species (from 1 to 81), with approximately half (347) examining a single species. The majority of studies have been conducted in estuaries (~525) and on the continental shelf (~190) while very few have been conducted on the shelf slope/rise and the deep sea (7), or the mesopelagic realm (7).

*Trophic Webs*. – A considerable challenge in constructing any database from disparate sources is annealing the data into a coherent, useful database. As with many ecological data, these Gulf of Mexico trophic data are very heterogeneous. The challenge is to integrate these data into a single database. We have broken the process down into five distinct yet overlapping phases: 1) data acquisition, entry and quality assurance, 2) normalization, 3) integration, 4) transformation, and 5) analysis (and visualization).

We have begun to work with several datasets to explore methods and software available to accomplish the above tasks. We will facilitate access to vast collections of trophic research data by providing:

1) digital, web-enabled access to \*raw\* trophic data derived from source material such as Excel spreadsheets, graphs, scans of notebooks or digital pictures of publications,

2) web access to computer programs (eg. Gephi, Network3D) that transform these materials to a normalized and integrated research dataset,

3) computer resources to normalize and integrate the \*raw\* data source whenever the conversion programs are updated or new \*raw\* data sources are acquired,

4) web access to a comprehensive normalized trophic dataset that was generated by (3) in open, non-proprietary, formats such as csv (comma separated values), and rdf (resource definition format), and

5) access to a list of links or references to studies, papers, research, and/or computer programs to make use of provided resources.

The scope of this project is primarily to provide access to a rich set of trophic data. This narrow focus will help to provide a reliable, trustworthy, and verifiable source for many peer-reviewed trophic research publications in the future. An example of the use of a normalized trophic dataset in an open, non-proprietary, format can be seen in Fig. 4A, where prey and predator species interactions are visualized using a force-directed placement graph (Fruchterman and Reingold 1991). The node size is proportional to the number of measured species interactions for that particular species. The graph was generated using Gephi 0.8 alpha (<http://www.gephi.org>). Other examples include the use of neo4j (http://neo4j.org), a graph database, gremlin (http://gremlin.tinkerpop.com), a graph traversal language, and dbpedia.org to analyze complex relationships between normalized entities such as taxa (species, genus, family) across geospatial, temporal, and interaction (e.g. predator-prey) dimensions (Fig. 4B). These two examples provide a glimpse into the potential of providing easy access to a comprehensive, normalized, integrated trophic set to accelerate scientific discoveries without having to invest scarce research funds for extracting species from their habitat.

*Simplified complexity*. – In addition to the science of synthesizing and analyzing the trophic data from the Gulf trophic interaction database, is the need to present this complexity in a simplified, yet meaningful, fashion to resource managers and the public. To some extent this is accomplished through the concept known to nearly everyone as the food chain or food web. Yet, these are often too simplistic and are usually not specific to one’s own backyard, so to speak. What is needed are concepts, diagrams, and models that are specific, simplified, and can be used as a tool to understand the concepts and the implications of management decisions on the fate of the species inhabiting the systems of interest to the weekend fisherman or the regional upper-level, fishery manager.

We are seeking to develop tools to meet these needs. One important aspect in this endeavor is the question of scale. Trophic interactions occur and have ramifications at many different temporal and spatial scales, and it is important to capture this in any attempt at rendering the issues in figures or models. One example of how this plays out can be seen in Fig. 5A. At a very local level on the scale of a few meters to tens of meters, we see a bonnethead (*Sphyrna tiburo* (Linnaeus, 1758)) consuming a blue crab (*Callinectes sapidus* Rathbun, 1896). This is a very specifically defined single trophic interaction. At larger scales, from tens to hundreds or thousands of meters, e.g. landscape scale (Polis et al. 2004), the diagrams become complex, spatially oriented food webs, and these can have different topologies depending on the habitat over which they occur, e.g. spatial food webs (Holt 1996). Then finally, at the scale of the entire Gulf, thousands to hundreds of thousands of meters, we see patterns, e.g. the Marine Trophic Index (Pauly and Watson 2005), that are the cumulative result of millions to trillions of trophic interactions that have occurred at smaller scales already described.

In formal education settings, science classes are rapidly evolving to include more research projects that use authentic data (NRC 2007; AAAS 2010). As teachers look for ways to leverage this trend, there is a strong need for verifiable resources that provide both data and the necessary tools for further data collection and analysis. To help meet these needs, the Gulf of Mexico trophic interactions database described in this paper will serve as one source of data for a new initiative currently underway in partnership with the Encyclopedia of Life (EOL: eol.org). While EOL currently provides a growing database of curated information about all species on Earth, the project's Learning and Education working group is also developing an online species interaction visualization tool that will provide an environment for adding and exploring species interaction data sets. The visualization tool (Fig. 5B) will combine interaction data along with species descriptions within an interactive interface to enable students to explore interactions across multiple ecosystems. An example use case would be for students to compare how interactions vary between similar species in two different ecosystems. They might also investigate the repercussions of the removal of one or more species. These types of inquiry driven challenges hold the possibility of changing how students view science and, it is hoped, will encourage a greater number to continue pursuing their interest in science as they consider future career options.

Use of database for fisheries modeling and management

The move toward an ecosystem-based approach to fisheries management in the Gulf of Mexico began in earnest in 2004 when the Gulf of Mexico Fisheries Management Council (GMFMC) (http://www.gulfcouncil.org/) became one of four regional US management councils to be awarded funding for an Ecosystem Science and Statistical Committee (ESSC). These committees were charged with exploring and pursuing approaches toward the implementation of ecosystem-based approaches in their respective ecosystem. In the Gulf, this approach included citizen surveys to get a sense of the interest and understanding of the public toward ecosystem-based fisheries management, committee meetings, and scientific workshops.

Approaches that have been explored by the Gulf Council ESSC include examination of modeling methods, in particular, Ecopath with Ecosim (Christensen et al. 2004). These models have been developed in an attempt to explore the system responses to the effects of differing management options with regards to issues of specific concern to the Gulf Council. An Ecopath model has been developed for the whole Gulf (Walters et al. 2008), modifying an existing model from the west Florida shelf (Mackinson et al. 2001, Okey and Mahmoudi 2002, Okey et al. 2004). During evaluation runs of the model at a workshop, it became evident that there were unexpected results, and that the trophic data, upon which the model is heavily dependent, were inadequate for many of the species in the model, or for selected life stages, or it was unknown what preyed on especially critical life stages, i.e. juvenile red snappers (*Lutjanus campechanus* (Poey, 1860)), of target fishery species.

These efforts at ecosystem or sub-ecosystem modeling in the Gulf had been preceded by a number of Ecopath models, mostly in Mexico, which were synthesized into a Gulf-wide model by Vidal and Pauly (2004). Since that time, Ecopath models in the Gulf LME have been developed for Mobile Bay, AL (Evans, NOAA, personal communication), Weeks Bay, AL (Althauser 2003), Galveston Bay, TX (Sutton and Guillen 2009), and the west Florida Shelf (Mackinson et al. 2001, Okey and Mahmoudi 2002, Okey et al. 2004). Only the west Florida shelf models were assembled with an ecosystem-based management approach as the driving objective.

The fishes of US waters of the Gulf of Mexico are managed by two groups, the Gulf of Mexico Fisheries Management Council (GMFMC) (http://www.gulfcouncil.org/), which manages commercial and recreational fisheries in US Federal waters, and the Gulf States Fisheries Management Commission (GSMFC) (<http://www.gsmfc.org/>), which manages cross jurisdictional (state/Federal waters) commercial and recreational species. In addition, the five coastal states each manage the fishes of their bays, estuaries and coastal waters out to six nautical miles into the Gulf (or nine nautical miles in the case of Texas and Florida).

The GMFMC manages 50 species of Gulf fishes under three different FMPs (Table 5), while the GSFMC manages eight fish species under the Interjurisdictional Fisheries (IJF) Management Program, with management plans for seven species currently under development (Table 6). An examination of available trophic references for the Gulf indicates that there are no trophic data for five of the 42 reef species managed by GMFMC (Table 5), and only one reference is available for eight of those reef species. For four of those eight, the only information on diet is from Veracruz, MX. Fourteen of the reef species have at least 10 references. All of the species currently managed by GSMFC have at least three references to trophic data while 11 of the 15 species have 10 or more references (Table 6).

In Mexico the fishes and fisheries of the Gulf of Mexico are managed by Comisión Nacional de Acuacultura y Pesca (CONAPESCA - National Commission on Aquaculture and Fishing) (http://www.conapesca.sagarpa.gob.mx), which is responsible for promoting, and developing the mechanism of coordination with different authorities in order to install regulations to facilitate the competitive development of fisheries and aquaculture in the country. They manage a total of 109 species of bony fishes and elasmobranchs, of which 37 are common to the US management programs. Meanwhile the Mexican states regulate sport and recreational fishing permits, and manage sessile species in lagoon systems and territorial seas off their coasts.

Conclusions

We began this paper by making the case that there are intellectual and practical reasons for preserving historical and currently produced trophic data for organisms in the Gulf of Mexico. While this task is difficult, it is without question, of great value. This was eminently illustrated by a recent special section in *Science* that describes the resurrection of an old data set that spawned more than 12 high impact papers in particle physics (Curry 2011). In addition, there are a scant few trophic databases world-wide, and these are primarily focused on commercially harvested species. Furthermore, FishBase, which is an excellent source of information on over 30,000 fishes world-wide, does not have the level of detail on food habits of organisms in the Gulf of Mexico needed for spatial trophic models or for network research.

The move toward ecosystem-based management has also pressed the need for detailed trophic data for the construction of models. This need has been urgently expressed by several researchers seeking trophic data for fisheries models of the Gulf of Mexico (D Chagaris, Florida Wildlife Research Institute, C Ainsworth, University of South Florida, pers comm). Lack of easily accessible data slows the model building process as data must be searched for, and it injects variability into the sources of data used in the different models. We point out that while there is ample data for many of the species currently managed by GMFMC and GSMFC, there are some species for which data are weak or lacking altogether (Tables 5 and 6). The value of the Gulf trophic database will be access to a common data pool for use in fisheries management models plus the ability to target data collection efforts on species lacking strong data.

The Gulf trophic database is nearing implementation. It will be web-based, freely accessible to the public, bi-lingual (English/Spanish), tri-national in scope (Cuba, Mexico, United States), spatially explicit, and cover the entire Gulf of Mexico from the estuaries to the deep sea. At present we currently have references to data for over 700 species of fishes, and will be adding data on other taxa as indicated in Table 3 as time and funding permit. Our data distribution maps (Fig. 3A and Fig. 3B) show the wide spatial coverage of the data, but also indicate areas where more data is needed (e.g. the deep sea). In addition, through the use of CMECS (endorsed in the spring of 2012 as the FGDC standard for marine habitat classification), we will report all habitat data, when available, in a common format. Currently metadata “lite” for all 747 references to food habits data that are being used in the construction of the database are online in the GulfGAME catalog.

A taxonomic gap analysis revealed that nearly half of the fishes listed for the Gulf of Mexico in the Gulfbase biodiversity database will be represented in the Gulf trophic database when all currently held data are loaded. This analysis also identified seven orders (of 44) and 100 families (of 236) of fishes without any data (many are deep sea taxa), while it shows that taxa which are commercially or recreationally important (e.g. Serranidae, Carangidae, Sciaenidae) are overrepresented in the list of fishes for which we have data.

Visualizations are a critical tool toward exploring patterns and gaining an understanding of data in large databases. We have just begun this exploration. Simple visualizations of the spatial extent of the data are very helpful in ascertaining the spatial gaps that may be present in the database. We have begun to investigate the complexities of the data through the use of Gephi, gremlin, and Network3D to explore patterns in trophic structure with data containing thousands of trophic interactions. And we are working with researchers at EOL to explore dynamical links to food webs to access data rich content provided by EOL in order to explore educational uses of the Gulf trophic database.

As we move forward with this project, we envision an opportunity to create a model database architecture that could be modified and adapted to other LME’s around the world. With this in mind, we are anticipating the creation of metadata standards for trophic data, and development of new data fields for the Darwin Core in regards to trophic data. We also see the development of a web of dynamic links to the webpages of data providers, data users, and informatics resources.

This manuscript was inspired by the theme “*Species Interactions in Marine Communities: the Invisible Fabric of Nature*” of the recent fisheries ecology symposium at Mote Marine Laboratory. We can think of no more important invisible fabric than that of the tangled web of trophic interactions that weaves the organisms of the Gulf of Mexico into a dynamic ecosystem. The field of ecology in general has been slow to join the realm of large databases and ecoinformatics (Michener et al. 2002, Jones et al 2005, Costello and Vanden Berghe 2006) in the way that the molecular biology community has embraced GenBank (<http://www.ncbi.nlm.nih.gov/genbank/>), many other interaction databases, and bioinformatics. We thus urge scientists around the Gulf of Mexico to join the effort to create a species interaction database for the Gulf. With the combined records of these thousands to millions of trophic interactions that we are building into the Gulf trophic database, scientists, managers, and the general public will be able to explore data and ask questions about trophic network structure of the Gulf of Mexico large marine ecosystem that currently are not possible.

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Table 1. Location and name of extant world-wide trophic databases, the parameters measured and other associated variables.. nd=no data, N/A=not applicable. \* indicates number of species estimated from FishBase, \*\* indicates data are not digitized, protocols were not standardized, \*\*\* indicates inclusion of records for taxa other than fish, i.e. birds, marine mammals, squid.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Sampling Locations | Name of Program1 | Responsible Organization | Approximate No. of Fish Species in Ecosystem | Approximate No. of Species in Database | Proportion of Total Species in Database | Number of stomachs analyzed | Total predator-prey records |
| NE US Atlantic continental shelf | FWDP | NOAA, NMFS, NEFSC, Woods Hole, MA | 643\* | >150 | .23 | >510,000 | >630,000 |
| NW US Pacific (Bering Sea, Gulf of Alaska) | REEM | NOAA, NMFS, AFSC, Seattle, WA | 1,088 | 106 | .10 | 191,474 | 850,000 |
| US West coast | REEM | NOAA, NMFS, Seattle, WA | 723\* | 22 | .03 | 20,606 | nd |
| Eastern Bering Sea (Japanese data) | REEM | NOAA, NMFS, Seattle, WA | 248\* | 19 | .08 | 31,772 | nd |
| Chesapeake Bay | CTILS | VIMS, Gloucester Point, VA | 267 | 47 | .18 | 14,302 | 33,571 |
| Southern Ocean | Southern Ocean Food Web Database | Australian Antarctic Data Center | 53\* | nd | nd | nd | 26,108\*\*\* |
| North Sea, Baltic Sea | ICES Stomach Data | ICES, Copenhagen, Denmark | 191\*  161\* | 35 | .18 | 37,324 | 201,514 |
| North Sea, Irish Sea, Celtic Sea | DAPSTOM | Cefas | 370 | 82 | .22 | 59,181 | 103,827 |
| Gulf of Mexico and associated estuaries | This study | CCS, TAMUCC, Corpus Christi, TX | 1,630 | 748 | .46 | nd | nd |

1webpage URLs:

FWDP (Food Web Dynamics Program): < http://www.nefsc.noaa.gov/pbio/fwdp/FWDP.htm>

REEM (Resource Ecology and Ecosystem Modeling): <http://[www.afsc.noaa.gov/REFM/REEM/data](http://www.afsc.noaa.gov/REFM/REEM/data)>

CTILS (Chesapeake Bay Trophic Information Laboratory Service): < http://www.fisheries.vims.edu/ctils/>

Southern Ocean Food Web Database: < http://data.aad.gov.au/aadc/trophic/>

ICES (International Council on the Exploration of the Sea) Stomach Data: <http://ecosystemdata.ices.dk/stomachdata/>

DAPSTOM ( ): < <http://www.cefas.defra.gov.uk/our-science/fisheries-information/fish-stomach-records.aspx>>

2 GrTyp=gear type, DTG=date/time group, Lat=latitude, Lon=longitude, StaNm=station number or name, CrNm=cruise number or name, LocNm=location name, Dep=depth, Tide=tidal stage, Shp=ship name, Haul=haul designation, Msh=mesh size of the trawl

3 Lh=life history stage, SFull=stomach fullness, StWt=stomach weight, Len=length of predator specimen, Wt=weight of predator, Sex=gender of the predator, N=number of predator specimens/stomachs, Ne=number of empty stomachs, Nwf=number of stomachs with food, Age-age of the organism

4 CI=condition index or digestive state of prey specimen, Lh=hife history stage, Len=length of prey specimen, Vol=volume of prey specimen, Wt=weight of prey, DS=digestive state, PctComp=percent composition of diet, PctN=percent of numerical count, FO=frequency of occurrence, Prts=parts of prey items, Wtot=total weigth of prey items

5 WTgr=water temperature at the sampling gear, WTsurf=water temperature at sea surface, WTbot=water temperature at sea bottom, WT=water temperature, Sal=salinity, DO=dissolved oxygen, pH=pH, WS=wind speed, WD=wind direction, Wea=weather, AT=air temperature, SS=sea state

6 BotTyp=bottom type

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Cruise, Haul and Sampling Information2 | Predator Parameters Collected3 | Prey Parameters Collected4 | Environmental Parameters  Collected5 | Habitat Parameters Collected6 | Data Publically Accessible? | Years Covered | Still Active? |
| Lat, Lon, DTG, GrTyp | Age, Len, Lh, Sex, Wt | Len, N, PctComp, Vol, Wt, Wtot |  |  | No | 1963-1972\*\*,  1973-present | Yes |
| Shp, CrNm, DTG, Haul, StNm, Lat, Lon, Dep | Len, Lh, SFull, StWt, Sex, Wt | CI, Len, Lh, N, Prts, Sex, Wt, Wtot | WTgr, WTsurf | BotTyp | Yes | 1982-present | Yes |
| nd | nd | nd | nd | nd | Yes | 1967-1999 | No |
| nd | nd | nd | nd | nd | Yes | 1979-1985 | No |
| GrTyp, DTG, Tide, Dep, Lat, Lon, StaNm, CrNm | Len, Ne, Sex, Wt, WtSt | Len, N, Wt | AT, DO, Sal, SS, Wea, WD, WS, WTsurf, WTbot |  | Yes |  | Yes? |
| LocNm, Lat, Lon, Dep, DTG | Len, Lh, N, Wt | FO, Len, Lh, N, PctWt, PctN, Wt | nd | nd | Yes (w/ permission) | 1960 - 2010 | No |
| Shp, DTG, StaNm, Lat, Lon, Dep | Age, Len, Nwf, Ne, Nreg, Ns, Wt, | CI, Len, N, Wt | WT | nd | Yes | 1980,  1985-1986, 1991 | No |
| GrTyp, DTG, Lat, Lon, StaNm, CrNm | Len, Ns, Sex, SFull, Wt, | CI, Len, N, Vol, Wt | nd | nd | Yes | 1893-2010 | Yes |
| GrTyp, DTG, Lat, Lon, CrNm, Msh, StaNm | Len, N, Ne, Nwf, SFull, Sex, Wt | CI, N, Len, Vol, Wt | DO, pH, Sal, WT | CMECS compliant | Yes, when launched | 1891- present | N/A |

Table 2. The 17 fish species most frequently found in food habits studies (each with 30 or more references) in the Gulf of Mexico compared to the number of source studies listed on the FishBase website, both world-wide and within the Gulf.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Family | Species | This  Study | FishBase –  World-wide | FishBase –  Gulf of Mexico |
| Sciaenidae | *Cynoscion nebulosus* | 86 | 2 | 1 |
| Sciaenidae | *Sciaenops ocellatus* | 66 | 2 | 1 |
| Sparidae | *Lagodon rhomboides* | 64 | 5 | 3 |
| Sciaenidae | *Leiostomus xanthurus* | 65 | 6 | 2 |
| Sciaenidae | *Micropogonias undulatus* | 61 | 3 | 2 |
| Ariidae | *Ariopsis felis* | 58 | 2 | 2 |
| Sciaenidae | *Cynoscion arenarius* | 57 | 2 | 2 |
| Sciaenidae | *Bairdiella chrysoura* | 51 | 3 | 1 |
| Lutjanidae | *Lutjanus campechanus* | 49 | 3 | 0 |
| Sparidae | *Archosargus probatocephalus* | 48 | 1 | 0 |
| Engraulidae | *Anchoa mitchilli* | 47 | 1 | 0 |
| Lutjanidae | *Lutjanus griseus* | 45 | 6 | 2 |
| Sciaenidae | *Pogonias cromis* | 40 | 1 | 0 |
| Paralichthyidae | *Paralichthys lethostigma* | 39 | 1 | 1 |
| Ariidae | *Bagre marinus* | 35 | 2 | 1 |
| Synodontidae | *Synodus foetens* | 32 | 3 | 0 |
| Ariidae | *Cathorops melanopus* | 30 | 0 | 0 |

Table 3. Taxonomic groups to be included in the database and the current status of in-hand and perceived references addressing food habits.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Group | Number of References in Hand | Estimated References Available | Total Number of Species Currently Cited with Diet/Host Data | Status of Search for References |
| Marine Mammals | 3 | 25 | 1 | Moderately searched |
| Sea Turtles | 9 | 10-15 | 3 | Well searched |
| Fishes | 737 | 775 | 745 | Well searched |
| Sea and Shore Birds | 4 | 100-200 | 4 | Just begun |
| Crustaceans | 19 | 25-50 | 58 | Moderately searched |
| Mollusks | 3 | 25 | 45 | Moderately searched |
| Polychaetes | ~25 | 100-200 | 99 | Moderately searched |
| Ctenophores | 5 | 10 | 2 | Moderately searched |
| Cnidarians | 5 | 10 | 6 | Moderately searched |
| Parasites | 44 | 310 | ~150 | Moderately searched |

Table 4. Investigators, number and types of ecosystems they sampled and data on the volume of food habits data present in their hard copy or electronic database. All information was acquired through personal communications with the investigator. Ecosystem types: E=estuary, CS=continental shelf. Modifiers for estuary: B=bay, M=marsh, L=lagoon. nd=no data.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Investigator | Number of Ecosystems Studied | Type of Ecosystem | Number of Species Studied | Number of Specimens Examined | Number of Predator-Prey Records |
| Abarca, L. | nd | E(L) | >100 | >1,000 | nd |
| Akin, S. | 1 | E(M) | 32 | 5,506 | nd |
| Arreguin-Sanchez, F. | 2 | E(L), CS | >50 | 200 | nd |
| Franco Lopez, J. | nd | E(L) | >150 | >10,000 | nd |
| Ibanez, A. | 1 | E(L) | 2 | 155 | 884 |
| Livingston, R. | 12 | E(B) | 257 | 10-50,000 | 100-500,000 |
| McMichael, B. | 2 | E(B), CS | 152 | 8,057 | 30,602 |
| Oakley, J. | 1 | E(B) | 24 | 483 | 997 |
| Simons, J. \* | 1 | CS | 56 | 5,863 | 5,673 |
| Slocum, J. | 1 | E(B) | 35 | 634 | 643 |
| Vega-Cendejas, M. | 8 | E(L) | 81 | 12,870 | nd |

\* All studies but this one has data at the individual specimen level. Data from this study was pooled up to 20 individuals at each unique sampling event.

Table 5. List of species for which the Gulf of Mexico Fishery Management Council has management plans and the number and extent of food habits data that is available for the Gulf trophic database. Abbreviations are defined as follows: AL=Alabama, FL=Florida, LA=Louisiana, MS=Mississippi, TX=Texas, Cam=Campeche, Qui=Quintana Roo, Tab=Tabasco, Tam=Tamaulipas, Ver=Veracruz, Yuc=Yucatan, Hab=Habana, US=United States, MX=Mexico, CU=Cuba.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Species name | Common name | Fishery management plan status | Number of food habits references collected | Geographic coverage of food habits data by state |
| *Scomberomorus cavalla* | king mackerel | Coastal Migratory Pelagics FMP | 17 | AL, FL, LA, MS, TX (US); Ver (MX) |
| *Scpmberomorus maculatus\** | Spanish mackerel | Coastal Migratory Pelagics FMP | 19 | AL, FL, LA, MS, TX (US); Ver (MX) |
| *Rachycentron canadum* | cobia | Coastal Migratory Pelagics FMP | 15 | AL, FL, LA, MS, TX (US); |
| *Scomberomorus regalis* | cero | Coastal Migratory Pelagics FMP | 2 | FL (US) |
| *Euthynnus alletteratus* | little tunny | Coastal Migratory Pelagics FMP | 5 | FL, LA, MS, TX (US) |
| *Coryphaena hippurus* | dolphin fish | Coastal Migratory Pelagics FMP | 11 | AL, FL, LA, MS, TX (US) |
| *Pomatomus saltatrix\** | bluefish | Coastal Migratory Pelagics FMP | 14 | AL, FL, LA, TX (US) |
| *Sciaenops ocellatus\** | red drum | Red Drum FMP | 66 | AL, FL, LA, MS, TX (US); Ver (MX) |
| *Etelis oculatus* | queen snapper | Reef Fish FMP | 0 | N/A |
| *Lutjanus analis* | mutton snapper | Reef Fish FMP | 6 | FL (US); Cam, Ver (MX) |
| *Lutjanus apodus* | schoolmaster | Reef Fish FMP | 11 | FL (US); Cam, Qui, Ver, Yuc (MX); Hab (CU) |
| *Lutjanus buccanella* | blackfin snapper | Reef Fish FMP | 0 | N/A |
| *Lutjanus campechanus* | red snapper | Reef Fish FMP | 49 | AL, FL, LA, MS, TX (US); Cam, Qui, Tab, Ver, Yuc (MX); |
| *Lutjanus cyanopterus* | cubera snapper | Reef Fish FMP | 2 | Ver (MX) |
| *Lutjanus griseus* | gray (mangrove) snapper | Reef Fish FMP | 45 | AL, FL, LA, MS, TX (US); Cam, Qui, Ver, Yuc (MX); |
| *Lutjanus jocu* | dog snapper | Reef Fish FMP | 3 | FL (US); Ver (MX) |
| *Lutjanus mahogoni* | mahogany snapper | Reef Fish FMP | 2 | Ver (MX) |
| *Lutjanus synagris* | lane snapper | Reef Fish FMP | 16 | FL, MS, TX (US); Cam, Ver, Yuc (MX); Hab (CU) |
| *Lutjanus vivanus* | silk snapper | Reef Fish FMP | 1 | FL (US) |
| *Ocyurus chrysurus* | yellowtail snapper | Reef Fish FMP | 7 | FL (US), Yuc (MX) |
| *Prtistipomoides aquilonaris* | wenchman | Reef Fish FMP | 5 | AL, MS (US); Ver (MX) |
| *Rhomboplites aurorubens* | vermilion snapper | Reef Fish FMP | 9 | AL, FL, LA, MS, TX (US); Yuc (MX) |
| *Epinephelus adscensionis* | rock hind | Reef Fish FMP | 5 | FL, TX (US) |
| *Epinephelus drummondhayi* | speckled hind | Reef Fish FMP | 2 | FL (US) |
| *Epinephelus flavolimbatus* | yellowedge grouper | Reef Fish FMP | 3 | AL, FL, MS (US) |
| *Epinephelus guttatus* | red hind | Reef Fish FMP | 3 | FL (US); Cam (MX) |
| *Epinephelus itajara* | goliath grouper | Reef Fish FMP | 11 | FL, TX (US); Cam, (MX) |
| *Epinephelus morio* | red grouper | Reef Fish FMP | 17 | FL (US); Cam, Qui, Yuc (MX) |
| *Epinephelus mystacinus* | misty grouper | Reef Fish FMP | 1 | FL (US) |
| *Epinephelus nigritus* | warsaw grouper | Reef Fish FMP | 3 | FL, TX (US) |
| *Epinephelus niveatus* | snowy grouper | Reef Fish FMP | 1 | FL (US) |
| *Epinephelus striatus* | Nassau grouper | Reef Fish FMP | 3 | FL (US) |
| *Mycteroperca bonaci* | black grouper | Reef Fish FMP | 9 | FL, TX (US); Yuc, (MX) |
| *Mycteroperca interstitialis* | yellowmouth grouper | Reef Fish FMP | 2 | FL (US) |
| *Mycteroperca microlepis* | gag | Reef Fish FMP | 13 | FL, LA (US); Qui, (MX) |
| *Mycteroperca phenax* | scamp | Reef Fish FMP | 1 | FL (US) |
| *Mycteroperca venenosa* | yellowfin grouper | Reef Fish FMP | 4 | FL (US) |
| *Caulolatilus crysops* | goldface tilefish | Reef Fish FMP | 2 | AL, MS (US) |
| *Caulolatilus cyanops* | blackline tilefish | Reef Fish FMP | 0 | N/A |
| *Caulolatilus intermedius* | anchor tilefish | Reef Fish FMP | 1 | Ver (MX) |
| *Caulolatilus microps* | blueline tilefish | Reef Fish FMP | 1 | Ver (MX) |
| *Lopholatilus chamaeleonticeps* | tilefish | Reef Fish FMP | 0 | N/A |
| *Seriola dumerili* | greater amberjack | Reef Fish FMP | 6 | AL, FL, MS (US) |
| *Seriola fasciata* | lesser amberjack | Reef Fish FMP | 1 | AL, MS (US) |
| *Seriola rivoliana* | almaco jack | Reef Fish FMP | 1 | AL, MS (US) |
| *Seriola zonata* | banded rudderfish | Reef Fish FMP | 0 | N/A |
| *Balistes capriscus* | gray triggerfish | Reef Fish FMP | 12 | TX, FL, MS (US); Ver (MX) |
| *Lachnolaimus maximus* | hogfish | Reef Fish FMP | 9 | FL (US) |
| *Diplectrum bivittaum* | dwarf sand perch | Reef Fish FMP | 9 | AL, FL, LA, MS, TX (US), Ver (MX) |
| *Diplectrum formosum* | sand perch | Reef Fish FMP | 11 | FL, TX (US); Ver, (MX) |

\*Also covered by GMFMC FMPs.

Table 6. List of species for which the Gulf States Marine Fishery Commission has or is developing management plans and the number and extent of food habits data that is available for the Gulf trophic database. Abbreviations are defined as follows: AL=Alabama, FL=Florida, LA=Louisiana, MS=Mississippi, TX=Texas, Cam=Campeche, Qui=Quintana Roo, Tab=Tabasco, Tam=Tamaulipas, Ver=Veracruz, Yuc=Yucatan, US=United States, MX=Mexico.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Species name | Common name | Fishery management plan status | Number of food habits references in bibliography | Geographic coverage of food habits data by state |
| *Cynoscion nebulosus* | spotted seatrout | Completed | 86 | AL, FL, LA, MS, TX (US); Tam, Ver (MX) |
| *Paralichthys albigutta* | Gulf flounder | Completed | 9 | FL, TX (US) |
| *Paralichthys lethostigma* | southern flounder | Completed | 39 | AL, FL, LA, MS, TX (US); |
| *Acipenser oxyrhinchus* | Gulf sturgeon | Completed | 3 | FL (US) |
| *Mugil cephalus* | striped mullet | Completed | 28 | FL, LA, TX (US); Tab, Tam, Ver (MX) |
| *Scomberomorus maculatus\** | Spanish mackerel | Completed | 19 | AL, FL, LA, MS, TX (US), Ver (MX) |
| *Brevoortia patronus* | Gulf menhaden | Completed | 19 | FL, LA, TX (US); Ver (MX) |
| *Pogonias cromis* | black drum | Completed | 40 | LA, MS, TX (US); Ver (MX) |
| *Micropogonias undulatus* | Atlantic croaker | Under development | 61 | AL, FL, LA, MS, TX (US) |
| *Menticirrhus americanus* | ground mullet | Under development | 23 | AL, FL, LA, MS, TX (US); Ver (MX) |
| *Leiostomus xanthurus* | spot | Under development | 65 | AL, FL, LA, MS, TX (US); Tam, Ver (MX) |
| *Lobotes surinamensis* | tripletail | Under development | 6 | AL, MS, TX (US), Ver (MX) |
| *Sciaenops ocellatus\** | red drum | Under development | 66 | AL, FL, LA, MS, TX (US); Ver (MX) |
| *Pomatomus saltatrix\** | bluefish | Under development | 14 | AL, FL, LA, TX (US); |
| *Alosa alabamae* | Alabama shad | Under development | 0 | N/A |

\*Also covered by GMFMC FMPs.

Figure Legends:

Figure 1. Schema for the Gulf of Mexico trophic interaction database.

Figure 2. Plot of habitat system types as interpreted from the trophic data references for the CMECS pilot study. These data are from approximately 60% of the total references collected to date.

Figure 3. Maps showing the location of a) all the sampling locations recorded from coordinates or drawn from maps, and b) the centroid of each study with the size and shade of the point giving an indication of the number of fishes examined for food habits.

Figure 4. The graph was created using Gephi 0.8 alpha (http://gephi.org) and the Fruchterman Reingold graph layout algorithm (http://wiki.gephi.org/index.php/Fruchterman-Reingold). The size of the (predator) species font is proportional to the out-degree of its (prey) species within the dataset. Or, the bigger the font size of the species, the more prey the predator has consumed, and b) a subgraph of a trophic data graph with about 15k nodes (two trophic datasets) that represent normalized and integrated entities including but not limited to species, genus, family, location, study, specimen and season and associated entity relationships such as "ate", "collected", "caught during" and "classified as". Graph was generated using an open-source, interactive, graph traversal.

Figure 5. A representation of a) how the complexity and representation of food habits data for the Gulf can be scaled from individual organisms to the entire Gulf, and b) how a food web can be dynamically linked to a biodiversity website for value-added information on the life history and biology for a species of interest.



figure 1

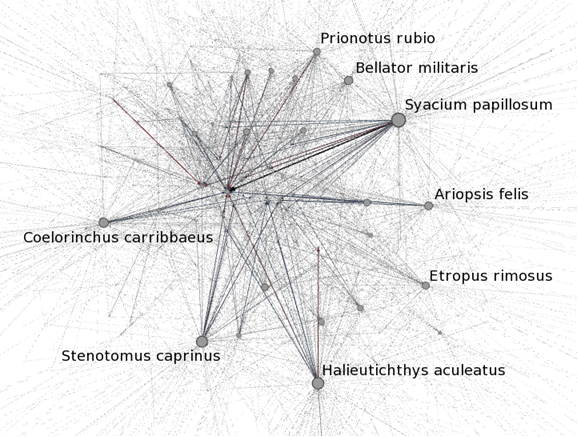


Figure 2





Figure 3



A..



B..

Figure 4



A..



B..

Figure 5