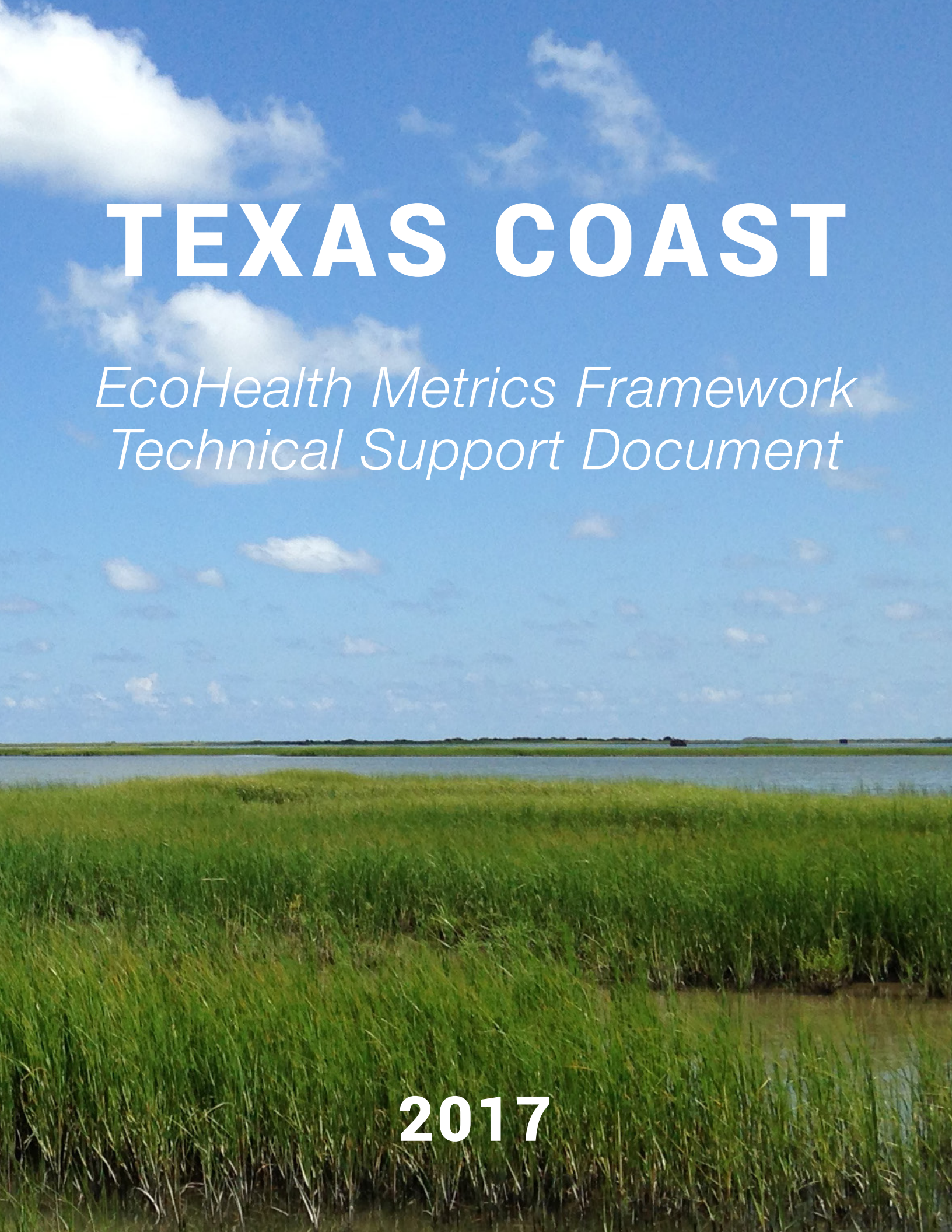

TEXAS COAST

EcoHealth Metrics Framework
Technical Support Document

2017

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I. Introduction — Vision for Gulf of Mexico EcoHealth Metrics

Abstract

The Harte Research Institute for Gulf of Mexico Studies has undertaken a multi-faceted project to develop and implement an integrated indicators and assessment framework. This framework, which we term the *Gulf EcoHealth Metrics*, is designed to characterize the health of the ecosystems of the Gulf of Mexico ecosystems, including their linkages to human communities, in support of management needs for restoring and sustaining a healthy Gulf of Mexico. Our vision is to develop a graphical representation of the environmental condition of the Gulf that will be scientifically based, widely accessible, and readily understandable by policy-makers, stakeholders, scientists, and, most importantly, the American public. A hierarchical structure, unified by a common conceptual framework, will provide the optimal basis for informing multiple audiences at the appropriate level of detail and aggregation, allowing one to dig deeper into the reasons for the various assigned metrics of ecosystem health. Additionally, the Gulf EcoHealth Metrics will be spatially explicit yet scalable, providing a way to compare the successful and not-so-successful outcomes across regions, habitats, and political boundaries. The Gulf EcoHealth Metrics will provide the scientific information and understanding necessary to evaluate the health of the Gulf, clearly demonstrate how well it is or is not progressing towards desired long-term goals, and inform the decision-making process on the policies and resources needed to achieve sustainability of a healthy Gulf of Mexico.

Introduction

The Gulf of Mexico is among the most ecologically diverse and valuable ecosystems in the world, comprising over 1.5 x 10^6 km^2 in area and consisting of offshore waters and coastal habitats of 11 US and Mexican states plus Cuba (Figure 1a). The Gulf's wetlands, beaches, coastal woodlands, and islands are major nurseries for breeding birds and provide foraging and stopover habitat for millions of birds that converge from some of the most important migratory flyways. Coastal marshes and near-shore habitats provide essential nursery habitat for ecologically, commercially, and recreationally important species of fish and invertebrates. Offshore habitats and species are biologically diverse and include deepwater corals, sponges, fish stocks, marine mammals, sea turtles, and other unique species and communities. These habitats are integral to the economic and cultural fabric of the Gulf, providing a range of ecosystem services, including fisheries, food and energy production, infrastructure protection, and recreational and wildlife-related activities. Testament to its impressive diversity is provided by a recent biotic survey that found over 15,400 species living in the Gulf of Mexico (Felder et al. 2009).

The Gulf's watershed covers 56% of the continental US (USEPA 2011), 40% from the Mississippi River Basin alone (Figure 1b). This watershed is a source of a wide range of anthropogenic stressors. Nutrients (N and P) and other pollutants (e.g., hydrocarbons, pesticides, industrial wastes) contribute to degraded water quality in the Gulf, including an average of over 17,000 km^2 of annually occurring hypoxic conditions (USEPA 2011). Oil and gas industry canals, pipelines, and other infrastructure crisscross the landscape, contributing to the loss of wetland habitat. Geologic land subsidence substantially exacerbates sea-level rise (Morton et al. 2005); e.g., ~5000 km^2 of wetlands in Louisiana

were lost in the last 7 decades (Couvillion et al. 2011). As a result of these and other natural and anthropogenic pressures, the Gulf's estuaries have become increasingly degraded for both human use and aquatic life. Several major threats to the health of the Gulf have been identified (Mabus 2010; USEPA 2011):

- loss of wetland habitats, coastal marshes, barrier islands, and shorelines;
- erosion of barrier islands and shorelines, undermining storm protection and reducing habitat for endangered or threatened species such as sea turtles and shorebirds;
- degradation of coastal estuaries, which provide essential nursery habitat for most of the Gulf fishery resources;
- overharvesting of commercially and recreationally important fisheries, exacerbated by the human health threats of methyl-mercury in finfish, harmful algal blooms (HABs), and human pathogens in shellfish;
- hypoxia offshore of the Mississippi River Delta;
- global climate change with potentially increased frequency and intensity of storms, accelerated sea-level rise, and attendant economic risks and loss of coastal habitats and natural resources.

Superimposed on these threats was the 20 April 2010 explosion on the *Deepwater Horizon* drilling platform operating in the Mississippi Canyon of the Gulf, resulting in the largest marine oil spill in US history, with an estimated 5×10^6 barrels released over 87 days (Mabus 2010; NAS 2012). The unprecedented combination of extreme depth of discharge (~1500 m) and massive use of dispersants (~ 3×10^6 L; Kujawinski et al. 2011) caused high uncertainty in predicting the transport and fate of oil and dispersant compounds and in understanding the severity and magnitude of ecological effects (Joye 2015).

In response to the oil spill, the Gulf Coast Ecosystem Restoration Task Force was established (Executive Order 13554, 5 October 2010) to develop a science-based Gulf of Mexico Regional Ecosystem Restoration Strategy to: restore and conserve habitat; restore water quality; replenish and protect living coastal and marine resources; and enhance community resilience (USEPA 2011). This strategy calls for an adaptive management framework using an integrated risk-based ecosystem assessment approach for informing decision-making to achieve specific restoration goals. This in turn requires the identification of indicators and measures of success to evaluate the efficacy of the restoration program in meeting its goals. Indicators, along with measures of performance, must be quantifiable and understandable to the public, reflect the desired Gulf condition, and be sensitive to ecosystem changes (USEPA 2011; NOAA 2015).

The purpose of the Gulf of Mexico EcoHealth Metrics project, which has been undertaken by the Harte Research Institute for Gulf of Mexico Studies, is to develop such an integrated set of indicators and associated metrics that can be used to characterize the health of the Gulf of Mexico ecosystems, including their linkages to human communities.

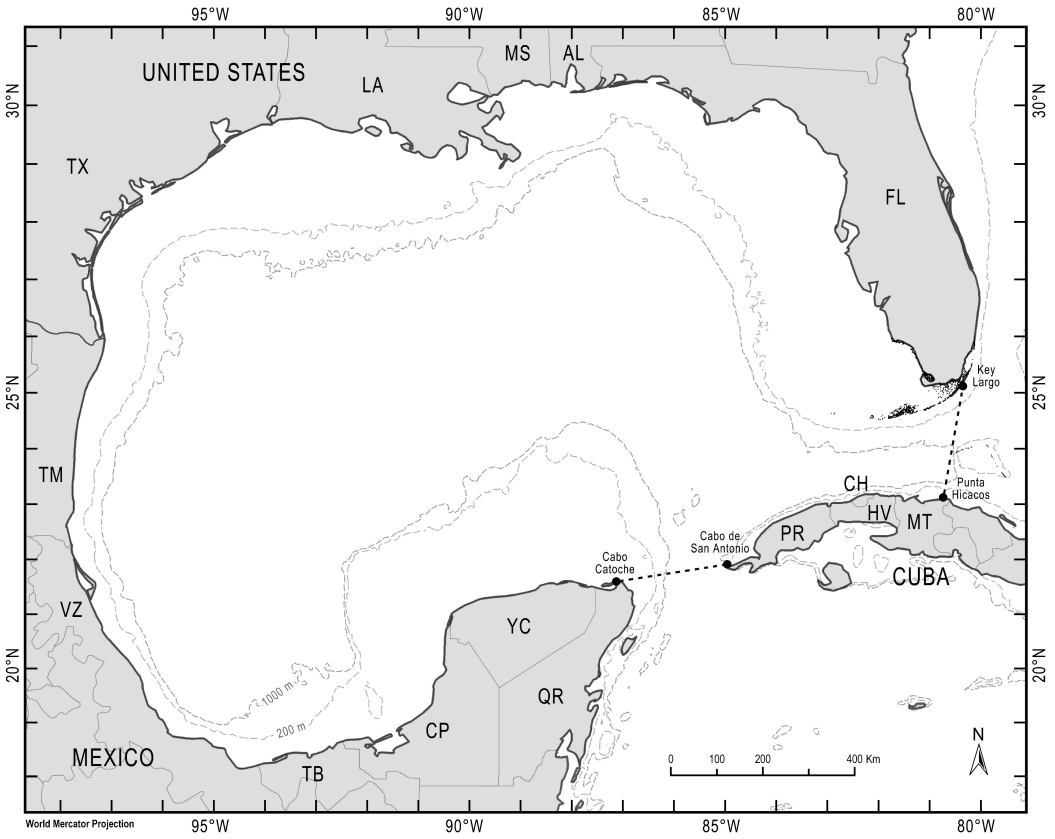

Figure 1a. The Gulf of Mexico, delimiting the geographic boundaries considered in the Gulf EcoHealth Metrics. Abbreviations for the states (counterclockwise) from Florida: FL = Florida, AL = Alabama, MS = Mississippi, LA = Louisiana, TX = Texas, TM = Tamaulipas, VZ = Veracruz, TB = Tabasco, CP = Campeche, YC = Yucatán, QR = Quintana Roo, PR = Pinar del Rio, CH = Ciudad de la Habana, HV = La Habana, MT = Matanzas. (Map prepared by Fabio Moretzsohn, Harte Research Institute for Gulf of Mexico Studies.)

Figure 1b. Map of the Gulf of Mexico watershed

Process for Developing the Gulf EcoHealth Metrics

Because the Gulf of Mexico is so complex and diverse, a systematic process for developing and implementing the EcoHealth Metrics is required. We envision a modular approach following these series of steps:

1. **Partitioning the Gulf of Mexico into discrete units —** The intent of partitioning was to reduce the scale of the problem to manageable levels by segmenting the Gulf by regions, by ecosystem/habitat types (e.g., mangrove, seagrass, and marsh communities), and by cross-cutting components (e.g., migratory birds, fish communities). The regional-EcoHealth Metrics we envision are: a) Western Gulf Coast (Texas); b) Eastern Gulf Coast (Florida); c) Northern Gulf Coast (Louisiana, Mississippi, Alabama); d) Mexican Gulf Coast; e) Cuban Gulf Coast. The Texas Coast has now been used as a proof-of-concept region for developing and testing the concepts and methodology for the Gulf EcoHealth Metrics.

2. **Develop Integrated Assessment/Decision Framework for EcoHealth Metrics—** The EcoHealth Metrics initiative required development of a new assessment framework and associated set of indicators to characterize the ecosystem health of the Gulf of Mexico, commensurate with the scale and complexity of the Gulf. The assessment framework that we have developed is an integration of previous ecological risk- and environmental management-based frameworks for assessing ecological health. This integrated framework is termed $DPSCR_4$, Drivers-Pressures-Stressors-Condition-Responses. Here, anthropogenic and natural *Drivers* are the fundamental forces driving the coupled human-environment system (e.g., industry, climate change), leading to *Pressures*, which are human activities and natural processes (e.g., oil/gas extraction, coastal development, sea-level rise). These in turn generate the chemical, physical, or biological environmental *Stressors* (e.g., toxic chemicals, habitat alteration, invasive species) that directly impinge on ecosystems. The environmental stressors cause effects on ecological *Condition* (i.e., changes to ecological structure, processes, and/or diversity). These effects are characterized on system-specific valued ecosystem components (VECs) that are designed to reflect ecologically significant changes to the essential characteristics of the ecosystem. Our framework has been extended explicitly to address ecosystem services and associated effects on human well-being, thus reflecting the complete coupled ecological-societal system. Management actions feed back to the ecological systems and associated ecosystem services through four types of *Responses*: 1) *Reduction of stressors* through regulation or other constraints on the associated drivers and pressures (e.g., land use policies, air pollution regulations); 2) *Remediation* through removal of existing stressors (e.g., clean-up of oil spills or toxic chemical sites); 3) *Restoration* of damaged ecosystems (e.g., planting of seagrasses); and 4) *Recovery* of ecosystems through natural processes once stressors are reduced or eliminated. From this conceptual framework are derived the specific indicators for use in characterizing ecological condition and the progress, or lack thereof, towards achieving ecological health and sustainability goals. Furthermore, the framework's tiered hierarchical structure communicates the EcoHealth Metrics to a diversity of audiences, from research scientists to environmental managers and decision-makers, with the level of

detail or aggregation appropriate for each targeted audience. The $DPSCR_4$ framework is documented in Section II.

3. **Initiate Texas Pilot Project —** As a demonstration and proof-of-concept pilot project, we focused on Texas coastal ecosystems for EcoHealth Metrics development and data acquisition, as reported here in the Texas Coast Report Card and EcoHealth Metrics Technical Support Document. The Texas coastal region was partitioned into its constituent ecological habitats and cross-cutting components (focused initially on fisheries, oyster reefs, seagrass communities, and resident and migratory birds), and a set of habitat-specific risk-based conceptual ecosystem models (CEMs) were constructed to graphically capture the relationships between stressors and effects on the valued ecosystem components of each (for examples of this type of conceptual model, see Cormier et al. 2000, Gentile et al. 2001, Ogden et al. 2005a, b). The conceptual modeling process involved scientists, managers, and stakeholders to ensure that the drivers and pressures were adequately identified and long-term sustainability goals appropriately defined. These conceptual models were then used to fully define the $DPSCR_4$ framework and indicators for each habitat and cross-cutting component. Existing data were acquired to populate the EcoHealth Metrics for the selected ecosystems of interest, along with appropriate techniques and tools for communicating the Texas EcoHealth Metrics to various targeted audiences. The Texas Coast Report Card is presented in Section III; the Technical Support Document is presented in Appendix A, and the CEMs are provided in Appendix B.

4. **Develop Regional Gulf EcoHealth Metrics —** Now that the Texas pilot has been completed, we propose next to apply the methodology and lessons learned to subsequent regions, e.g., Northern Gulf Coast EcoHealth Metrics, Eastern Gulf Coast EcoHealth Metrics, etc. The following components are envisioned:

    - **Texas EcoHealth Metrics —** The next steps for the EcoHealth Metrics for Texas are: a) to enhance the existing metrics through development of additional databases on ecological condition; b) develop similar databases on the stressors of importance to each system; and c) incorporate other coastal systems of importance in Texas, in particular coastal marshes and mangroves. The initial Texas seagrass EcoHealth Metrics demonstrated a paucity of essential data on seagrass spatial extent and health; thus, one important activity would be to build upon the seagrass mapping and monitoring plans developed for Texas a decade ago but never implemented. Another envisioned project would examine coastal marshes and the mangrove/marsh ecotone utilizing a satellite- and aerial-based hyperspectral imagery as a synoptic indicator for sea-level rise across Texas and the northern Gulf. Expansion of condition and stressor databases will require enhanced linkages to relevant federal and state agencies, non-governmental organizations, and other potential sources of environmental data.
    - **Northern and Eastern Gulf Coast EcoHealth Metrics —** We believe the next step in expanding EcoHealth Metrics Gulf-wide is to tailor our framework to the coastal ecosystems of Florida that comprise the eastern Gulf of Mexico. The process we envision is to convene a workshop that engages knowledgeable

practitioners to: develop Florida-specific EcoHealth Metrics for important coastal ecosystems; develop conceptual models of the coupled human-ecological systems for those ecosystems; rank the pressure-stressor-VEC relationships as they exist in Florida; identify specific indicators and metrics and potential data sources; initiate a Florida EcoHealth Metrics communications strategy; and transfer the methodology and approach to an appropriate Florida-based institution. A subsequent step would be to follow the same process, but focused on the unique coastal ecosystems of Louisiana, with their particular vulnerability to sea-level rise and to petrochemical-related stressors, as well as a separate activity characterizing the similar coastal ecosystems that extend from coastal Mississippi through the Florida panhandle.

- **Mexican Coast EcoHealth Metrics —** The Mexican Gulf of Mexico shoreline is predominantly sandy beach habitat with some rocky seashores in Veracruz and Campeche. Over 35 coral reefs exist in offshore waters, and over 20 coastal lagoons and estuaries extend from Texas to the Caribbean in this region. Mangroves line lagoon and estuary shorelines and seagrass beds and oyster reefs are present in some. Fisheries data are the only long-term biotic datasets available in Mexico, and report card activity there should include collaboration with academic institutions, and federal and state agencies.
- **Cuban Coast EcoHealth Metrics —** Cuba's northwestern shoreline from its far western tip to Punta Hicacos, just east of Havana, constitutes the island's Gulf of Mexico region. Coral reefs are common on the narrow continental shelf, and seagrasses exist near shore. The coastline is mostly sandy beaches with scattered limestone rocky shores. There are some barrier islands, which protect extensive mangrove lagoons, and several small estuaries with mangrove shorelines. Fisheries data are the only long-term biotic datasets available in Cuba, and report card activity there should include collaboration with academic institutions, and federal and provincial agencies.
- **Cross-Cutting Gulf-Wide and Pelagic EcoHealth Metrics —** A cross-cutting Gulf EcoHealth Metrics initiative would begin by extending the Texas bird and fisheries report cards throughout the Gulf of Mexico, integrating databases from other states and regions with synoptic databases such as Cornell Lab of Ornithology's eBird. Two key at-risk components from the *Deepwater Horizon* oil spill require attention: a new project needs to be developed on Gulf marine mammals, a critically important cross-Gulf valued ecosystem component; and similarly, the continental slope and abyssal benthic ecosystems are essential but largely unknown components of the greater Gulf of Mexico ecosystem. We also envision explicit linkages to large-scale remote-sensing atmospheric and oceanographic observing systems that are commensurate with the spatial scale of the open Gulf of Mexico.

5. **Integrated Gulf EcoHealth Metrics —** The final implementation of the EcoHealth Metrics for the Gulf of Mexico is envisioned to be the development of an integrated framework that incorporates each of the regional EcoHealth Metrics into a comprehensive assessment of the health of the Gulf of Mexico and its progress, or lack of progress, towards achieving sustainability goals. A series of new

methodological advances, along with development of new environmental databases including synoptic observations and monitoring, will be necessary to attain this goal.

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II. DPSCR$_4$ Framework for EcoHealth Metrics Assessment-Decision Process

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Abstract
The purpose of the EcoHealth Metrics initiative is to develop an assessment framework and associated set of indicators to characterize the ecosystem health of the Gulf of Mexico. The assessment framework presented here has been developed as an integration of previous ecological risk- and environmental management-based frameworks for assessing ecological health, commensurate with the scale and complexity of the Gulf. This conceptual framework is designed to identify the natural and anthropogenic drivers, pressures, and stressors impinging on ecosystems and the ecological conditions that result. Four types of societal and ecological responses are also identified, including reduction of pressures and stressors, remediation of existing stressors, active ecosystem restoration, and natural ecological recovery. From this conceptual framework are derived the specific indicators for use in characterizing ecological condition and the progress, or lack thereof, towards achieving ecological health and sustainability goals. Furthermore, a tiered hierarchical structure is presented to communicate the EcoHealth Metrics to a diversity of audiences, from research scientists to environmental managers and decision-makers, with the level of detail or aggregation appropriate for each targeted audience. A five-step process for constructing the EcoHealth Metrics is detailed: 1) Create the conceptual model for the ecosystem; 2) Select EcoHealth Metrics indicators; 3) Define goals and benchmarks for assessing ecosystem health and sustainability; 4) Analyze the indicators to characterize condition and trends; and 5) Communicate results to the appropriate audiences. Ultimately the EcoHealth Metrics will apply to the entire Gulf of Mexico and all its constituent regions and ecosystems, but we began by focusing on the conceptual framework and assessment methodology and the initiation of a proof-of-concept pilot project focused on the coastal ecosystems of Texas.

History of ecological health assessment frameworks
The EcoHealth Metrics research project builds upon existing indicators and assessment frameworks for ecological health to develop a new, more integrative, management-driven framework that connects ecological sustainability and human well-being to ecological health and ecosystem services. Environmental assessment indicators and frameworks are becoming more widespread as tools to characterize the status and trends of ecosystem health and to inform the allocation of resources for sustainability of healthy marine and coastal environments. The Gulf of Maine ecosystem indicators partnership (Mills 2006), Chesapeake Bay Report Card (Williams et al. 2009, 2010; IAN 2013), US National Coastal Condition Report (USEPA 2012), Florida Keys Ecosystem Report Card (NOAA 2011), Ocean Health Index (Halpern et al. 2012), San Francisco Bay Index (PEEIR 2005), scorecards for Marine Protected Areas (CEC 2011), Southeast Queensland

healthy waterways report cards (Pantus and Dennison 2005), Mississippi River report card (americaswatershed.org), and Australia's Great Barrier Reef Report Card (Australian and Queensland Governments 2010) are a few examples of indicators and assessments being used to inform the public and decision-makers about the health and sustainability of coastal ecosystems.

We have conducted a review of the frameworks for these and many other environmental assessments as well as the literature on ecological indicators, ecological recovery, and stress ecology. Two approaches dominate, the first derived from the perspective of stress ecology (e.g., Odum 1969, 1985; Holling 1973; Barrett et al. 1976) and its derivatives, ecological indicators and ecological risk assessment (e.g., Kelly and Harwell 1989, 1990; Gentile and Slimak 1990; USEPA 1992, 1998; Gentile et al. 1993; Environment Canada 1993; Harwell et al. 1999; Dale and Beyeler 2001; USEPA SAB 2002; Doren et al. 2009). In this approach, ecological condition or health is a result of causal stress-effect relationships, as manifested in specific indicators of various components (both structural and functional) of ecosystems. Here *stressors* are defined as physical, chemical, or biological agents that can cause effects on ecological systems. *Effects* are manifested as changes in specific ecological attributes that are ecologically and/or societally important, often termed *Assessment Endpoints* (USEPA 1998) or *Valued Ecosystem Components* (VECs) (CCME 1996; Harwell et al. 2011). This approach seeks to elucidate the causal mechanisms of ecological effects from human activities and natural processes; consequently, it is closely related to hypothesis-driven scientific studies on how ecosystems and their components respond to environmental stressors, whether natural or anthropogenic. However, the limitation of this approach, particularly at larger scales, is that there may be too many environmental stressors to be managed, exacerbated by too many interactions among stressors and too many pathways leading to effects (see, for instance, FAO [undated]).

The second approach is based on the Pressure-State-Response (PRS) framework (OECD 1991, 1993) and its derivative, the Drivers-Pressures-State-Impacts-Response (DPSIR) framework (EEA 1999; Weber 2010). In the OECD PSR framework, *Pressures* are broad categories of human activities (e.g., energy, agriculture) but explicitly excluding natural processes; *State* is the quality and quantity of the environment and natural resources; and *Response* is how society responds to changes in state through environmental and economic policies. The Organization for Economic Co-operation and Development (OECD), created under the Marshall Plan in the aftermath of World War II, provides advice and promotes policies to improve economic development and social well-being in Europe (see www.oecd.org), but it has no legal, regulatory, or management authority. Consequently, this framework was initially developed by economists and policy analysts for policy makers, aimed at a broad-scale view of general relationships between human pressures and the environment, rather than at scientific understanding of cause-effect relationships or specific steps for environmental management (FAO undated).

The European Environmental Agency (EEA), an agency of the European Union with the mission to provide the environmental agencies of member nations with independent information to be used in developing and implementing environmental management policies (see eea.europa.eu), extended the OECD PSR framework to a more practical and scientifically sound basis. In the EEA's DPSIR framework, *Drivers* are the fundamental forces causing *Pressures* which affect the *State* of the environment; *Impacts* are how the state changes because of the pressures; *Responses* are societal feedbacks through adaptation or curative action. The *Pressures* in DPSIR initially also excluded natural processes, except for climate change, but more recent applications have relaxed that exclusion (e.g., Weber 2010). DPSIR has been adopted by the United Nations, European Union, and some US agencies, as it is more attuned to the needs of decision-makers, stakeholders, and the public

when addressing environmental issues on large scales. However, a significant deficiency of the PSR or DPSIR approach, is that pressures are typically defined at such a broad level (e.g., population growth, agricultural production) that their relationships to the state of the environment are by necessity correlative instead of causal. Hence, it may provide insufficient specificity of the relationships between human activities and ecological effects to identify what needs to be managed and what management actions would be required in order to achieve a healthy environment.

Irrespective of the framework used for assessing environmental condition, the specific indicators to measure have also been a topic of considerable research and discussion over the past three or four decades. Consequently, there is an extensive literature on ecological indicators (e.g., since 2001, a peer-reviewed journal, *Ecological Indicators*, has been dedicated to the topic; see also MacKenzie et al. 1990). Some of the early literature on ecological indicators (e.g., Kelly and Harwell 1989, 1990; Gentile and Slimak 1990; Hunsaker and Carpenter 1990; Cairns et al. 1993) explored the utility and classes of ecological indicators in different applications and criteria for selecting indicators. Other publications proposed specific indicators or indices: for example, Karr (1981) proposed a fish community-based index of biotic integrity that has been widely used to assess stream health condition; Landres et al. (1988) discussed the utility and limitations of vertebrates as indicator species, a central approach used by the US Fish & Wildlife Service to characterize wildlife habitat quality. Ecological indicators have been suggested from the molecular (e.g., Goksøyr and Förlin 1992) to the landscape levels (e.g., Hunsaker et al. 1990). Clearly, there is a plethora of indicators that could be used to characterize ecological health, but a key issue is identifying the set of indicators that are most efficacious for understanding ecological condition and informing environmental management. We suggest that the specific sets of indicators to be used will logically emerge from the proposed integrated assessment/decision framework discussed in the next section.

DPSCR$_4$ Framework — *Need for a New Synthesis Framework*

Based on this literature review of conceptual frameworks and indicators for assessing environmental health, we concluded that developing an assessment framework for an ecosystem of the scale and complexity of the Gulf of Mexico, and with the diversity of audiences that need to be informed, requires a new conceptual framework that builds upon the strengths of the existing frameworks while avoiding their deficiencies. We propose that this new framework should be a synthesis of the ecological-risk-based and DPSIR approaches. The advantage of the risk-based, stress-effect approach is its focus on defining the causal relationships between stressors and ecological effects, i.e., how the things that an ecosystem "sees" (the environmental stressors) cause changes in the state of ecological attributes that are important ecologically and/or societally. This risk-based approach avoids the potential deficiency of the OECD PSR or the EEA DPSIR approach, in which pressures are often defined at such a broad level that their relationships to the state of the environment are only correlative instead of causal, and thus environmental management decisions may be inadequately science-based. On the other hand, the advantage of the DPSIR approach is that it avoids a potential limitation of the stress-effects approach, where there may be simply too many cause-effect relationships at very large scales (e.g., national or larger) to manage each one separately (FAO [undated]). Therefore, this approach is more attuned to the needs of decision-makers, stakeholders, and the public when addressing environmental issues on such large scales, and perhaps more attuned to reporting on health at the level of resolution that is relevant to those audiences.

The synthesis framework that we propose is a merging of the two, consisting of *Drivers*, *Pressures*, *Stressors*, *Condition*, and *Responses* elements (Figure 1), each of which is defined below in the specific context of the new framework. Additionally, the *Responses* component in our

framework is divided into two categories, *societal responses*, i.e., changes in management within the societal system, and *ecological responses*, i.e., changes in the ecological system. These are further partitioned into *Reduction* of stressors and associated pressures (such as through regulations limiting discharges of pollutants or controlling land use); *Remediation* (actions aimed at directly reducing existing contaminant stressors, such as oil spill clean-up or toxic waste removal); *Restoration* (actions to directly renew or restore a damaged or altered ecological system, such as planting trees or reconstructing wetland habitats); and *Recovery* (natural ecological processes of recovery once the stressor is gone, such as an injured population returning to its pre-event condition). To accommodate the stressor *Reduction,* stressor *Remediation,* ecological *Restoration*, and ecological *Recovery* aspects, the acronym for this new framework is $DPSCR_4$.

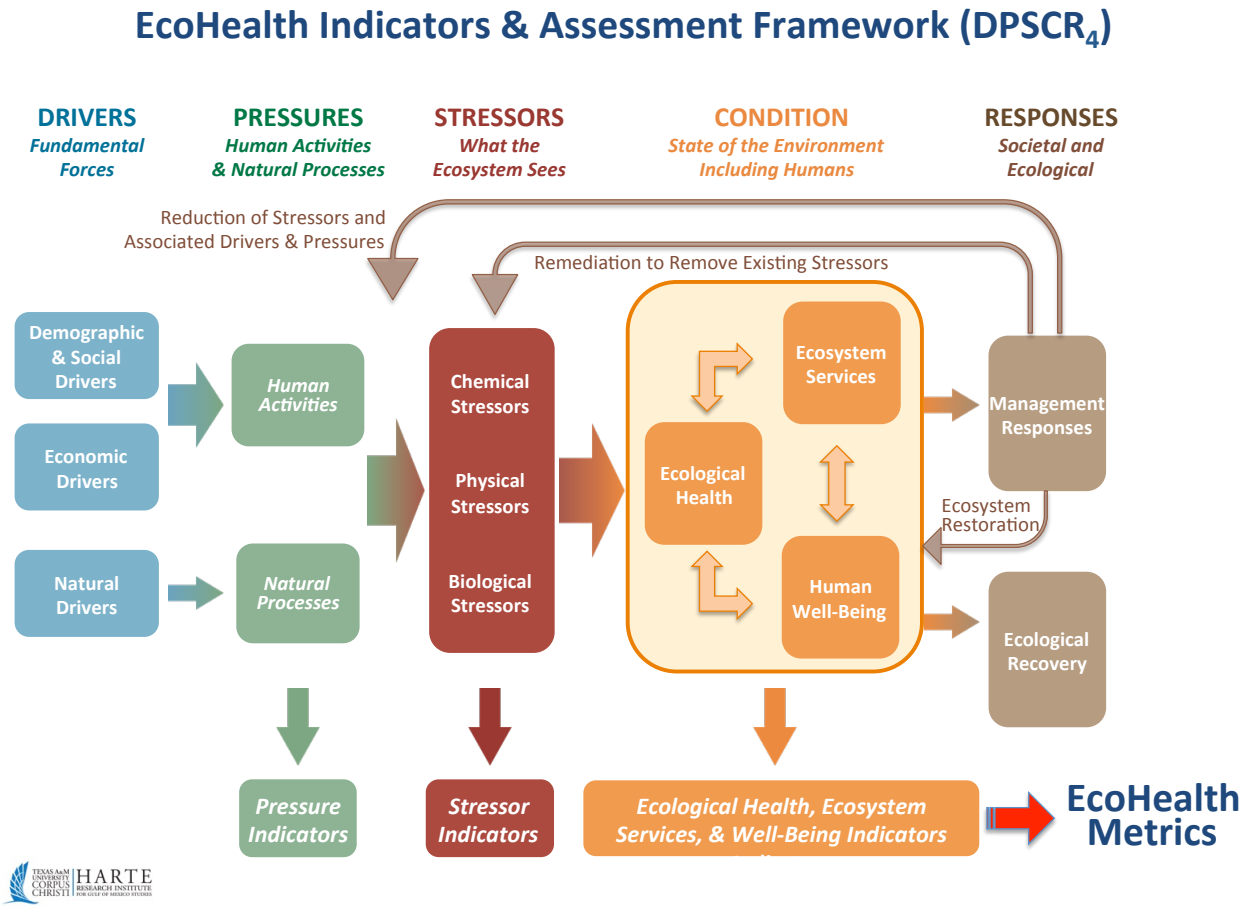


Figure 1.

There are several advantages of this new construct. For example, the full sequence of causal relationships is delineated from the ultimate source (fundamental societal or natural drivers) through their manifestation as pressures (human activities and natural processes) and the resulting environmental stressors that the system actually sees, to the effects on ecological condition and the

responses that ensue, either through societal actions or natural ecological recovery processes. Second, by scaling taking these relationships from the broad scale down to the specific cause-effect process, the Gulf EcoHealth Metrics framework can characterize the system simultaneously from the big-picture policy level to the specific cause-effect hypothesis-driven scientific level and back. When nested within a hierarchy of reporting levels, as discussed below, this framework can inform interested audiences at all levels. Similarly, this framework is ideal for aggregation and disaggregation, in which finer-scale issues may be explored and illuminated, or in which broader relationships can be more readily perceived. Moreover, this framework can adapt and evolve as more information is gathered and the system becomes better understood, or as things change over time or space. Consequently, the EcoHealth Metrics can become both responsive to new needs or questions and useful in identifying uncertainties and new areas of research or monitoring. Finally, the $DPSCR_4$ provides the basis and rationale for identifying the specific sets of indicators in the EcoHealth Metrics for pressures, stressors, and condition, the particular suite of attributes desired for each indicator, and insights into the societal actions that could be implemented to achieve ecological health.

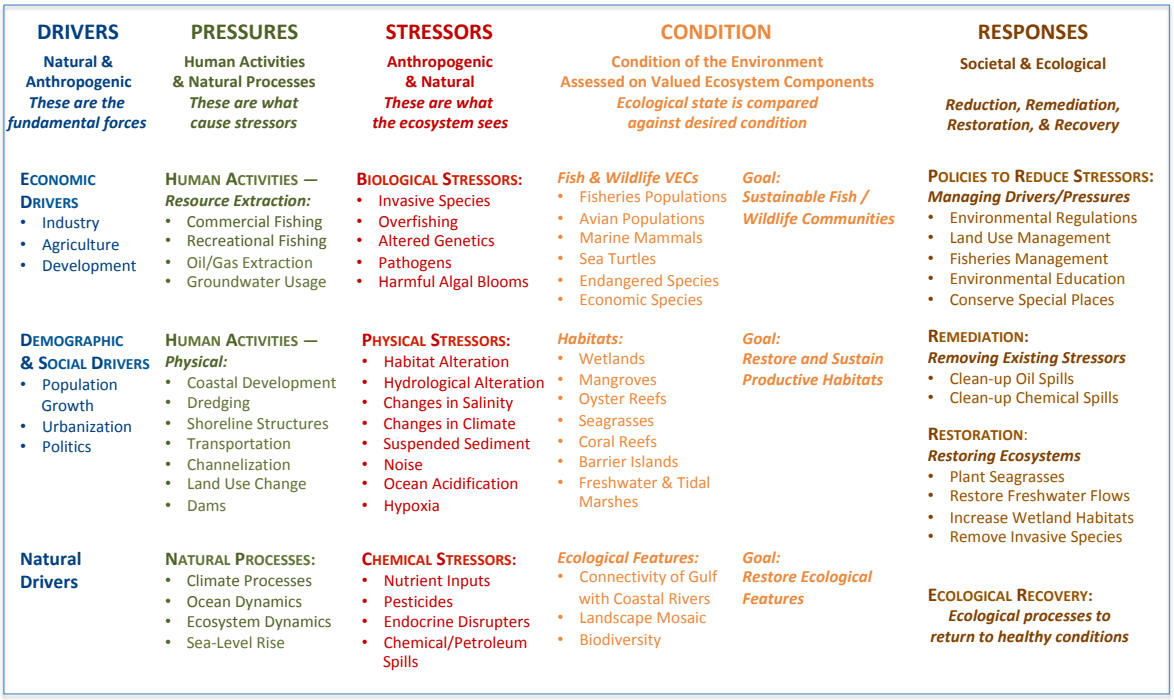
Elements and Definitions of $DPSCR_4$

The terminology that we have incorporated into the $DPSCR_4$ framework includes terms that have been used elsewhere in similar contexts, but there is often inconsistency across the literature in usage of many of these terms. Consequently, to ensure clarity, we define each element here to provide the specific meaning of the words as they are used in the $DPSCR_4$ framework. Additionally, we provide a few examples of various components of the $DPSCR_4$ framework using information specific to the Gulf of Mexico to illustrate the process (Figure 2).

Drivers are the fundamental forces, natural or anthropogenic, that ultimately drive the system. Examples include demographic drivers, e.g., global population growth or demographic age structure; social drivers, e.g., expansion of human populations into previously undeveloped sensitive habitats; economic drivers, e.g., agriculture, urbanization, industrial and energy development; and natural drivers, e.g., the unequal distribution of solar energy across latitudes. Drivers tend to be large-scale, long-term forces that are not easily controlled or diverted.

Pressures are human activities or natural processes that generate environmental stressors. They also tend to be large-scale and long-term, but often can be highly variable over space and time. Examples of anthropogenic pressures (i.e., human activities) include aquaculture; geophysical resource harvesting such as oil exploration and mining; biological resource harvesting such as fishing and forestry; coastal development; marine transport; recreation and tourism; flood control; and the anthropogenic component of global climate change and sea-level rise. Natural processes include ocean dynamic processes, such as upwelling and currents; climate processes, such as jet stream dynamics, monsoons, and El Niño-Southern Oscillations; sediment dynamics such as erosion, subsidence, and sedimentation; episodic events such as earthquakes, tsunamis, and hurricanes; and the natural processes component of global climate change and sea-level rise.

Figure 2. Example $DPSCR_4$ Elements for the Gulf of Mexico



Stressors are what the ecosystem directly experiences, i.e., the physical, chemical, or biological factors that can directly cause an ecological effect. Stressors are the critical point of intersection between the drivers/pressures and the resultant effects on ecological systems; consequently, these are the central cause-and-effect relationships for scientific inquiry and hypothesis testing. Examples of chemical stressors include oil and chemical spills, altered nutrient inputs, pesticides, and other xenobiotics. Example of physical stressors include habitat alteration and loss; altered sedimentation and light regimes; altered salinity regimes; drought; hypoxia; and hydrologic alterations. Examples of biological stressors include invasive and introduced exotic species; over-fishing or over-harvesting; pathogens and disease; harmful algal blooms; and altered genetics. Stressors may secondarily generate other stressors; e.g., hydrologic alterations can lead to hypoxia, invasive species, and altered regimes of flooding, sedimentation, turbidity, light, and salinity.

Stressors may involve natural attributes of a system (e.g., the salinity regime of an estuary), which only becomes a stressor when there is a change in the attribute over time or space (e.g., reduced freshwater inflow causing hypersalinity in locations or at times where none previously existed), or it may involve something novel to the ecosystem, such as toxic xenobiotic chemicals or habitat alterations. An environmental stressor may result from one or more pressures or even a mix of natural and anthropogenic pressures. For example, water management that reduces freshwater flows (anthropogenic) and ENSO-induced alterations in precipitation patterns (natural) both can produce a similar stressor (changes in the salinity regime of an estuary). Finally, stressors are system-specific,

and what is a stressor to one ecosystem (e.g., fire in a mangrove forest) may not be a stressor to another ecosystem (e.g., fire in a grassland).

Ecological Condition: The state of the ecosystem is its condition or "health". Because there is an almost unlimited number of specific aspects of an ecosystem that could be used to characterize an ecosystem, a subset of attributes must be identified that are important either ecologically and/or societally, often termed *Assessment Endpoints* (UPEPA 1998) or *Valued Ecosystem Components* (VECs; CCME 1996, Harwell et al. 2011). It is advantageous to select a parsimonious set of VECs, with some VECs representative of other similar components of the ecosystem, thereby reducing the number of attributes and causal relationships that need to be characterized to a reasonable and practical set. The set of VECs selected to characterize ecosystem condition should not only focus on endangered or economic species, as is often done, but also consider ecological scale and hierarchy, and both ecological structure and ecosystem processes. Examples of structural VECs include endangered species, economically important species (e.g., a valuable fisheries population), intertidal or benthic communities, and primary producers. Functional VECs are ecological processes, such as primary productivity, biogeochemical cycling, nutrient dynamics, and trophodynamics. VECs may also broadly relate to environmental quality, such as water quality, habitat mosaic across the landscape, and biodiversity. Particularly useful for our integrated assessment framework is the subset of VECs that consists of ecological services, including provisioning services (e.g., fish stocks), regulating services (e.g., loss of carbon storage associated with habitat loss), and cultural services (e.g., environmentally related recreation and tourism) (UNEP WCMP 2011; Egoh et al. 2012; Hattam et al. 2015).

There is not a unique set of VECs that could be selected for an ecosystem, but the set should be selected such that if there is a significant change in the ecosystem, it would be manifested in one or more VECs and, conversely, if there is a change in one or more VECs, then the ecosystem can be considered to be changed. This obviates the problem that any stressor, no matter how small, may change some aspect of the ecosystem; our focus, however, is on identifying only ecologically significant effects (Gentile and Harwell 1998). Properly selected VECs can be both an aid in reducing the dimensionality of the ecosystem characterization problem to a manageable level and a means to distinguish those changes that matter from those that do not.

Finally, in characterizing a VEC (e.g., Brown Pelican), it may be appropriate to measure the VEC directly (e.g., number of pelicans in a population), but often *indicators* need to be identified that indirectly reflect on the condition of the VEC. For instance, indicators could include the pelican population age-structure, the frequency distribution of eggshell thicknesses, the areal extent and distribution of breeding colonies, or the body-burden of PCBs in adult pelicans. Other examples of VECs and associated indicators for the Gulf include:

- VEC *water quality*: indicators chlorophyll *a*, transparency, total suspended solids;
- VEC *coral community health*: indicators coral cover, juvenile recruitment, algal cover, coral composition;
- VEC *seagrass community health*: indicators areal extent, seagrass density, nutrient status, community composition;
- VEC *habitat mosaic*: indicators spatial frequency of habitat types and patch-size distributions.

In general, the metrics for each indicator should collectively represent the condition of the VEC at a particular point in time and space. It is the indicators that will form the foundation of the Gulf EcoHealth Metrics, including not only indicators characterizing the VECs, but also indicators characterizing the stressors and pressures, thereby identifying risks to the environment and/or possible causes for observed effects, as well as targets for responses to reduce stressors and improve

environmental health. Additionally, the particular levels or trends characterized in the effects indicators can be compared with specific benchmarks, such as historical conditions, desired goals for the particular VEC, or benchmarks between impacted conditions and recovery (Harwell et al. 1996). This comparison allows assignment of qualitative categories of condition, such as degraded, fair, or healthy, or quantitative ecological health metrics, such as grades, scores, or indices.

Responses: The *Response* in the original PSR and DPSIR frameworks was meant to capture feedbacks by society in response to the ecological impacts, particularly environmental and economic policies and programs intended to prevent, reduce, or mitigate pressures and/or environmental damage (OECD 1993; EEA 1999). In the new framework, we expand *Responses* to include both such regulatory actions and other interventions to reduce stressors or facilitate ecological processes. Four types of *Responses* are identified: *Reduction* of stressor sources*, Remediation* of existing stressors*,* ecological *Restoration*, and ecological *Recovery*.

Stressor source *Reduction* consists of societal responses targeted at the management of the drivers and pressures in order to reduce stressors. Examples include policies to reduce greenhouse gas emissions or require more effective wastewater treatment systems. Stressor source reduction responses may also entail activities like enhanced educational programs focused on the environment, or providing consumers with clearer information on the source and safety of seafood in the markets, among many other examples.

Remediation is the set of actions specifically aimed at reduction or elimination of a chemical stressor that has been released into the environment. This component was added to the framework to reflect the suite of clean-up (i.e., remedial) activities, often implemented under Natural Resources Damage Assessment (NRDA) regulations (derived from CERCLA [1980]) and the Oil Pollution Act of 1990 (OPA 90) regulations (NOAA 1996a, 2010).

Restoration is where intervention is made directly into the ecological system in order to undo ecological damage that has been done or to accelerate or enhance the process of ecological recovery, discussed next; it also a component of NRDA regulations (NOAA 1996b). *Restoration* may entail such actions as removal of invasive species; reconstruction of wetlands; planting of trees in riparian habitats; adding riffles and pools to a stream; or introduction of an endangered or extirpated species into its former habitat.

The final "R" in our framework differs from the others in that it involves the natural ecological *Recovery* processes of an ecosystem, usually once a stressor has been eliminated or reduced below adverse effects levels. *Recovery* reflects ecological resilience, i.e., whether or not and how quickly an ecosystem returns to normal once it is no longer under stress (Holling 1973). Thus, recovery is an internal ecological feedback process, rather than a societal one. An ecosystem has recovered from an incident, such as a chemical or oil spill, once the stressors are gone and all VECs have returned to some baseline condition, given dynamical ecosystem changes and natural variability. Consequently, recovery occurs when there no longer are ecologically significant adverse effects. The corollary is that recovery cannot fully proceed until the stressors are reduced to below an effects threshold. Where stressors are continuing or periodic, ecological feedbacks may entail permanent changes or even ecological phase shifts in place of recovery. More thorough discussions of ecological recovery are presented in Harwell et al. (2013) and Harwell and Gentile (2014).

Gulf EcoHealth Metrics Reporting Structure

The $DPSCR_4$ EcoHealth Metrics framework needs to be further structured to inform a diversity of audiences with differing concerns and levels of scientific understanding, and to accommodate multiple scales and ecological hierarchy. An assessment hierarchy (Figure 4), which we colloquially

term the "wedding cake", reflects the differing types of audiences to be informed by an ecosystem health assessment, from the top level of officials and the general public down to the environmental scientific community. The $DPSCR_4$ framework overlays this structural hierarchy, emphasizing tier-relevant components and indictors.

The top level is the target of the original OECD PSR framework, focused on the overall condition of the environment, the broad pressures that influence it, and the societal responses that ensue. It requires very few indicators of health and thus constitutes the greatest degree of aggregation into the most-simple-to-understand synthesis metrics and formats.

The next lower level is the realm of people who make or attempt to influence environmental decisions and policy. This tier emphasizes impacts from pressures on the environment and specific societal responses to mitigate impacts by managing pressures. This level requires more information because the audience tends to be more engaged in the issues of concern.

Next is the level of hands-on environmental managers, e.g., managing a park or conservation lands. These individuals need to understand a diversity of environmental issues relevant to their specific locations or ecosystem types. Consequently, it is important for this audience to understand the specific stressors and impacts those stressors have on their ecosystems, and specific remediation/restoration activities they might implement to achieve management goals.

At the base of the hierarchy is the scientific community whose hypothesis-driven focus is on environmental stressors, their effects on ecological condition, and whether effects constitute adverse health compared to baseline or benchmark conditions; remediation/restoration activities to improve the health of the environment; the ecological processes underlying ecosystem recovery; and determining when recovery has been attained. Indicators at this tier are numerous and aggregation is minimal, consistent with the many hypotheses concerning stress-effects relationships in ecosystems.

This hierarchical structure not only reflects differing issues of concern and levels of understanding, but also presents a dynamic framework for aggregating information into more integrative indicators at higher levels and for channeling specific information requests from higher tiers down to the appropriate level. As information is acquired by scientific investigations or through environmental monitoring, updated or new indicators can be provided to the tiers above. Concomitantly, information needs identified at higher levels can guide the scientific investigations performed, inform the allocation of resources to reduce important uncertainties, or encourage development of new integrative metrics. The $DPSCR_4$ hierarchy provides the template for this two-way information exchange to occur and ultimately may lead to more efficacious acquisition and utilization of research and monitoring data.

The hierarchical structure also facilitates aggregation across spatial and ecological scales (Figure 4), an essential aspect for characterizing the health of such a large and complex ecosystem as the Gulf of Mexico. The Gulf can be partitioned into several regional-scale subunits based on geographical, ecological, and/or political boundaries; indeed, different regions might be delineated for different purposes. The regional-scale indicators are then integrated into an overall Gulf of Mexico EcoHealth Metrics, not just by averaging the values of the regional indicators, as this could simply average out the important information needed to characterize the health of the system. Rather, both spatially explicit indicators, showing how the health varies over space, and new integrative indicators are needed to characterize ecosystem health in ways that are uniquely informative.

Gulf EcoHealth Metrics
Hierarchical Reporting Structure for Various Audiences

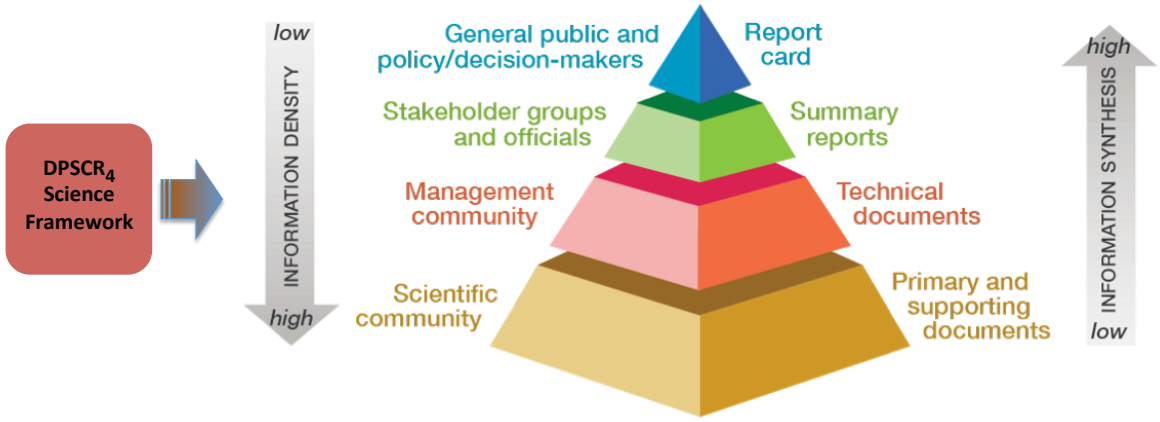


Figure 3.

Within each region are delineated specific habitat types of concern, like seagrass or salt marsh communities, and within each habitat are identified the specific set of relevant VECs and associated indicators. Figure 5 shows how one habitat type may be a component of more than one region. Moreover, other cross-cutting ecological components exist that are not spatially fixed like habitats, yet are very relevant to ecosystem health, such as migratory birds and marine mammals. As one integrates cross-cutting and habitat-specific indicators into regions, spatially explicit and/or integrative indicators are developed to characterize the ecosystems health.

At the lowest tier of the hierarchy, the indicators that are the ultimate foundation of the Gulf EcoHealth Metrics are specific qualitative or quantitative metrics that reflect the relevant characteristics of each VEC and each pressure and stressor over time and space. The utility of each indicator relates to fidelity to condition, data availability, ability to interpret and explain results, and spatial and temporal applicability (Kelly and Harwell 1989, 1990; Dale and Beyeler 2001). Development of databases and monitoring for each indicator, including establishment of reference or benchmark conditions (Harwell et al. 1996, 1999a), can provide the foundation for understanding the dynamics of each VEC, its trajectory over time and space, and its health or recovery status.

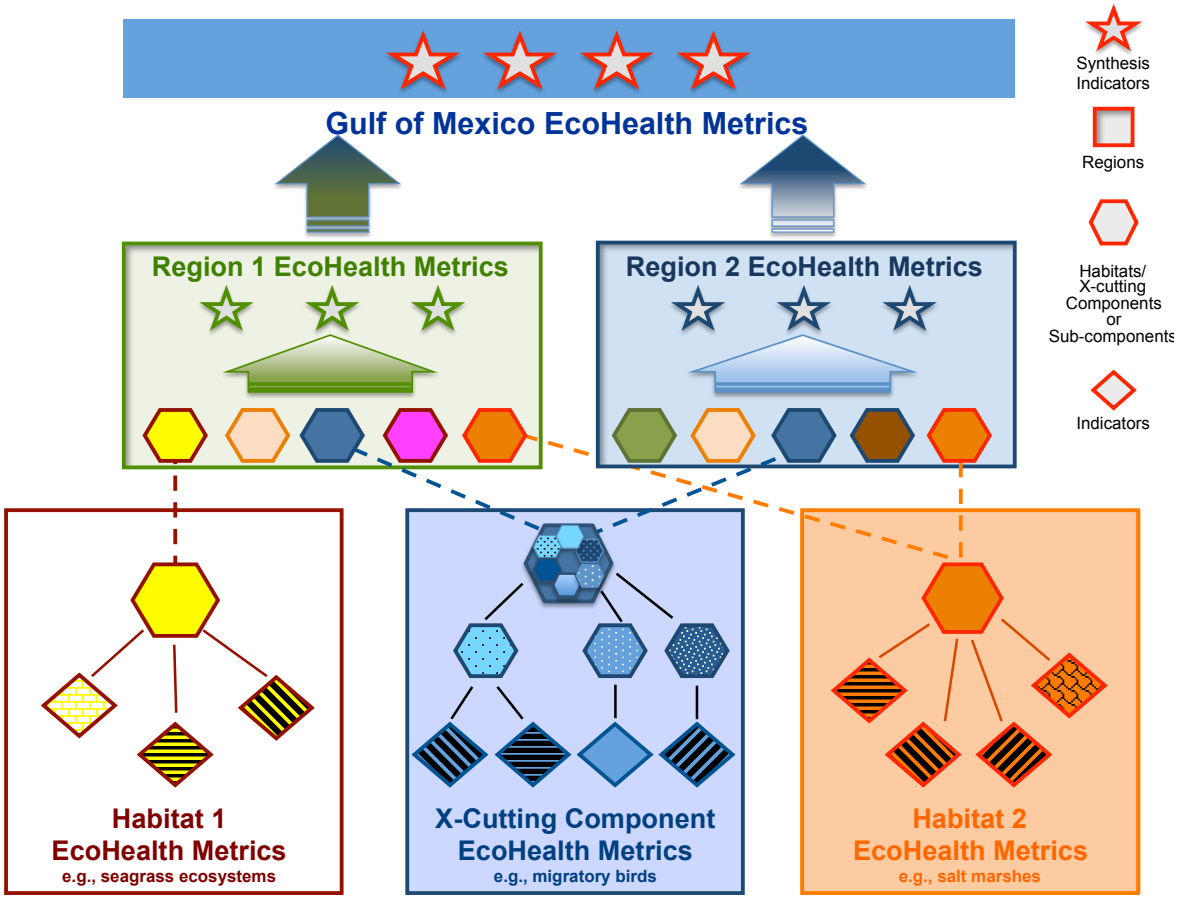


Figure 4. Aggregation scheme for elements of the Gulf of Mexico EcoHealth Metric.

Constructing the Gulf EcoHealth Metrics

The construction of the Gulf of Mexico EcoHealth Metrics using the $DPSCR_4$ framework is a complex process, emphasizing indicators for pressures, stressors, and condition/effects. It will follow the following steps (Figure 5):

1.) *Develop the conceptual framework for the EcoHealth Metrics* — This process involves disaggregating the Gulf into manageable reporting units, and developing conceptual models to define the specific elements of the EcoHealth Metrics. The Gulf will be partitioned into regions/subregions and habitat-based or cross-cutting components that comprise the Gulf ecosystems. The partitioning could be done based on political boundaries, geomorphic boundaries (e.g., coastal lagoons, estuaries), or biogeographical boundaries (e.g., tropical mangroves, warm temperate salt marshes); irrespective of the partitioning approach, the selected assessment regions should collectively cover the domain of the Gulf.

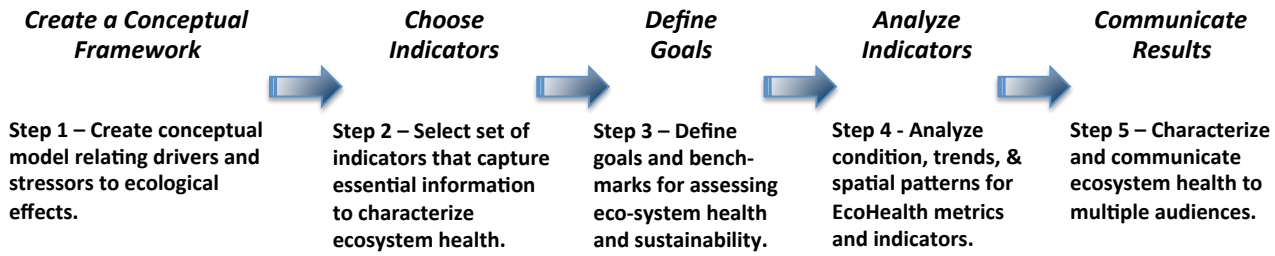


Figure 5. Five-Step Process for Constructing EcoHealth Metrics

Next, each region/subregion will be partitioned into its constituent ecological habitats. A set of habitat-specific risk-based conceptual models can then be constructed to graphically capture the relationships between stressors and effects on the VECs of each habitat; collectively, the conceptual ecosystem models (CEMs) for a region should reflect the connectivity among all the ecosystem components. In this type of conceptual model are shown the drivers/pressures for the system of concern, the environmental stressors that result from those pressures, the valued ecosystem components for each specific habitat within the region, and the causal links among each of these elements. In this type of CEM (Figure 6), the top tier (rectangles) are pressures, in this case human activities that impinge on the Mission-Aransas landscape (http://missionaransas.org/). The next tier (ovals) are the environmental stressors that result from the pressures to which they are linked in the graphic, with thicker lines representing stronger linkages. At the bottom tier are the VECs identified for the landscape-level attributes of Mission-Aransas NERR, again showing the weighted linkages with the specific stressors that cause effects on the VEC. For additional examples of this risk-based class of conceptual ecosystem models, see Cormier et al. (2000), Gentile et al. (2001), and Ogden et al. (2005a, b).

Separately, a similar risk-based conceptual model will be constructed for each cross-cutting VEC, such as migratory birds and marine mammals, capturing the drivers and stressors that affect that component across the region- or Gulf-wide domain. The conceptual modeling process should involve scientists, managers, and stakeholders to ensure that the drivers and pressures are adequately identified and long-term sustainability goals are appropriately defined.

2.) *Select EcoHealth Metrics indicators* — From each risk-based conceptual model, indicators will be identified for the key relationships within the $DPSCR_4$ assessment framework. These indicators will be used for effective, spatially explicit reporting on the state of each VEC, pressure, and stressor. Selected indicators should be data-driven, reliably measurable, and/or based on integrative techniques. Collectively, the goal is for a parsimonious set of indicators that captures the information needed to characterize and evaluate ecosystem health, reflecting current status and future trends for pressure/stressors and for ecological condition. Moreover, indicators should be chosen with consideration of their use within the EcoHealth Metrics (see Table 1) (Kelly and Harwell 1989, 1990). For example, ecological indicators could include both early-warning indicators (i.e., red flags indicating potential harm, but with a potential for high false positives) and diagnostic indicators (i.e., reflecting specific effects from a particular stressor). Similarly, the set of pressure and stressor indicators should reflect both short-term variability and long-term conditions and trends.

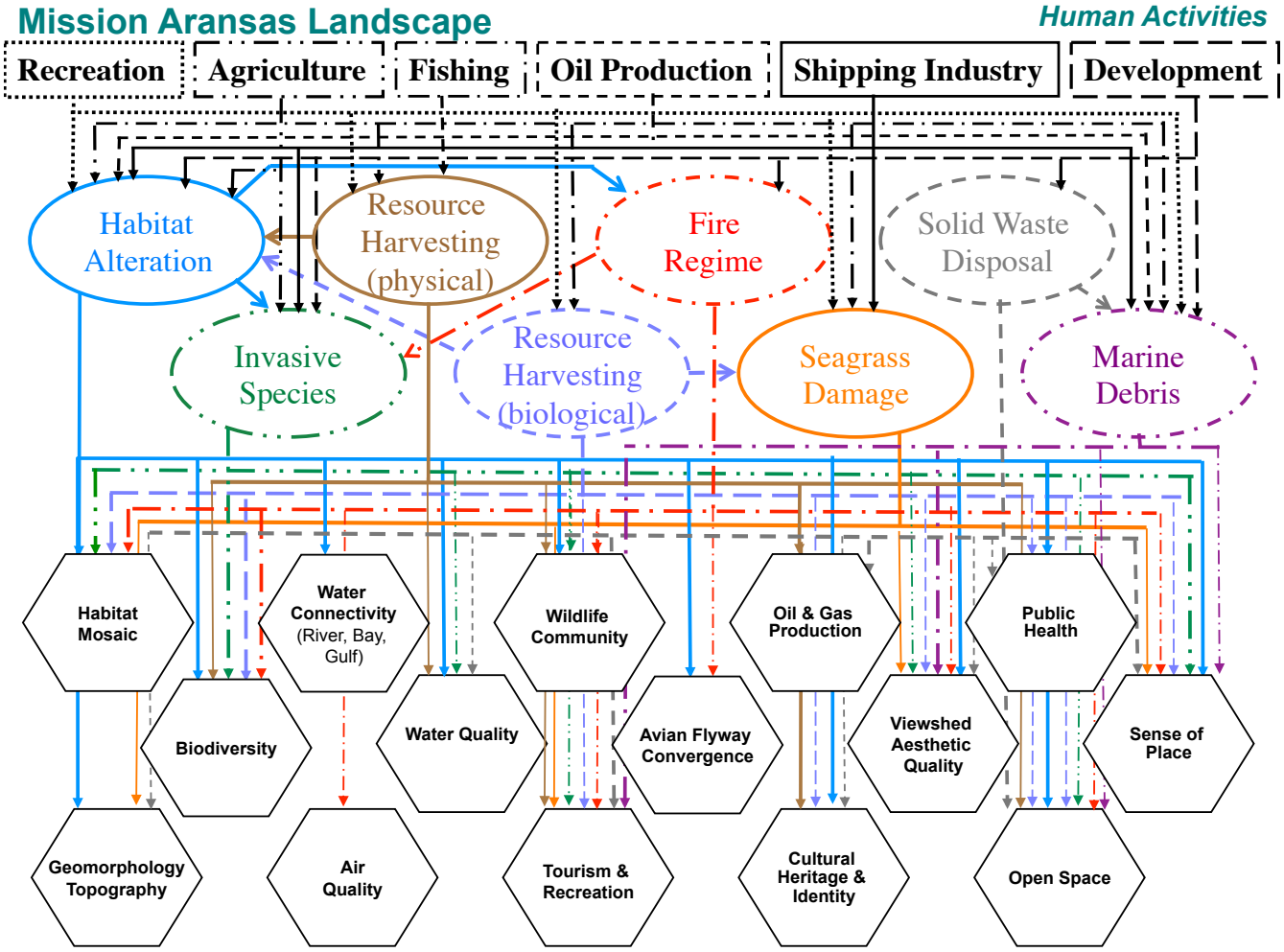


Figure 6. Example conceptual ecosystem model (CEM) for the Mission-Aransas National Estuarine Research Reserve.

3.) *Define goals, benchmarks, and thresholds for assessment* — Goals are defined here as the desired condition for the particular ecosystem or ecosystem component, often identified in the context of ecological sustainability. Benchmarks are defined here as milestones along the way from the current condition towards the desired sustainable state (Harwell et al. 1999a). Additionally, thresholds may be identified that mark particular levels of health, often useful for communicating ecosystem condition. A quantitative or qualitative metric defining a desired condition or goal for each indicator should be established, allowing indicator metrics to be assessed and reported in the Gulf EcoHealth Metrics. Goals and benchmarks can be set in several ways, including using established regulatory metrics (e.g., numerical ambient water quality criteria; Stephan et al. 1985); identifying biologically or ecologically relevant data values from the literature (e.g., defining hypoxia to be $\leq$ 2.0 $mg \cdot l^{-1}$ dissolved oxygen; Rabalais et al. 2002); comparisons to historical conditions prior to major impacts (e.g., assessing areal coverage of seagrass communities in the northern Gulf; Carter et al. 2011); or measurements of benchmarks that have been achieved in similar ecosystems elsewhere. Thresholds can be "pass/fail" (e.g., does a measurement meet the threshold or not?), or they may array along a gradient in a multiple threshold scheme.

PURPOSES OF INDICATORS	CRITERIA FOR SELECTING INDICATORS

• *intrinsic importance* – key: indicator is the endpoint
  o example: economically important species; endangered species
• *early-warning indicators* – key: rapid indication of effects
  o quick response time
  o low signal-to-noise ratio; low discrimination
  o screening tool; accept false positives
• *diagnostic indicators* – key: reliability in predicting effects
  o high stressor-specificity
  o high signal-to-noise ratio
  o minimize false positives
• *process/functional indicators* – key: process is the endpoint
  o monitoring other than biota (e.g., decomposition rates)
	• *signal-to-noise ratio*
	  o sensitivity to stressor
	  o intrinsic stochasticity
	• *rapid response*
	  o early exposure
	  o quick dynamics (e.g., short life span)
	• *reliability/specificity of response*
	• *ease/economy of monitoring*
	  o available field protocols
	  o pre-existing database
	  o low-cost tools
	• *relevance to the endpoint*
	  o answers the "so what?" question
	• *feedback to management*

Table 1. Purposes of Indicators and Criteria for Selecting Them
(modified from Kelly and Harwell 1989).

4.) *Characterize results* — Once data and thresholds are established, there are several options for characterizing the condition of the VECs. In general, indicator values are evaluated against specific goals, benchmarks, or thresholds. These may be standardized into assigned condition categories, and values for individual indicators may be integrated to produce an overall index or other metrics for the VEC, pressure, or stressor. These may be spatially integrated into a characterization for the subregion or region of concern, and these in turn may be further integrated with other subregion/region results using an area-weighting approach.

Assessment metrics can be qualitative (e.g., alphabetic grades or stoplight colors), or quantitative based on numeric assessment values (e.g., achieving 90% of a target value). Overlain on each indicator metrics can be up/down arrows indicating trends of improvement, degradation, or no change in environmental condition from previous values. Qualitative characterizations are simple and easily comprehended, but may oversimplify conditions or not adequately allow for nuances. Numeric assessments can be more precise, but precision may be mistaken for accuracy, and numeric assessments can be overly precise given natural variability and uncertainty (e.g., reporting 3 significant digits would be misleading for a metrics with an interannual variability of 25%). Numeric assessments tend to be more technical, and therefore less understandable by some audiences but more useful for others. Various combinations of qualitative/quantitative indicators can be used, avoiding the pitfalls of a single approach.

5.) *Communicate results* — The communication of results is the central purpose of the Gulf EcoHealth Metrics; it should be multifaceted and transparent, structured hierarchically into the wedding cake design described previously (see Figure 4). Each Gulf EcoHealth Metrics document should be a graphics-rich, synthesis document that aggregates results to create an easily understandable message about the overall health of the ecosystem. Hierarchy-appropriate graphics should illustrate the important attributes of the ecosystem and its links to humans. For example, the conceptual model of the Mission-Aransas ecosystem shown in Figure 6 is aimed at scientists, presenting in considerable detail the many habitats, drivers/pressures, VECs, and causal linkages among the pressures-stressors-effects of the Mission-Aransas NERR. However, while the sheer complexity of the Mission-Aransas required such great detail to adequately characterize the system

(the illustration in Figure 6 is only one of 36 such graphics needed to fully represent Mission-Aransas), it would be prohibitively complex to inform the general public. By contrast, Figures 7a and 7b represent a similar ecosystem presented in less detail to more appropriately communicate to an audience of decision-makers and the public, with the commensurate need-to-know information captured in easier-to-understand graphics.

Underlying information, source documents, and linkages to data sources are important to providing transparency of process and accessibility to information appropriate for managers, decision-makers, program managers, and scientists. The Gulf EcoHealth Metrics should be readily accessible, such as through website access. The series of Chesapeake Bay Report Cards (e.g., IAN 2007, 2013; ecoreportcard.org) provide examples of the types of communications we envision.

Assessment results could be communicated on an annual and/or multi-year production and release cycle. Advantages to an annual cycle include keeping the status of the resource in the public eye, frequent tracking of progress (or lack of progress) toward achieving goals, and reflecting the inherent interannual variability in many environmental indicators (e.g., seasonality of climate and life cycles). However, many important processes and indicators do not appreciably vary interannually (e.g., land use change), and it can be prohibitive to maintain data collection, analysis, and reporting timelines to support an annual EcoHealth Metrics. Alternative reporting cycles involving multiple years (e.g., 5-year reporting cycle) allow more time for analysis and interpretation, enhanced clarity of trends, and the use of more integrative or longer response-time

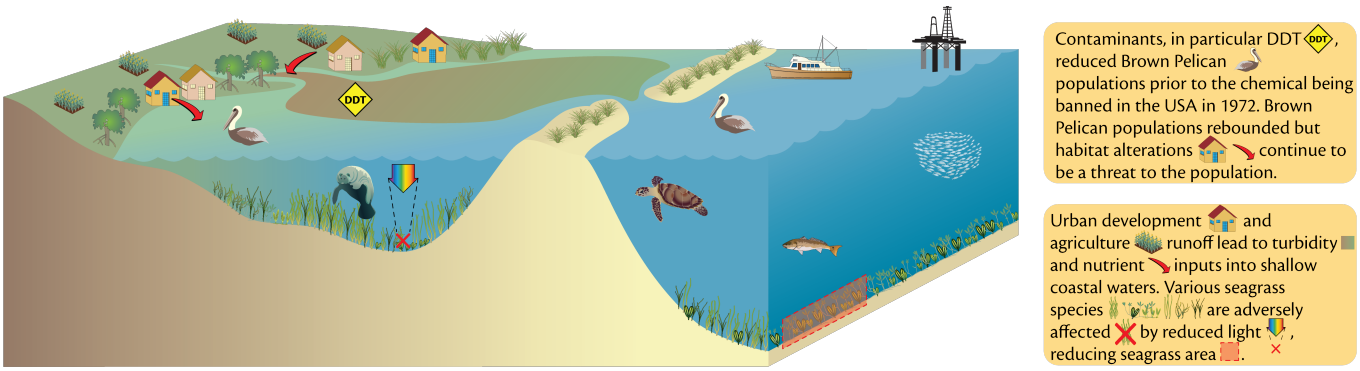


Figure 7a. Example conceptual model of a Gulf coastal ecosystem targeted at decision-makers and the public (from McKinney et al. 2011).

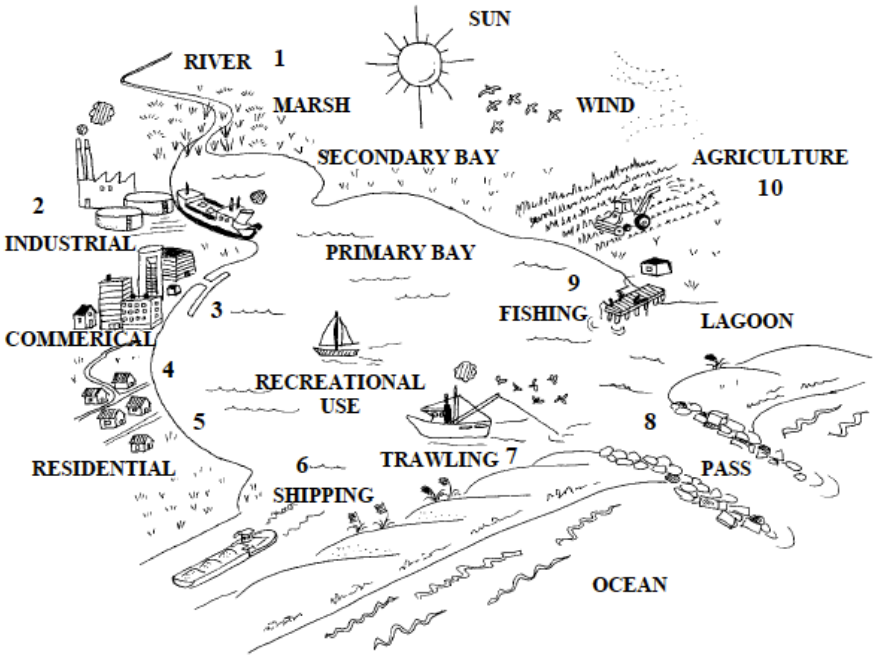


Fig. VI.1B. The role of humans in the CCBNEP Bay Area System. Human activities can impact the bay ecosystem in a variety of ways, most of which tend to have harmful effects on the productivity and diversity of the ecosystem. 1 – Impounding rivers cut off fresh water inflow to the bay. 2 – Industry can introduce toxic compounds to the air or water that can stress or kill many estuarine species. 3 – Construction on the shore of the bay destroys productive marsh habitats, and can increase turbidity. 4 – Runoff from cities can introduce contaminants to the bay and increase turbidity. 5 – Water treatment can bring high nutrients into the bay that may lead to eutrophication. 6 – Motor boats can scar seagrass beds and leak fuel. 7 – Trawling and dredging may disturb or kill the organisms living in sediment. Shrimping also produces by-catch. 8 – Creating or reinforcing passes, channels and causeways can alter estuarine circulation. 9 – Fishing may remove too many top predators from an ecosystem. 10 – Agriculture can introduce nutrients to the bay, through fertilizer or simple runoff, or can introduce toxins to the bay in the form of pesticides.

Figure 7b. Example conceptual ecosystem model showing major pressures affecting the Corpus Christi Bay National Estuary Program system (from CCBNEP 1996).

indicators. While we anticipate that the Gulf EcoHealth Metrics will be issued annually, more in-depth reporting will occur on a longer time cycle, similar to the series of Everglades System Status reports and updates (http://www.evergladesplan.org/pm/recover/recover.aspx).

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Larry Handley (USGS); Tom Frazer (School of Natural Resources and Environment, University of Florida); John Ogden (deceased); Warren Pulich (Meadows Center for Water and the Environment, Texas State University–San Marcos); John Rappole (Conservation Biology Institute, Smithsonian Institution); Elizabeth Smith (International Crane Foundation); Kim Withers (Department of Life Sciences, Texas A&M University–Corpus Christi); Chris Wood (eBird Project, Cornell Lab of Ornithology).

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Harwell Gentile & Associates, LC

University of Maryland CENTER FOR ENVIRONMENTAL SCIENCE INTEGRATION AND APPLICATION NETWORK

III. Data and Analyses for Texas Coastal Systems Components

III-1. Gulf of Mexico Ecological Health Report Card

Fisheries Health Data Support Document

Submitted by:
The Harte Research Institute for Gulf of Mexico Studies
Center for Sportfish Science and Conservation

Executive Summary

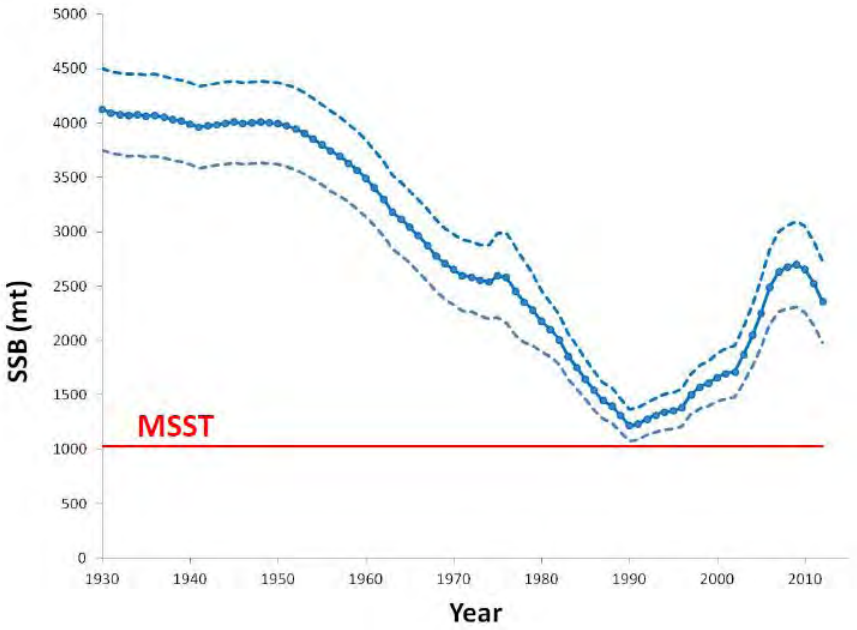
Modern fisheries management seeks to maintain or improve fisheries for future generations. By incorporating science, socio-economics, and technology, today's fisheries managers are able to detect changes within a fishery with accuracy. Cooperation between Federal, state, and private fisheries research groups within the state of Texas has led to effective management of most of the state's coastal fisheries. The majority of Texas' commercial and recreational landings is comprised of a handful of species.

Proper management has led to plentiful populations of Redfish, Spotted Seatrout, Black Drum, King Mackerel, and Gulf shrimp, despite heavy fishing pressure. Managing the stressors to these fisheries have had minimal effect on their productivity as monitoring data indicate that they have been stable, and in some cases increasing, over the past decade, particularly in State waters. Some challenges still exist with the Southern Flounder and Blue Crab fisheries, which have exhibited an overall decline over the past 20 years. Abundance and landings data for these species suggest that overfishing or other environmental factors may be occurring. These may require additional assessments and regulations to prevent further decline and facilitate rebuilding these populations. Perhaps the most studied and certainly the most discussed fishery on the Texas coast is Red Snapper. This once overharvested species has experienced an impressive rebound over the past decade. However, increased illegal fishing pressure from Mexico, along with high discard mortality rates continue to be concerns. Despite recovery, contention regarding access to this fishery, particularly for recreational anglers, continues to be the largest management concern. Managers should continue striving to improve fishery access and proper allocation of this resource.

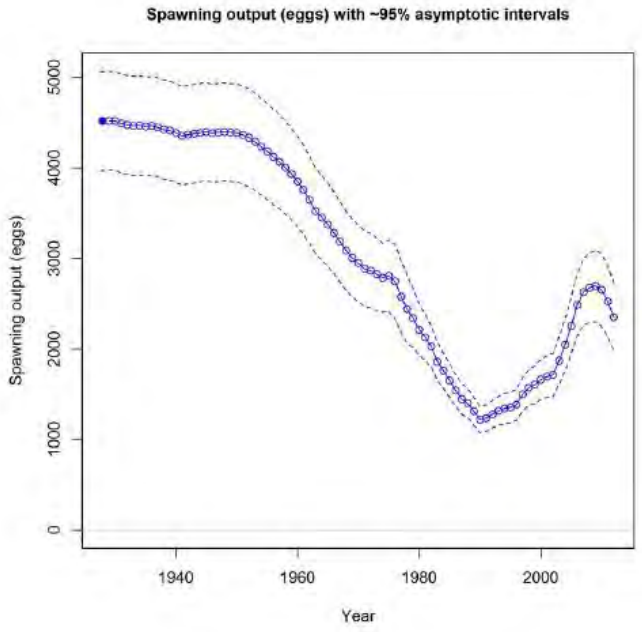
Continued communication between private anglers, commercial interests, and mangers is key to keeping Texas' fisheries healthy and sustainable. This report card seeks to provide the public with a synthesis of the best and most recent data available. As fisheries change, continued report cards will be necessary to update the public on the condition of their fisheries resources.

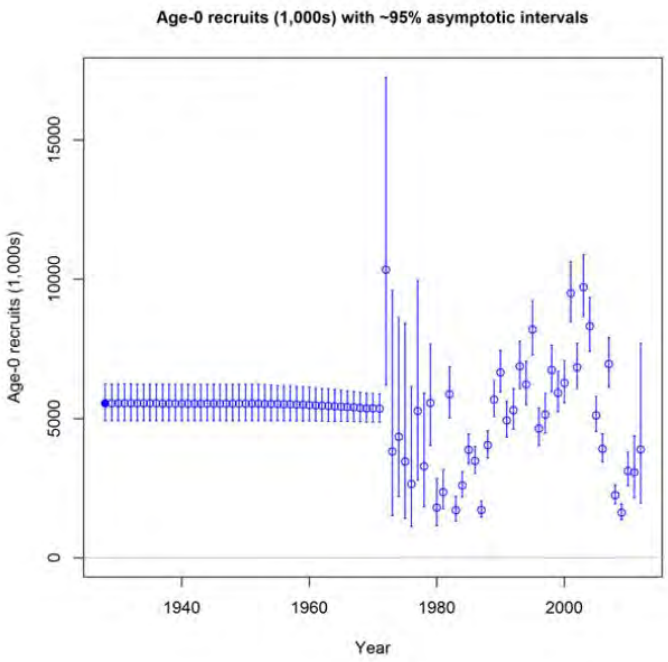
Species: King Mackerel (Gulf of Mexico Region)
Metrics:

Abundance

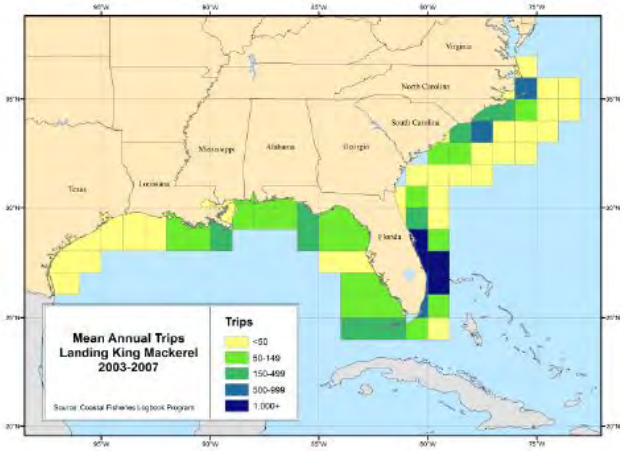


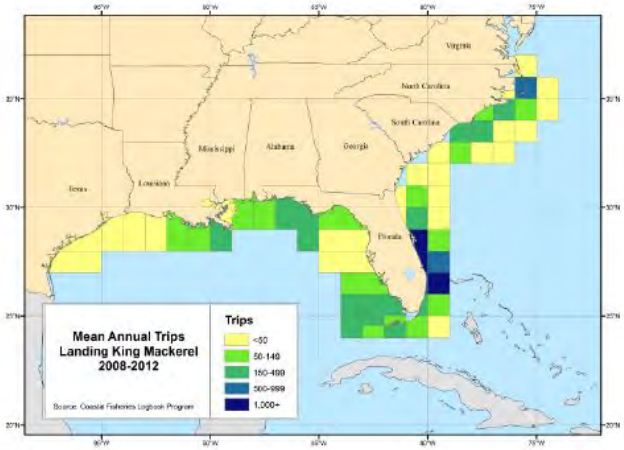
Recruitment



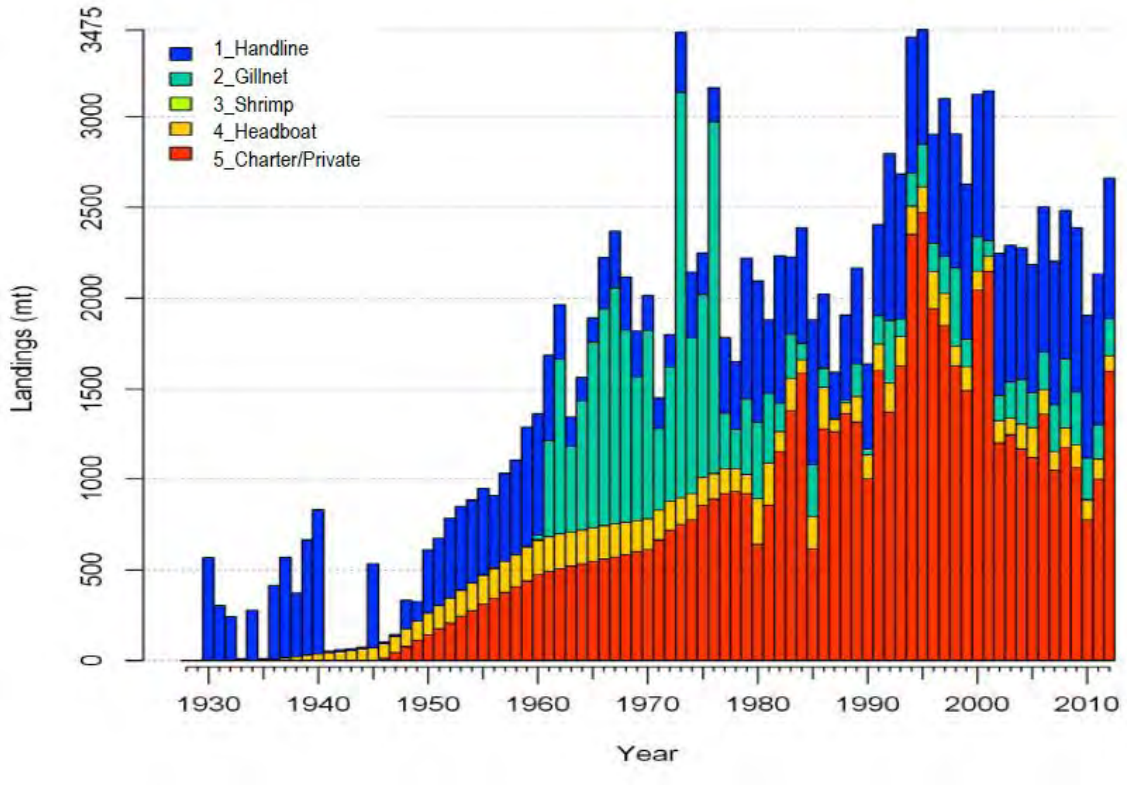

Age-0 recruits (1,000s) with ~95% asymptotic intervals
Age-0 recruits (1,000s)
0
5000
10000
15000
1940
1960
1980
2000
Year

Effort (CPUE)


Mean Annual Trips
Landing King Mackerel
2003-2007
Trips
<50
50-149
150-499
500-999
1,000+
Virginia
North Carolina
South Carolina
Georgia
Alabama
Mississippi
Louisiana
Texas
Florida


Mean Annual Trips
Landing King Mackerel
2008-2012
Trips
<50
50-149
150-499
500-999
1,000+
Virginia
North Carolina
South Carolina
Georgia
Alabama
Mississippi
Louisiana
Texas
Florida

Landings



Particular Stressor(s) of Concern:

- Biological
    - Discard mortality
- Climate (Temperature Changes* long term)
    - Climate Change

Stressor Implications:

Discard mortality from the shrimping industry hindered King Mackerel survival in the past. The reduction of commercial shrimping pressure in the past decade has alleviated much of this discard mortality. Increased fishing pressure from charters and headboats could potentially lead to increased discard mortality in the recreational sector but this has not proven to be a large issue at this point.

There are concerns that climate change may be impacting the reproductive capabilities of King Mackerel. Recent recruitment surveys have begun to collect temperature data and models are incorporating this data to better predict population trends.

Benchmark: Minimum Stock Size Threshold - Spawning Stock Biomass > ~ 1000 metric tons

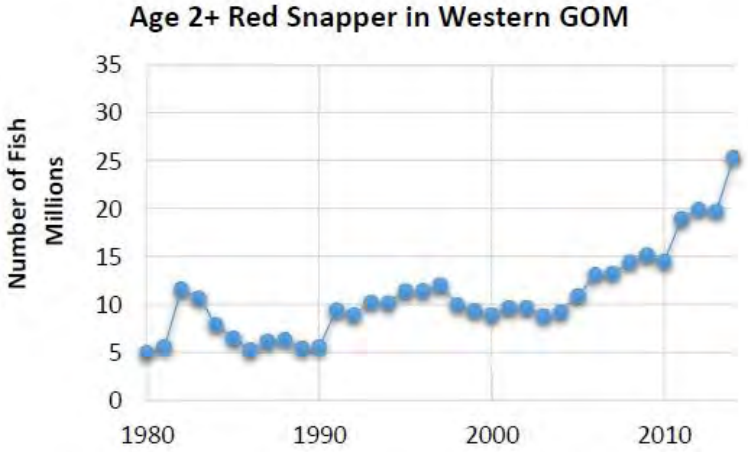
Fishery Grade: (A) This population has generally been increasing since 1990 and is neither overfished or undergoing overfishing.

Citations:

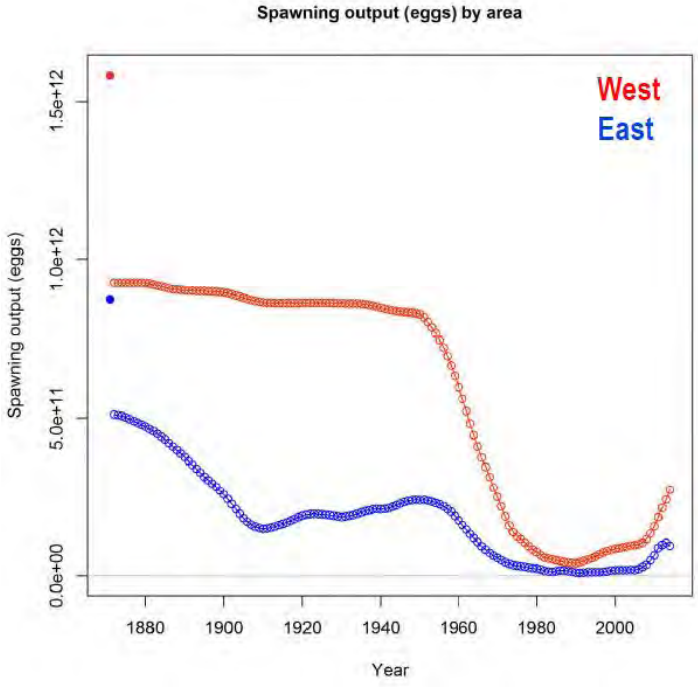
SEDAR 38: Southeast Data, Assessment, and Review. (2014, September). Stock Assessment Report: Gulf of Mexico King Mackerel. Retrieved from: <http://sedarweb.org/docs/sar/SEDAR_38_SA_SAR.pdf>

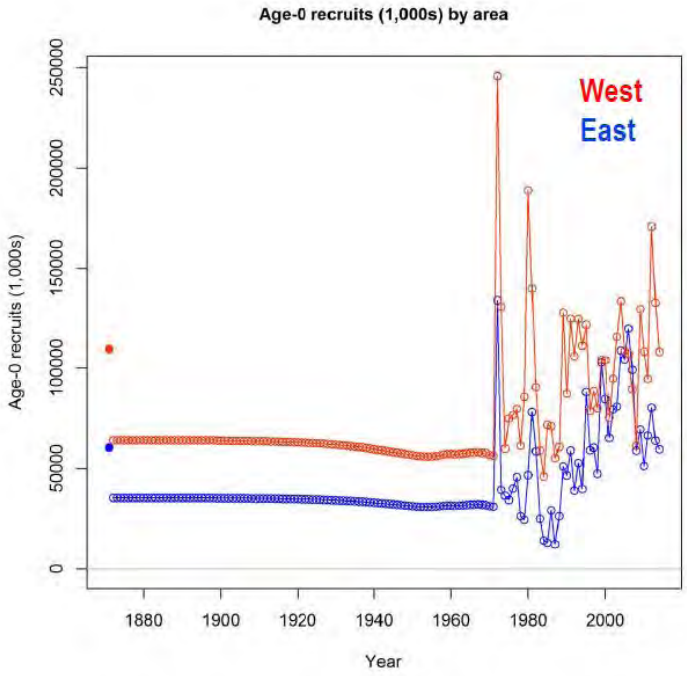
Species: Red Snapper (Western Region)
Metrics:

Abundance



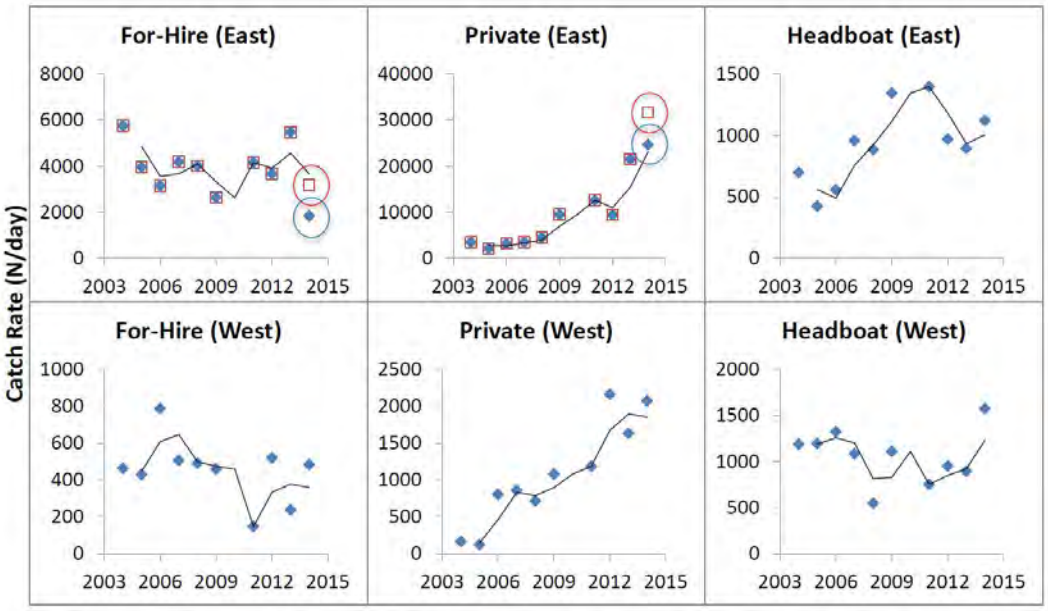
Recruitment





Effort (CPUE)

(Recreational)

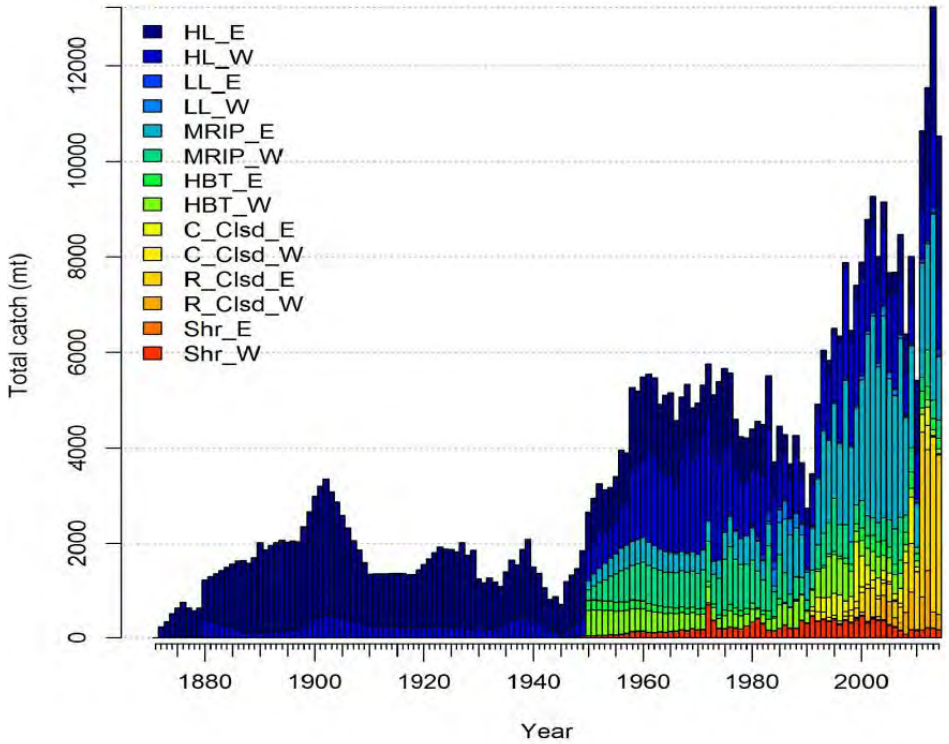


(Commercial)

Fleet	Year	Vessels	Trips	Days at sea	Crew days	Avg. days/Trip	Avg. crew/trip	Avg. red snapper landings (lbs/trip)	Avg. total landings (lbs/trip)
Vertical line	2002	403	4,382	9,436	28,945	2.2	3.1	940	1,324
	2003	400	4,384	9,974	30,578	2.3	3.0	912	1,323
	2004	418	4,714	10,953	32,982	2.3	2.9	777	1,215
	2005	409	4,163	10,217	30,240	2.5	2.9	794	1,273
	2006	374	4,404	11,785	35,087	2.7	3.0	902	1,348
	2007	283	2,435	9,926	30,664	4.1	2.9	1,061	2,310
	2008	273	2,104	8,349	25,200	4.0	2.8	990	2,458
	2009	266	2,217	8,526	25,593	3.8	2.8	949	2,426
	2010	322	2,639	10,308	28,344	3.9	2.7	1,067	2,145
	2011	314	3,064	12,032	33,234	3.9	2.7	965	2,227
Longline	2002	53	187	1,224	4,146	6.5	3.4	848	3,808
	2003	53	206	1,352	4,696	6.6	3.9	942	3,920
	2004	57	330	1,603	5,845	4.9	4.2	1,212	3,258
	2005	59	289	1,608	5,502	5.6	3.8	888	3,366
	2006	56	281	1,695	5,782	6.0	3.8	876	3,182
	2007	33	127	1,193	4,518	9.4	3.8	1,393	4,672
	2008	29	131	1,217	4,443	9.3	3.7	597	5,368
	2009	24	78	791	3,192	10.1	4.1	734	6,211
	2010	36	195	2,056	6,767	10.5	3.3	518	5,232
	2011	42	224	2,352	7,672	10.5	3.2	445	7,220

Source: SEFSC coastal logbook program, 2012

Landings



The "landings" figure above is actually total removals, meaning it incorporated bycatch and discard mortality.

Particular Stressor(s) of Concern:

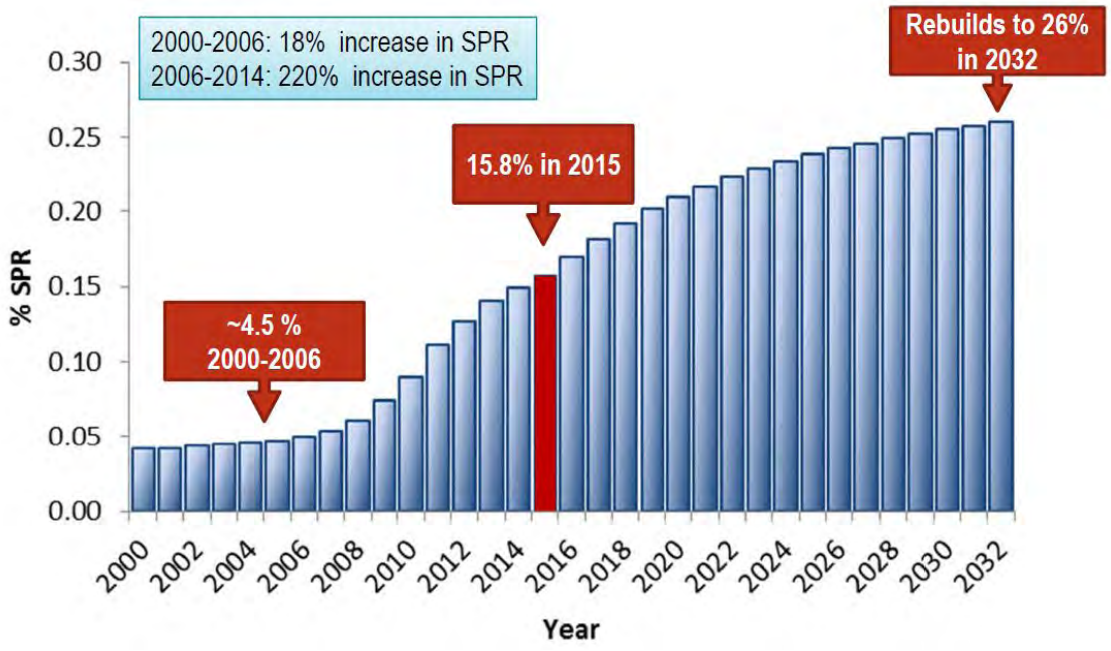
- Biological (Illegal Harvest)
    - Poaching, foreign vessels
- Biological
    - Discard mortality/barotrauma

Stressor Implications:

Out-of-season harvest has proven difficult to account for in management decisions. In addition, illegal harvest of Red Snapper in the United States' Exclusive Economic Zone by Mexican fishing fleets is an increasingly common problem in the Western Gulf of Mexico. Financial support would allow law enforcement agencies to patrol longer for illegal fishing activity, as well as provide scientists with a more accurate illegal harvest estimate.

Given that most Red Snapper are caught at depth and brought to the surface rapidly, barotrauma and its associated release mortality are a large management concern. More research on rapid descent and mortality reduction devices is needed to decrease discard/release mortality related to barotrauma.

Benchmark:



The Western Gulf of Mexico Red Snapper population is being managed for spawning potential ratio, which is the number of eggs a group of fish produces under fishing pressure versus what those same fish could produce if not undergoing fishing pressure.

Fishery Grade: (B–)

Citations:

Gulf of Mexico Fishery Management Council. (2013, April). Red Snapper Individual Fishing

Quota Program 5-year Review. Retrieved from: <http://gulfcouncil.org/docs/amendments/Red%20Snapper%205year%20Review%20FINAL.pdf>

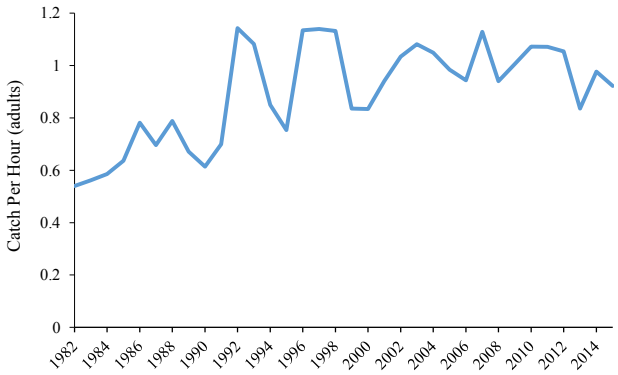
NOAA Fisheries, Southeast Regional Office. (2015, April 20). 2015 Gulf of Mexico Red Snapper Recreational Season Length Estimates NOAA Fisheries, Southeast Regional Office. Retrieved from: <http://sero.nmfs.noaa.gov/sustainable_fisheries/lapp_dm/documents/pdfs/2015/rs_2015_rec_quota_projection.pdf>

SEDAR Red Snapper 2014 Update Assessment. (2015, September 7). SEDAR Update assessment: Stock Assessment of Red Snapper in the Gulf of Mexico 1872-2013- with Provisional 2014 Landings. Retrieved from: <http://sedarweb.org/docs/suar/SEDARUpdateRedSnapper2014_FINAL_9.15.2015.pdf>

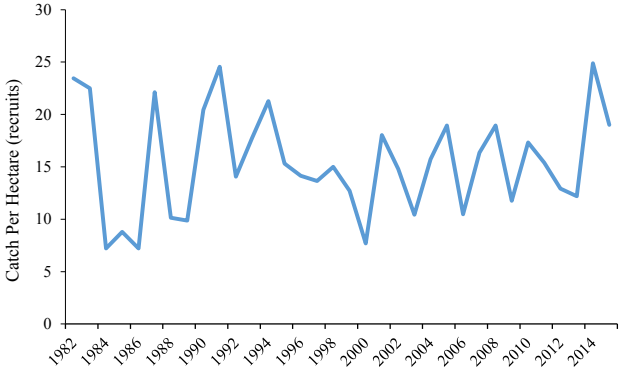
Species: Redfish

Metrics:

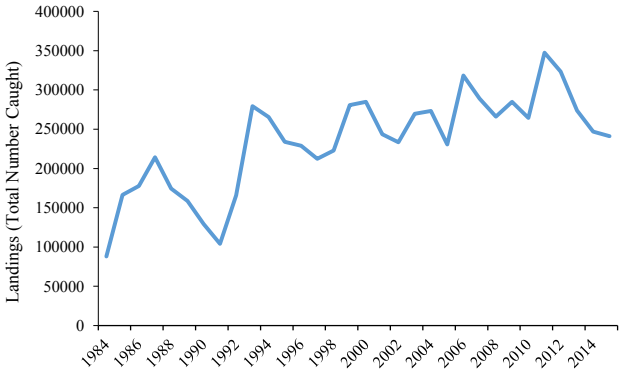
Abundance/Effort (CPUE)



Recruitment



Landings



Particular Stressor(s) of Concern:

- None

Stressor Implications:

Red Drum (Redfish) rely on tidal inlets to egress from and ingress to Texas' bays during various parts of their lifecycle. Weather events and anthropogenic factors threaten tidal inlets and

the critical role they play in the Red Drum's lifecycle. Continued monitoring habitat and access through tidal inlets along the Texas coast is critical to the management of this species.

Benchmark: In order to maintain healthy Red Drum populations, CPUE, recruitment, and landings should remain at current levels.

Fishery Grade: (A+) This population has been increasing steadily since the early 1980's and is not overfished or undergoing overfishing.

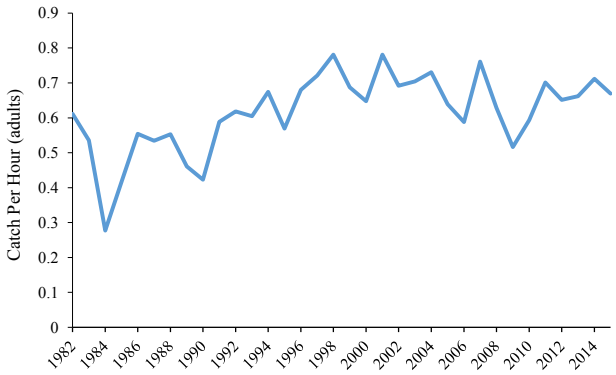
Citations:

Fisher, Mark. 2016. Science Director, Texas Parks and Wildlife. Personal Communication.

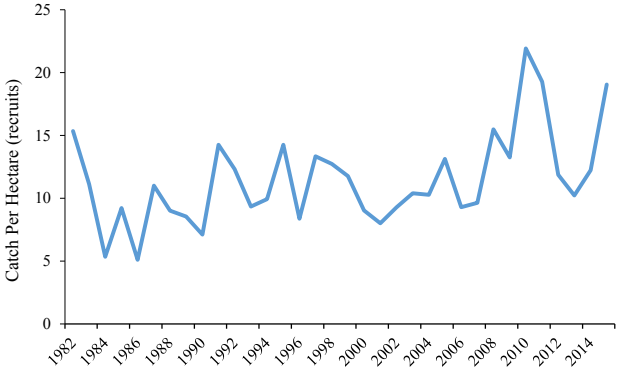
Species: Spotted Seatrout

Metrics:

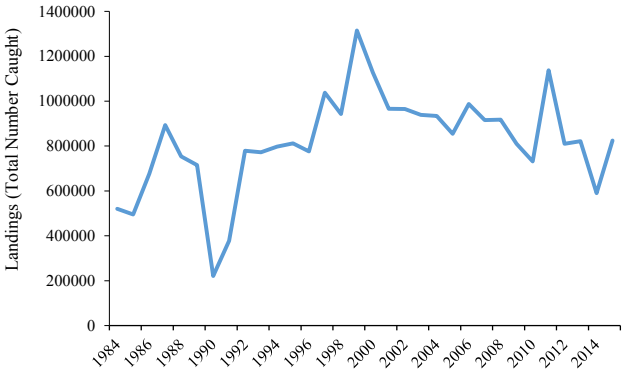
Abundance/Effort (CPUE)



Recruitment



Landings



Particular Stressor(s) of Concern:

- None

Stressor Implications:

- None

Benchmark: Current CPUE, recruitment, and landings are maintaining a healthy population of Spotted Seatrout.

Fishery Grade: (A+) This stock increased during the 1990's and has maintained a healthy population despite high landings. Recruitment levels are slowly increasing, suggesting that slot limits are effective in allowing individuals of this species a chance to reproduce. Given that the CPUE and abundance are stable current management scenarios should be continued.

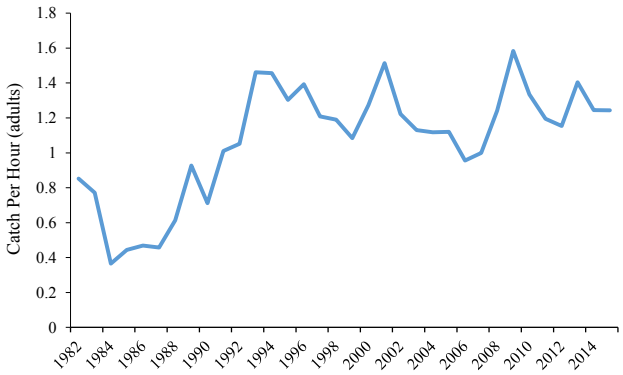
Citations:

Fisher, Mark. 2016. Science Director, Texas Parks and Wildlife. Personal Communication.

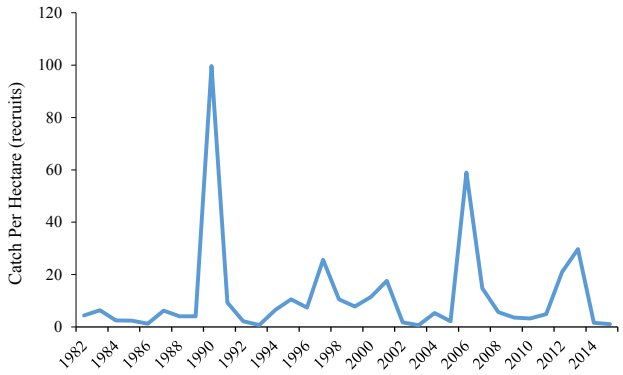
Species: Black Drum

Metrics:

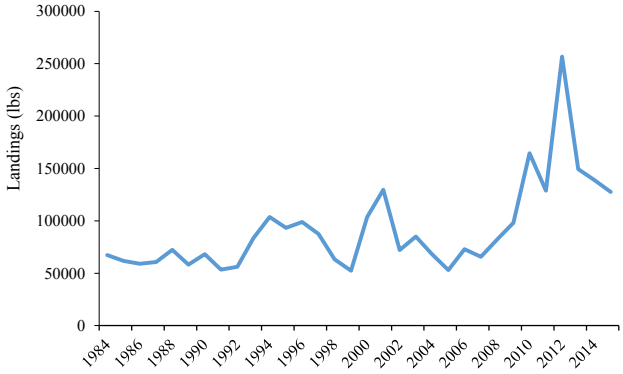
Abundance/Effort (CPUE)



Recruitment



Landings



Particular Stressor(s) of Concern:

- None

Stressor Implications:

Black drum are somewhat dependent on a healthy benthic forage base. Declines in this forage base due to declining water quality and development may eventually impact this species.

Likewise, this species preys heavily on Blue Crabs. The reduction of Blue Crabs may serve to restrict Black Drum populations in the future.

Benchmark: Current Black Drum population metrics indicate the population is large and stable.

Fishery Grade: (A) This stock has generally increased throughout the state since 1988 despite increased commercial landings. Recruitment levels do show large amounts of annual variation but have generally been steady since 1990. There is concern that the species may be overpopulated in some regions of the state. This may be negatively impacting the forage base and eventually the Black Drum population itself.

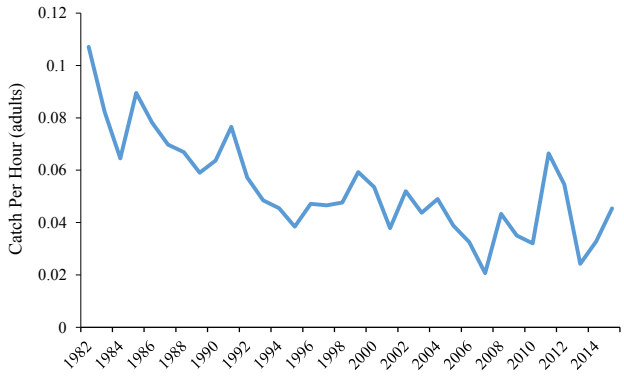
Citations:

Fisher, Mark. 2016. Science Director, Texas Parks and Wildlife. Personal Communication.

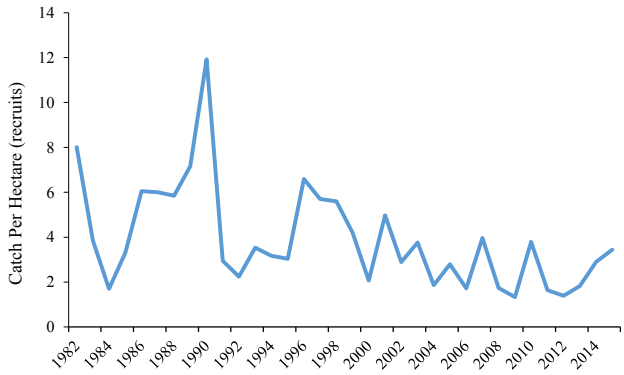
Species: Southern Flounder

Metrics:

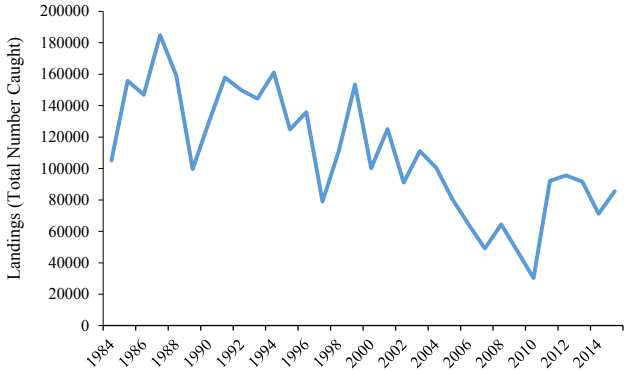
Abundance/Effort (CPUE)



Recruitment



Landings



Particular Stressor(s) of Concern:

- Overfished/Overfishing
- Physical (Salinity Regime)
    - Decreased freshwater inflow
- Climate (Temperature Changes* long term)
    - Increased water temperature

Stressor Implications:

More information regarding adult flounder sex ratios, spawning success, and recruitment dynamics is necessary for proper species management. Much research indicates that water temperature may influence sex ratios for this species, meaning that rising water temperatures could heavily influence this species' sex structure. Likewise, Southern Flounder may require access to lower salinities during certain portions of their lifecycle. Decreased freshwater inflow across the Texas coast could be playing a role in decreasing flounder populations. Despite regulatory changes the population is not recovering to historic levels.

Benchmark: All contemporary benchmarks for Southern Flounder remain low in comparison to historic levels and may require additional management to recover.

Fishery Grade: (C) This species has exhibited decreasing recruitment, CPUE, and landings since the early 1980's. Although this decline has somewhat leveled off in recent years, Southern Flounder continue to be found at lower levels then they were historically.

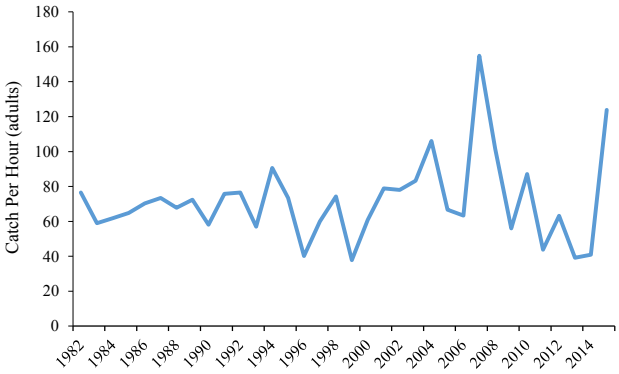
Citations:

Fisher, Mark. 2016. Science Director, Texas Parks and Wildlife. Personal Communication.

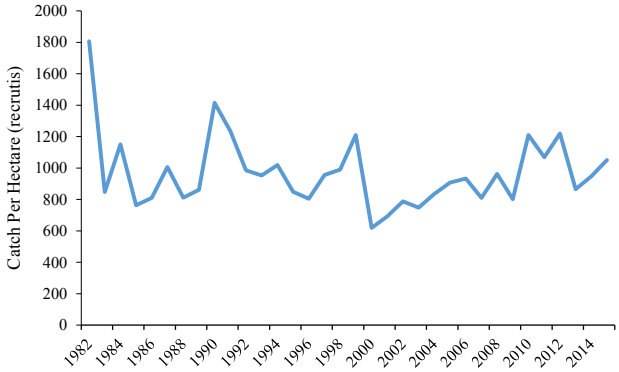
Species: Shrimp (White, Pink, and Brown Shrimp)
Metrics:

Abundance/Recruitment

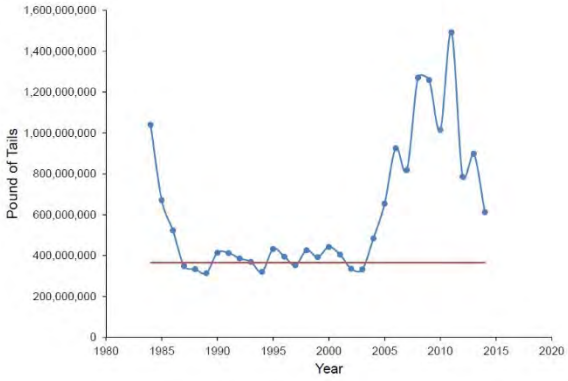
(State Combined Abundance)



(State Combined Recruitment)

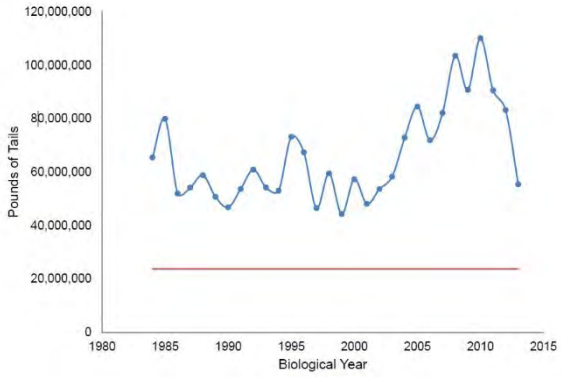


(Federal White Shrimp)



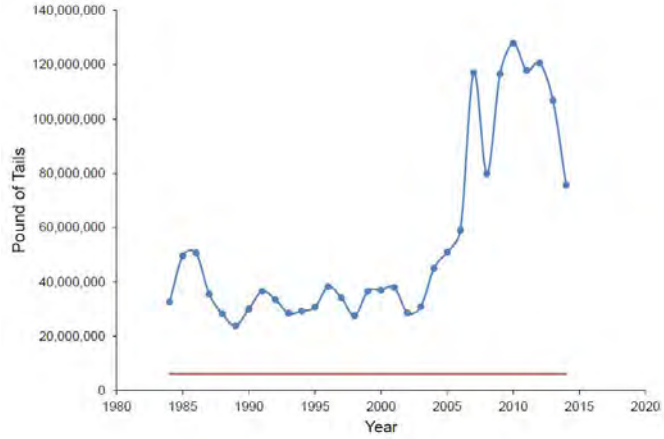
Blue – SSB; Red - SSB*msy*

(Federal Pink Shrimp)



Blue – SSB; Red – SSB*msy*

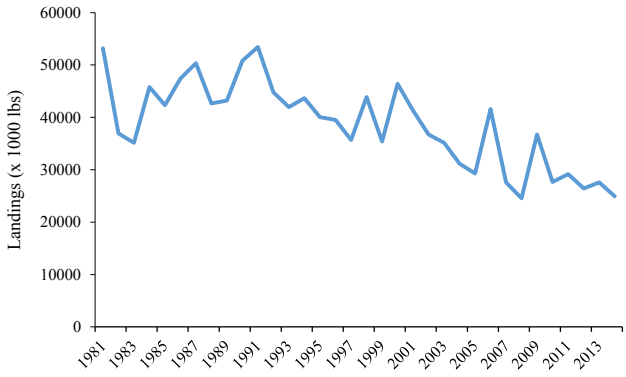
(Federal Brown Shrimp)



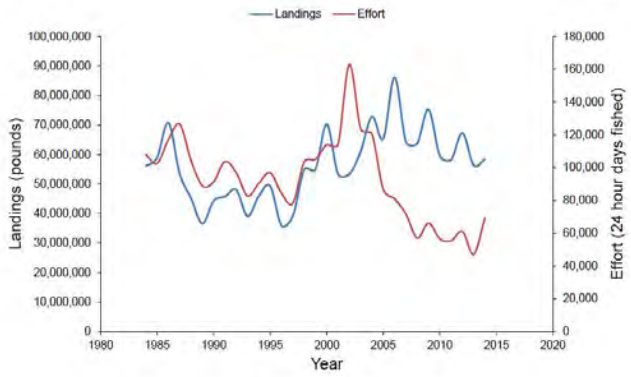
Blue – SSB; Red – SSB*msy*

Effort (CPUE)/Landings

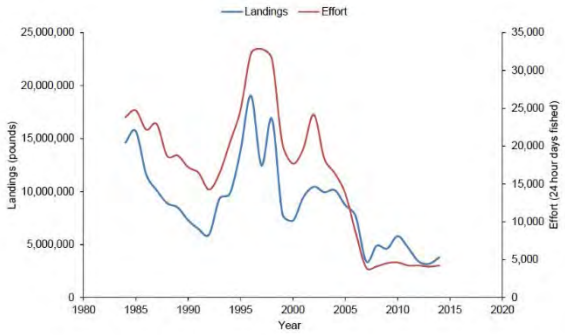
(State Combined Landings)



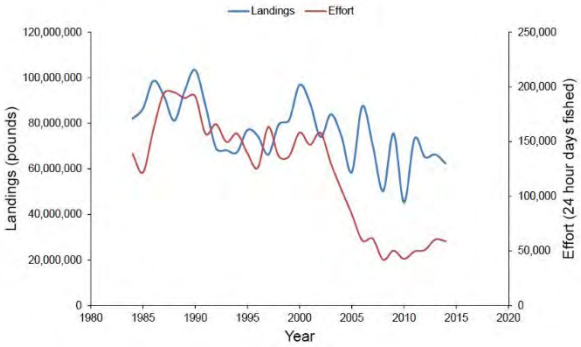
(Federal White Shrimp)



(Federal Pink Shrimp)



(Federal Brown Shrimp)



Particular Stressor(s) of Concern:

- Climate (Ocean acidification)
- Physical (Salinity Regime)
    - Decreased freshwater inflow

Stressor Implications:

A variety of crustaceans including penaeid shrimps need freshwater inflow for some stage of their development. Ensuring freshwater inflow will be essential to maintaining healthy populations. In addition, emerging research is revealing that decreasing pH in the world's oceans impacts the chemical structure of shrimp exoskeletons. Establishing the chemical microstructure of penaeid shrimp exoskeletons may provide a baseline in future studies if the oceans continue to acidify.

Benchmark: Maintaining the current harvest levels for each species or group in both Federal and State waters is appropriate given the present population levels.

Fishery Grade: (A+) Penaeid shrimp populations are high in both Texas state waters and in the U.S. exclusive economic zone. These populations have continued to rise since the mid-1980's with the decline in commercial landings.

Citations:

Fisher, Mark. 2016. Science Director, Texas Parks and Wildlife. Personal Communication.

NOAA Fisheries A. (2015, December). Stock Assessment Update for White Shrimp (*Litopenaeus setiferus)* in the U.S. Gulf of Mexico for 2014. Retrieved from: <http://gulfcouncil.org/council_meetings/BriefingMaterials/BB-04-2016/D%20-%205(b)%20White%20Assess_Rpt-_2015_CPT.pdf>

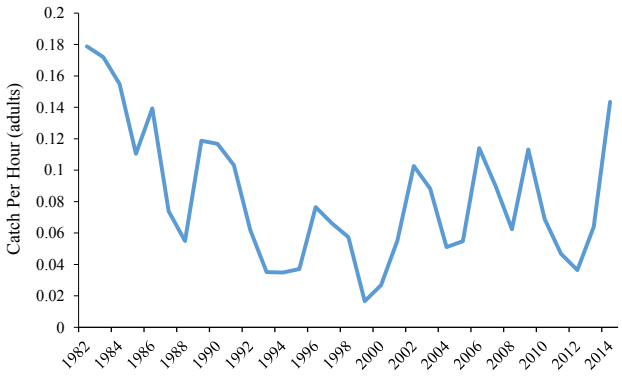
NOAA Fisheries B. (2015, December). Stock Assessment Update for Pink Shrimp (*Farfantepenaeus duorarum)* in the U.S. Gulf of Mexico for 2014. Retrieved from: <http://gulfcouncil.org/council_meetings/BriefingMaterials/BB-04-2016/D%20-%205(c)%20%20Pink%20Assess_Rpt-2015_CPT.pdf>

NOAA Fisheries C. (2015, December). Stock Assessment Update for Pink Shrimp (*Farfantepenaeus aztecus*) in the U.S. Gulf of Mexico for 2014. Retrieved from: <http://gulfcouncil.org/council_meetings/BriefingMaterials/BB-04-2016/D%20-%205(a)%20Brown%20Assess_Rpt_2015_CPT.pdf>

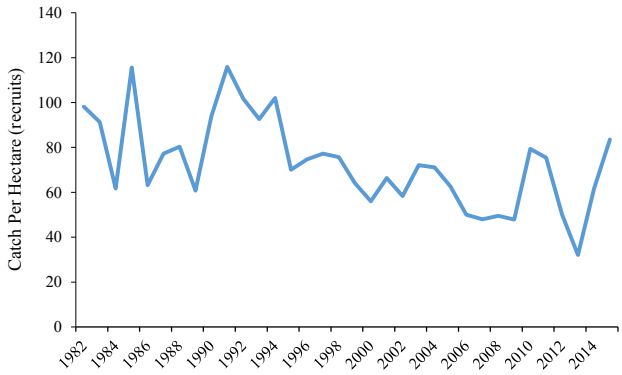
Species: Blue Crab

Metrics:

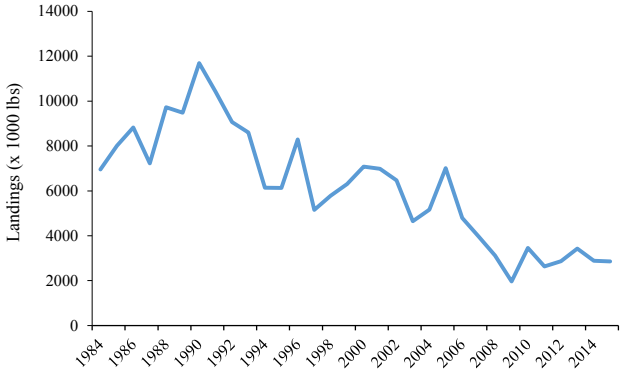
Abundance/Effort (CPUE)



Recruitment



Landings



Particular Stressor(s) of Concern:

- Physical (Salinity and Precipitation Regime)
    - Freshwater inflow
- Biological (Overfishing)
    - Potential Overharvest

Stressor Implications:

Reducing the harvest and placing recreational bag and possession limits would help increase Blue Crab survival and reproduction rates. In addition, Blue Crabs need access to freshwater inflow for various parts of their lifecycle, mainly for reproduction. Decreased levels of freshwater inflow along the Texas coast are almost certainly playing a role in the Blue Crab's decline. An emerging concept in Blue Crab management is understanding how parasites impact this species. More information is needed on how salinity and parasites influence Blue Crab development and reproduction.

Benchmark: Given the downward trends in population metrics, Blue Crab populations should be closely monitored.

Fishery Grade: (C) This fishery has exhibited an overall decline since 1990, and the overall downward trend in CPUE suggests that overfishing may be taking place.

Citations:

Fisher, Mark. 2016. Science Director, Texas Parks and Wildlife. Personal Communication.

III-2. Gulf of Mexico Ecological Health Report Card

Seagrass Health Data Support Document

Submitted by:
Christopher P. Onuf, Ph.D., U.S. Geological Survey

Assembling the Ingredients of an EcoHealth Report Card for Texas Seagrasses

Christopher P. Onuf, Ph.D., U. S. Geological Survey (retired)

Seagrasses are widely recognized as critical elements of a healthy coastal marine ecosystem because of the many goods and services they provide, including support of commercial and artisanal fisheries, sediment stabilization and coastal protection, water column filtration and nutrient cycling, mitigating climate change by acting as a carbon dioxide sink, and maintaining biodiversity and threatened species, among others (Green and Short, 2003). Accordingly, seagrass meadows were selected along with oyster reefs, fisheries, and birds as the four ecosystems to monitor in a pilot investigation for the Texas coast to gauge the overall health of the Gulf of Mexico ecosystem (Harwell, et al., 2015?). In a workshop held at Harte Research Institute, Texas A&M University, Corpus Christi, in March 2016, regional experts identified valued properties and functions of seagrass ecosystems (Valued Ecosystem Components or VECs), ranked the impact of stressors on those VECs, and proposed indicators and metrics for VECs to consider for application in monitoring and reporting to all stakeholders on the health of the Texas seagrass ecosystem. As the regional expert tasked with fleshing out this framework toward implementation, I assessed the current status of Texas seagrasses, sought data sources for application in an ecohealth tracking program, evaluated the feasibility of the proposed indicators and metrics for use in routine monitoring, and set the environmental context in which monitoring must operate to detect change in ecosystem health.

Current Status

The absence of mapping and monitoring of seagrass health in Texas, proposed in 2002 but never implemented, significantly limits our ability to assess current seagrass health. From approximately decennial surveys from the 1960s to 1998, seagrass meadows covered two-thirds of Laguna Madre, with a trajectory toward larger, more "climax" species – manatee grass, then turtle grass – displacing the "pioneer" shoal grass. However, Hurricane Alex in 2010 led to large stormwater discharges into Lower Laguna Madre that decreased salinity to near fresh water and reset the clock on the successional process, eliminating much of the manatee grass and turtle grass away from the Gulf outlet. At around the same time, Upper Laguna Madre experienced prolonged drought and unusually high salinities in its middle section, leading to loss of manatee grass. Based on more sporadic sampling, Texas mid-coast seagrasses historically and currently are much less dense or extensive, and are subject to many anthropogenic stressors, especially hydrologic alterations and salinity regime changes, that may have affected their condition. The small, remnant seagrasses of the Galveston Bay system, along with the more extensive seagrass beds of Aransas Bay, were likely devastated by unprecedented quantities of freshwater inputs from Hurricane Harvey in 2017.

Data Sources

Despite the gaps and limitations in our current knowledge of seagrass status and trends, Texas is fortunate in having two invaluable natural resource monitoring programs for its bays that should allow effective tracking of seagrass ecosystem health in the immediate future. From 2011 to 2015, Dr. Ken Dunton, University of Texas Marine Science Institute, sampled seagrasses and water quality yearly from Aransas Bay to the south end of Laguna Madre. Permanent locations were randomly set in each of 567 tessellated hexagons with >50% seagrass cover as determined from vegetation maps generated during the 2004/2007 NOAA Benthic Habitats Assessment (Figure 1). In 2015 sampling was extended

to San Antonio Bay and in 2017 to Matagorda and Galveston Bays. Species composition and areal cover were obtained from four replicate quadrat samples per station at each of the cardinal directions from the vessel. Leaf tissues of *Thalassia testudinum* and *Halodule wrightii* were analyzed for carbon and nitrogen and stable isotope ratios of carbon and nitrogen. Water quality sampling just before plant sampling included depth, conductivity, temperature, salinity, dissolved oxygen, chlorophyll fluorescence, pH, TSS, water transparency (texasseagrass.org). Texas Parks and Wildlife Department (TPWD) Coastal Fisheries Division has a similar statistically rigorous sampling regime in which 20 beach seine samples are collected each month from each of seven bay systems from Galveston Bay to the Mexican border. Catches were enumerated by species and up to 19 individuals measured. Before setting the bag seine, depth, water temperature, salinity, dissolved oxygen, and turbidity were measured. Similar hydrological data were collected before gill net sampling (resource monitoring methods.doc obtained from mark.fisher@tpwd.texas.gov).

Evaluating Proposed Indicators and Metrics

At the Texas EcoHealth Workshop, several VECs were identified for the seagrass community. Following is a discussion of potential metrics/databases that could be used for assessing these VECs. Seventeen seagrass VECs were identified in three categories as follows, with proposed indicators and metrics and commentary about utility and feasibility.

A.) *SEAGRASS STRUCTURAL ATTRIBUTES*

AREAL EXTENT/DISTRIBUTION – Hectares of seagrass determined from aerial photography and ground-truthing (see forwarded Onuf-Kuhn email 13Feb17, attached). This perhaps is the single most important element of a seagrass monitoring process. We should argue strongly for mapping at 10-year interval. This is expensive and hard to accomplish; however, the underlying objective of the seagrass monitoring workshop that I attended in October 2017 was to coordinate an effort to secure Deepwater Horizon settlement funding for seagrass mapping of the entire US Gulf Coast to provide a more rigorous "baseline" than could be cobbled together for Deepwater Horizon – mostly from Handley et al. (2007) "Seagrass Status and Trends in the Northern Gulf of Mexico: 1940-2002". Dunton's protocol (texasseagrass.org) for measuring % cover at hundreds of stations that were mapped as seagrass in the 2004/2007 NOAA Benthic Habitat Assessment might be a serviceable surrogate.

LANDSCAPE MOSAIC – Size distribution of patches, inter-patch distances, patch orientation/shape – infeasible without aerial photography. A possible alternative from Dunton seagrass cover and condition survey protocol might be a measure of variation among the 4 quadrat determinations of % cover made "at each of the four cardinal locations from the vessel".

SEAGRASS SPECIES COMPOSITION - % cover by species, hectares by species, mixed species vs mono-specific beds – already part of Dunton survey protocol or easily extracted from the data base.

SEAGRASS BIOMASS – Dry weight above live and dead, dry weight root and rhizome, total dry weight, ash-free dry weights, C content – infeasible at the scale of routine monitoring for the whole coast. A usable surrogate might be % cover x canopy height, already part of Dunton survey protocol. (Canopy height reported in Results but not mentioned in Methods.)

B.) *SEAGRASS FUNCTIONAL ATTRIBUTES*

PRIMARY PRODUCTION – g C fixed per m2 per hour, g O_2 produced per m^2 per hour, scale to per day and per year - infeasible at the scale of routine monitoring for the whole coast. However, if deemed important at a specific location, an assessment of production from shoot elongation and shoot density in clipped plots then core sampled a month or so later, such as reported in Dunton's first seagrass publication (1990), would serve.

WATER QUALITY – Light attenuation (Secchi/Kd), optical properties (TSS, chla, color), stable isotopes/CNP (eutophication tracking), pH – already part of Dunton survey protocol, except Secchi depth, that might not be measurable most of the time where seagrasses occur, and P.

EROSION CONTROL – mm sediment added or lost per unit time, chalk block dissolution rates - infeasible at the scale of routine monitoring for the whole coast; however, measuring chalk block dissolution rates might be useful in locations of special concern.

NURSERY FUNCTION – Number and size of juveniles of species x, total number of individuals per catch, catch as a function of time (season/year) – too much else besides seagrass influences juvenile abundances for them to be a good indicator of nursery function. I have proposed to Greg Stunz and Mark Fisher using proportion of redfish surviving the half month after maximum density in bag seine samples and their change in length over that period as derivatives of ongoing routine sampling that are more reflective of nursery function. Data provided by Mark Fisher show that bag seine sampling does not capture redfish small enough to get at nursery function of seagrass meadow; therefore, infeasible at the scale of routine monitoring for the whole coast.

ESSENTIAL FISH HABITAT – Number and size of juveniles and adults of species x, total number of juveniles per catch, catch as a function of time – I'd just as soon duck this one. If there are species that only occur in seagrasses (pipefish maybe?), then we have a handle. Otherwise, a weak indicator might be contrasts between catches in areas with and without seagrass.

SECONDARY PRODUCTION – Invertebrate infauna, sessile and motile epifauna, biomass, abundance, other metrics of quantity and C, see also EFH metrics – Actual determination of secondary production is infeasible at the scale of routine monitoring for the whole coast. I guess invertebrate abundance in bag seines is related to secondary production but distantly enough that I doubt it should be part of an assay of ecosystem health.

CONDITION OF THE SEAGRASS PLANTS – Photosynthesis indicators (gas exchange rates and chl), nutrient indicators (tissue N and P content, NH4, NO3), morphological indicators (shoot density, leaf length each species present) – Dunton protocol already measures tissue N but not P, % cover by species and canopy height, perhaps addressing the morphological indicators. Gas exchange measurements are infeasible at the scale of routine monitoring for the whole coast. I don't know enough about the use of plant pigments in assessing plant “health” to argue for or against their inclusion.

BIOGEOCHEMICAL DYNAMICS – Detritus decomposition rates/mass loss, decomposer community composition and abundance, microbial C and N processing rates, microbial community genomics and proteomics - infeasible at the scale of routine monitoring for the whole coast.

C.) *SEAGRASS ECOSYSTEM SERVICES*

REDFISH – TPWD trawl or gill net sampling? Even more than for nursery function, too much else besides seagrass influences redfish abundance in a bay for it to be a good indicator of seagrass ecosystem service. Comparisons of catch between seagrass covered and bare locations of the same depth might be extractable from Coastal Fisheries monitoring data by classifying sampling locations in conjunction with TPWD Seagrass Viewer but not without considerable effort.

SPOTTED SEA TROUT - TPWD trawl or gill net sampling? See comment for redfish.

RECREATIONAL FISHING – TPWD creel surveys? This would require information from fishermen on where the catch came from.

FORAGING WATERFOWL – Beau Hardegree, USFWS Corpus Christi, added pintail, widgeon, bufflehead, scaup, and teal as waterfowl users of Texas bays, although none are so tightly tied to seagrasses as redheads. Historically, an annual survey of wintering redheads was carried out. According to Dan Collins, Migratory Bird Coordinator for FWS Region 2, the survey was discontinued in 2012. The TPWD waterfowl monitoring program of the coast is at too coarse a scale to be useful. I don't know whether game wardens compile data on bag checks that would be of any use.

HURRICANE/STORM MITIGATION – Shoreline retreat with and without seagrass meadows offshore? How different from erosion control?

Setting the Environmental Context

Ideally, a program for monitoring the health of Texas seagrasses will consist of regular (annual) sampling of amount and condition of the plants across their whole range of occurrence in association with a suite of appropriate environmental parameters. This is precisely what the Dunton program does. Unfortunately, as noted in **Data Sources**, the attendant environmental measures are single determinations just before plant sampling – unlikely to capture conditions that might have impacted the plants at any other time over the previous year. Also, at least at present, all results are reported as bay-system means that may well mask important changes at a more local level. I have attempted to address these issues by expanding spatial and temporal coverage using a complementary data base – the hydrological sampling associated with TPWD's Coastal Fisheries monitoring program (see **Data Sources**), and by attempting to divide Texas bays into more meaningful functional segments.

SALINITY

Seagrass cover increases sharply from north to south along the Texas (Figure 2). Likewise, there is a

strong north-south gradient in salinity (Figure 3) that almost certainly bears on the distribution of seagrasses. It is obvious that any program for tracking the extent and condition of Texas seagrasses has to have a handle on salinity effects before we can have a hope of detecting any other effects, and a single measurement of salinity at the time of plant sampling cannot possibly provide that handle.

To capture the salinity regime most relevant to seagrass distribution and condition, I chose the hydrological data associated with Coastal Fisheries bag seine sampling – 20 samples per month each for the 7 bay systems from Galveston Bay south, of which four are shown here. At the grossest level, Galveston Bay is fresher than seawater most of the time, Matagorda and Aransas Bays are in the 25 to 35 ppt range most of the time, and Upper Laguna Madre is at or above marine salinity the great majority of the time. To achieve more explanatory value, I have refined the spatial dimension. All of Galveston Bay's 0.1% of the state's seagrass endowment is in West Bay, the saltiest part of the Galveston Bay System. Only 13% of 5 years of salinity observations were <20 ppt for West Bay compared to 39% for the main stem of Galveston Bay, 59% for East Bay, and 80% for Trinity Bay (Figure 3, top), suggesting that long periods of low salinity, say <15 or 20 ppt, do not allow the development of persistent seagrass meadow. The same pattern applies in the next 3 bay systems down the coast. The seagrasses are more abundant in those bays than Galveston Bay (Figure 2), and heavily concentrated in the lower parts of the bays, the parts with lowest exposure to low salinity. In Matagorda Bay 8,15, and 26% of observations were <20 ppt in Lower, Middle and Upper reaches respectively (Figure 3, upper middle), and in the Aransas Bay System 8% of observations in Aransas Bay (=Lower) were <20 ppt while 24% were <20 ppt in Copano Bay (=Upper) (Figure 3, lower middle). This analysis cannot be extended south because essentially there are no observations <20 ppt south of Aransas Bay (Figure 3, bottom).

The analysis so far is based on a pooling of five years of salinity observations by bay segment. Given that Texas is notorious for periods of prolonged drought punctuated by episodes of extreme rainfall and runoff, it is probable that the aggregate salinity regime for long periods cannot capture the duration of rare extreme conditions that are likely most influential on the seagrasses. I addressed this possibility by compiling the frequency of extreme salinity observations by year Figure 4). In 4 years out of 5, 5% or less of salinity observations were <20 ppt in West Bay of the Galveston Bay system, and then in 2015 60% of observations were <20 ppt. Something similar applies the next 3 systems down the coast – 4 years 5% or less of salinity observations <20 ppt in lower and middle bay segments, and then in 2015, 35 to 55% of observations <20 ppt. Since we know that thousands of hectares of seagrass meadow have long persisted in Aransas Bay, a lower salinity threshold is indicated – perhaps 15 ppt, occurring for 10 to 33% of observations in bay segments where seagrasses are concentrated compared to 58 to 100% in bay segments where seagrasses are rare or absent.

Suffice it to say, this analysis provides no answers, but it sets the stage for getting answers in short order. Dunton seagrass surveys are being conducted along the entire Texas coast this year from Galveston Bay to Lower Laguna Madre. Thanks to Hurricane Harvey and in conjunction with the temporal and spatial resolution provided by Texas Parks and Wildlife Coastal Fisheries monitoring, we shall have the acid test of how salinity impacts seagrass distribution along the Texas coast.

The TPWD Coastal Fisheries monitoring program also routinely collects turbidity, water temperature, and dissolved oxygen data at its sampling locations. The following example analyses are offered to demonstrate their value in assessments of ecosystem health.

TURBIDITY

Ken Dunton does not include turbidity in his monitoring program, because nephelometric measures of turbidity by light scattering do not map onto extinction coefficient very closely. Hence, his sampling of total suspended solids instead. Here, I hope to show that we cannot afford to ignore the possible influence of turbidity on Texas seagrasses, using Matagorda Bay as an example and argue that turbidity be added to the Dunton surveys (Figure 5). The underlayment is Texas Parks and Wildlife's Seagrass Viewer scene of Matagorda Bay showing concentrations of seagrasses and depth contours. Overlaid on it are turbidity-frequency graphs for the landward extremities of the bay system - top right, and shore segments of the lower and middle bay - bottom right. I chose the turbidity data associated with gill net rather bag seine sampling on the assumption it would be more representative of the depth range where light limitation might be a factor. The remaining bit of information to interpret this welter of data is that the prevailing winds in this region are very strongly from the southeast when seagrasses are growing. The tributary bays – Lavaca, Keller, Carancahua, Tres Palacios - the recipients of discharges from the watershed, are turbid much of the time: turbidity >20 NTU for 39 to 60% of observations over 5 years . This is even more strongly the case for the north shore of the east arm and the northeast shore of the middle bay – blue and red bars, lower right graph - bearing the brunt of wave action produced by the long fetch of the prevailing southeast winds: turbidity >20 NTU 68 and 70% of observations over 5 years. In contrast, the south and west shores are much less turbid. The relatively low turbidity of the main bay north shore seems anomalous to me. The largest concentrations of seagrasses are associated with the low turbidity south and west shores. The seagrasses in turbid Keller and Carancahua Bays occur in shallow waters along their south shores, very well protected from wave-generated turbidity. The seagrass concentrations along the north shore are anomalous with respect to turbidity. However, the concentrations cannot be as extensive as currently portrayed: according to the depth contours, those seagrasses extend deeper than 2 meters, which they don't even reach in Laguna Madre. (The same is true for the concentration along the west shore – it can't extend so deep as currently shown.)

As with salinity, this analysis is inadequate to determine a relationship between turbidity-frequency and seagrass distribution. Nevertheless, the patterns are tantalizing, and I think if Ken Dunton added nephelometric turbidity to his battery of water quality measures, in conjunction with his measures of total suspended solids, chlorophyll, and extinction coefficient, that meaningful relations between turbidity and extinction coefficient are achievable. If so, the spatial and temporal resolution of Coastal Fisheries monitoring can increase greatly the power of the Dunton surveys.

DISSOLVED OXYGEN AND TEMPERATURE

In this period of rapid regional climate change, keeping track of water temperature and dissolved oxygen is certain to be ever more consequential in monitoring health of the Gulf of Mexico ecosystem. The spatial and temporal coverage of the Coastal Fisheries monitoring program is a valuable resource here too, with the hitch that time of day is so influential. Fortunately, there is a time stamp as well as a date stamp for every observation. Presumably, dissolved oxygen is lowest and most critical early morning, before the sun gets high enough for photosynthesis to counteract respiratory demands (Figure 6) and in July (upper left) very credible projections can be made by simple regression up to ~1 PM and undoubtedly even better ones from modeling, and differences among years probably would be detectable. The effect of time of day is muted in December (lower left) and dissolved oxygen < 5 mg/l is a rare occurrence. Similarly, the effect of time of day on temperature is strong in July (upper right) and weak in December (lower right). Given the strength of the regression in July between temperature and time of day 8 AM to 3 PM in all years, a long term trend in summer temperature would be detectable.

Conclusions

This report is a harangue in support of a wedding between data bases. Previous determinations of seagrass distribution and condition have been too sporadic in space and time and different in methodologies to serve as a useful baseline for a monitoring program of ecosystem health. The Matagorda and San Antonio Bay systems are particularly lacking in historical data. Fortunately, this situation is now being remedied with the extension in 2017 of Ken Dunton's systematic sampling seagrass cover and condition at permanent stations to the entire Texas coast. However, the sampling of associated environmental parameters only at the once yearly time of plant sampling severely limits the power of the program to interpret change. The main objective of this report has been to demonstrate how the high frequency and broad spatial coverage of TPWD Coastal Fisheries hydrological sampling associated with bay bag seine and gill net sampling can effectively complement the Dunton seagrass monitoring program by expanding the temporal dimension of environmental sampling. The remaining gaps to be filled are to conduct a mapping of seagrasses for the entire coast (see AREAL EXTENT/DISTRIBUTION in **Evaluating Proposed Indicators and Metrics** above) and to provide Ken Dunton with the necessary equipment to add include nephelometric turbidity to his sampling program (see TURBIDITY in **Setting the Environmental Context** above).

Acknowledgments

This report would not have been possible without the papers and feedback provided by Greg Stunz, Mark Fisher, and Faye Grubbs on nursery function, Paul Montagna on secondary production, Warren Pulich on upper and mid-coast seagrasses, Patrick Biber on VECs-Stressors and VECs-Indicators matrices, Mike Wetz and Jace Tunnell on water quality data sources, Lisa Gonzalez on the Galveston Bay ecohealth report card, Beau Hardegree and Dan Collins on waterfowl use of seagrass meadows, Nathan Kuhn on seagrass mapping, and Heath Kelsey on decoding time in the TPWD Coastal Fisheries database. Most of all, I wish to thank Ken Dunton for access to and discussion about his seagrass percent cover and condition database and Mark Fisher for access to the hydrological data of the TPWD Coastal Fisheries monitoring program. Wes Tunnell made me aware of the opportunity to participate in this important project and Larry McKinney made it happen. Mark Harwell and Jack Gentile were my guides throughout this process.

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LC. Whitepaper presented at Harte Research Institute workshop on EcoHealth Metrics, Corpus-Christi, TX.

mark.fisher@tpwd.texas.gov provided "resource monitoring methods.doc" to describe the TPWD Coastal Fisheries monitoring program and kindly supplied bay bag seine hydrological data and gill net turbidity data for 2011-2015 as Excel spreadsheets.

Onuf-Kuhn email 13Feb17. "Coast-wide Seagrass Mapping?" Appendix 1.

texasseagrass.org. Dunton survey protocol described in "Final Seagrass Report Tier 2 2014-2015.pdf". Seagrass data contained in "Results, Raw Data from Tier 2 Sampling Effort, 2011-2015 results".

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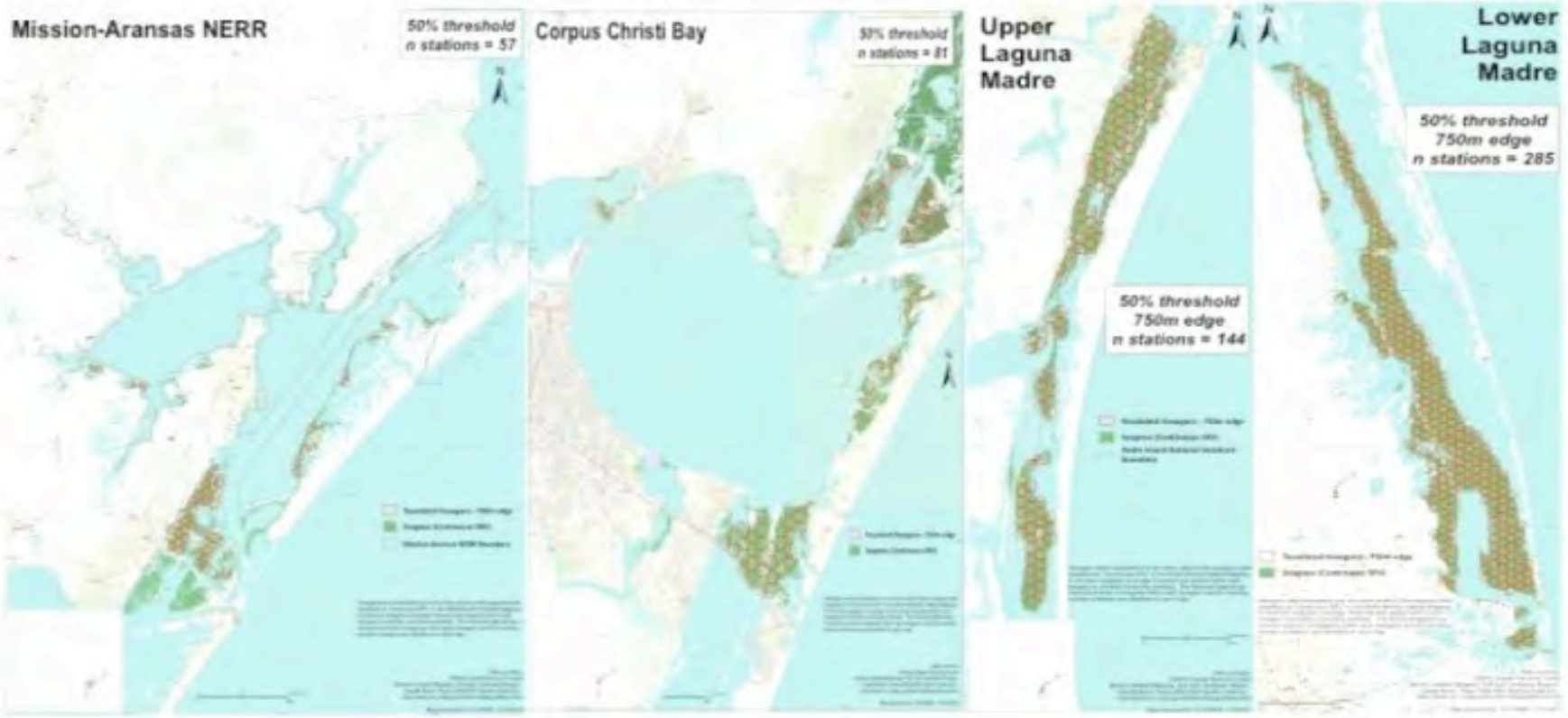

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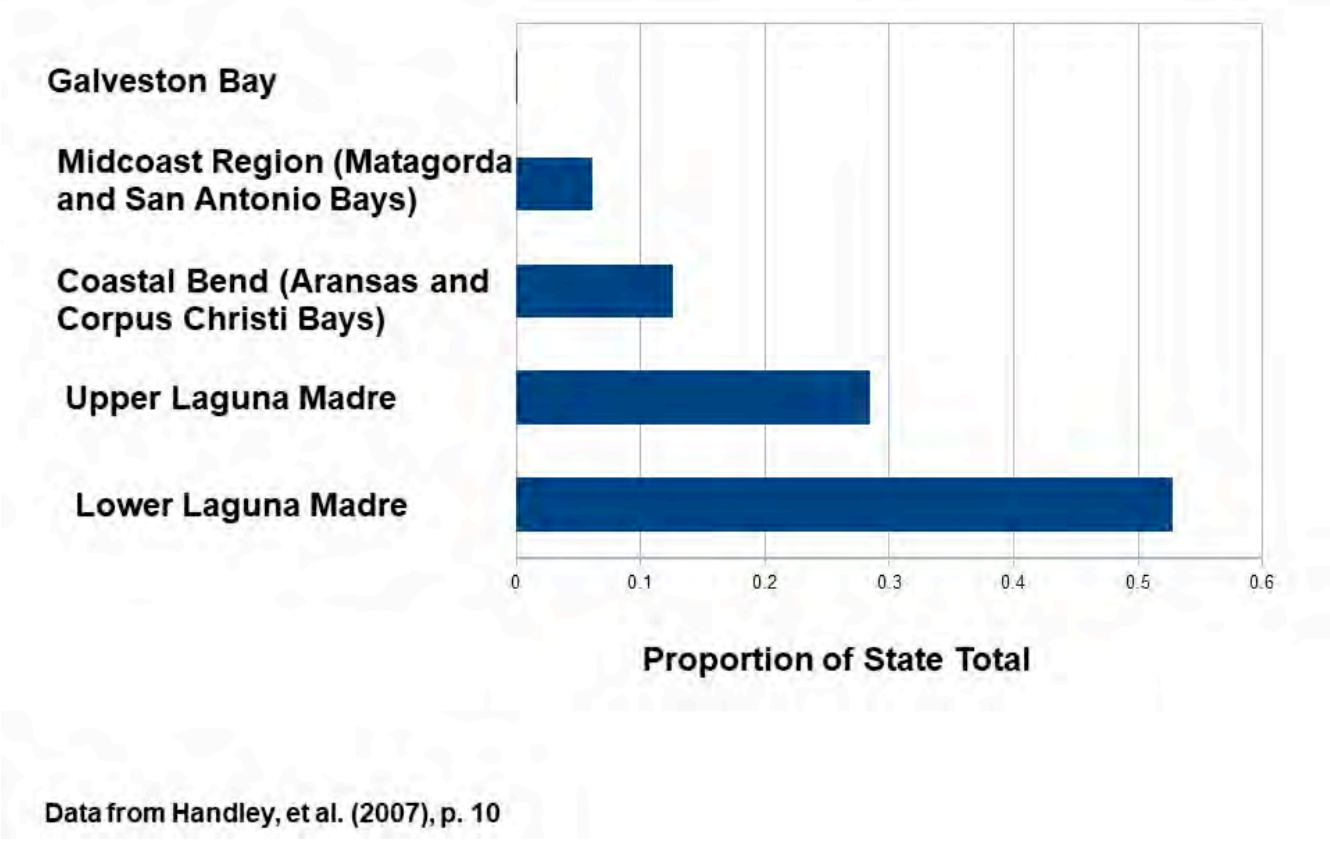
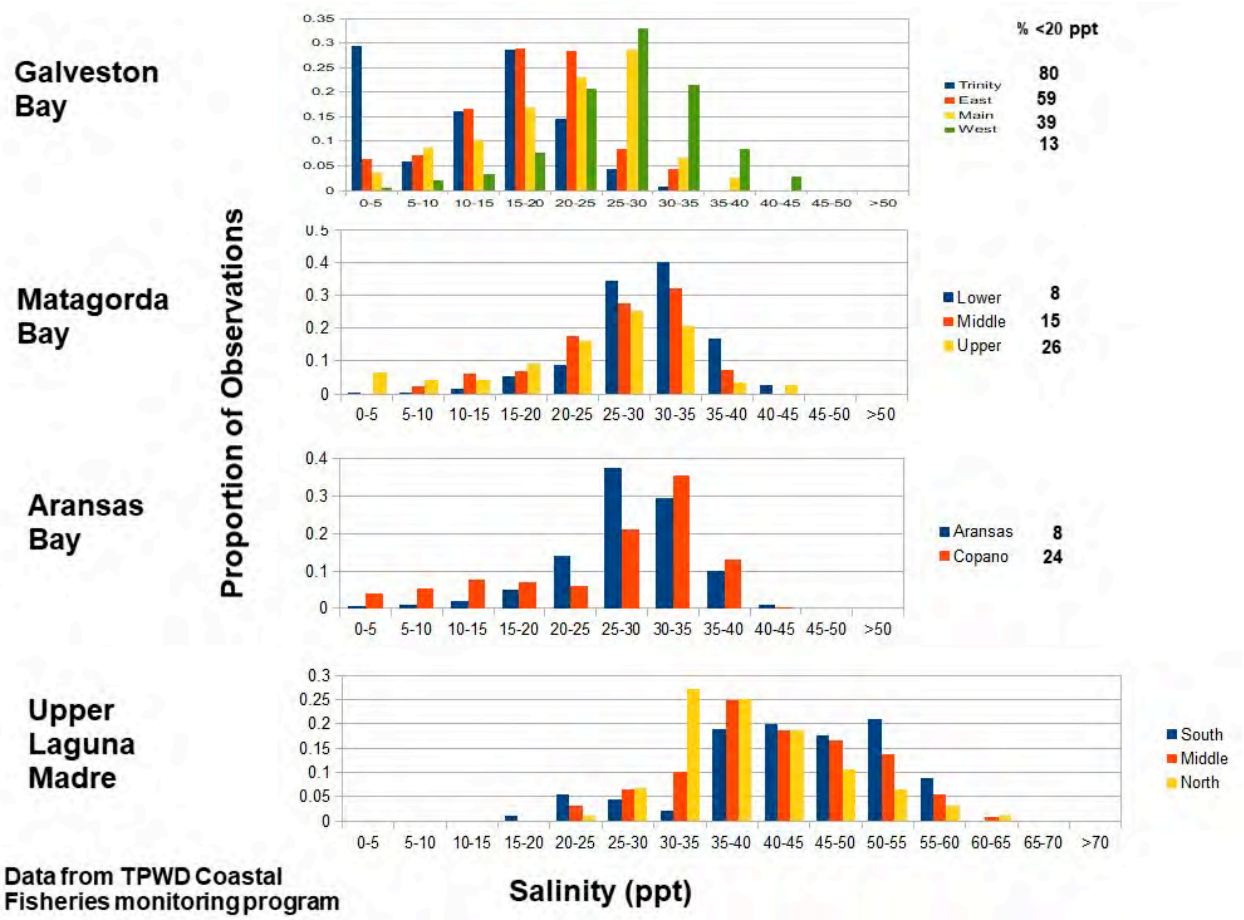


Figure 2. Gradient in seagrass cover along the Texas coast.



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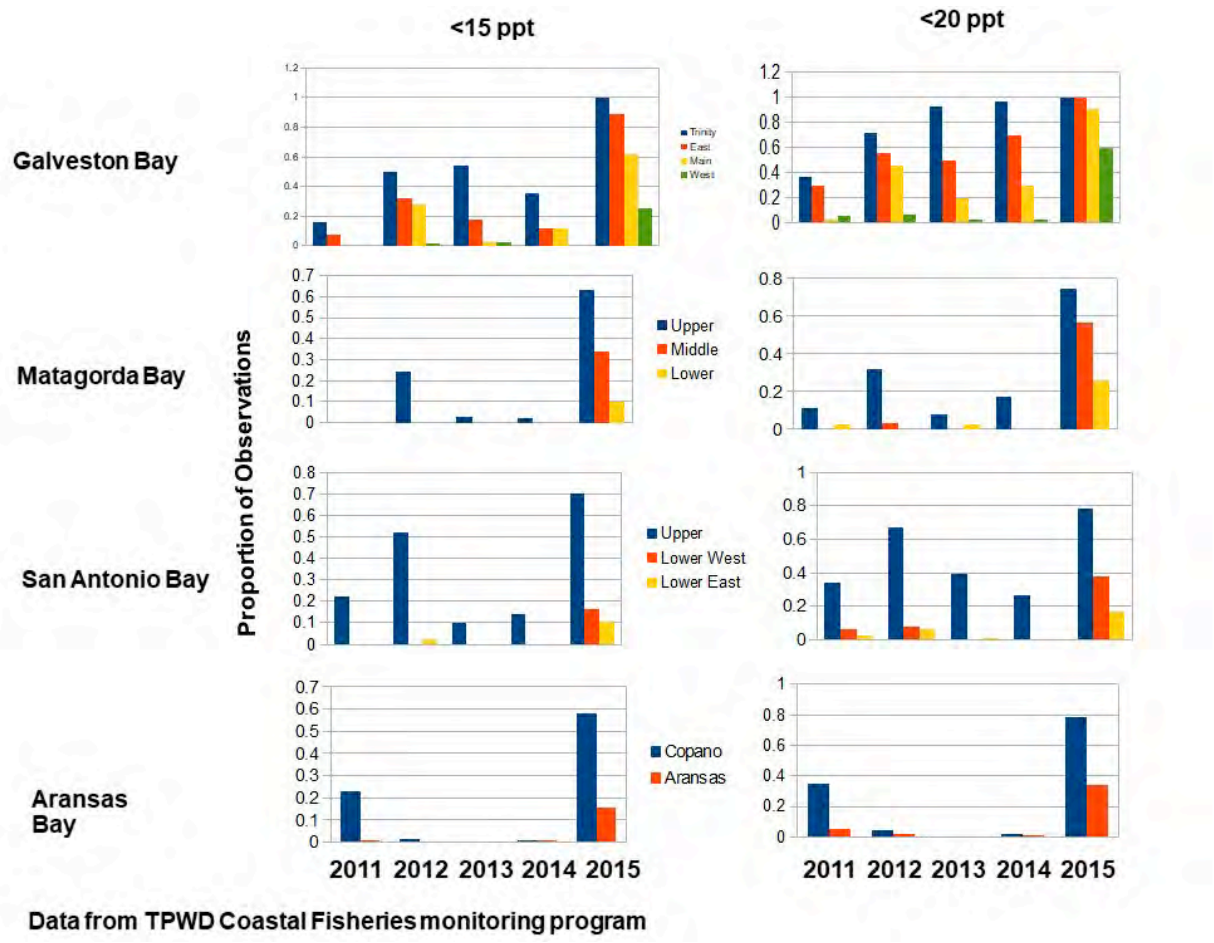

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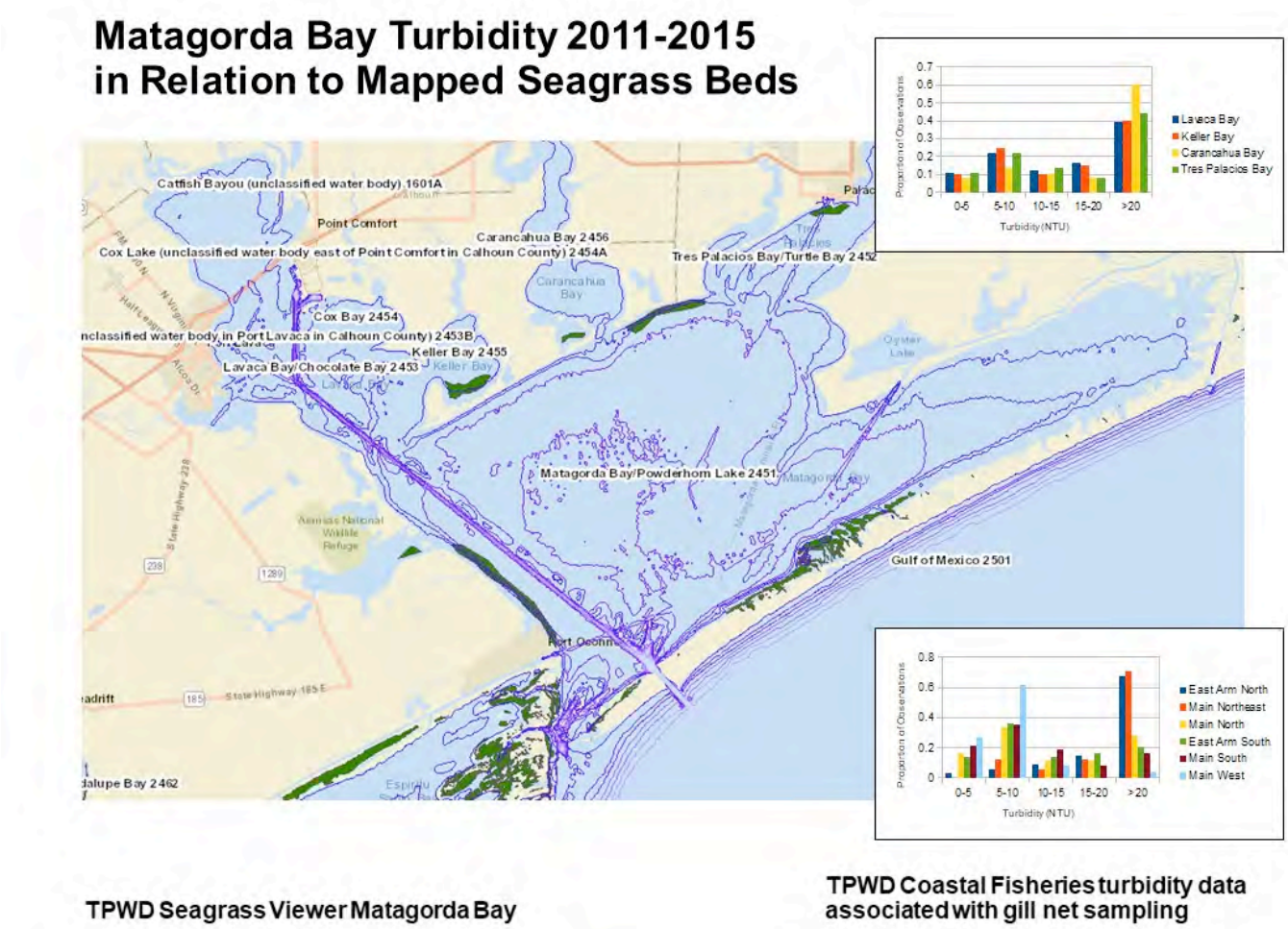

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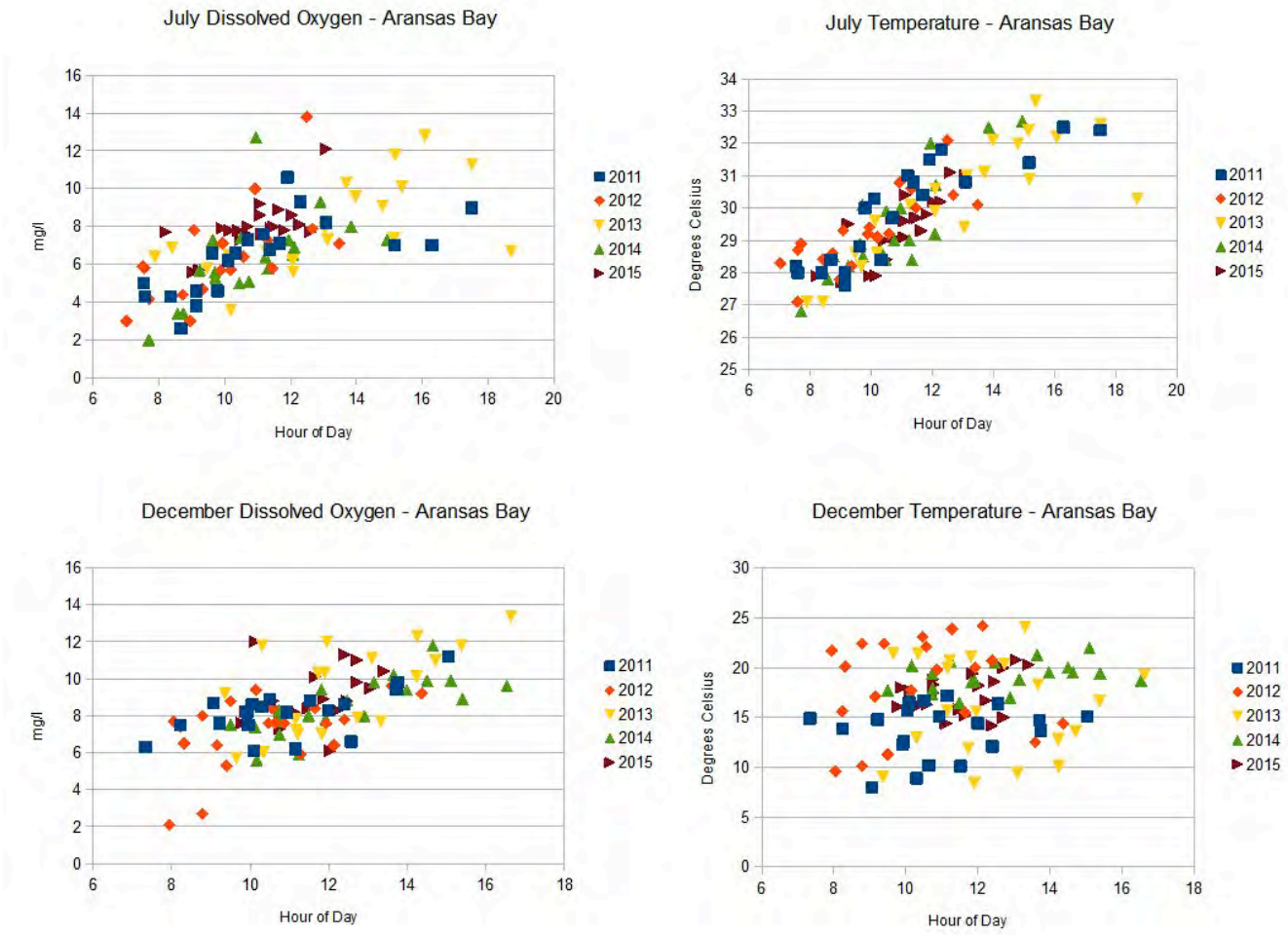

Figure 6. Dissolved oxygen and temperature in Aransas Bay.

Appendix 1. Extract from Onuf-Kuhn Email Exchange on Seagrass Mapping

From: Christopher Onuf
Sent: Monday, February 13
To: Nathan Kuhn, Texas Parks and Wildlife Department
Subject: Coast-wide Seagrass Mapping?

I am assisting with the seagrass component of Harte Institute's GOM ecohealth metrics initiative. At the moment, I'm evaluating proposed measures of Valued Ecosystem Components of seagrass meadows. At the top of the list is Areal Extent/Distribution; however, judging from your Seagrass Mapper and the 2014-2015 final report of Ken Dunton's MANERR to Lower Laguna Madre survey of seagrass cover and condition, the 2004/2007 NOAA Benthic Habitat Assessment was the last coast-wide seagrass mapping effort, yes? What happened to a 5-year or even 10-year mapping cycle as called (hoped) for in the Conservation Plan? Is there a new mapping effort scheduled or at least in planning? If not, I guess I have to rate this lynch pin for assessing the health of seagrasses as infeasible. Could you bring me up to speed about what is going on and what isn't?

Thanks, Chris

---------- Response ----------

From: **Nathan Kuhn**
Date: Mon, Feb 13, 2017
Subject: RE: Coast-wide Seagrass Mapping?
To: Christopher Onuf
Cc: Nathan Kuhn

Dear Chris,

You are correct that NOAA's mapping effort was the last large scale attempt to map seagrasses for most of the Texas coast. Aside from some recent mapping done to map the seagrasses in West Galveston (and Christmas) Bay (which is now in the Seagrass Viewer), and some ongoing prop scar studies at specific locations, I am not aware of any new mapping completed. (However, I think Ken has expanded his statewide monitoring protocol to cover every bay with seagrass now, which does provide at least a form of a map.)

The seagrass monitoring plan, which was an outgrowth of the Conservation Plan, did call for regular coast wide mapping on a 5 year interval. However, the funding is just not there (at least at the state level) to do that kind of coast wide mapping. I think the best we can hope for is to shoot for about a 10 year interval using grant funding as available.

For the last 6 months or so, I have been heading up a small group of interested individuals from the Seagrass workgroup and others (Warren, Larry Handley, Mark Finkbeiner, TNRIS, etc.) who have done seagrass or other mapping to look into what would be required to conduct another coast wide seagrass mapping effort for Texas. We have met a few times already and we are working through all

the details of how we would want to proceed with another statewide mapping effort if funds were available. After that, we may then start looking for (grant) funding to conduct a mapping effort.

FYI, Larry Handley is trying to pull together a meeting this year, I think, of seagrass mappers to try to record all of the knowledge that is out there, so if he hasn't contacted you already, he will probably be trying to pretty soon. (He has retired as well, but is doing this through GOMA and CNL World, where he works now).

Please let me know if you have any more questions.

Thanks, Nathan

III-3. Gulf of Mexico Ecological Health Report Card

Texas Oyster Supporting Documentation

Submitted by:

Jennifer Beseres Pollack, Ph.D.

Terrence A. Palmer, M.S.

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Introduction to Oysters in Texas

Eastern oysters, *Crassostrea virginica*, are conspicuous features of estuaries across the U.S. Gulf of Mexico and Atlantic coast. Oysters provide are ecologically and economically important. Traditionally, oysters were valued primarily as a fisheries commodity. However, their numerous ecological benefits are now widely recognized. As suspension feeders, oyster filter phytoplankton and other particles from bay waters, and can benefit submerged aquatic vegetation by increasing light penetration. As reef-builders, oysters create habitat for fish and crustaceans, and support economically important fishery stocks through the provision of prey species. Oyster reefs can also serve as a living breakwater, reducing wave energy, stabilizing sediments, and protecting estuarine habitats such as marsh and seagrass. Oysters in the Gulf of Mexico provide over half of the nation's harvest, and Texas contributes the second-largest amount, after Louisiana.

Oysters in Texas live primarily on subtidal (continuously submerged) reefs in estuaries that lie along a climatic and salinity gradient, with cooler and wetter conditions in the northeast and warmer and drier conditions in the southwest. Because they are relatively long-lived, immobile once set, and display predictable responses to stress, oysters are valued bioindicators of change in coastal ecosystems. A broad understanding of the status of oyster populations in Texas can provide key insights into overall bay health.

Oyster populations in the Gulf of Mexico and worldwide have experienced substantial reductions over the past century, with habitat loss attributed to water quality degradation, resource overharvest, disease, and sedimentation. Habitat restoration efforts have increased in recent years, both number and in scale, and have addressed a broad range of benefits above those solely of fishery harvest. In Texas, restoration efforts have been largely successful due to the existence of natural oyster populations that can produce larvae to seed new reefs, as well as year-round warm waters that promote oyster growth. These characteristics support resilience and rapid recovery of oyster populations following disturbance and increase the success of habitat restoration efforts.

Texas Estuary Locations and Nomenclature

Table 1. Standard estuary and bay names of Texas estuaries (ordered north to south)

Estuary	Major Area/Bay	Bay
Sabine-Neches	Sabine Lake	Sabine Lake
Trinity-Jacinto	Galveston Bay	East Galveston Bay
		Lower Galveston Bay
		Trinity Bay
		Upper Galveston Bay
		West Galveston Bay
Cedar Lakes	Cedar Lakes	Cow Trap Lake
East Matagorda	East Matagorda	East Matagorda Bay
Lavaca-Colorado	Matagorda Bay	Lavaca Bay
		Matagorda Bay
Guadalupe	San Antonio Bay	Espiritu Santo Bay
		San Antonio Bay
Mission-Aransas	Aransas Bay	Aransas Bay
		Copano Bay
		Mesquite Bay
Nueces	Corpus Christi Bay	Corpus Christi Bay
		Nueces Bay
Laguna Madre	Laguna Madre	Lower Laguna Madre
		Upper Laguna Madre

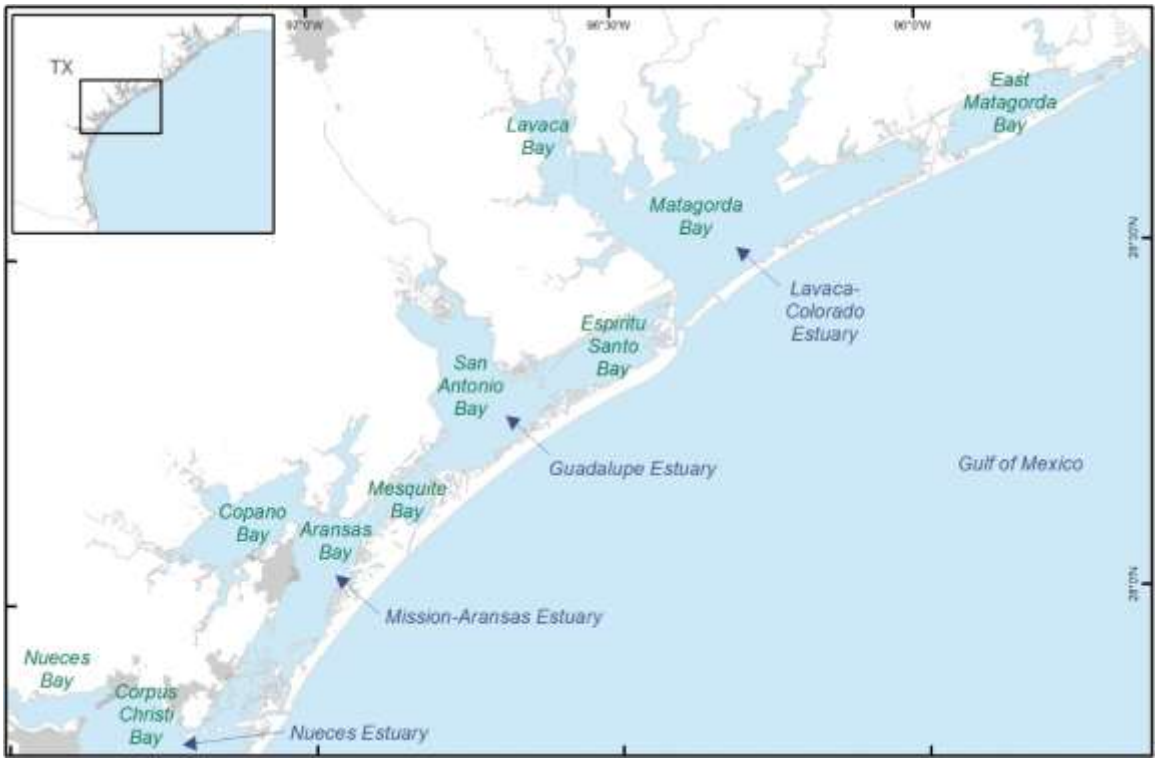

Figure 1. Texas Estuary and Bay names in the mid-Texas coast

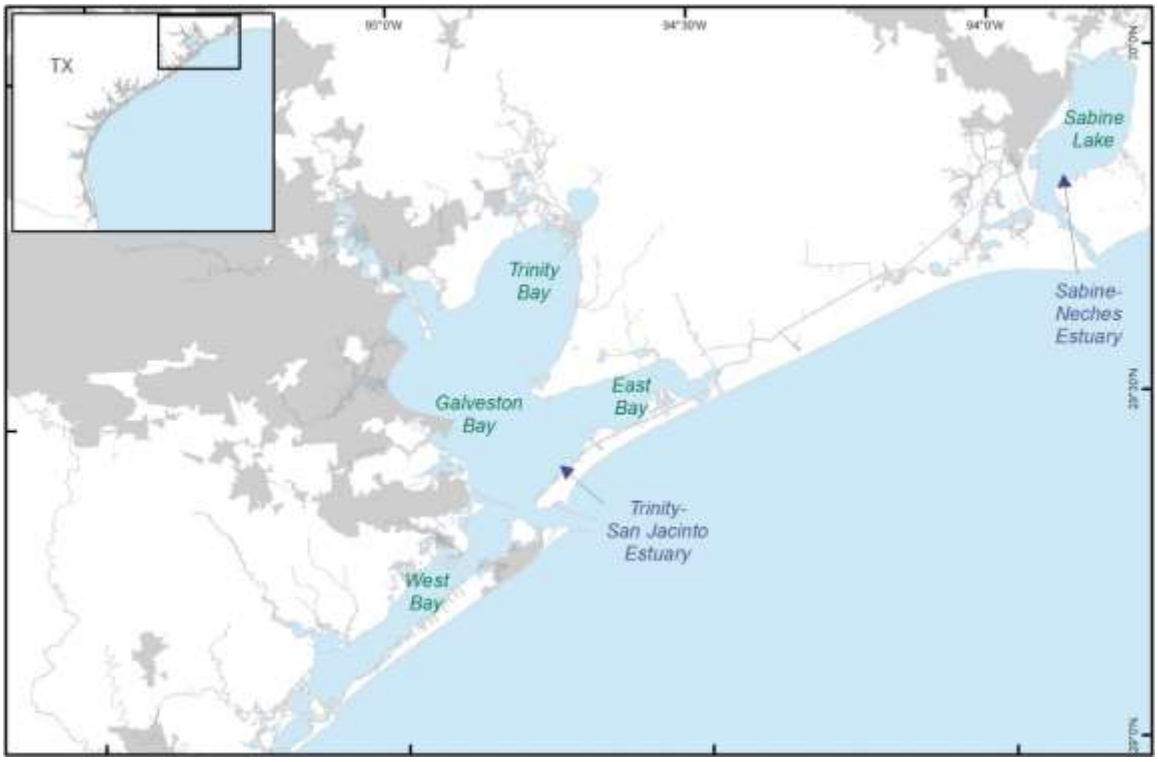

Figure 2. Texas Estuary and Bay names in the upper-Texas coast

Commercial Fisheries Landings

Oyster fishery landings data were obtained from Texas Parks and Wildlife Department (TPWD). These data include the amounts (sacks, barrels) and estimated live weights of landings by commercial oyster fishermen. The live weights were summed by year for each bay to give an annual yield in live weight/year and plotted.

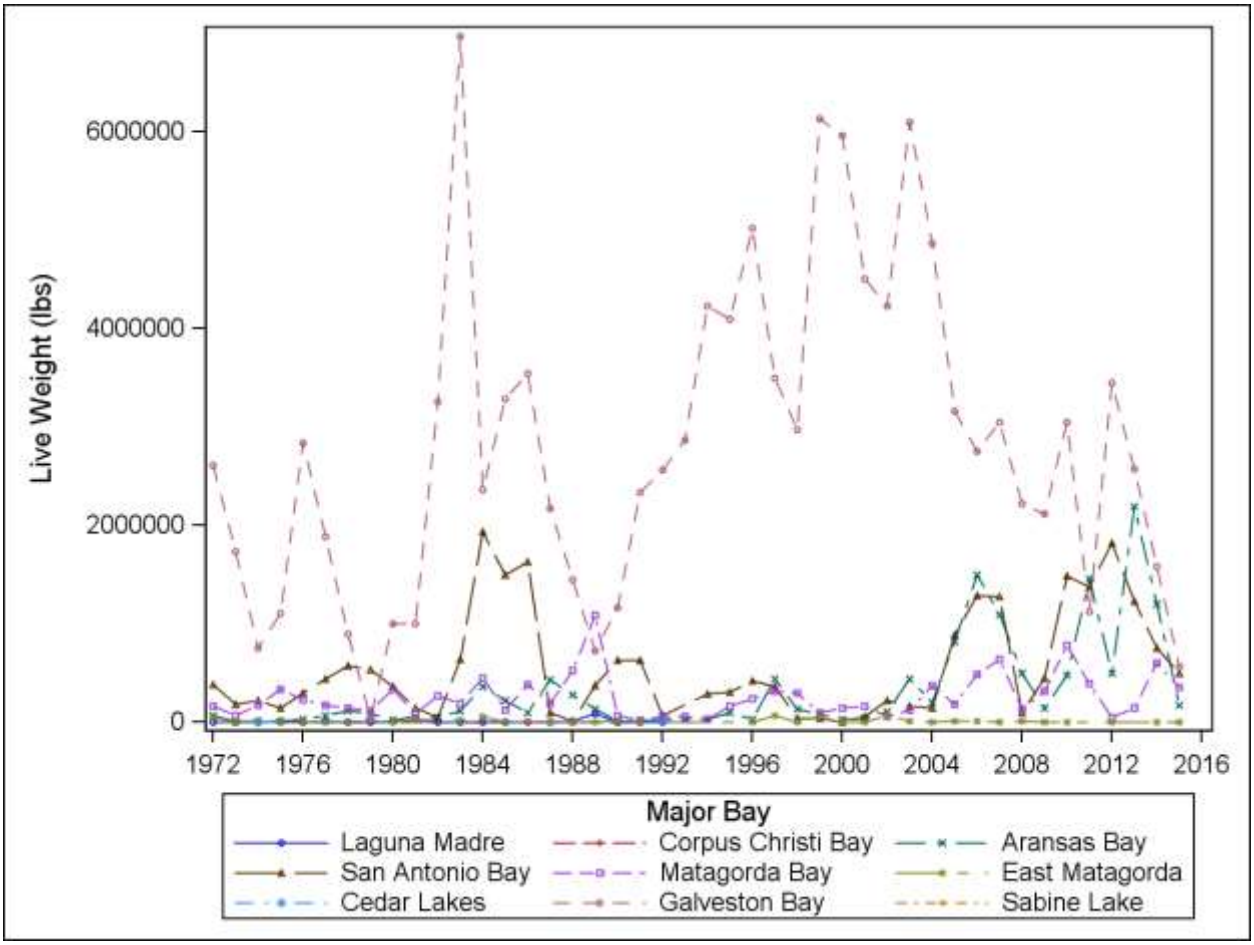

Figure 3. Annual weight of oysters landed by commercial fisherman in each Texas Estuary

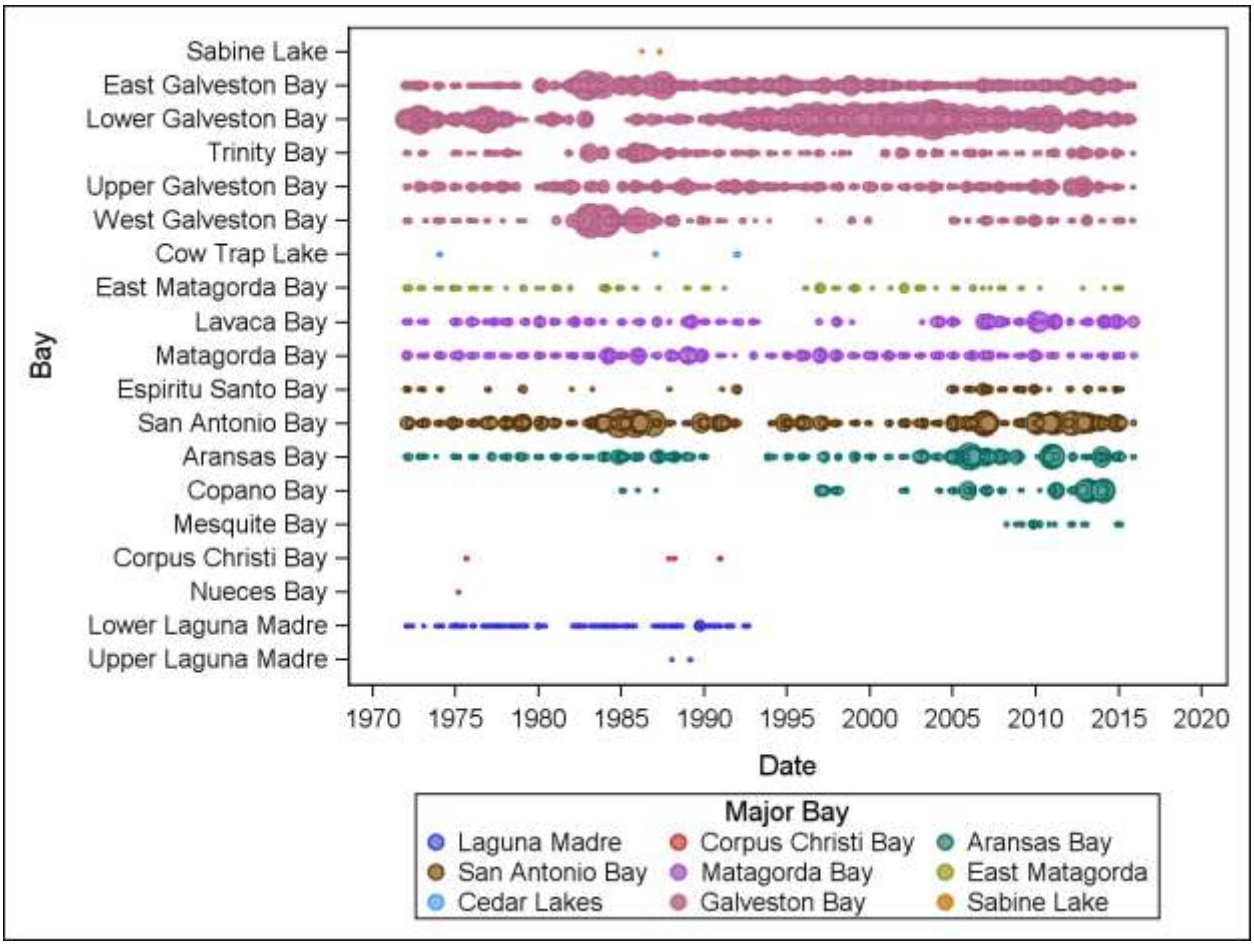

Figure 4. Annual commercial oyster landings in each Texas Bay. The size of each bubble is proportional to the live weight landed in each year. Different colors indicate the different estuaries where each bay is located.

TPWD Fisheries Independent Monitoring Program

Oyster sampling in each major oyster-producing Texas estuary (Guadalupe, Mission-Aransas, Lavaca-Colorado, Sabine-Neches, and Trinity-San Jacinto Estuaries) has been conducted by TPWD using a standardized fishery-independent monitoring program (FIMP) since 1986 (Martinez-Andrade et al., 2005). The FIMP generally utilizes a stratified-random sampling design whereby ten stations from each major bay are sampled twice a month. Sampling at each station occurs by towing a 0.5 m wide dredge linearly for 30 s. No oysters have been sampled as part of the TPWD FIMP south of the Mission-Aransas Estuary.

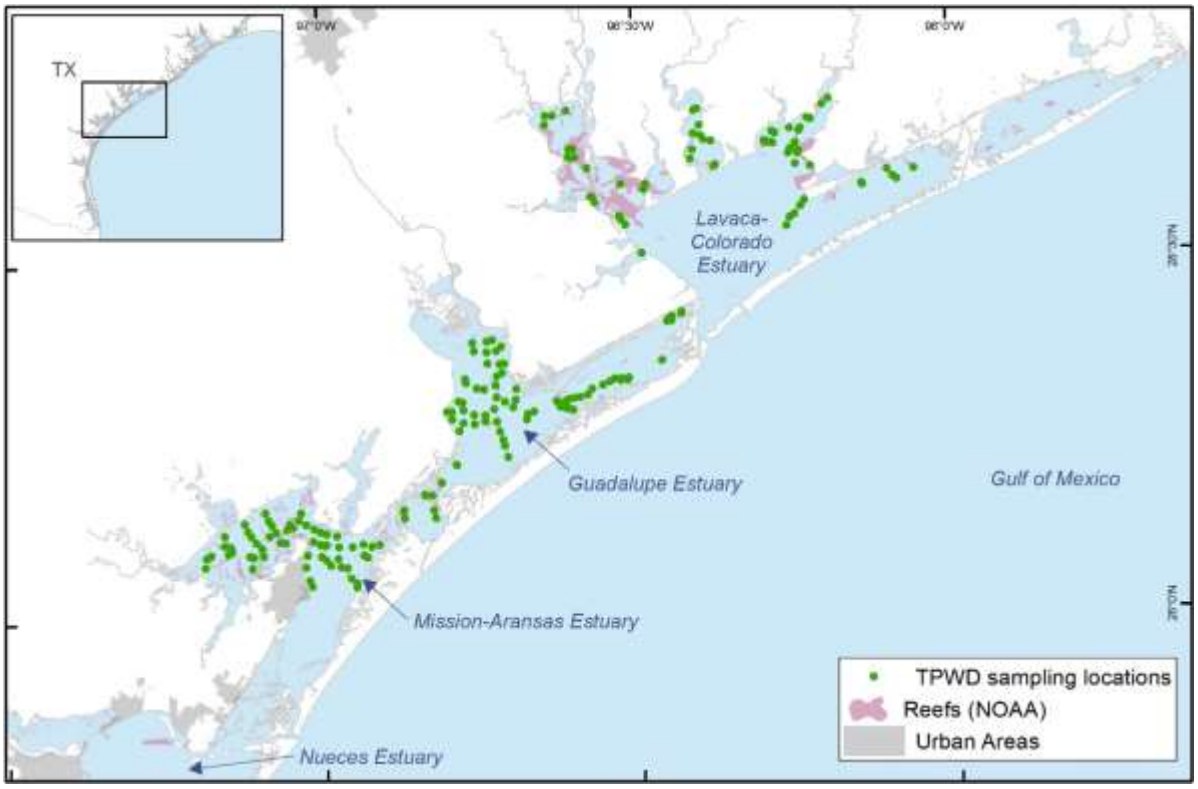

Figure 5. Locations of stations sampled in TPWD fisheries independent monitoring program: Mid-Texas coast

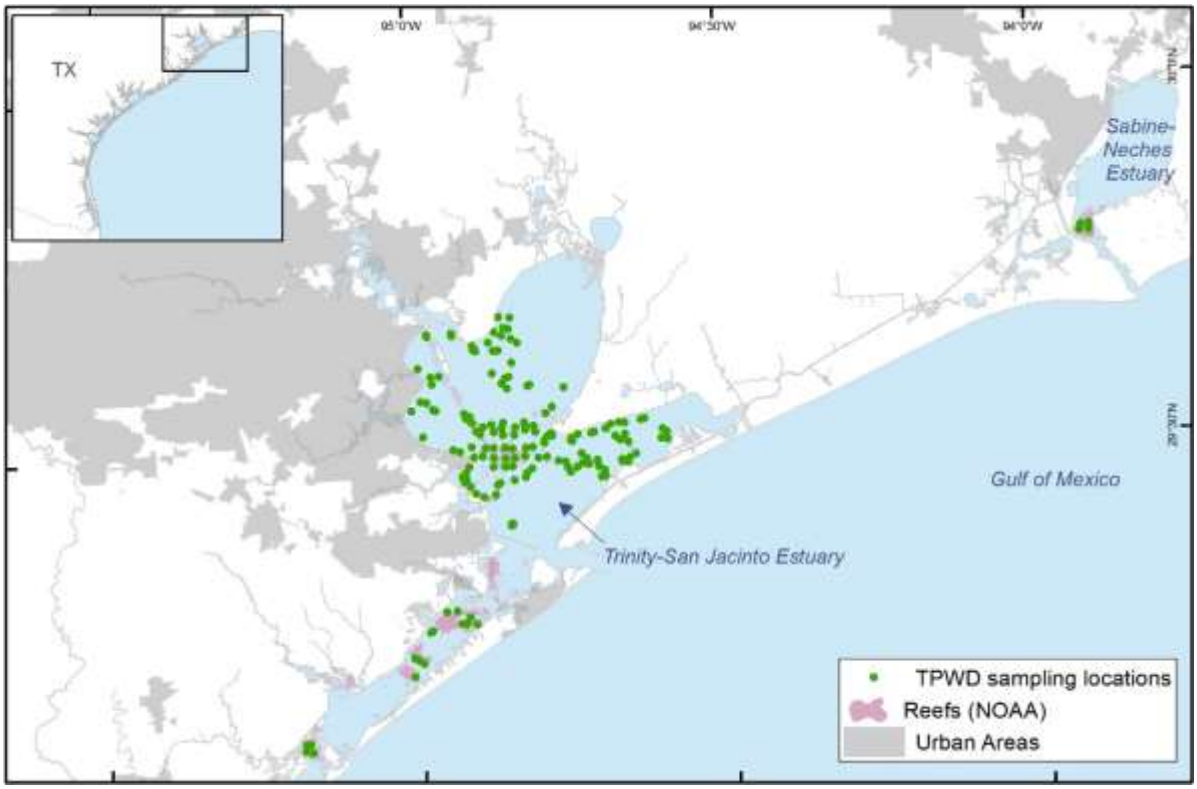

Figure 6.. Locations of stations sampled in TPWD fisheries independent monitoring program: Upper-Texas coast

Time Series: Water Quality

Salinity, temperature, dissolved oxygen concentration, and turbidity were measured at the bottom of the water column each time the oyster dredge was pulled. These variables were averaged by month and then by year for each estuary. Time series line plots and bubble plots were created for all estuaries (Figure 7 to Figure 13).

Salinity

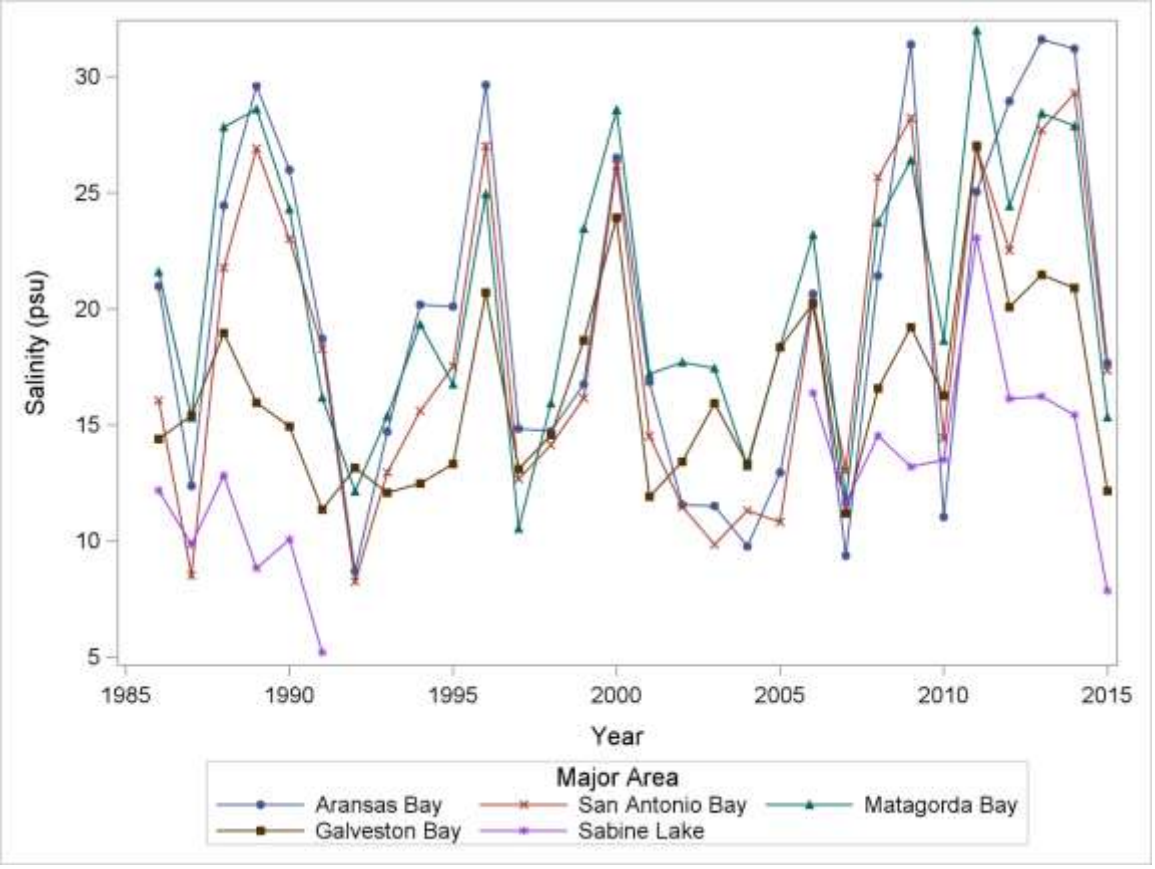

Figure 7. Line plot of mean annual salinity in each estuary from 1986 to 2015

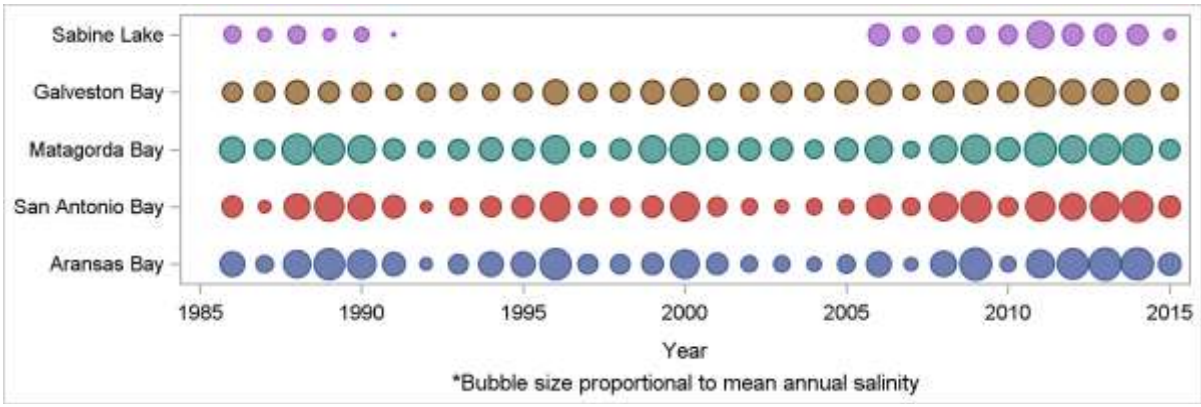

Figure 8. Bubble plot of mean annual salinity in each estuary from 1986 to 2015

Temperature

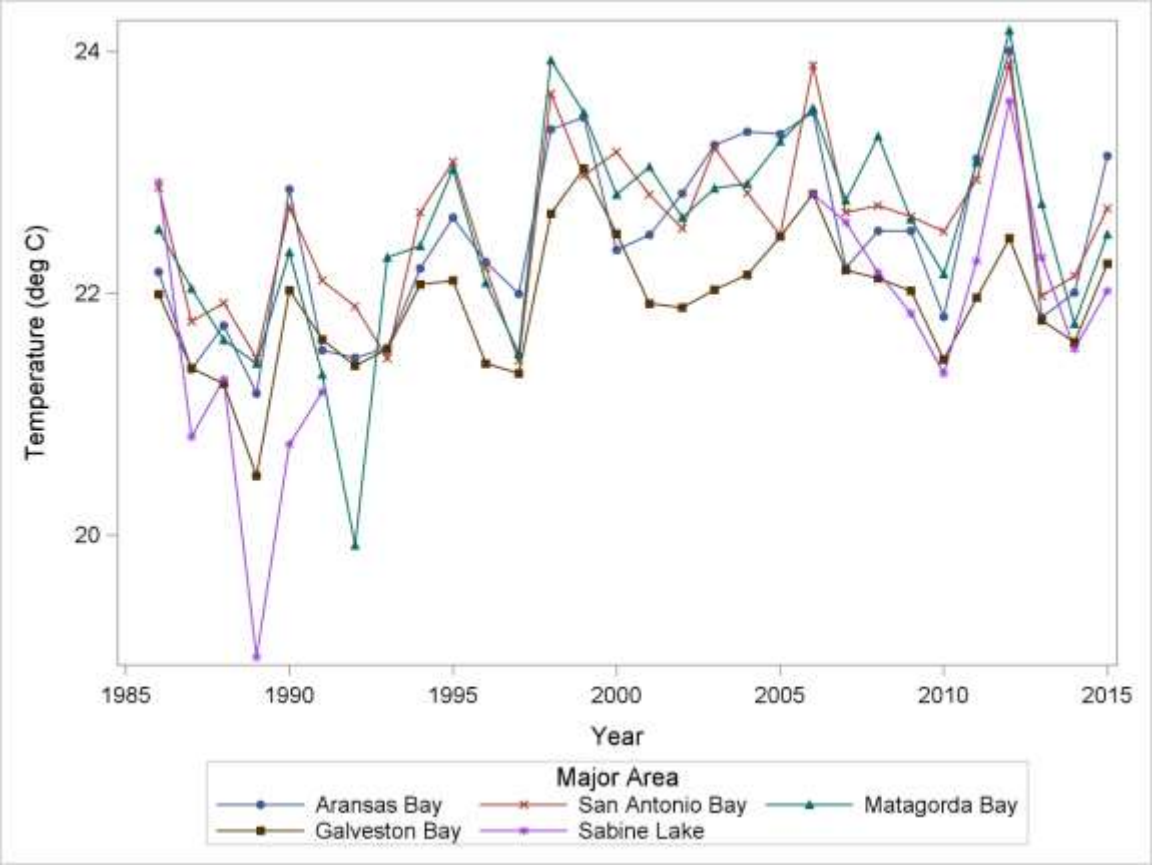

Figure 9. Line plot of mean annual water temperature in each estuary from 1986 to 2015

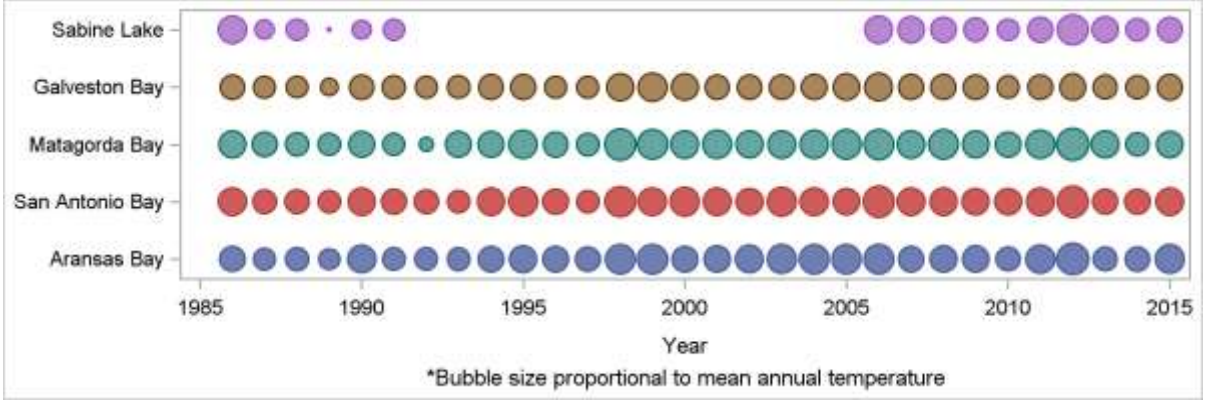

Figure 10. Bubble plot of mean annual water temperature in each estuary from 1986 to 2015

Dissolved Oxygen

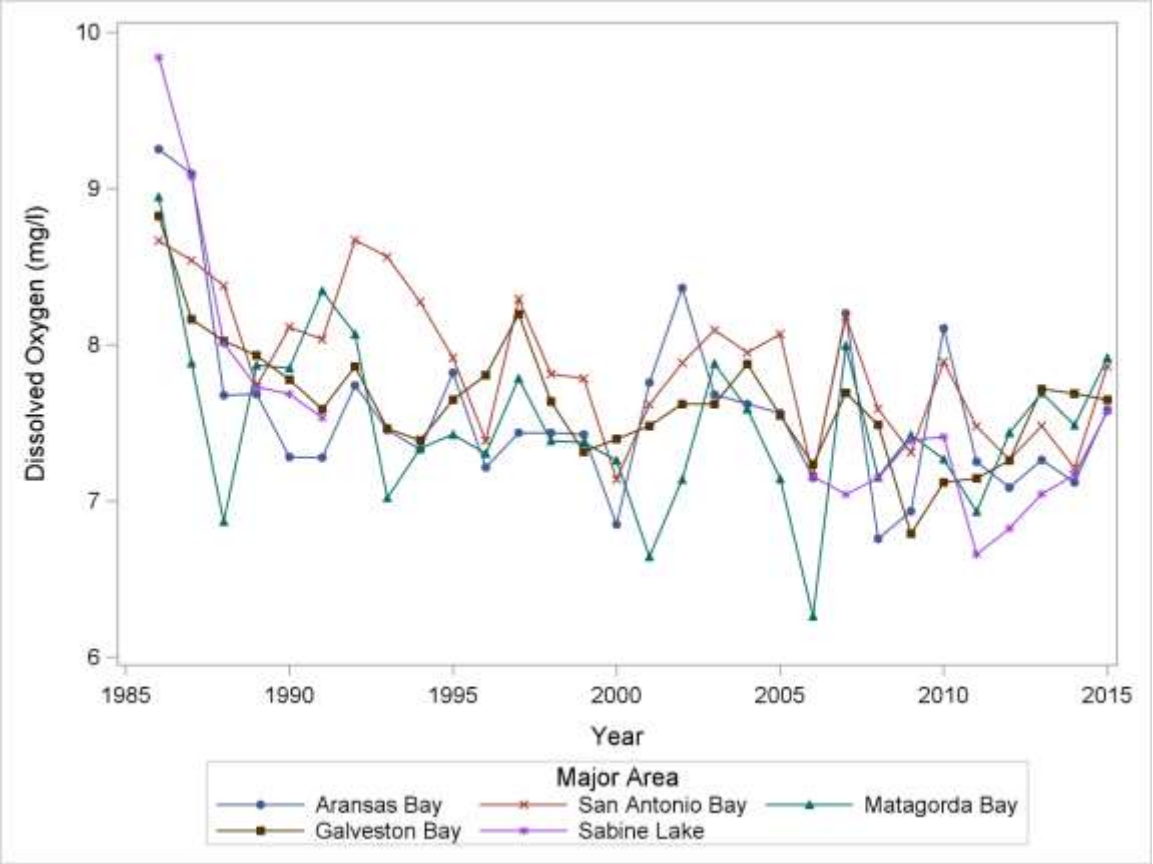

Figure 11. Line plot of mean dissolved oxygen concentration in each estuary from 1986 to 2015

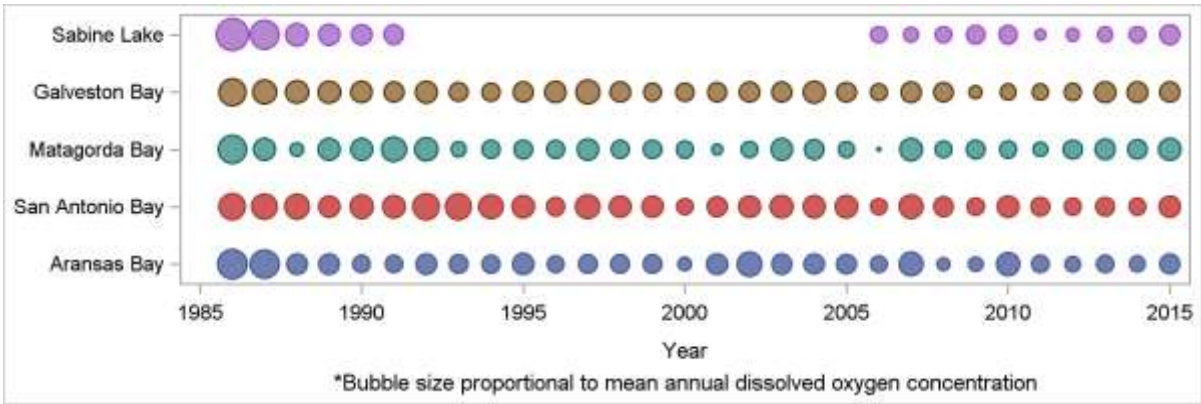

Figure 12. Bubble plot of mean dissolved oxygen concentration in each estuary from 1986 to 2015

Turbidity

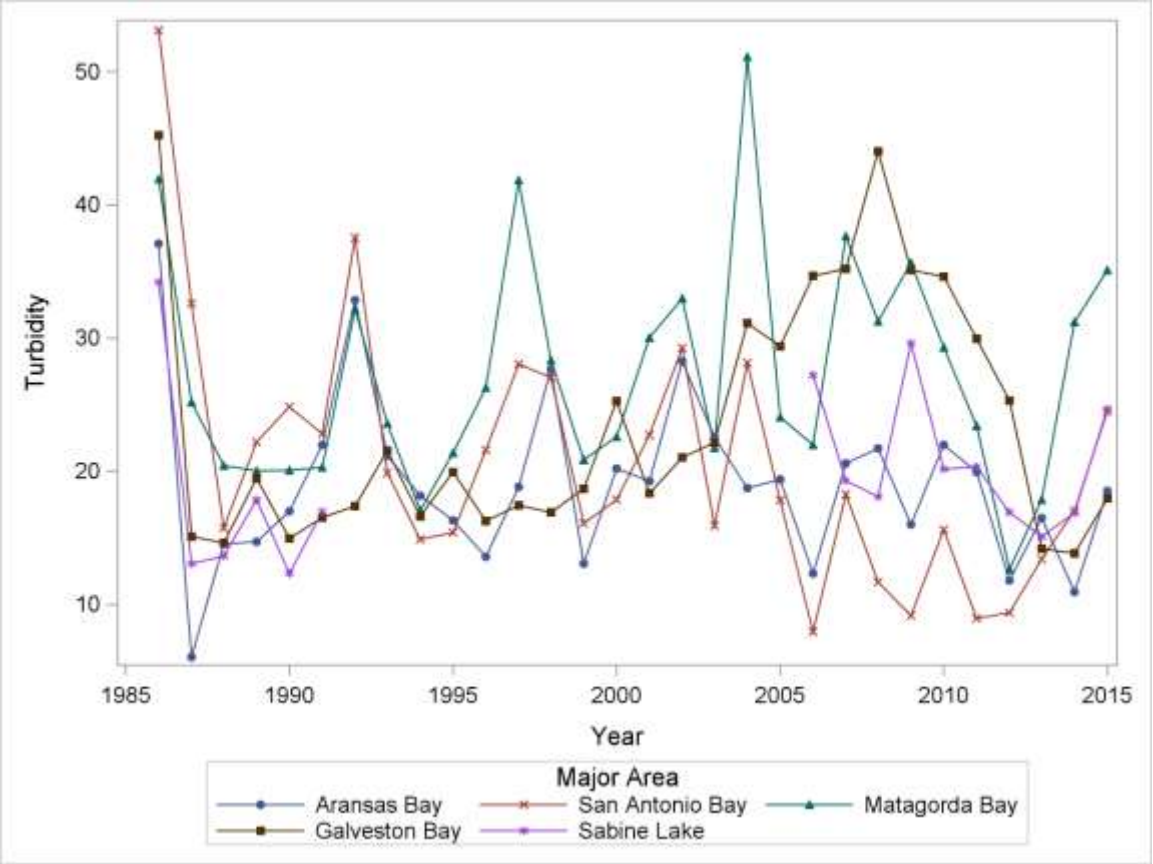

Figure 13. Line plot of mean turbidity in each estuary from 1986 to 2015

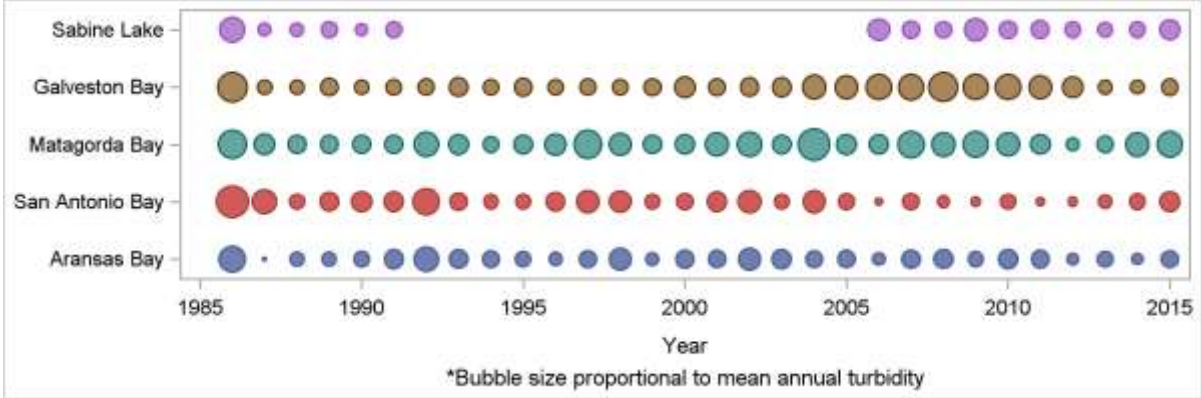

Figure 14. Bubble plot of mean turbidity in each estuary from 1986 to 2015

Time Series: Oysters

Live oyster abundance was determined by summing the number of oysters caught in each pull of the dredge to determine the number of oysters caught per 30-s tow (including instances where no oysters were caught). Abundances were averaged by month and then year to determine the annual mean catch per unit effort (CPUE) per estuary or bay (depending on the spatial detail being investigated).

Abundance Among Estuaries

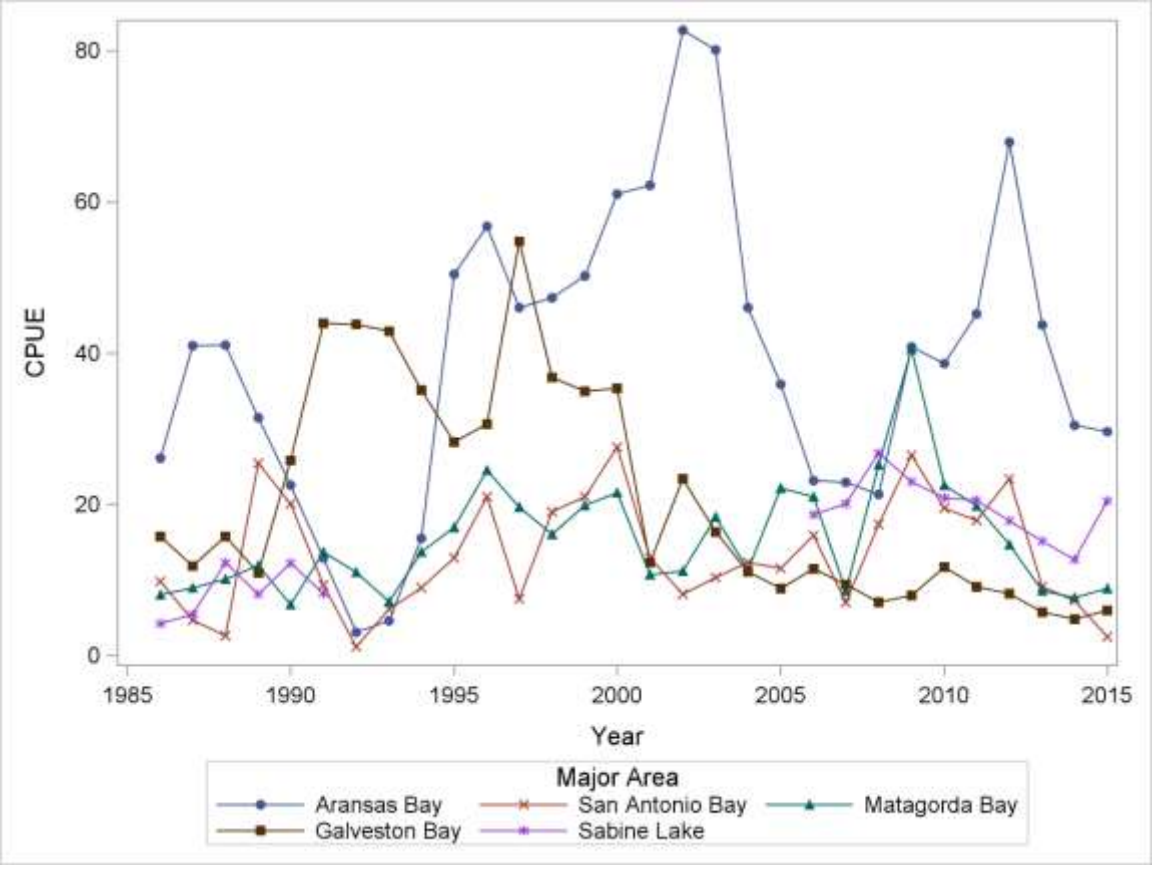

Figure 15. Line plot of mean oyster catch per unit effort (CPUE) in each estuary from 1986 to 2015

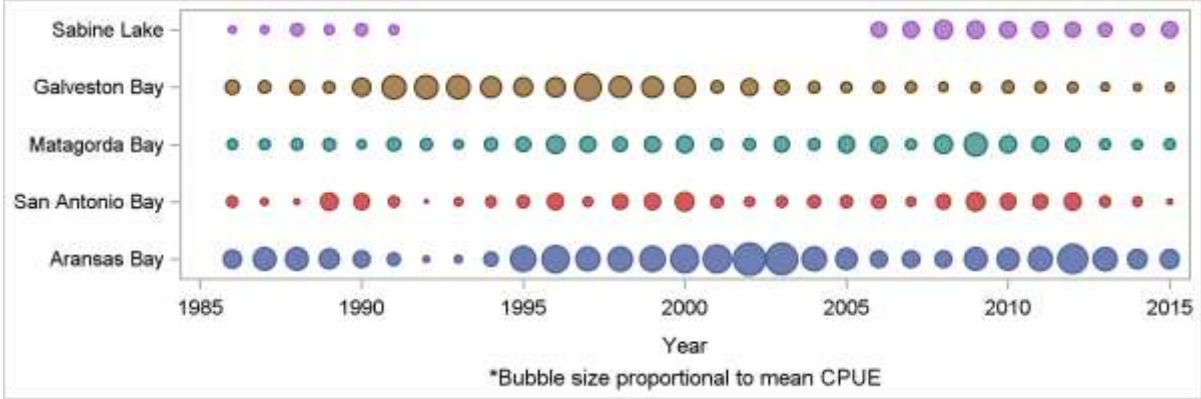

Figure 16. Bubble plot of mean oyster catch per unit effort (CPUE) in each estuary from 1986 to 2015

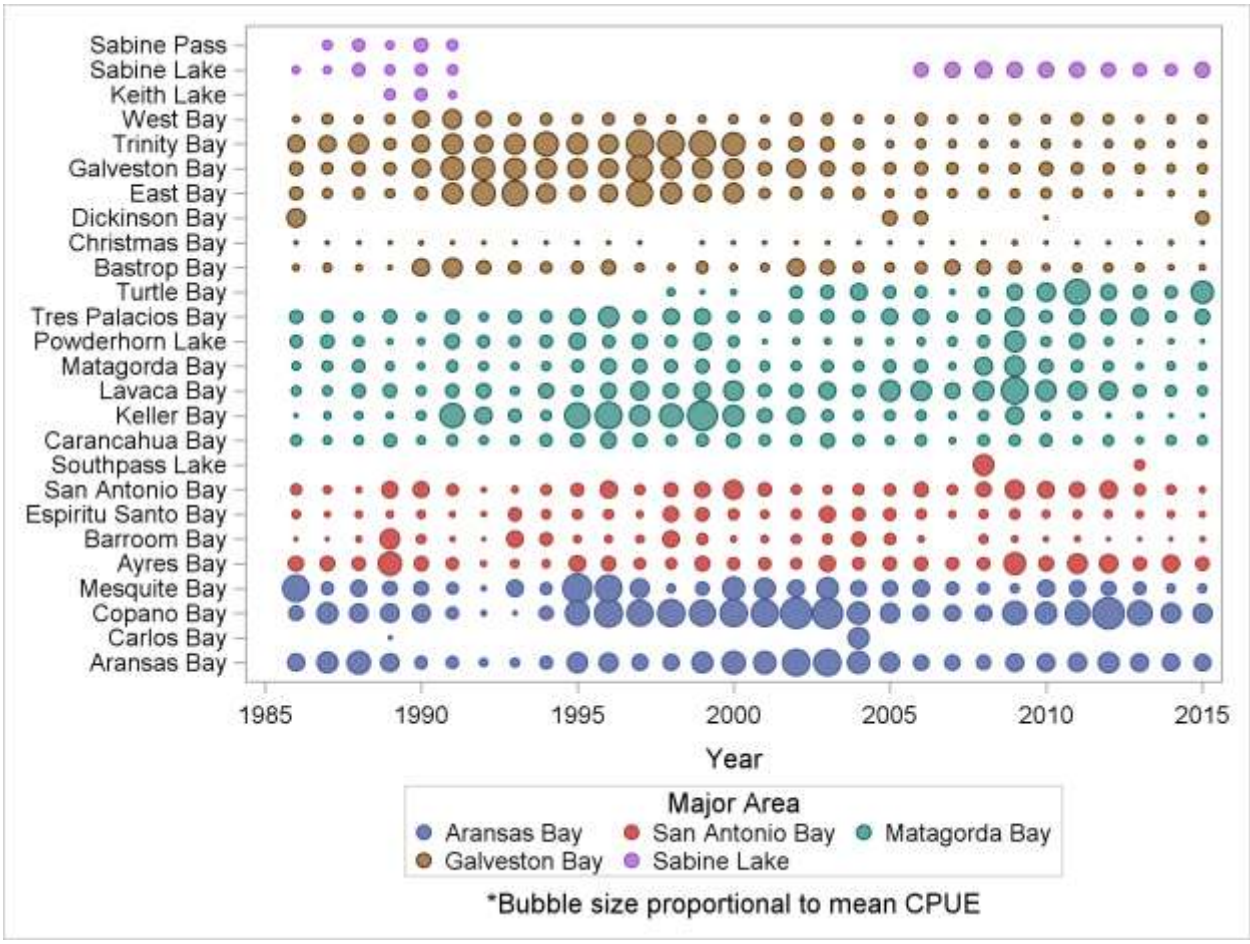

Figure 17. Bubble plot of mean oyster catch per unit effort (CPUE) within and among estuaries from 1986 to 2015

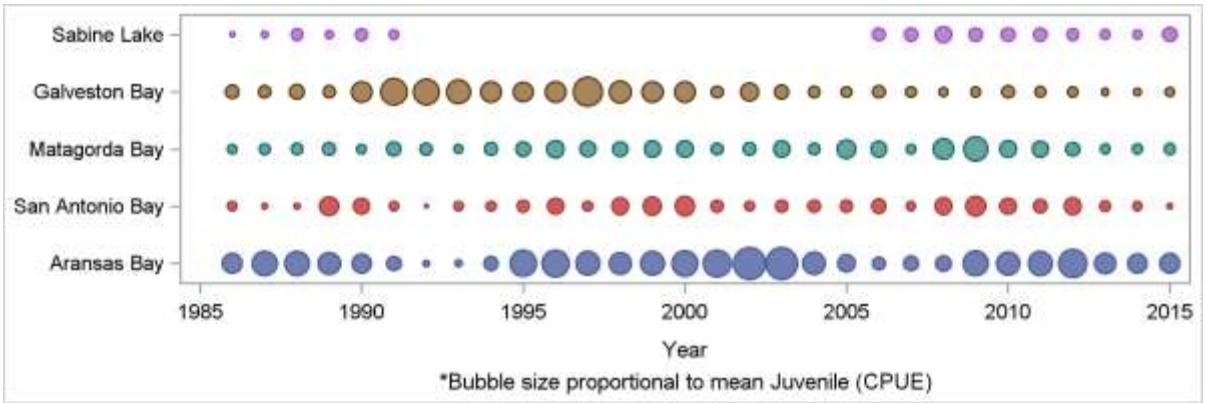

Figure 18. Bubble plot of mean Juvenile (25 < x <76 mm) oyster catch per unit effort (CPUE) among estuaries from 1986 to 2015

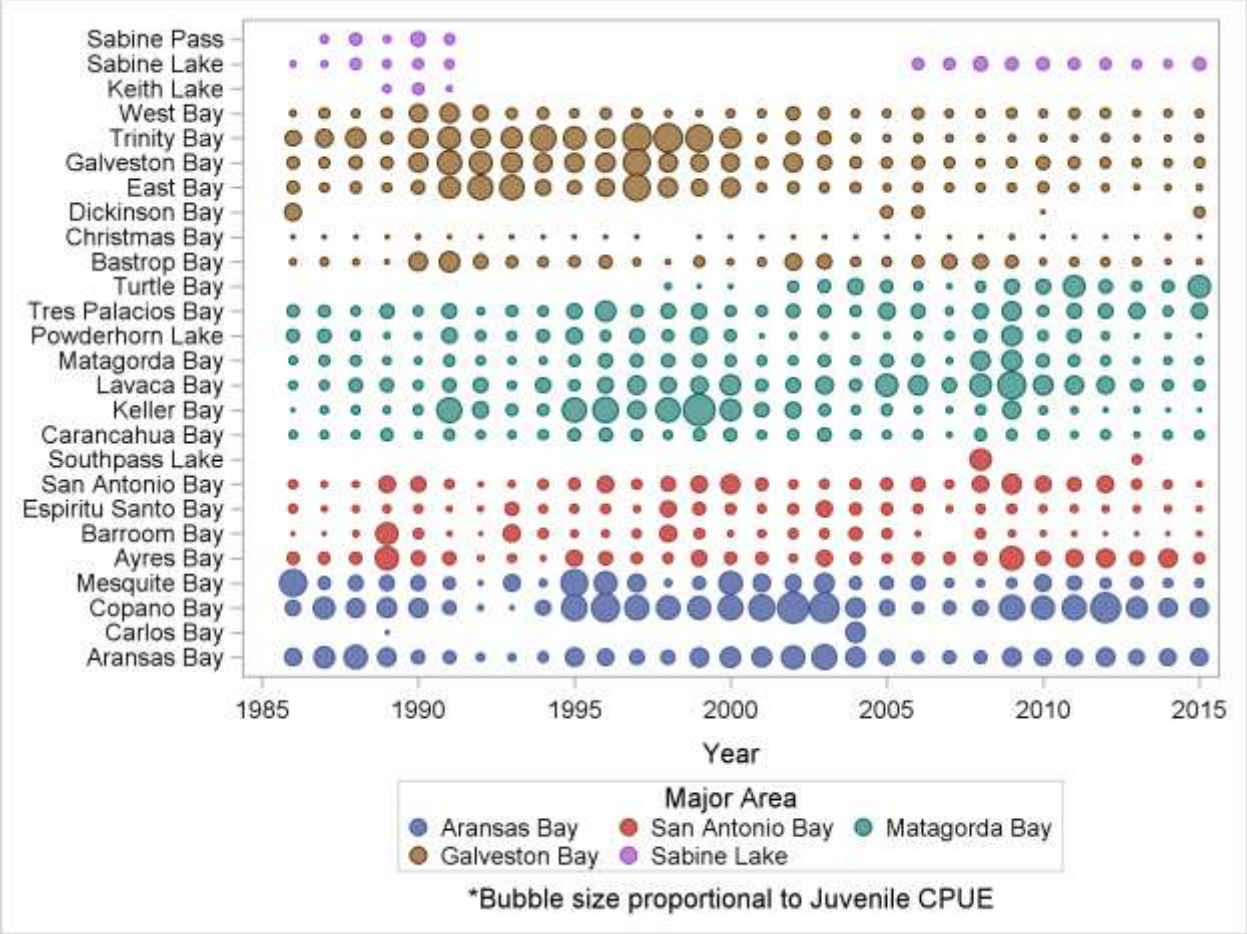

Figure 19. Bubble plot of mean Juvenile (25 < x <76 mm) oyster catch per unit effort (CPUE) within and among estuaries from 1986 to 2015

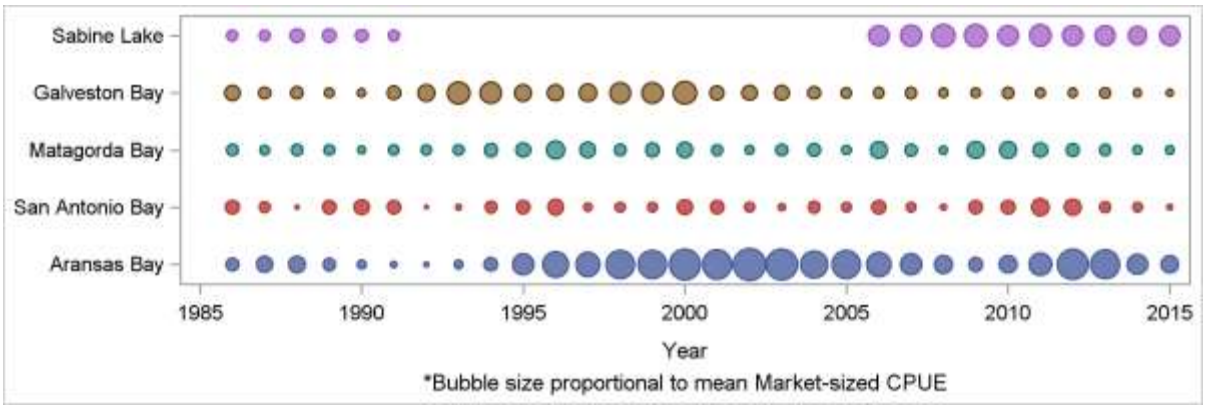

Figure 20. Bubble plot of mean Market-sized (≥75 mm) oyster catch per unit effort (CPUE) among estuaries from 1986 to 2015

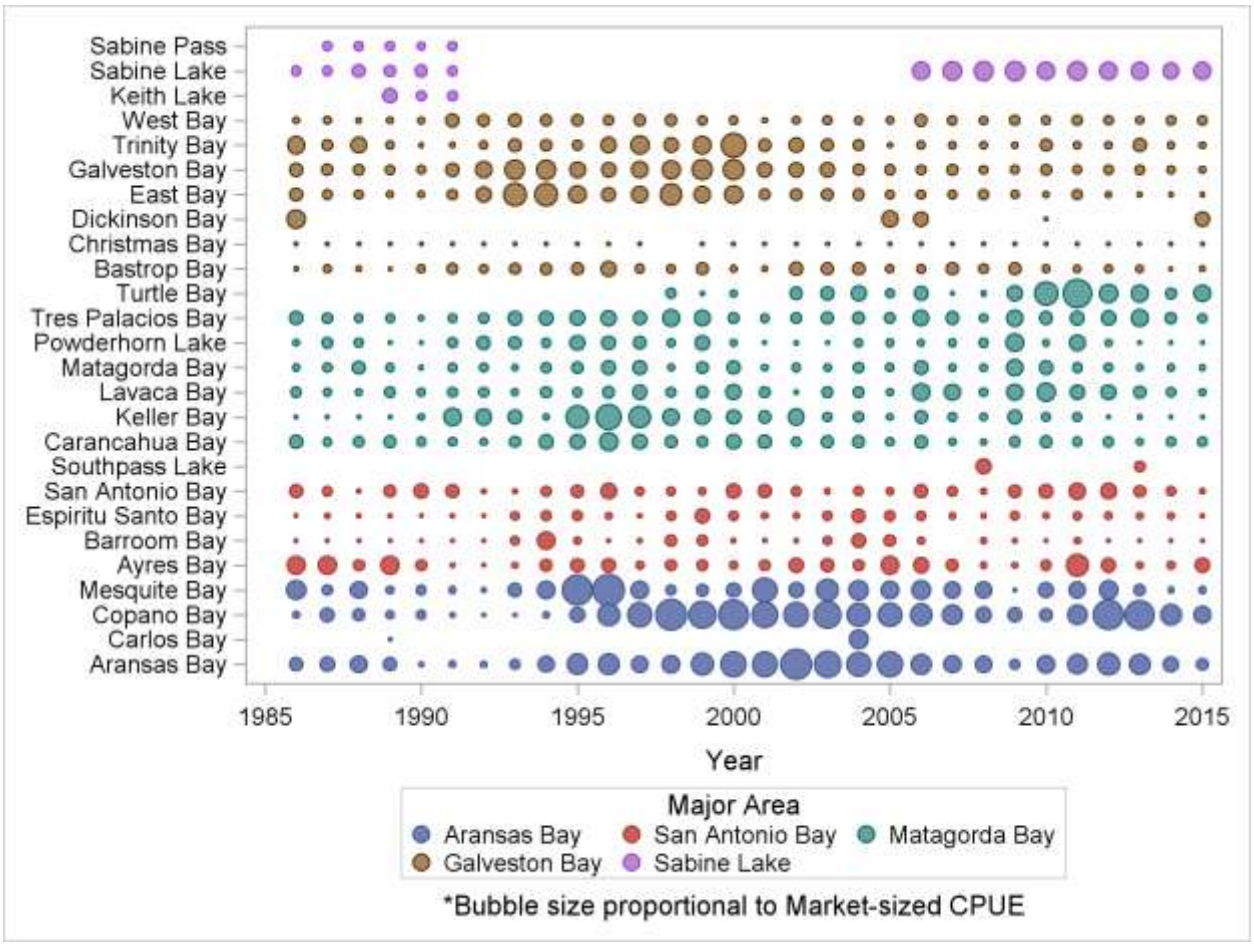

Figure 21. Bubble plot of mean Market-sized (≥75 mm) oyster catch per unit effort (CPUE) within and among estuaries from 1986 to 2015

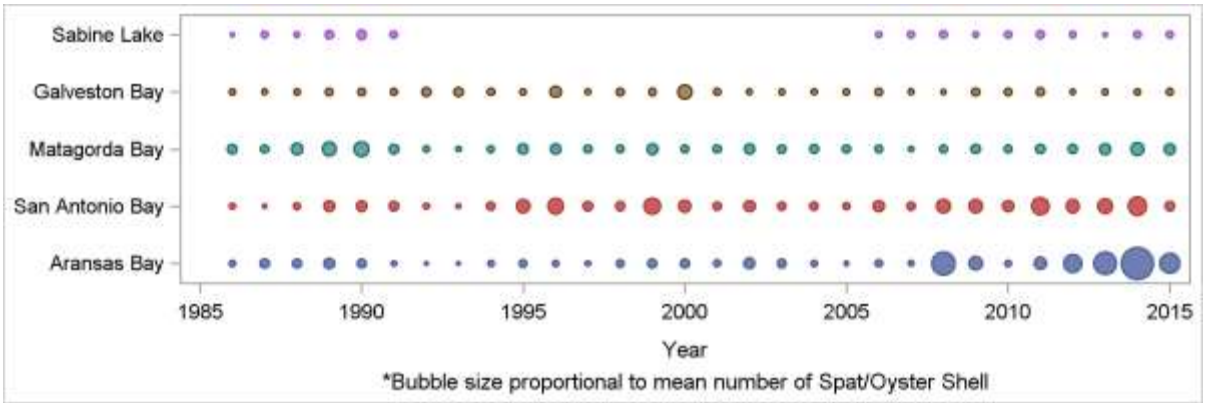

Figure 22. Bubble plot of spat caught (per oyster shell) among estuaries from 1986 to 2015

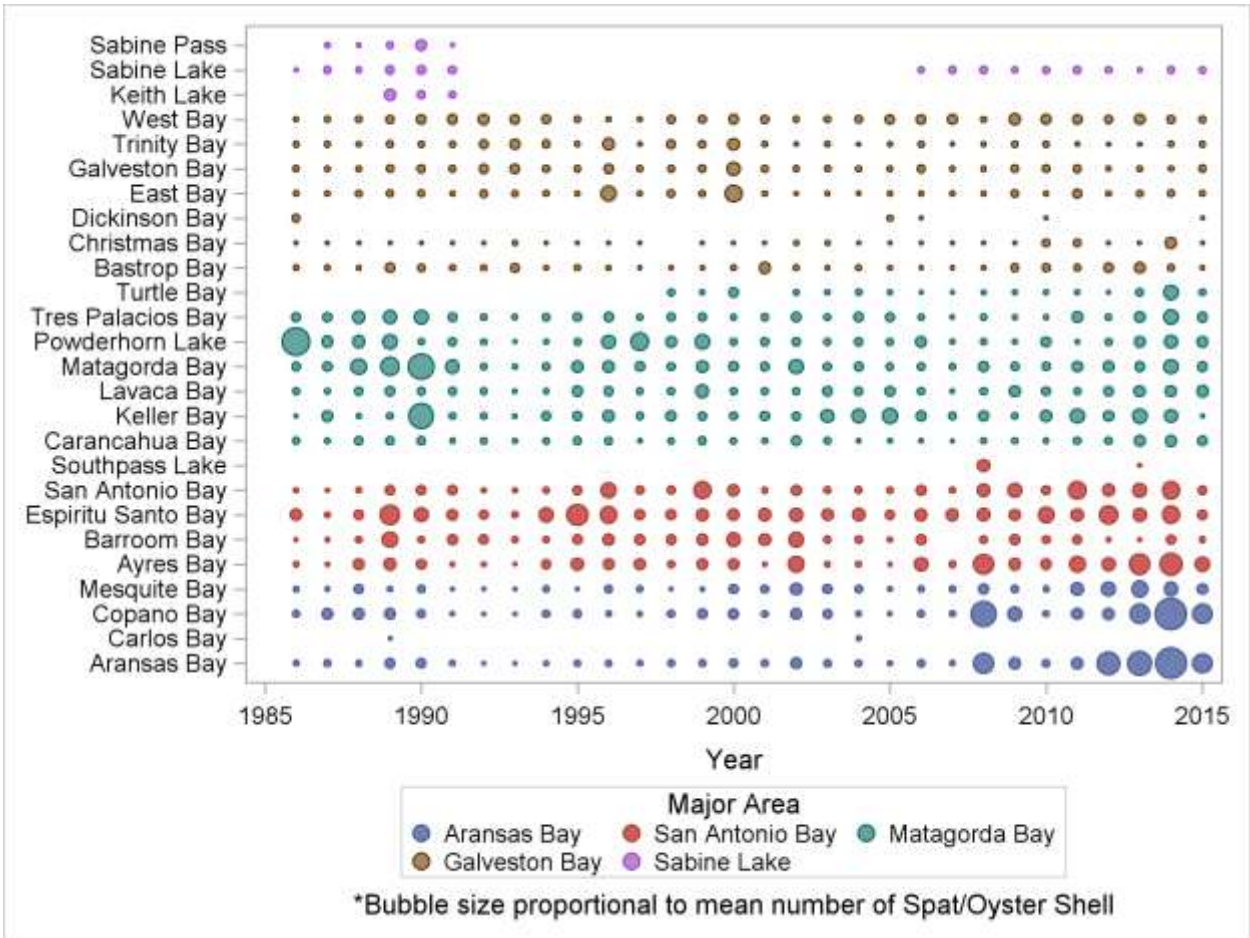

Figure 23. Bubble plot of spat caught (per oyster shell) within and among estuaries from 1986 to 2015

Abundance Within Estuaries

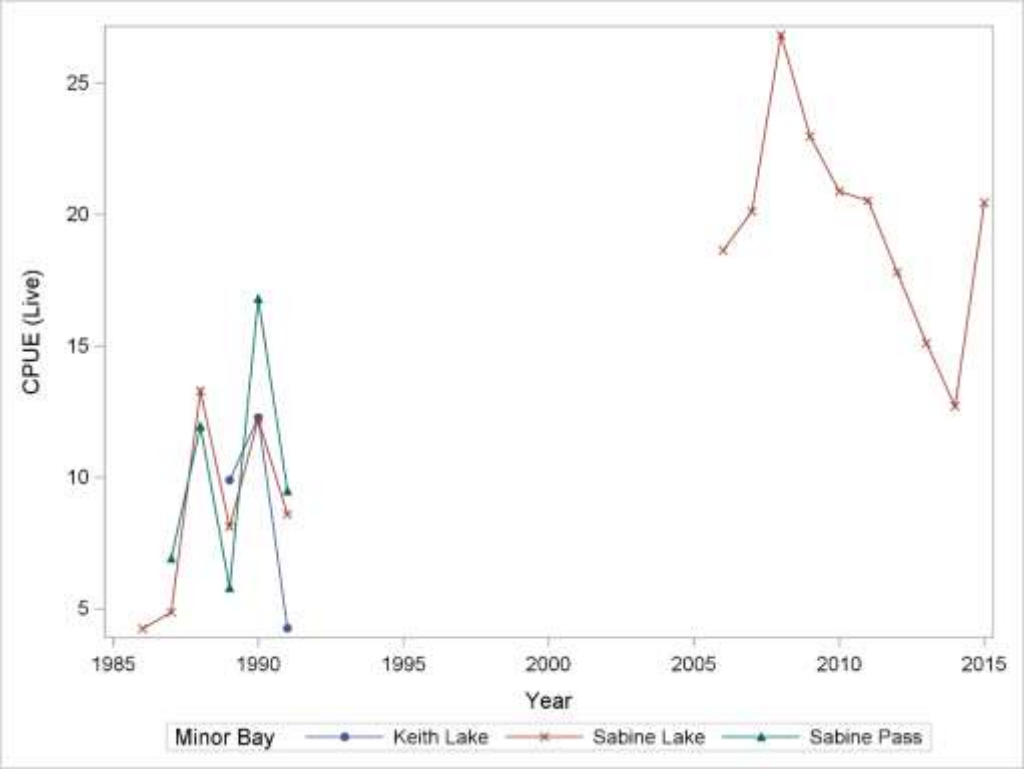

Figure 24. Line plot of mean oyster catch per unit effort (CPUE) in the Sabine-Neches Estuary from 1986 to 2015

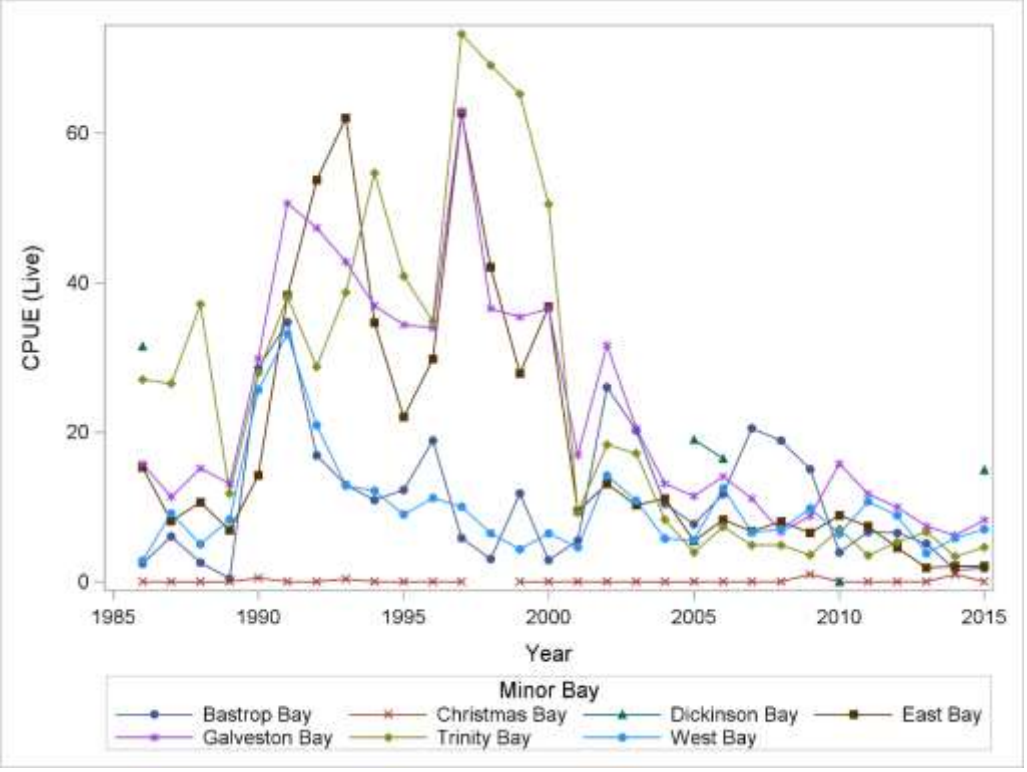

Figure 25. Line plot of mean oyster catch per unit effort (CPUE) in the Trinity-Jacinto Estuary from 1986 to 2015

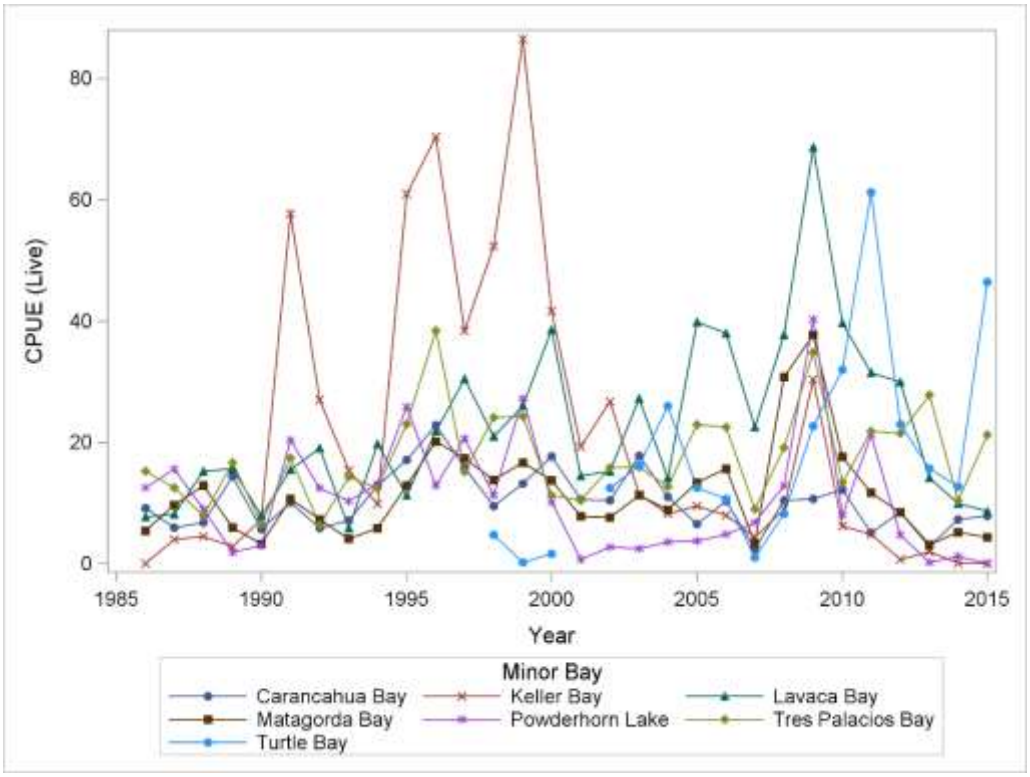

Figure 26. Line plot of mean oyster catch per unit effort (CPUE) in the Lavaca-Colorado Estuary from 1986 to 2015

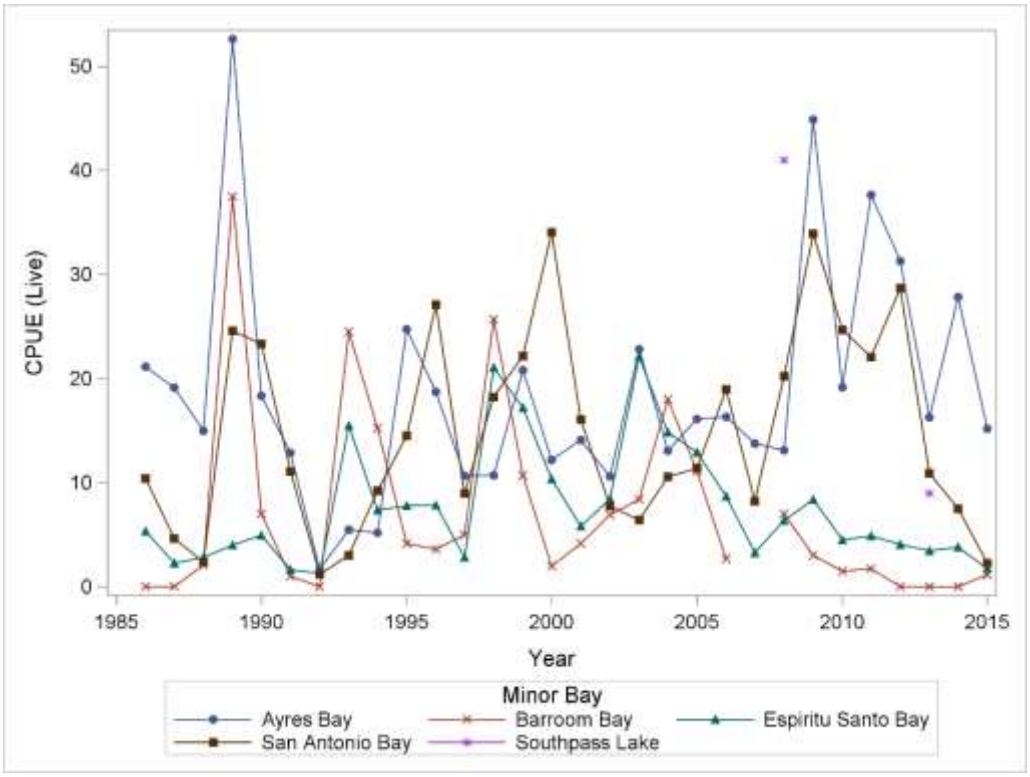

Figure 27. Line plot of mean oyster catch per unit effort (CPUE) in the Guadalupe Estuary from 1986 to 2015

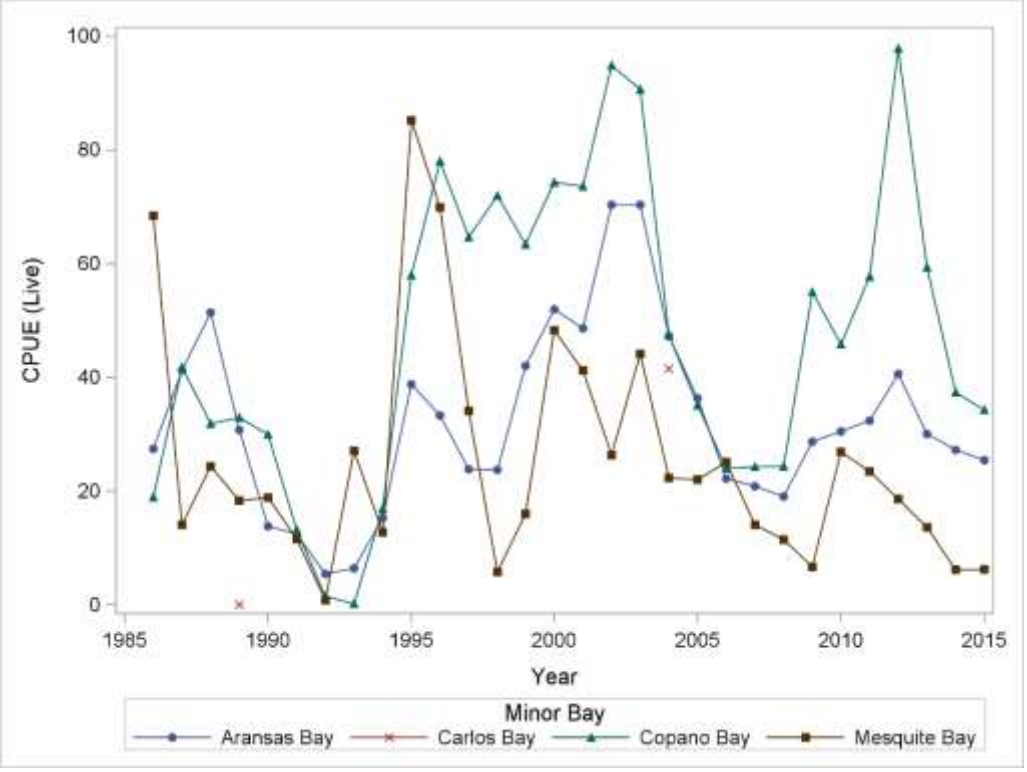

Figure 28. Line plot of mean oyster catch per unit effort (CPUE) in the Mission Aransas Estuary from 1986 to 2015

Live : Total Oysters Ratio

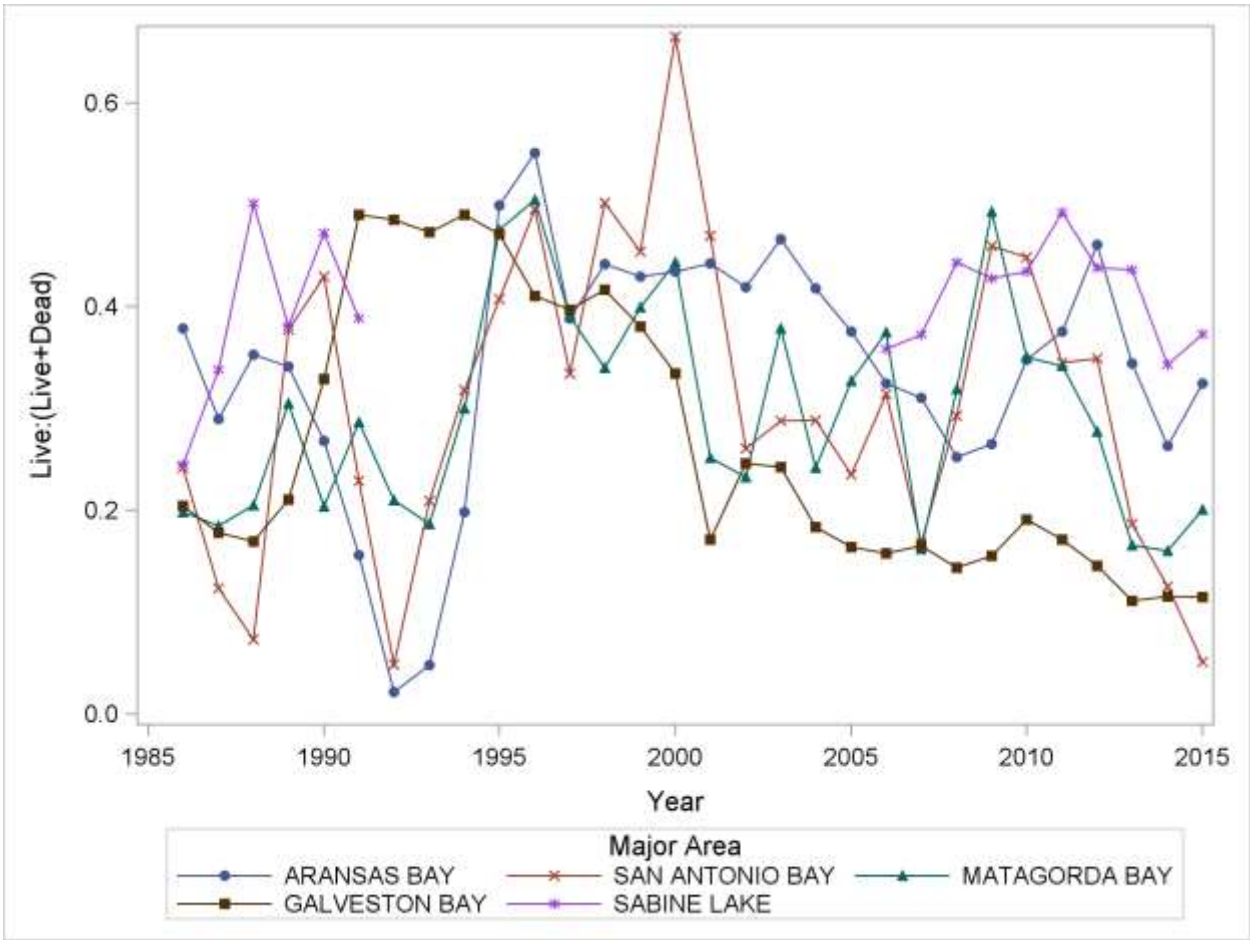

Figure 29. Line plot of live:total oysters among estuaries from 1986 to 2015

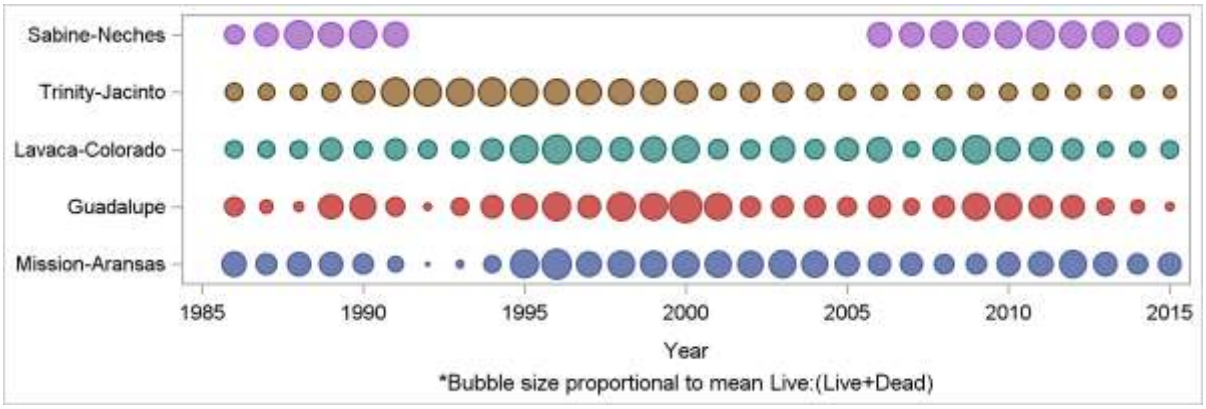

Figure 30. Bubble plot of live:total oysters among estuaries from 1986 to 2015

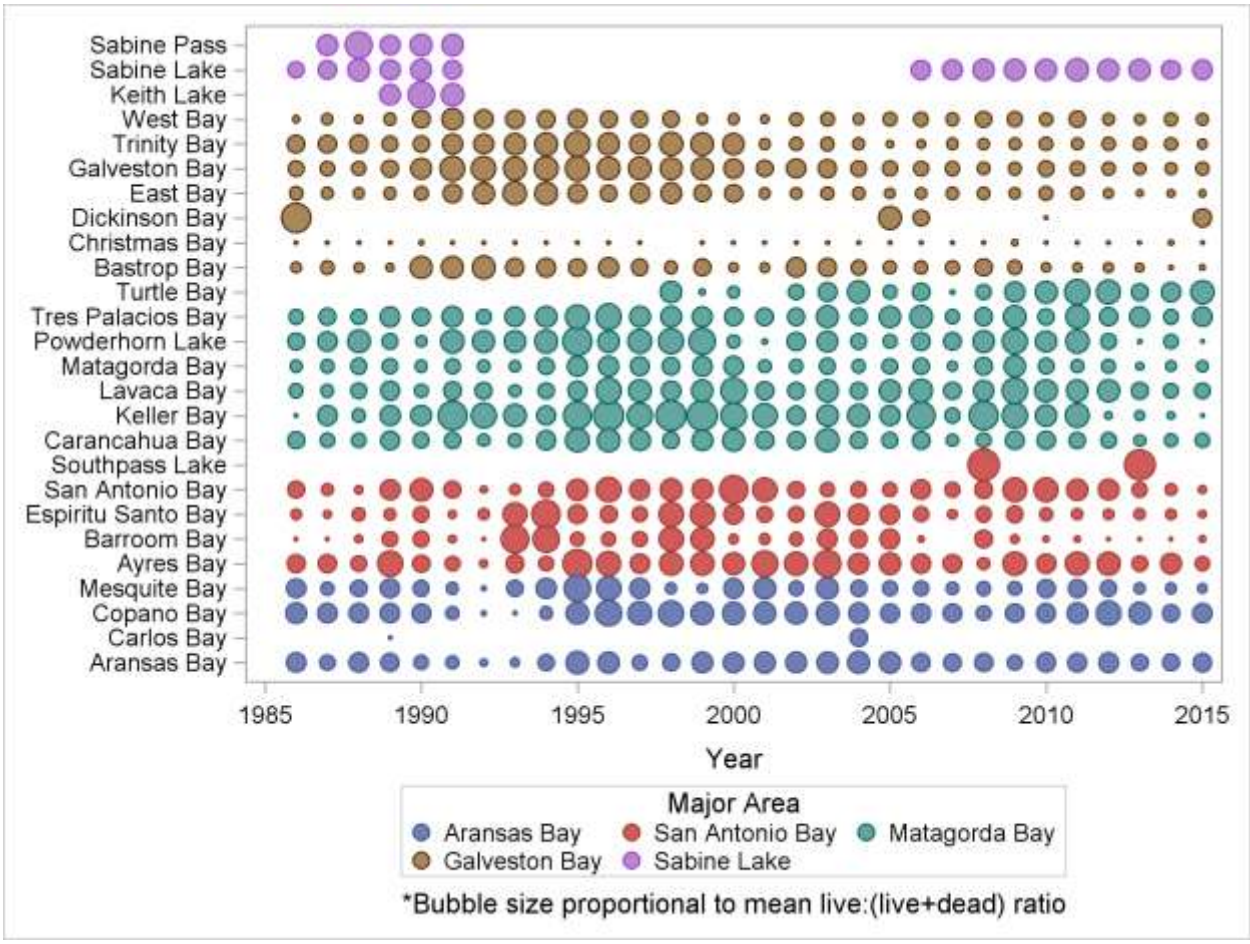

Figure 31. Bubble plot of live:total oysters within and among estuaries from 1986 to 2015

Shell Height

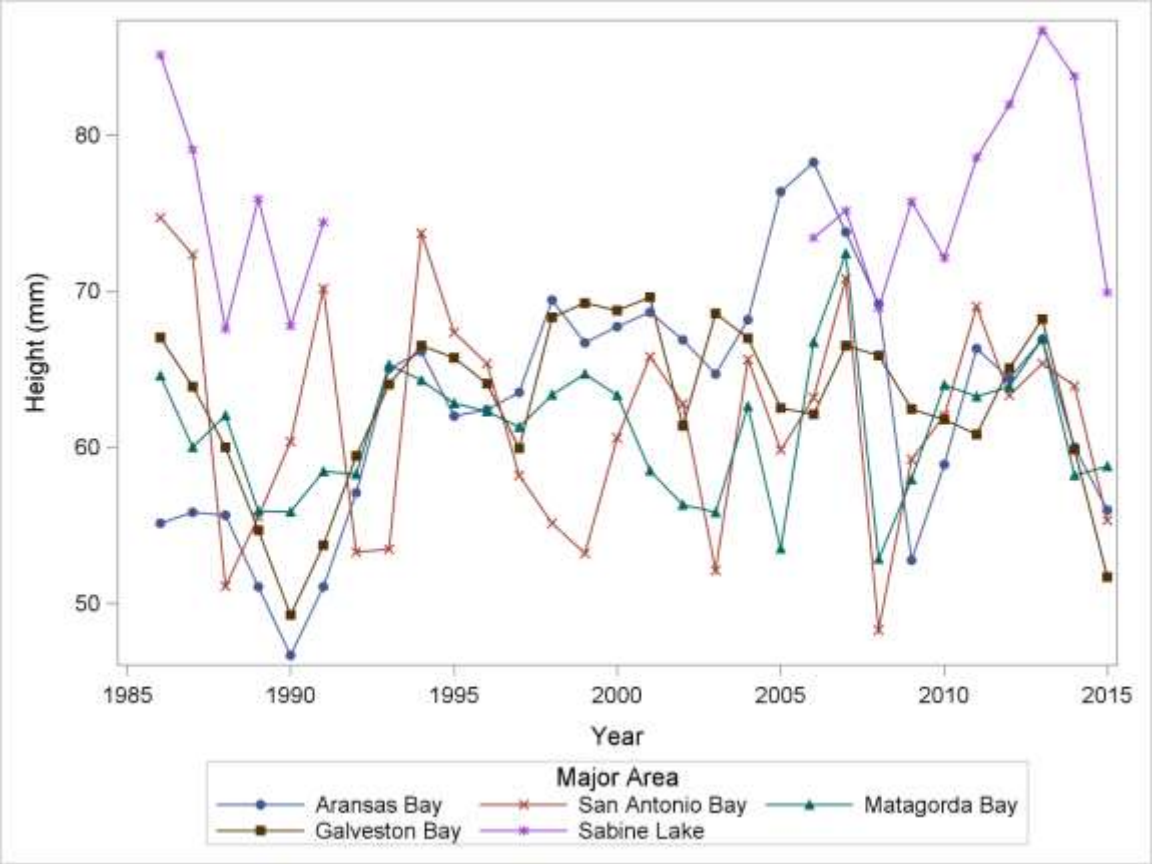

Figure 32. Line plot of mean shell height in each estuary from 1986 to 2015

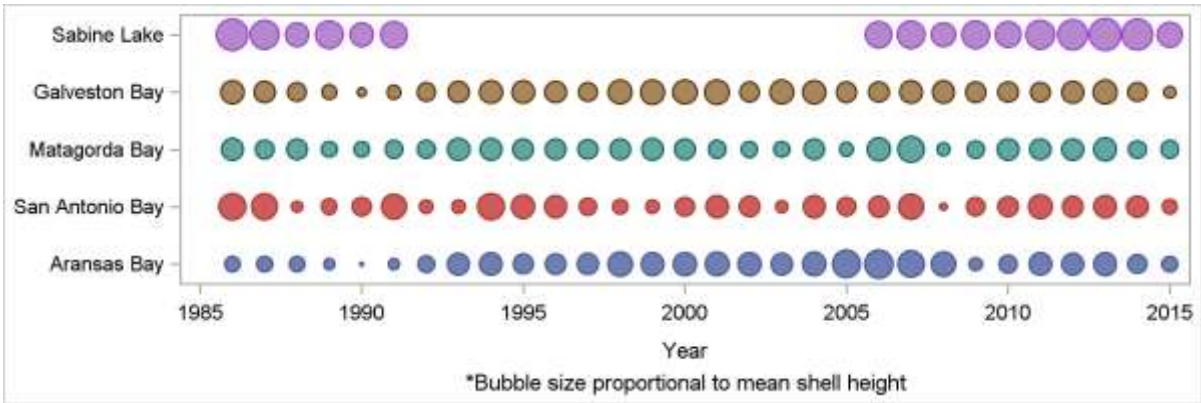

Figure 33. Bubble plot of mean shell height in each estuary from 1986 to 2015

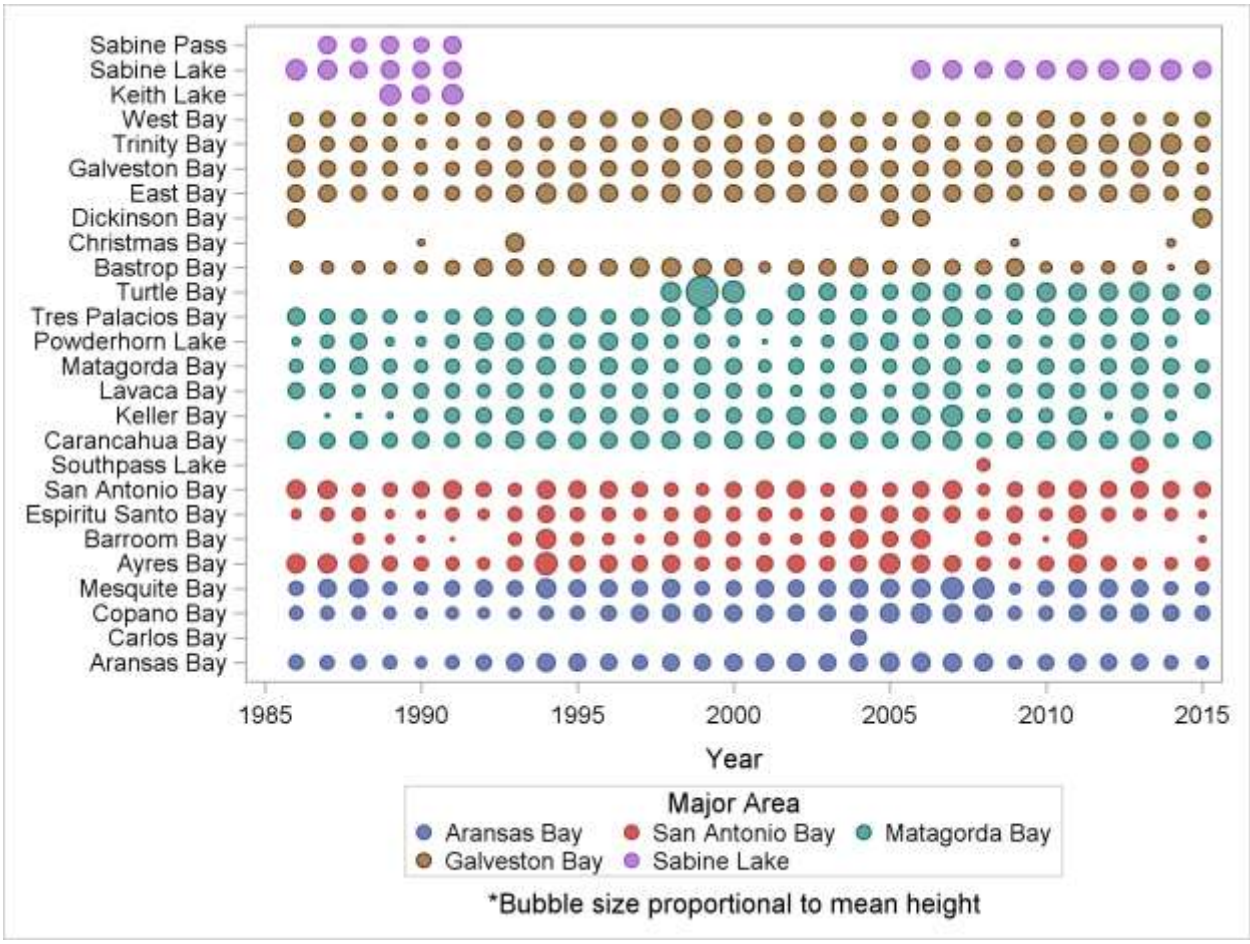

Figure 34. Bubble plot of mean shell height among and within each estuary from 1986 to 2015

Evaluation criteria for report card

Current status (color of circle)

- Determined by comparing 5 year average oyster abundance (2011-2015) to quartiles of abundance calculated using all years (1986-2015).
- Good (green) = 5-year mean is at or above the median
- Fair (yellow) = 5-year mean is between Q1 and median
- Poor (red) = 5 year mean is at or below Q1
- Minimal natural oyster populations (gray) = No TPWD data, just local knowledge, applies to CCBay and LM

Trend (direction of arrow)

- Determined by assessing Spearman correlation between oyster abundance and years
- Increasing (up arrow) = significant increase ($p<0.05$; positive rho) in oyster abundance for all years (1986-2015) and/or past 20-years (1995-2015)
- Stable (sideways arrow) = no significant trend to the data
- Decreasing (down arrow) = significant decrease ($p<0.05$; negative rho) for all years (1986-2015) and/or past 20-years (1995-2015)
- Unknown (no arrow) = No TPWD data, just local knowledge, applies to CCBay and LM

Table 2. Bay, current status, and trend for oyster populations.

Bay	**Current status (color of circle)**	**Trend (arrow direction)**
Sabine	Good (=green)	Stable/Increasing* (=diagonally up) *limited data
Galveston Bay	Poor (=red)	Decreasing (=down)
Matagorda Bay	Fair (=yellow)	Stable (=sideways)
San Antonio Bay	Good (=green)	Stable (=sideways)
Aransas Bay	Good (=green)	Decreasing (=down)
Corpus Christi Bay	Minimal natural oyster populations (=gray)	Unknown
Laguna Madre	Minimal natural oyster populations (=gray)	Unknown

Table 3. Spearman correlation between numberes of oysters and years.

Major_area	rho_allyears	p_allyears	rho_20years	p_20years	rho_10years	p_10years	rho_5years	p_5years
Sabine Lake	0.63529	0.0082	-0.41818	0.2291	-0.41818	0.2291	-0.40000	0.5046
Galveston Bay	-0.69299	<.0001	-0.90677	<.0001	-0.68485	0.0289	-0.70000	0.1881
Matagorda Bay	0.25428	0.1751	-0.29323	0.2096	-0.49091	0.1497	-0.70000	0.1881
San Antonio Bay	0.13771	0.4680	-0.25263	0.2826	-0.26061	0.4671	-0.90000	0.0374
Aransas Bay	0.19377	0.3049	-0.51278	0.0208	0.46667	0.1739	-0.90000	0.0374

Table 4. Number of oysters, median, Q1, Q2, mean of 2011-2015, and 2015.

Major_area	number_Median	number_Q1	number_Q3	number_2011_15	number_2015
Sabine Lake	16.4491	10.1859	20.4810	17.3104	20.4370
Galveston Bay	14.0389	9.1047	34.9951	6.7704	5.9480
Matagorda Bay	13.6821	8.9133	19.8241	11.9007	8.8798
San Antonio Bay	11.9224	7.4745	19.4875	12.0205	2.4333
Aransas Bay	40.9295	23.1728	50.2419	43.3958	29.6250

References

Martinez-Andrade, F., P. Campbell, & B. Fuls, 2005. Trends in relative abundance and size of selected finfishes and shellfishes along the Texas coast: November 1975-December 2003. Management Data Series Number 232. Texas Parks and Wildlife Department, Coastal Fisheries Division. Austin, Texas.

III-4. Gulf of Mexico Ecological Health Report Card

Bird Populations Data Support Document

Submitted by:
Kim Withers

Texas EcoHealth Metrics
Bird Populations Data Support Document

Kim Withers

Texas coastal habitats support a wide variety of resident, breeding, and migratory birds. During the breeding season, large colonies of spoonbills, herons, egrets, gulls, terns, and skimmers raise their young on barrier beaches and bay islands. In winter, millions of waterfowl and shorebirds find a safe haven where food is plentiful and the climate is mild. During migration, the Texas coast is an important hemispheric stopover where many Neotropical birds rest and refuel. Consequently, Texas is the number one bird-watching destination in North America. With at least 400 species, two-thirds of the state's bird diversity resides near the Gulf. Iconic species like Piping Plover and Whooping Crane attract nature tourists from all over the world. Ecotourism adds hundreds of millions of dollars to the state's economy and creates thousands of jobs, especially in coastal communities. Birds are also important ecosystem components functioning as predators, scavengers, and prey. Because of their mobility, birds link ecosystem processes and fluxes across space and time.

Background (Expert Workshop Deliberations)

At the Harte Research Institute's EcoHealth Metrics workshop, a group of experts in the field of avian population ecology recommended that two temporally defined groups of birds be used to represent avian health of the Texas Coast: migrating/wintering birds and resident breeding birds. Although participants also identified marsh birds and Neotropical and wintering migrants as important components of the Gulf of Mexico avifauna, difficulties with accessing suitable trends data, either on the birds themselves, or on proxy data such as habitat coverage, combined with the added complexity of additional species, resulted in their omission from this initial report card prototype. Workshop participants expressed the desire that these two bird categories may be included in a subsequent iteration since they represent groups of birds that are likely being subjected to stressors that have resulted or will result in population declines.

While breeding birds are often emphasized in these exercises, workshop participants agreed that the role of the Gulf of Mexico as an important wintering area also needed to be a focus. Breeding and wintering/migrating make up almost the entirety of a bird's annual cycle; however, many birds spend proportionally more time migrating and on wintering grounds. This underscores the need to recognize the potentially outsized role of coastal Texas habitats in bird survival. After much discussion, three guilds were chosen to represent the two aspects of a bird's annual cycle: shorebirds (migrating/wintering), colonially breeding waterbirds, and waterfowl (both winter/migration and breeding).

As much as 80% of shorebird mortality is caused by food shortages on wintering grounds (e.g., Goss-Custard 1979, among others). Other researchers (e.g., Johnson and Baldassare 1988) have related shorebird site fidelity in wintering areas and migratory staging areas to susceptibility to population declines under poor conditions. This is well illustrated in the relationship between Red Knot and other shorebirds with the horseshoe crab in Delaware Bay (USA), an important

migratory stopover and staging area for northbound migrants. For centuries, shorebirds on their way to the breeding grounds make one last stop at Delaware Bay to replenish their nutrient and lipid reserves on the incredibly abundant horseshoe crab eggs that have been deposited in the intertidal zone during spring. Horseshoe crabs are also used as bait in conch and American eel fisheries and by the pharmaceutical and medical industries. As demand for horseshoe crabs increased in the 1980s and 1990s, shorebird population sizes dropped dramatically, with Red Knot populations declining by more than 75%. Despite horseshoe crab harvest restrictions, no recovery of Red Knot was detectable through 2007 (Niles et al. 2009).

The concentration of colonially breeding waterbirds into a few areas while nesting makes them and their young vulnerable to a variety of threats: disturbance from navigation, chemical spills, mortality from entanglement and drowning in commercial fishing gear, depletion of forage fish (food for themselves and their young), and mammalian and avian predators, among others (USFWS 2002). In addition, many of these birds are much less abundant than they were at the turn of the twentieth century because of market hunting for feathers and plumes and the loss of more than half of the wetlands in the contiguous United States. Thus, colonially breeding waterbirds were identified as the best indicators for the breeding component of the annual cycle.

Waterfowl use Texas coastal habitats during all stages of the annual cycle, and population sizes are, or can be, affected by conditions in breeding areas and/or wintering areas. Food shortages caused by poor habitat conditions in wintering areas not only cause mortality but may also affect reproductive success the following spring. Drought is particularly problematic with regard to carrying capacity in both wintering (Petrie et al. 2016) and breeding areas (Moon et al. 2017). Other stressors, including predation and disturbance may also affect both breeding and wintering waterfowl.

Choices of Indicators

The list of birds and the characteristics that make them suitable candidates as indicators are in Appendix 1. It was hoped that the same species from each guild could be used for both the wintering and breeding/migrating assessments; however, this proved to be unworkable. In addition, there was an early bias toward birds that were already “of concern” which was likely to bias the assessment if all birds chosen fit into that category. Ultimately, the birds that were chosen to represent the guilds capture differing life histories within the guild and for which suitable and sufficient data on their abundance were available. These choices and the rationale for their selection are described in the sections below.

The criteria for data to be both “suitable” and “sufficient” included: 1) the public availability of the data and the likelihood that data would continue to be collected for the foreseeable future; 2) availability of several decades (more than 20 years) of historic coverage with few missing entries; and 3) the method by which data had been collected had not changed over the course of the survey and was unlikely to change in the future. I divided the coast into three regions (upper, middle, lower) because there are differences in the availability of habitat in each of the regions, and because the potential for important regional changes to be obscured if the coast was considered as a unit.

Migrating & Wintering Birds

Data from Audubon's Christmas Bird Count (CBC; National Audubon Society 2010), were used to assess population trends for the wintering birds that were identified as potentially useful indicators of two coastal bird guilds: shorebirds and waterfowl. Data are collected from within a 24 km (15 mi) diameter "count circle" between December 14 and January 5 each winter. At least 10 volunteers are needed for each circle, and generally each circle's volunteers are divided into smaller parties that follow assigned routes, counting every bird that is seen. Data from each party are turned in to a compiler for aggregation and reporting. There are limitations to the data; for example, typically not all areas in a count circle can be covered, but these limitations remain relatively stable, resulting in a reasonably well standardized count each year. Indeed, more than 200 peer-reviewed articles have used CBC data and US federal agencies often use the data when making decisions about birds (National Audubon Society 2010). This dataset was chosen because: 1) the count has been going since the early 1900's and there is sufficient temporal coverage (24-50 years) for the circles that were chosen for analysis; 2) the method is stable and has been used consistently for at least the last 50 years; 3) the data are freely available; and 4) the survey will continue for the foreseeable future, so the same data can be used to update the report card in the future. The data used for this analysis was the "count per party hour" which standardizes the counts per the unit effort (i.e., standardization of the data which takes into consideration the numbers of hours parties expend in counting birds) analogous to "catch per unit effort (CPUE) standardizations used in fisheries analyses.

The circles initially chosen were:

- Upper Coast
    - TXBP – Bolivar Peninsula (N 29.55, W -94.47): 1967-2015
    - TXFR – Freeport (N 29.02, W -95.36): 1967-2015
- Mid Coast
    - TXAR – Aransas National Wildlife Refuge (N 28.23, W -96.88): 1972-2015
    - TXCF – Corpus Christi – Flour Bluff (N 27.66, W -97.29): 1967-2015
- Lower Coast
    - TXLA – Laguna Atascosa National Wildlife Refuge (N 26.24, W -97.38): 1991-2015
    - TXCT – Coastal Tip (N 26.03, W -97.23: 1986-2015

These circles were chosen because they were along the coast (although many transgressed the coast to more upland areas) and had good temporal coverage. Circles generally had counts for the chosen species during most, if not all, years.

The representative species for the migrating and wintering birds were:

- Least Sandpiper (LESA) represents the small shorebird guild. It has a mixed feeding strategy (tactile and probing) and is mostly found on tidal flats.
- Piping Plover (PIPL) is a shorebird species of special interest because there are both threatened and endangered populations; the primary wintering population in Texas is the

threatened Great Plains population. Piping Plovers use both beach and tidal flat habitats and are sight foragers.

- Red Knot (REKN) is a medium-sized shorebird species of special interest with both threatened and endangered subspecies. The threatened *rufa* subspecies winters in Texas. This species is also of special interest because its significant reliance on Texas beaches flats and seagrass during winter was unknown until recently. Red Knots are long-distance migrants and specialized molluskivores.
- Lesser Scaup (LESC) is a species of diving duck that represents wintering waterfowl. It is widespread in Texas estuarine habitats during winter.

Breeding Birds

The Breeding Bird Survey Data (USGS Patuxent Research Center https://www.pwrc.usgs.gov/bbs/) dataset was used to capture the breeding birds that were identified as useful indicators of particular coastal bird guilds. Data are collected along routes that follow roads and that consist of 50 stops where the numbers of birds seen and heard are recorded. This dataset was chosen because: 1) the survey has been going on since at least the 1960s; 2) it uses a method that is stable and has been used consistently throughout the entire time the survey has been conducted; 3) the data are freely available; and 4) it is likely that the survey will continue into the future, so that the same data could be used for assessment by report card users. The metric used for this analysis was the yearly sums of the 50 stops for each species on each route that was chosen for inclusion.

- Upper Coast
  - Winnie
  - Danbury
- Mid-Coast
  - Indianola
- Lower Coast
  - Laguna Atascosa

I chose these routes because they were identified as encompassing coastal habitats (in both their descriptions and locations on a map) and because they had good temporal coverage, although nearly every route has missing years periodically. Routes also have reasonable amounts of data for the species that were chosen.

The representative species for the breeding guilds were:

- Mottled Duck (MODU) represents waterfowl that breed in brackish marshes and is a species of particular interest and concern Gulf-wide as one of the only, if not the only, waterfowl species that breeds along the coast.
- Great Egret (GREG) represents colonially breeding wading birds that nest in vegetated habitats.
- Originally, Black Skimmer (BLSK) was chosen to represent colonially breeding birds that use unvegetated habitats (including gulls, terns, and a few shorebirds); however, BLSK was not well represented in any of the BBS routes on the Texas coast, thus

- Two tern species were chosen to represent the guild: Forster's Tern (FOTE) and Gull-billed Tern (GBTE). Neither of these species were counted in the Winnie dataset, thus the Danbury route was also chosen on the Upper Coast, with only FOTE counted. Both species were counted at Indianola and Laguna Atascosa. Generally speaking, none of these terns were exceptionally abundant, but the combination of the two species provides a reasonable indicator for the guild.

Initial Statistical Analysis – Methods and Summary

The same methods were used for each dataset. I summarized and graphed the data by decade to look for obvious patterns. I analyzed the data for each circle/route and species in decadal blocks, running time-series regressions both within decades and across the entire dataset. In addition, I used analysis of variance to determine if there were differences among the decades. These differences, when they existed, were used to identify a reasonable baseline decade as the index for comparisons and to determine trends.

Migrating & Wintering Birds

Tables and figures depicting the summarization of the CBC data and the initial statistical analyses are in Appendices 2-7.

Least Sandpiper — Least Sandpiper populations appear to be stable at most sites, although there are large standard deviations associated with most decadal means, resulting in no significant differences among decades at any site. During the 1990-1999 decade on the Bolivar Peninsula (TXBP, upper coast) and the 2000-2009 decade in the Aransas National Wildlife Refuge (TXAR, mid coast), there were increasing trends in the numbers of Least Sandpipers reported, but overall populations were stable at these sites. The overall trend at Laguna Atascosa Wildlife Refuge (lower coast) was negative. Although the choice is somewhat arbitrary, the 1990-1999 decade appears to be a reasonable choice for a baseline.

Piping Plover — Piping Plovers were not abundant within any count circle despite the fact that the Texas coast is the most significant wintering area for the species, which is a short-distance migrant that winters almost exclusively along the Gulf of Mexico and southern Atlantic. They are reasonably well represented in the Bolivar Peninsula circle (TXBP, upper coast) and Corpus Christi – Flour Bluff circle (TXCF, mid coast) but not in other count circles, so I will restrict my discussion to these two circles. In data from the Bolivar Peninsula, there were significant differences among decades; abundance was significantly greater between 1980-1989. In addition, Piping Plover exhibited a negative trend in abundance during the 1990-1999 decade and overall in TXBP. In the Corpus Christi – Flour Bluff circle there were no significant differences in abundance among decades, and no significant decadal or overall trends. For this species, only data from the TXBP and TXCF circles should be used and the 1990-1999 decade, while somewhat arbitrarily chosen, appears to be a reasonable baseline at both sites.

Red Knot—Red Knots were not particularly well represented in the data that were analyzed. Their presence on the coast is fairly episodic in general; as long-distance migrants they have been thought to only stopover along the Texas coast on the way to more distant wintering or

breeding grounds. Recent research has shown that at least a portion of the population, particularly first-year birds, may spend most or all of the winter here; however, whether or not they will be consistently captured in Christmas Bird count data is questionable. Of the data examined, reasonable numbers were detected in the Bolivar Peninsula (TXBP) and Freeport (TXFR) circles on the upper coast and the Corpus Christi – Flour Bluff (TXCF) circle on the mid coast. Overall trends were negative in TXBP and TXFR and stable in TXCF.

- *Trends in the abundance of this species are of interest for a variety of reasons; however, I do not think it is a suitable indicator species. Its episodic presence, combined with its parochial food habits means that its abundance, which is already low, may fluctuate wildly and is not linked to changes in pressures and stressors that the EcoHealth Metrics report card is trying to detect, measure, and track.*

Lesser Scaup—This species was counted in all circles, although abundances in some circles were orders of magnitude higher than in others. Lesser Scaup, like many wintering waterfowl, may be found in large "rafts." There was a great deal of variability in the numbers counted as indicated by the large standard deviations associated with most decadal means. Overall trends were stable in all circles; abundance declined in the Bolivar Peninsula circle and increased in the Corpus Christi – Flour Bluff circle during the 2000-2009 decade. There were no significant differences in abundances among decades in any circle. Again, the choice of baseline decade is somewhat arbitrary, but the 1980-1989 appears to be a reasonable.

After the initial analysis was completed, the following changes were made to simplify the subsequent trends analysis.

1. Eliminate Red Knot as an indicator – data are too sparse for it to be a suitable indicator
2. It does not appear that the use of more than one circle in each region is necessary.
    a. The following circles are eliminated from subsequent trends analyses
        i. Upper Coast: Freeport (TXFR)
            1. Mean abundances of both Least Sandpiper and Lesser Scaup are lower than those in the Bolivar Peninsula and elsewhere along the coast.
            2. No useful data for Piping Plover
        ii. Mid Coast: Aransas National Wildlife Refuge (TXAR)
            1. No useful data for Piping Plover
            2. For the remaining species, the data are very similar to those from the Corpus Christi – Flour Bluff circle, which has useful data for Piping Plover.
        iii. Lower Coast: Laguna Atascosa Wildlife Refuge (TXLA
            1. Substantially less temporal coverage than other circles
            2. No useful data for Piping Plover
            3. Mean abundances of Lesser Scaup are lower than in other circles
    b. The following circles should be retained
        i. Upper Coast: Bolivar Peninsula
            1. The ranges of abundances of all species are similar to the other retained circles
            2. Data available to assess Piping Plover

ii. Mid Coast: Corpus Christi – Flour Bluff
    1. The ranges of abundances of all species are similar to the other retained circles
    2. Data available to assess Piping Plover
iii. Lower Coast: Coastal Tip
    1. Temporal coverage, while reduced, is greater than that represented by TXLA
    2. The ranges of abundances of all species are similar to the other retained circles
    3. Data available to assess Piping Plover

Breeding Birds

Mottled Duck—Mottled Duck populations have been relatively stable at all sites since the 1990s or 2000s. There were significant declines at three sites in either the 1980's (Winnie, Danbury) or 1990s (Indianola); at Winnie, there was another decline between the 1990s and 2000s. Laguna Atascosa showed no significant trends but the population there is smaller overall. Overall trends are negative at Winnie and Danbury, and stable (no trend) at Indianola and Laguna Atascosa. Analysis of variance results show that there were significant differences between decades at Winnie and Indianola but not at other sites. The baseline for this species should be probably be set as 1980s decade, since this decade was the first decade of significant decline on most routes after which populations appear to have generally stabilized albeit at lower numbers.

Great Egret—Populations of Great Egret tend to be variable regardless of the area of the coast. This species exhibited a significant recent positive trend (2000-2009) at Winnie and Laguna Atascosa followed by stability, while it exhibited a significant negative trend during the same time period at Danbury and during 1990-1999 at Indianola. Overall trends are negative at Winnie and positive at Laguna Atascosa and stable (no trend) at Danbury and Indianola. Analysis of variance results showed that there were differences between decades at Winnie, but no significant differences elsewhere. The baseline for this species can be set as the 1960s-1970s decade.

Terns—Data for Gull-billed Terns were available at Indianola and Laguna Atascosa. Populations are stable at Laguna Atascosa with a recent negative decline at Indianola after several decades of stability. However, despite the recent negative decline at Indianola, the overall trend was positive. There were no significant differences in the numbers of GBTE by decade at the two sites.

Data for Forster's Terns were available at Danbury, Indianola, and Laguna Atascosa. Populations at all sites appear to be stable overall, although there may be a declining trend beginning at Indianola; the p-value for the regression of data for the 2010 decade was 0.06. There were significant differences in decadal means at Indianola with the 1990s significantly greater than all other decades; a similar pattern is shown by the ANOVA at Danbury. This peak, followed by a return to prior abundances suggests that the populations of FOTE during the 1990's are outliers.

Baselines for both tern species should be the 1960s-1980s decades. Ultimately, there were too few Gull-billed Terns to be useful indicator, so Forster's Terns were the only tern analyzed in the subsequent trends analysis. The baseline decades remained the same.

Trends Analysis or "Grades"

Much of this discussion has been devoted to the process used to determine the best available indicators, based on the suitability and sufficiency of the available data, and a summarization of those data so that a baseline decade(s) could be established. In this section, the trends in the abundances of the indicator species subsequent to the baseline decade(s) in each region of the coast are presented with the purpose of assigning both an estimate of current condition (e.g., health and grade) and population trend.

Methods

I used the Wilcoxon signed-rank test for one sample (α=0.05) to determine if the variations in the annual count of birds in all years subsequent to the baseline decade were random (the null hypothesis). I used the median of the baseline decade as the null hypothesis. In other words, I asked the question "did the count in year X vary randomly around the median of the baseline decade?" If the null hypothesis is true, then in a random sample ~1/2 of the annual counts should be less than the median (minus signs) and ~1/2 of the counts should be more than the median (+ signs). I combined the data for the decades subsequent to the baseline decade for the signed-rank test to increase the degrees of freedom and make the analysis more robust. I used regression to confirm the pattern, using only the data after the baseline data for the analysis. The regression results are not presented since they did not conflict with the results of the more conservative signed-rank test.

Instead of letter grades, initially I proposed using a traffic signal to denote the status of the population in question. Traffic-signal-like constructs are used in fisheries stock assessments and management planning (e.g., Halliday et al. 2001) and are intuitively straightforward in most cases. Although most fisheries examples use a suite of indicators to determine the color shown by the traffic light, there is no reason why a single metric cannot be used. In fact, additional indicators could easily be added in the future, if desired, using the traffic-signal approach especially to, for example, capture habitat metrics, which are not easily available at this time. There are several ways that the results of the traffic-signal assessment can be presented. The decision rules as to what color the light will be is based on the results of the Wilcoxon test: Green = "increasing," defined as the null hypothesis (random) was rejected and the number of annual counts in the time series that were greater than the median exceeds the number of times the annual count was less than the median; Yellow = "stable," that is the null hypothesis is not rejected; and Red = "decreasing," defined as the null hypothesis (random) was rejected and the number of annual counts in the time series that were less than the median exceeds the numbers of times the annual count was greater than the median.

Results & Trends Summary

In Tables 1 and 2, the results of the Wilcoxon signed-rank tests on the Christmas Bird Count data (Table 1) and Breeding Bird Survey data (Table 2) are presented. In Figure 1, two different ways the results of the Christmas Bird Count data can be depicted using a traffic-signal-like approach are presented.

For wintering birds, the Least Sandpipers are in good shape (either increasing or stable) in all regions of the coast but the other two indicator species are either stable or declining. On the upper coast Piping Plover are declining, which is troubling, since this species is already federally listed and has designated critical habitats and a recovery plan, which may be part of the reason why the species' abundance is stable on the rest of the coast. The Lesser Scaup appears to be doing poorly on the middle coast and but is stable elsewhere on the coast.

For breeding birds, Forster's Terns are increasing on the mid-coast and stable elsewhere. Great Egret population trends improve moving south along the coast; declines on the upper coast appear to be substantial and related to loss/alteration of nesting habitat. Mottled duck populations are declining on the upper coast, possibly as a result of reduced rice culture. Elsewhere on the coast, Mottled Ducks appear to be stable.

Overall, bird populations on the upper coast appear to be subjected to more pressures and stressors that result in population declines because of loss of habitat and food availability, human disturbance, and predation. Least Sandpipers (wintering/migration) is the only indicator bird showing positive trends; one-half of indicators are declining and one-third are stable.

Table 1. Results of the Wilcoxon signed-rank test on wintering bird indicator species. For LESA and PIPL, the time series after the baseline decade (1990s) consisted of 16 years (=annual counts). For LESC, the time series after the baseline decade (1980s) consisted of 26 years (= annual counts). Bold indicates a significant departure from random (α=0.05).

Species		Upper	Middle	Lower
LESA	Baseline median	0.5445	0.9780	3.9150
	Asymptotic significance	**0.007**	**0.001**	0.836
	Color	Green (12/16 >median	Green (13/16 >median)	Yellow
PIPL	Baseline median	0.1044	0.1978	0.5436
	Asymptotic significance	**0.001**	0.215	0.877
	Color	Red (15/15 <median)	Yellow	Yellow
LESC	Baseline median	6.0878	11.6667	2.7481
	Asymptotic significance	0.166	**<0.0001**	0.166
	Color	Yellow	Red (22/26 <median)	Yellow

LESA = Least Sandpiper; PIPL = Piping Plover; LESC = Lesser Scaup

On the middle coast, only Lesser Scaup populations appear to be declining. Although waterfowl populations can fluctuate greatly, the time series encompasses 16 years and it is likely that the trend is real. This region of the coast is the only region in which two of six species exhibit increasing trends. On the lower coast, five of six species are stable. There are no significant declines, but by the same token, only a single species (Great Egret) that is increasing. While stability is certainly better than decline, it is somewhat troubling that no other species are increasing.

Table 2. Results of the Wilcoxon signed-rank test on breeding bird indicator species. For FOTE and MODU, the time series after the baseline decade (1980s) consisted of 23 years (=years the route was run). For GREG, the time series after the baseline decade (1960-70s) consisted of 23 years (= years the route was run). Bold indicates a significant departure from random (α=0.05).

Species		Upper	Middle	Lower
FOTE	Baseline median	3.0	1.0	2.0
	Asymptotic significance	0.068	**0.002**	**0.002**
	Color	Yellow	Green (16/23 >median)	Yellow (12/20 = median)
GREG	Baseline median	11.0	34.5	5.0
	Asymptotic significance	**<0.0001**	0.067	**<0.0001**
	Color	Red (29/30 <median)	Yellow	Green (20/28 >median)
MODU	Baseline median	11.0	9.0	5.0
	Asymptotic significance	**0.012**	0.144	0.755
	Color	Red (20/23 <median)	Yellow	Yellow

Forster's Tern - FOTE; Great Egret – GREG; Mottled Duck – MODU

Summary

Generally, populations of the indicator species in the middle and lower coasts appear to be stable but are not presently achieving the desired management goal of increasing population sizes. The variation in population status along the coast also suggests a cautionary note: ongoing disturbance and habitat loss on the upper coast will continue to negatively affect coastal bird populations unless stopped; and stable or even increased population sizes on the middle and lower coast are unlikely to counterbalance losses on the upper coast. Indeed, because most populations outside the upper coast are stable rather than growing, additional or accelerating habitat loss in the middle and lower coast could cause populations to decrease in the coming decades.

a)

UPPER TEXAS COAST

BREEDING BIRDS **WINTERING BIRDS**

b)

	Upper	Middle	Lower
Breeding Birds			
Forster's Tern			
Great Egret			
Mottled Duck			
Wintering Birds			
Least Sandpiper			
Piping Plover			
Lesser Scaup			

Figure 1. Two ways to graphically depict the status of birds on the Texas Coast using the traffic-signal approach. In a) each region would have a similar graphic depicting the status of birds in the region. The consolidated approach of b) consolidates the statuses for easier comparisons among regions. The species graphics of a) could be incorporated into b) for a more artistic approach.

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Appendix 1. Bird Trends/Issues – the species chosen in our last meeting are bolded and underlined

Shorebirds

Species	Texas Timing	Gulf Timing	Texas Habitat	Population Trend	Conservation Status	Issues (Texas & GOM)
SNPL	R (year-round; nests)	R in parts of GOM; W/MS others	Beach, tidal flats, washovers	Breeding – stable to declining on Gulf Coast	None (Pacific Coast breeding population is Threatened)	Nesting habitat, disturbance/predation during nesting Wintering habitat
AMOY	R (year-round, nests)	R (year-round, nests) except in Bay of Campeche (W, MS)	Beaches, salt marsh, shell/dredge islands, oyster reef	Stable to declining	None	Winter habitat Nesting habitat Disturbance/predation SLR
PIPL	W, MS	W, MS	Beach, tidal flats, washovers	Stable?	Threatened/Endangered (USFWS)	Winter habitat,
REKN	W, MS	W, MS	Beach, sand flats	Declining	Threatened (USFWS)	Wintering habitat, especially beaches
SAND	W, MS	W, MS	Beach, tidal flats, washovers	Declining	None	Wintering habitat, especially beaches
LESA	W, MS	W, MS	Tidal flats, beach	Declining?	None	Wintering habitat, disturbance, environmental contamination
RUTU	W, MS	W, MS	Beach, tidal flats	Stable?	None	Winter habitat, environmental contamination
WILL	R (year-round, nests)	R in parts of GOM; W/MS others	Beach, tidal flats, wetlands	Stable	None	Winter habitat Breeding habitat Disturbance
LBCU	W, MS	W, MS	Beach, tidal flats, wet coastal grasslands and ag fields (esp. rice)	Stable to declining	Highly Imperiled (US SCP)	Winter habitat

SNPL = Snowy Plover; AMOY = American Oystercatcher; PIPL = Piping Plover; REKN = Red Knot; SAND = Sanderling; LESA = Least Sandpiper; RUTU = Ruddy Turnstone; WILL = Willet; LBCU = Long-billed Curlew

Colonially breeding waterbirds

Species	Texas Timing	Gulf Timing	Texas Habitat	Population Trend	Conservation Status	Issues (Texas & GOM)
BLSK	R (year-round, nests)	R (year-round, nests) except in Bay of Campeche and south Florida	Nests: spoil islands, coastal beaches, barrier beaches <30% vegetation; in other areas on roofs Foraging: shallow waters NB – similar to nesting, foraging	Stable overall? Declines in colonies in Texas over last 40 years	No Federal status; states (not including Texas) range from Special Concern to Endangered	Nesting habitat, Nesting disturbance Predation during nesting
GREG	R (year-round, nests)	R (year-round, nests)	Nesting: spoil islands, woody vegetation, trees/shrubs Foraging: relatively shallow water; fresh, estuarine, salt W: similar to nesting, foraging	Stable or increasing	State listed: Endangered CN, PA; Special Concern: FL NA Waterbird Plan: not currently at risk	Nesting habitat Disturbance – nest and roosts Contaminants
LETE	N, MS	N, MS	Nesting: spoil islands, mudflats, shell islands above high tide; bare or sparsely vegetated; historically beaches Foraging: shallow water MS: coastal, beaches mixed flocks	Stable	Interior population Federally endangered; state listed in numerous states including Texas	Nesting habitat Disturbance Predation
FOTE	R (year round, nests)	W, MS; R (parts of LA, AL)	"Marsh Tern" Nesting: Fresh, brackish, SW marshes; open, deeper water NB: 90% of coastal habitats	Stable?	Species of special concern in MI, MN; Endangered IL, WA; no federal status	Habitat degradation Disturbance at nest sites Predation at nest sites
LAGU	R (year round, nests)	R (year round, nests)	Coastal areas, littoral zone	Stable to increasing	None, considered a pest in some areas	Disturbance at nest sites, foraging areas Habitat degradation
BRTE	R (year round, nests)	R (year round, nests)	Coastal areas, breeds on small islands w/o predators and with consistent food supplies within 30-50 km; coastal roost sites w/ 75 km of foraging areas in NB	Stable to increasing except in FL, where nesting # have declined somewhat	De-listed	Pesticides (DDT) Oil spills Fishing gear Habitat degradation Disturbance @ nest and roost sites
ROSP	R (year round,	N, W other parts of the	N: islands or over standing water;	Stable? FL breeding	FL: Special Concern, Rare	Habitat degradation,

	nests)	GOM	trees, shrubs, on the ground F: Shallow fresh to marine habitats	pop is small and probably most vulnerable		especially foraging habitat Disturbance at nest
AWPE	Mostly W, few areas R (LM, mid coast)	W, MS	Shallow coastal bays, inlets, and estuaries, heavily dependent on estuaries with forage fish at temps above 4 °C in Jan	Stable?	None	Habitat degradation

BLSK = Black Skimmer; GREG = Great Egret; LETE = Least Tern; FOTE = Forster's Tern; LAGU = Laughing Gull; BRTE = Bridled Tern; ROSP = Roseate Spoonbill; AWPE America White Pelican

Waterfowl

Species	Texas Timing	Gulf Timing	Texas Habitat	Population Trend	Conservation Status	Issues (Texas & GOM)
MODU	R (year round, nests)	R (year round, nests)	Coastal marshes, inland freshwater marshes, rice fields	Stable to steeply declining in W Gulf Possibly increasing in FL	FL: Special concern TX, LA, MS: species of conservation concern	Harvest? Habitat degradation/loss, esp. prairie grasslands & seasonal wetlands Hybridization w/ feral domestic MALL Drought/saltwater intrusion Contaminants?
LESC	W, MS	W, MS	Lakes/reservoirs, fresh to brackish coastal bays and estuaries; more saline waters during severe weather	Declining? Survey methods inconsistent	Continental population lower the NAWMP goal	Harvest? Habitat degradation/loss (all phases of annual cycle)
REDH	W, MS	W, MS	Coastal areas, esp. LM, Chandeleur, Apalachee Bay, with seagrass; needs brackish to FW ponds in Texas, Mexico due to hypersalinity	Wild fluctuations, not well understood	Met 2002 NAWMP goal	Harvest? Habitat degradation, particularly Prairie Potholes Drought in PP
NOPI	W, MS	W, MS	Shallow inland freshwater and estuarine habitats; may forage in fallow fields in the uplands and rice fields closer to the coast	One of the most abundant waterfowl; fluctuate w/ condition of Prairie Potholes	Below NAWMP goal in 2013	Harvest? Drought in PP Habitat degradation in breeding & wintering areas

MODU = Mottled Duck; LESC = Lesser Scaup; REDH = Redhead; NOPI = Northern Pintail

Appendix 2. CBC data summary and analysis: Upper Coast—Bolivar Peninsula Circle (TXBP)

Table 2.1. Bolivar Peninsula Circle (TXBP) regression results: Least Sandpiper (LESA).

Decade	Trend	N (years)
1967-1979	NS – stable	13
1980-1989	NS – stable	10
1990-1999	Sig – positive	10
2000-2009	NS – stable	10
2010-2015	NS – stable	6
Overall	NS – stable	49

Table 2.2 Bolivar Peninsula Circle (TXBP) regression results: Piping Plover (PIPL).

Decade	Trend	N (years)
1967-1979	NS – stable	13
1980-1989	NS – stable (p=0.048; neg)	10
1990-1999	Sig – negative	10
2000-2009	NS – stable	10
2010-2015	NS – stable	6
Overall	Sig – negative	49

Table 2.3. Bolivar Peninsula Circle (TXBP) regression results: Red Knot (REKU).

Decade	Trend	N (years)
1967-1979	NS –stable	13
1980-1989	NS – stable	10
1990-1999	NS – stable	10
2000-2009	NS – stable	10
2010-2015	NS – stable	6
Overall	Sig – negative	49

Table 2.4. Bolivar Peninsula Circle (TXBP) regression results: Lesser Scaup (LESC).

Decade	Trend	N (years)
1967-1979	NS – stable	13
1980-1989	NS – stable	10
1990-1999	NS – stable	10
2000-2009	Sig – negative	10
2010-2015	NS – stable	6
Overall	NS – stable	49

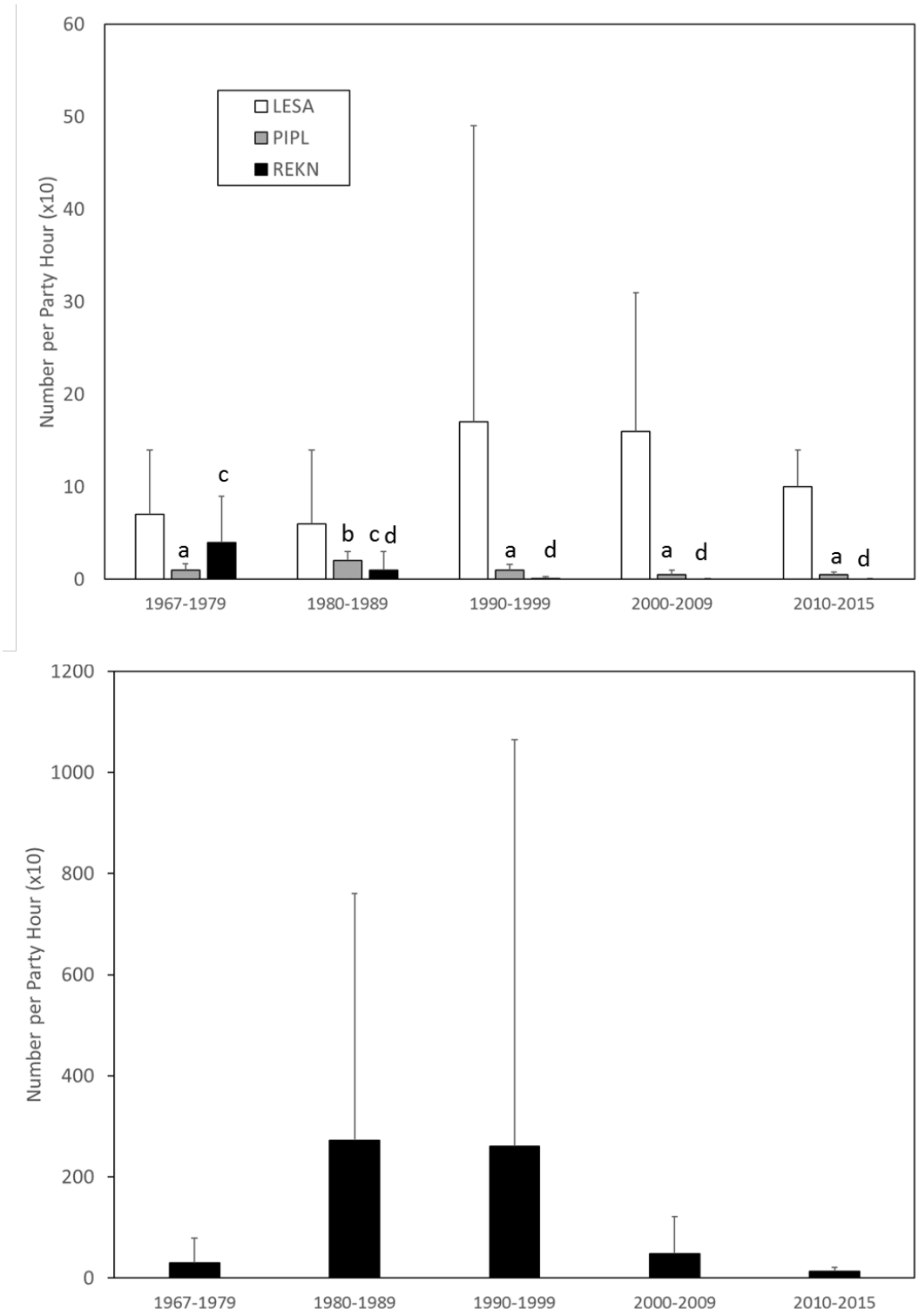

Figure 2.1. Mean numbers per party hour (x10) of shorebirds (top) and Lesser Scaup (LESC, bottom) in the Bolivar Peninsula Christmas Bird Count circle (TXBP) by decade with standard deviation. Bars with the same letter (or no letters) are not significantly different from one another.

Appendix 3. CBC data summary and analysis: Upper Coast—Freeport Circle (TXFR)

Table 3.1. Freeport Circle (TXFR) regression results: Least Sandpiper (LESA).

Decade	Trend	N (years)
1967-1979	NS – stable	13
1980-1989	NS – stable	10
1990-1999	NS – stable	10
2000-2009	NS – stable	10
2010-2015	NS – stable	6
Overall	NS – stable	49

Table 3.2. Freeport Circle (TXFR) regression results: Piping Plover (PIPL).

Decade	Trend	N (years)
1967-1979	NS – stable	13
1980-1989	NS – stable	10
1990-1999	NS – stable	10
2000-2009	NS – stable	10
2010-2015	NS – stable	6
Overall	NS – stable	49

Table 3.3. Freeport Circle (TXFR) regression results: Red Knot (REKU).

Decade	Trend	N (years)
1967-1979	NS – stable	13
1980-1989	Sig – negative	10
1990-1999	NS – stable	10
2000-2009	NS – stable	10
2010-2015	NS – stable	6
Overall	Sig – negative	49

Table 3.4. Freeport Circle (TXFR) regression results: Lesser Scaup (LESC).

Decade	Trend	N (years)
1967-1979	NS – stable	13
1980-1989	NS – stable	10
1990-1999	NS – stable	10
2000-2009	NS – stable	10
2010-2015	NS – stable	6
Overall	NS – stable	49

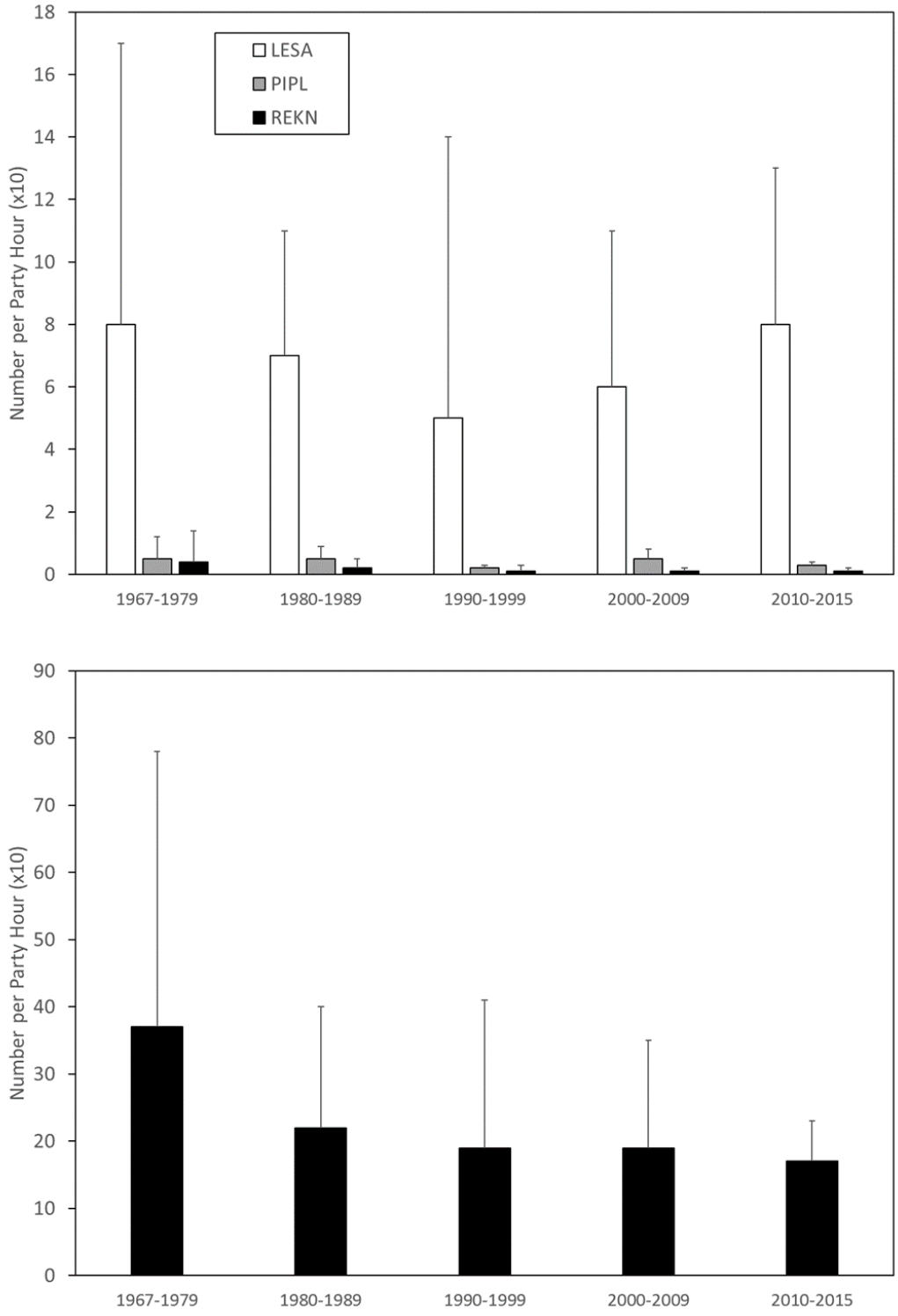

Figure 3.1. Mean numbers per party hour (x10) of shorebirds (top) and Lesser Scaup (LESC, bottom) in the Freeport Christmas Bird Count circle (TXFR) by decade with standard deviation. Bars with the same letter (or no letters) are not significantly different from one another.

Appendix 4. CBC data summary and analysis: Mid Coast—Aransas National Wildlife Refuge Circle (TXAR)

Table 4.1. Aransas National Wildlife Refuge Circle (TXAR) regression results: Least Sandpiper (LESA).

Decade	Trend	N (years)
1972-1979	NS – stable	8
1980-1989	NS – stable	10
1990-1999	NS – stable	10
2000-2009	Sig – positive	10
2010-2015	NS – stable	6
Overall	Sig – positive	43

Table 4.2. Aransas National Wildlife Refuge Circle (TXAR) regression results: Piping Plover (PIPL).

Decade	Trend	N (years)
1972-1979	NS – stable	8
1980-1989	NS – stable	10
1990-1999	NS – stable	10
2000-2009	NS – stable	10
2010-2015	NS – stable	6
Overall	NS – Stable	43

Table 4.3. Aransas National Wildlife Refuge Circle (TXAR) regression results: Red Knot (REKU).

Decade	Trend	N (years)
1972-1979	Not enough data	8
1980-1989	Not enough data	10
1990-1999	NS – stable	10
2000-2009	Not enough data	10
2010-2015	NS – stable	6
Overall	NS – stable	43

Table 4.4. Aransas National Wildlife Refuge Circle (TXAR) regression results: Lesser Scaup (LESC).

Decade	Trend	N (years)
1972-1979	NS – stable	8
1980-1989	NS – stable	10
1990-1999	NS – stable	10
2000-2009	NS – stable (p=0.06, pos)	10
2010-2015	NS – stable	6
Overall	NS – stable	43

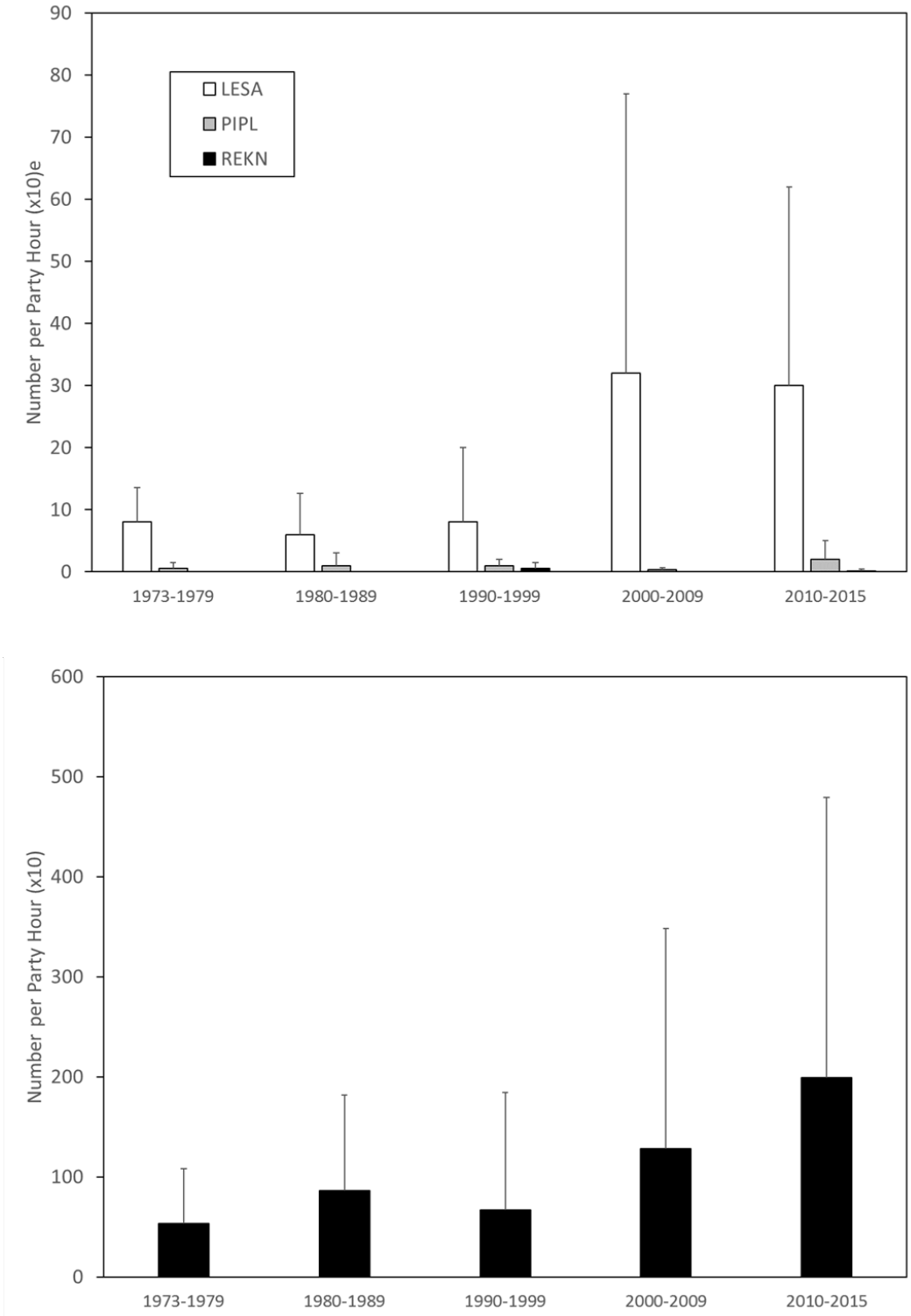

Figure 4.1. Mean numbers per party hour (x10) of shorebirds (top) and Lesser Scaup (LESC, bottom) in the Aransas National Wildlife Refuge Christmas Bird Count circle (TXAR) by decade with standard deviation. Bars with the same letter (or no letters) are not significantly different from one another.

Appendix 5. CBC data summary and analysis: Mid Coast—Corpus Christi – Flour Bluff Circle (TXCF)

Table 5.1. Corpus Christi – Flour Bluff Circle (TXCF) regression results: Least Sandpiper (LESA).

Decade	Trend	N (years)
1967-1979	NS – stable	13
1980-1989	NS – stable	10
1990-1999	NS – stable	10
2000-2009	NS – stable	10
2010-2015	NS – stable	6
Overall	NS – stable	49

Table 5.2. Corpus Christi – Flour Bluff Circle (TXCF) regression results: Piping Plover (PIPL).

Decade	Trend	N (years)
1967-1979	NS – stable	13
1980-1989	NS – stable	10
1990-1999	NS – stable	10
2000-2009	NS – stable	10
2010-2015	NS – stable	6
Overall	NS – stable	49

Table 5.3. Corpus Christi – Flour Bluff Circle (TXCF) regression results: Red Knot (REKU).

Decade	Trend	N (years)
1967-1979	NS – stable (p=0.06; negative)	13
1980-1989	NS – stable	10
1990-1999	NS – stable	10
2000-2009	NS – stable	10
2010-2015	NS - stable	6
Overall	NS – stable	49

Table 5.4. Corpus Christi – Flour Bluff Circle (TXCF) regression results: Lesser Scaup (LESC).

Decade	Trend	N (years)
1967-1979	NS – stable	13
1980-1989	NS – stable	10
1990-1999	NS – stable	10
2000-2009	Sig – positive	10
2010-2015	NS – stable	6
Overall	NS – stable	49

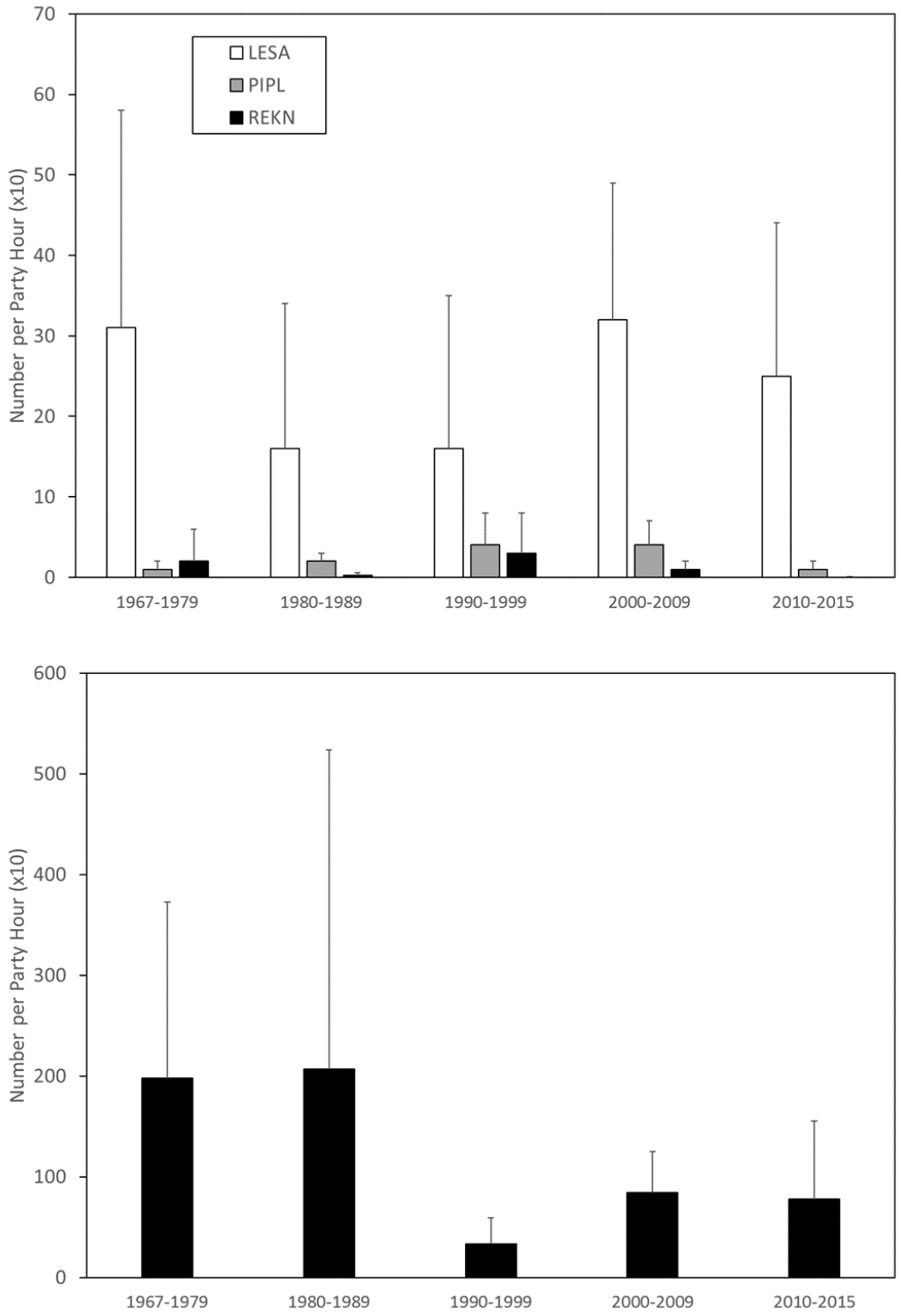

Figure 5.1. Mean numbers per party hour (x10) of shorebirds (top) and Lesser Scaup (LESC, bottom) in the Corpus Christi – Flour Bluff Christmas Bird Count circle (TXCF) by decade with standard deviation. Bars with the same letter (or no letters) are not significantly different from one another.

Appendix 6. CBC data summary and analysis: Lower Coast—Laguna Atascosa National Wildlife Refuge (TXLA)

Table 6.1. Laguna Atascosa National Wildlife Refuge Circle (TXLA) regression results: Least Sandpiper (LESA).

Decade	Trend	N (years)
1991-1999	NS – stable	9
2000-2009	NS – stable	10
2010-2015	NS – stable	6
Overall	Sig – negative	25

Table 6.2. Laguna Atascosa National Wildlife Refuge Circle (TXLA) regression results: Piping Plover (PIPL).

Decade	Trend	N (years)
1991-1999	NS – stable	9
2000-2009	NS – stable	10
2010-2015	NS – stable	6
Overall	Sig – negative	25

Table 6.3. Laguna Atascosa National Wildlife Refuge Circle (TXLA) regression results: Red Knot (REKU).

Decade	Trend	N (years)
1991-1999	NS – stable	9
2000-2009	Not enough data	10
2010-2015	Not enough data	6
Overall	NS – stable	25

Table 6.4. Laguna Atascosa National Wildlife Refuge Circle (TXLA) regression results: Lesser Scaup (LESC).

Decade	Trend	N (years)
1991-1999	NS – stable	9
2000-2009	NS – stable	10
2010-2015	NS – stable	6
Overall	NS – stable	25

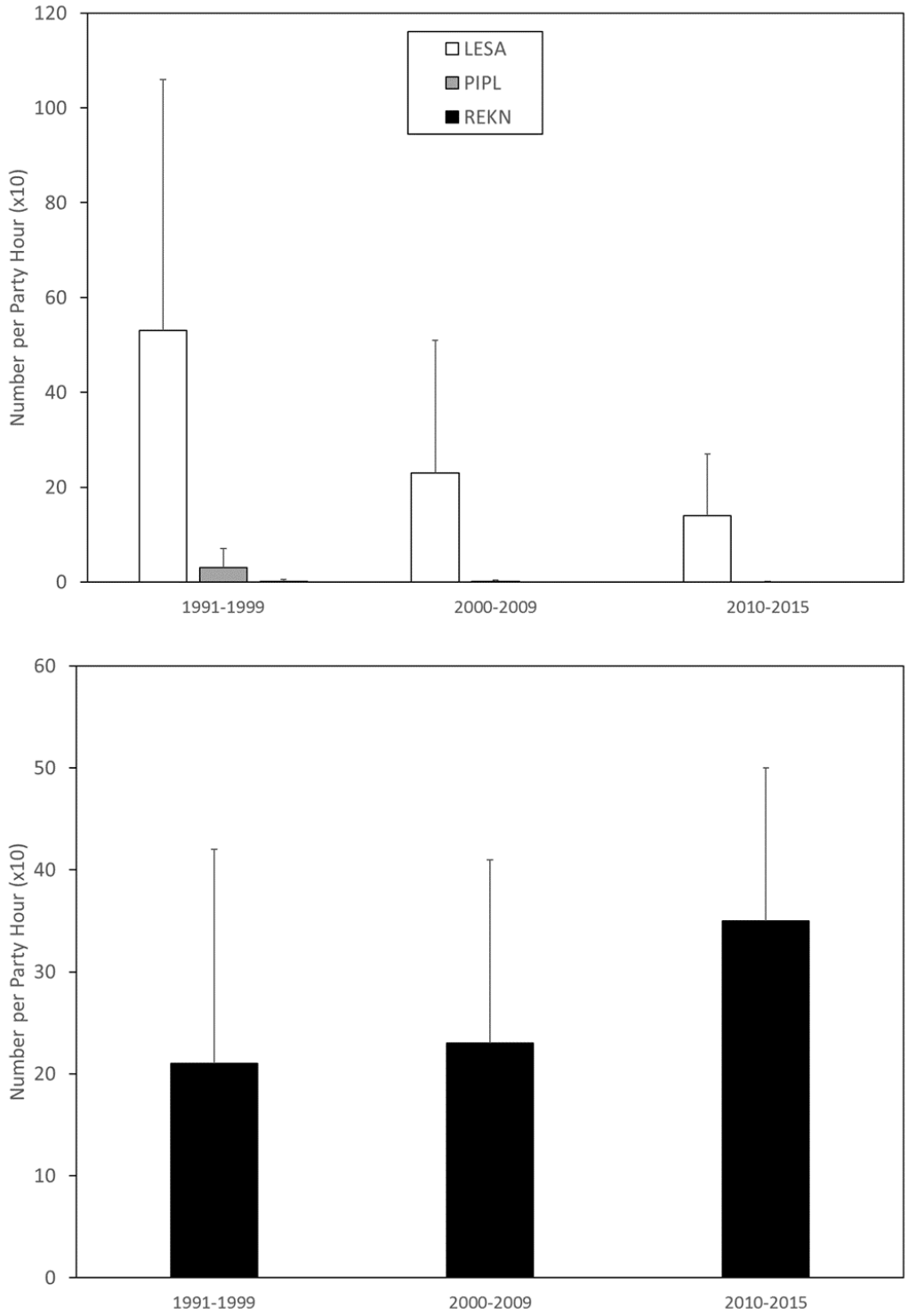

Figure 6.1. Mean numbers per party hour (x10) of shorebirds (top) and Lesser Scaup (LESC, bottom) in the Laguna Atascosa National Wildlife Refuge Christmas Bird Count circle (TXAR) by decade with standard deviation. Bars with the same letter (or no letters) are not significantly different from one another.

Appendix 7. CBC data summary and analysis: Lower Coast—Coastal Tip (TXCT)

Table 7.1. Coastal Tip Circle (TXCT) regression results: Least Sandpiper (LESA).

Decade	Trend	N (years)
1986-1989	NS – stable	4
1990-1999	NS – stable	10
2000-2009	NS – stable	10
2010-2015	NS – stable	6
Overall	NS – stable	30

Table 7.2. Coastal Tip Circle (TXCT) regression results: Piping Plover (PIPL).

Decade	Trend	N (years)
1986-1989	NS – stable	4
1990-1999	Sig – negative	10
2000-2009	NS – stable	10
2010-2015	NS - stable	6
Overall	NS – stable	30

Table 7.3. Coastal Tip Circle (TXCT) regression results: Red Knot (REKU).

Decade	Trend	N (years)
1986-1989	Not enough data	4
1990-1999	NS – stable	10
2000-2009	NS – stable	10
2010-2015	NS – stable	6
Overall	NS – stable	30

Table 7.4. Coastal Tip Circle (TXCT) regression results: Lesser Scaup (LESC).

Decade	Trend	N (years)
1986-1989	NS – stable	4
1990-1999	NS – stable	10
2000-2009	NS – stable	10
2010-2015	NS – stable	6
Overall	NS - stable	30

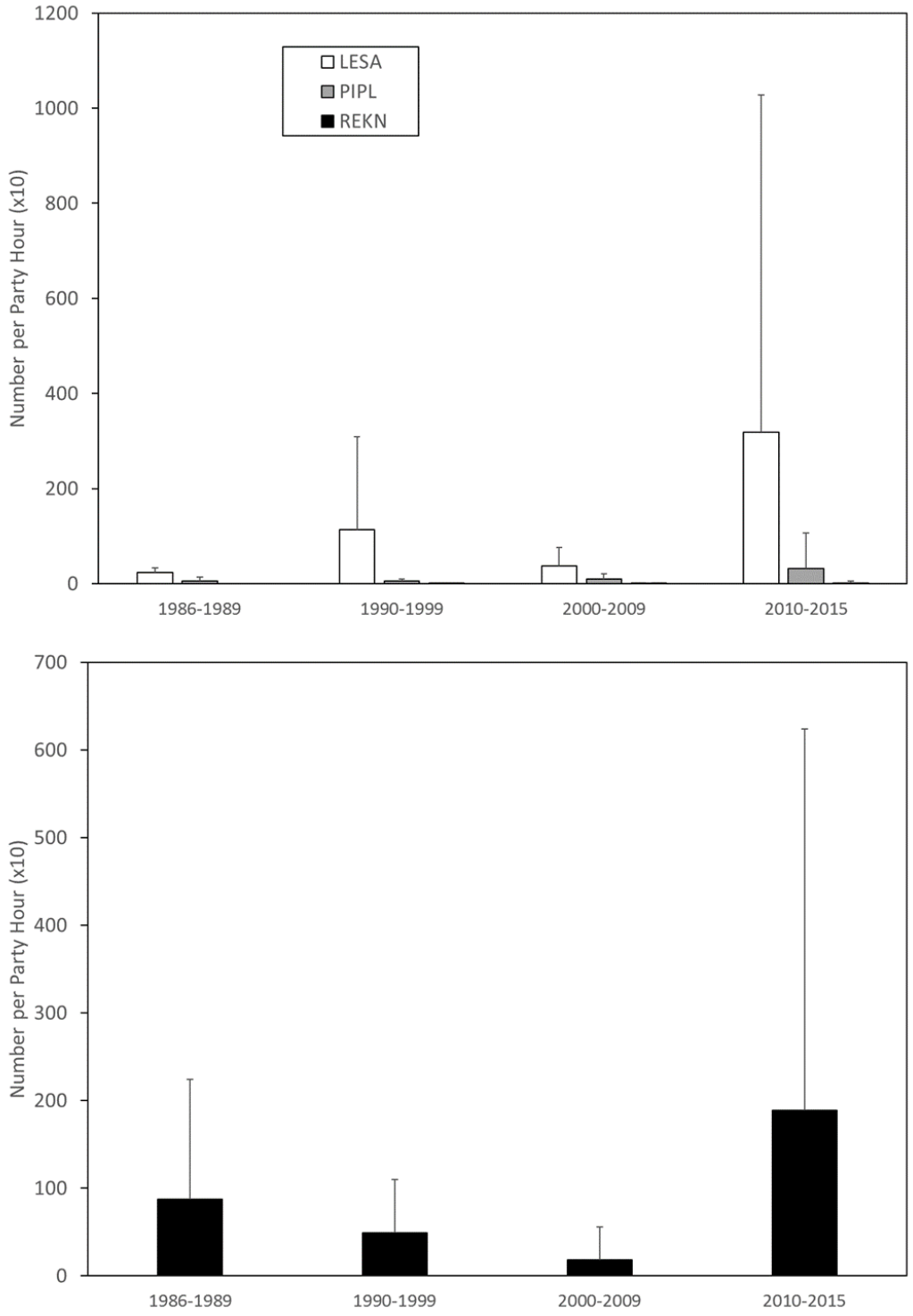

Figure 7.1. Mean numbers per party hour (x10) of shorebirds (top) and Lesser Scaup (LESC, bottom) in the Coastal Tip Christmas Bird Count circle (TXCT) by decade with standard deviation. Bars with the same letter (or no letters) are not significantly different from one another.

Appendix 8. BBS data summary and analysis: Upper Coast—Winnie Route

Table 8.1. Winnie Route regression results: Mottled Duck (MODU)

Decade	Trend	N (years)
1967-1979	NS – stable	13
1981-1989	Sig – negative	7
1990-1997	NS – stable	6
2000-2009	NS – stable	10
2010-2016	NS – Stable	7
Overall	Sig – negative	43

Table 8.2. Winnie Route regression results: Great Egret (GREG)

Decade	Trend	N (years)
1967-1979	NS - stable	13
1981-1989	NS - stable	7
1990-1997	NS - stable	6
2000-2009	Sig - positive	10
2010-2016	NS - stable	7
Overall	Sig - negative	43

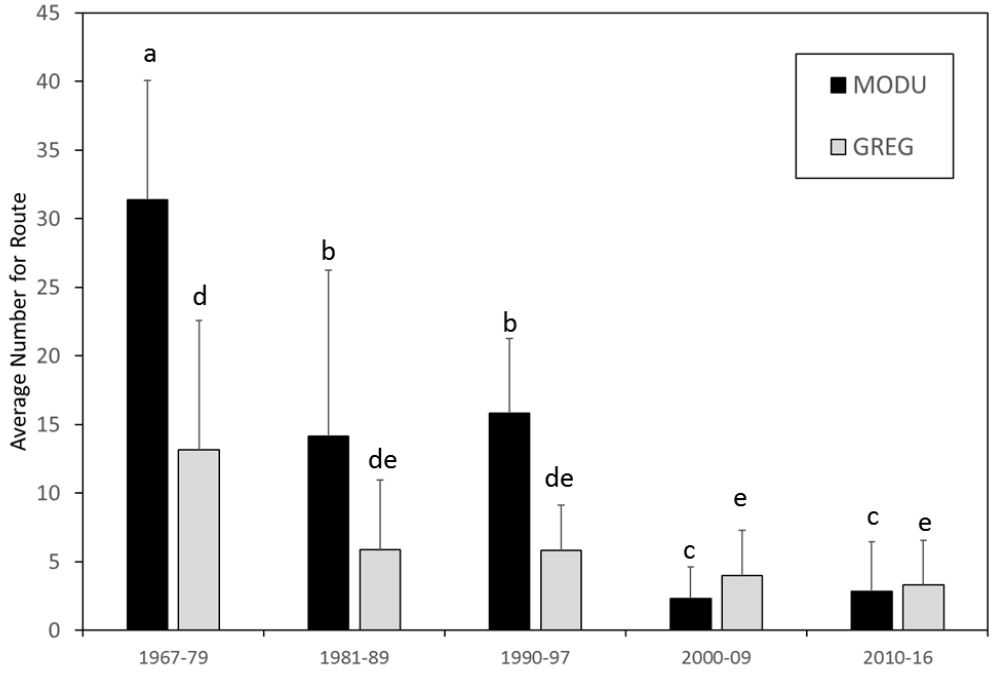

Figure 8.1. Mean numbers of breeding birds on the Winnie BBS route by decade with standard deviation. Bars with the same letter are not significantly different from each other.

Appendix 9. BBS data summary and analysis: Upper Coast—Danbury Route

Table 9.1. Danbury Route regression results: Mottled Duck (MODU)

Decade	Trend	N (years)
1967-1978	NS - stable	6
1980-1989	Sig - negative	8
1990-1999	NS - stable	10
2001-2009	NS - stable	7
2010-2015	NS - stable	6
Overall	Sig – negative	37

Table 9.2. Danbury Route regression results: Great Egret (GREG)

Decade	Trend	N (years)
1967-1978	NS - stable	6
1980-1989	NS - stable	8
1990-1999	NS - stable	10
2001-2009	Sig - Negative	7
2010-2015	NS - stable	6
Overall	NS – stable	37

Table 9.3. Danbury Route regression results: Forster's Tern (FOTE)

Decade	Trend	N (years)
1967-1978	--	
1980-1989	NS – stable	8
1990-1999	NS - stable	10
2001-2009	NS – stable	7
2010-2015	NS - stable	6
Overall	NS – stable	37

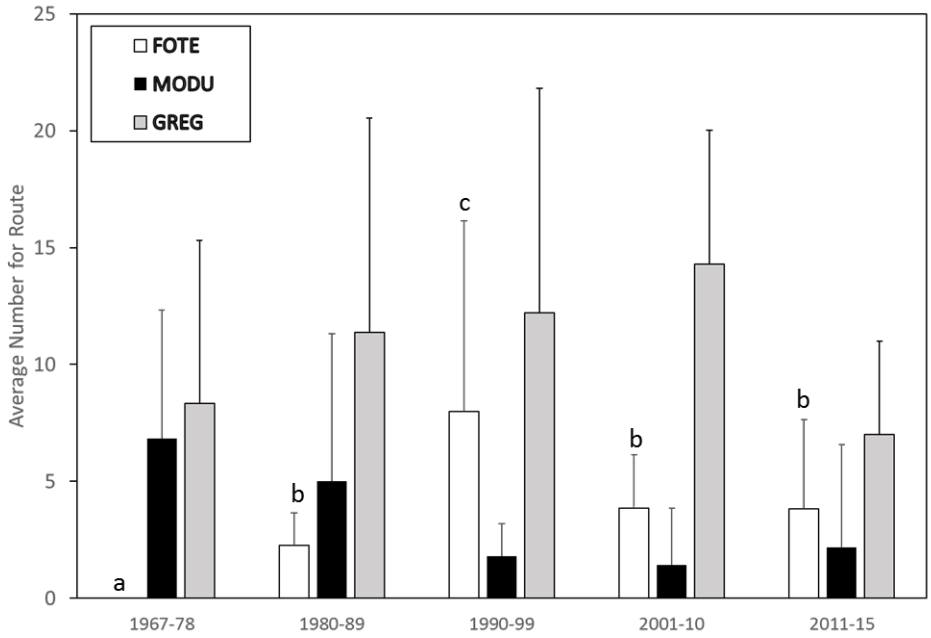

Figure 9.1. Mean numbers of breeding birds on the Danbury BBS route by decade with standard deviation. Bars with the same letter are not significantly different from each other.

Appendix 10. BBS data summary and analysis: Mid-Coast—Indianola Route

Table 10.1. Indianola Route regression results: Mottled Duck (MODU)

Decade	Trend	N (years)
1967-1979	NS - stable	10
1980-1988	NS - stable	7
1990-1999	Sig - negative	8
2000-2009	NS - stable	10
2010-2014	NS - stable	5
Overall	NS – stable	39

Table 10.2. Indianola Route regression results: Great Egret (GREG)

Decade	Trend	N (years)
1967-1979	NS - stable	10
1980-1988	NS - stable	7
1990-1999	Sig - negative	8
2000-2009	NS - stable	10
2010-2014	NS - stable	5
Overall	NS – stable	39

Table 10.3. Indianola Route regression results: Gull-billed Tern (GBTE)

Decade	Trend	N (years)
1967-1979	Sig - positive	10
1980-1988	NS - stable	7
1990-1999	NS – stable	8
2000-2009	NS – stable	10
2010-2014	Sig – neg	5
Overall	Sig – positive	39

Table 9. Indianola Route regression results: Forster's Tern (FOTE)

Decade	Trend	N (years)
1967-1979	NS - stable	10
1980-1988	NS - stable	7
1990-1999	NS - stable	8
2000-2009	NS - stable	10
2010-2014	NS (but close 0.06) - negative	5
Overall	NS – stable	39

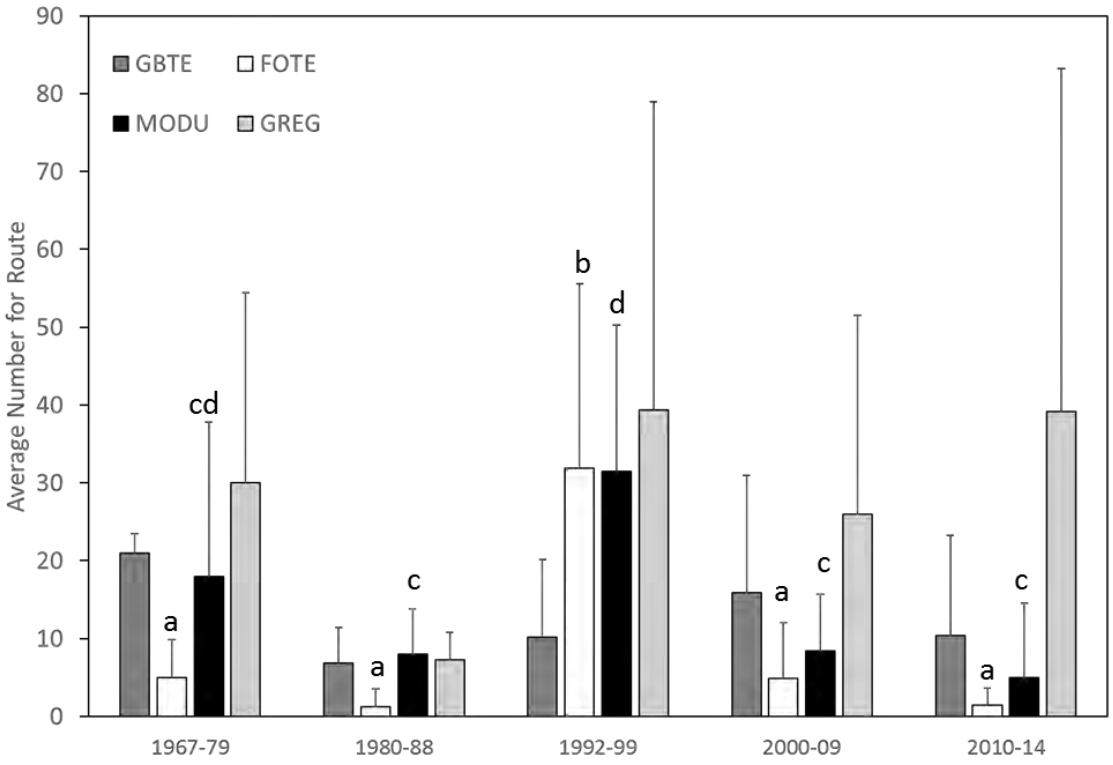

Figure 10.1. Mean numbers of breeding birds on the Indianola BBS route by decade with standard deviation. Bars with the same letter are not significantly different from each other.

Appendix 11. BBS data summary and analysis: Lower Coast—Laguna Atascosa Route

Table 11.1. Laguna Atascosa Route regression results: Mottled Duck (MODU)

Decade	Trend	N (years)
1969-1979	NS – stable	11
1984-1989	NS – stable	6
1990-1999	NS – stable	8
2000-2009	NS – stable	8
2010-2016	NS – stable	6
Overall	NS – stable	39

Table 11.2. Laguna Atascosa Route regression results: Great Egret (GREG)

Decade	Trend	N (years)
1969-1979	NS – stable	11
1984-1989	NS – stable	6
1990-1999	NS – stable	8
2000-2009	Sig - positive	8
2010-2016	NS – stable	6
Overall	Sig – positive	39

Table 11.3. Laguna Atascosa Route regression results: Gull-billed Tern (GBTE)

Decade	Trend	N (years)
1969-1979	NS – stable	11
1984-1989	NS – stable	6
1990-1999	NS – stable	8
2000-2009	NS – stable	8
2010-2016	NS – stable	6
Overall	NS – stable	39

Table 14. Laguna Atascosa Route regression results: Forster's Tern (FOTE)

Decade	Trend	N (years)
1969-1979	NS – stable	11
1984-1989	NS – stable	6
1990-1999	NS – stable	8
2000-2009	NS – stable	8
2010-2016	NS – stable	6
Overall	NS – stable	39

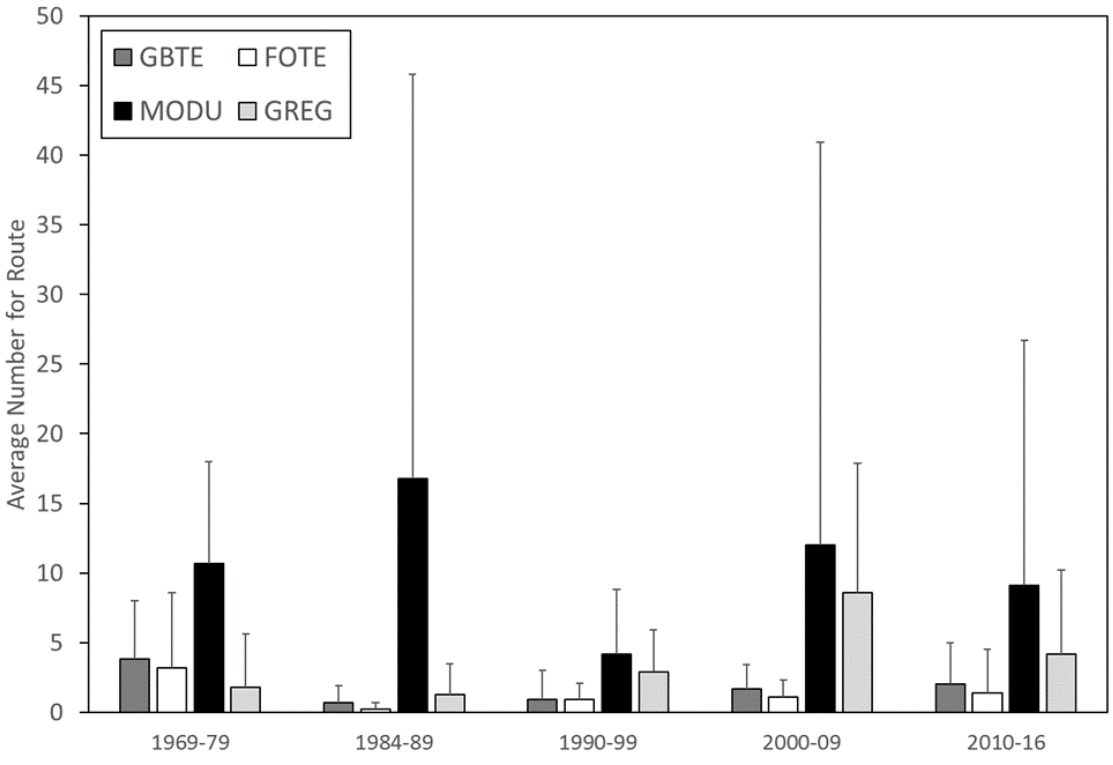

Figure 11.1. Mean numbers of breeding birds on the Laguna Atascosa BBS route by decade with standard deviation. Bars with the same letter are not significantly different from each other.

IV. Conceptual Ecosystem Models

All CEMs for all components

IV-1. Fisheries Health Data Conceptual Ecosystem Models

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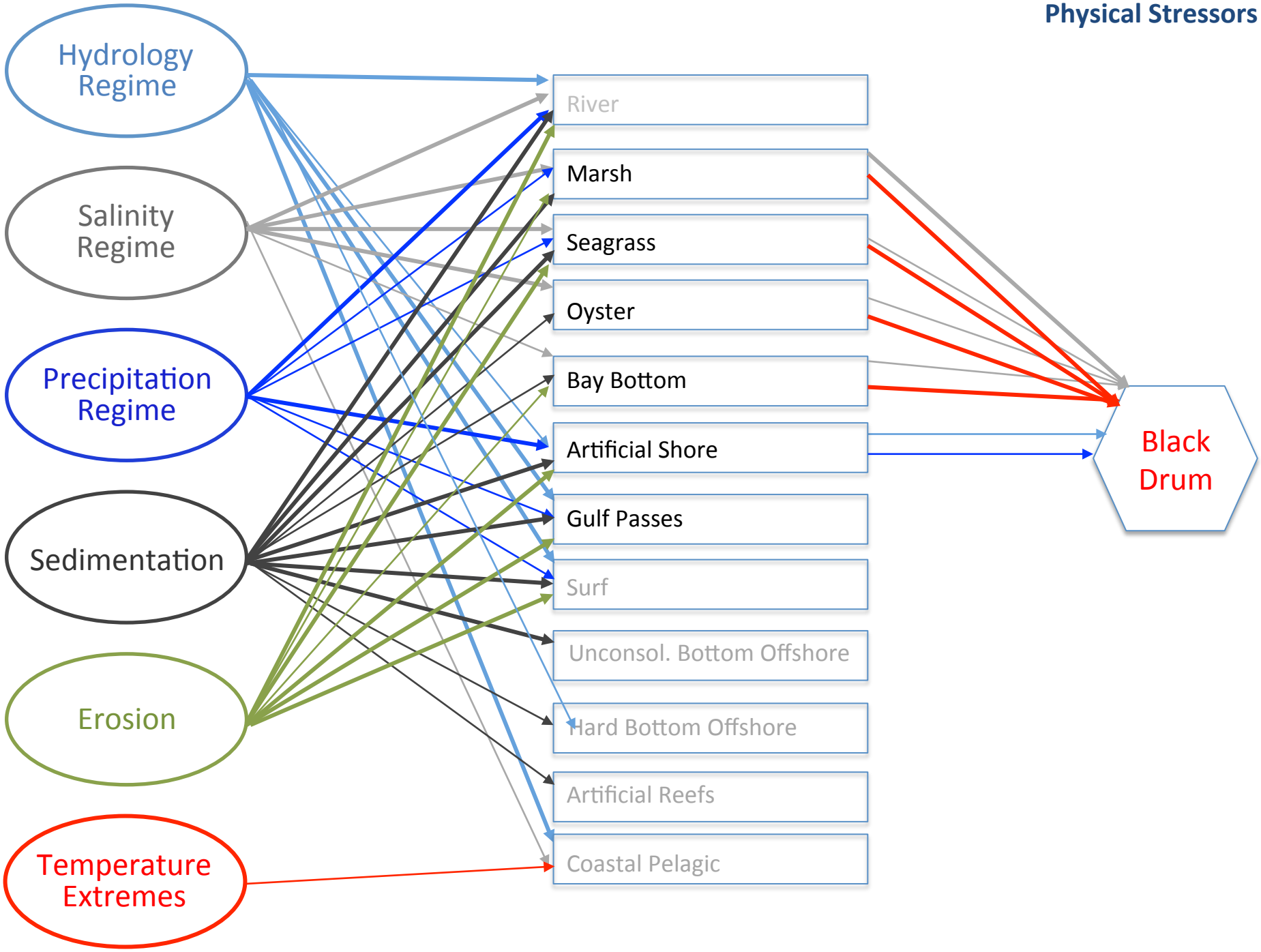
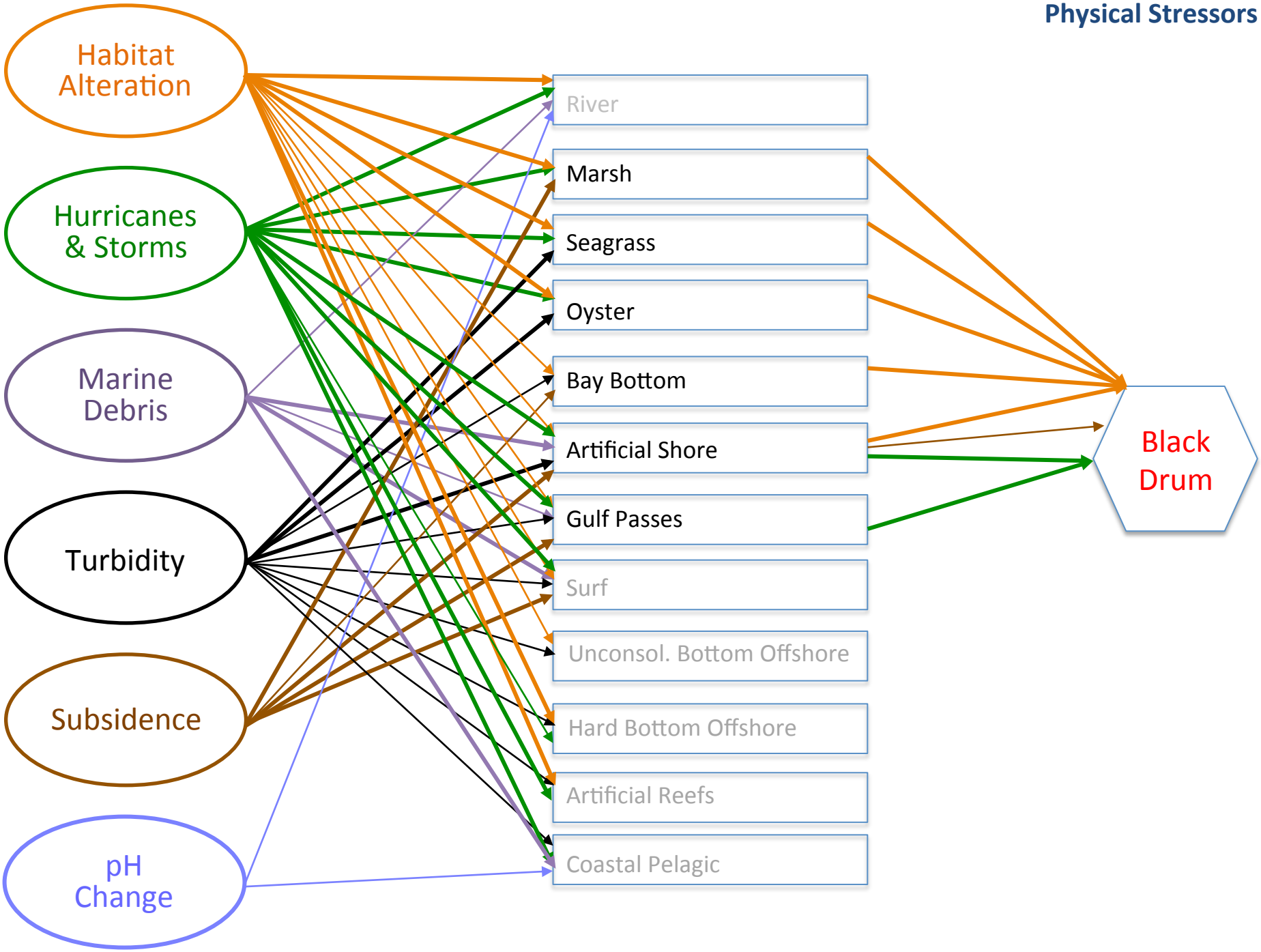
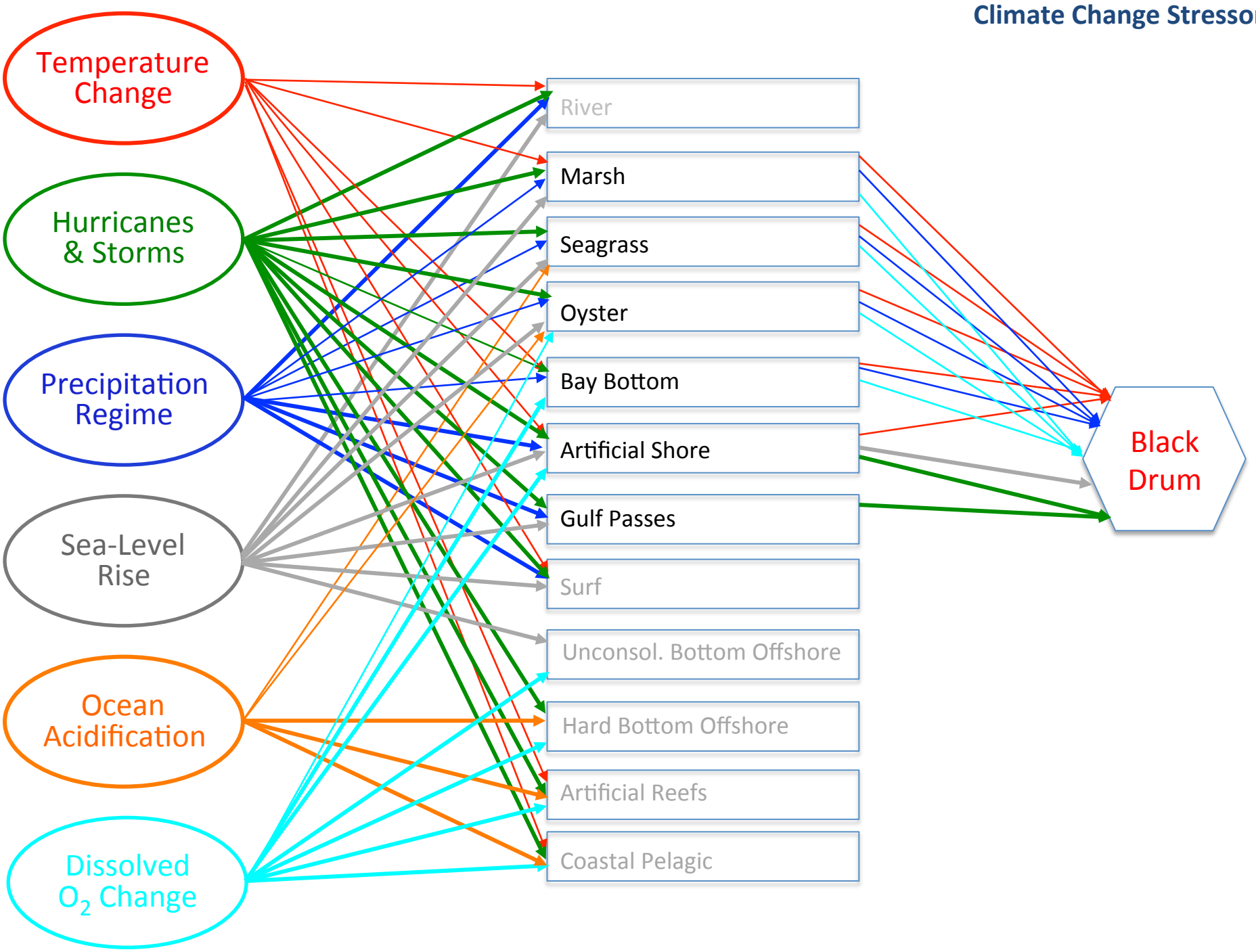


Physical Stressors - 2

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Sea-Level Rise
Ocean Acidification
Dissolved O_2 Change
River
Marsh
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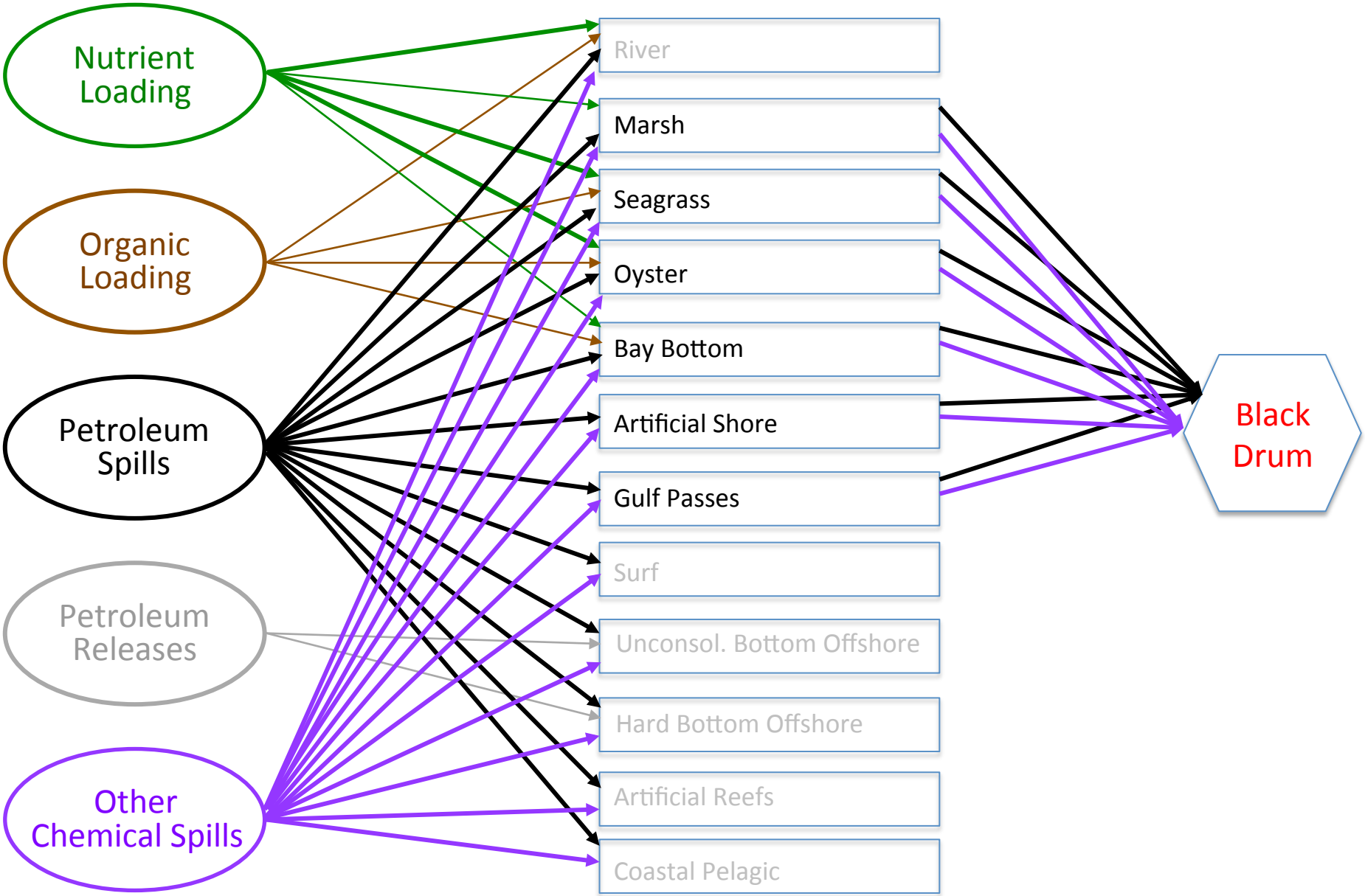
Bay Bottom
Artificial Shore
Gulf Passes
Surf
Unconsol. Bottom Offshore
Hard Bottom Offshore
Artificial Reefs
Coastal Pelagic
Black Drum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Seagrass
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Surf
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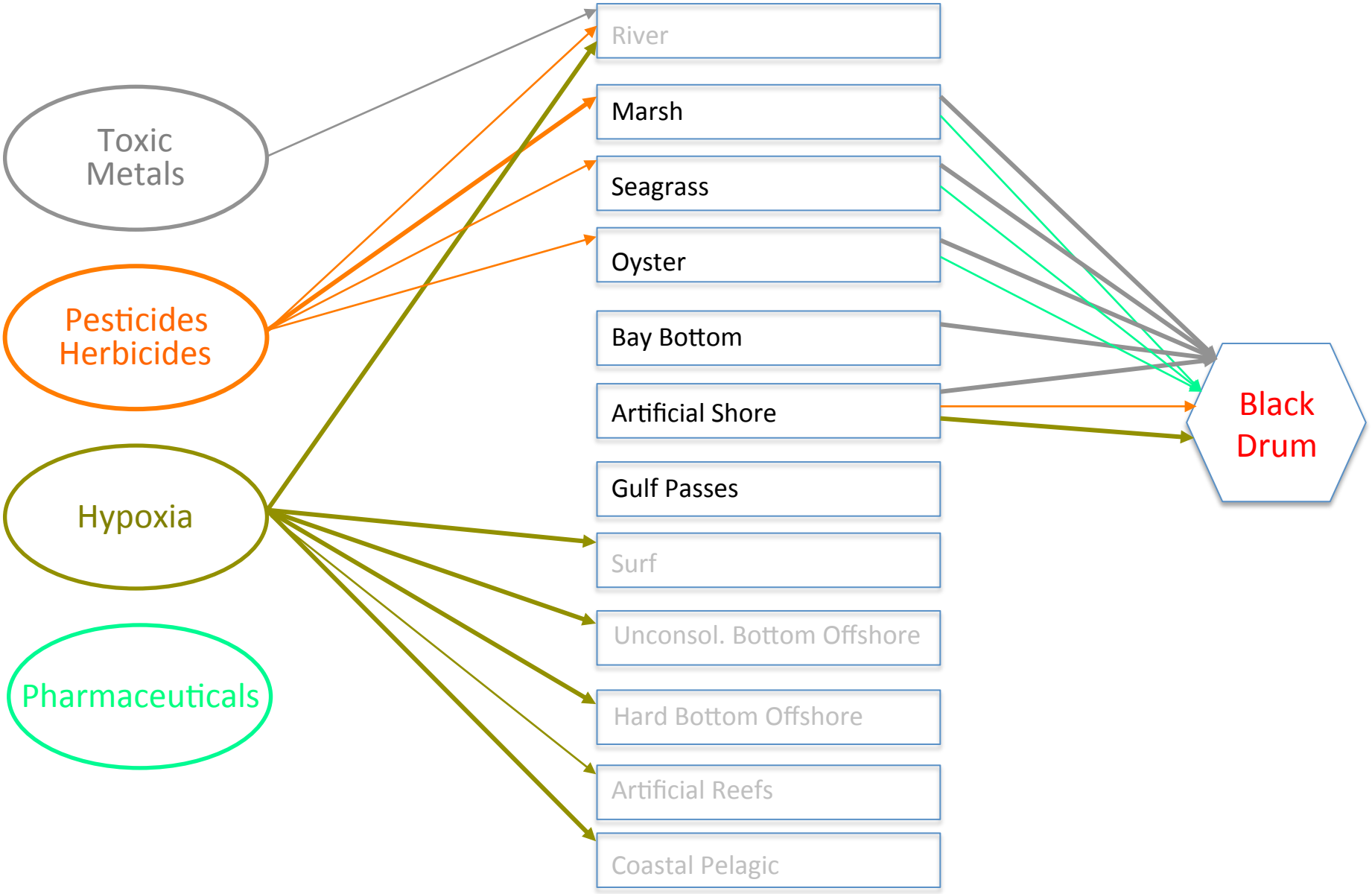
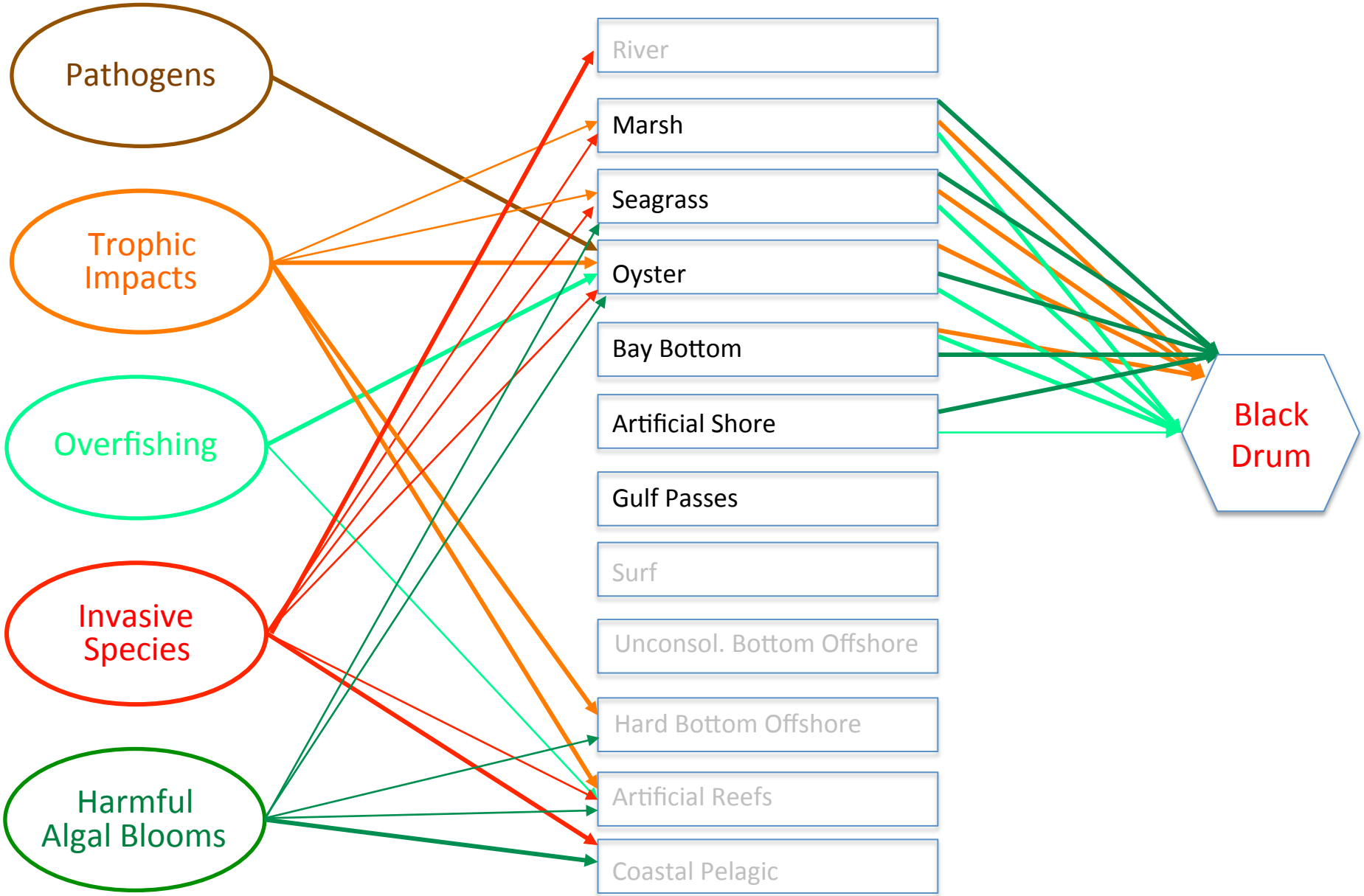
Hard Bottom Offshore
Artificial Reefs
Coastal Pelagic
Black Drum

Chemical Stressors - 2



Biological Stressors



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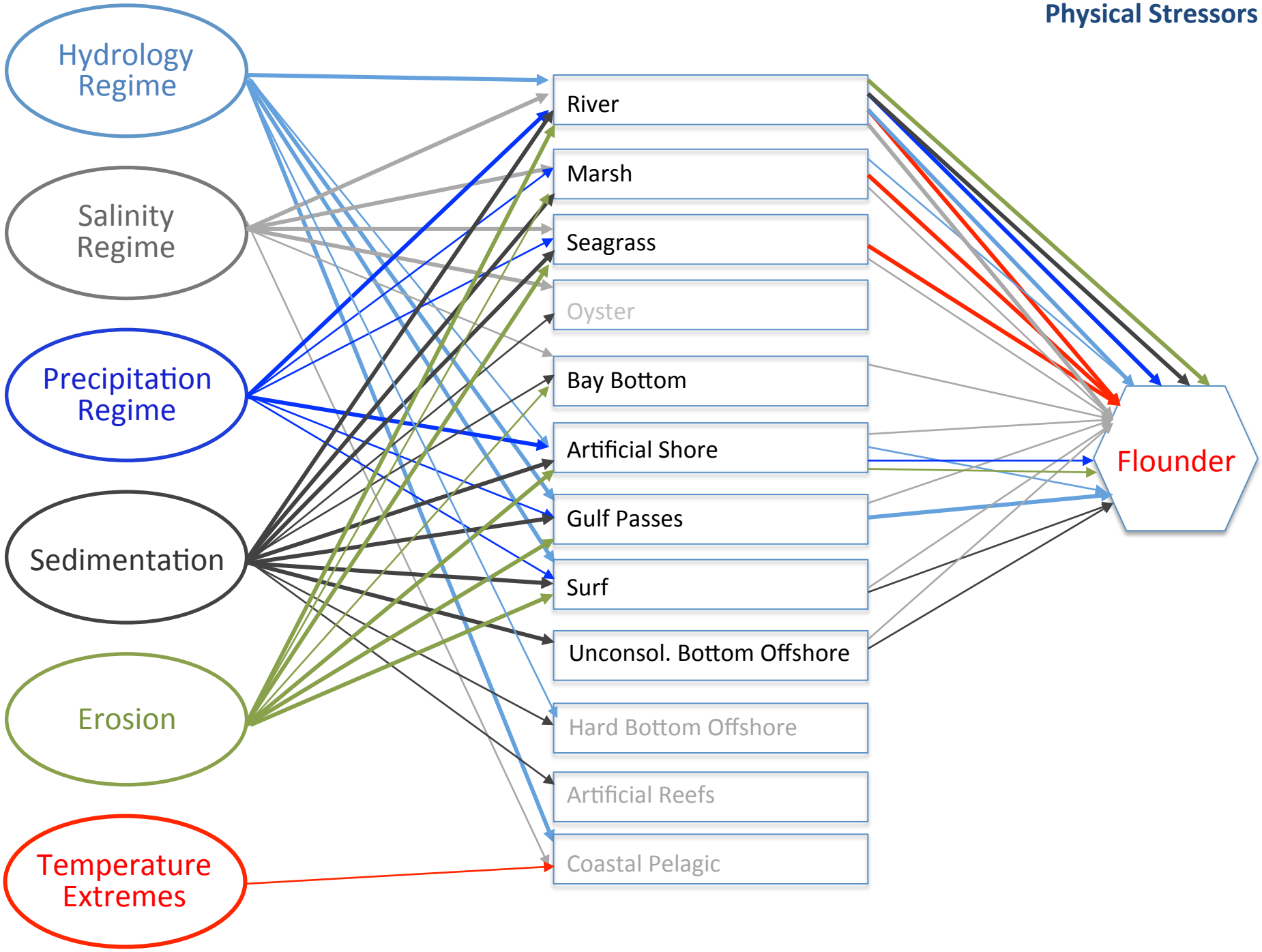

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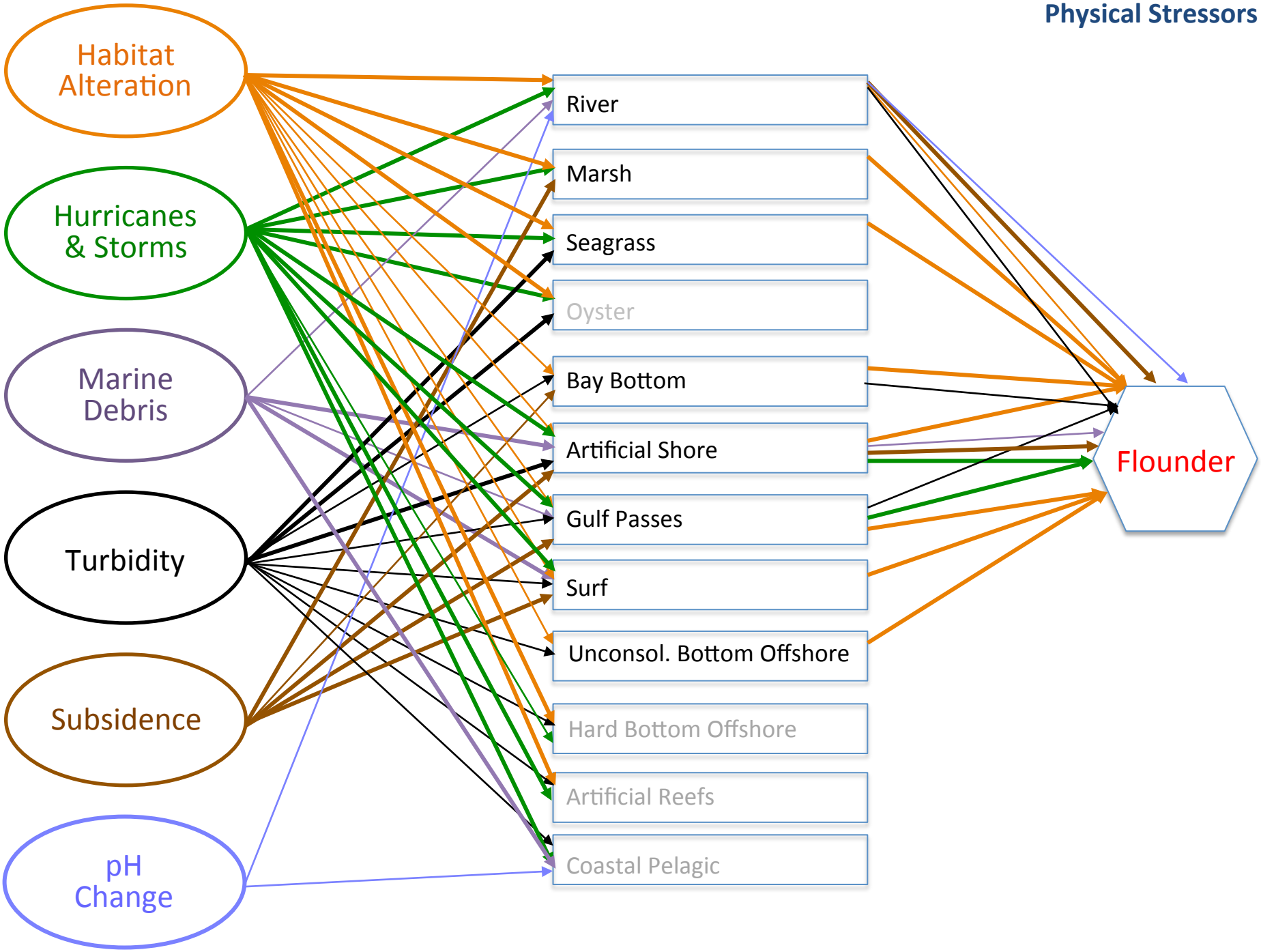

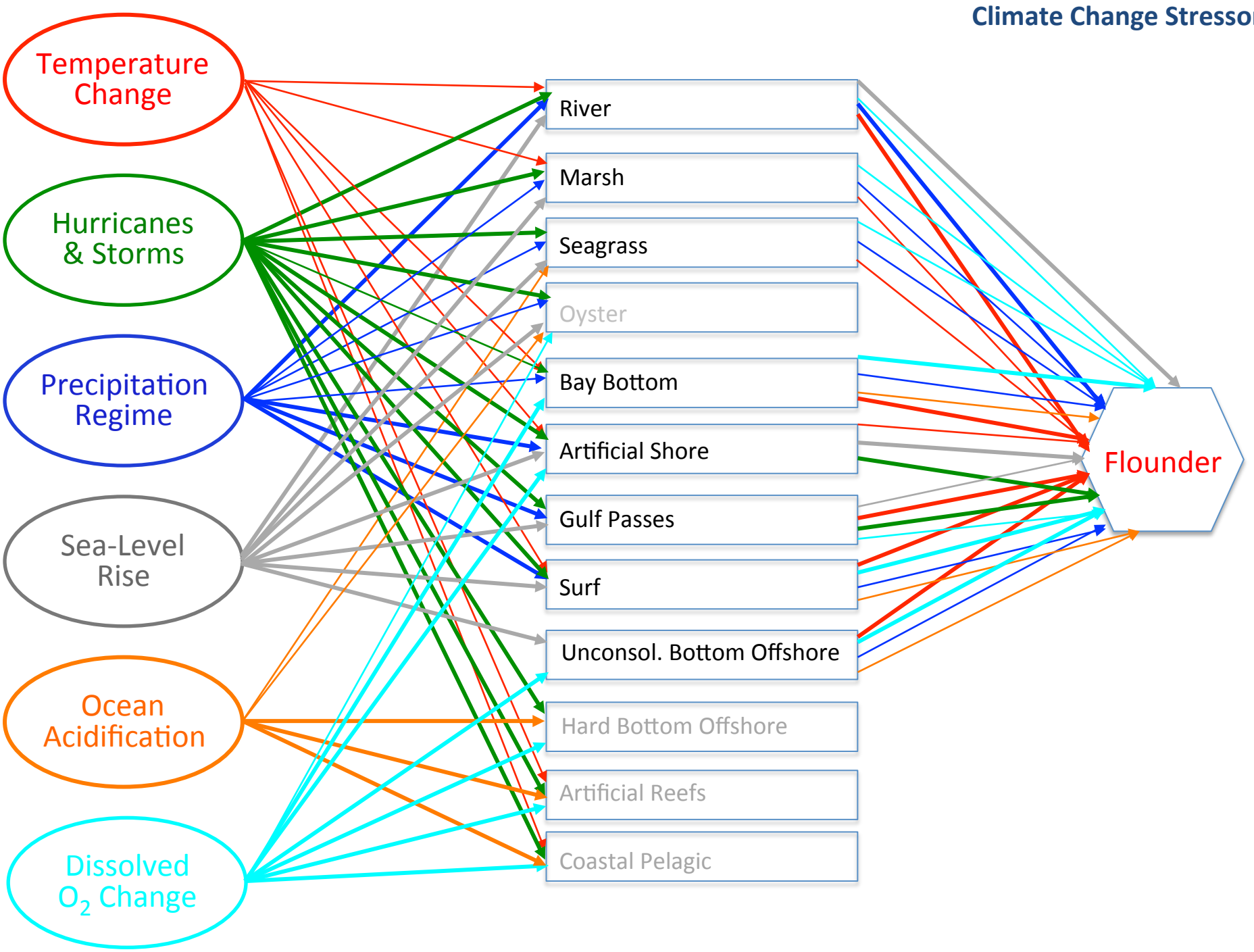
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Precipitation Regime
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Ocean Acidification
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River
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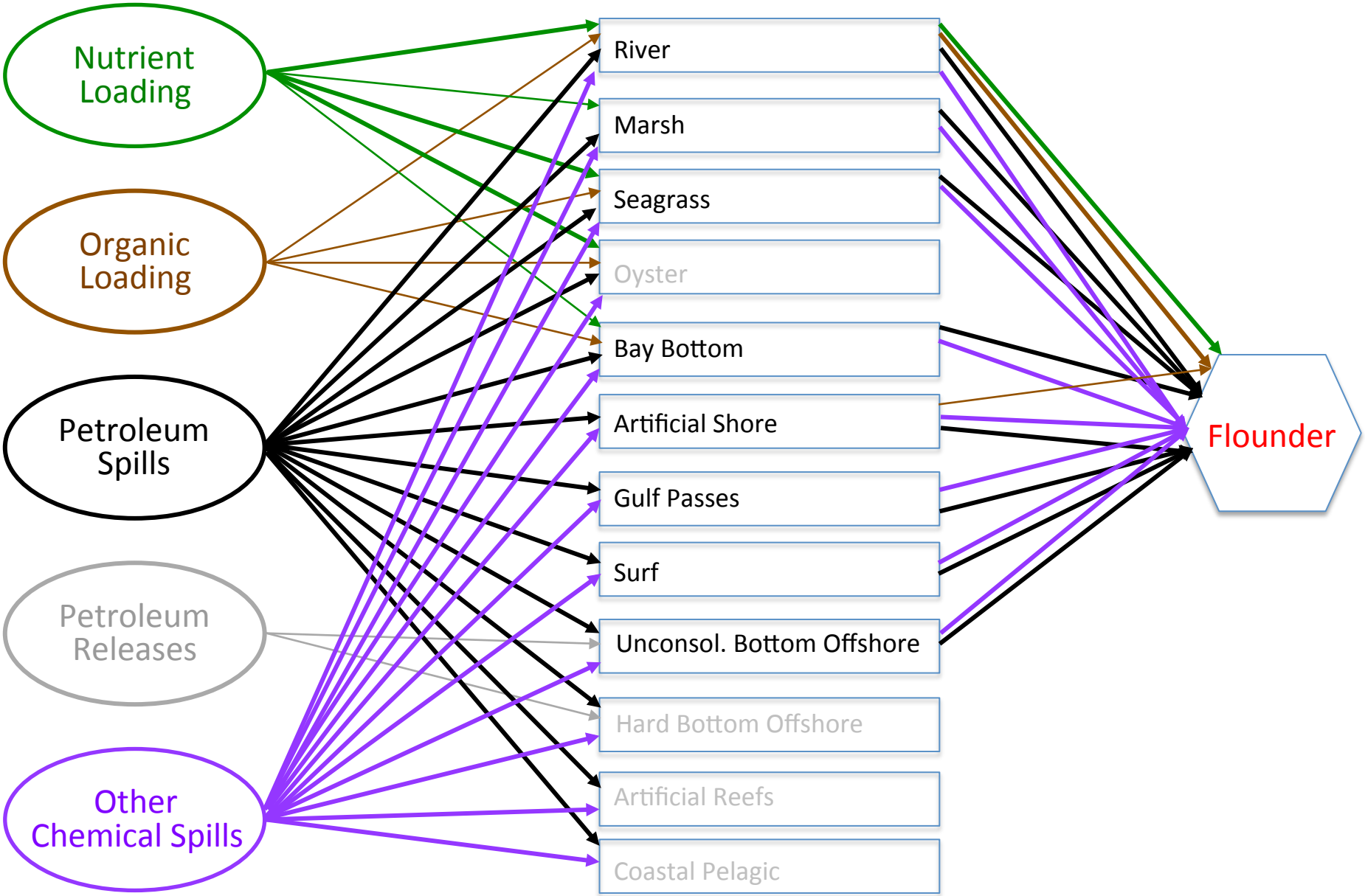
Artificial Reefs
Coastal Pelagic
Flounder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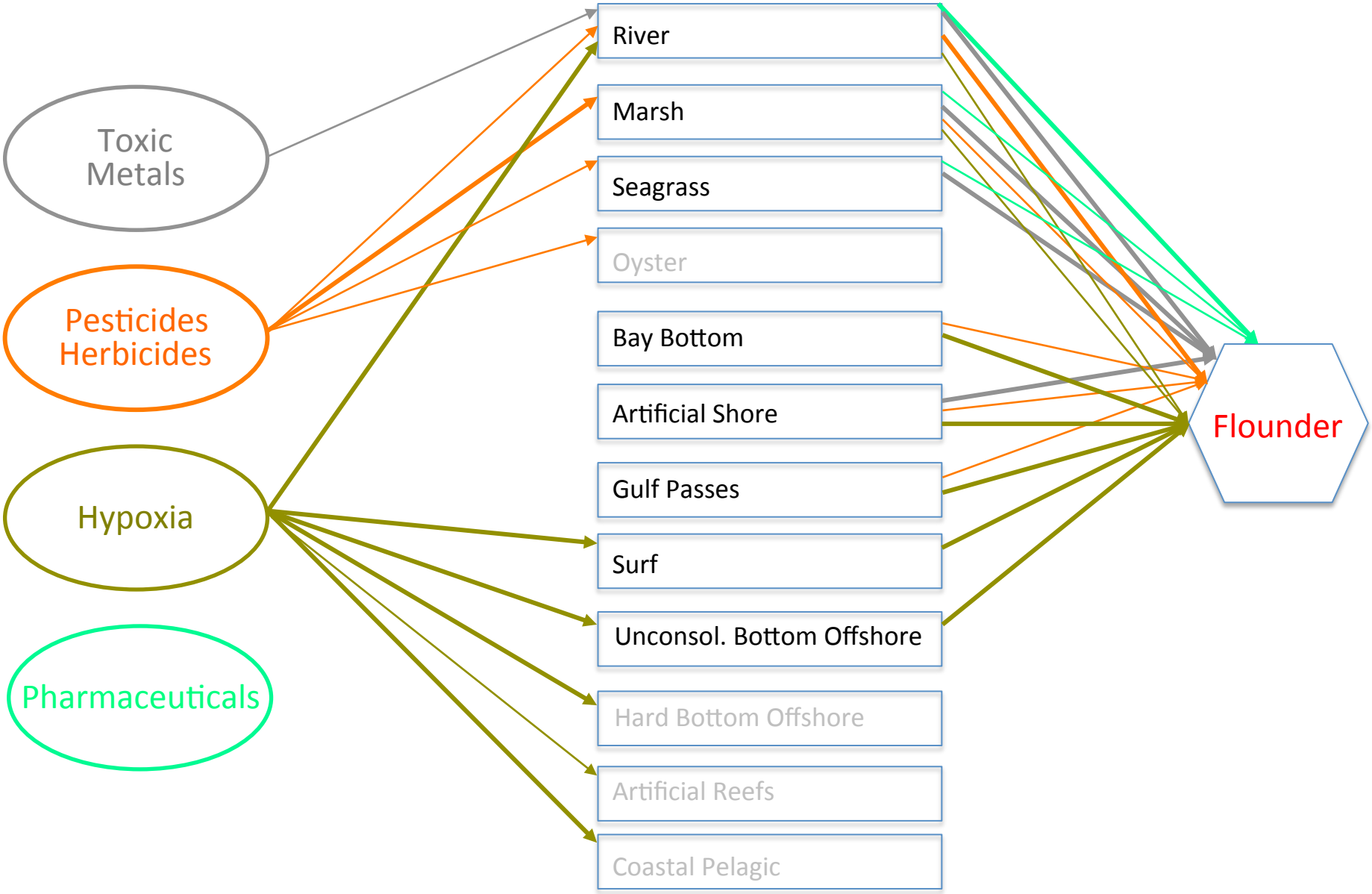
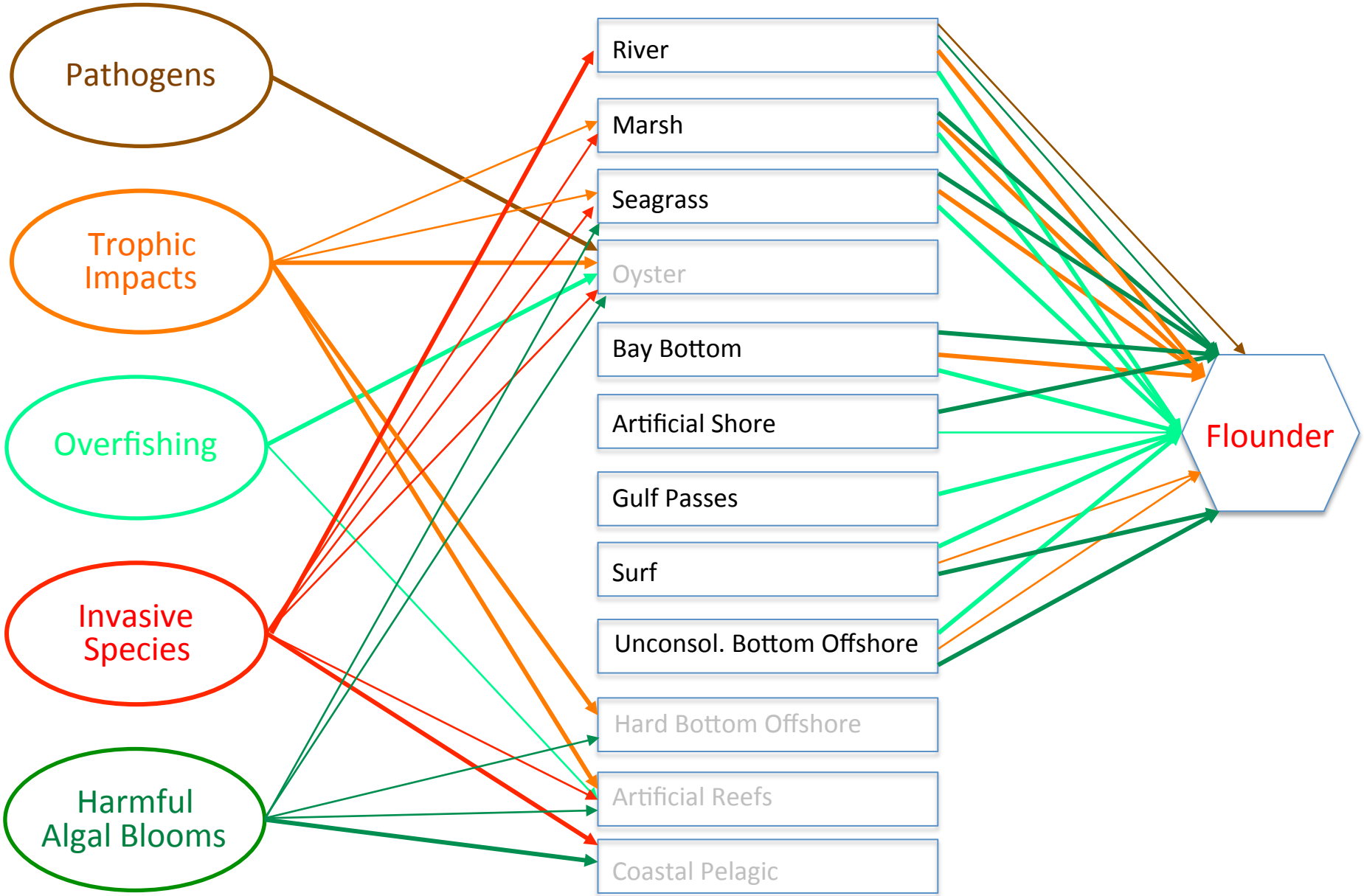
Coastal Pelagic
Flounder

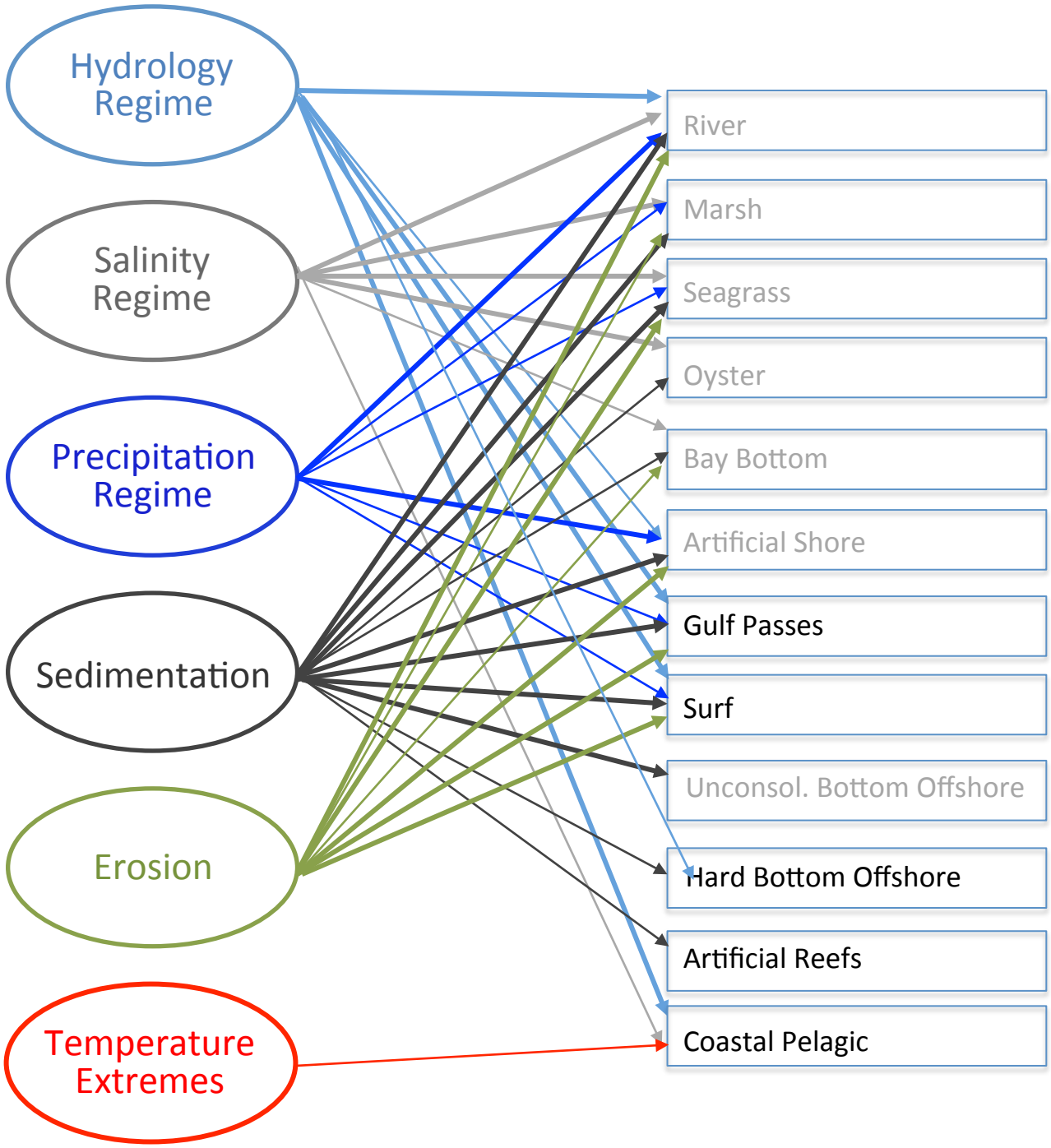
Chemical Stressors - 2



Biological Stressors

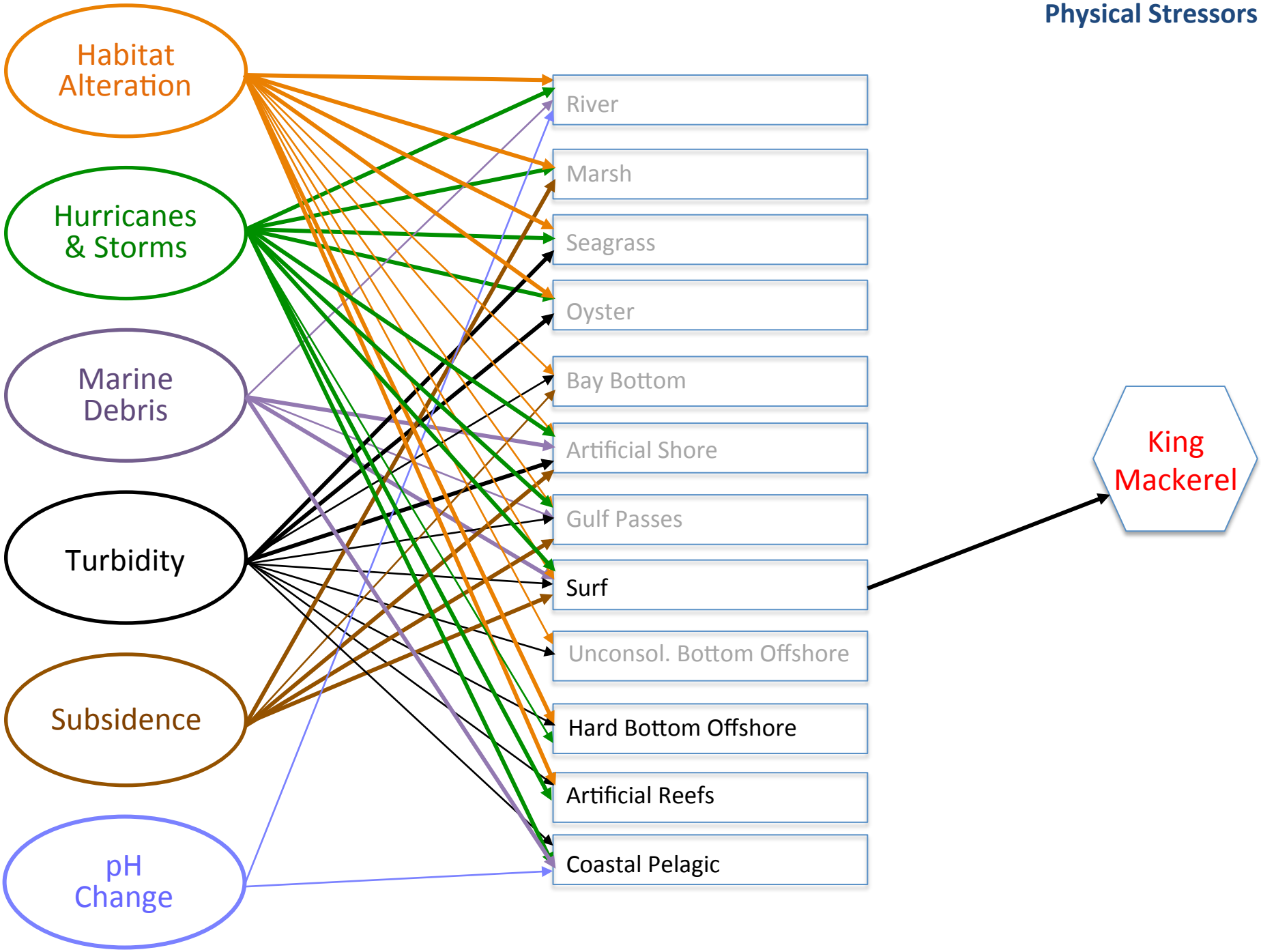


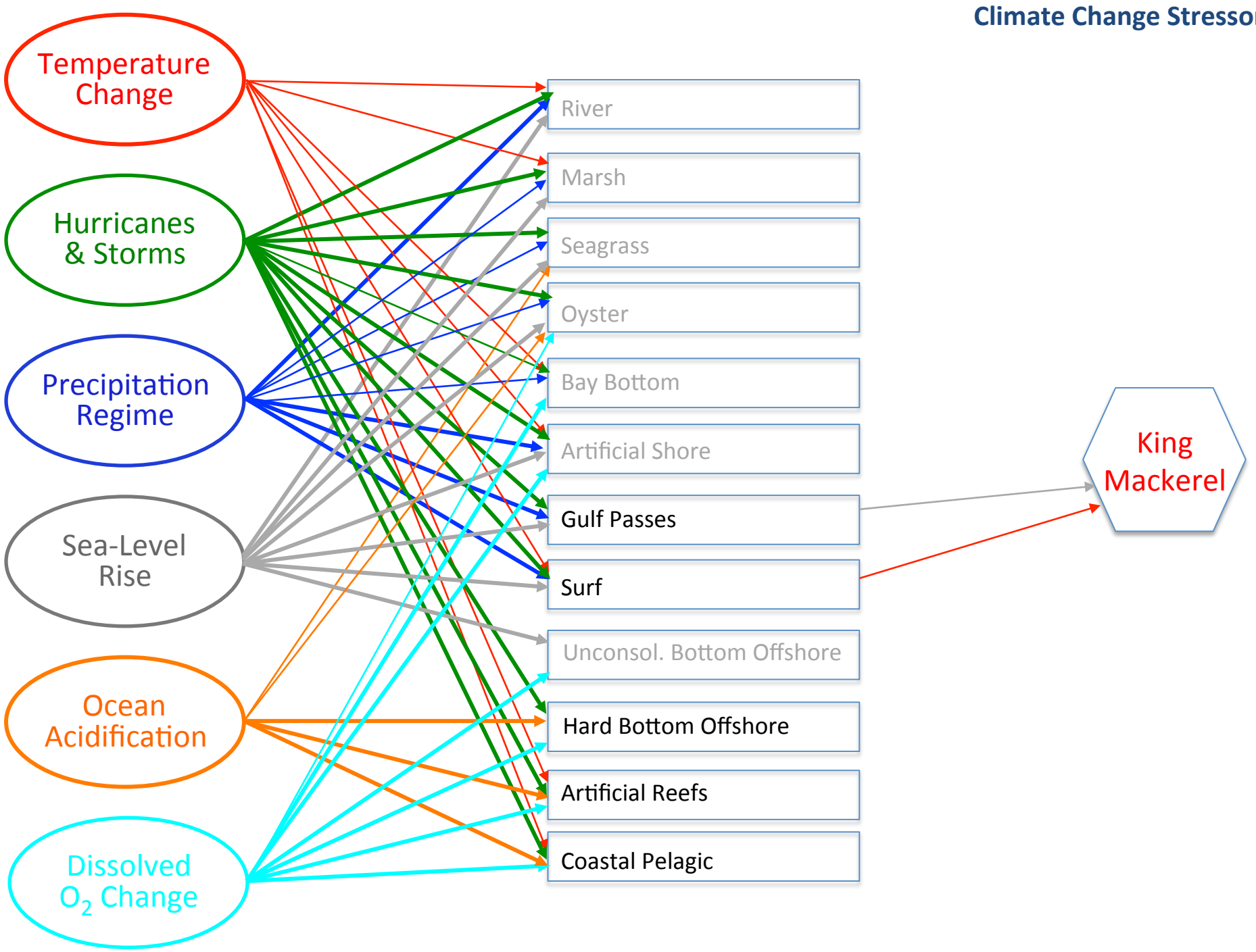
Physical Stressors - 1



King Mackerel

Physical Stressors - 2

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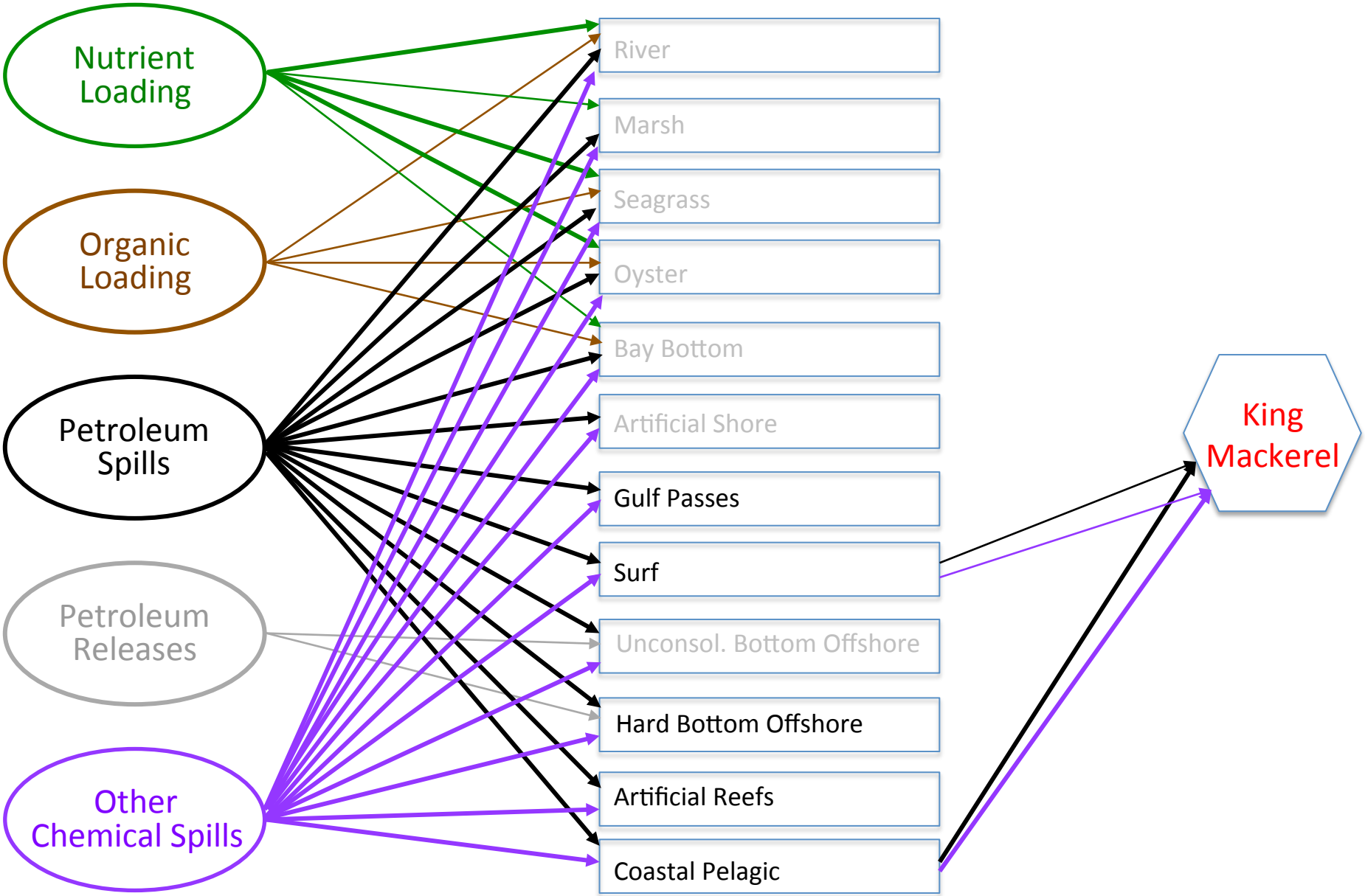
Coastal Pelagic
King Mackerel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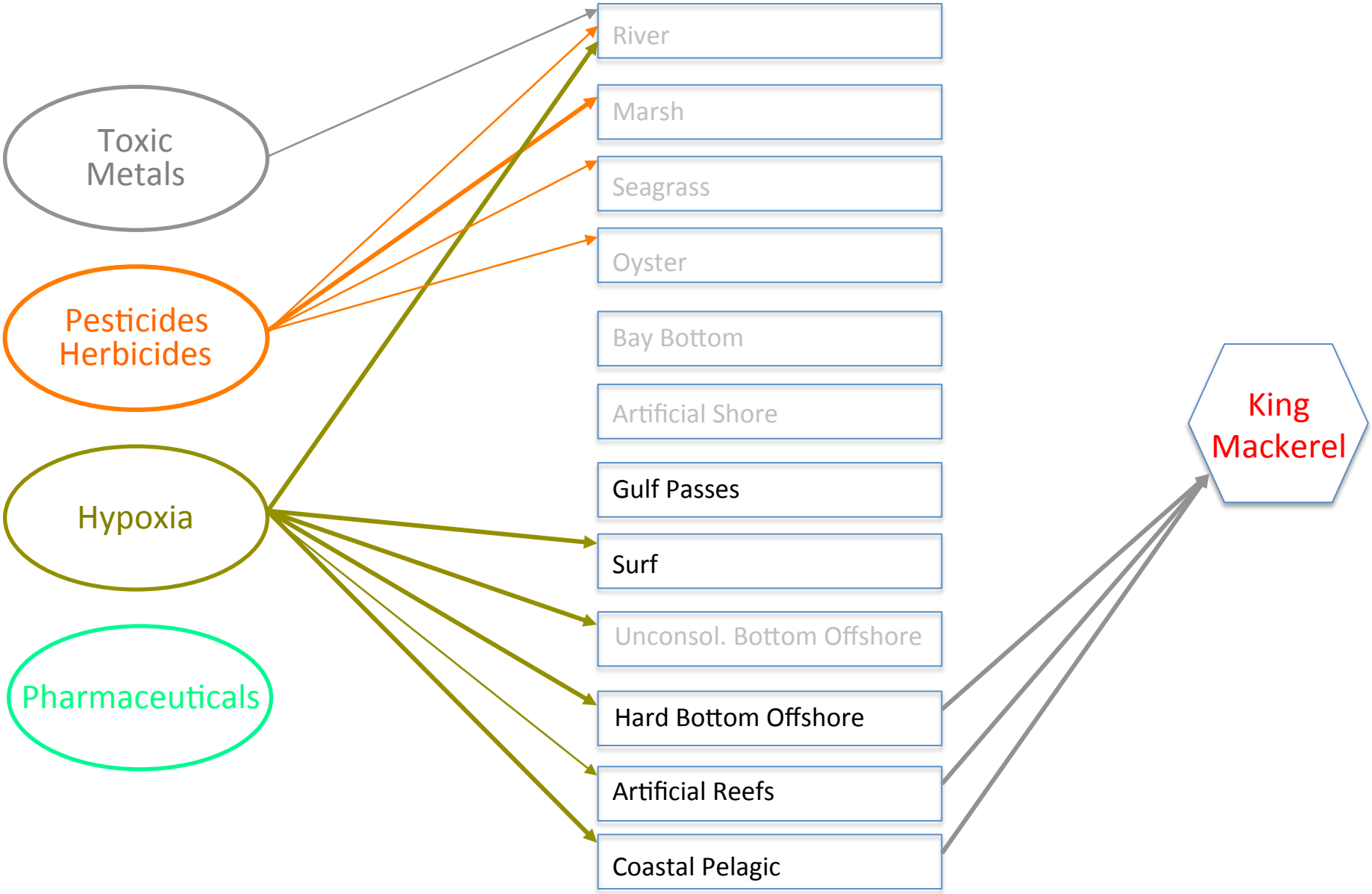
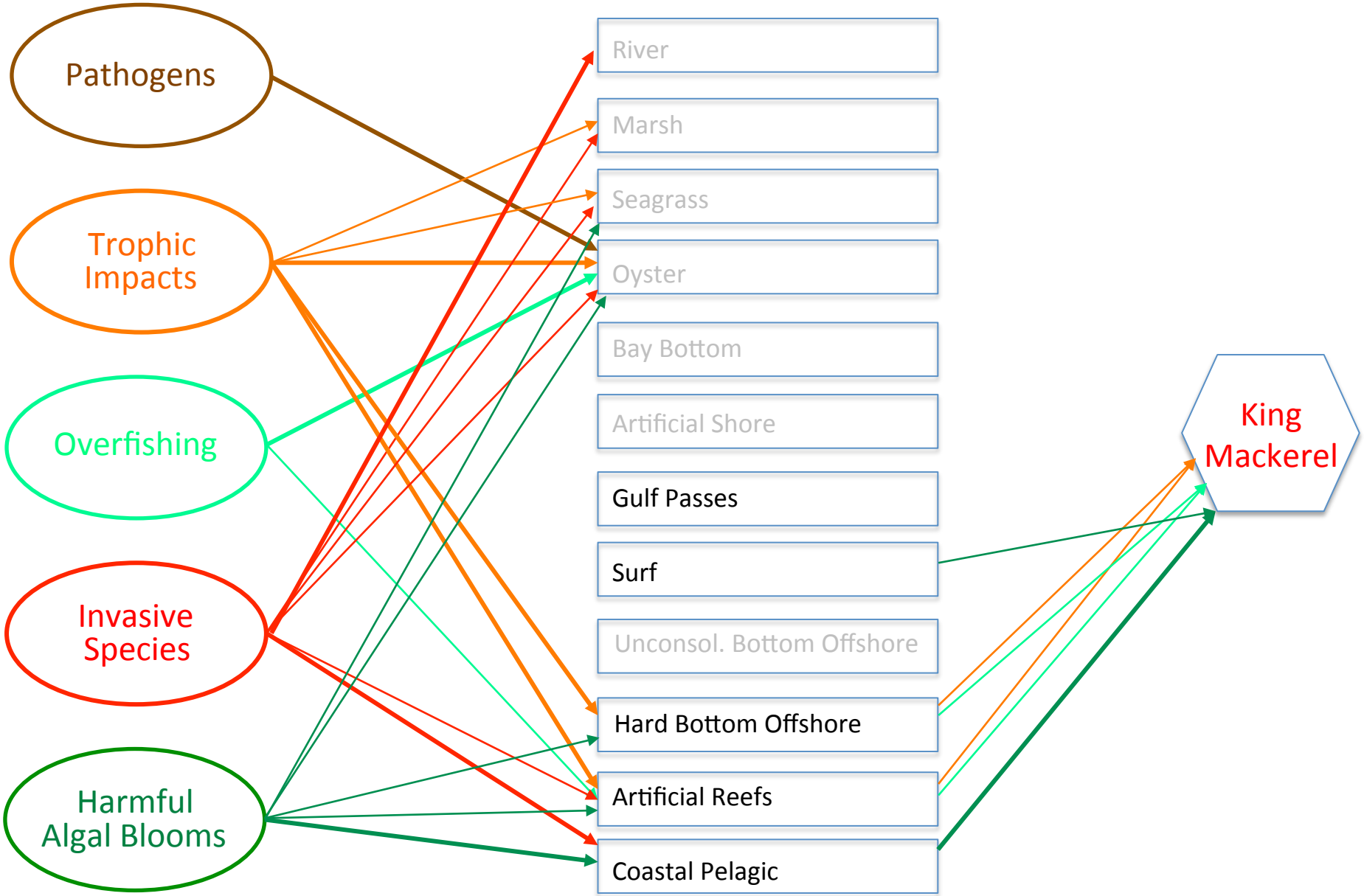
Artificial Reefs
Coastal Pelagic
King Mackerel

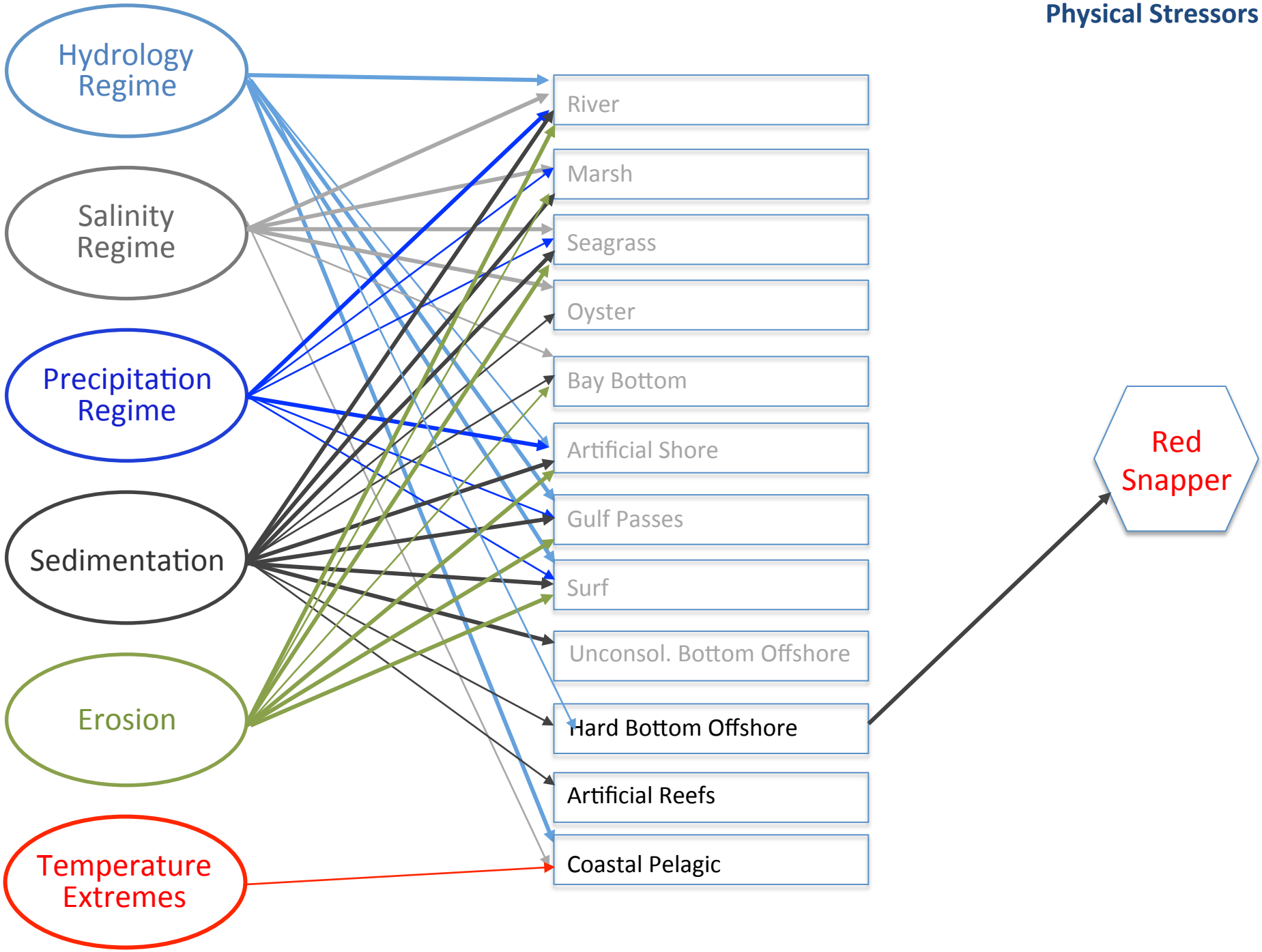
Chemical Stressors - 2



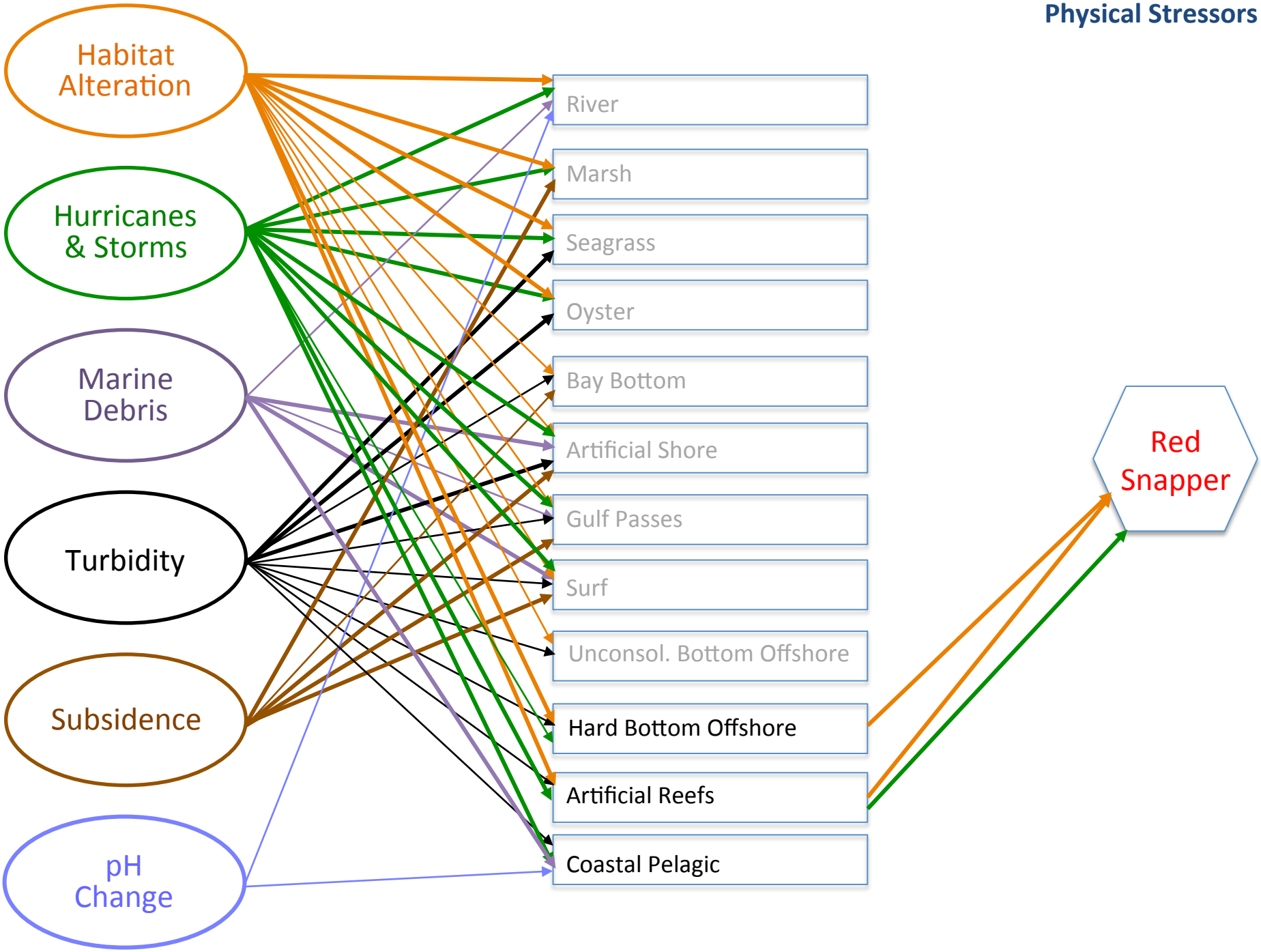
Biological Stressors

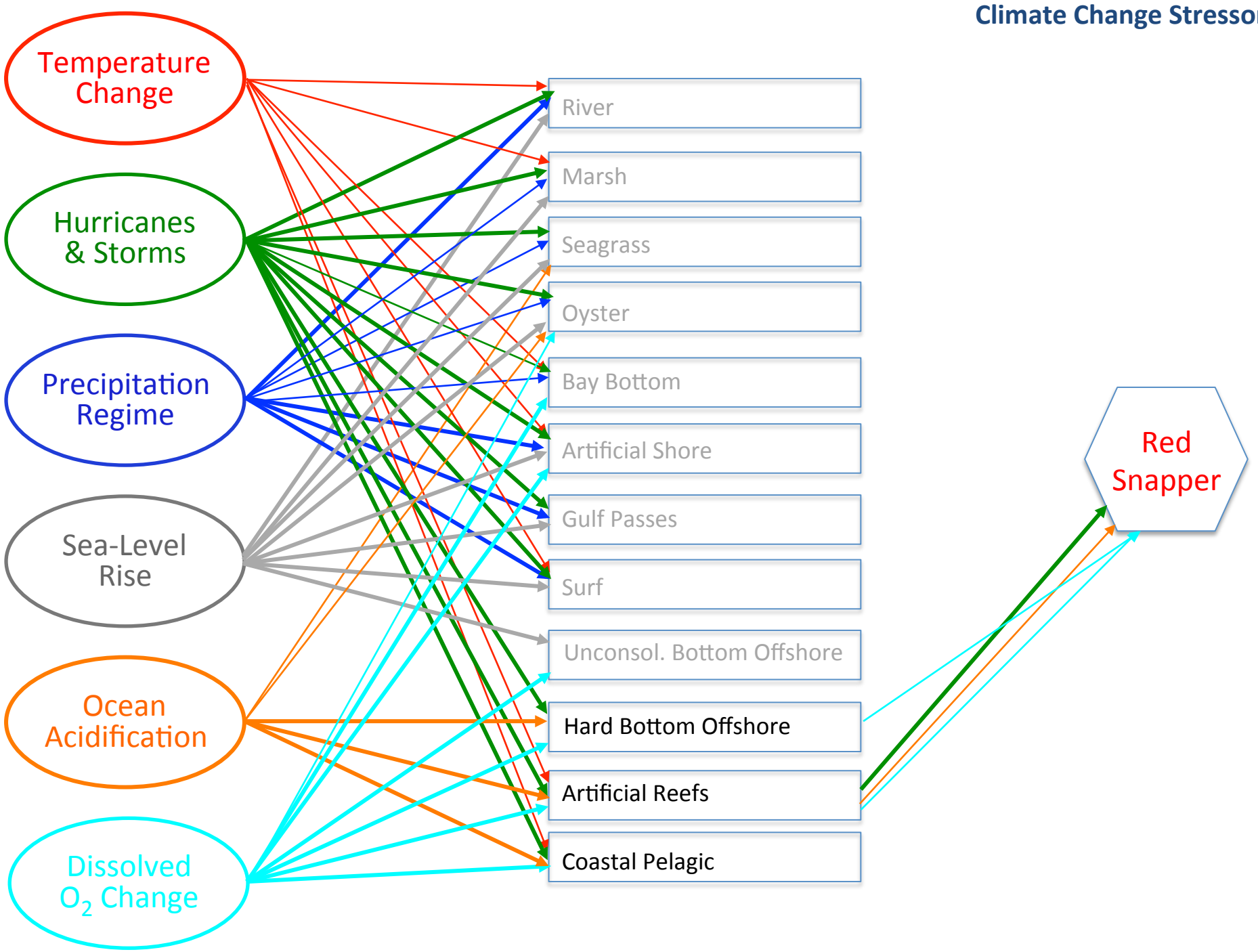


Physical Stressors - 1



Physical Stressors - 2

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Precipitation Regime
Sea-Level Rise
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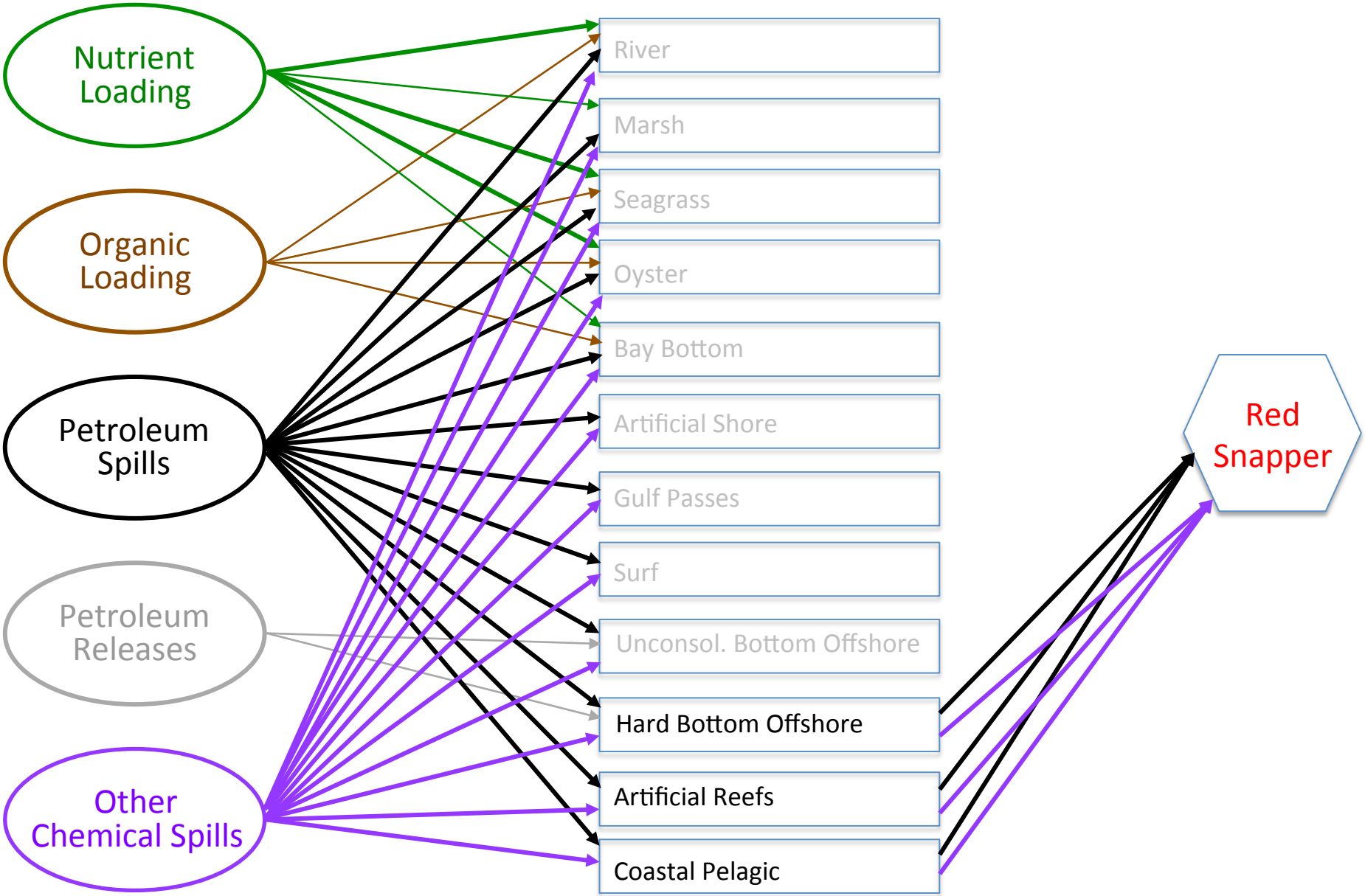
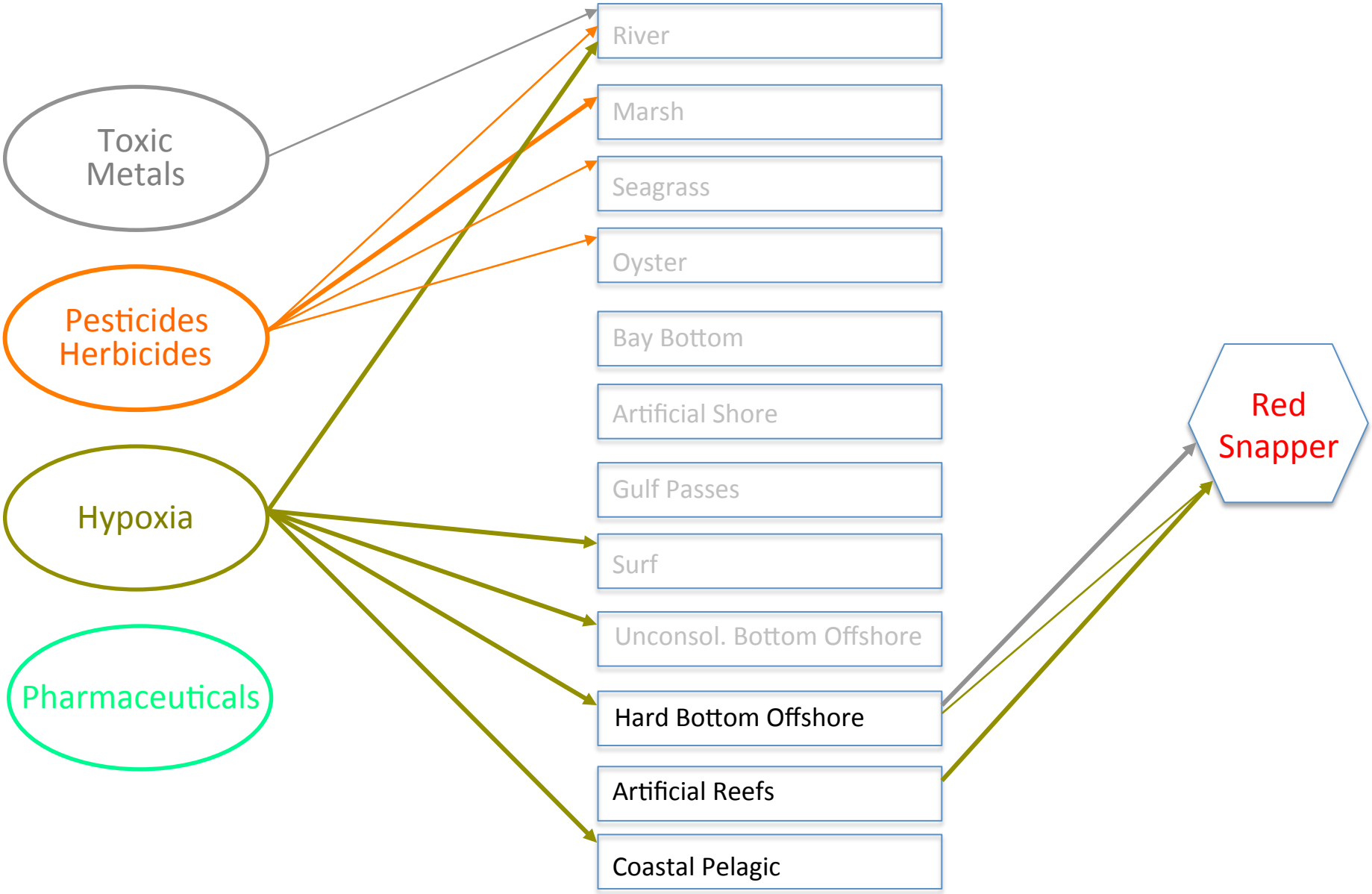
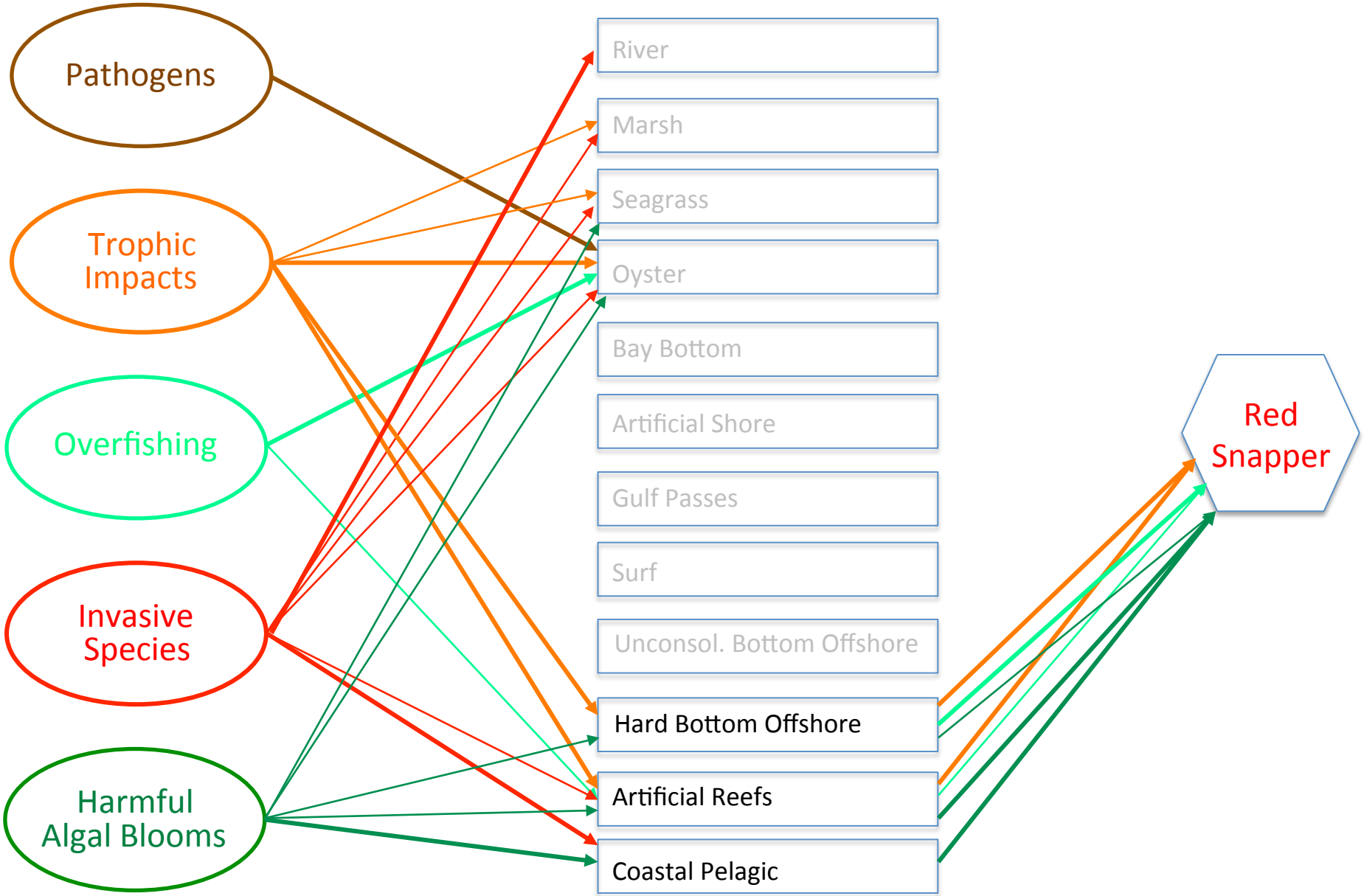
Artificial Shore
Gulf Passes
Surf
Unconsol. Bottom Offshore
Hard Bottom Offshore
Artificial Reefs
Coastal Pelagic
Red Snapper

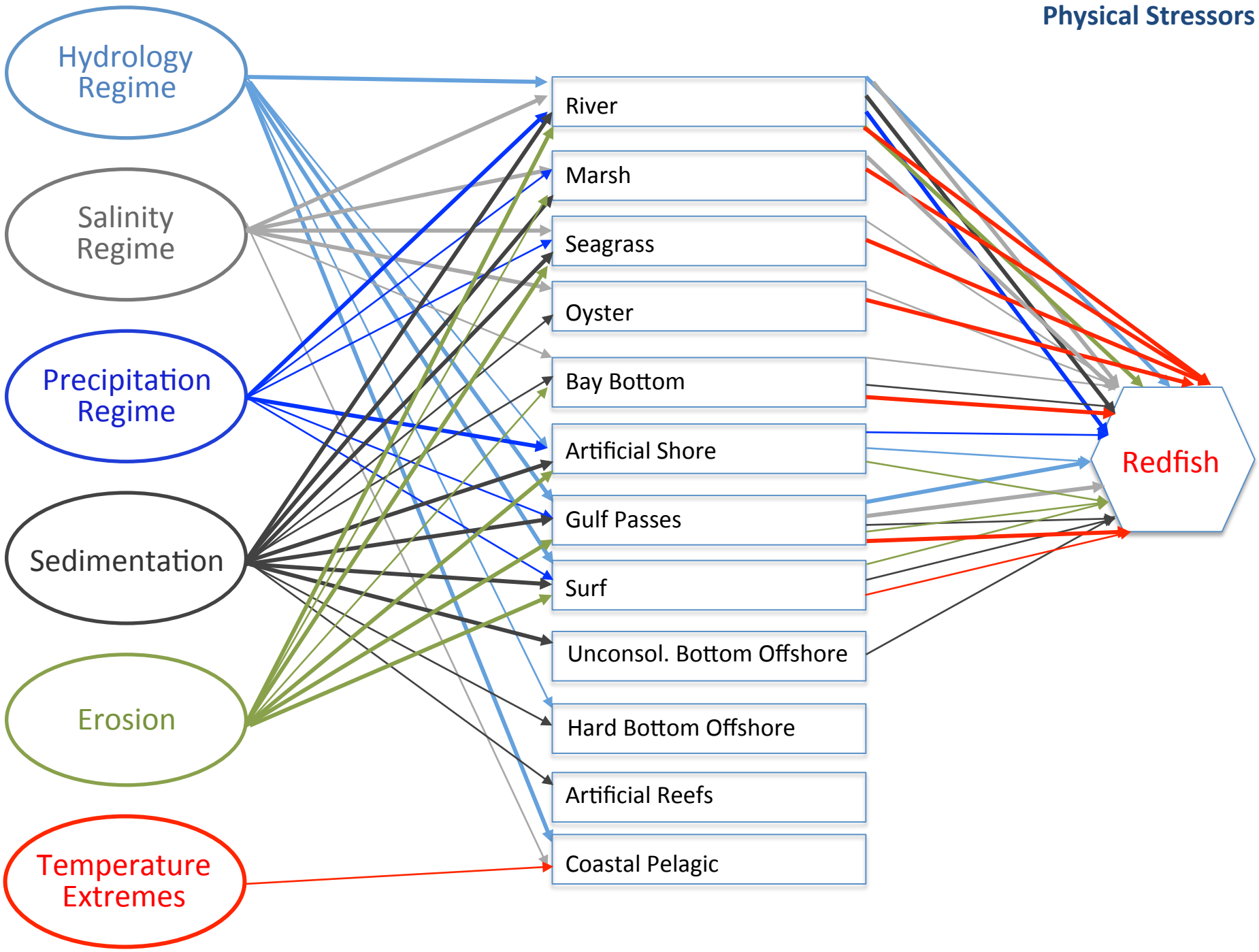

Nutrient Loading
Organic Loading
Petroleum Spills
Petroleum Releases
Other Chemical Spills
River
Marsh
Seagrass
Oyster
Bay Bottom
Artificial Shore
Gulf Passes
Surf
Unconsol. Bottom Offshore
Hard Bottom Offshore
Artificial Reefs
Coastal Pelagic
Red Snapper

Chemical Stressors - 2



Biological Stressors




Physical Stressors - 1
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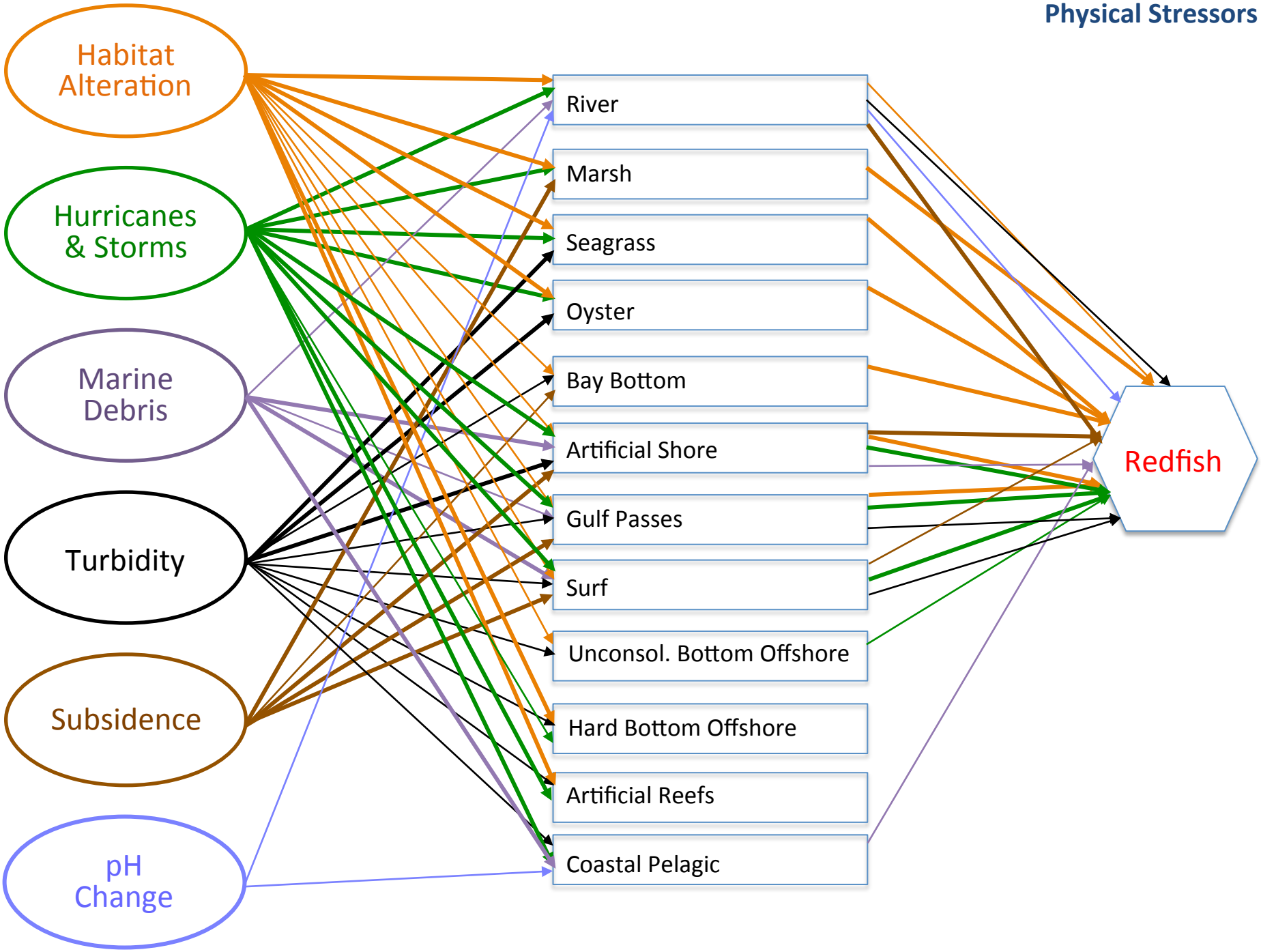
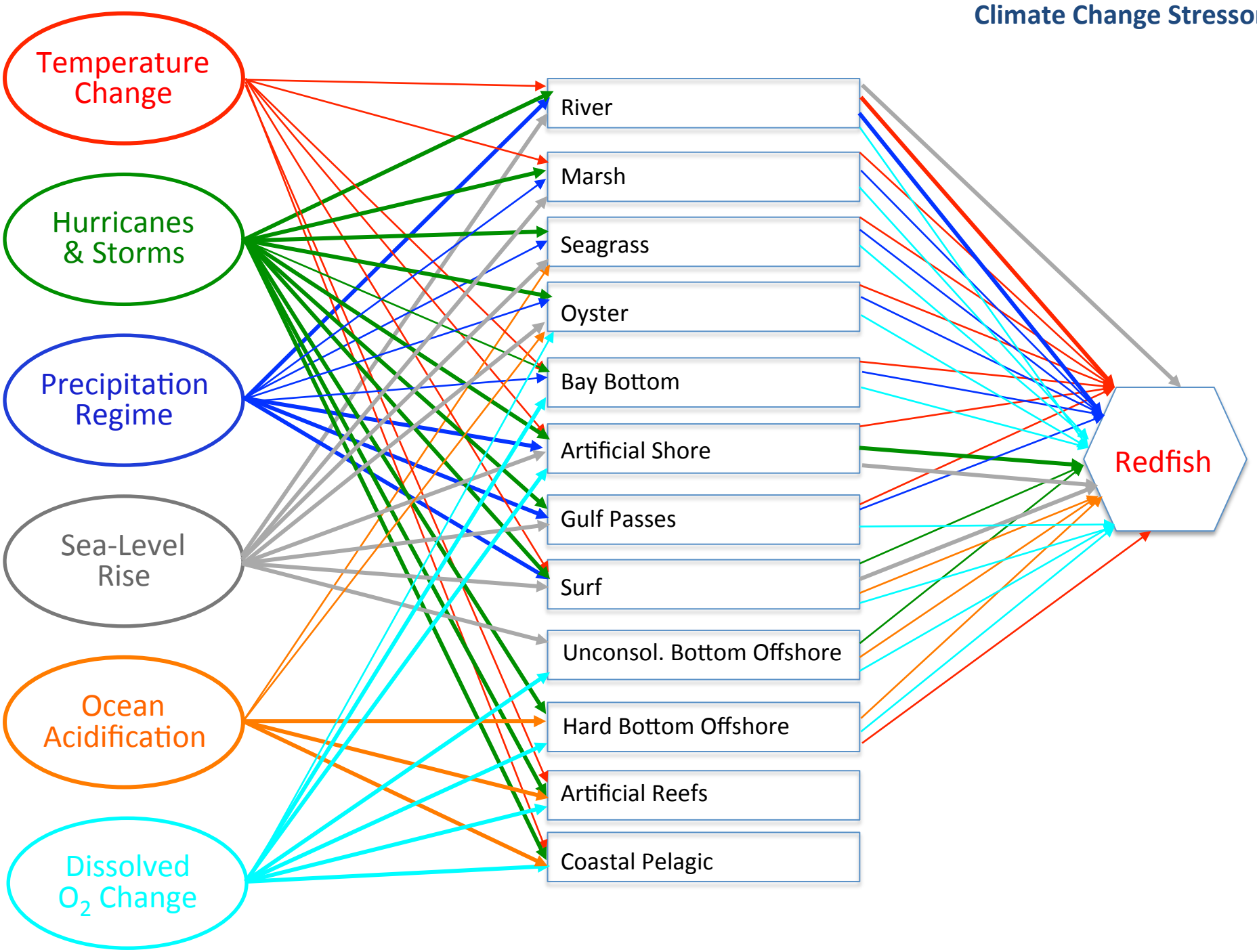
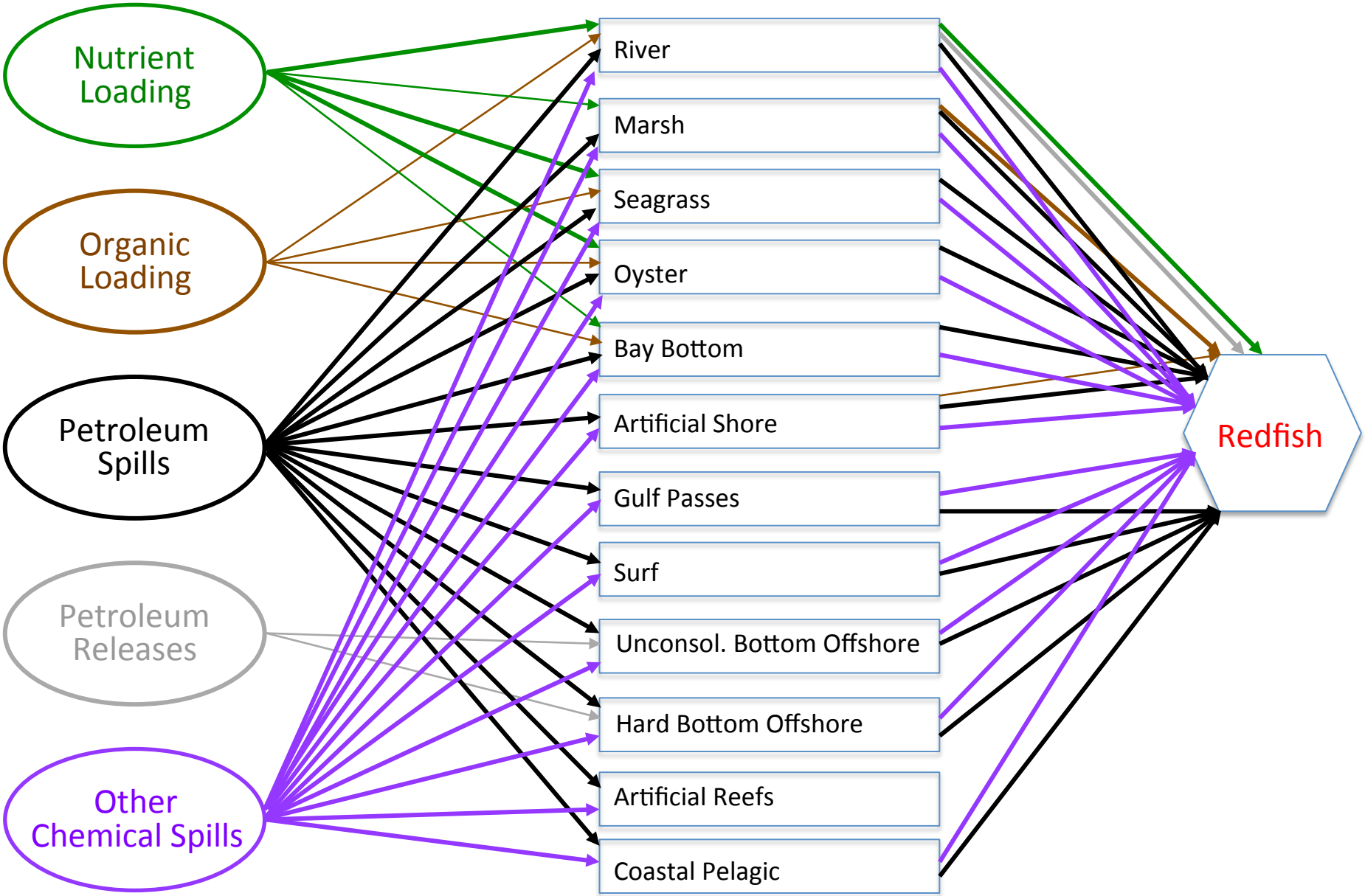
Salinity Regime
Precipitation Regime
Sedimentation
Erosion
Temperature Extremes
River
Marsh
Seagrass
Oyster
Bay Bottom
Artificial Shore
Gulf Passes
Surf
Unconsol. Bottom Offshore
Hard Bottom Offshore
Artificial Reefs
Coastal Pelagic
Redfish

Physical Stressors - 2




Climate Change Stressors
Temperature Change
Hurricanes & Storms
Precipitation Regime
Sea-Level Rise
Ocean Acidification
Dissolved O_2 Change
River
Marsh
Seagrass
Oyster
Bay Bottom
Artificial Shore
Gulf Passes
Surf
Unconsol. Bottom Offshore
Hard Bottom Offshore
Artificial Reefs
Coastal Pelagic
Redfish


Nutrient Loading
Organic Loading
Petroleum Spills
Petroleum Releases
Other Chemical Spills
River
Marsh
Seagrass
Oyster
Bay Bottom
Artificial Shore
Gulf Passes
Surf
Unconsol. Bottom Offshore
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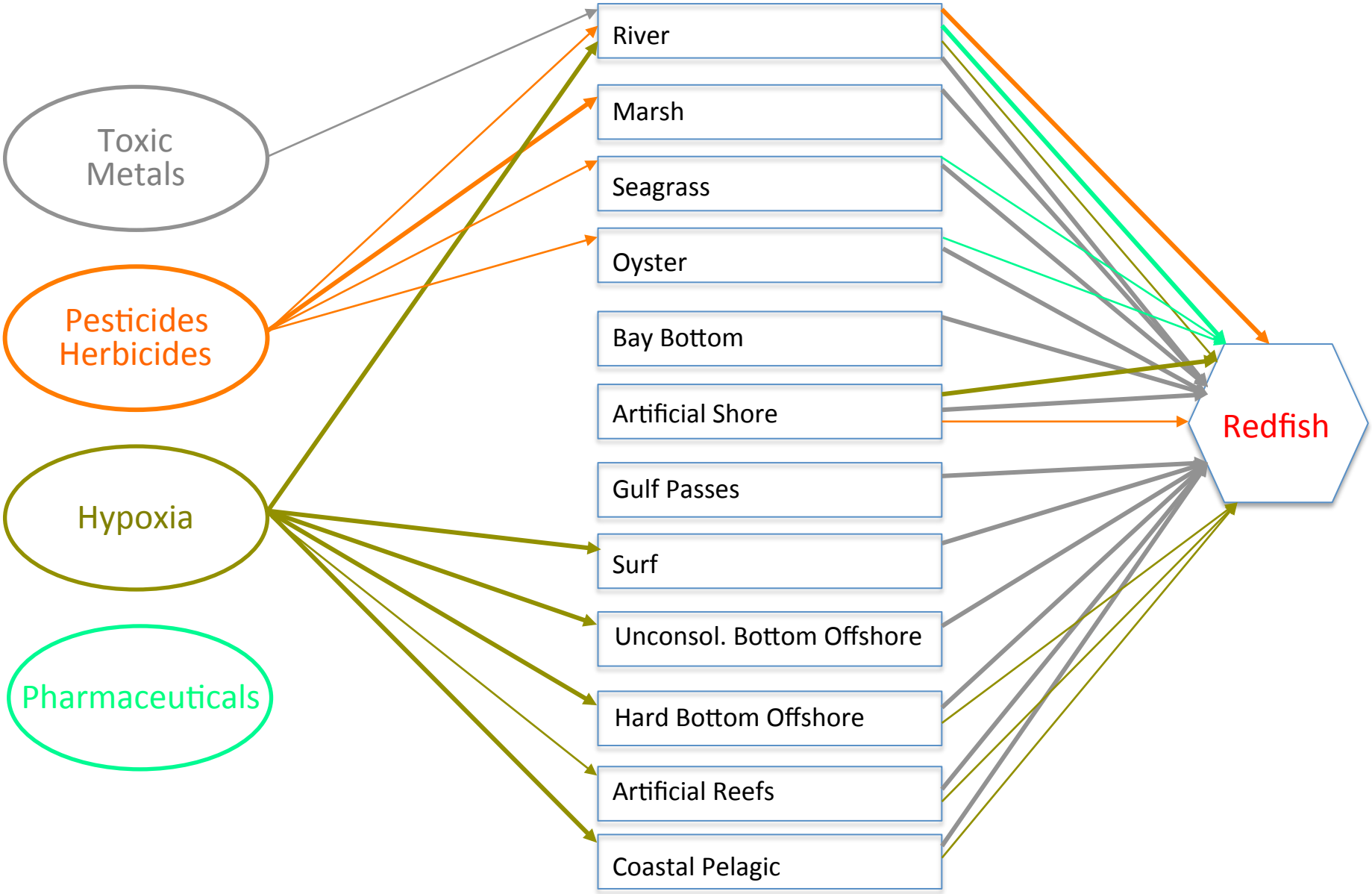
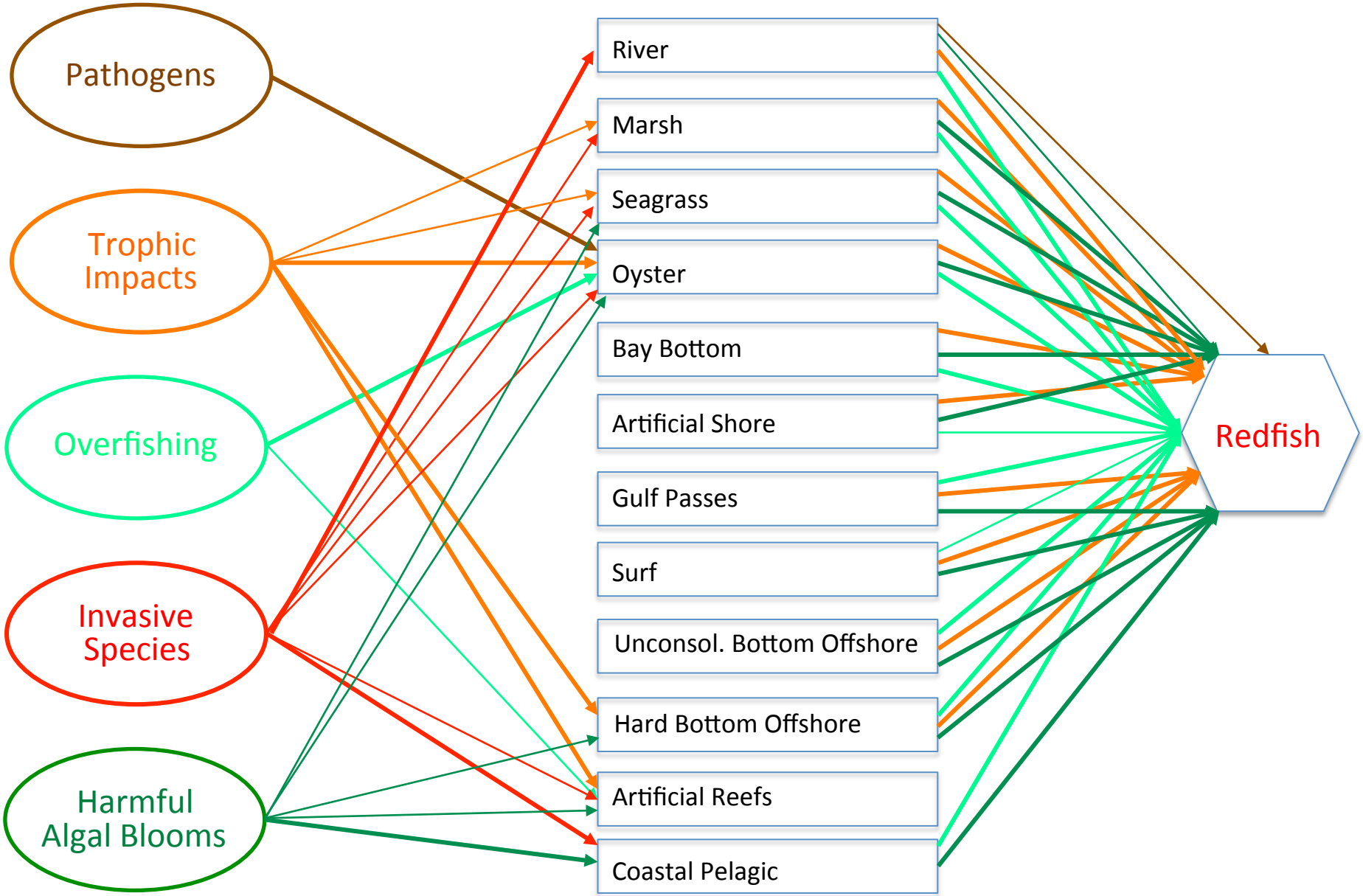
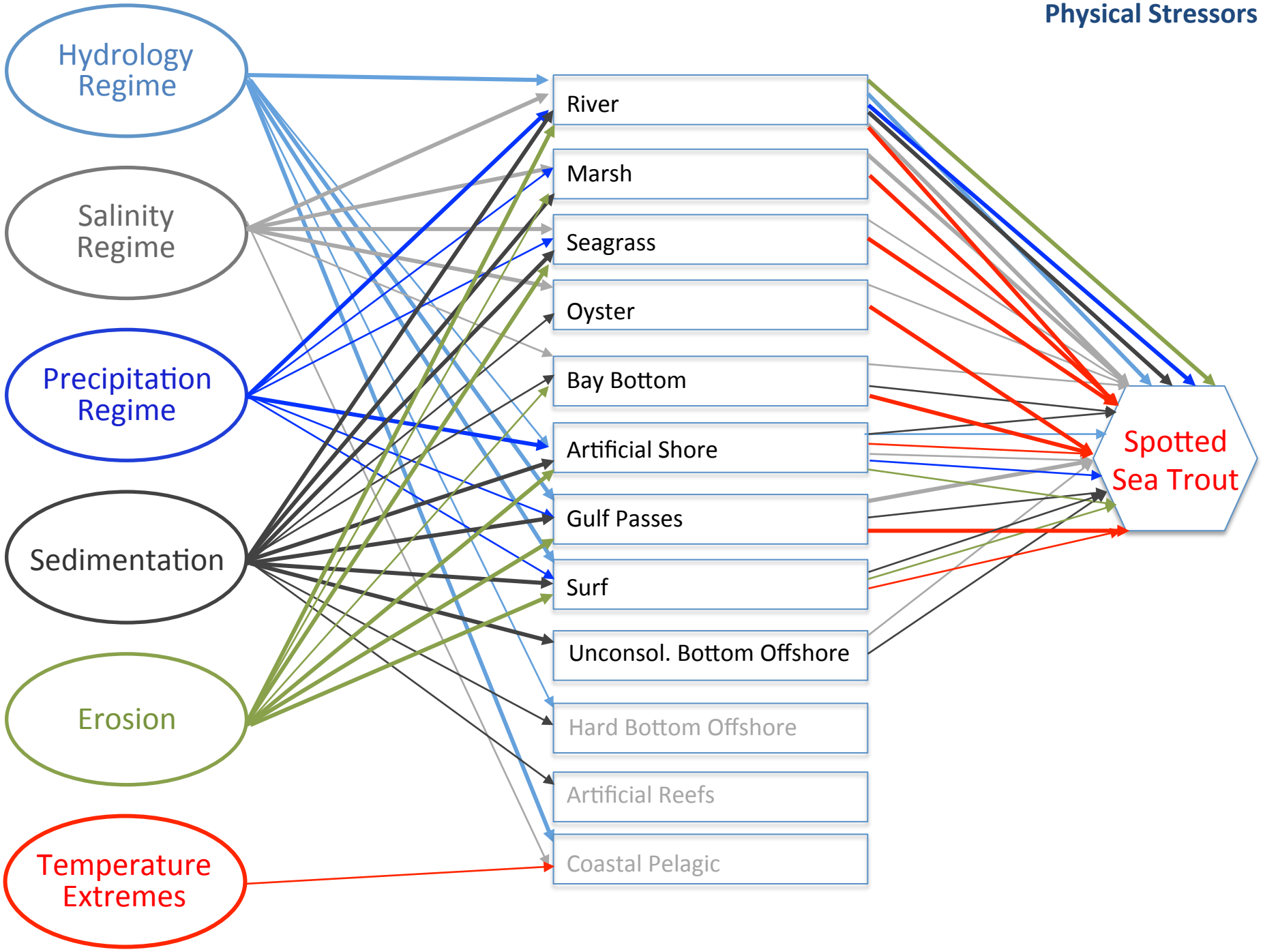
Artificial Reefs
Coastal Pelagic
Redfish

Chemical Stressors - 2

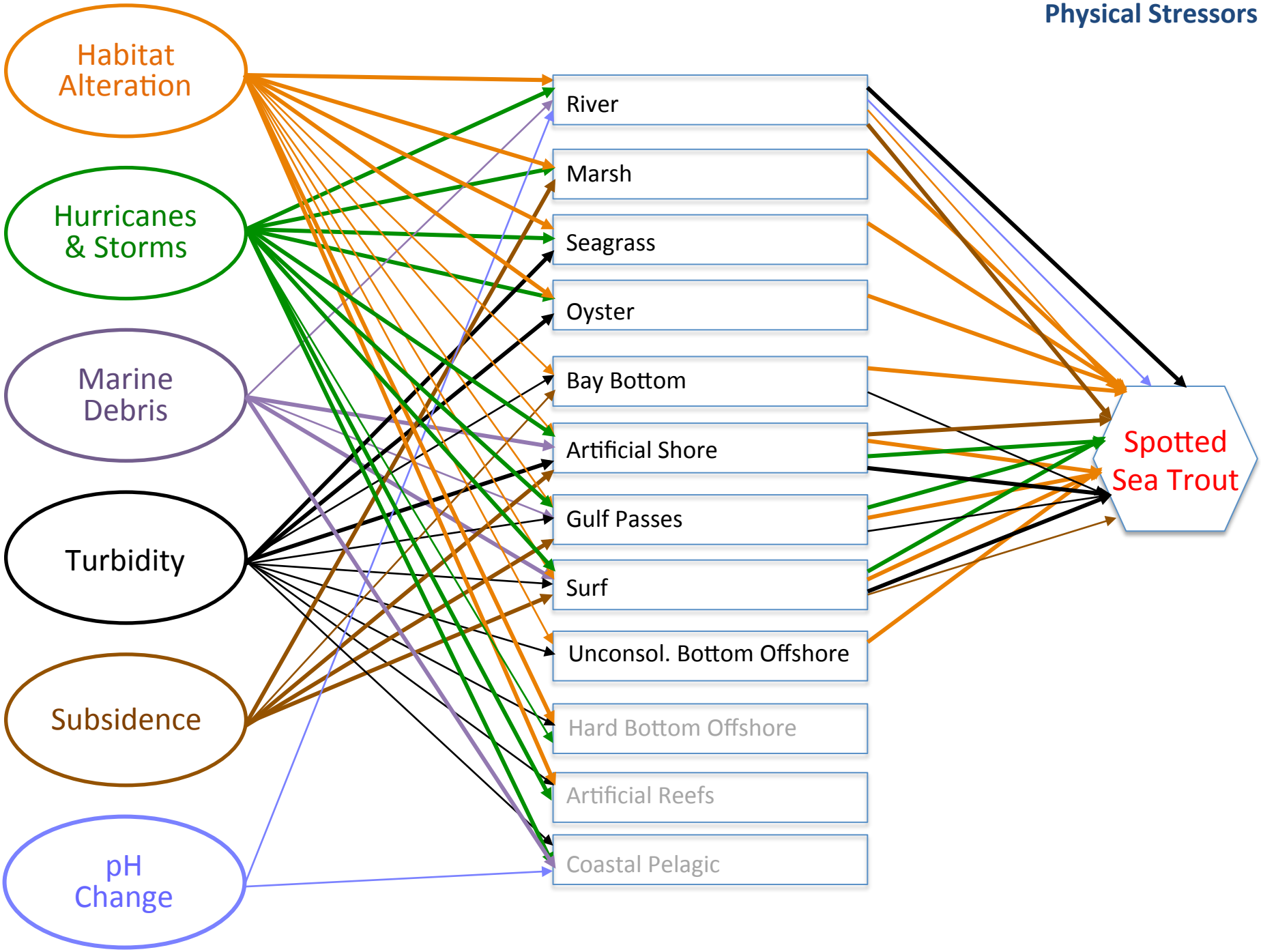


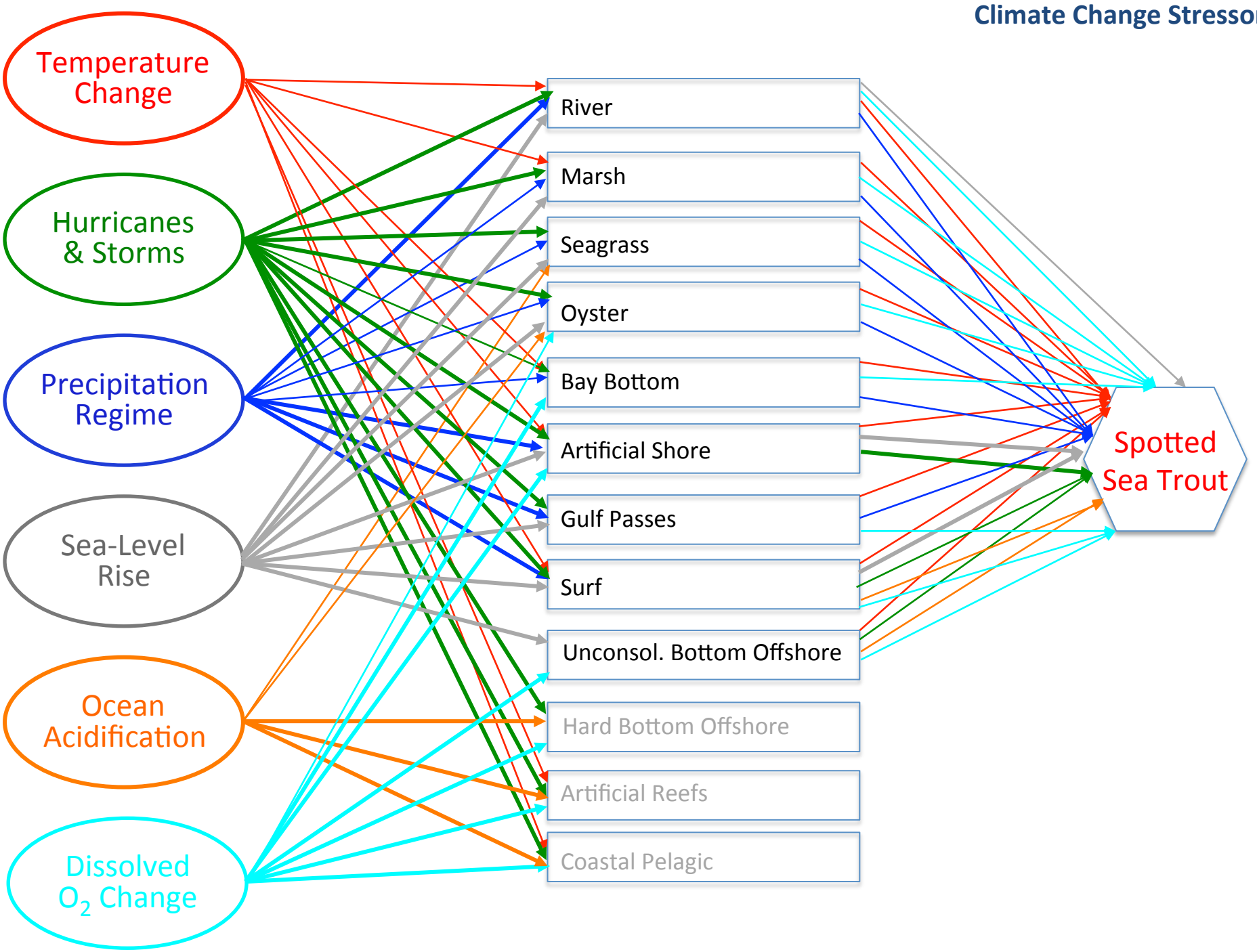
Biological Stressors




Hydrology Regime
Salinity Regime
Precipitation Regime
Sedimentation
Erosion
Temperature Extremes
River
Marsh
Seagrass
Oyster
Bay Bottom
Artificial Shore
Gulf Passes
Surf
Unconsol. Bottom Offshore
Hard Bottom Offshore
Artificial Reefs
Coastal Pelagic
Spotted Sea Trout

Physical Stressors - 2




Climate Change Stressors
Temperature Change
Hurricanes & Storms
Precipitation Regime
Sea-Level Rise
Ocean Acidification
Dissolved O_2 Change
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Marsh
Seagrass
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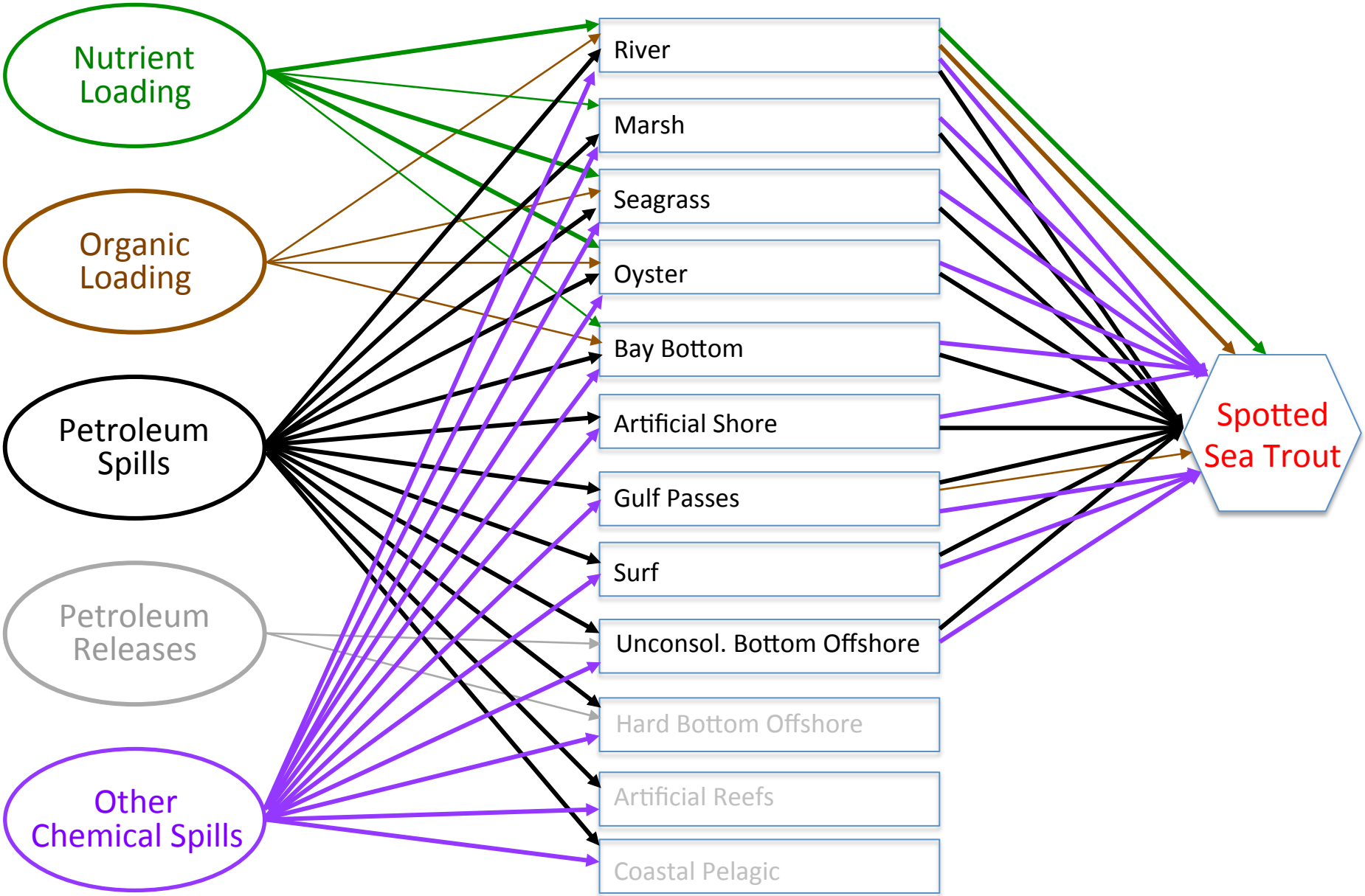
Hard Bottom Offshore
Artificial Reefs
Coastal Pelagic
Spotted Sea Trout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Organic Loading
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Petroleum Releases
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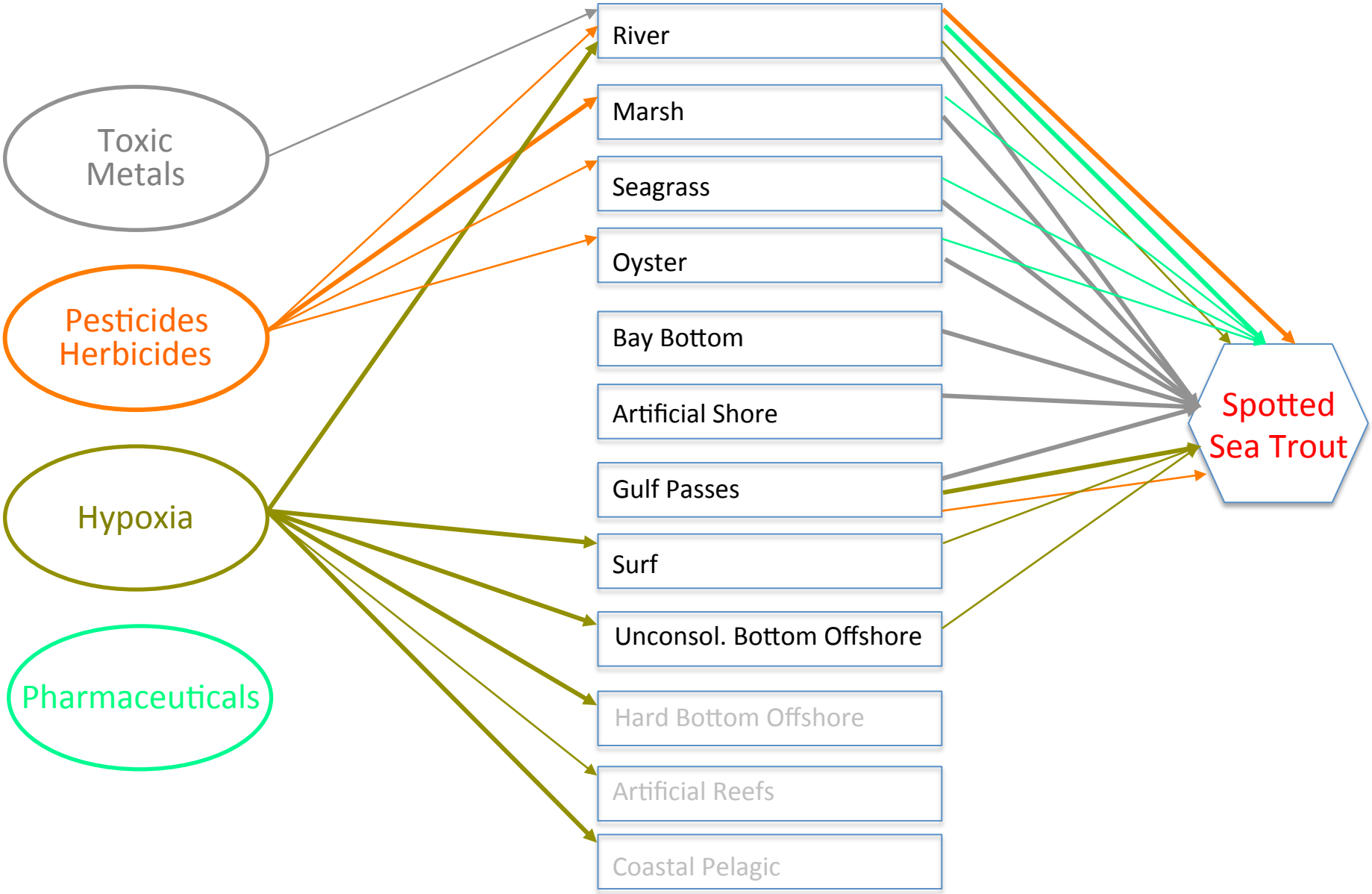
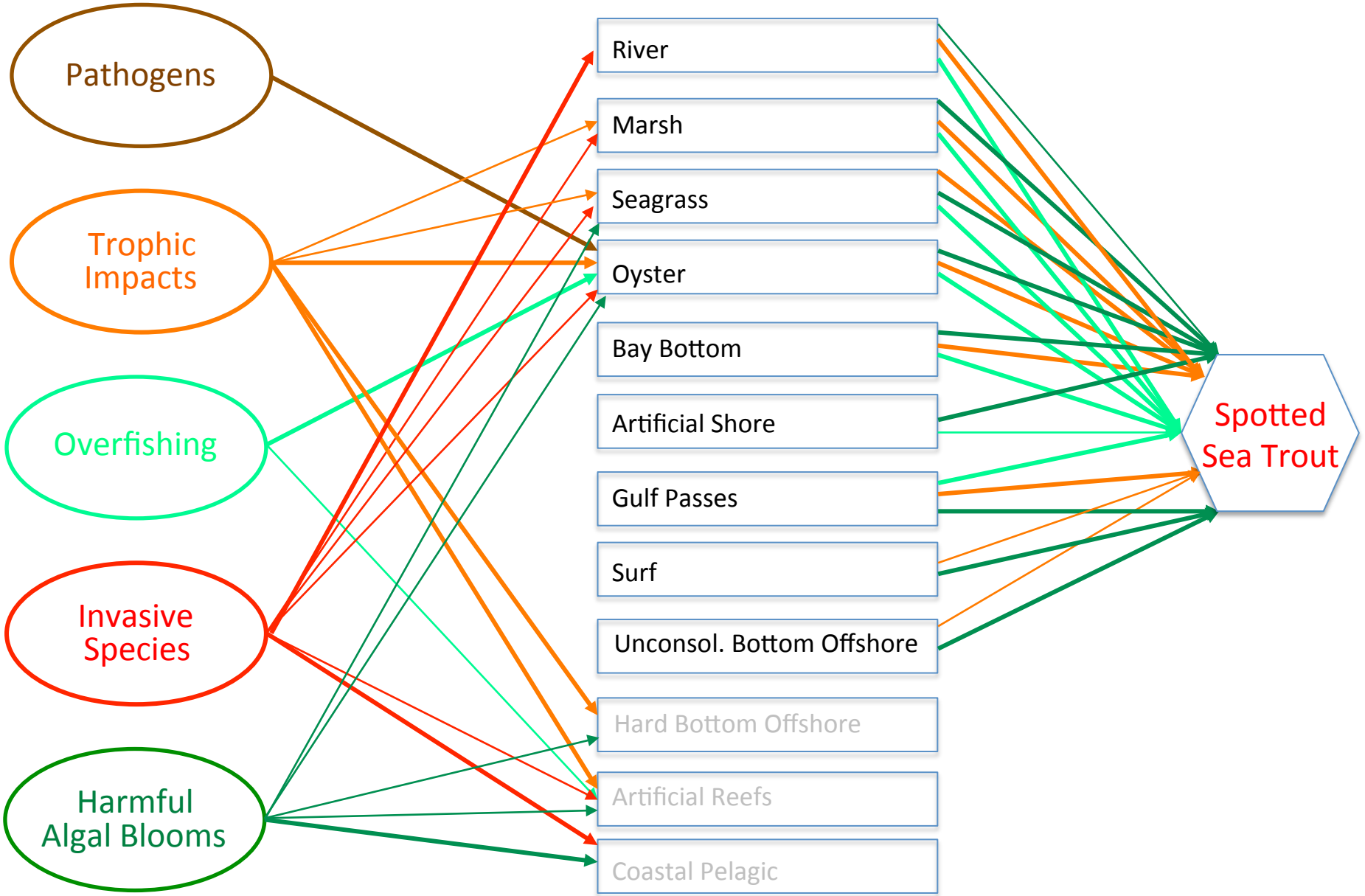
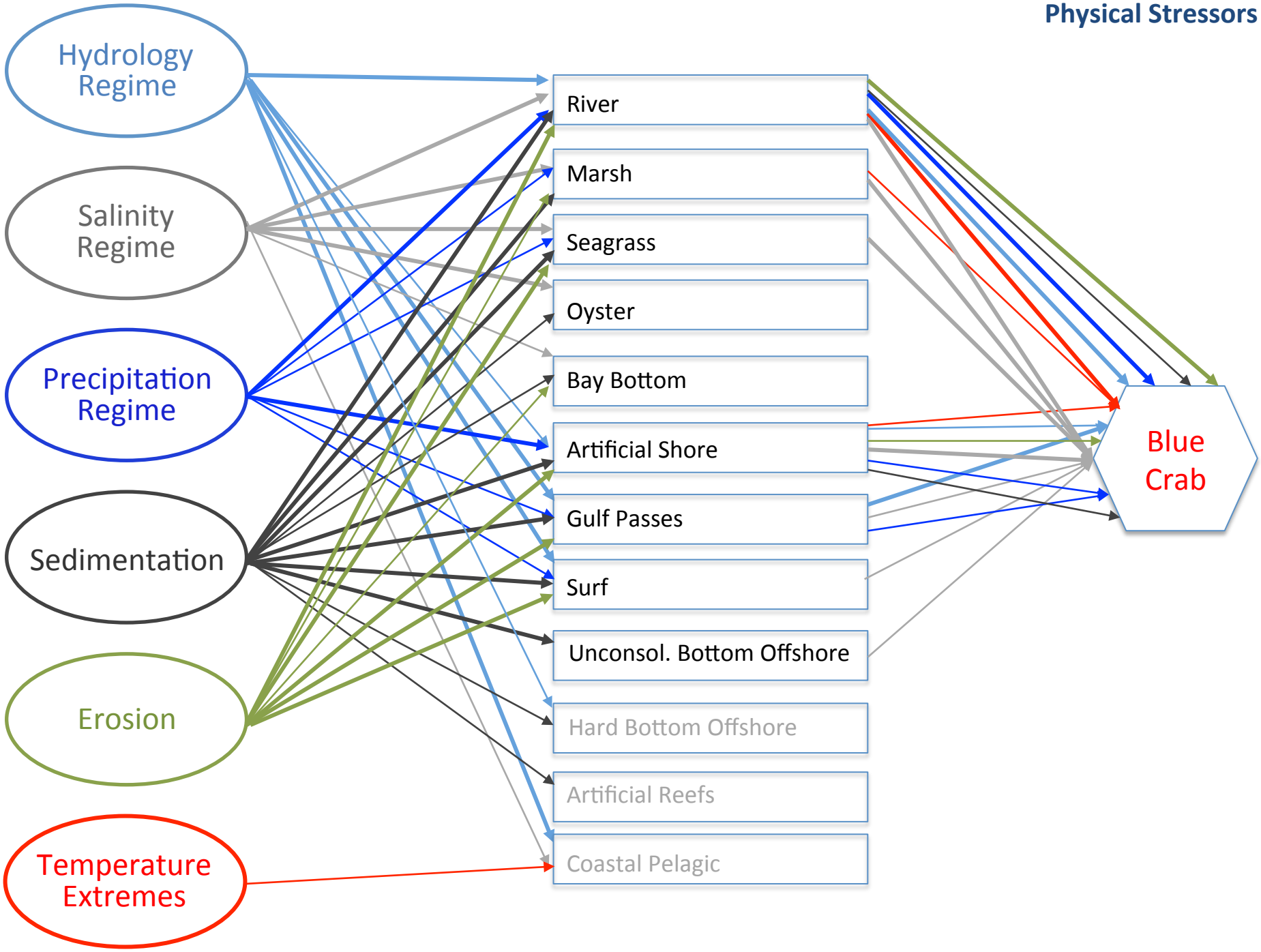
Chemical Stressors - 2



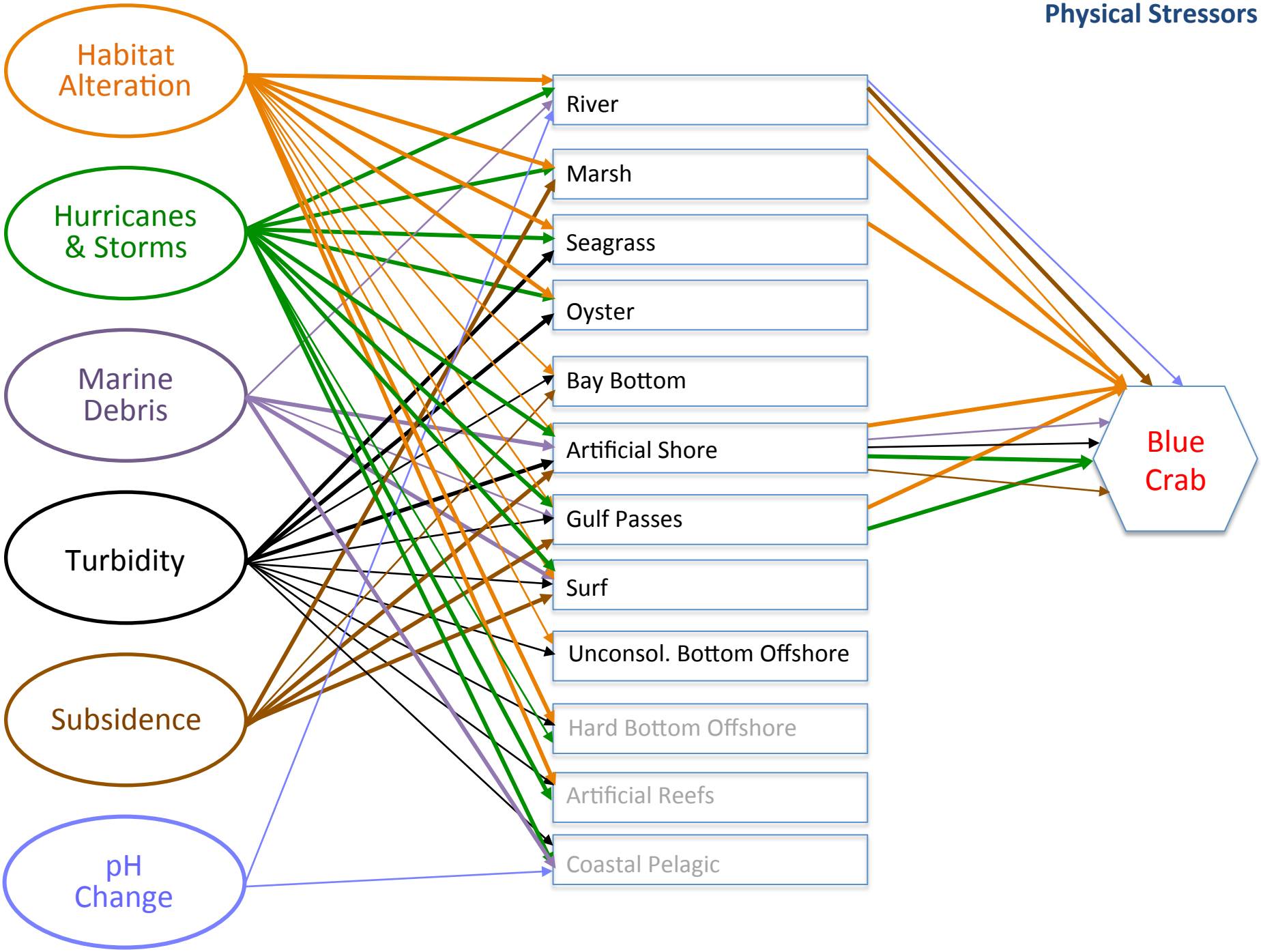
Biological Stressors

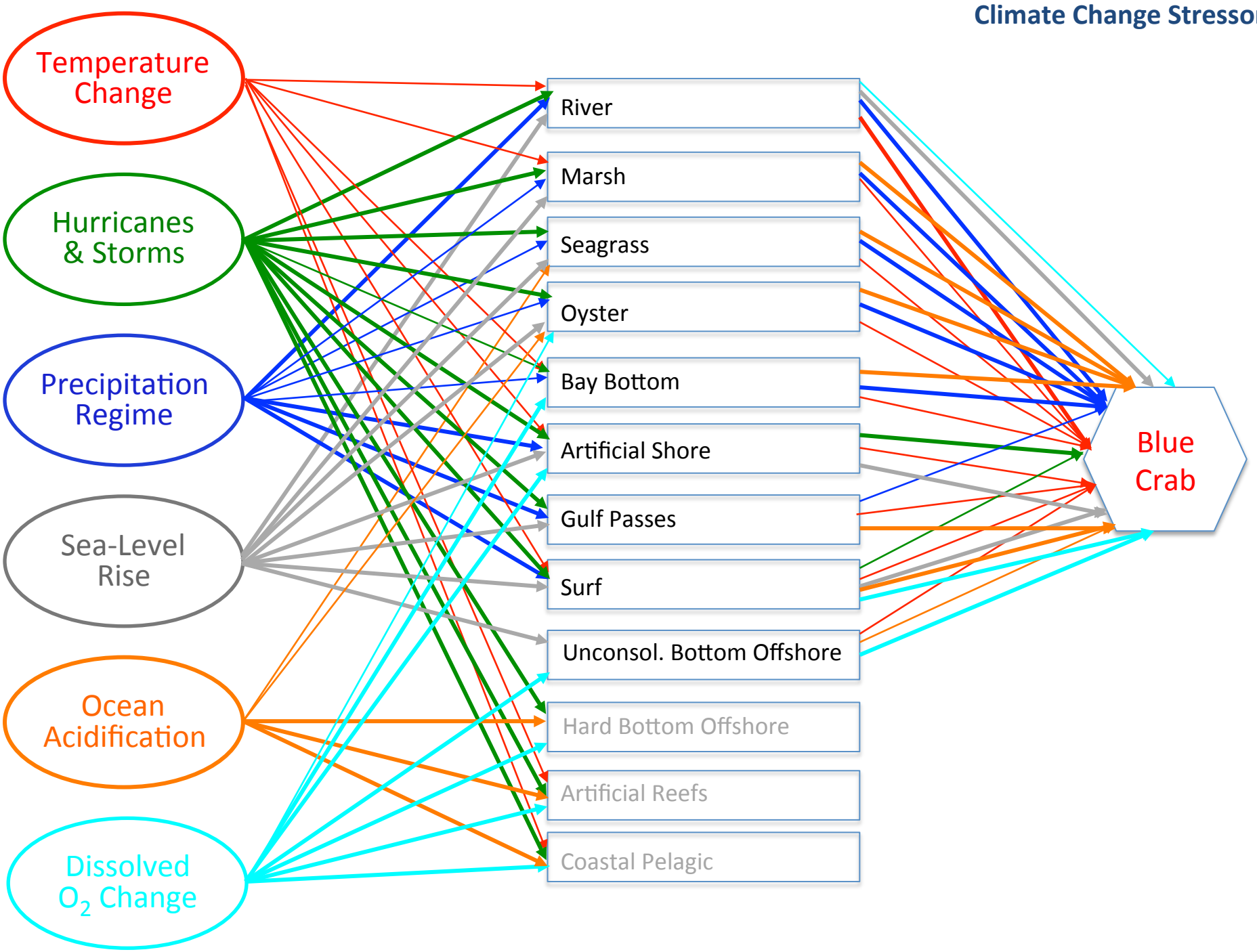


Physical Stressors - 1



Physical Stressors - 2




Climate Change Stressors
Temperature Change
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Precipitation Regime
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Ocean Acidification
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Seagrass
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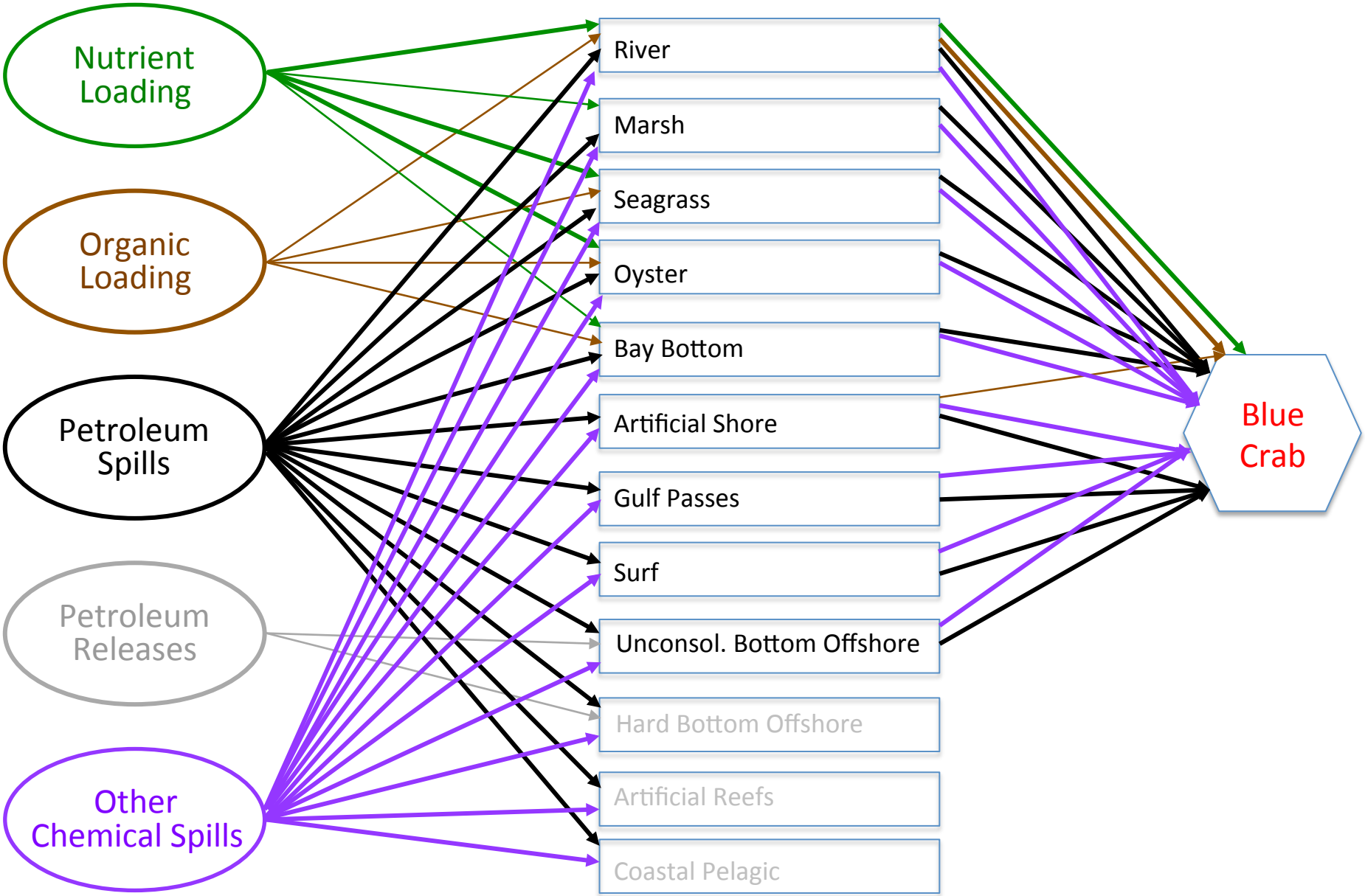
Bay Bottom
Artificial Shore
Gulf Passes
Surf
Unconsol. Bottom Offshore
Hard Bottom Offshore
Artificial Reefs
Coastal Pelagic
Blue Crab


Nutrient Loading
Organic Loading
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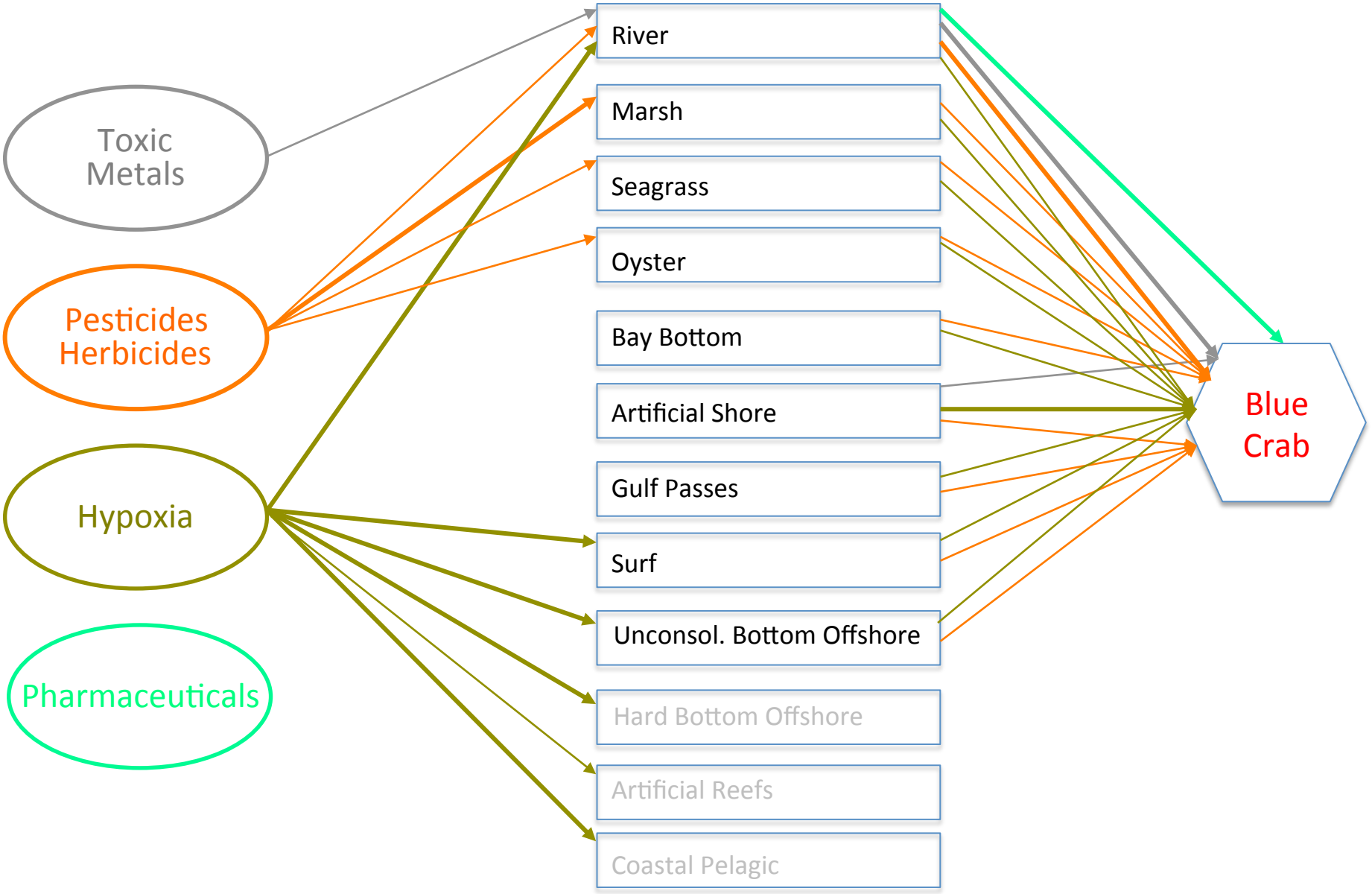
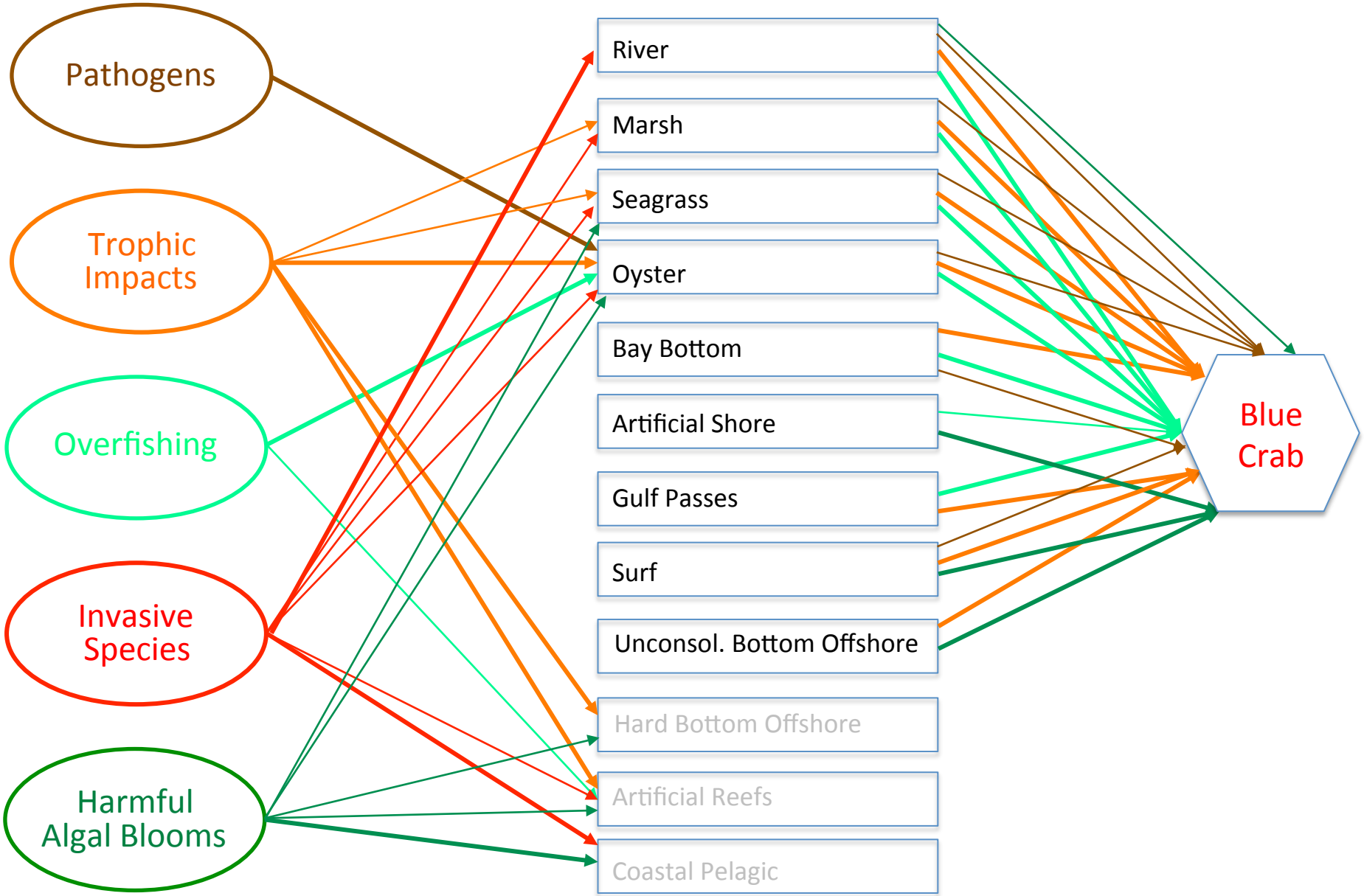
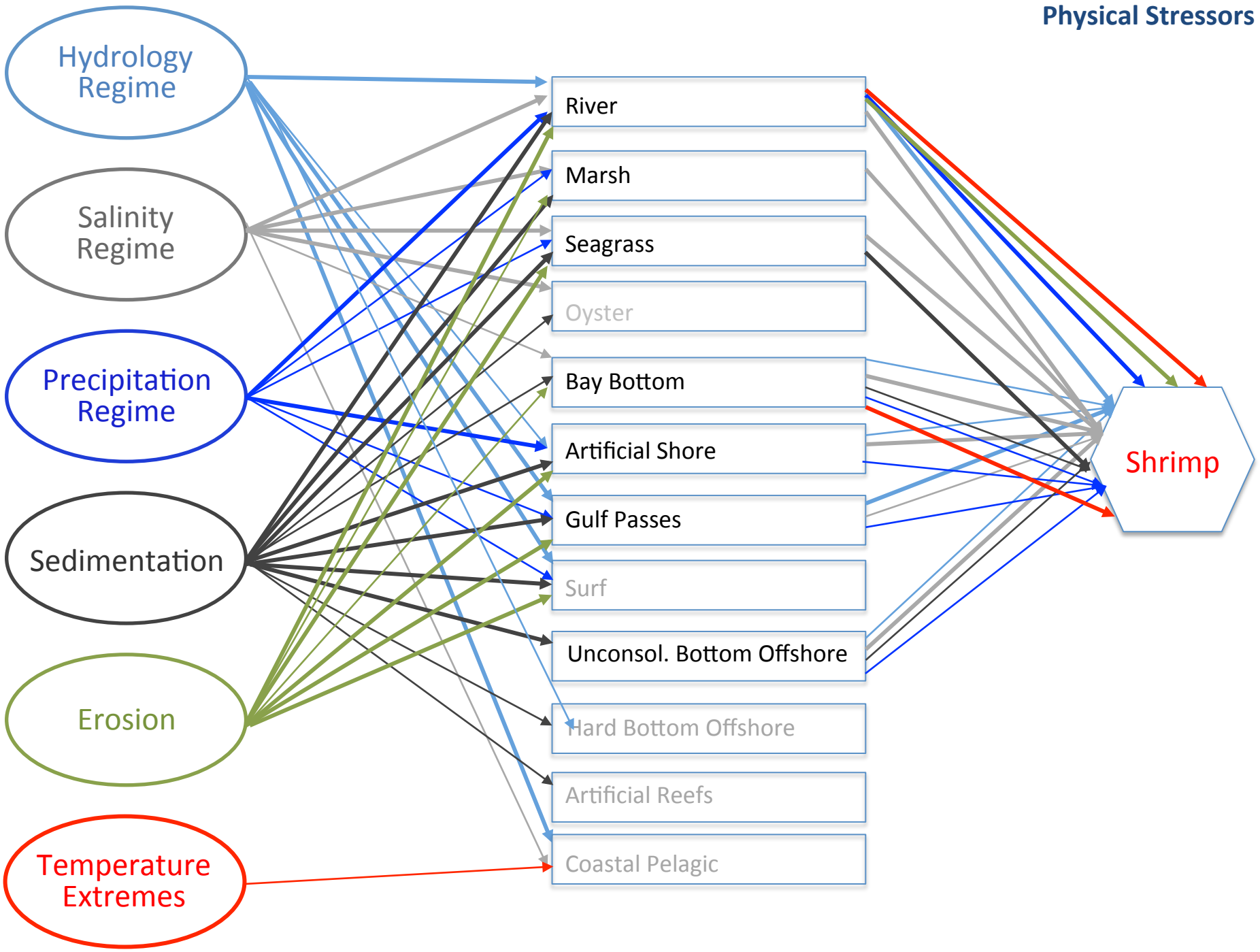
Blue Crab

Chemical Stressors - 2



Biological Stressors




Physical Stressors - 1
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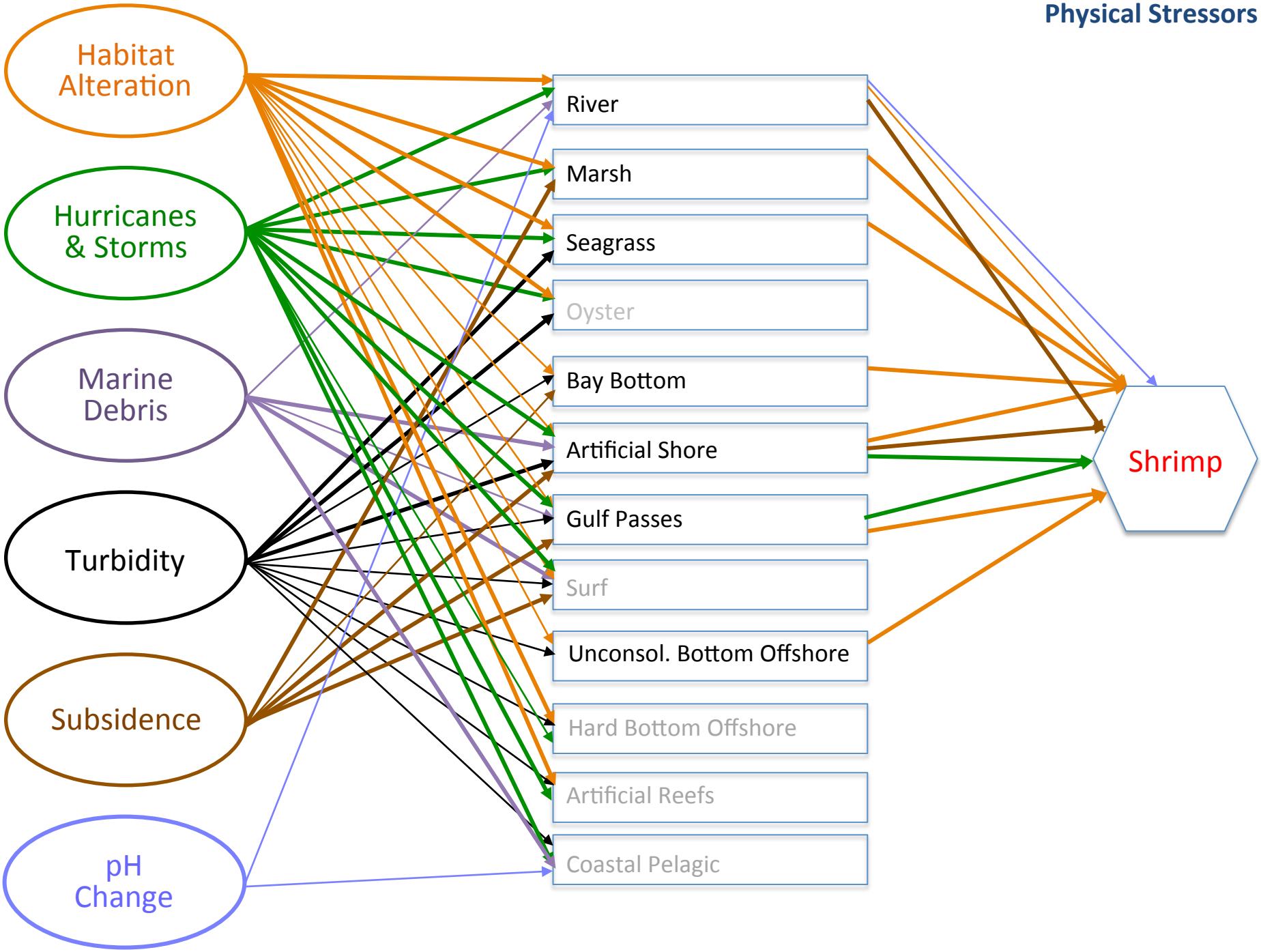
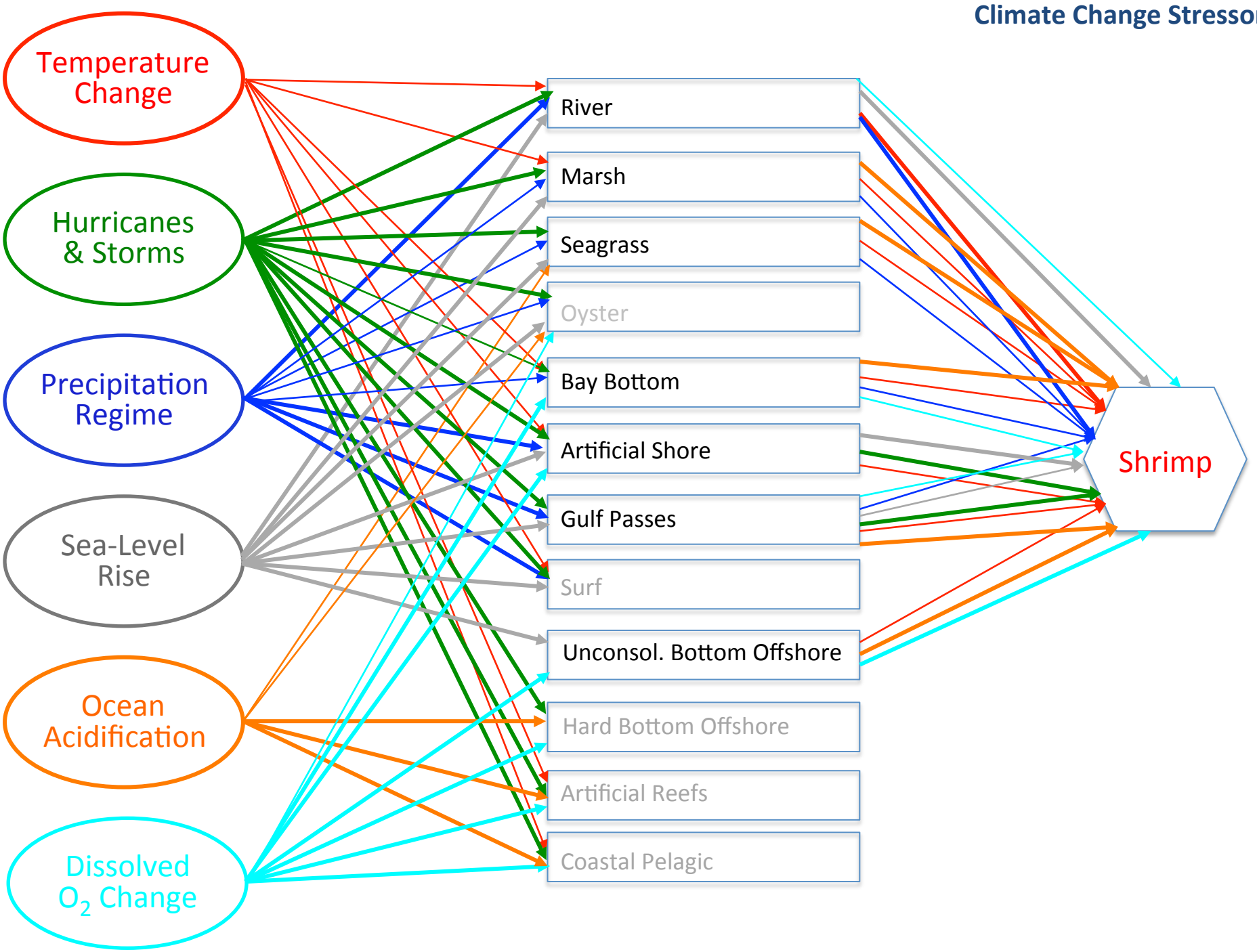
Shrimp

Physical Stressors - 2

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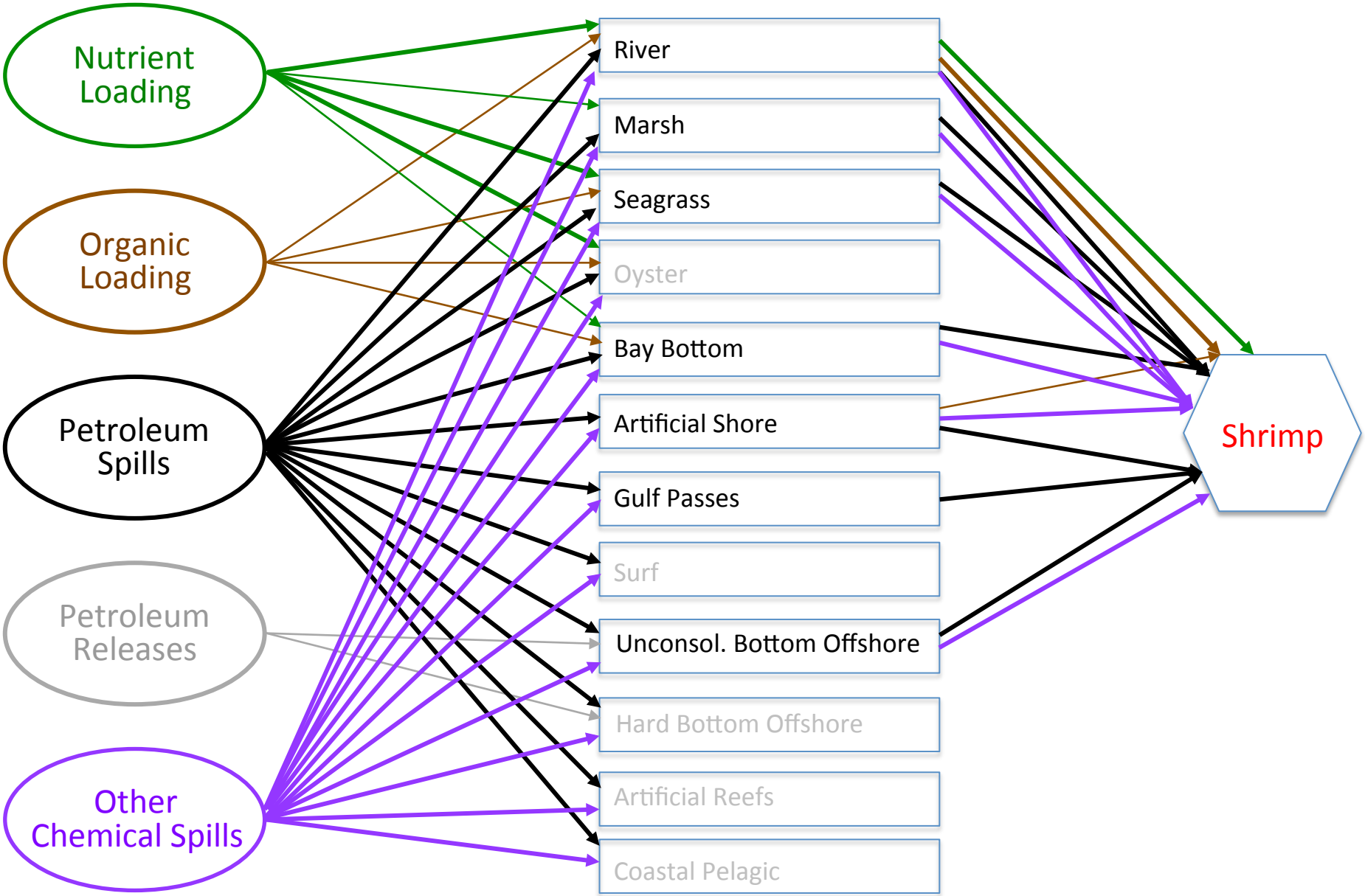
Shrimp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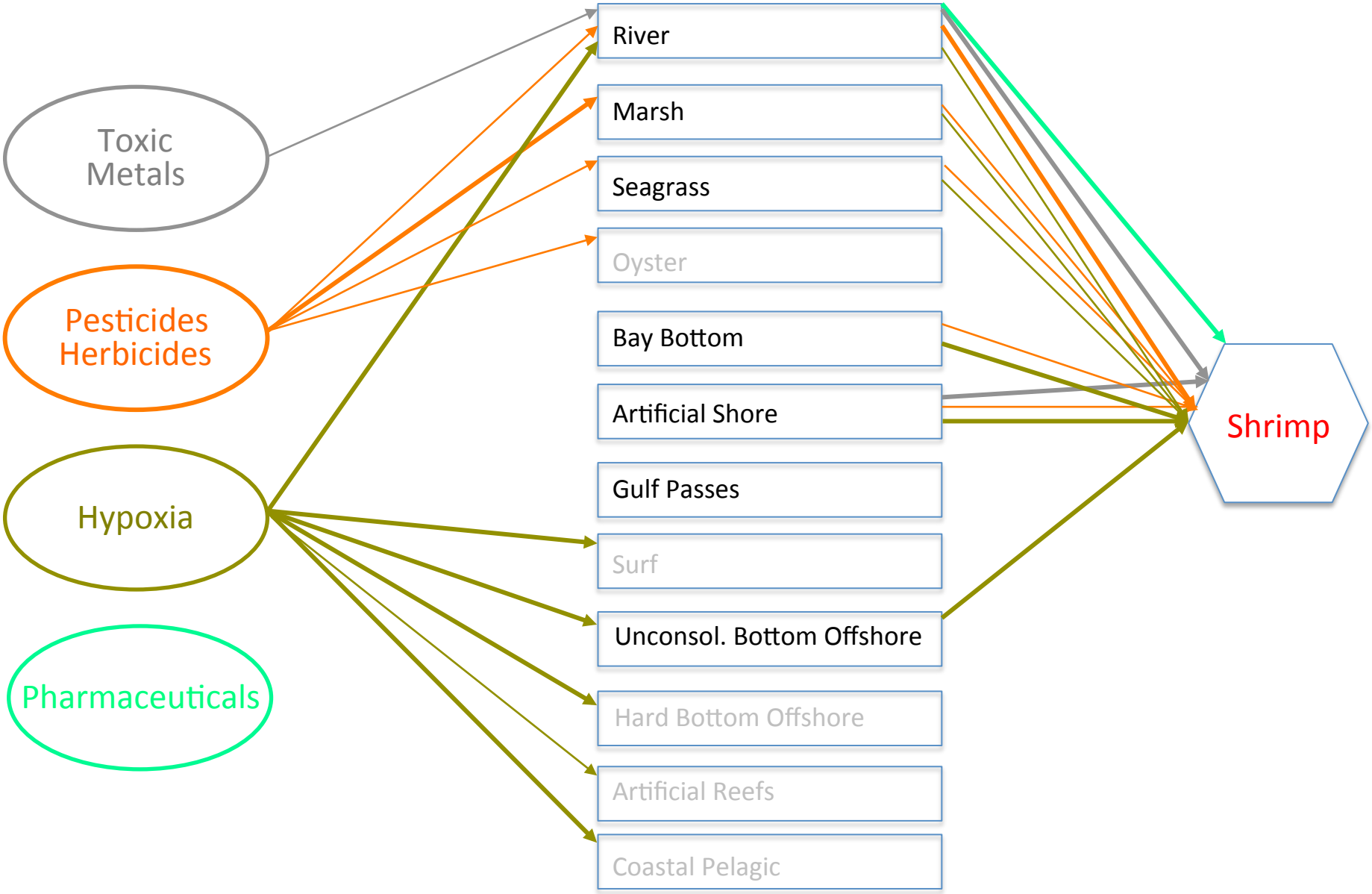
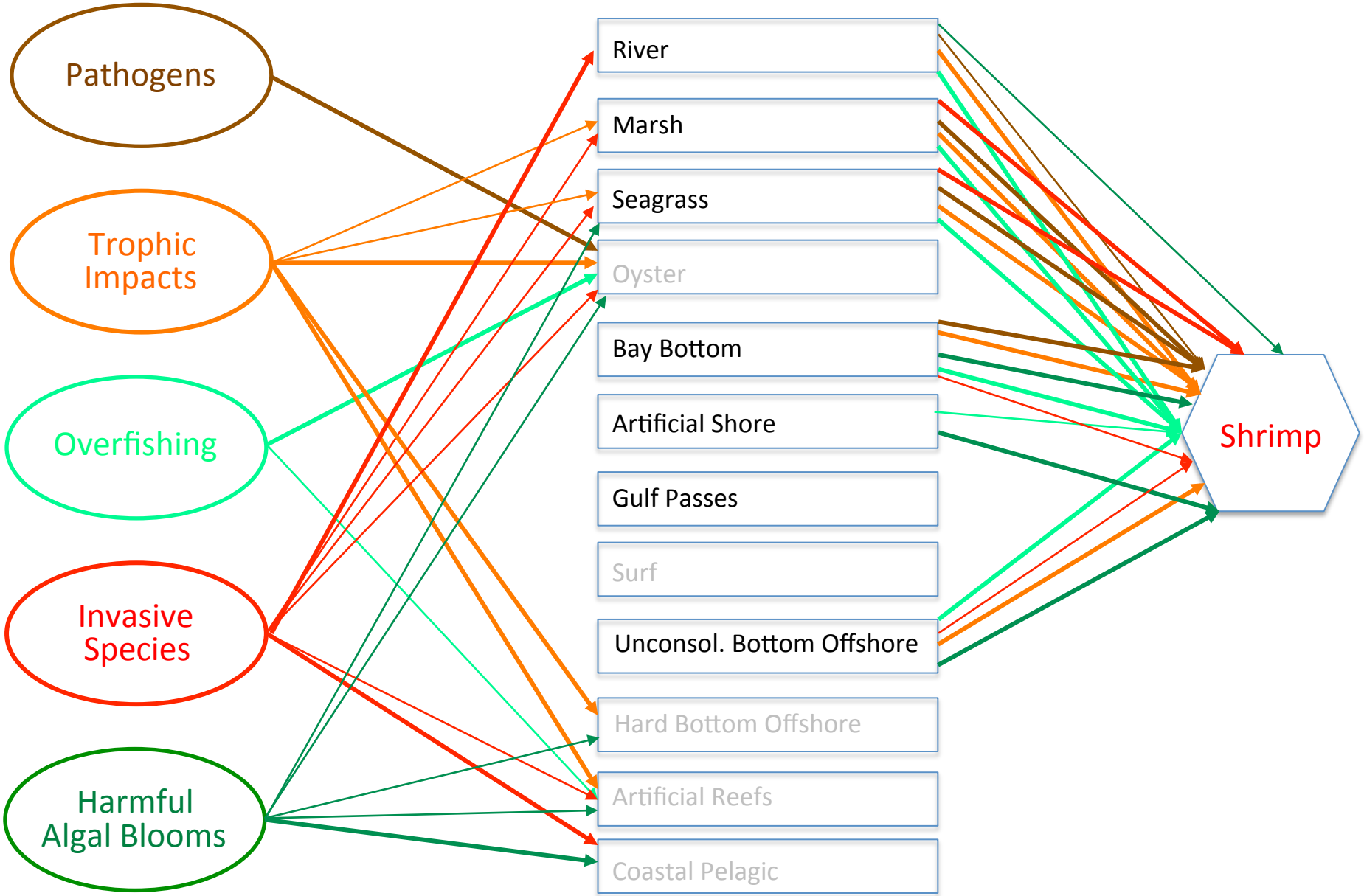
Artificial Reefs
Coastal Pelagic
Shrimp

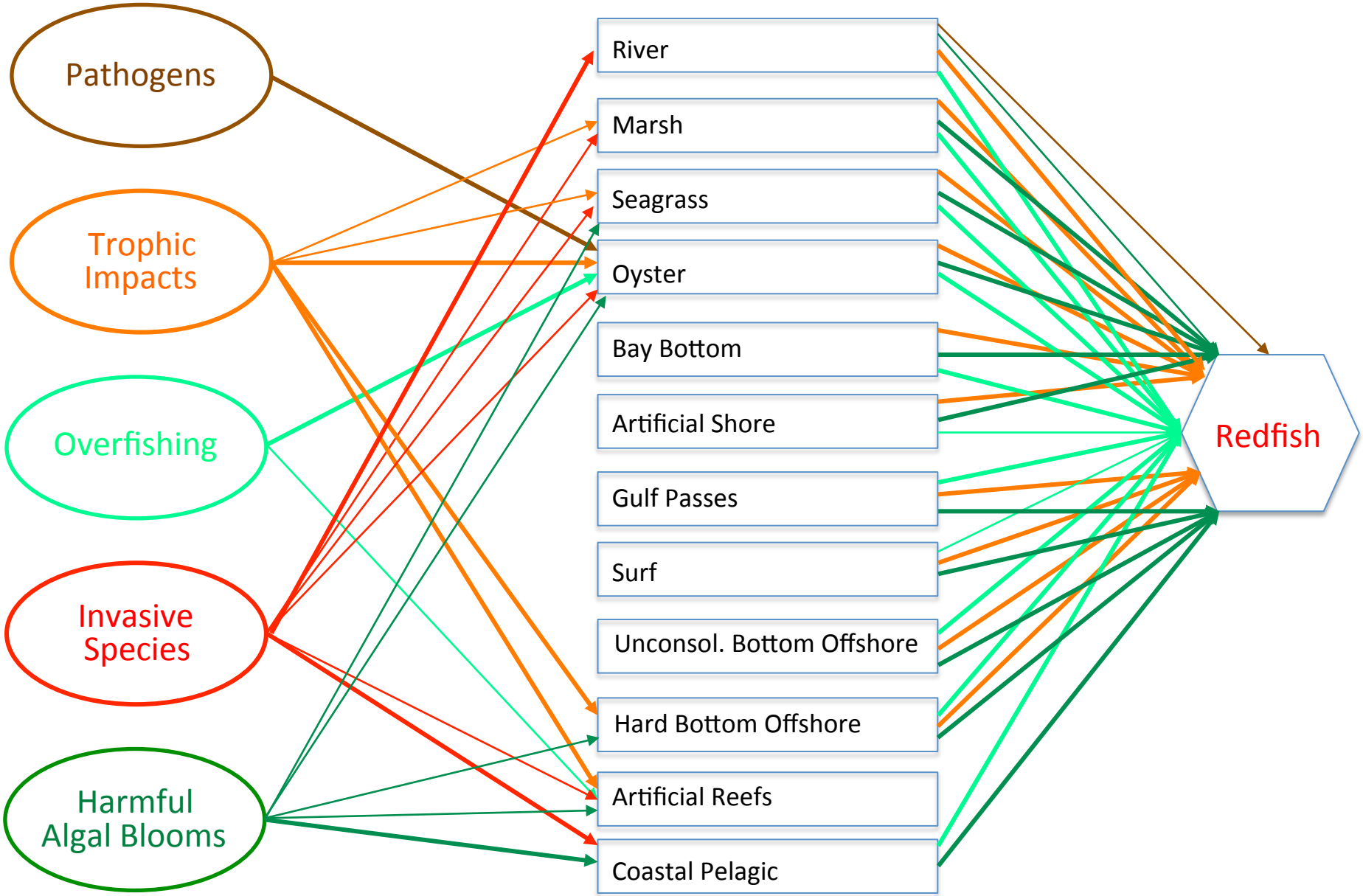
Chemical Stressors - 2



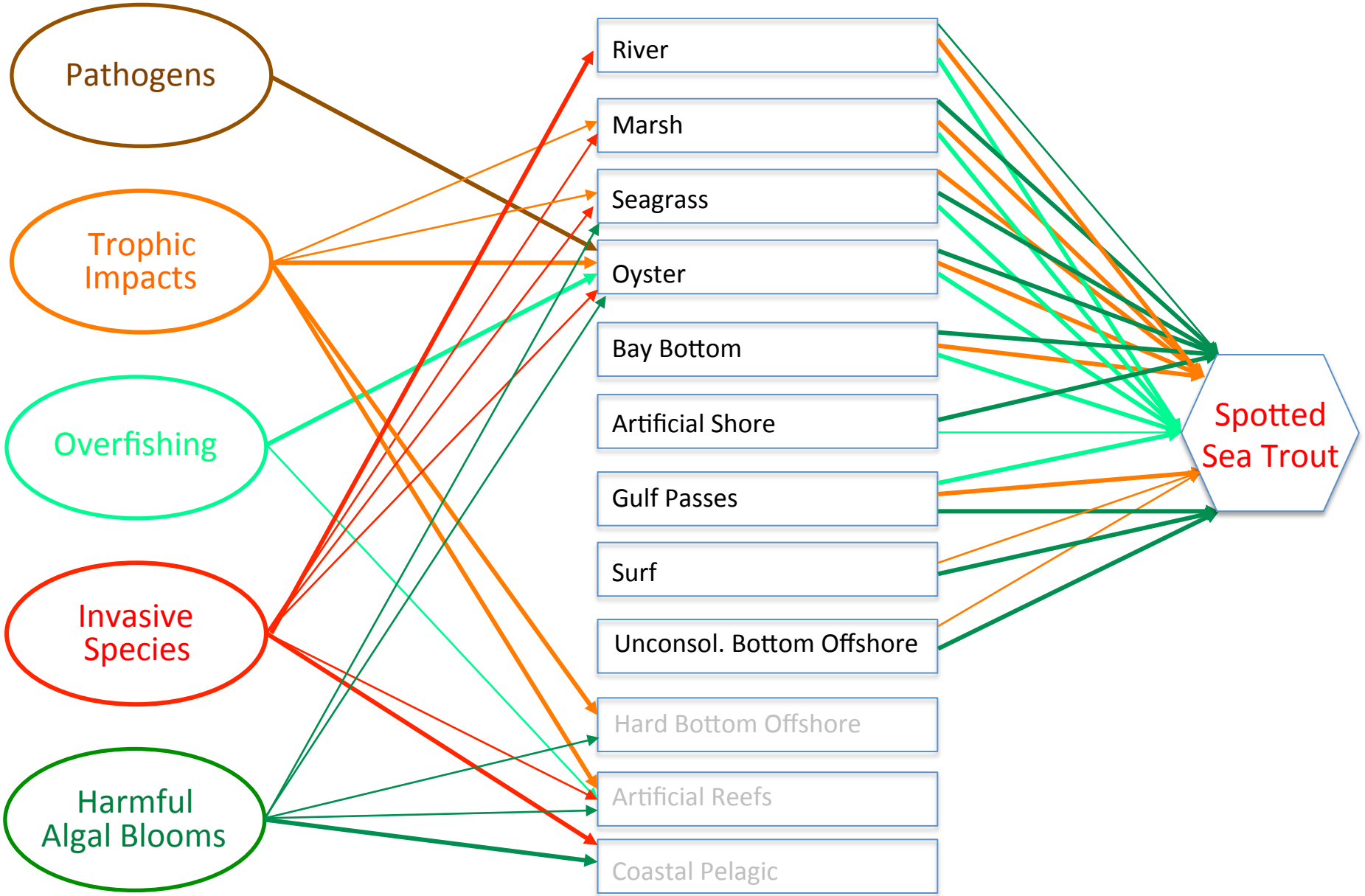
Biological Stressors



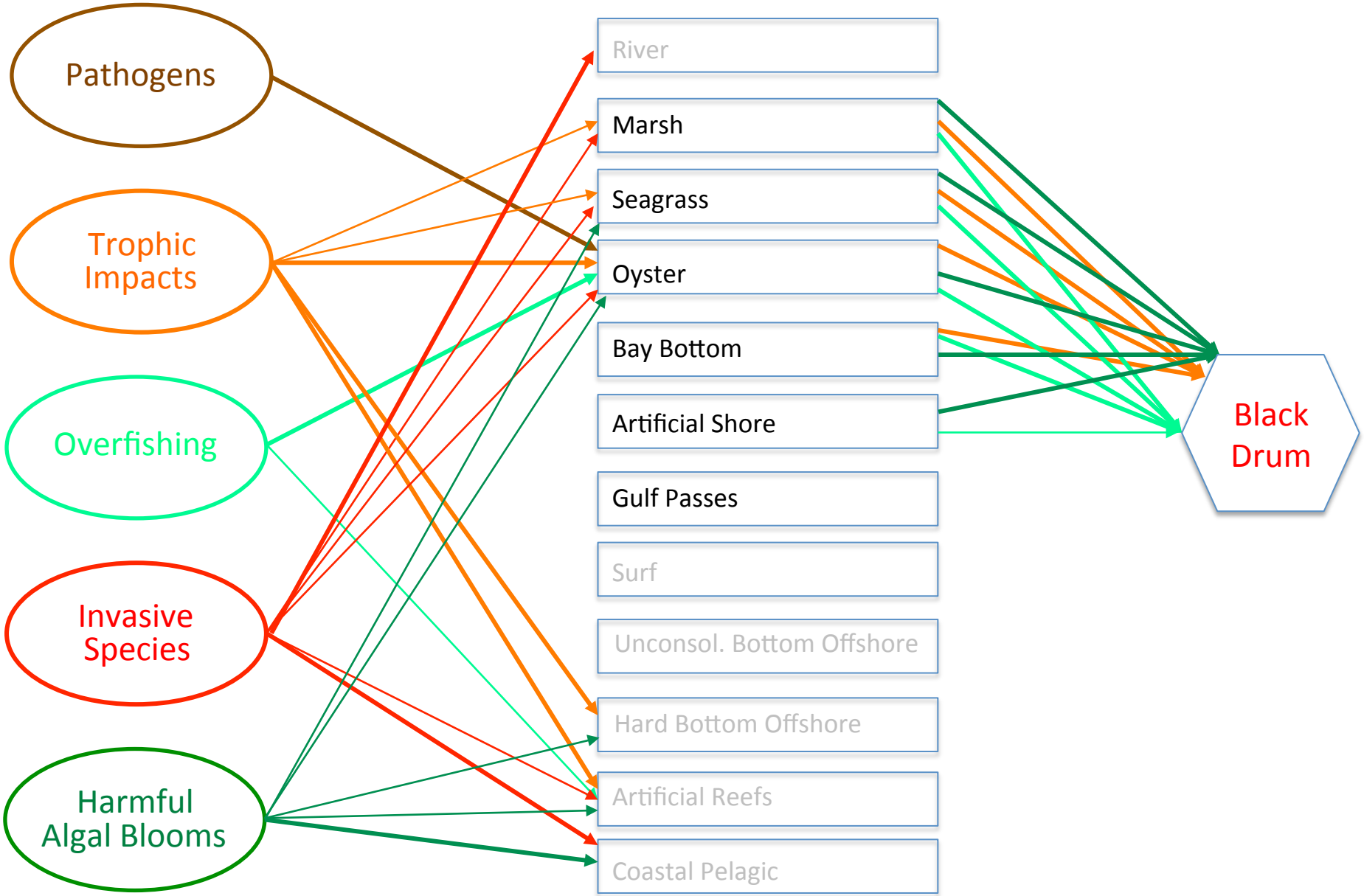
Biological Stressors



Biological Stressors



Biological Stressors



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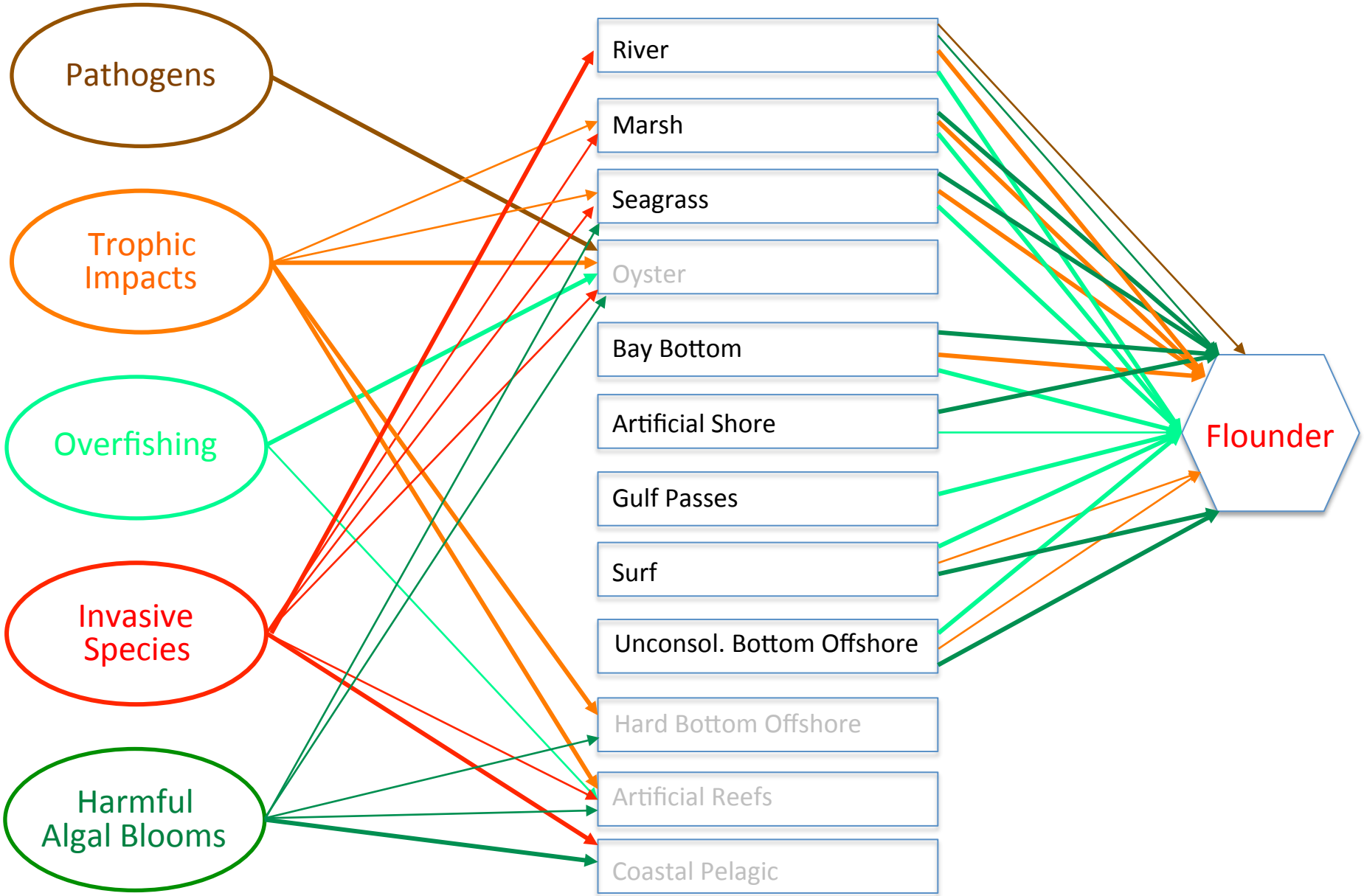
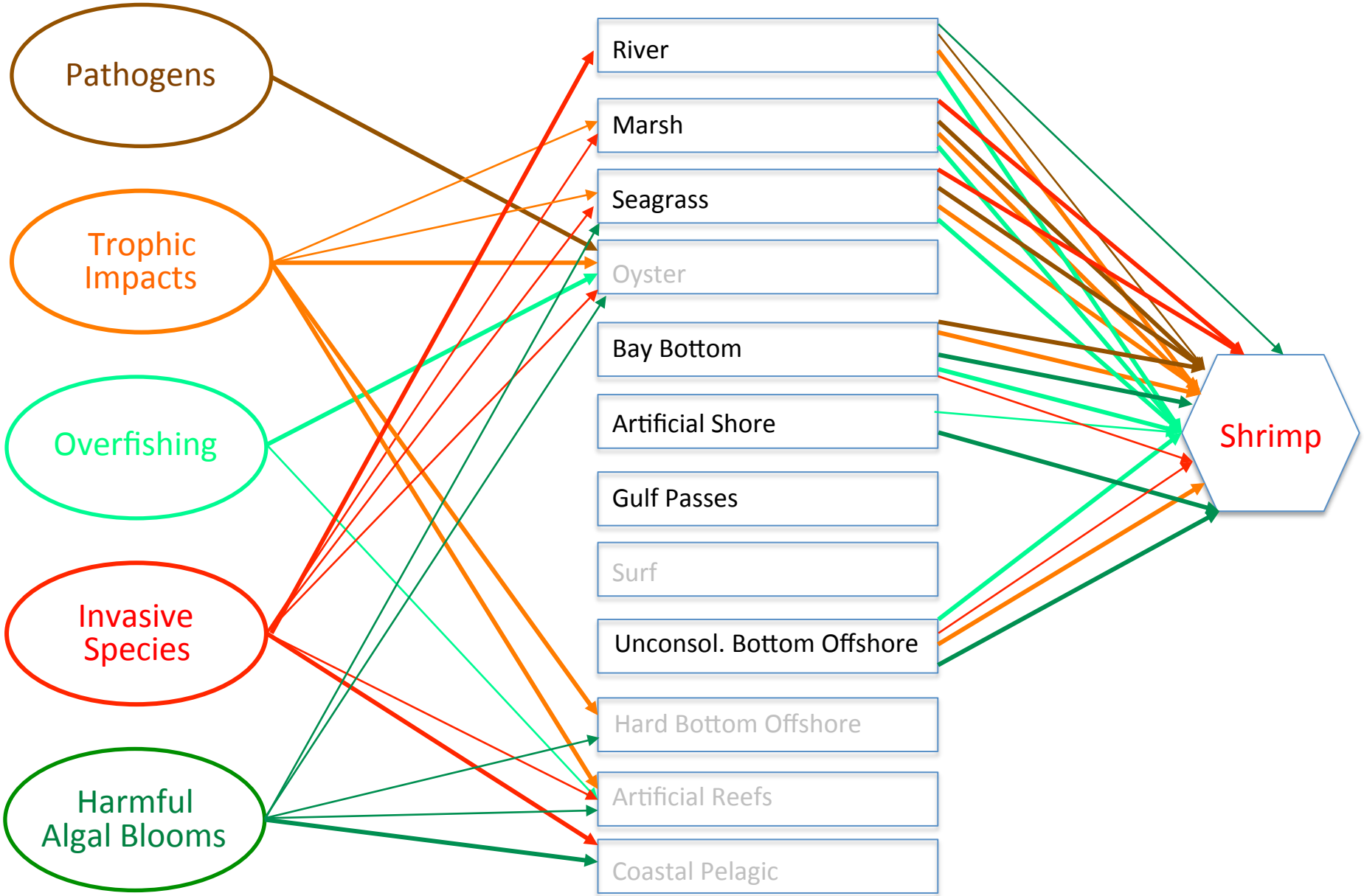


Biological Stressors



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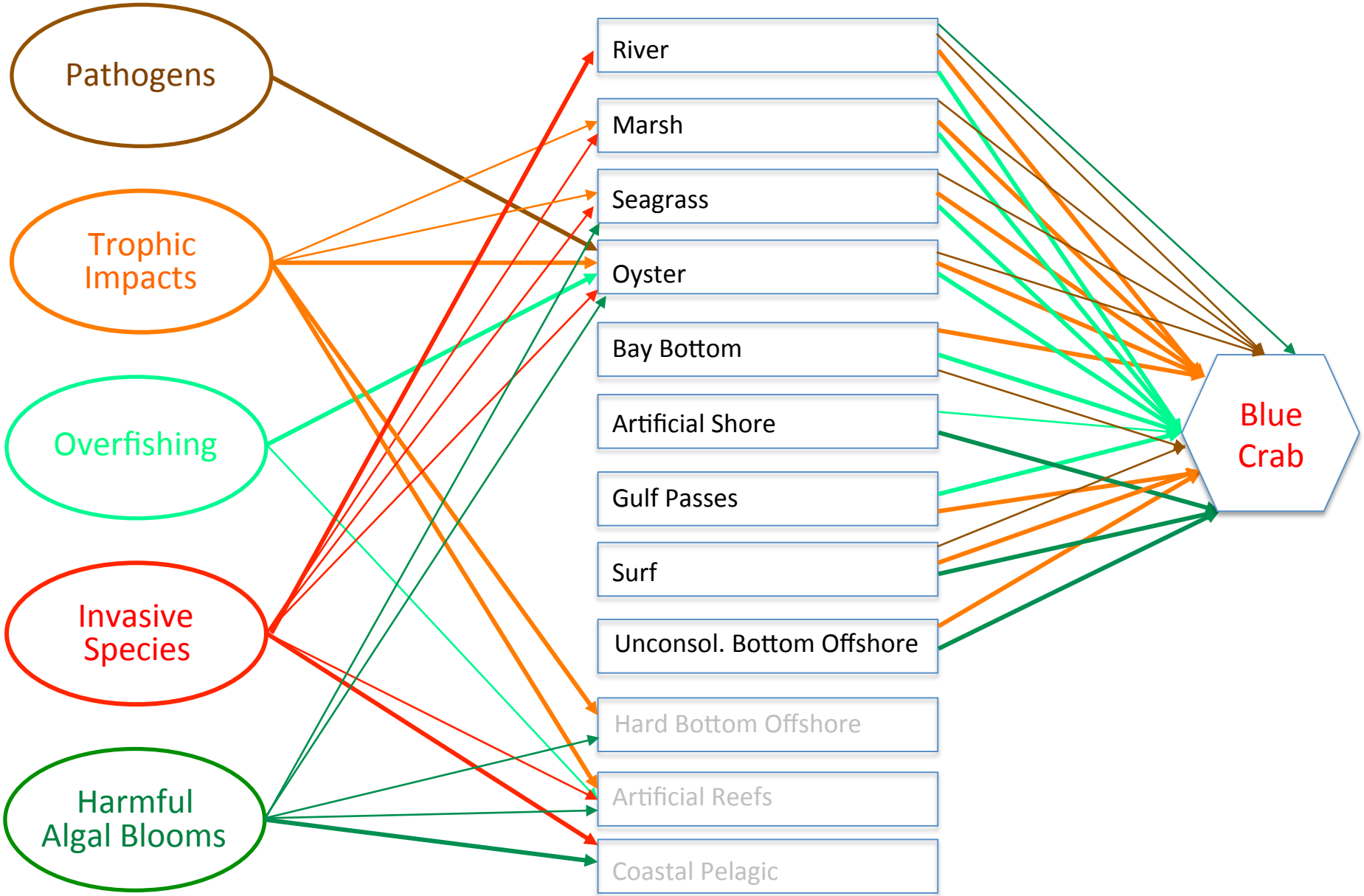
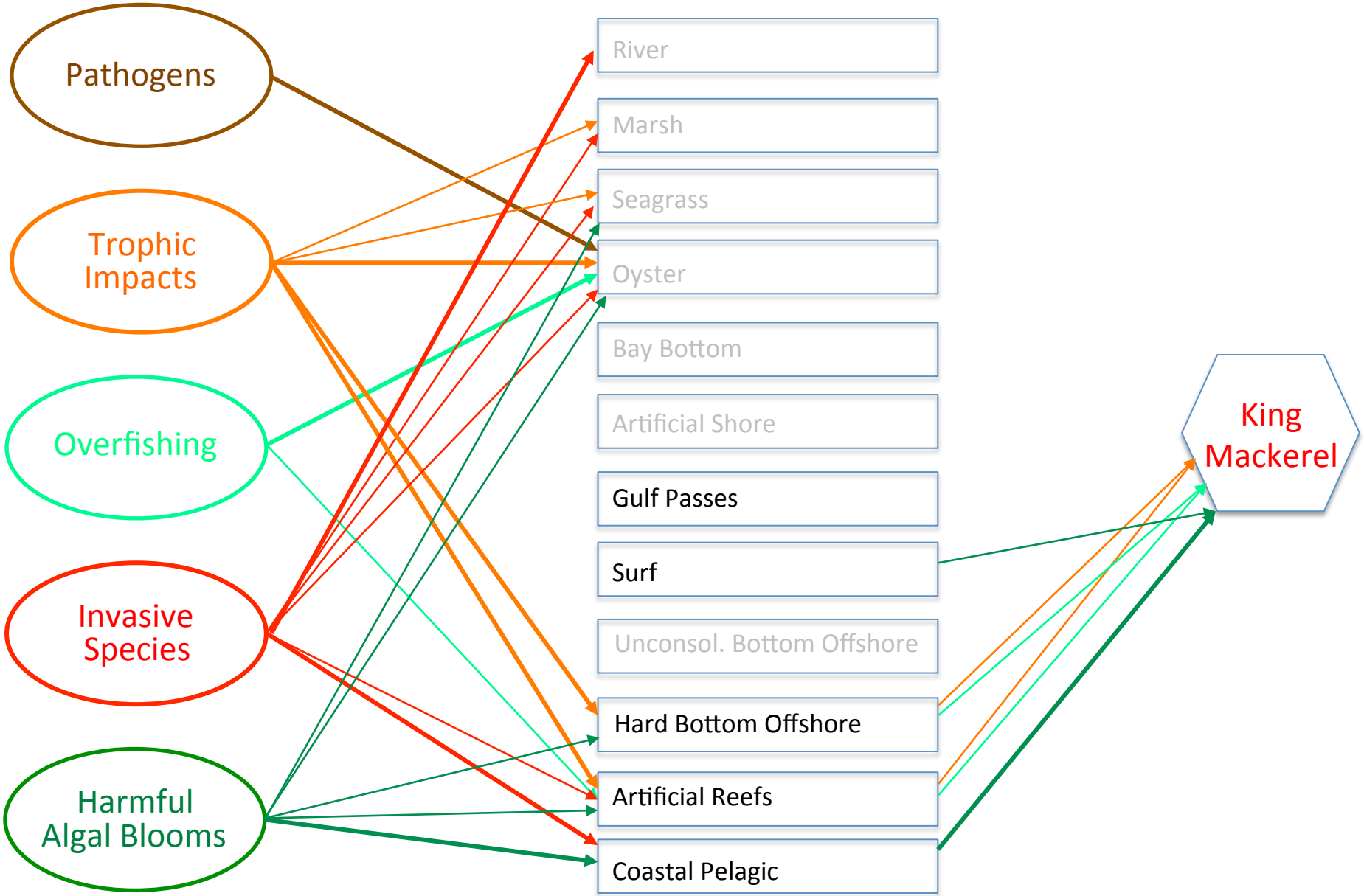
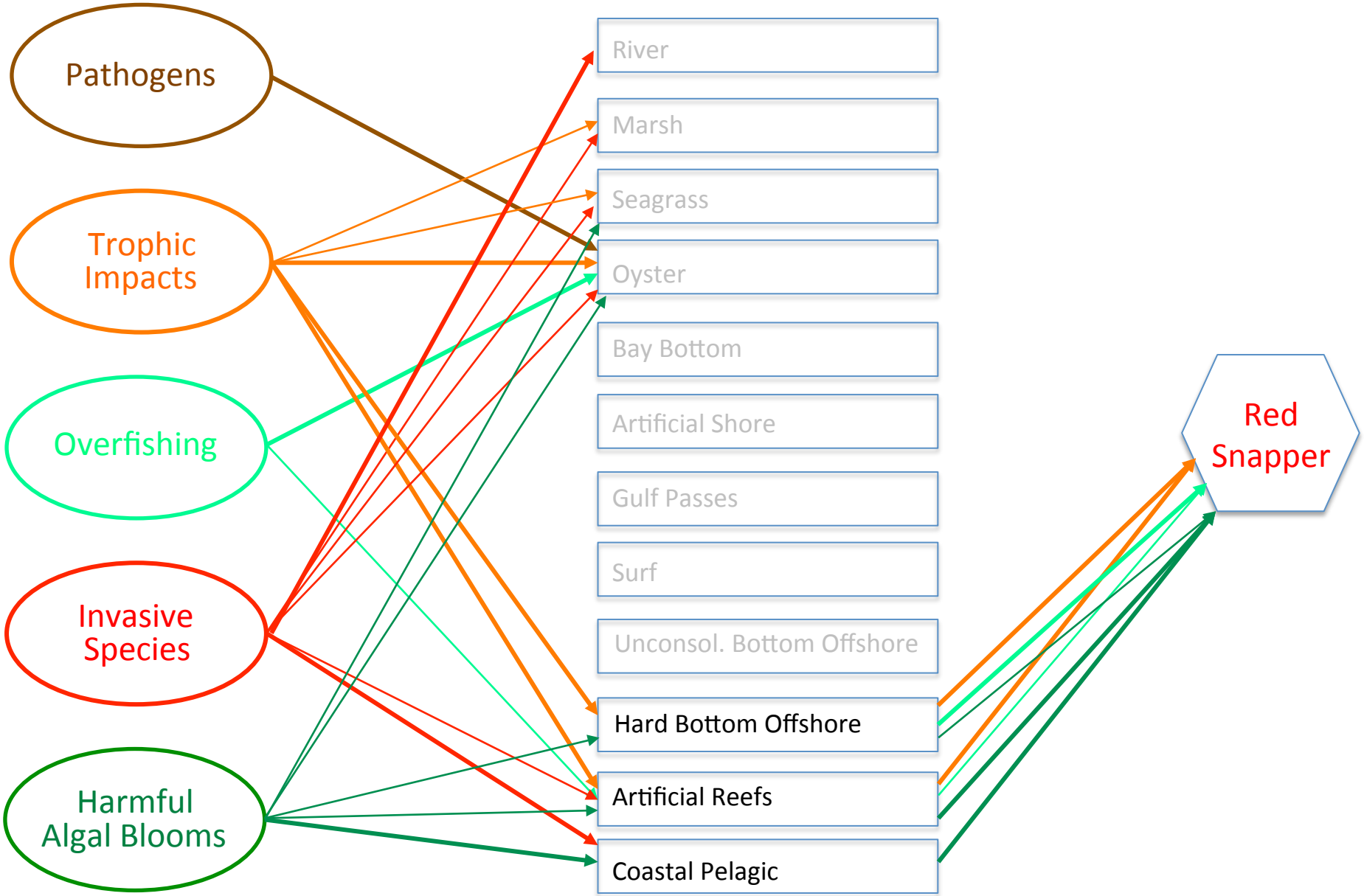
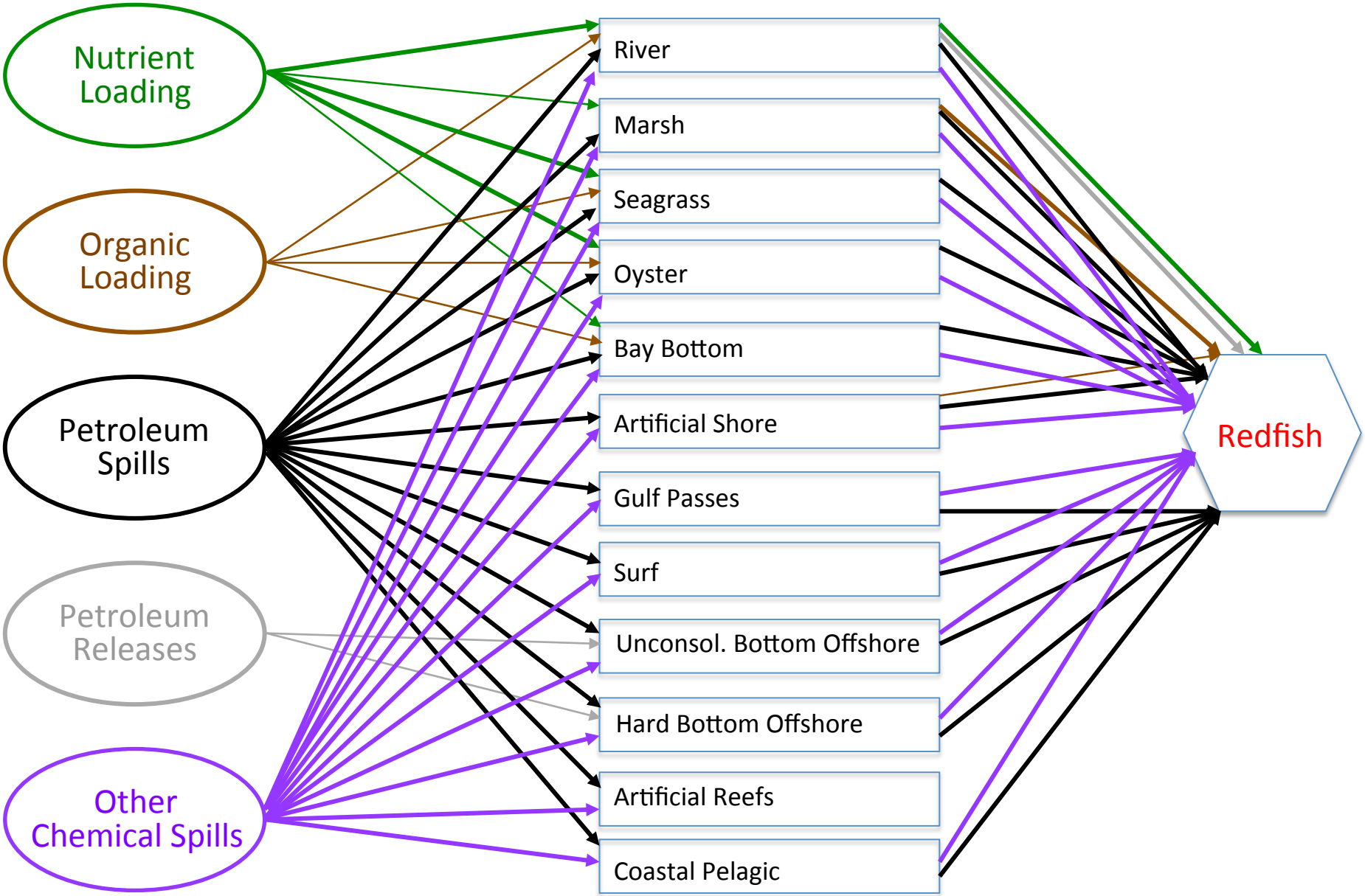


Biological Stressors



Biological Stressors




Nutrient Loading
Organic Loading
Petroleum Spills
Petroleum Releases
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Oyster
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Artificial Shore
Gulf Passes
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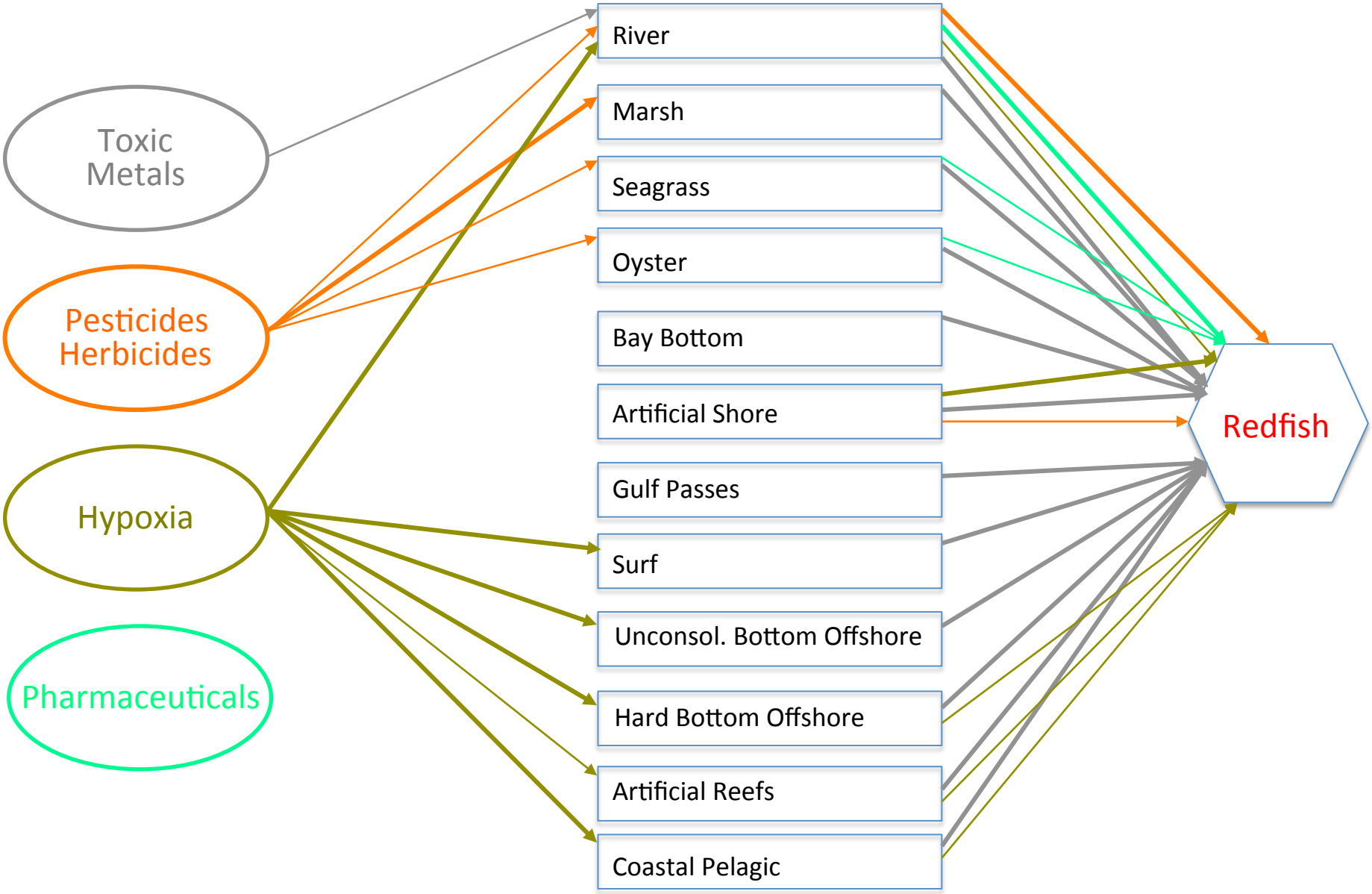
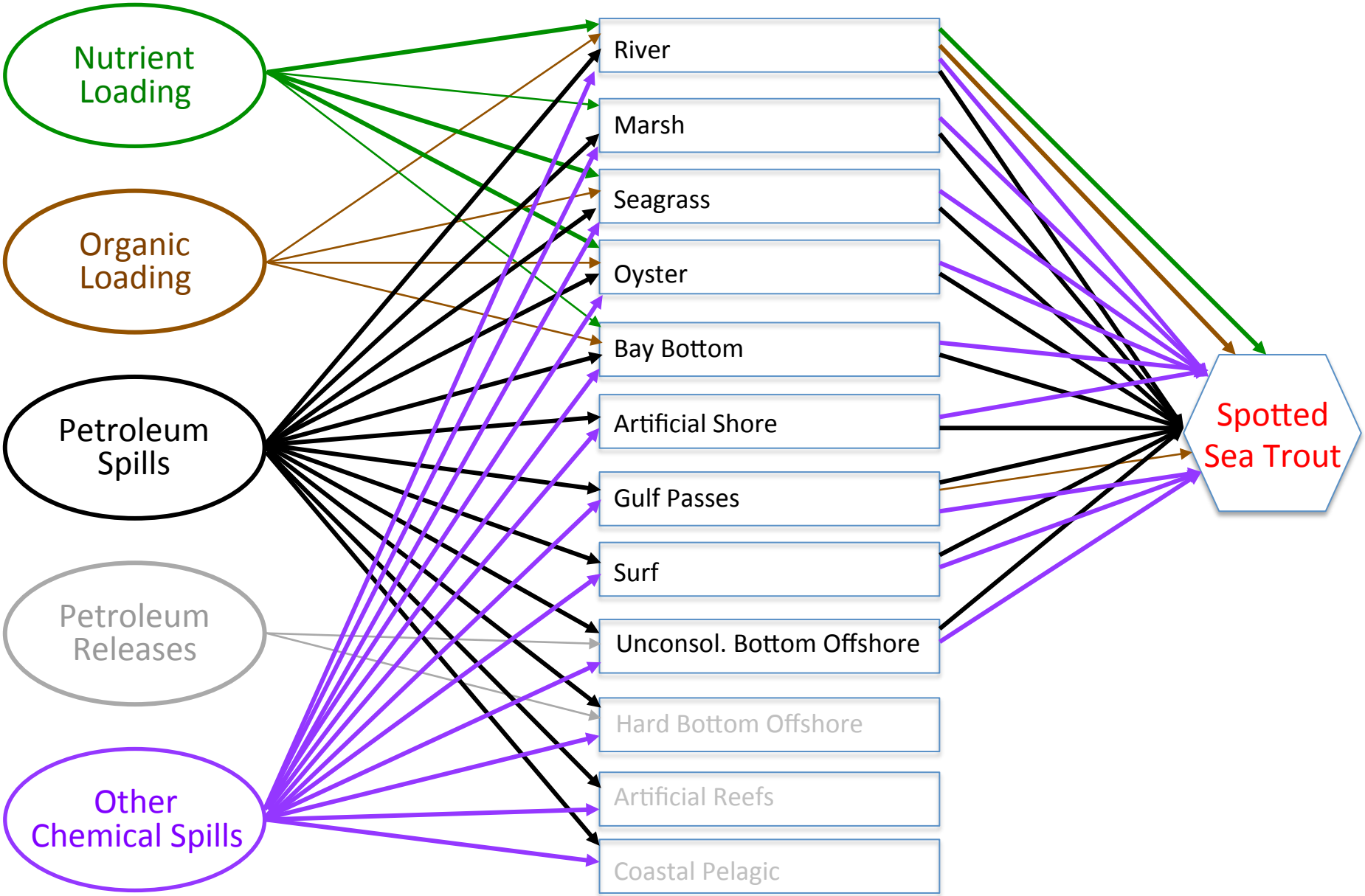
Hard Bottom Offshore
Artificial Reefs
Coastal Pelagic
Redfish

Chemical Stressors - 2

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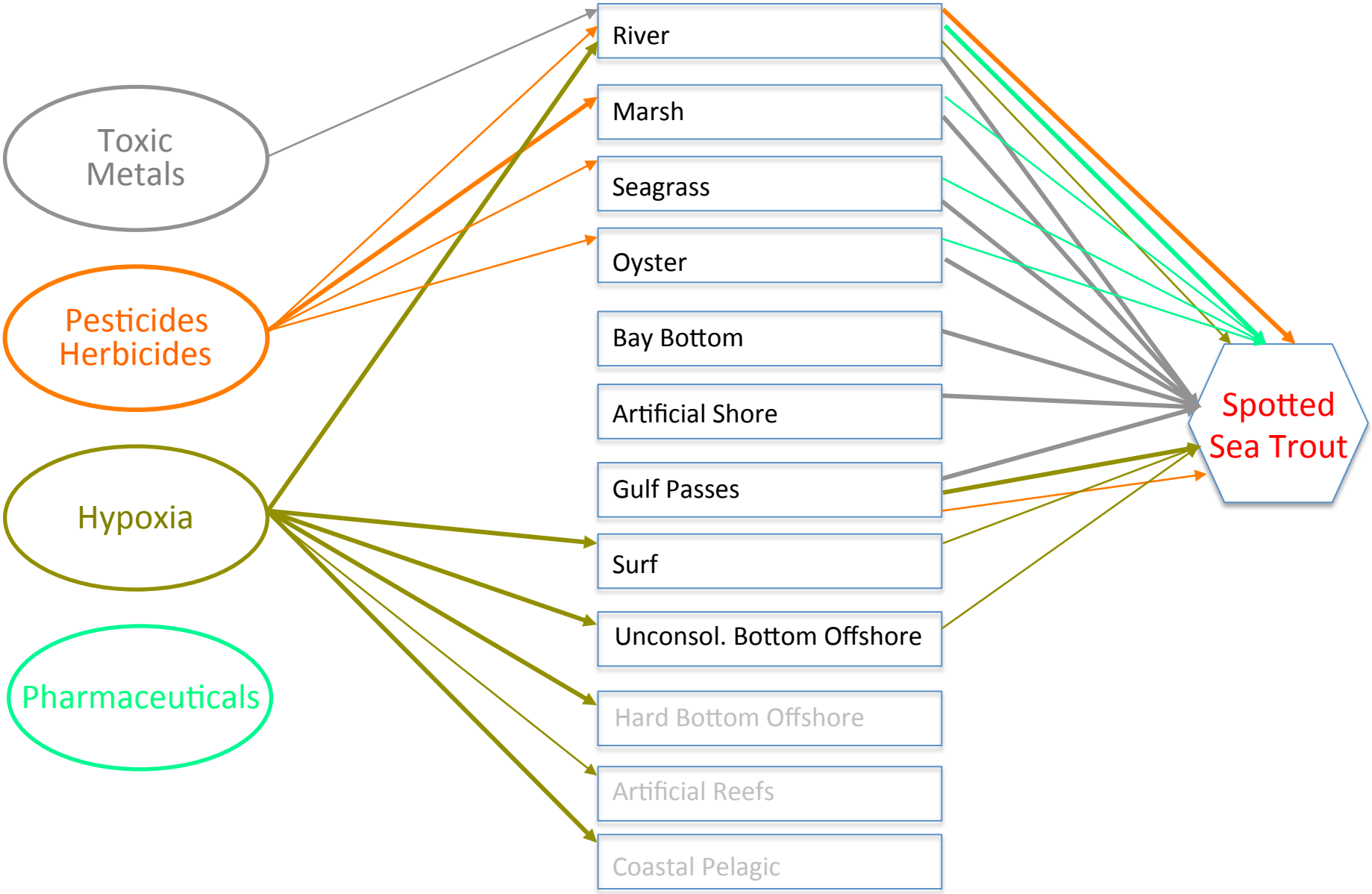
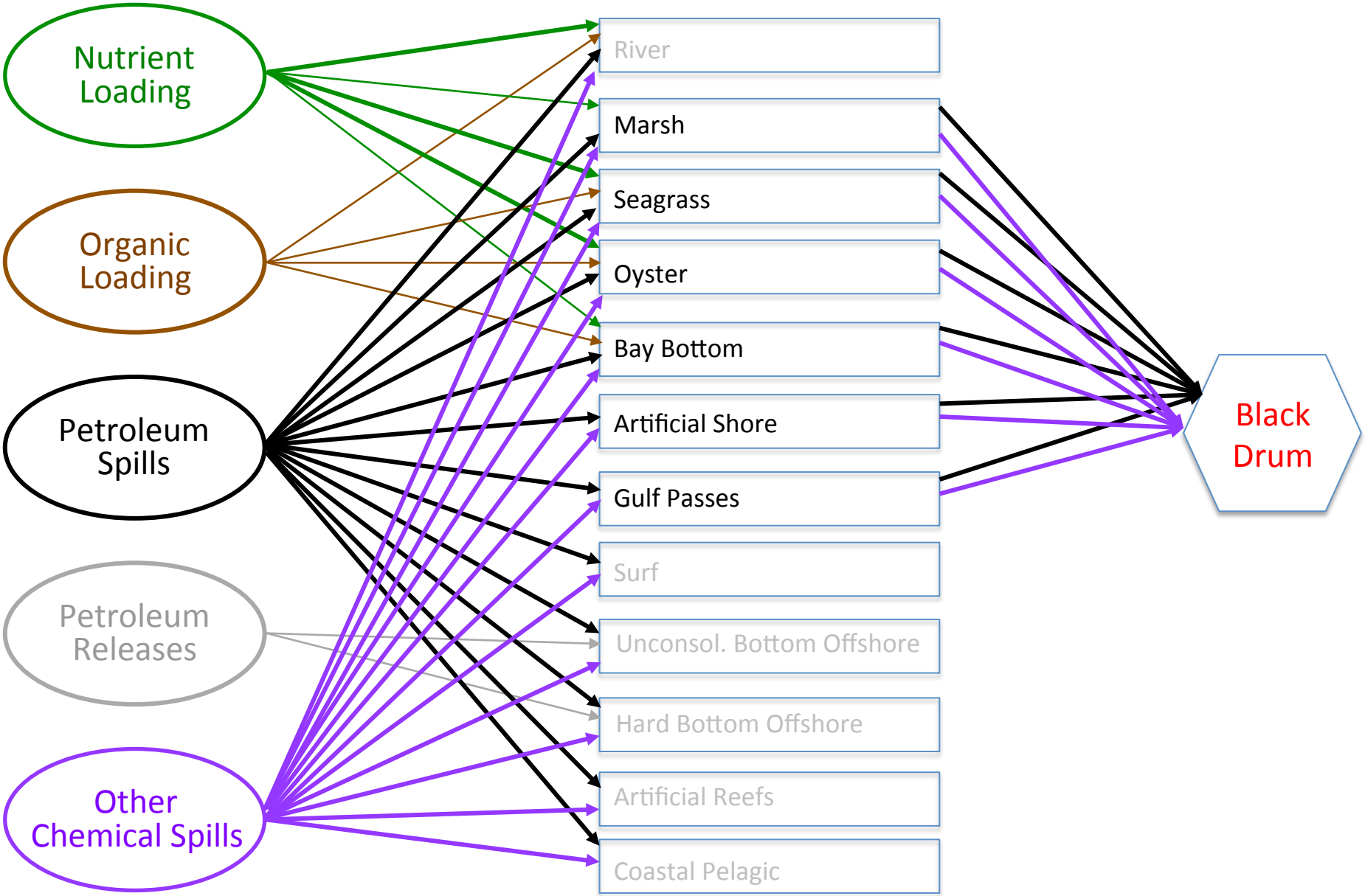
Coastal Pelagic
Spotted Sea Trout

Chemical Stressors - 2

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Gulf Passes
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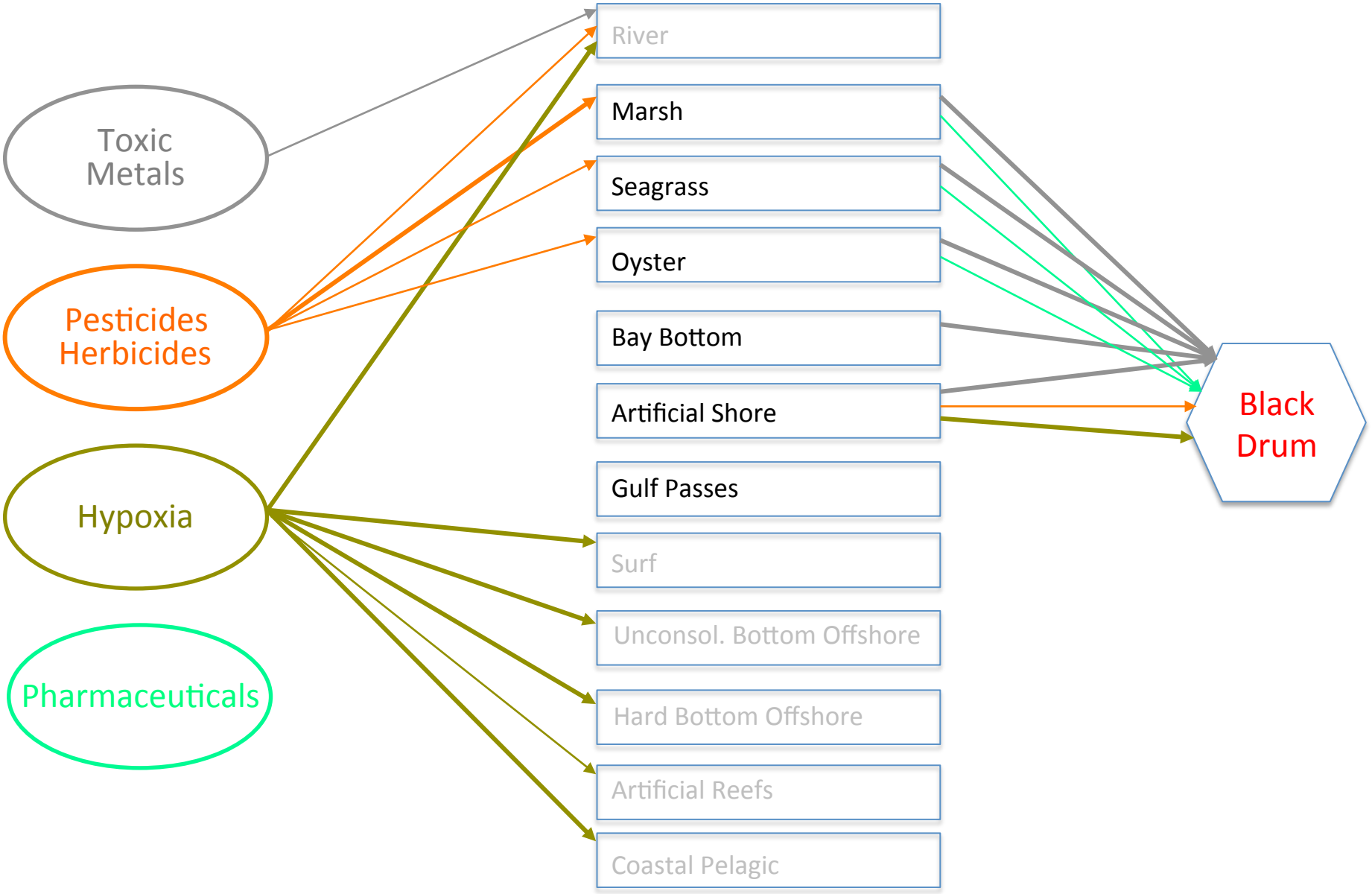
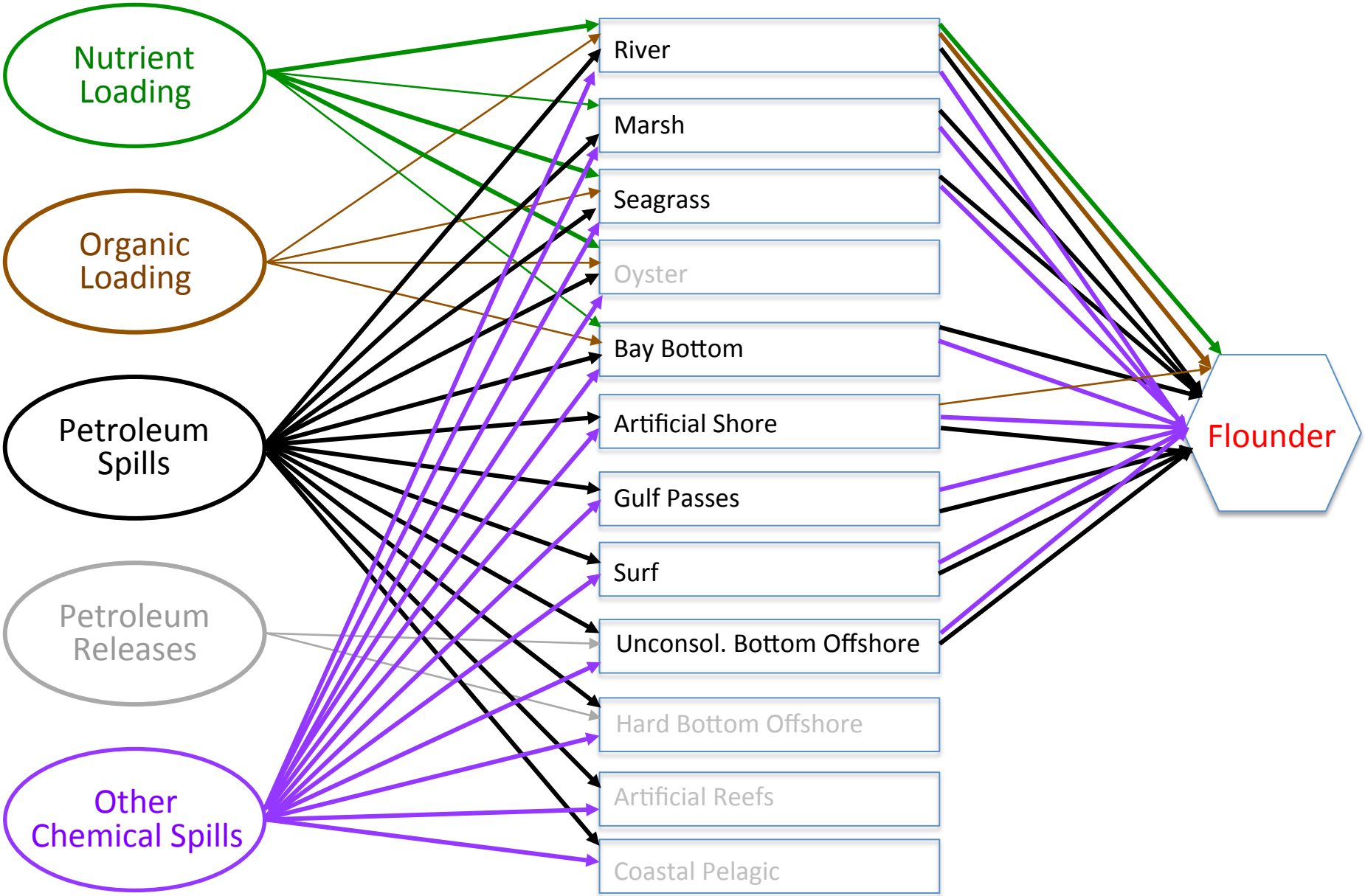
Unconsol. Bottom Offshore
Hard Bottom Offshore
Artificial Reefs
Coastal Pelagic
Black Drum

Chemical Stressors - 2

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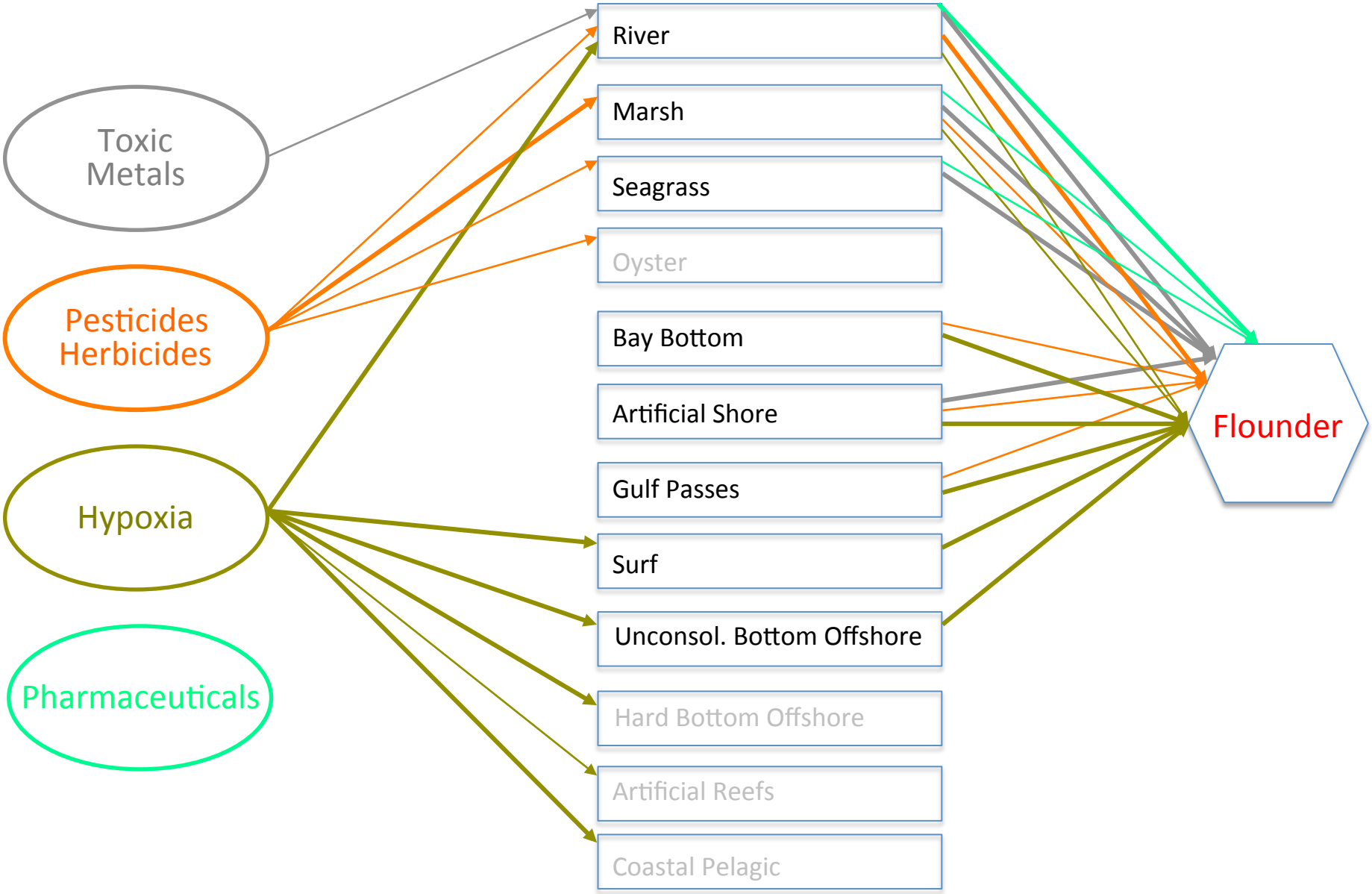
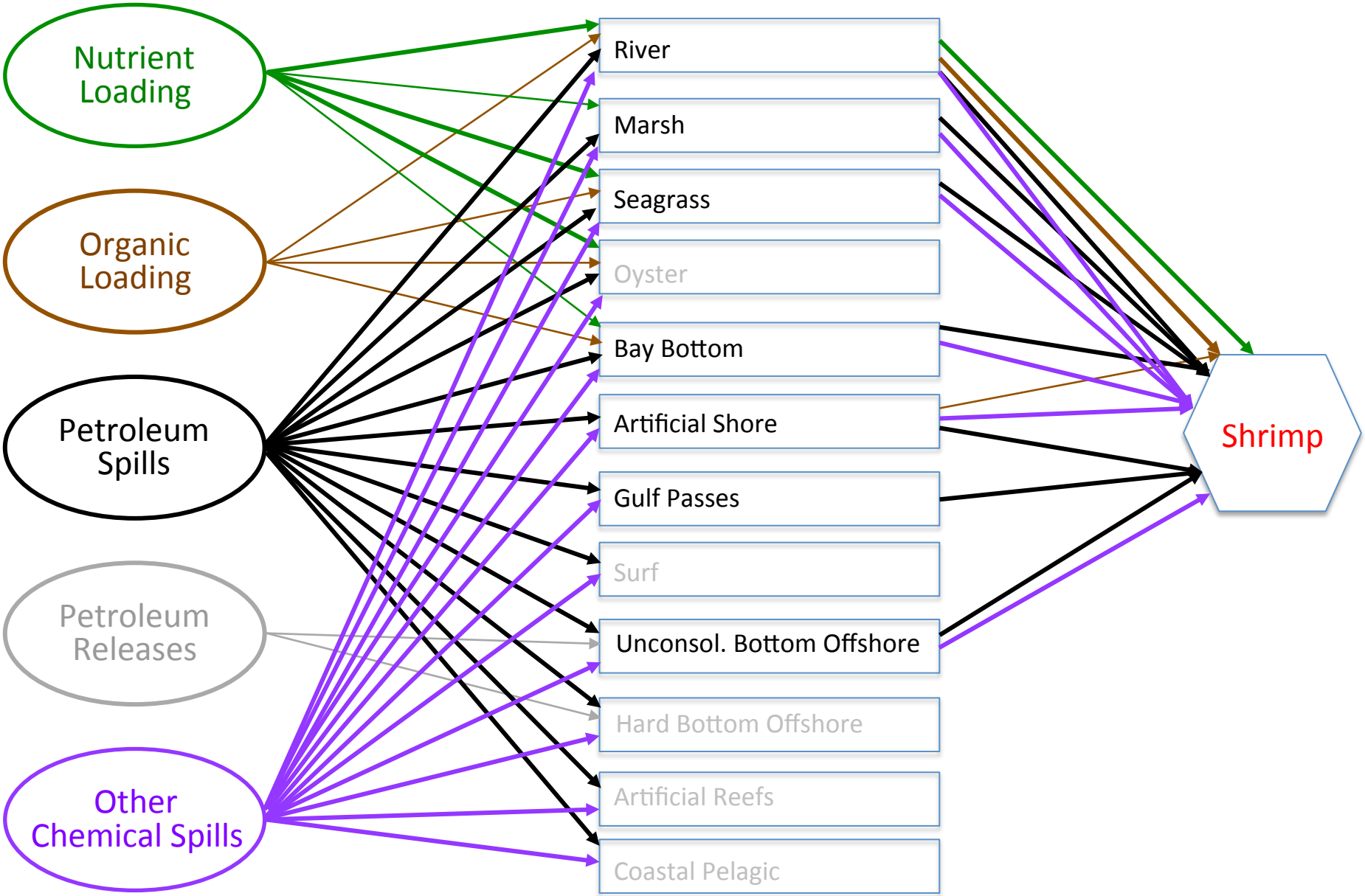
Unconsol. Bottom Offshore
Hard Bottom Offshore
Artificial Reefs
Coastal Pelagic
Flounder

Chemical Stressors - 2

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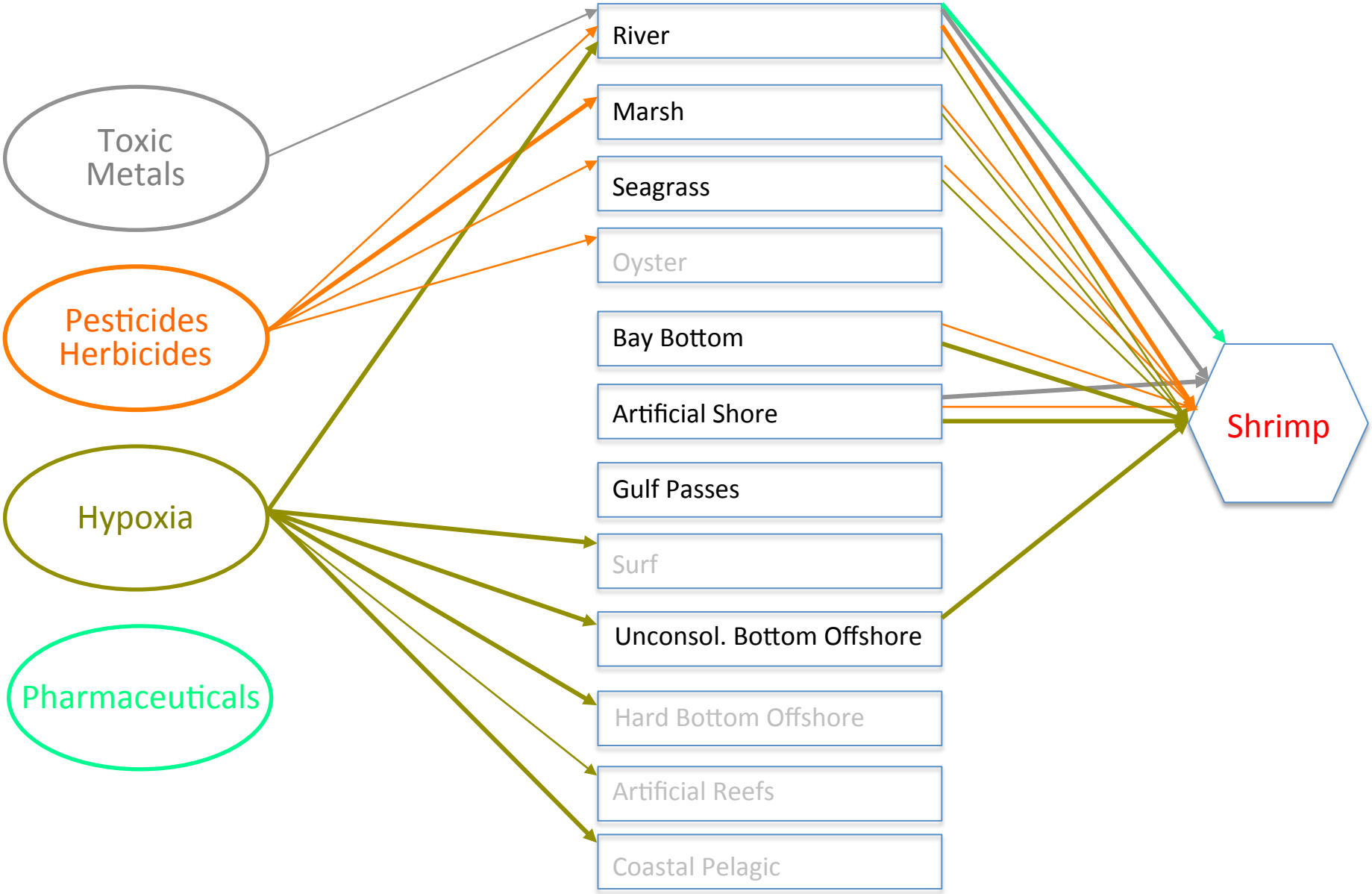
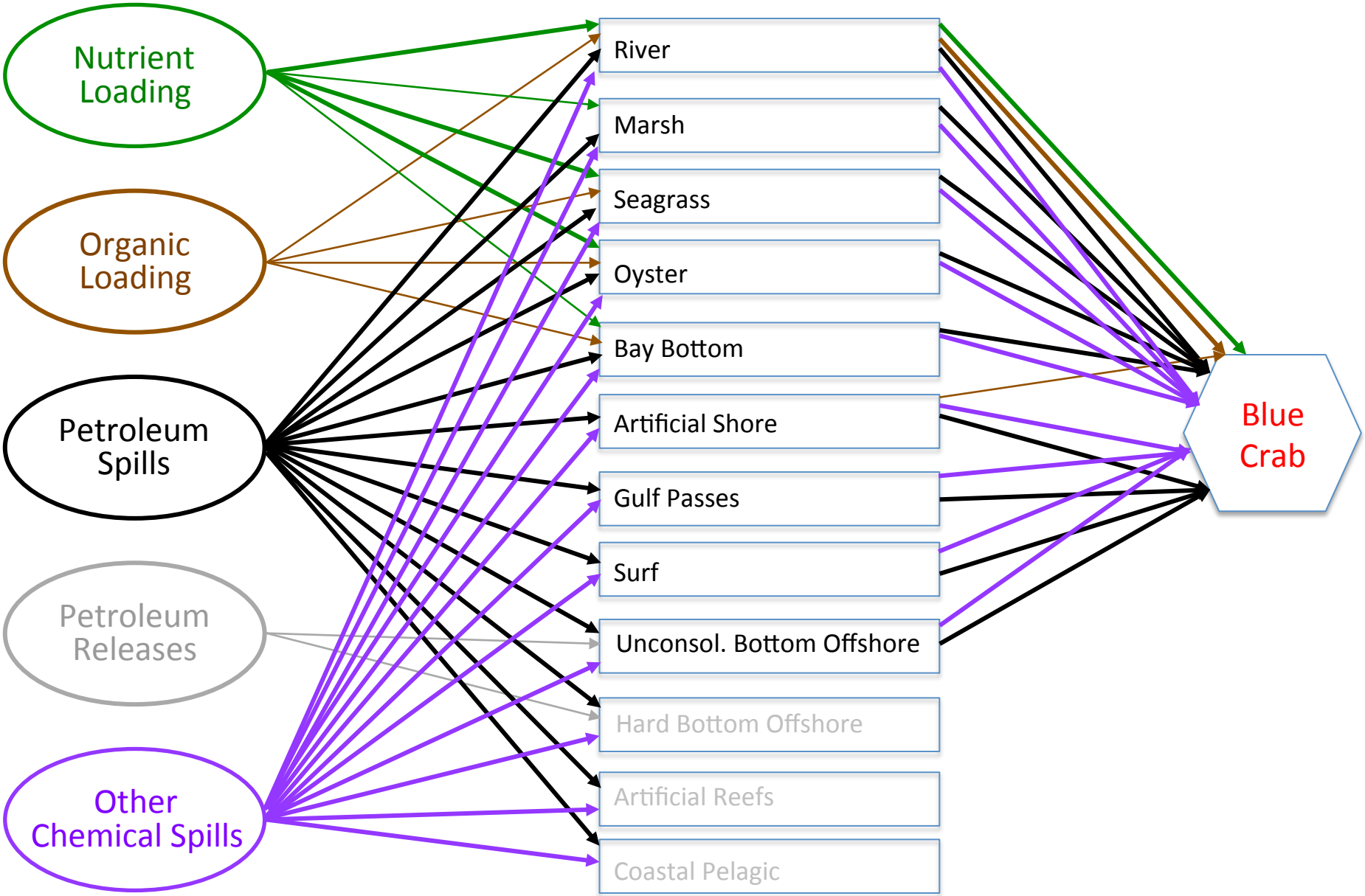
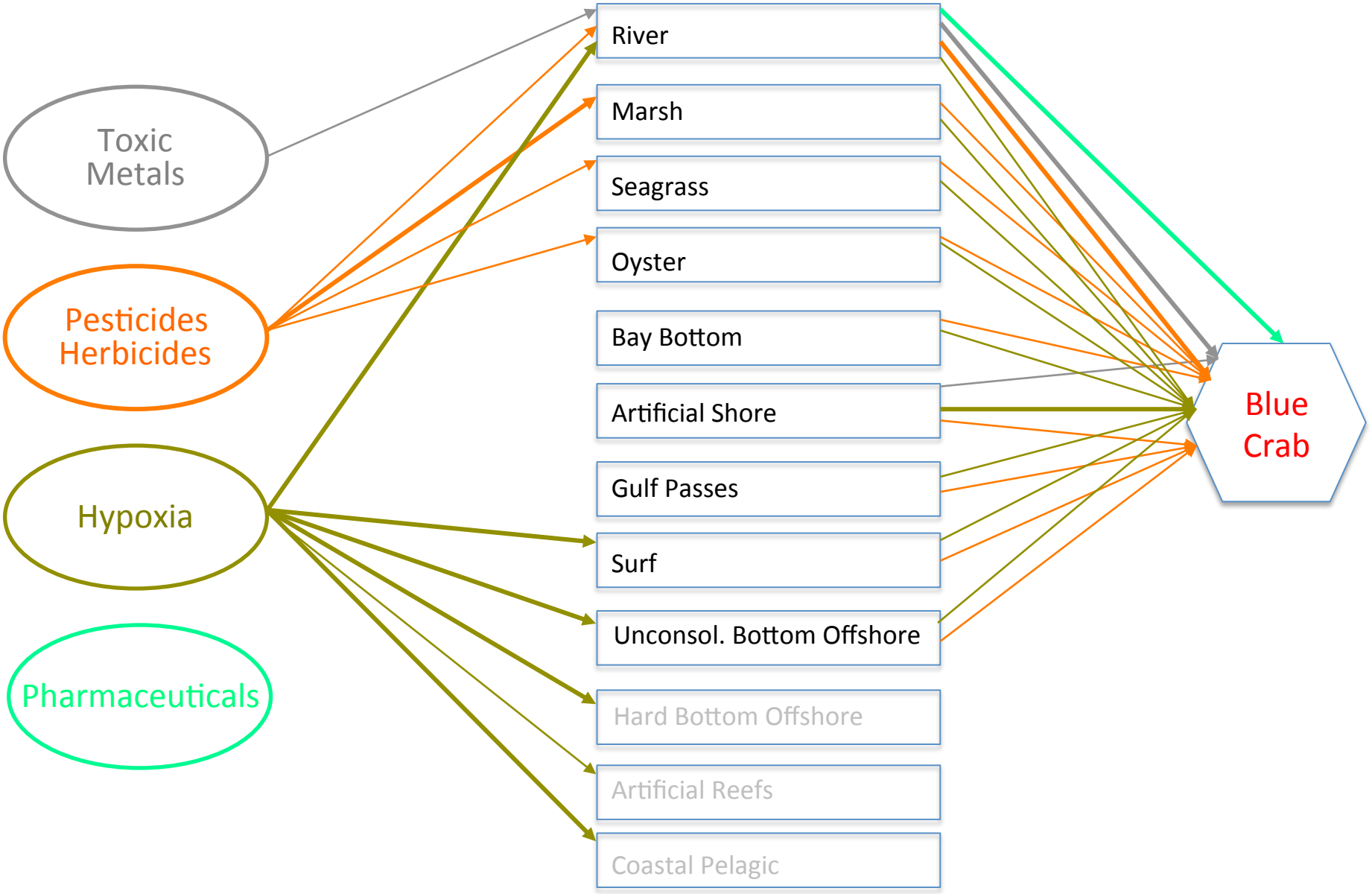
Coastal Pelagic
Shrimp

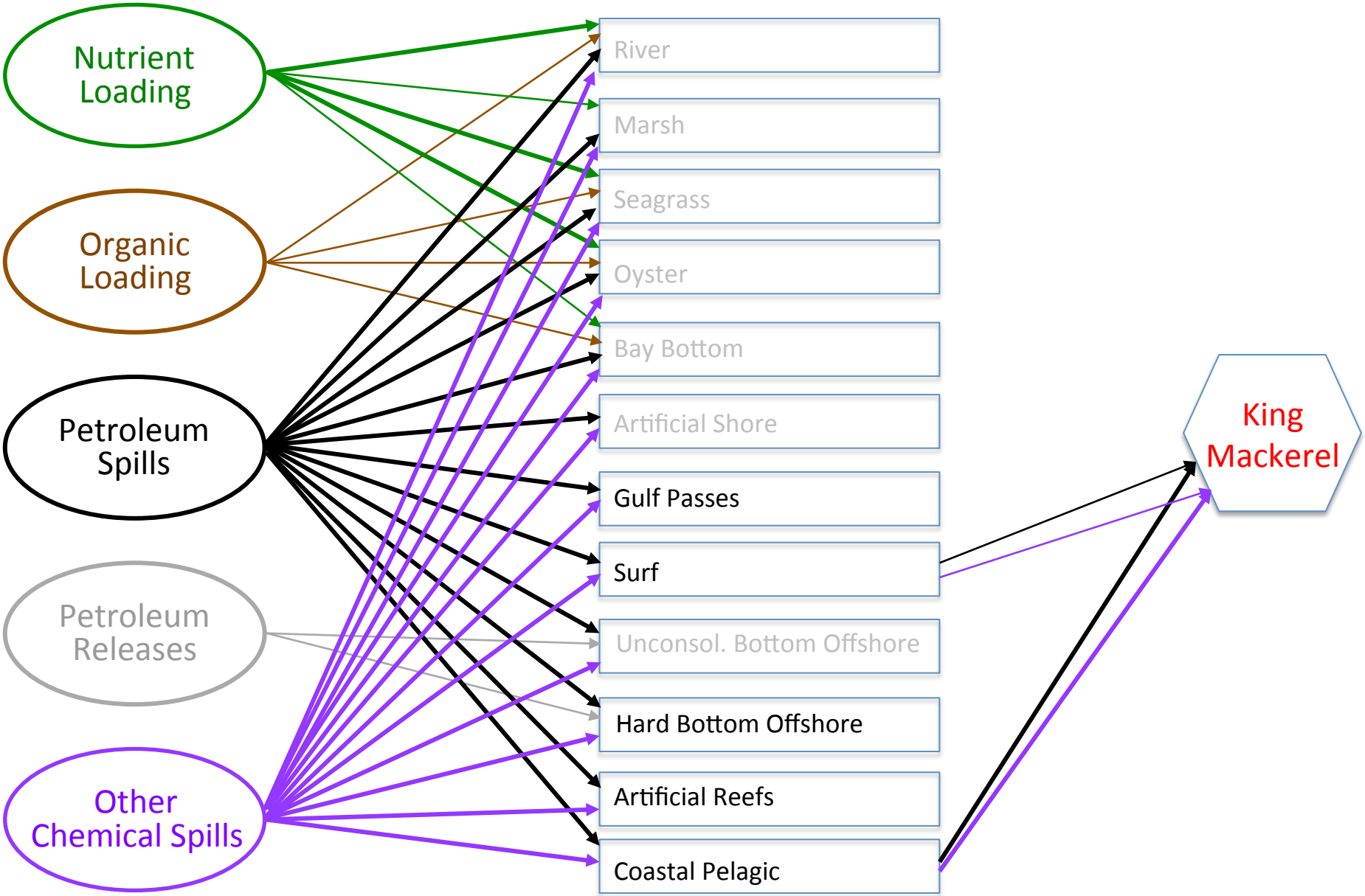
Chemical Stressors - 2



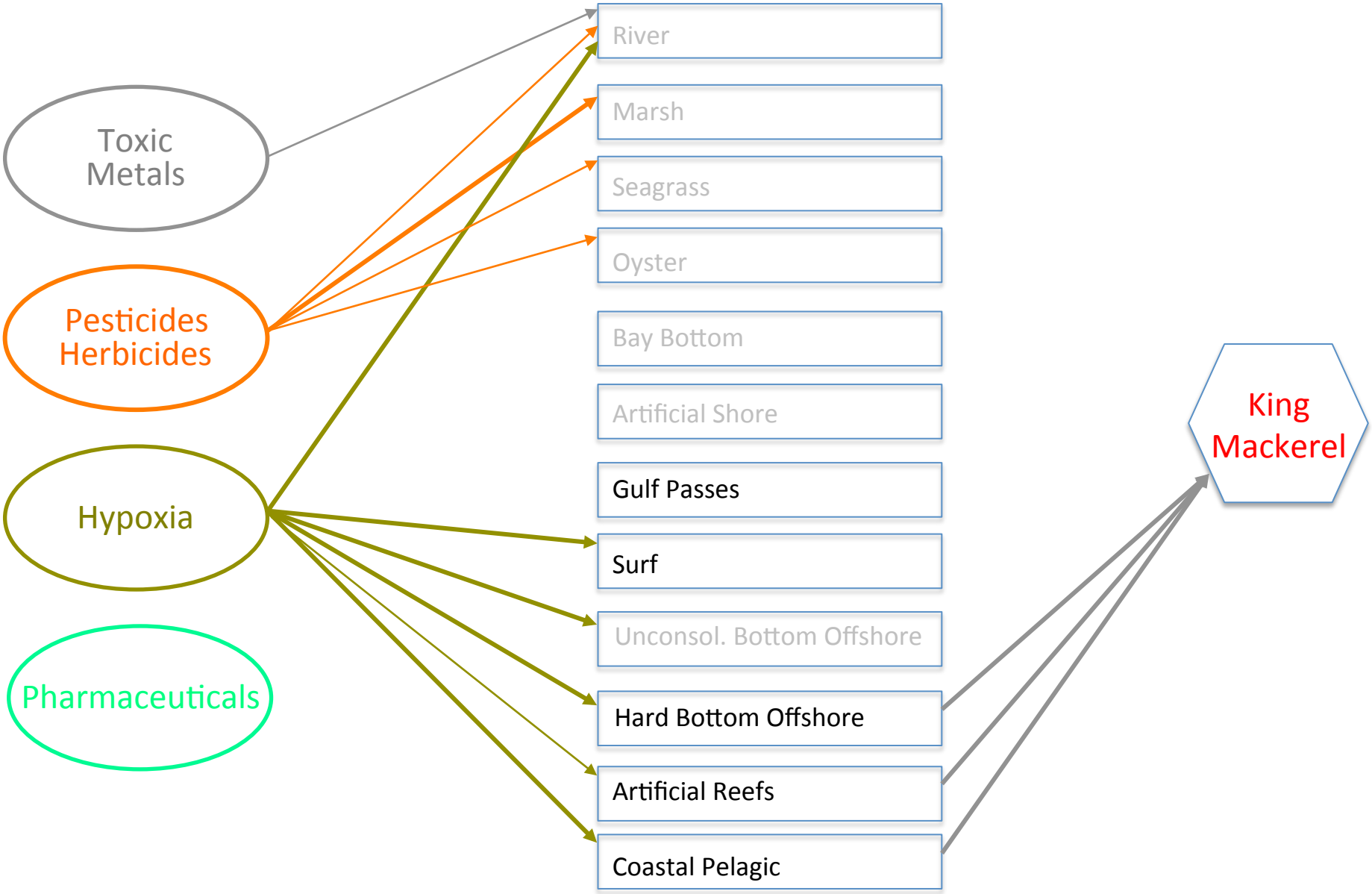

Nutrient Loading
Organic Loading
Petroleum Spills
Petroleum Releases
Other Chemical Spills
River
Marsh
Seagrass
Oyster
Bay Bottom
Artificial Shore
Gulf Passes
Surf
Unconsol. Bottom Offshore
Hard Bottom Offshore
Artificial Reefs
Coastal Pelagic
Blue Crab

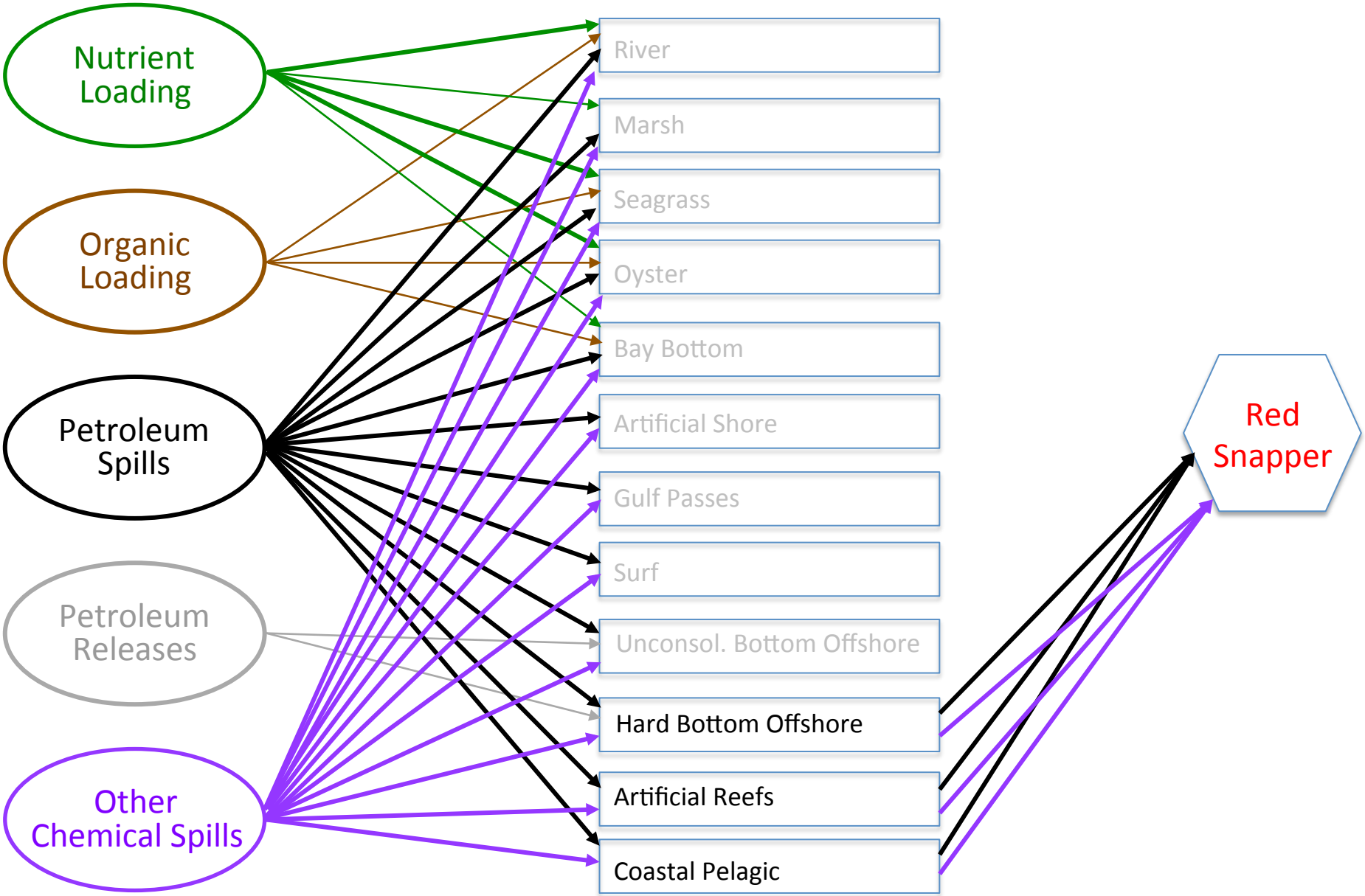
Chemical Stressors - 2



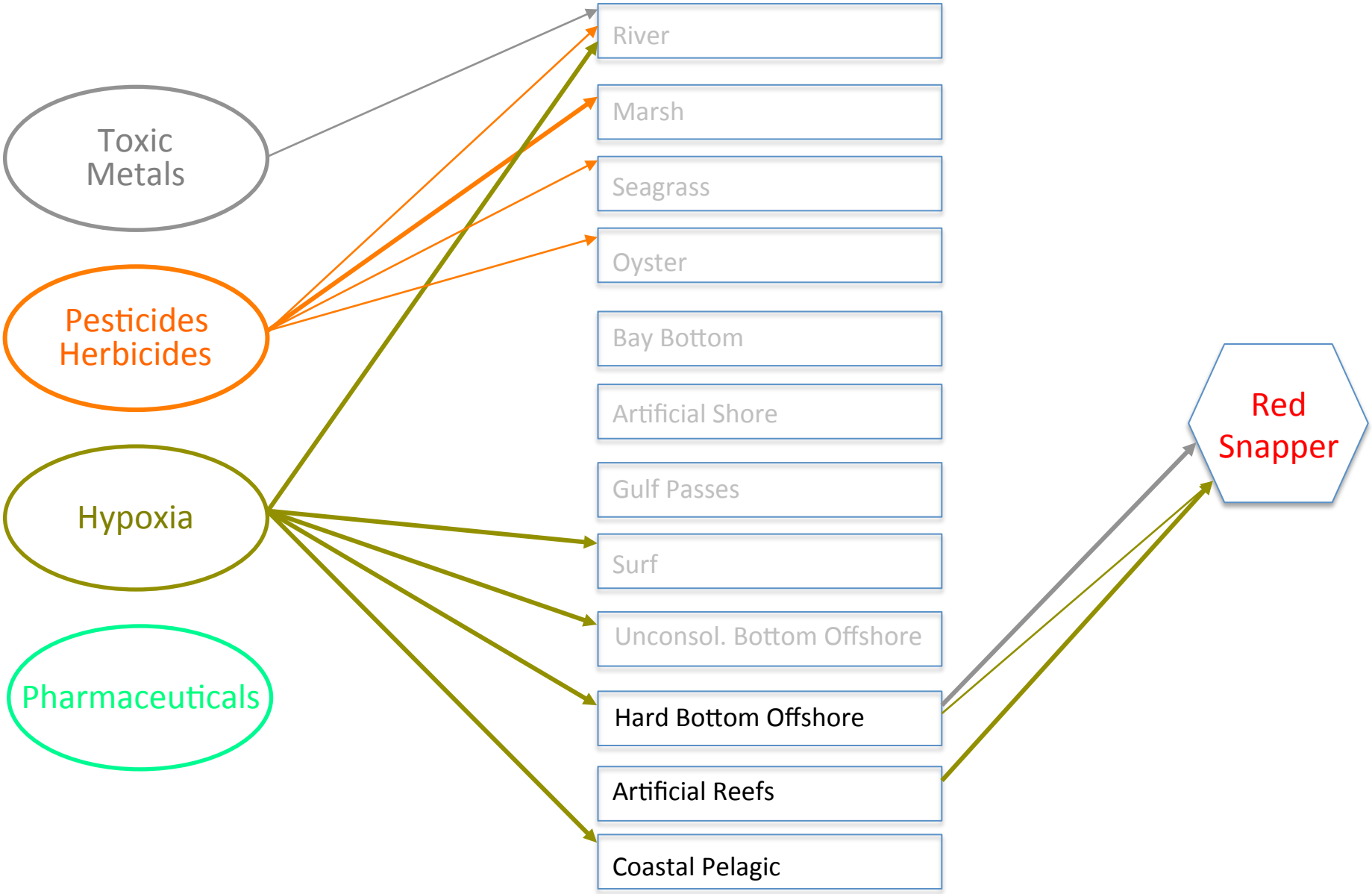

Nutrient Loading
Organic Loading
Petroleum Spills
Petroleum Releases
Other Chemical Spills
River
Marsh
Seagrass
Oyster
Bay Bottom
Artificial Shore
Gulf Passes
Surf
Unconsol. Bottom Offshore
Hard Bottom Offshore
Artificial Reefs
Coastal Pelagic
King Mackerel

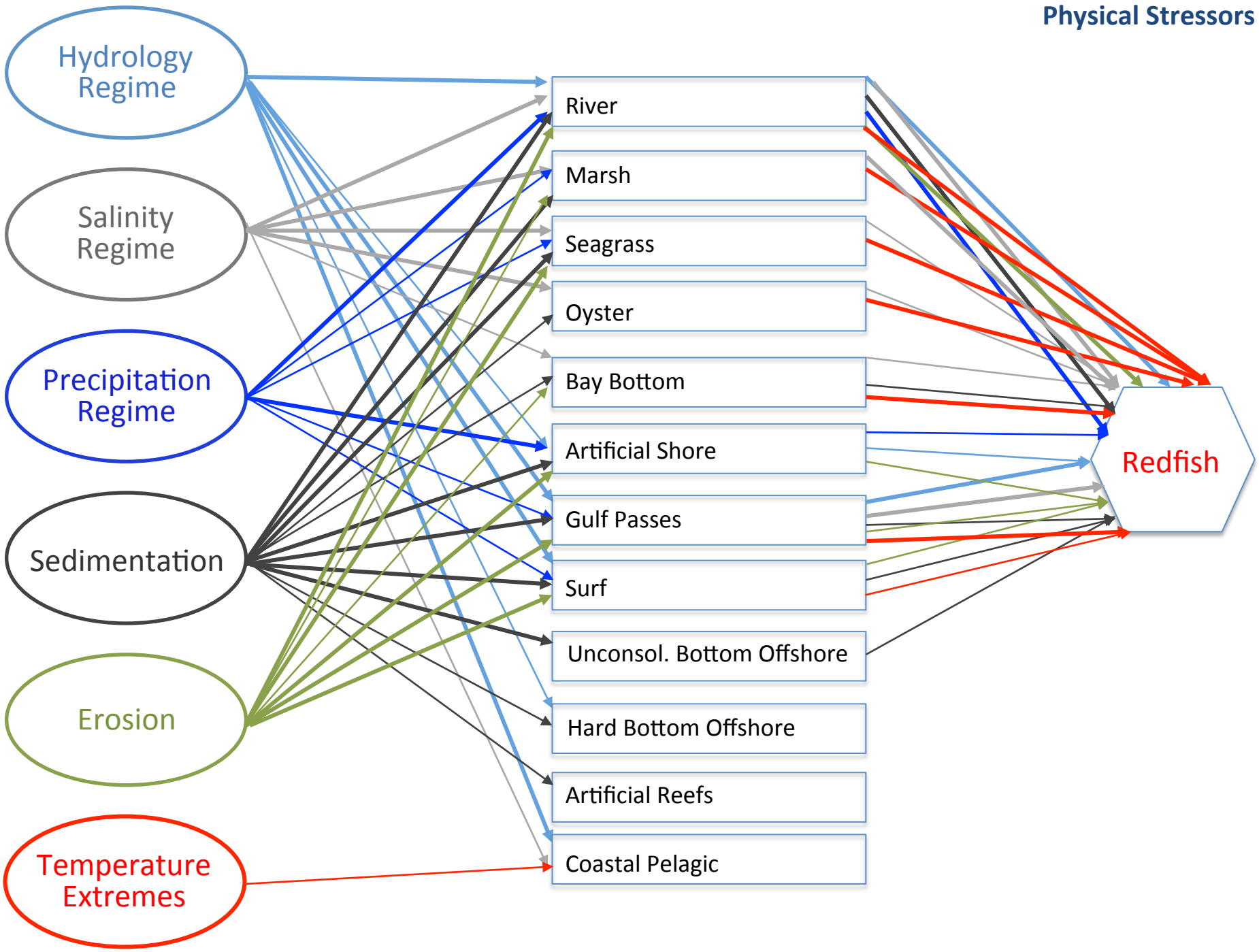
Chemical Stressors - 2



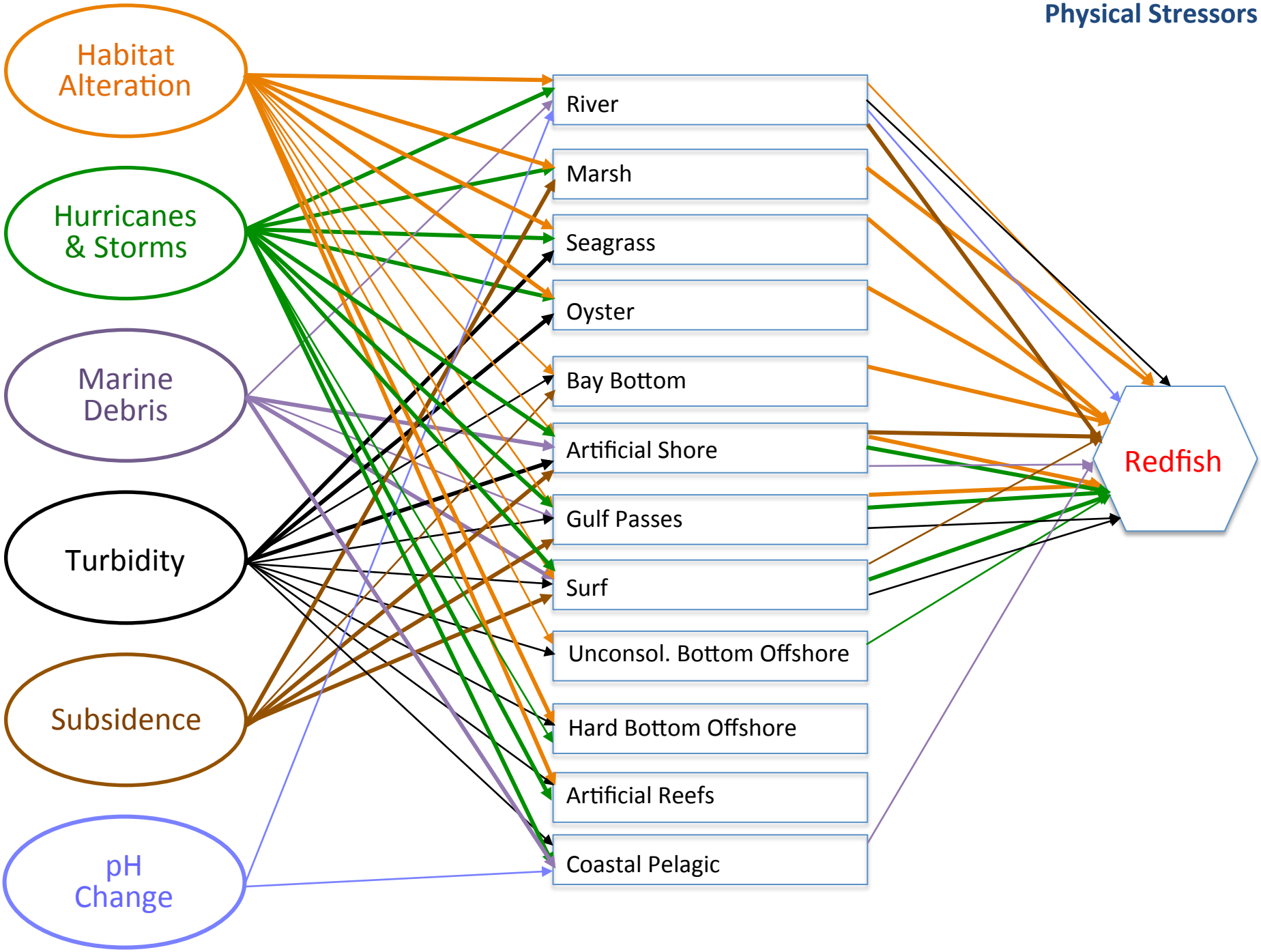

Nutrient Loading
Organic Loading
Petroleum Spills
Petroleum Releases
Other Chemical Spills
River
Marsh
Seagrass
Oyster
Bay Bottom
Artificial Shore
Gulf Passes
Surf
Unconsol. Bottom Offshore
Hard Bottom Offshore
Artificial Reefs
Coastal Pelagic
Red Snapper

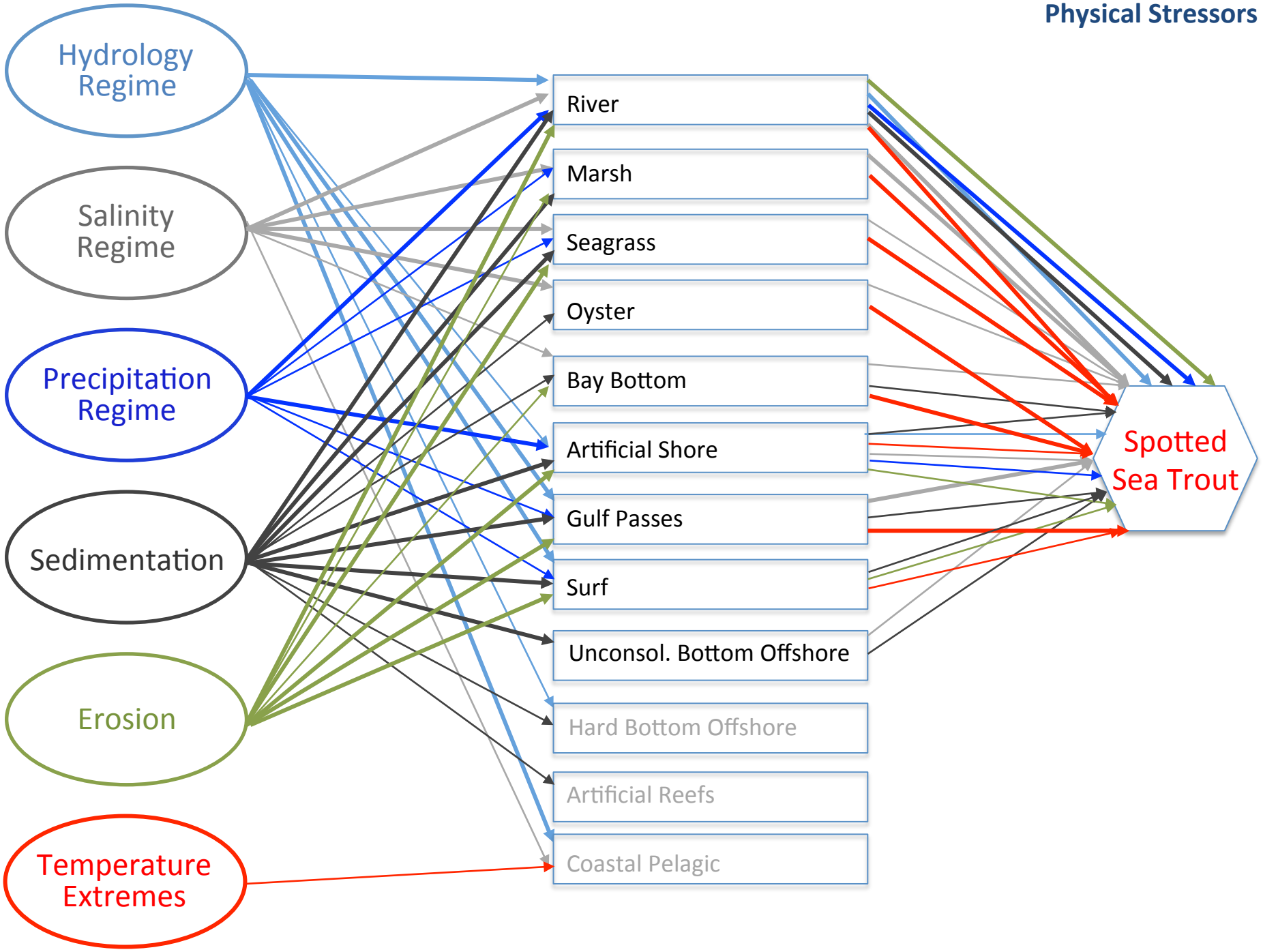
Chemical Stressors - 2



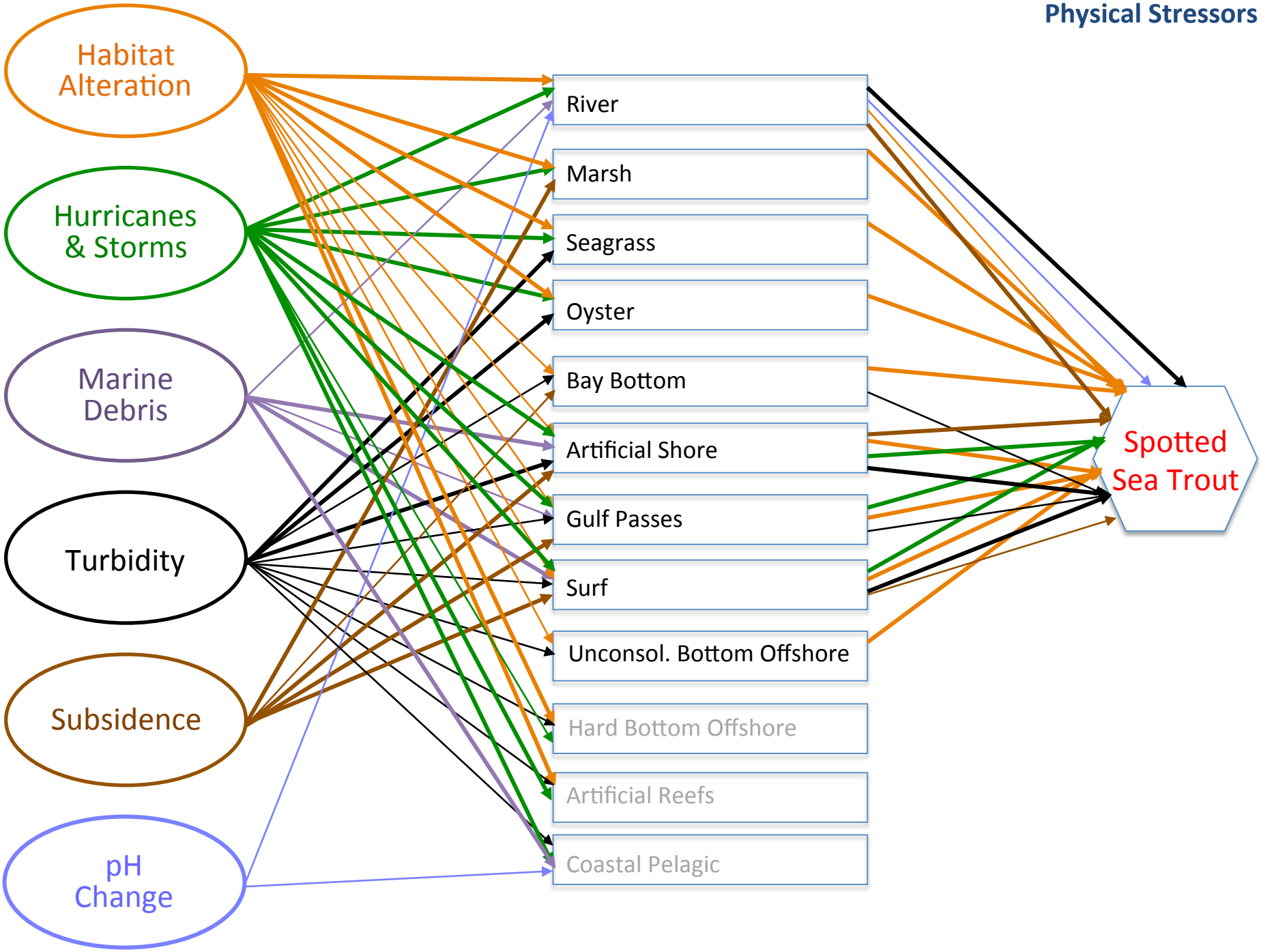

Physical Stressors - 1
Hydrology Regime
Salinity Regime
Precipitation Regime
Sedimentation
Erosion
Temperature Extremes
River
Marsh
Seagrass
Oyster
Bay Bottom
Artificial Shore
Gulf Passes
Surf
Unconsol. Bottom Offshore
Hard Bottom Offshore
Artificial Reefs
Coastal Pelagic
Redfish

Physical Stressors - 2

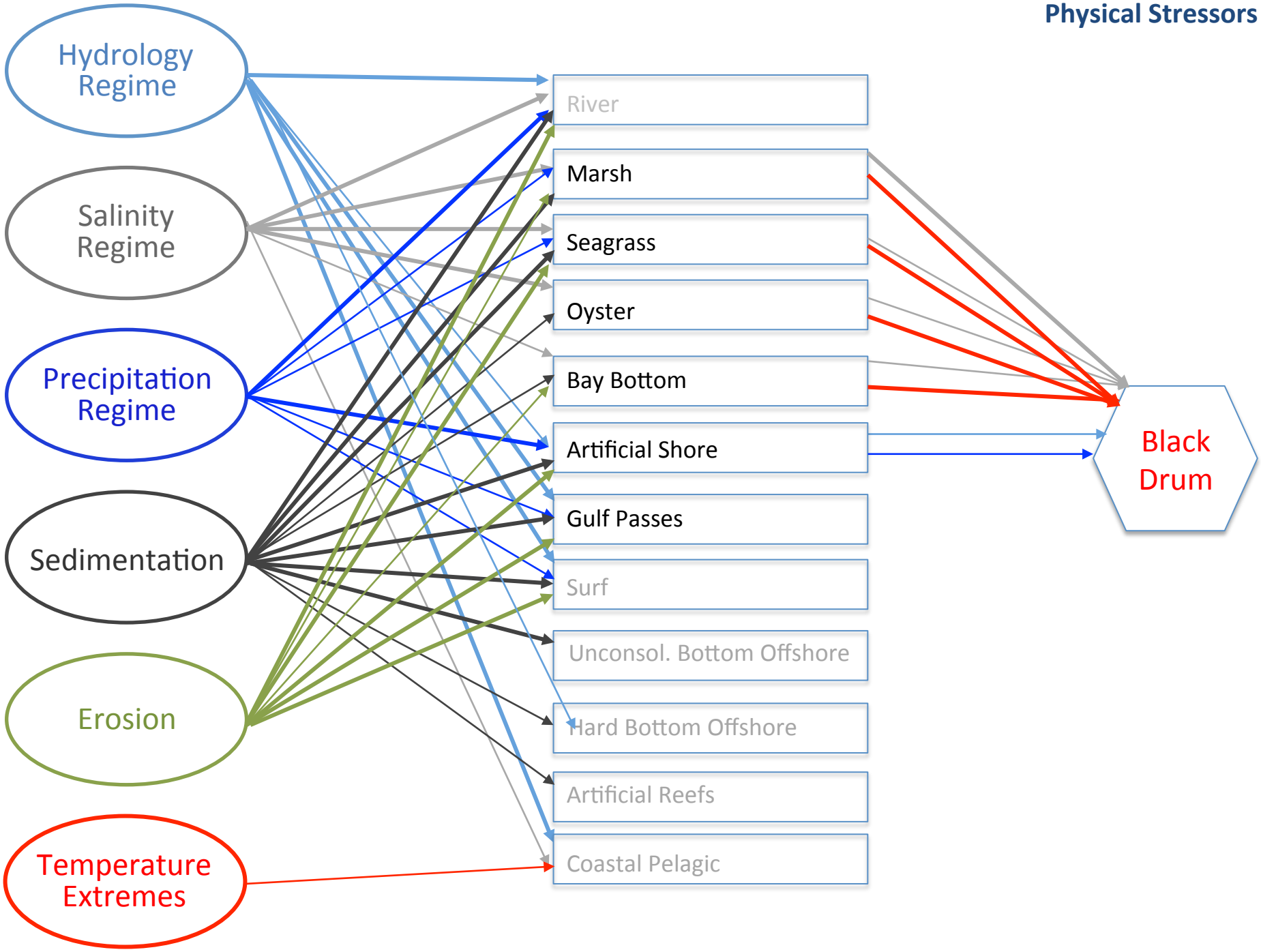



Hydrology Regime
Salinity Regime
Precipitation Regime
Sedimentation
Erosion
Temperature Extremes
River
Marsh
Seagrass
Oyster
Bay Bottom
Artificial Shore
Gulf Passes
Surf
Unconsol. Bottom Offshore
Hard Bottom Offshore
Artificial Reefs
Coastal Pelagic
Spotted Sea Trout

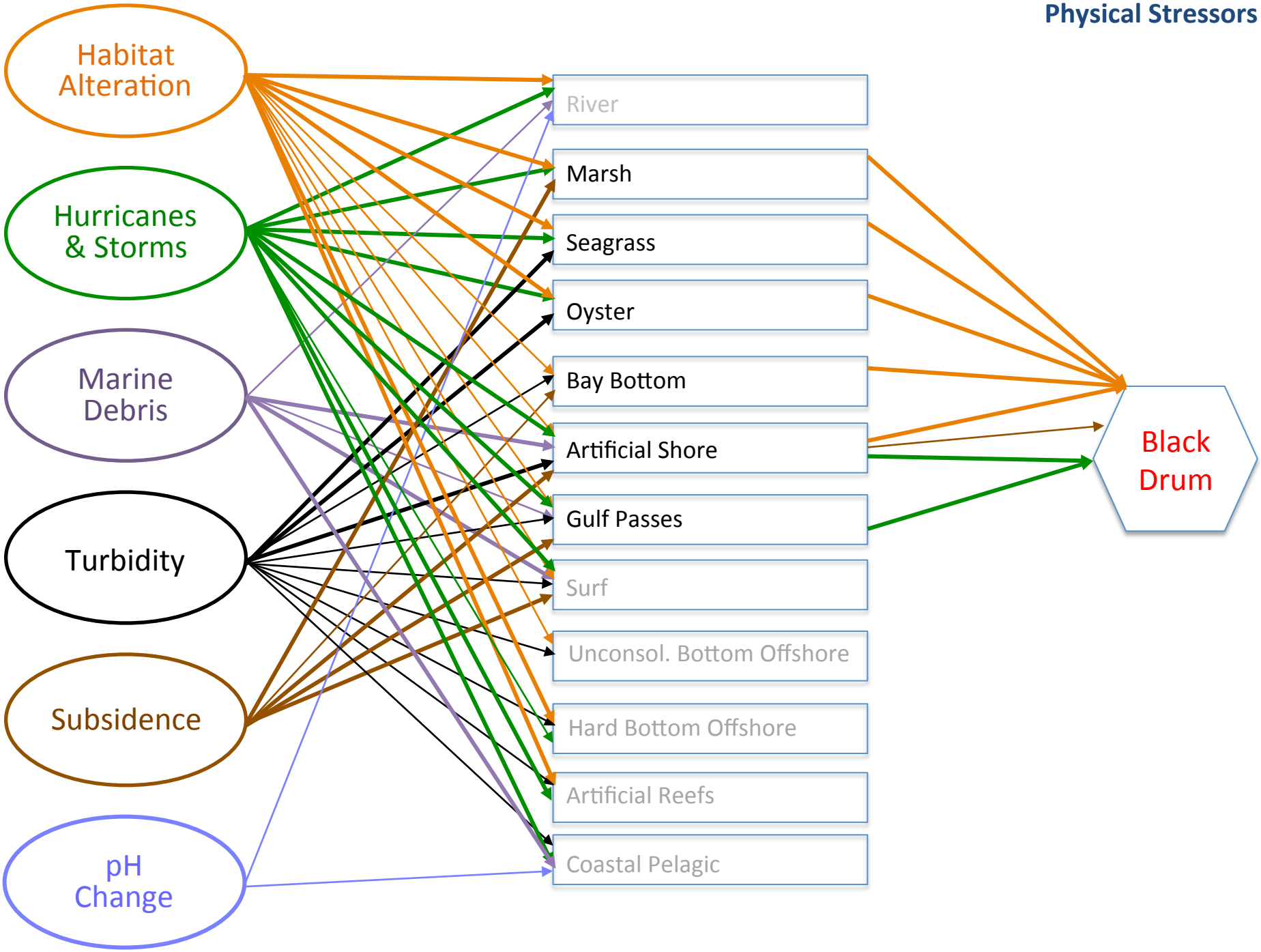
Physical Stressors - 2



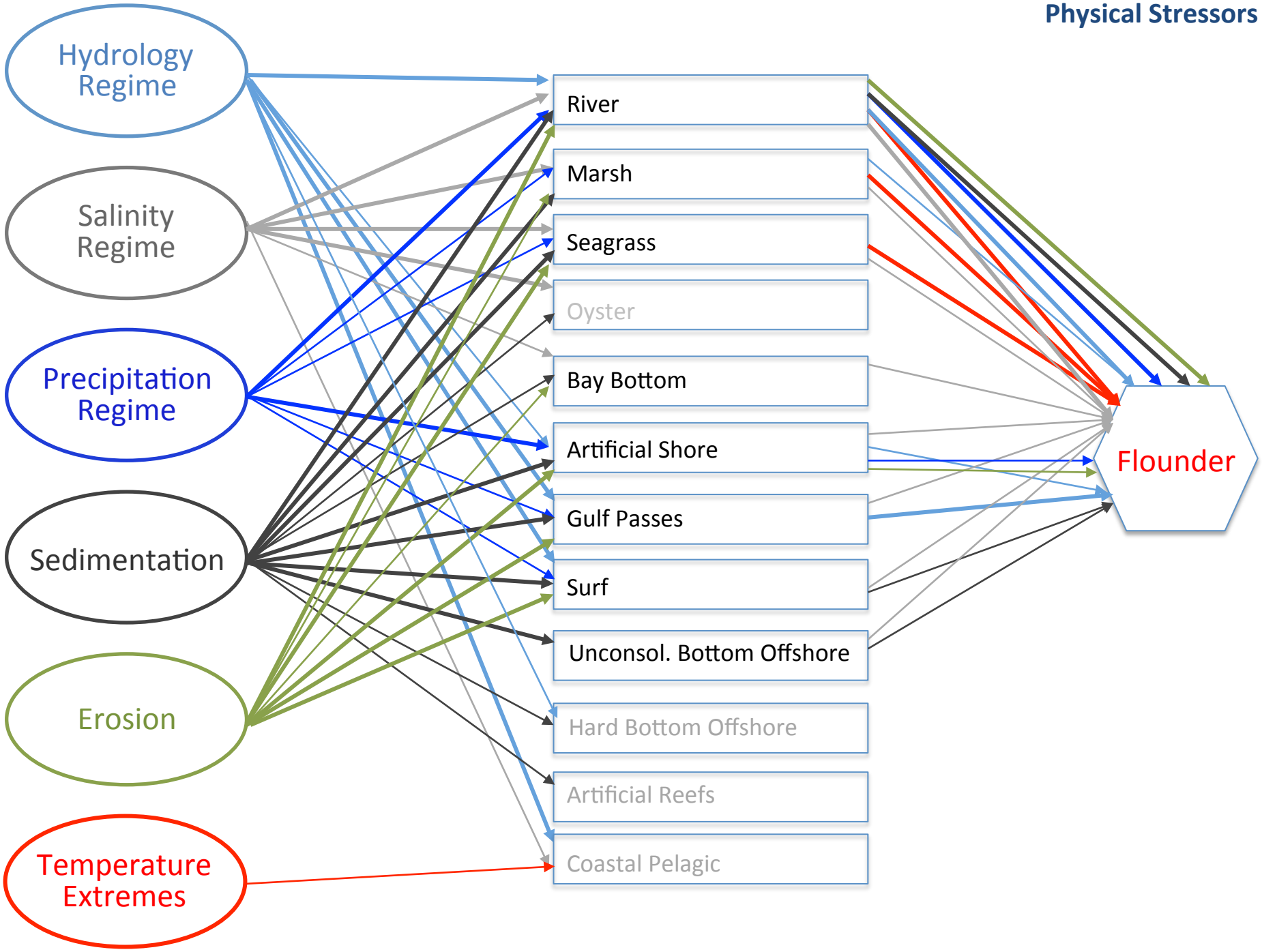
Physical Stressors - 1



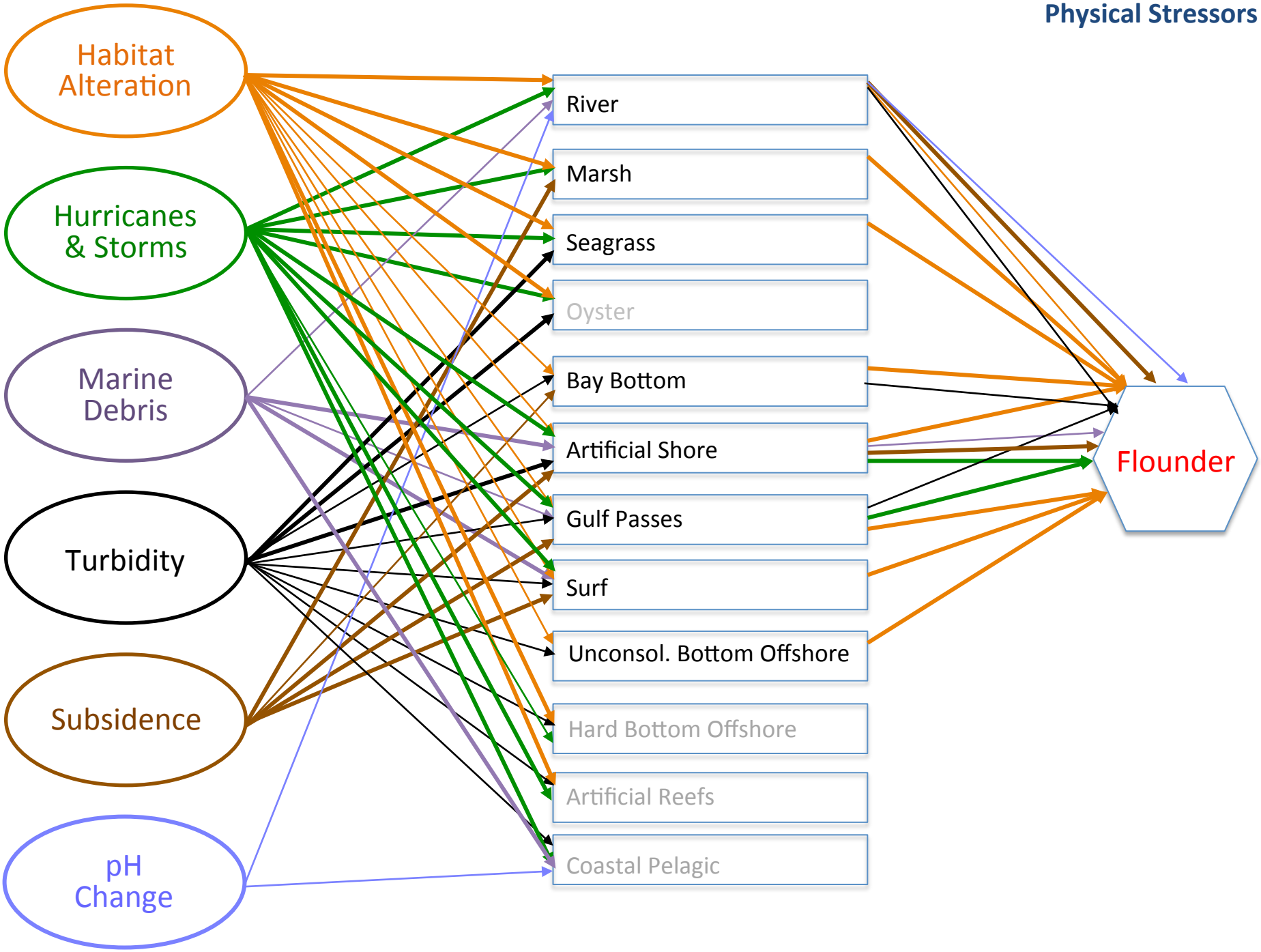
Physical Stressors - 2

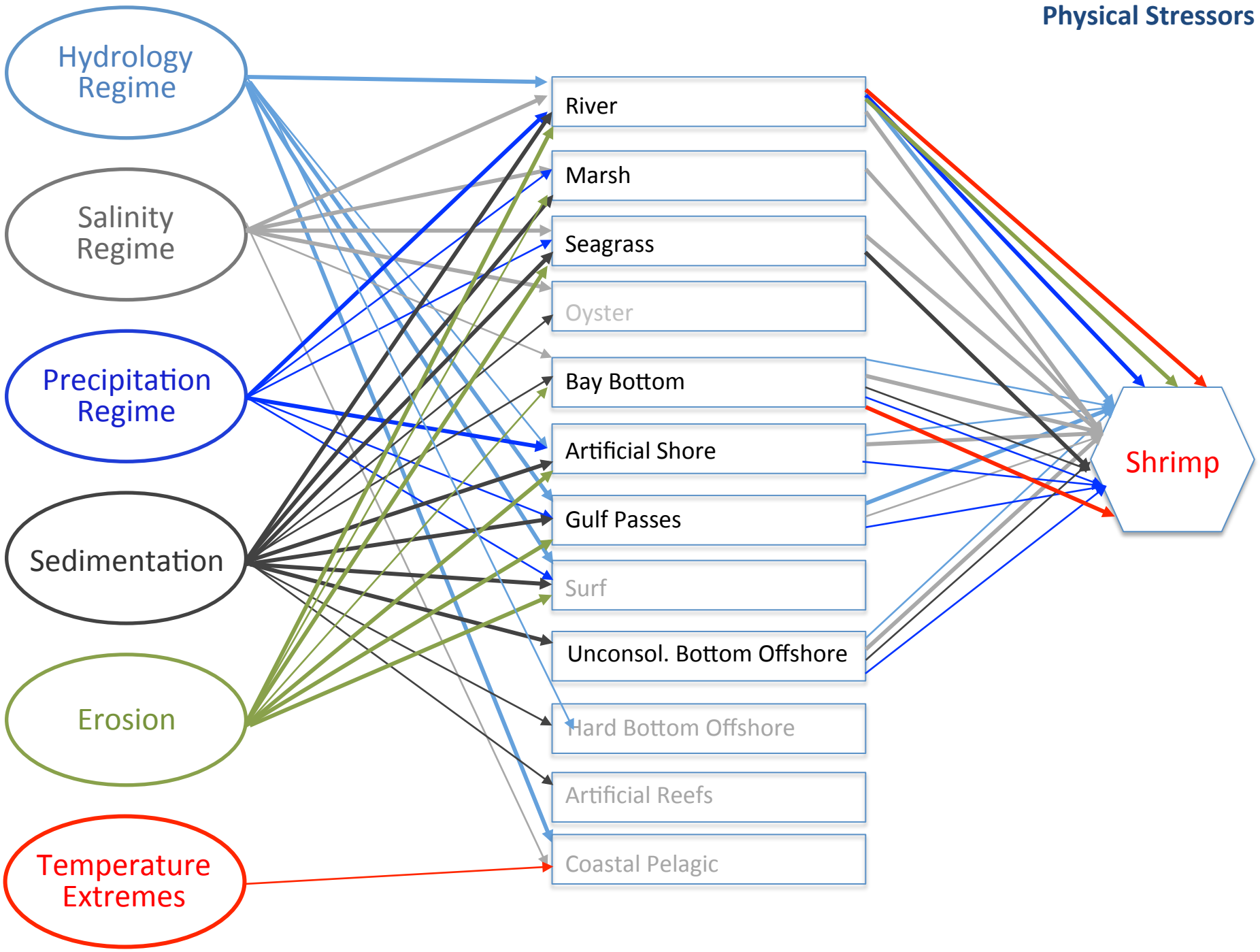


Physical Stressors - 1

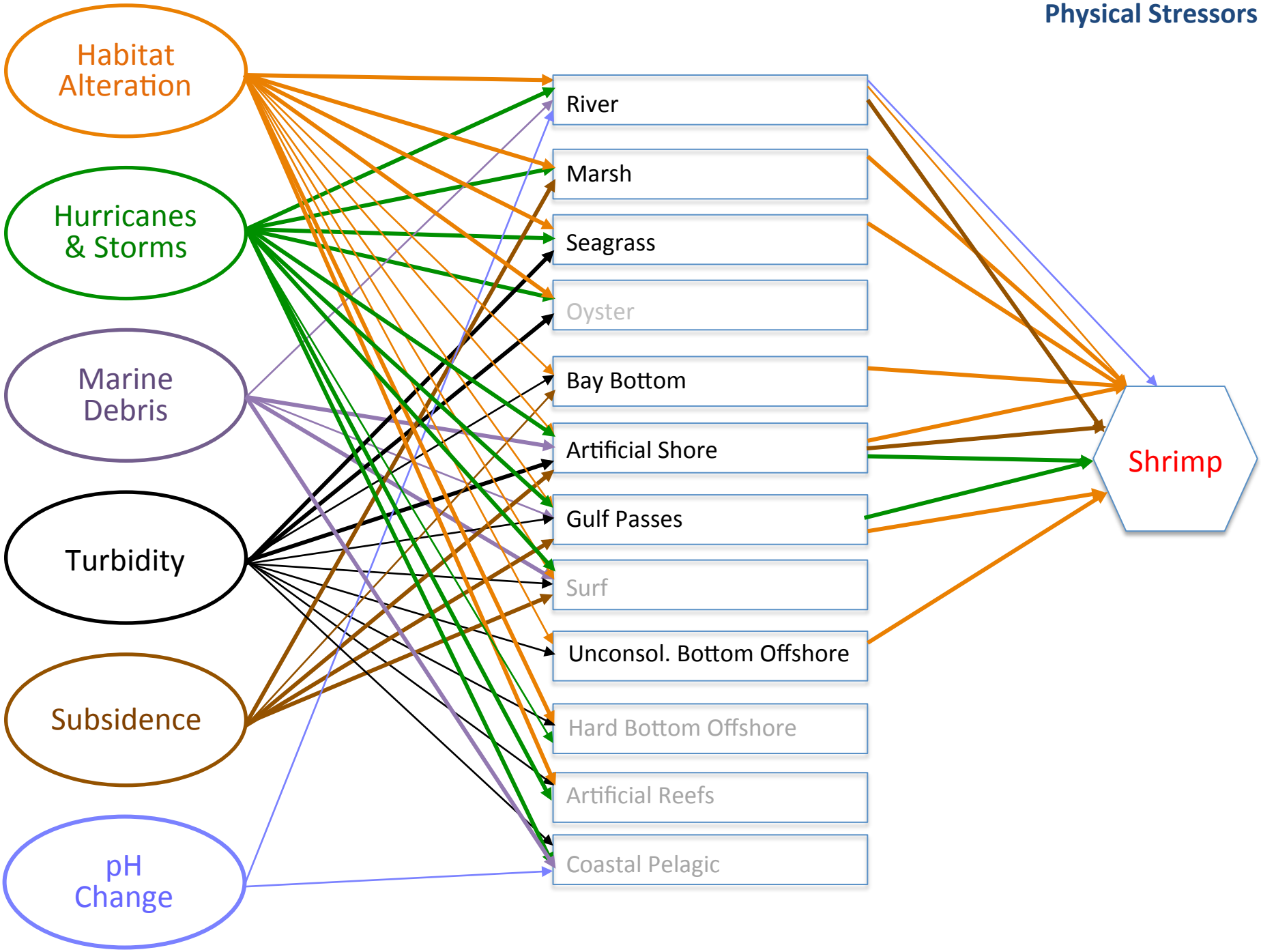


Physical Stressors - 2

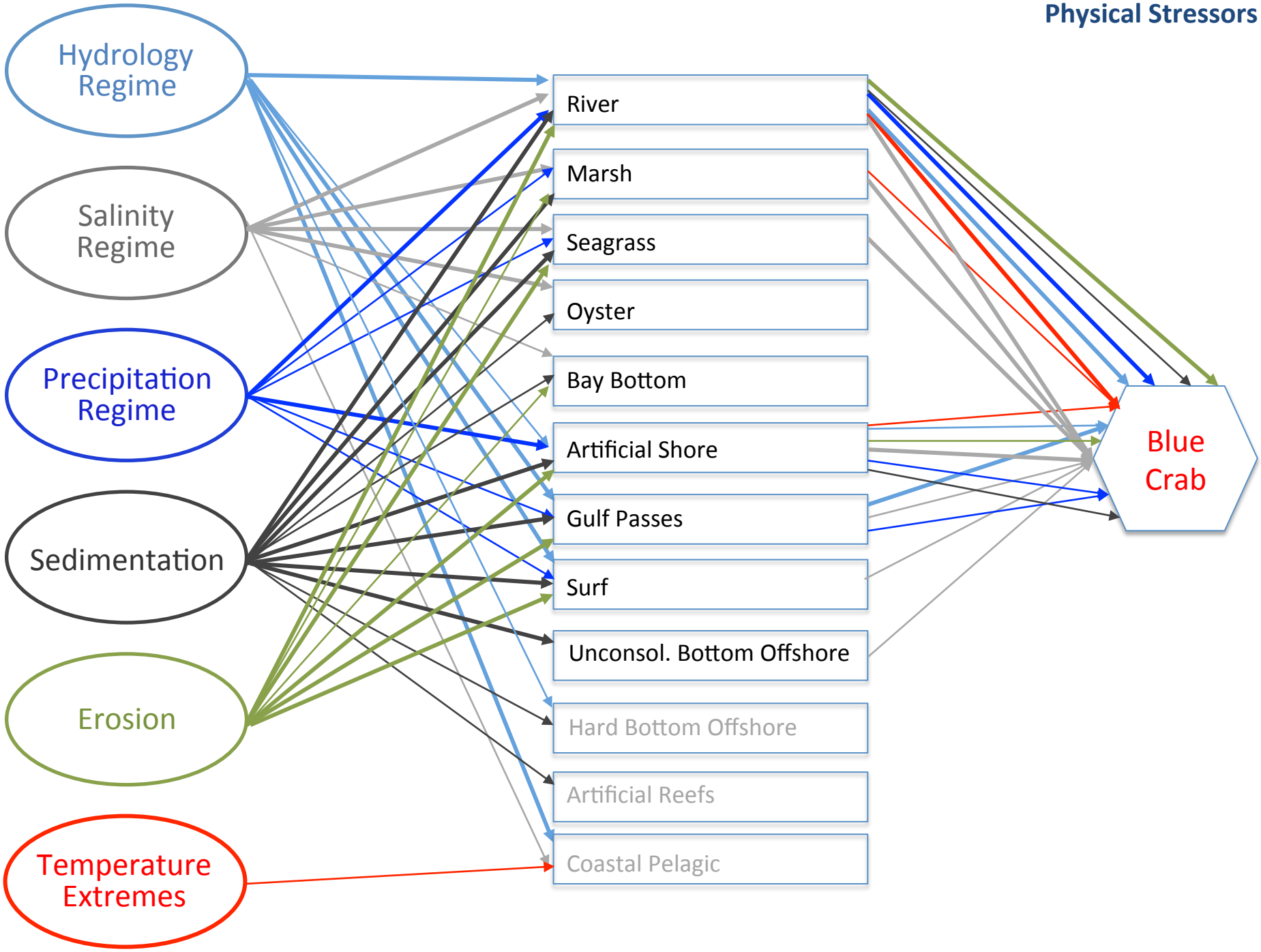



Physical Stressors - 1
Hydrology Regime
Salinity Regime
Precipitation Regime
Sedimentation
Erosion
Temperature Extremes
River
Marsh
Seagrass
Oyster
Bay Bottom
Artificial Shore
Gulf Passes
Surf
Unconsol. Bottom Offshore
Hard Bottom Offshore
Artificial Reefs
Coastal Pelagic
Shrimp

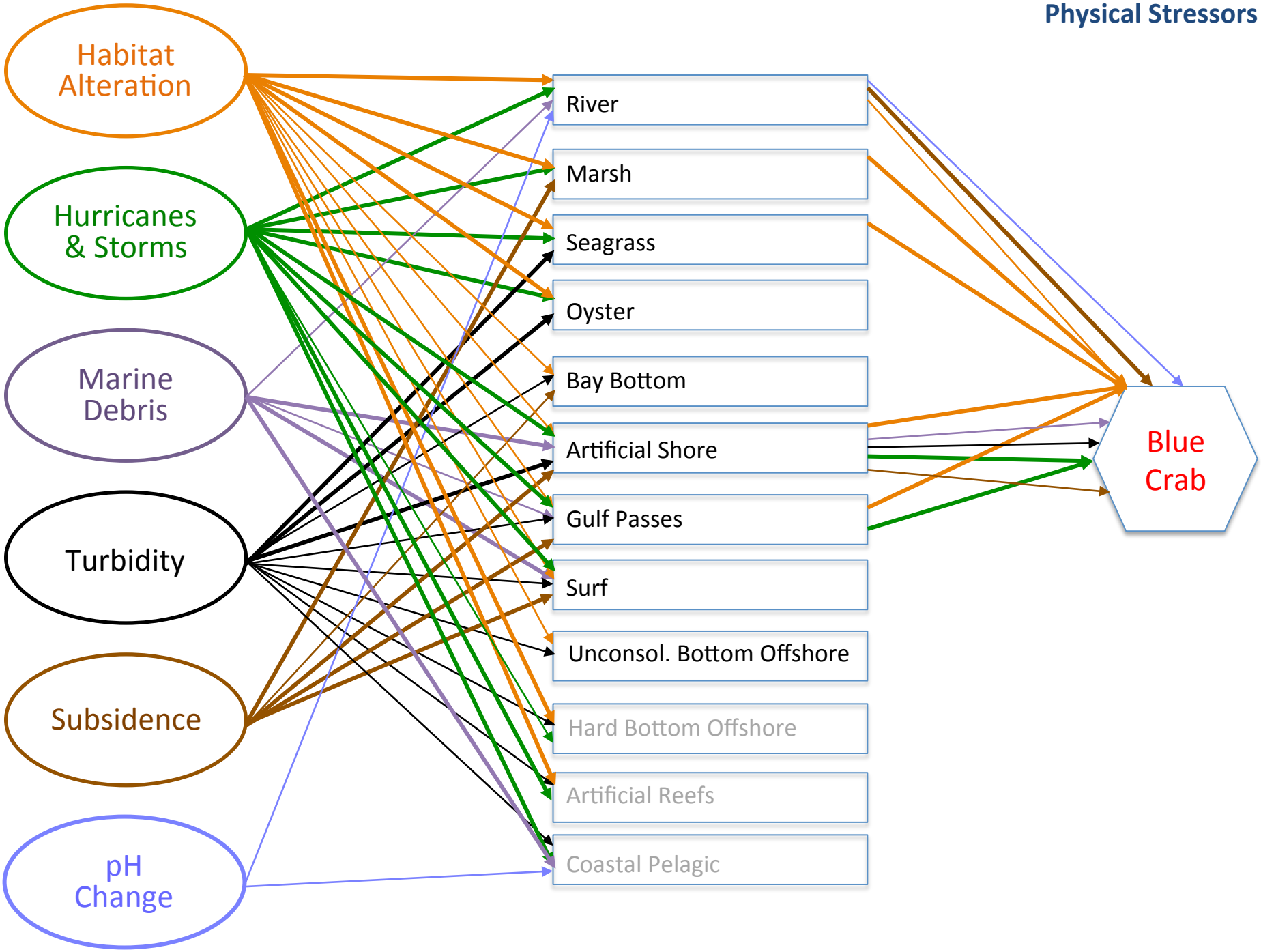
Physical Stressors - 2



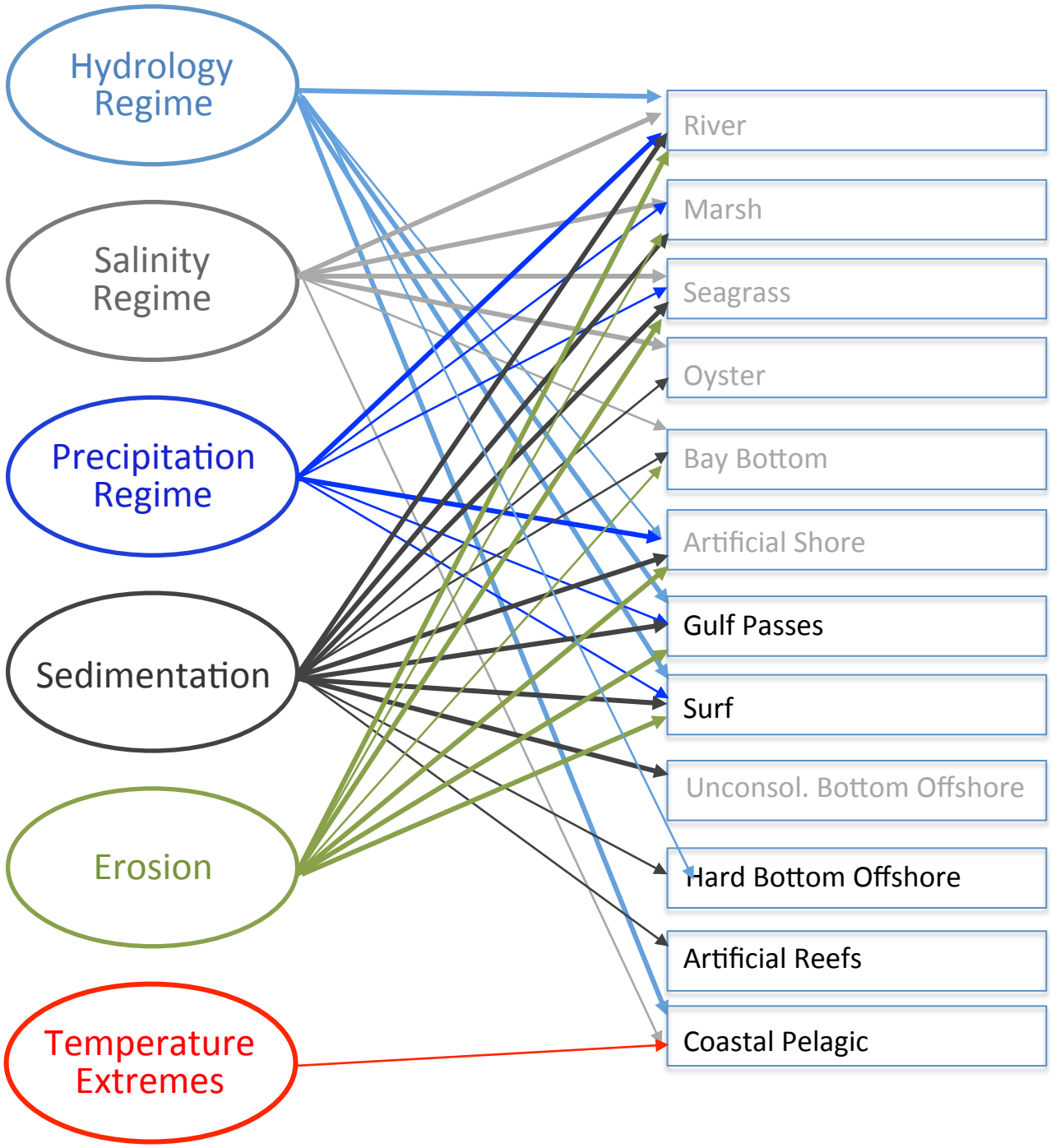
Physical Stressors - 1



Physical Stressors - 2

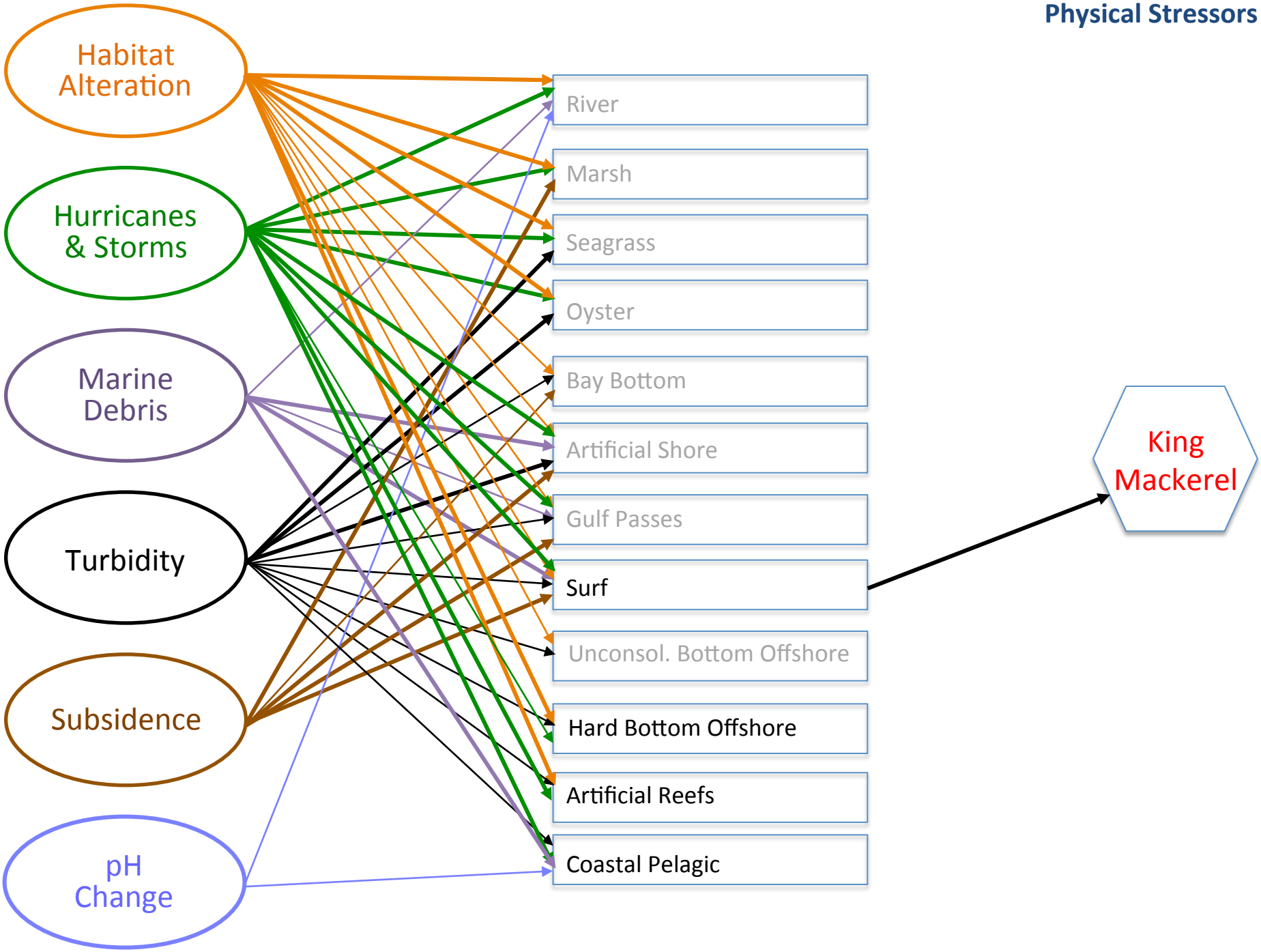


Physical Stressors - 1

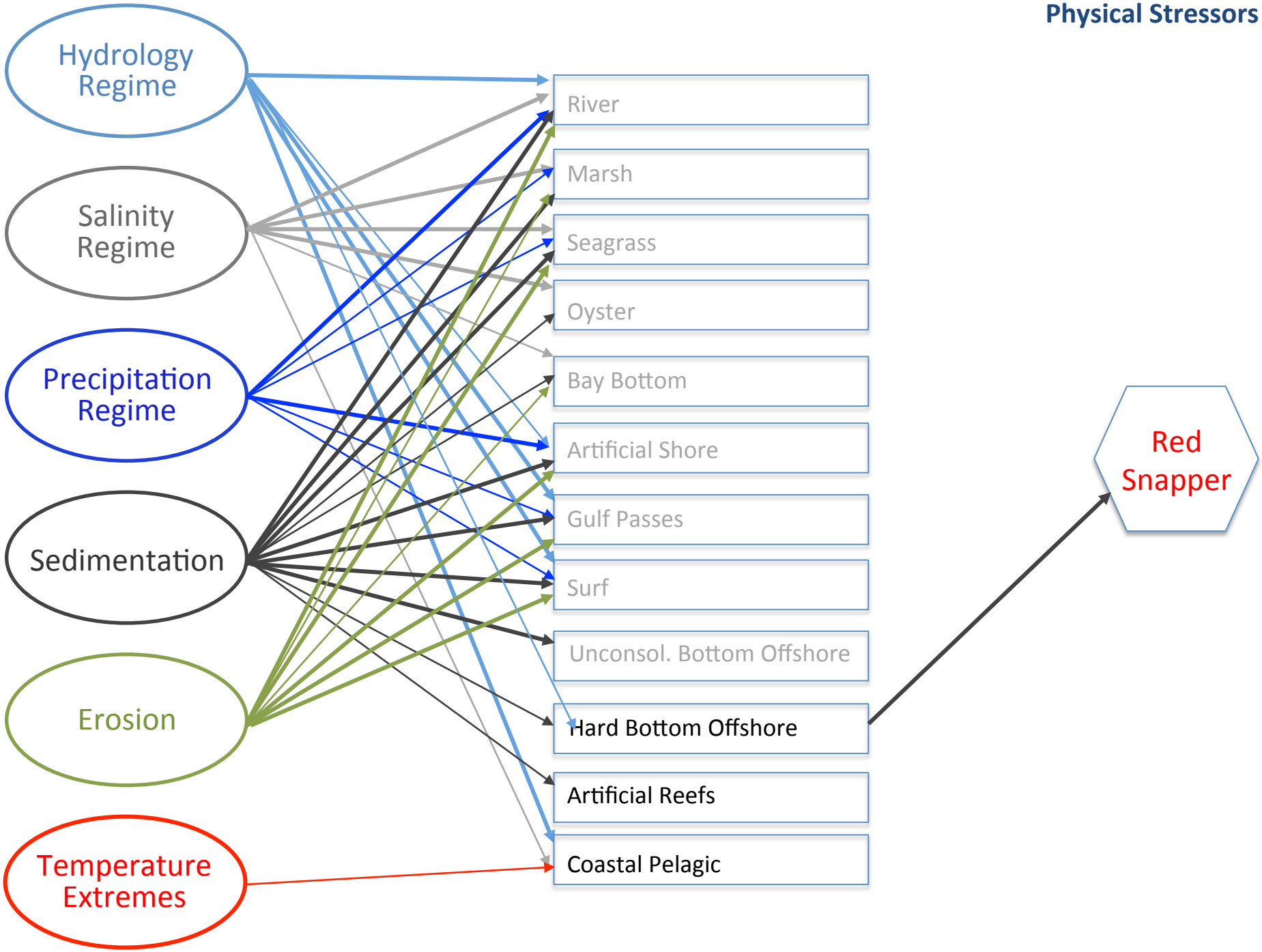


King Mackerel

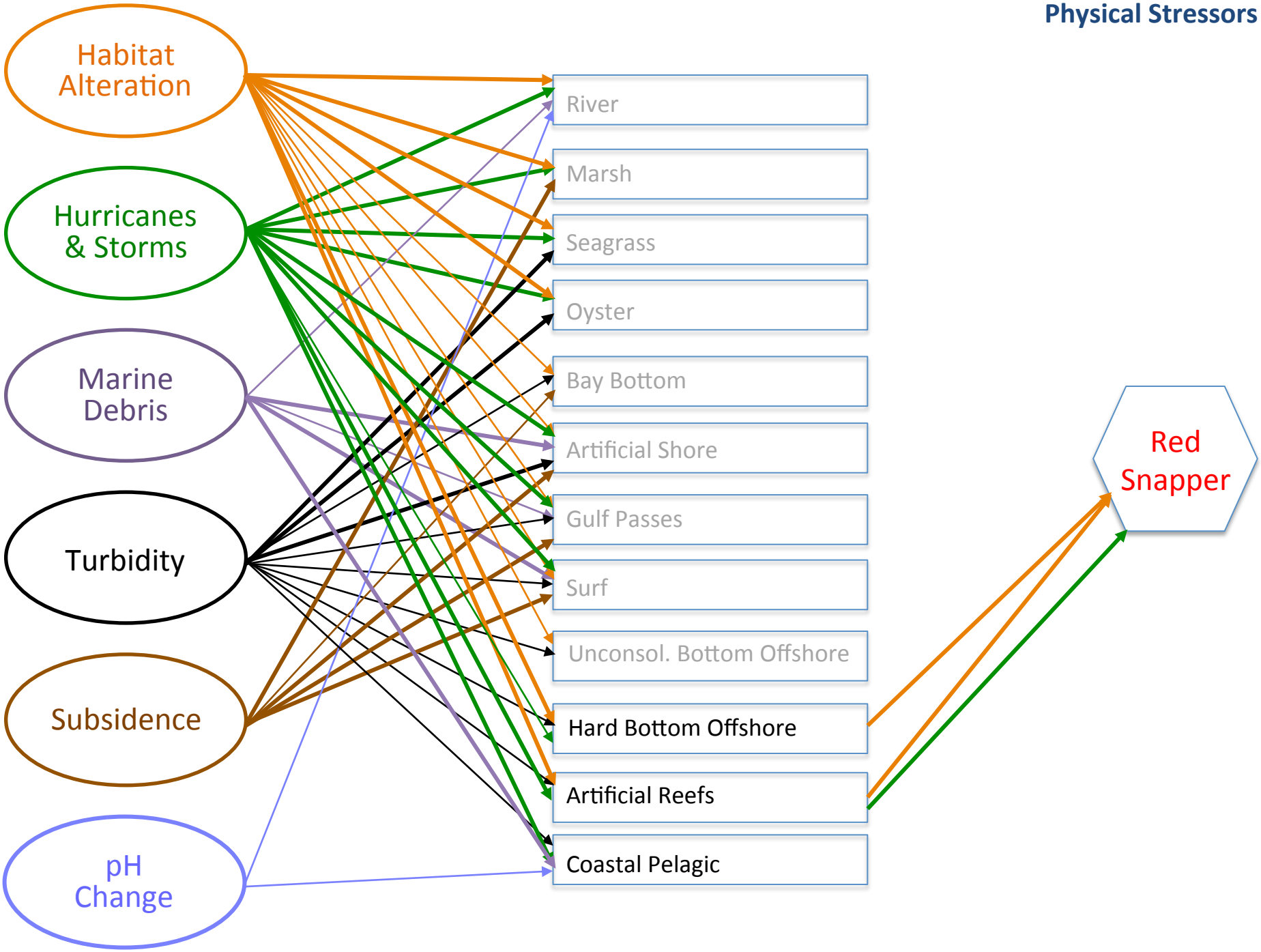
Physical Stressors - 2



Physical Stressors - 1



Physical Stressors - 2

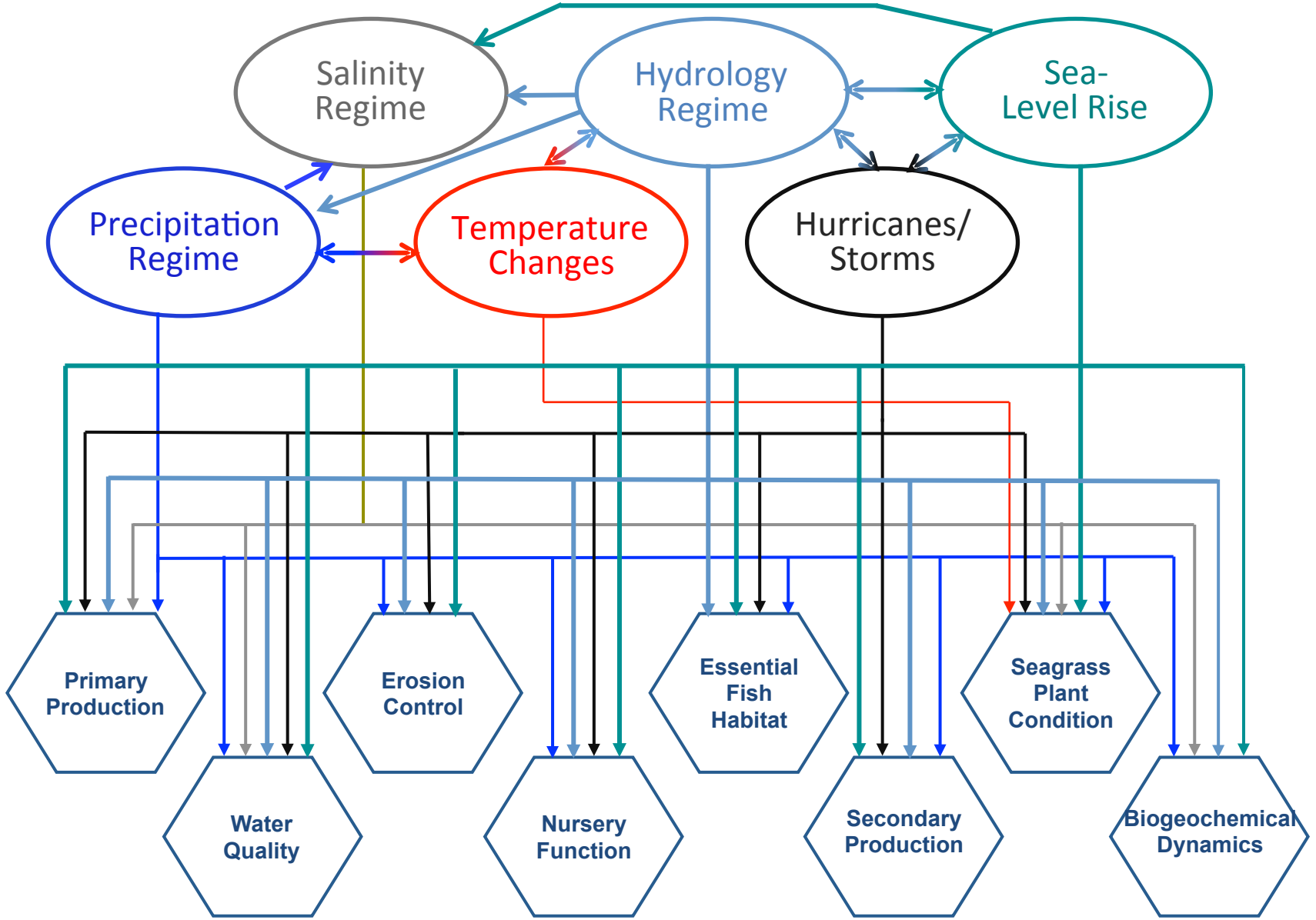


IV-2. Seagrass Health Data Conceptual Ecosystem Models

Texas Seagrass Communities

Climate Change Stressors

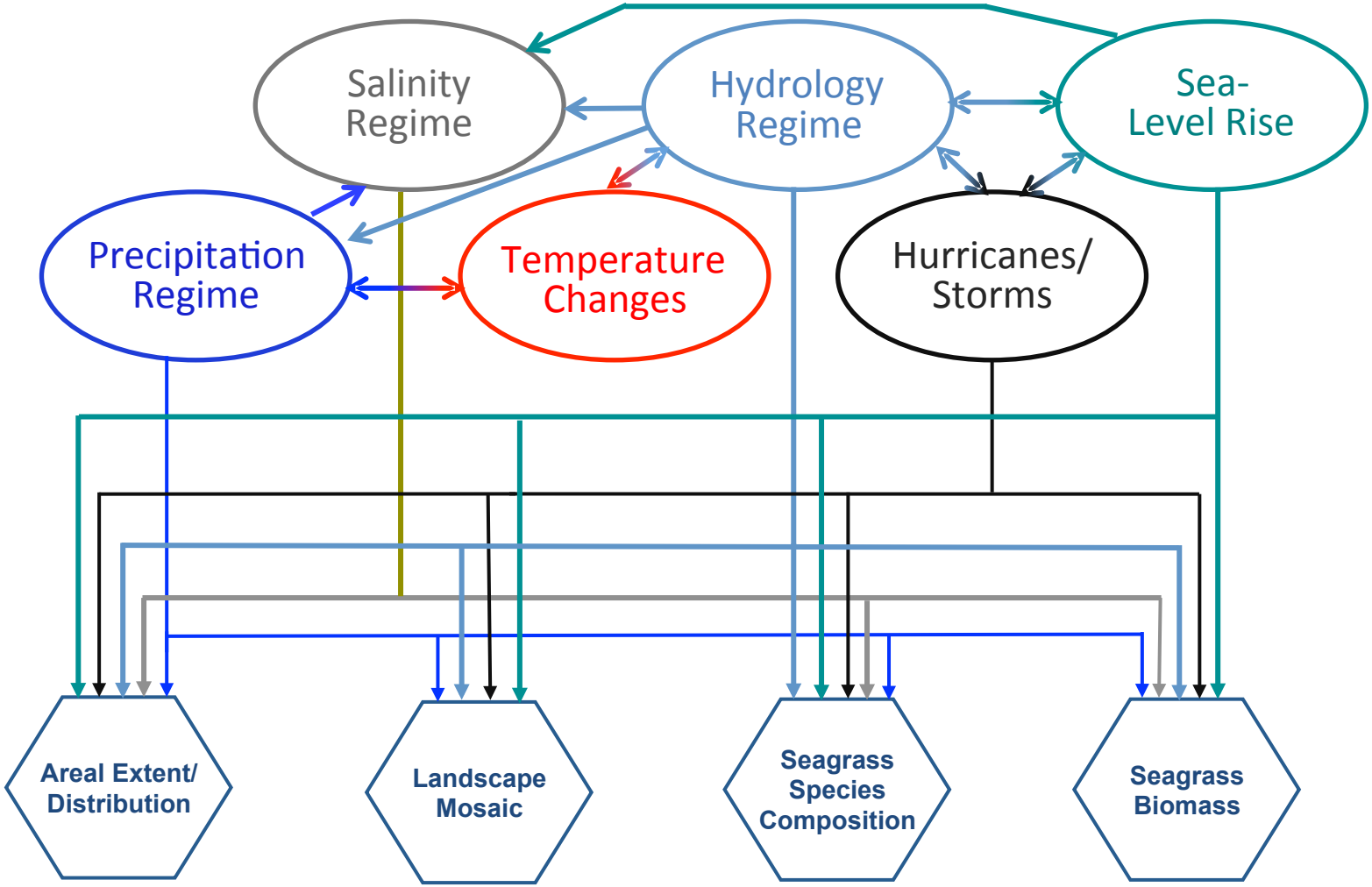
Seagrass Functional Attributes



Texas Seagrass Communities

Climate Change Stressors

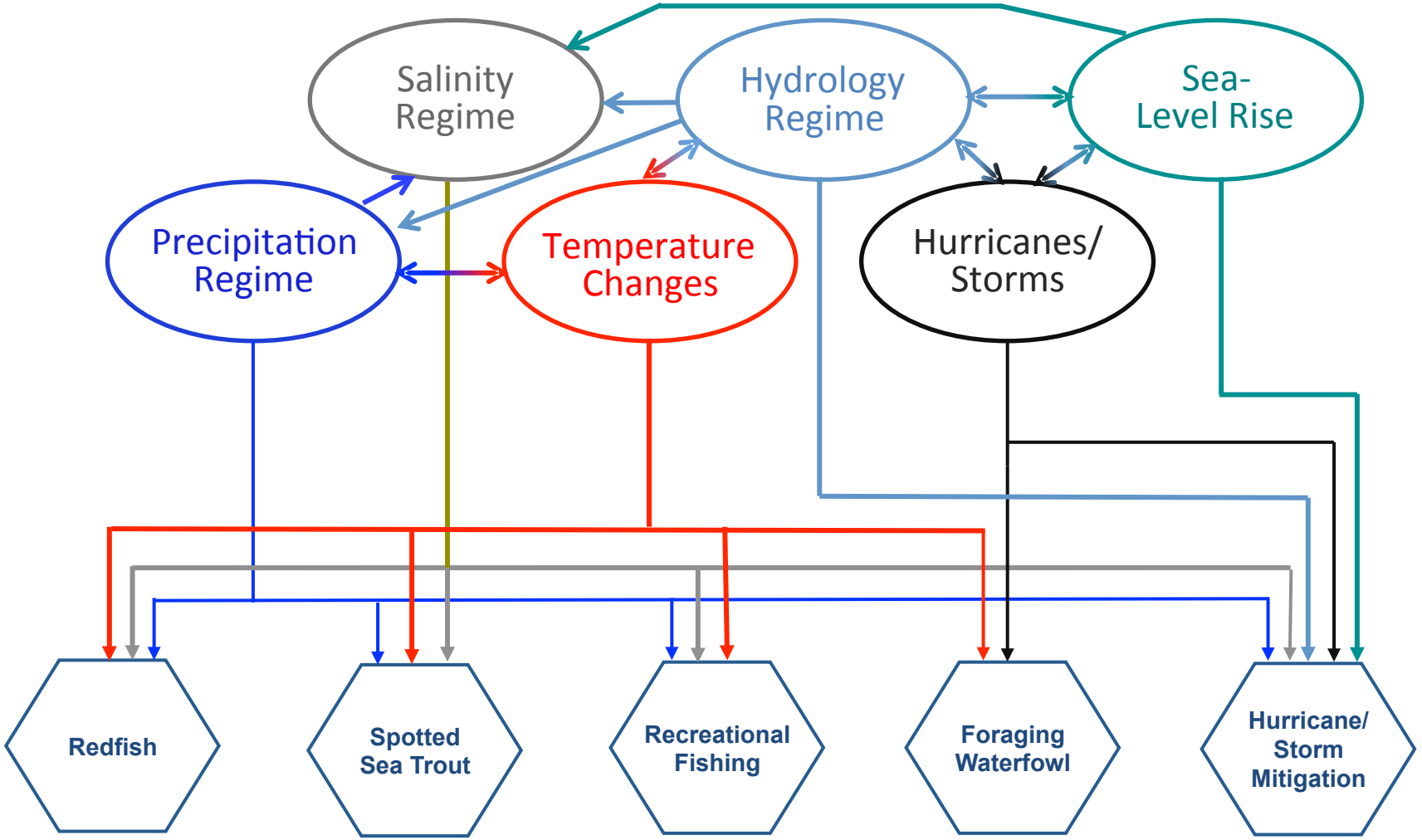
Seagrass Structural Attributes



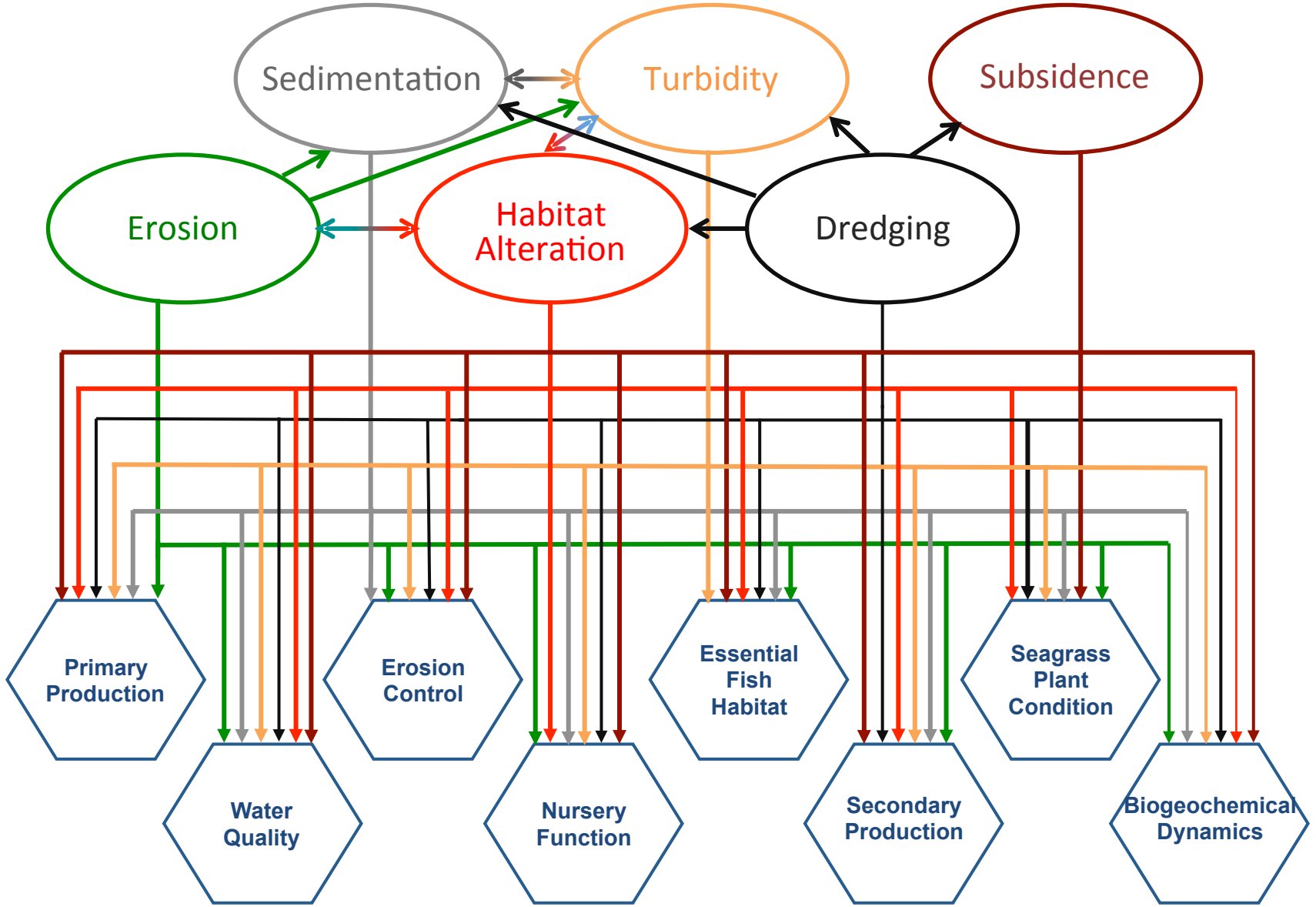
Texas Seagrass Communities

Climate Change Stressors

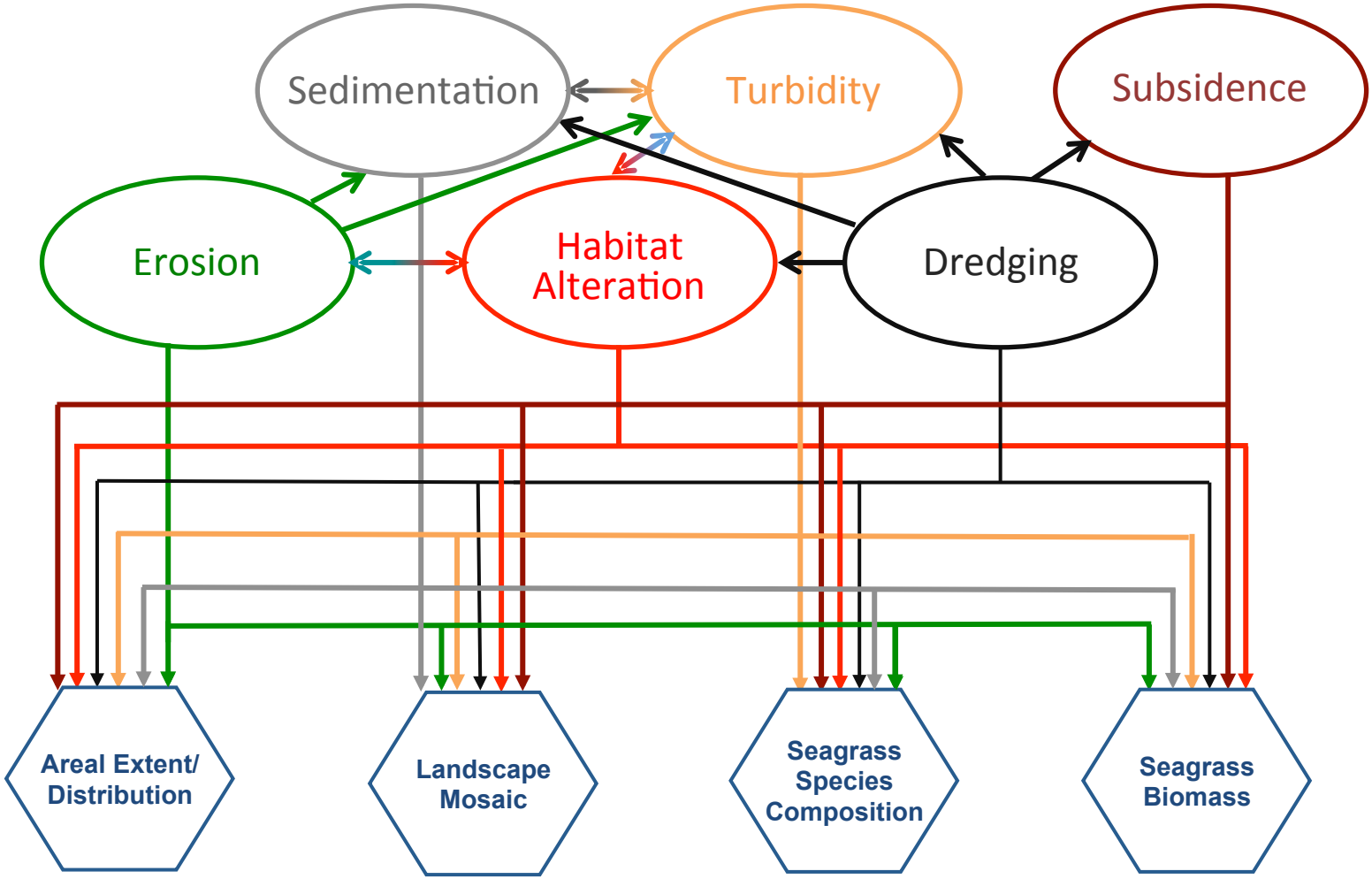
Seagrass Ecosystem Services



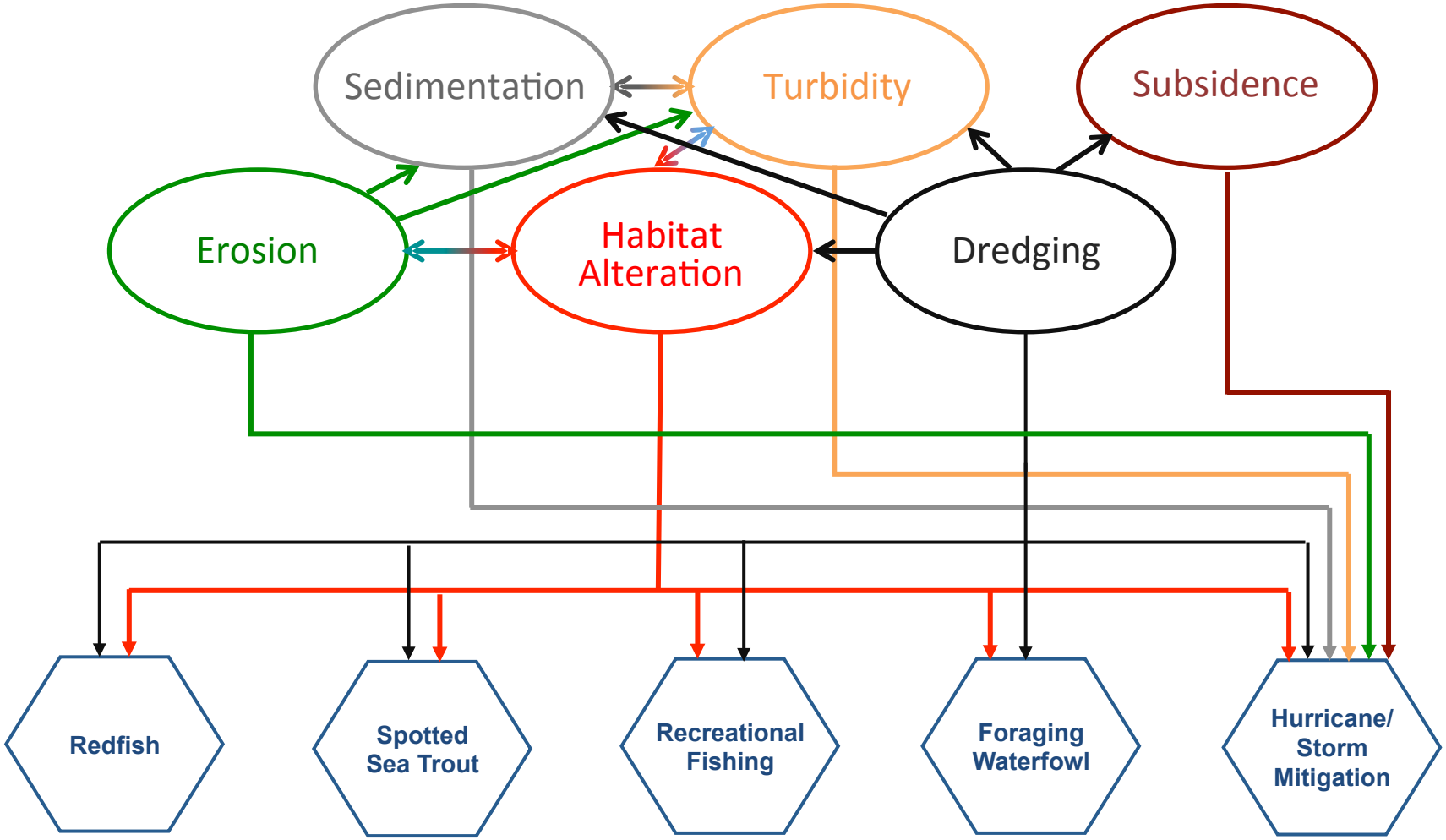
Texas Seagrass Communities



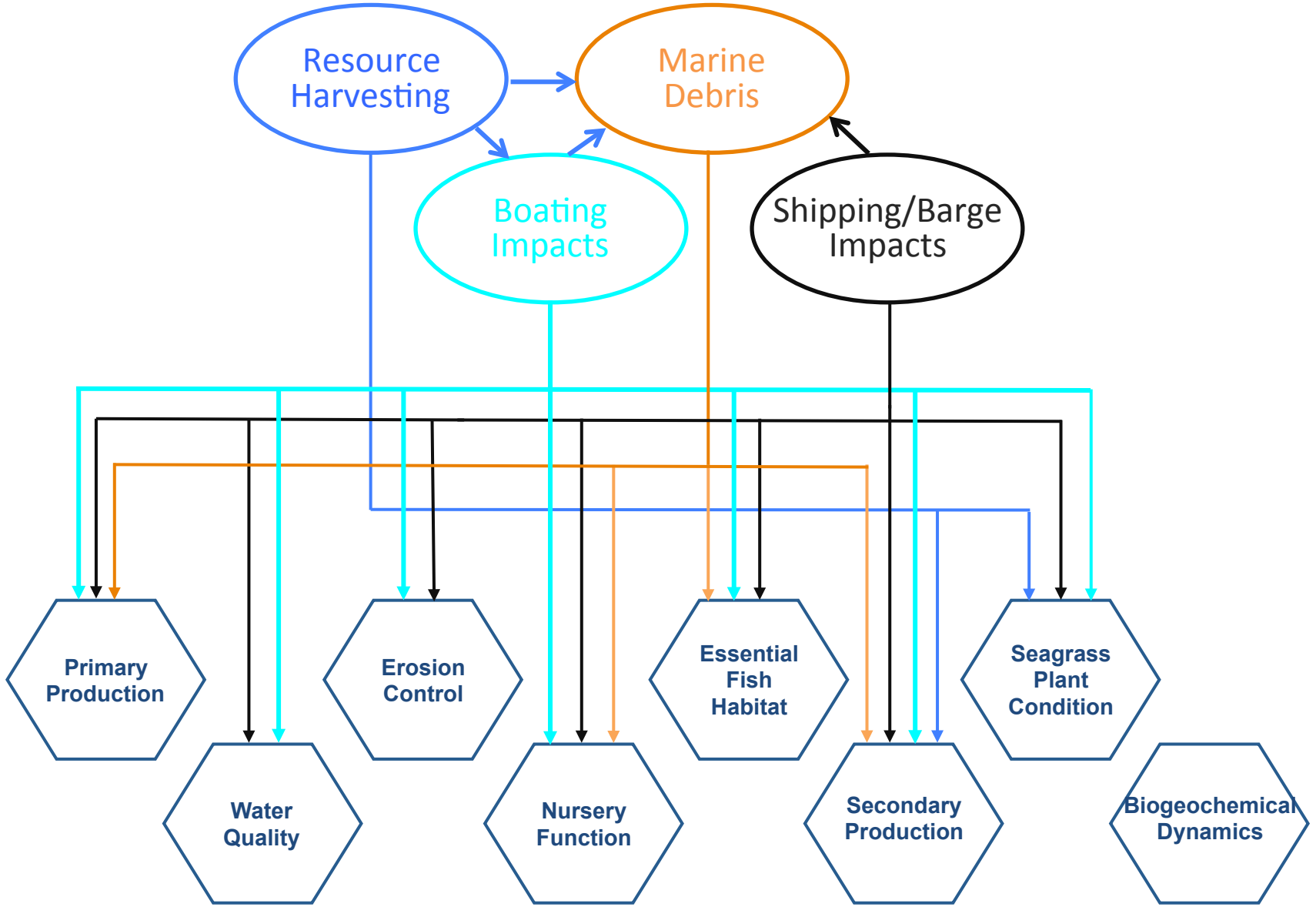
Texas Seagrass Communities



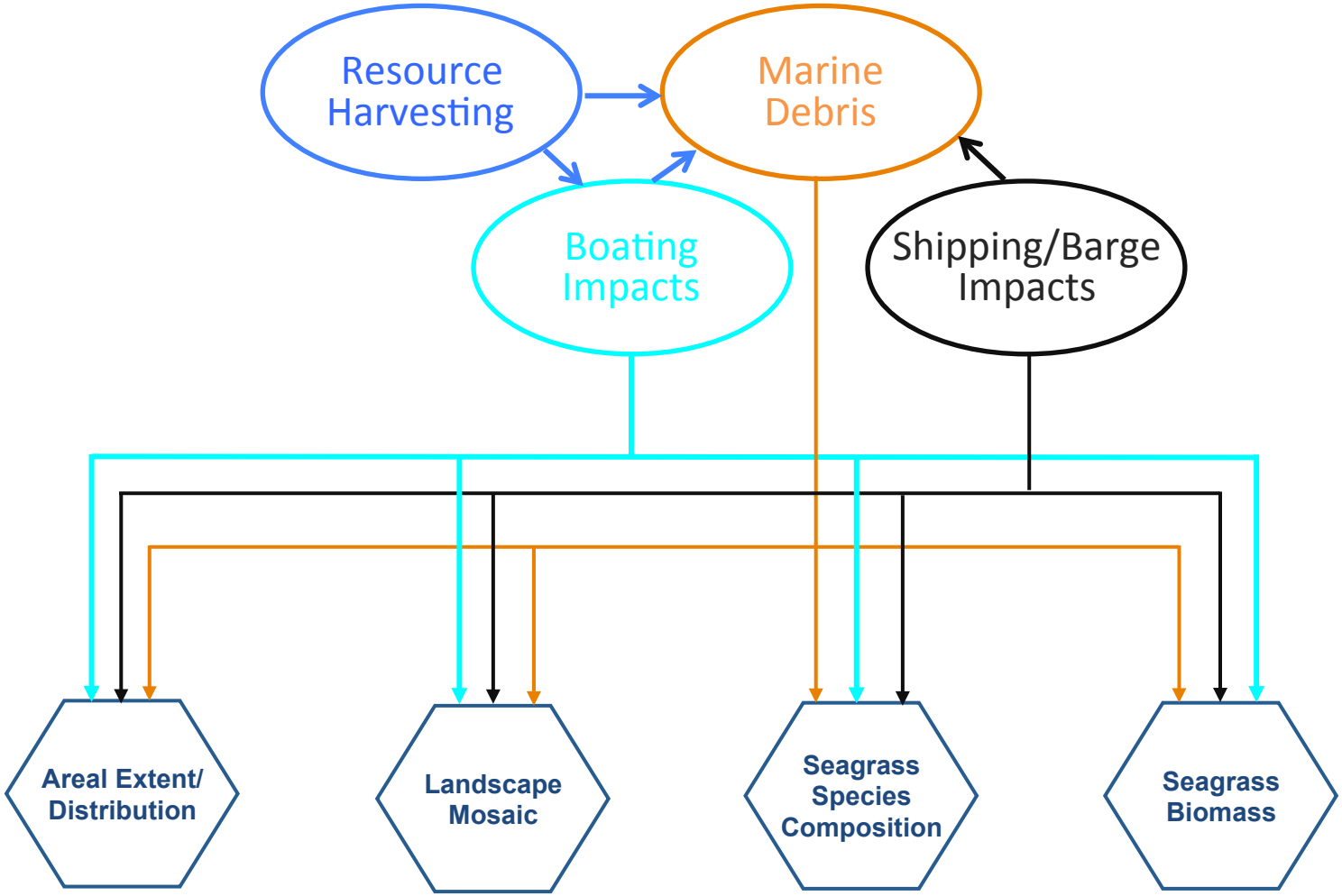
Texas Seagrass Communities



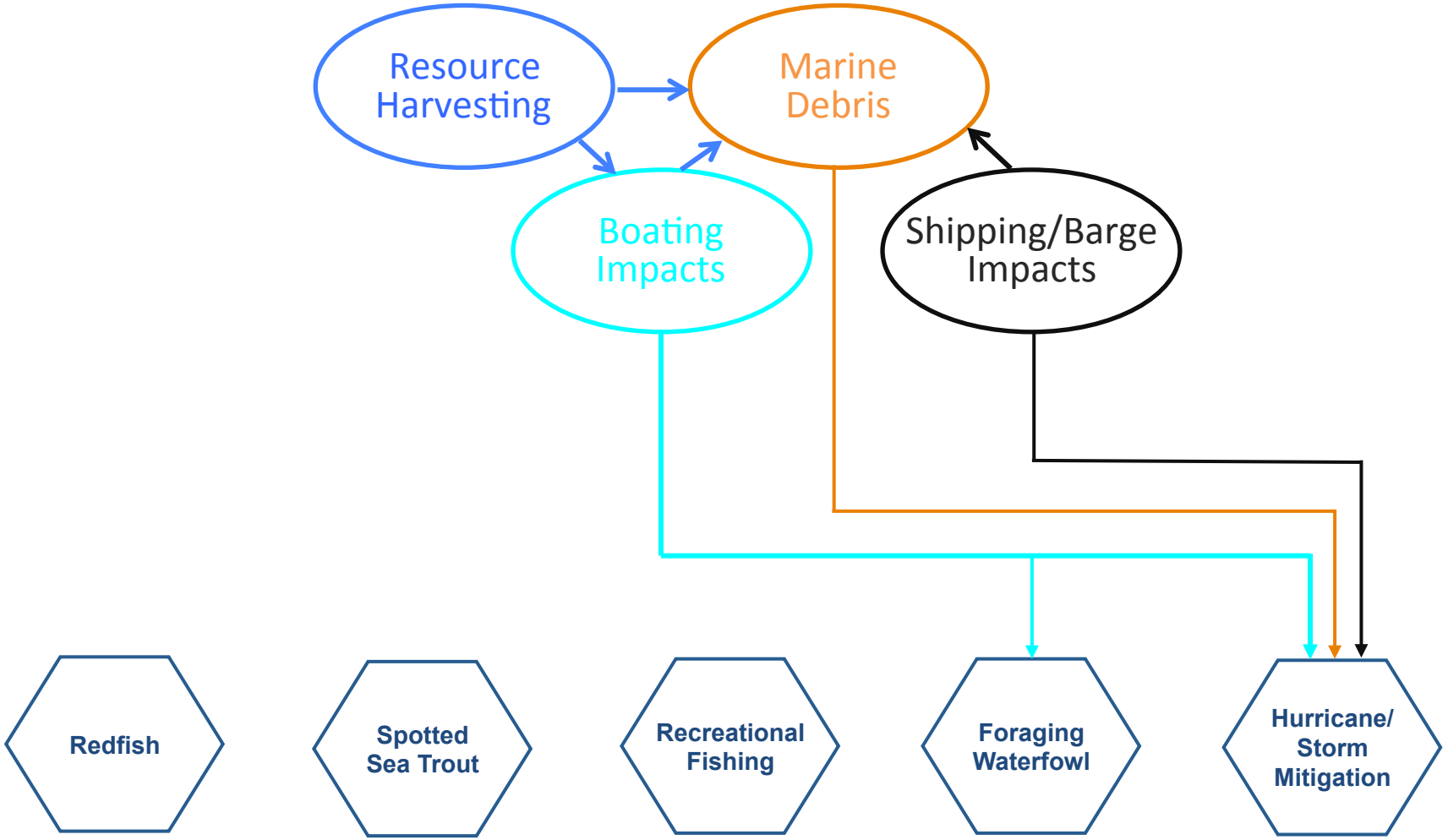
Texas Seagrass Communities



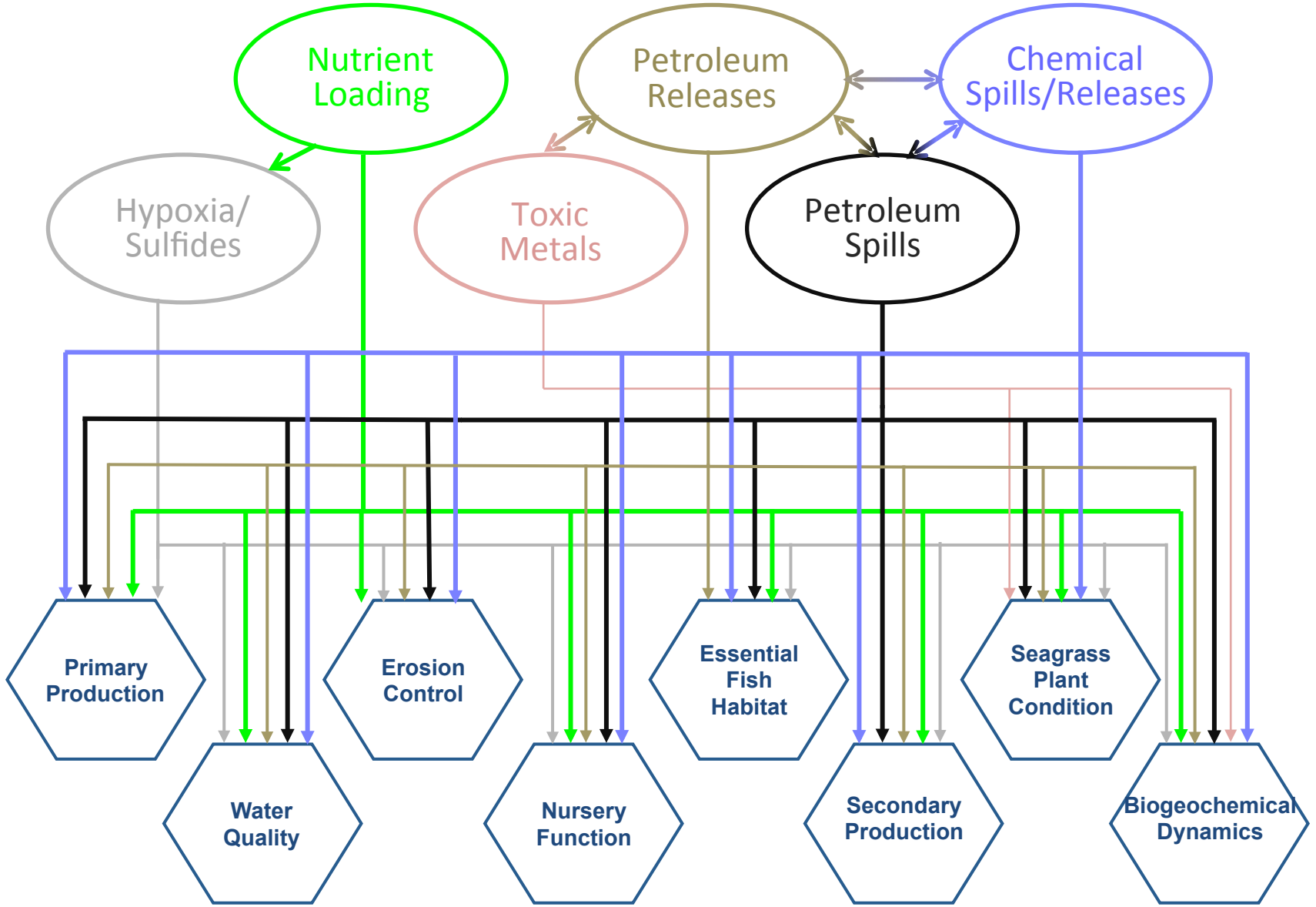
Texas Seagrass Communities



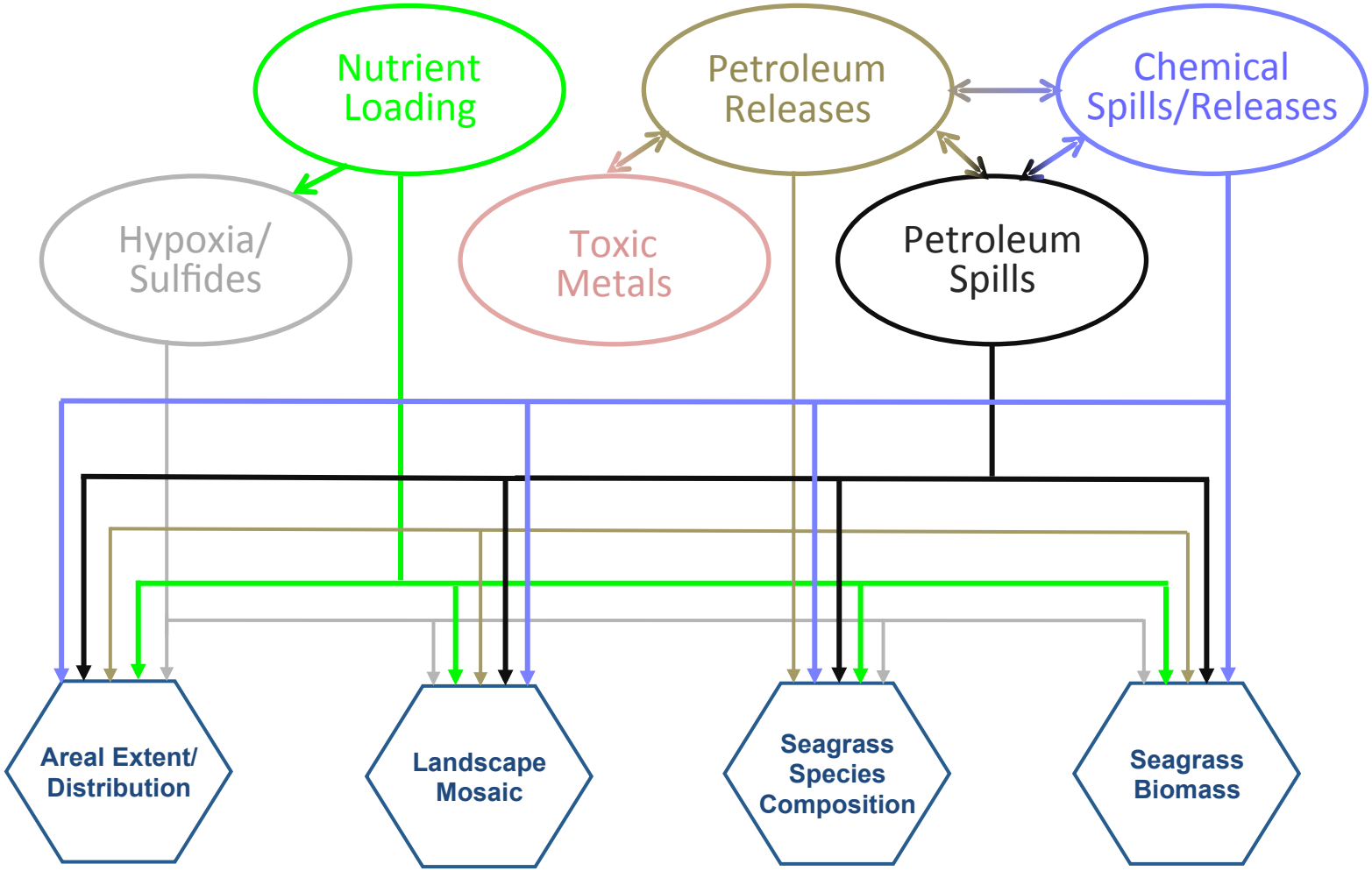
Texas Seagrass Communities



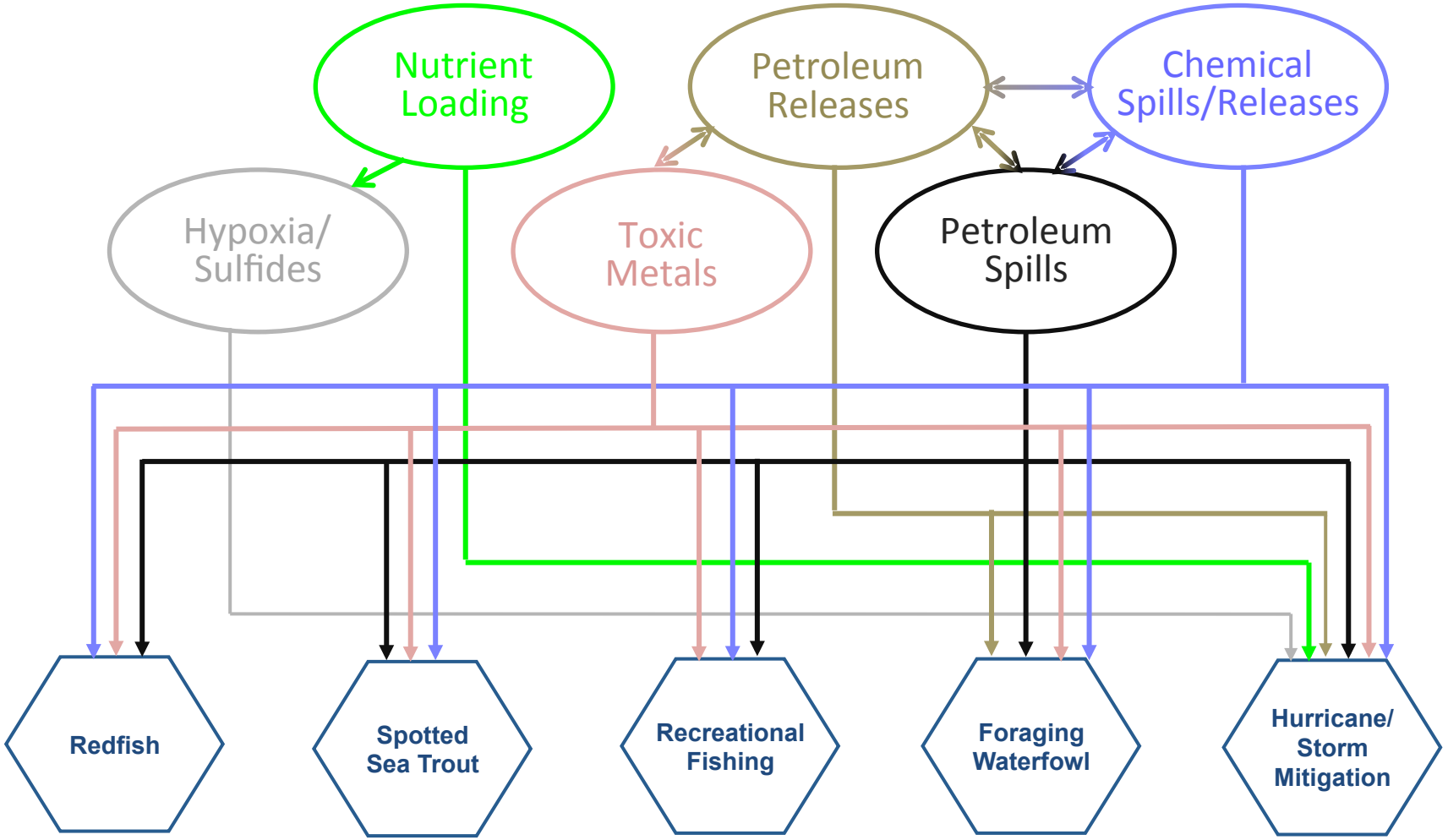
Texas Seagrass Communities



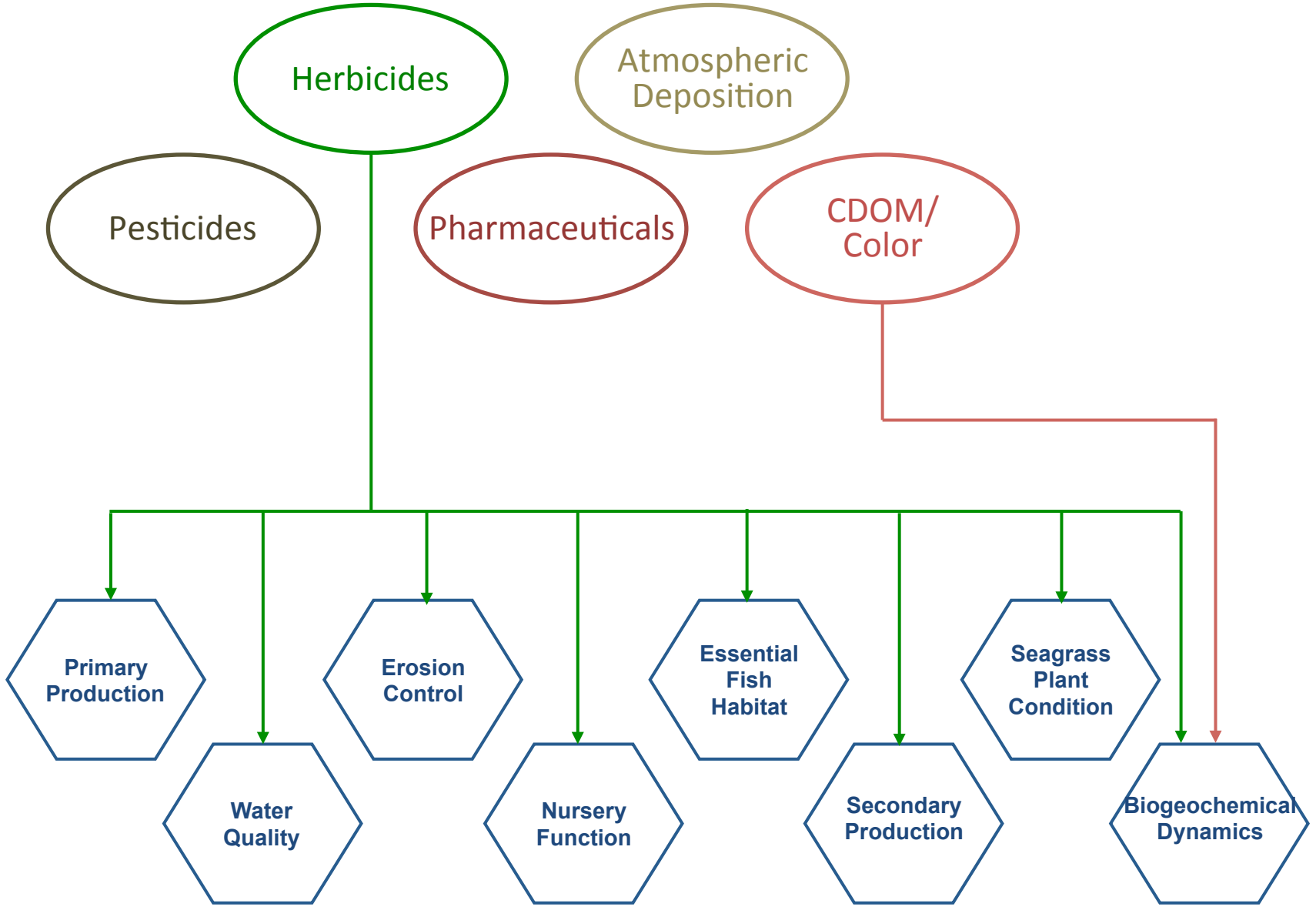
Texas Seagrass Communities

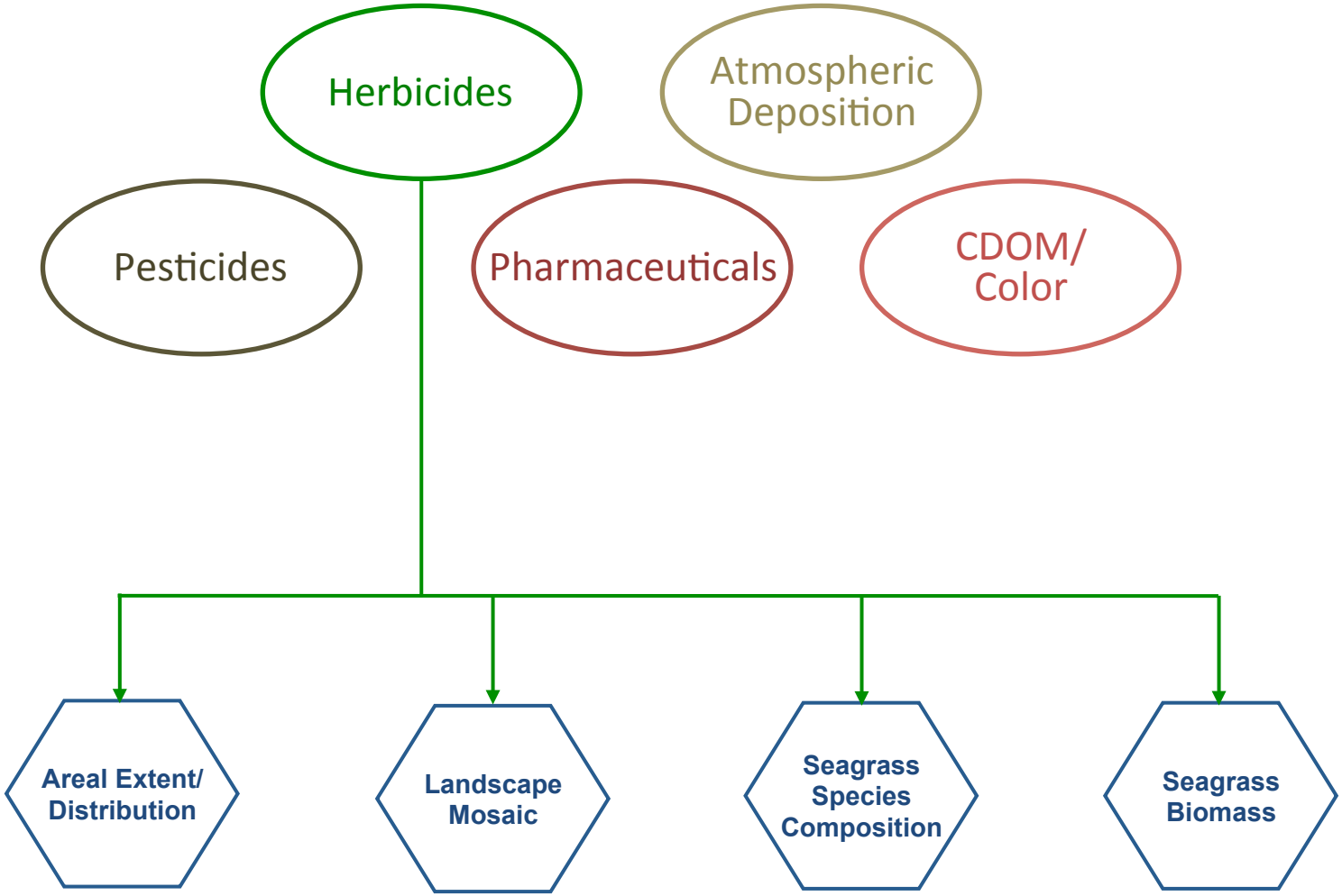


Texas Seagrass Communities

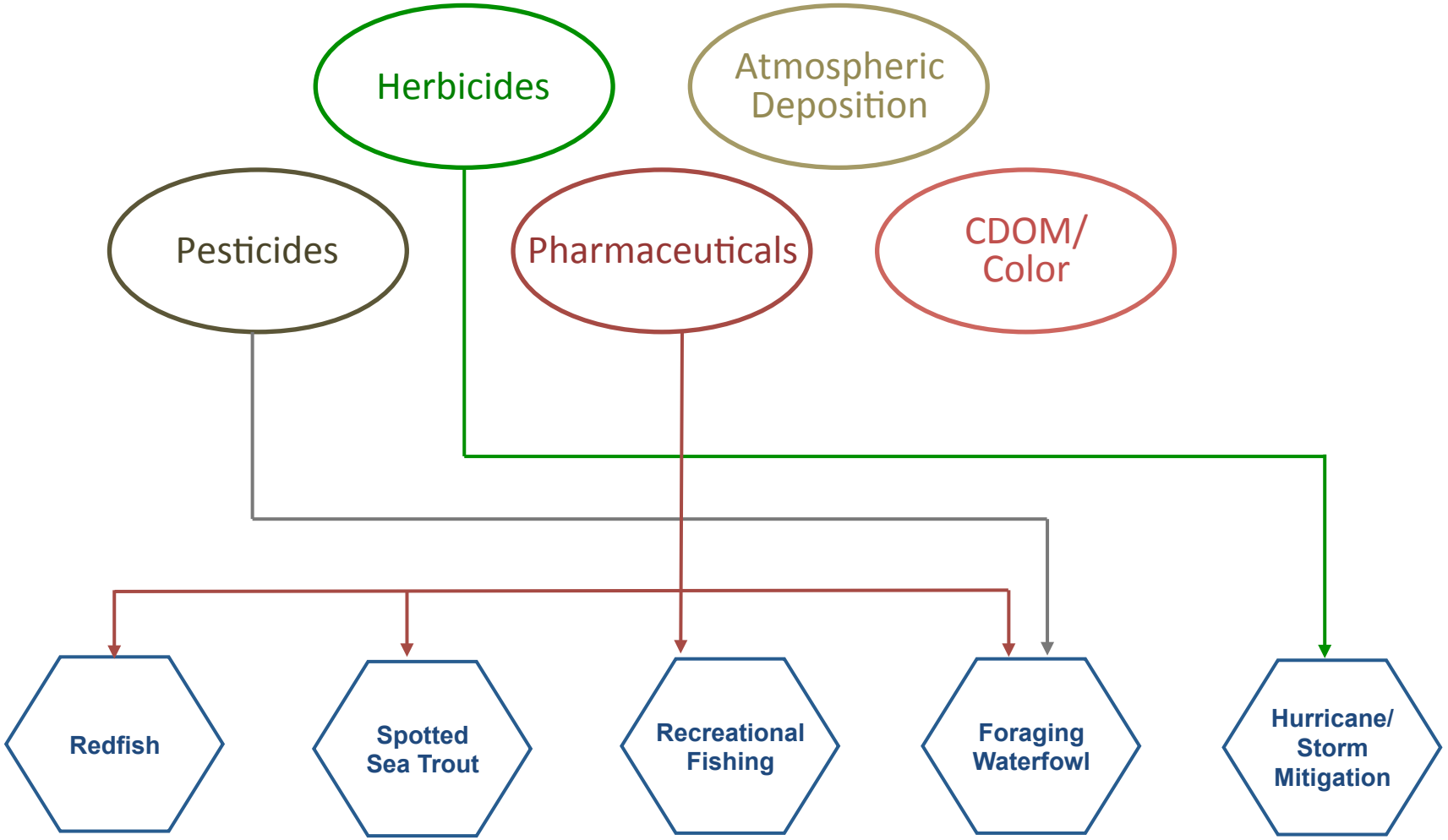


Texas Seagrass Communities




Herbicides
Atmospheric Deposition
Pesticides
Pharmaceuticals
CDOM/ Color
Areal Extent/ Distribution
Landscape Mosaic
Seagrass Species Composition
Seagrass Biomass

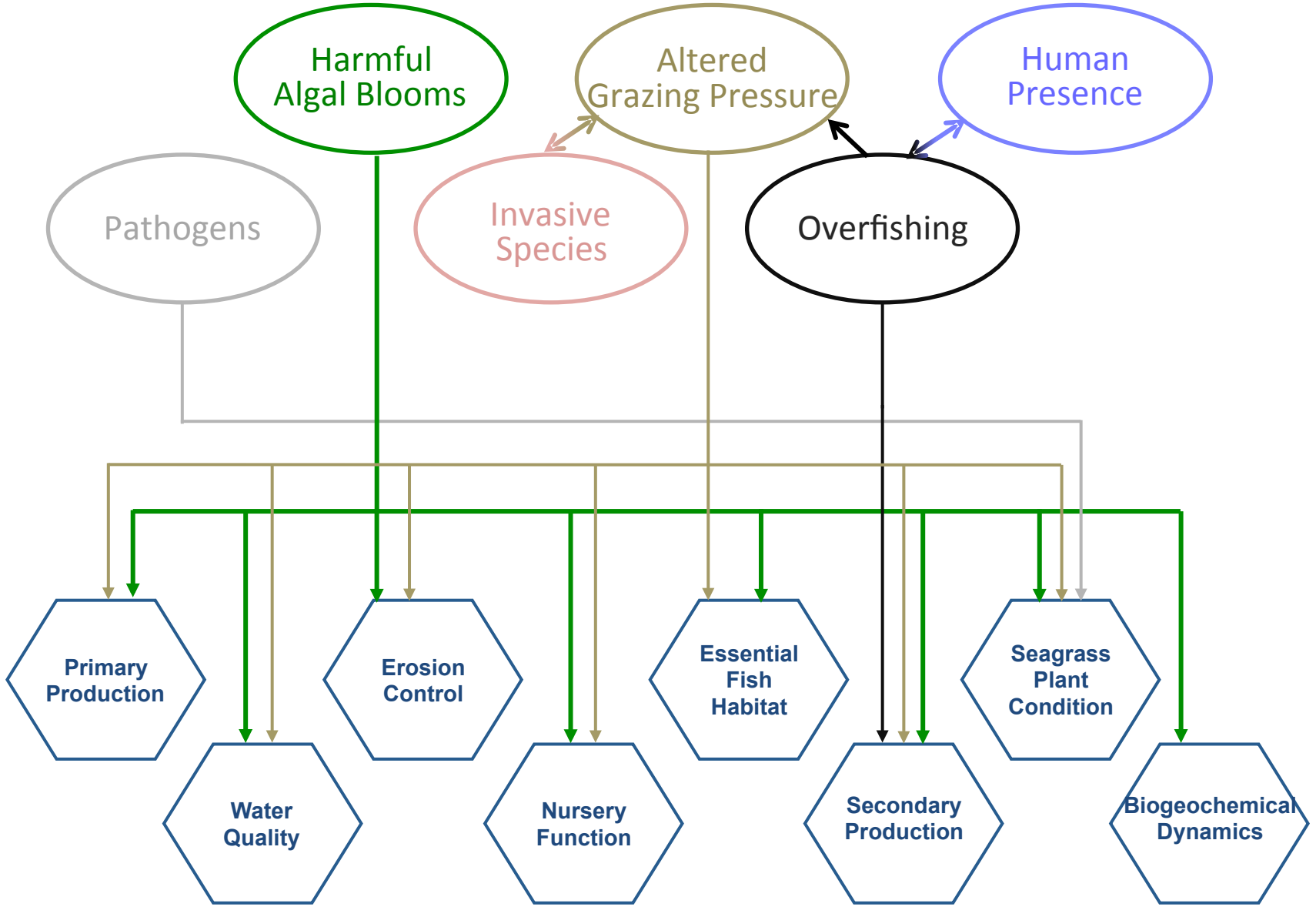
Texas Seagrass Communities



Texas Seagrass Communities

Biological Stressors

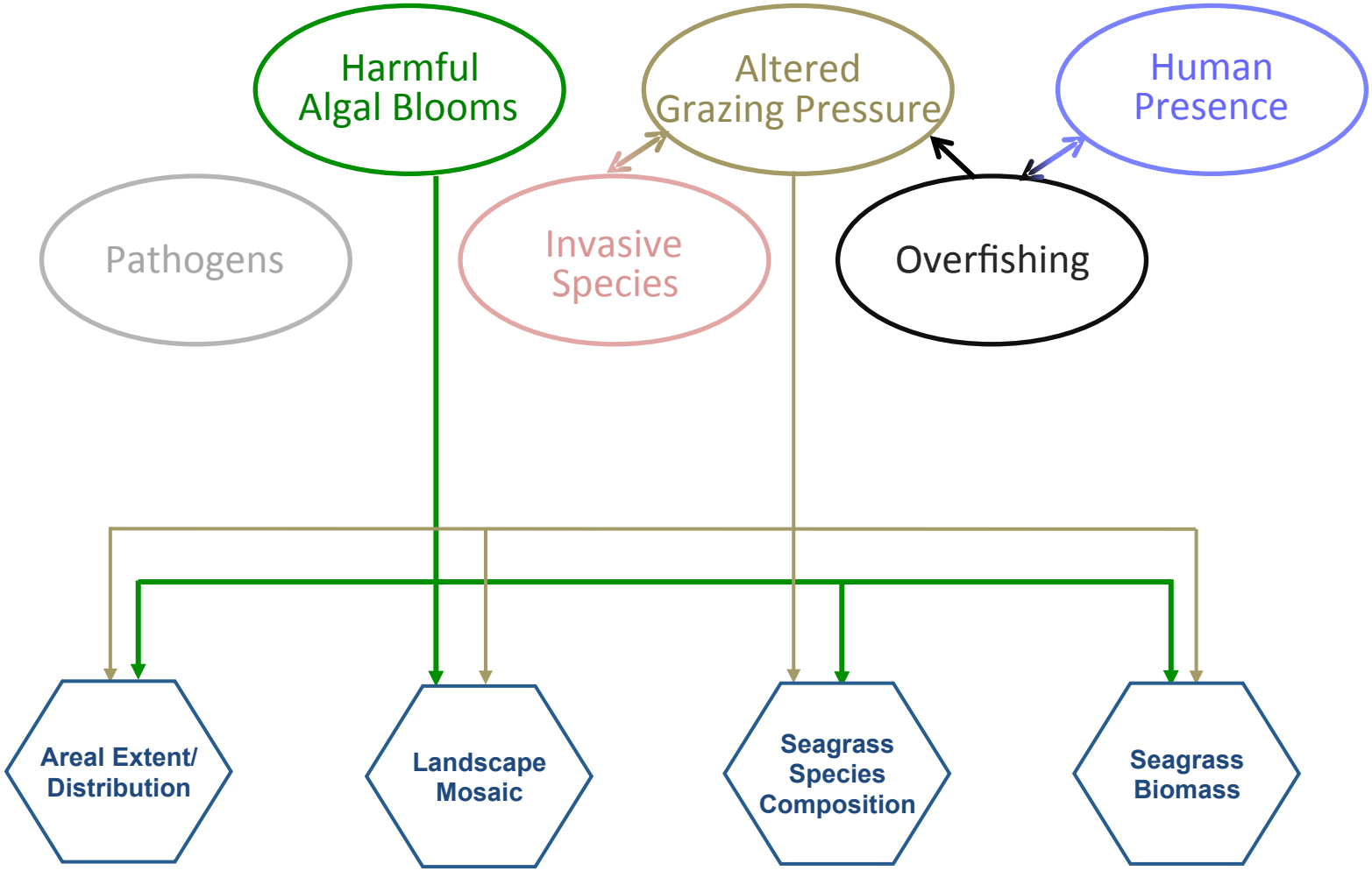
Seagrass Functional Attributes



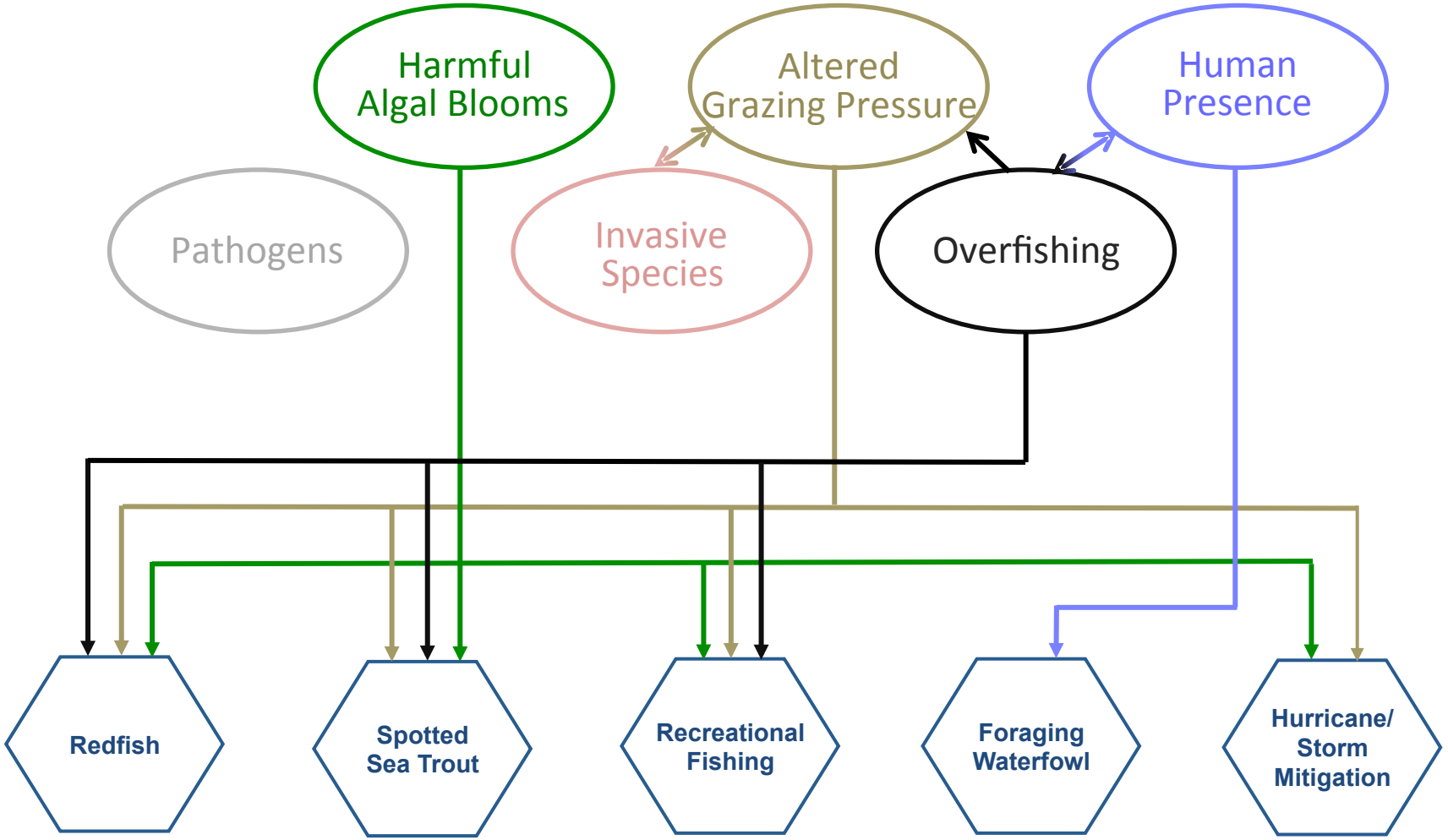
Texas Seagrass Communities

Biological Stressors

Seagrass Structural Attributes

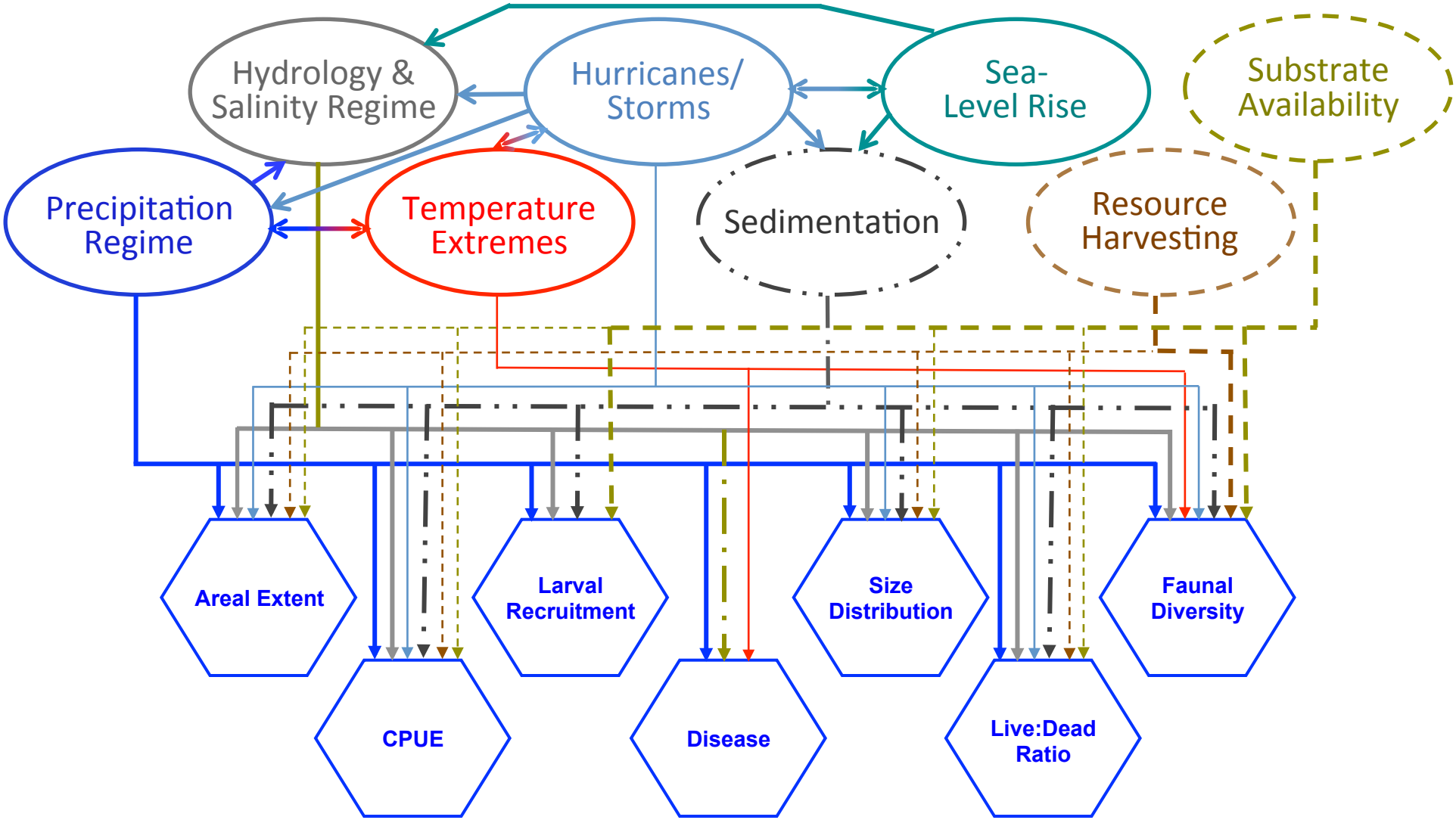


Texas Seagrass Communities



IV-3. Oyster Reef Health Data Conceptual Ecosystem Models

Texas Oyster Reefs

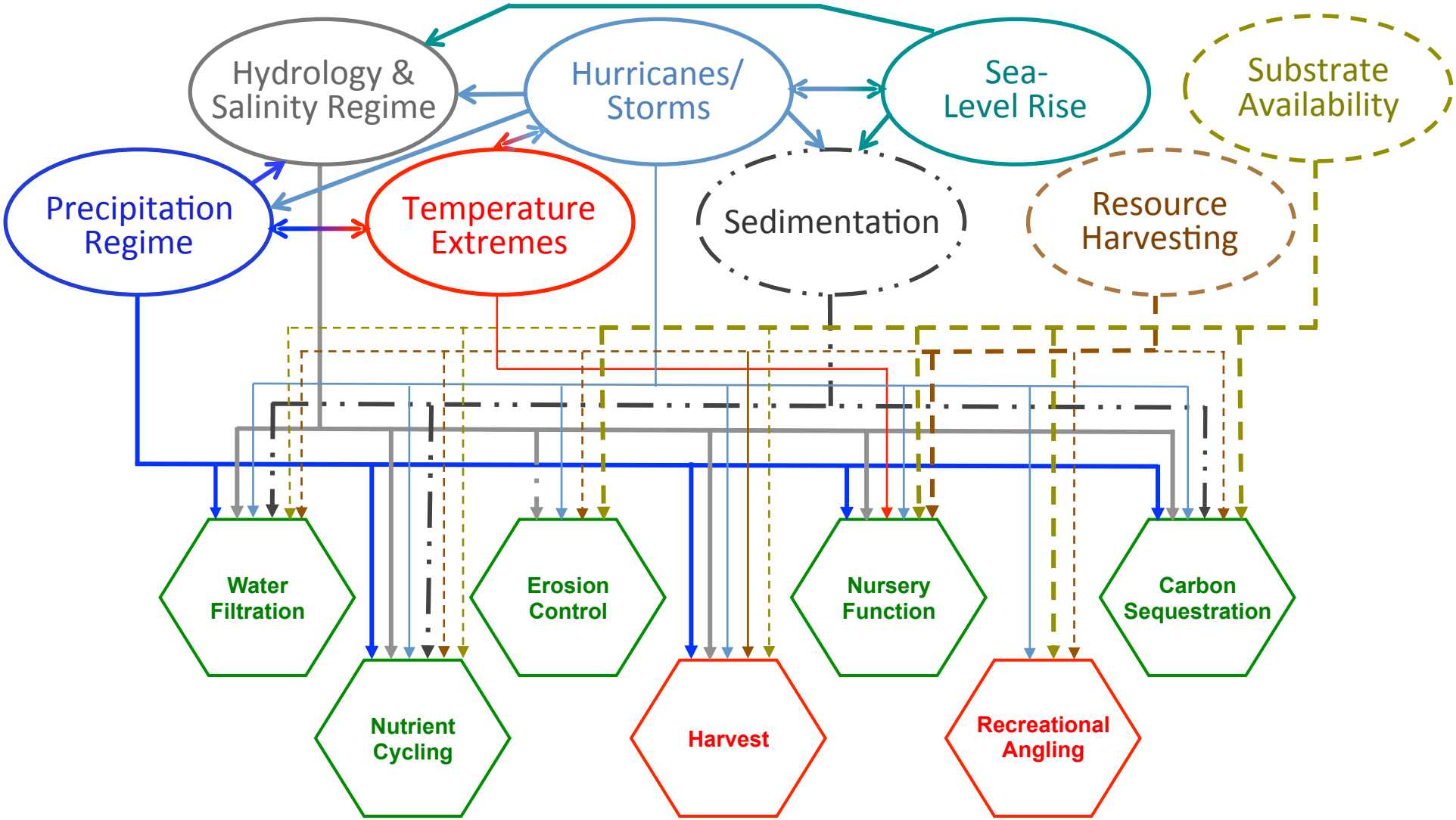


Texas Oyster Reefs

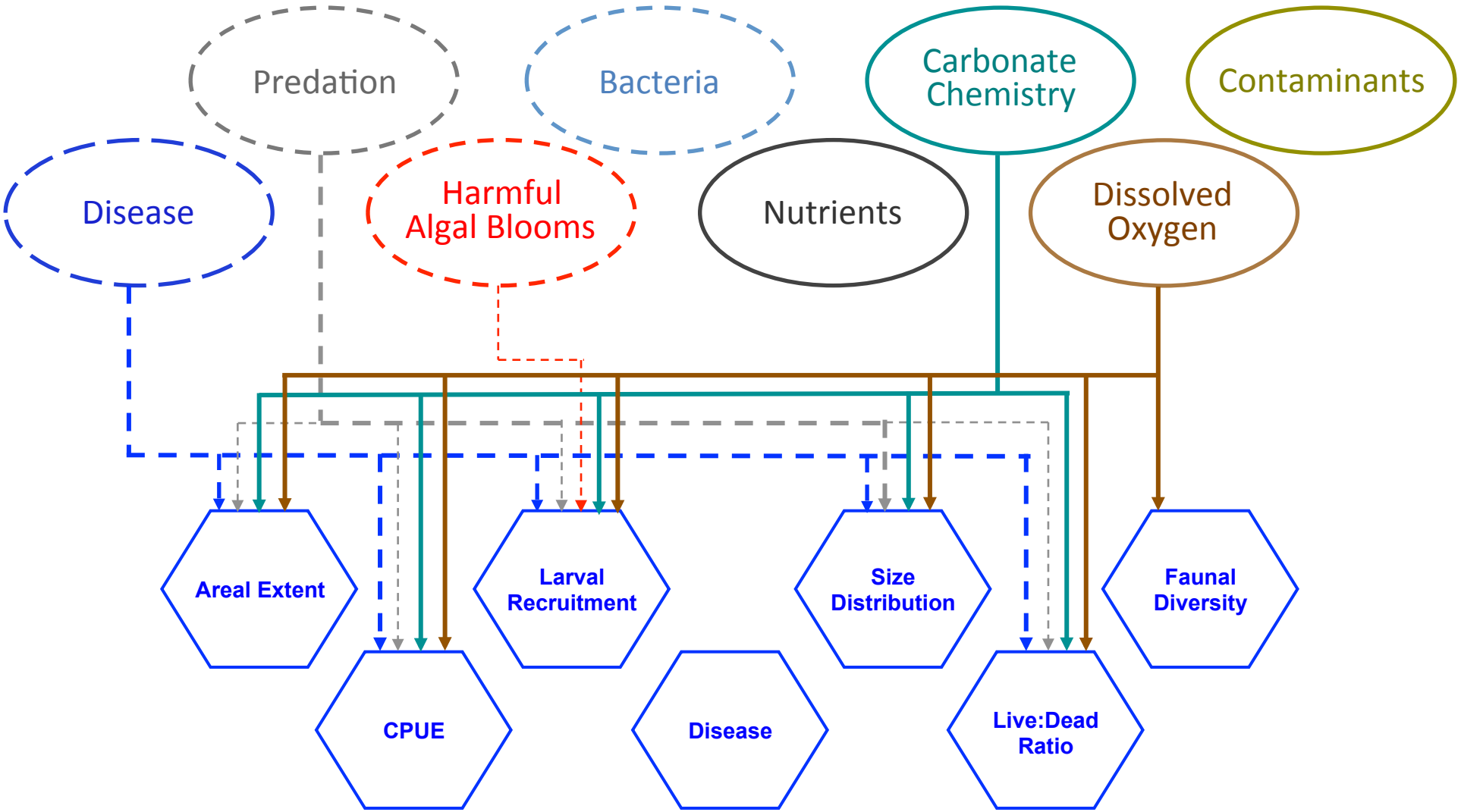
Climate Change & Physical Stressors - 2

Functional Indicators

Reef Products



Texas Oyster Reefs

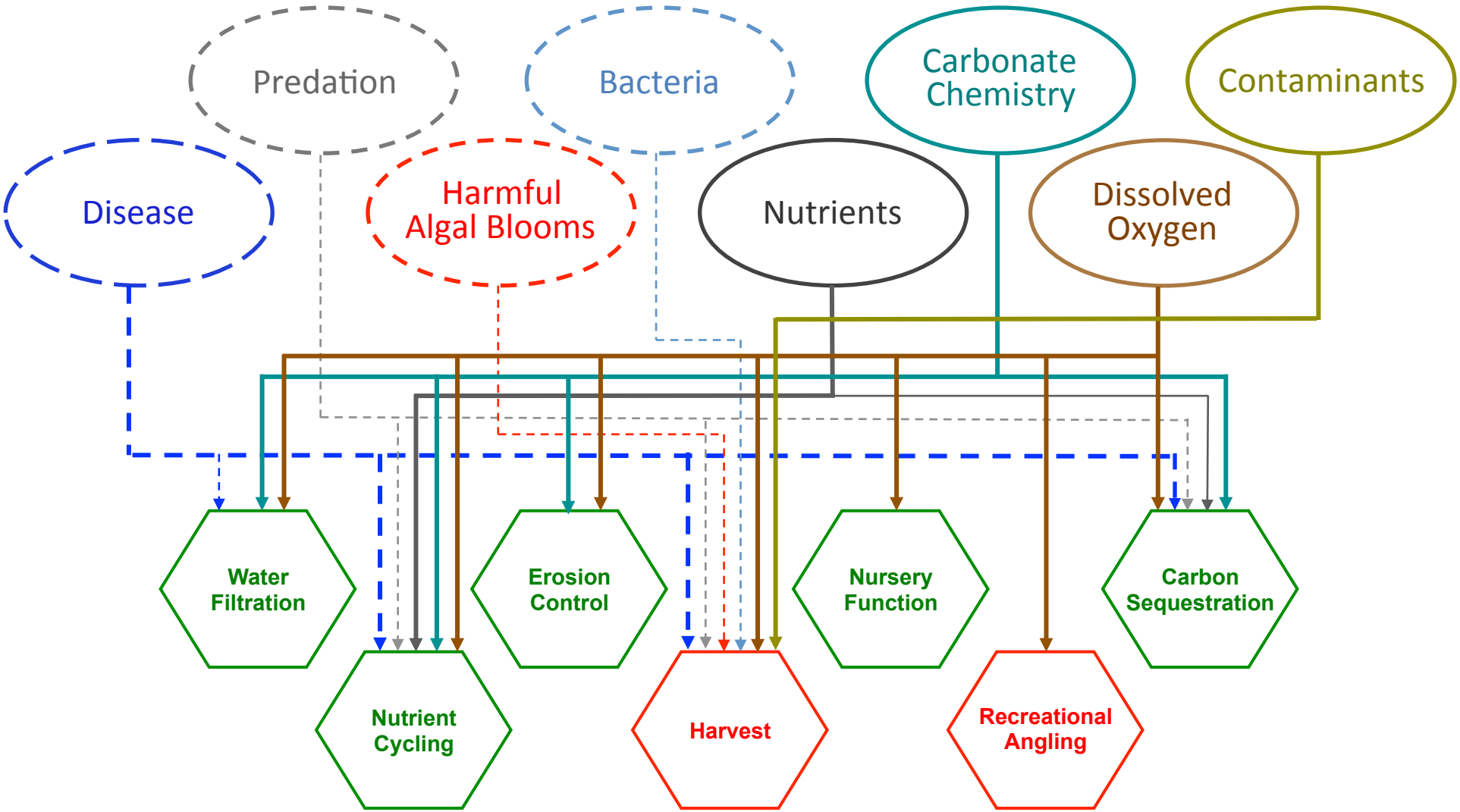


Texas Oyster Reefs

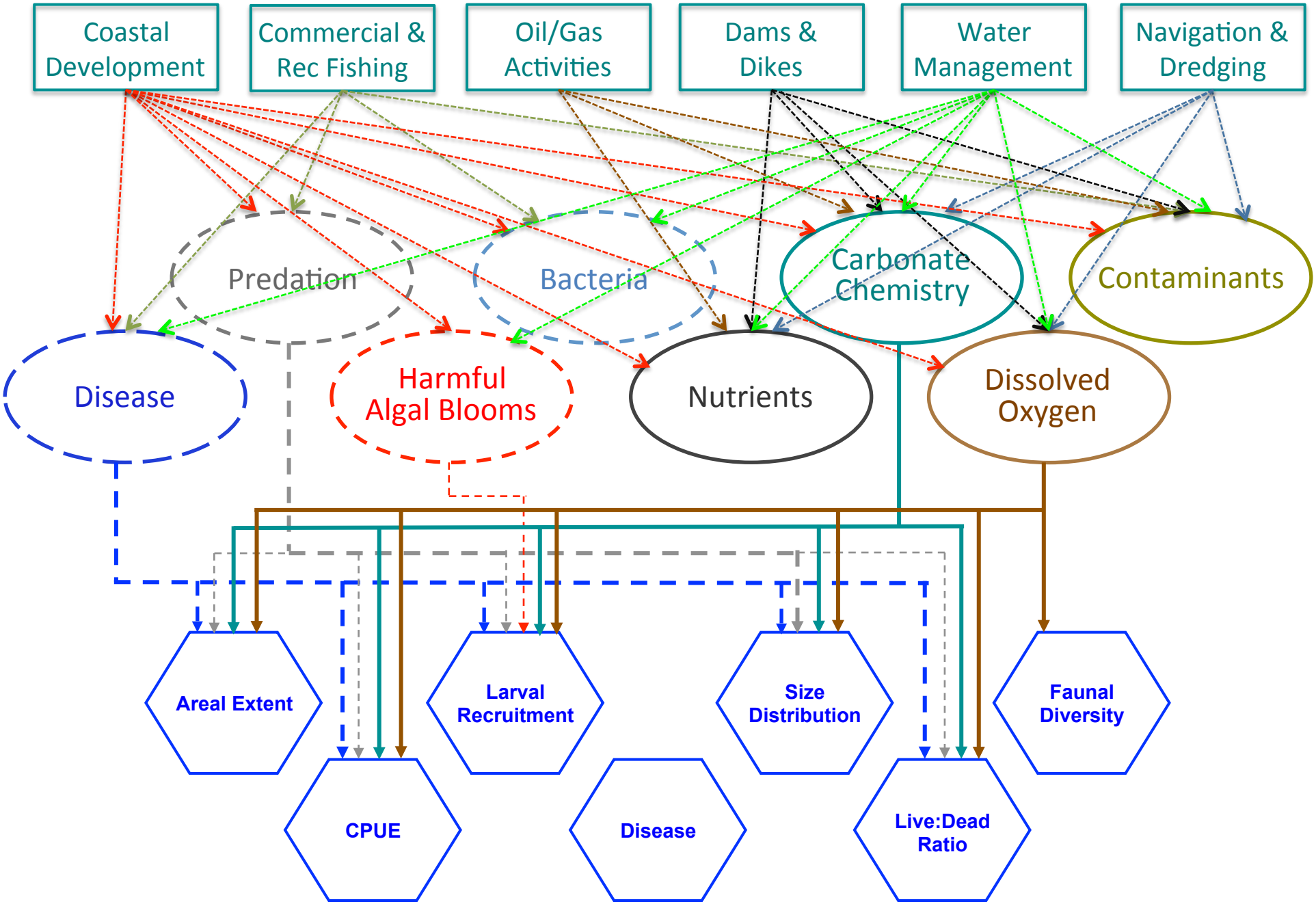
Biological & Chemical Stressors - 2

Functional Indicators

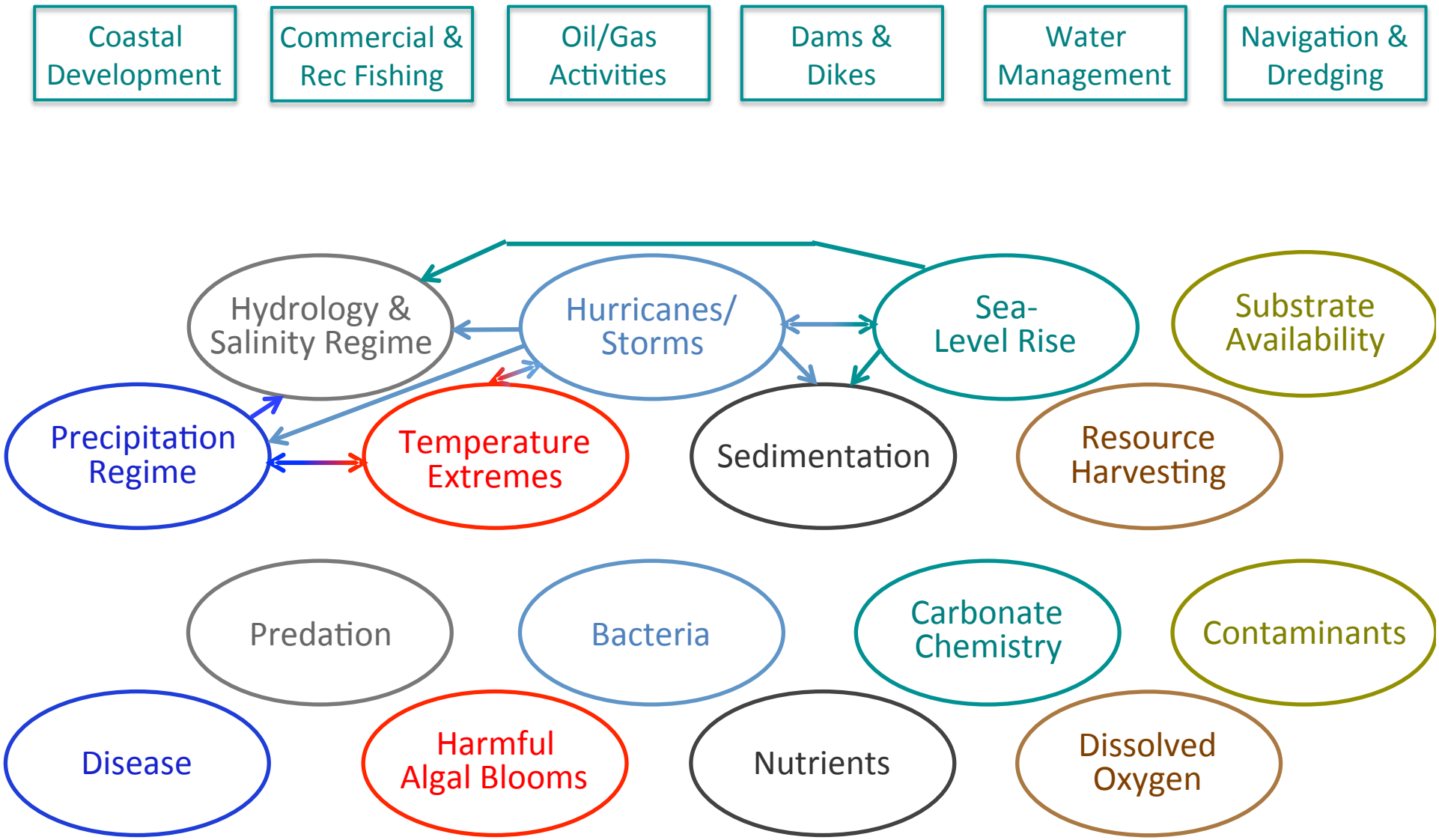
Reef Products



Texas Oyster Reefs

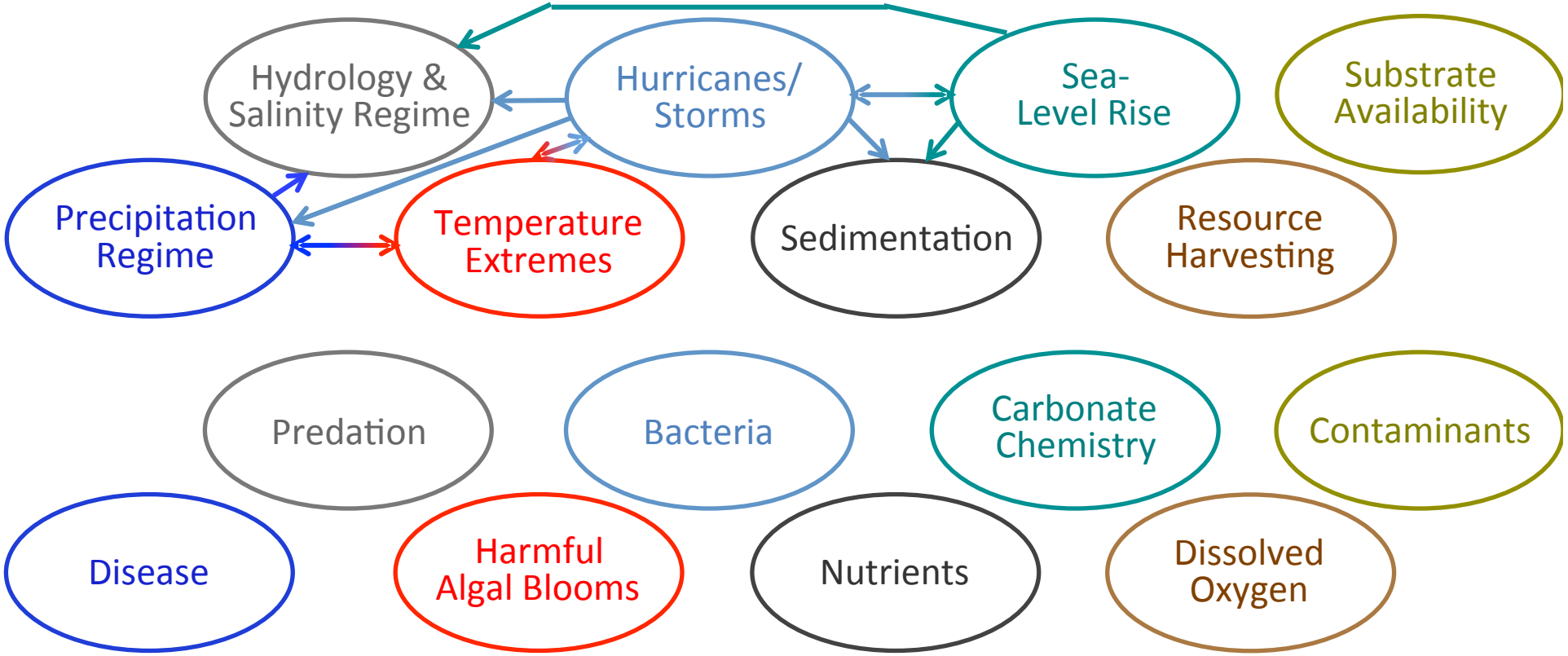


Texas Oyster Reefs



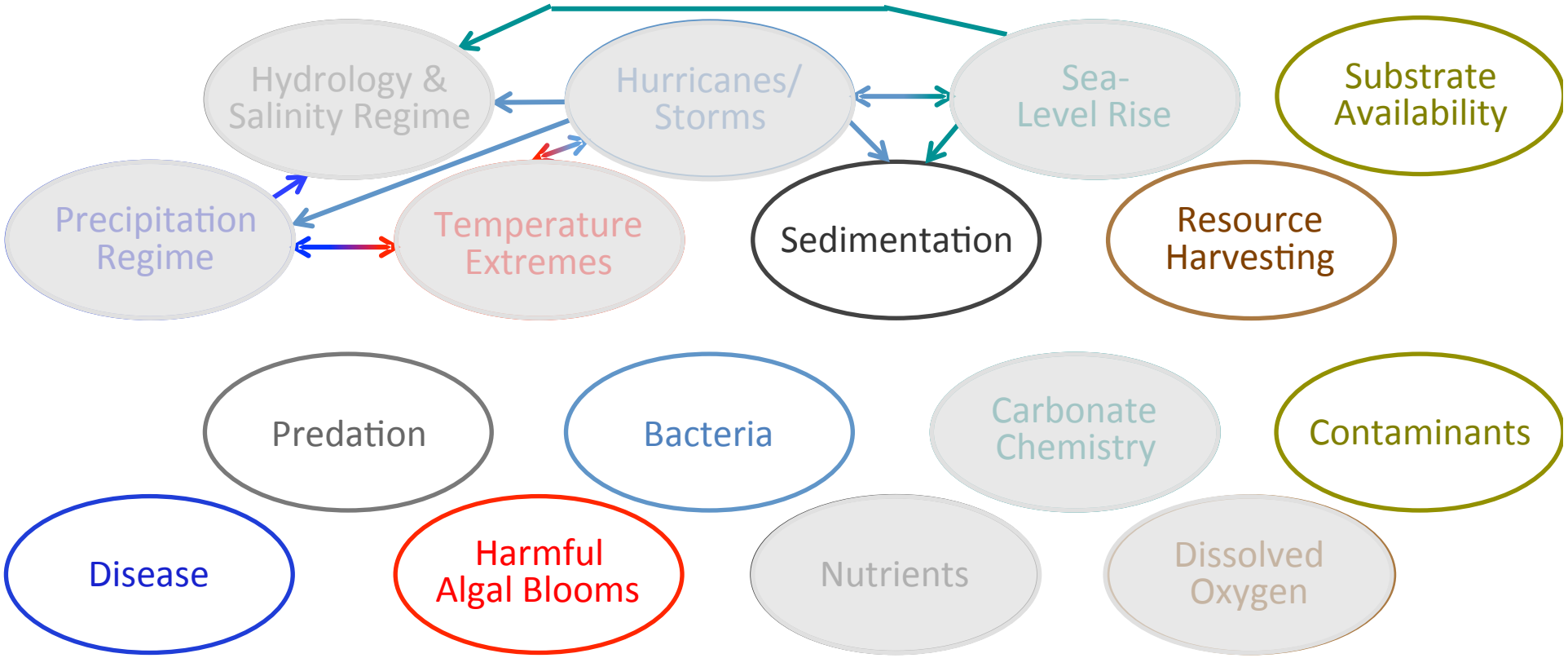
Texas Oyster Reefs

Coastal Development | Commercial & Rec Fishing | Oil/Gas Activities | Dams & Dikes | Water Management | Navigation & Dredging



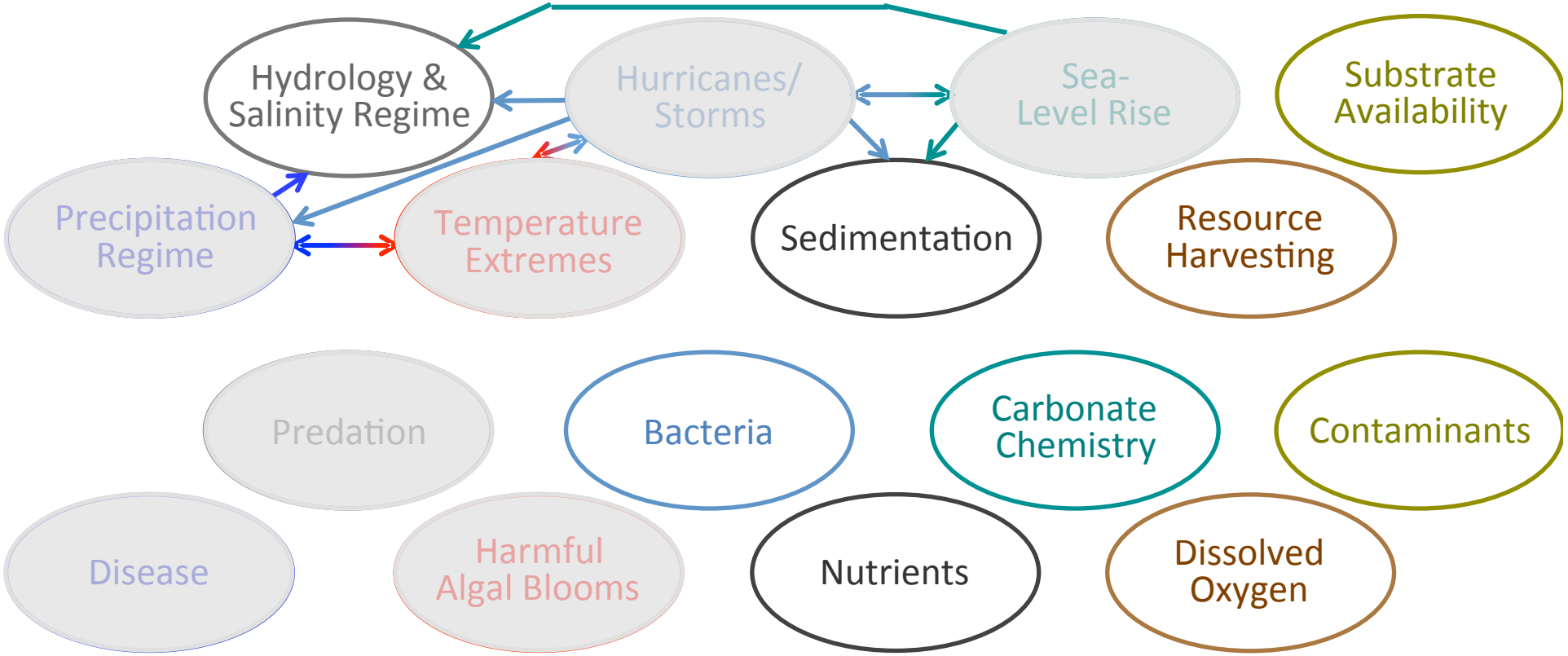
Texas Oyster Reefs

Coastal Development | **Commercial & Rec Fishing** | Oil/Gas Activities | Dams & Dikes | Water Management | Navigation & Dredging



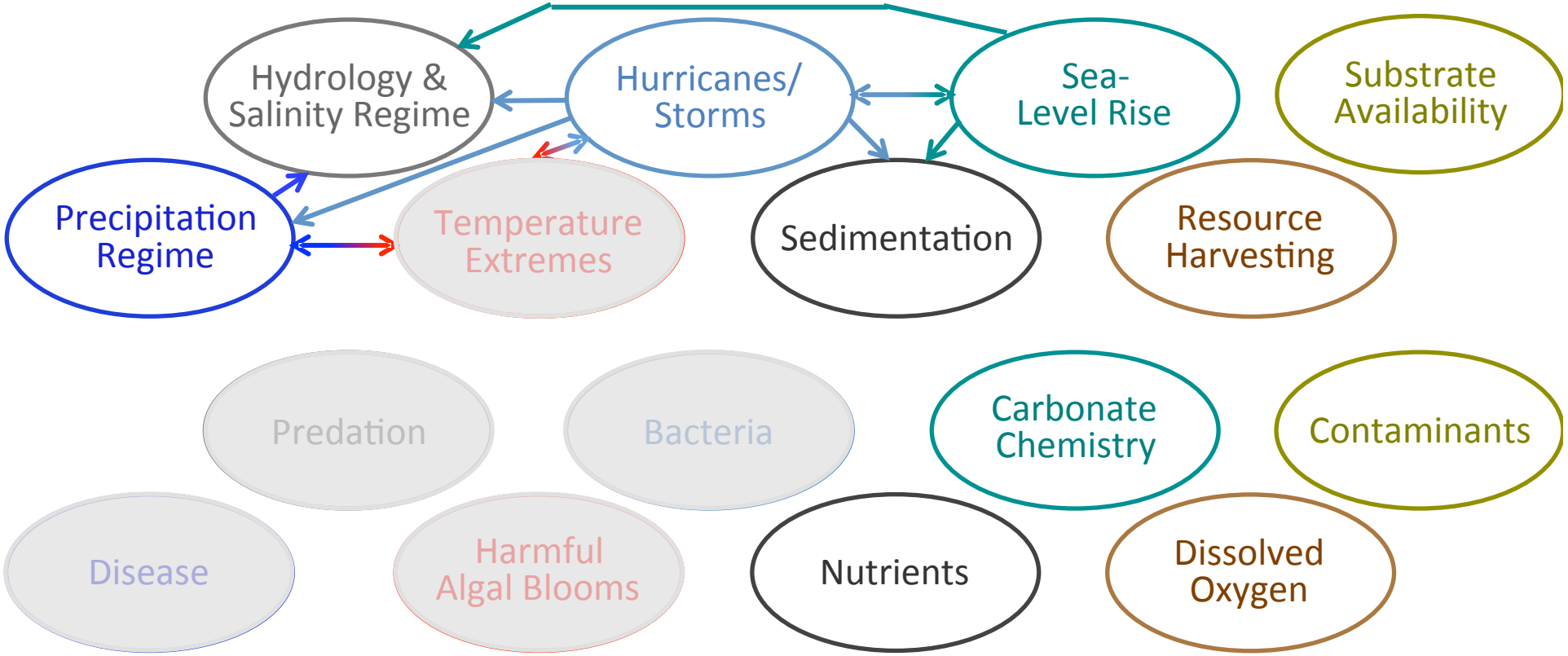
Texas Oyster Reefs

Coastal Development | Commercial & Rec Fishing | **Oil/Gas Activities** | Dams & Dikes | Water Management | Navigation & Dredging



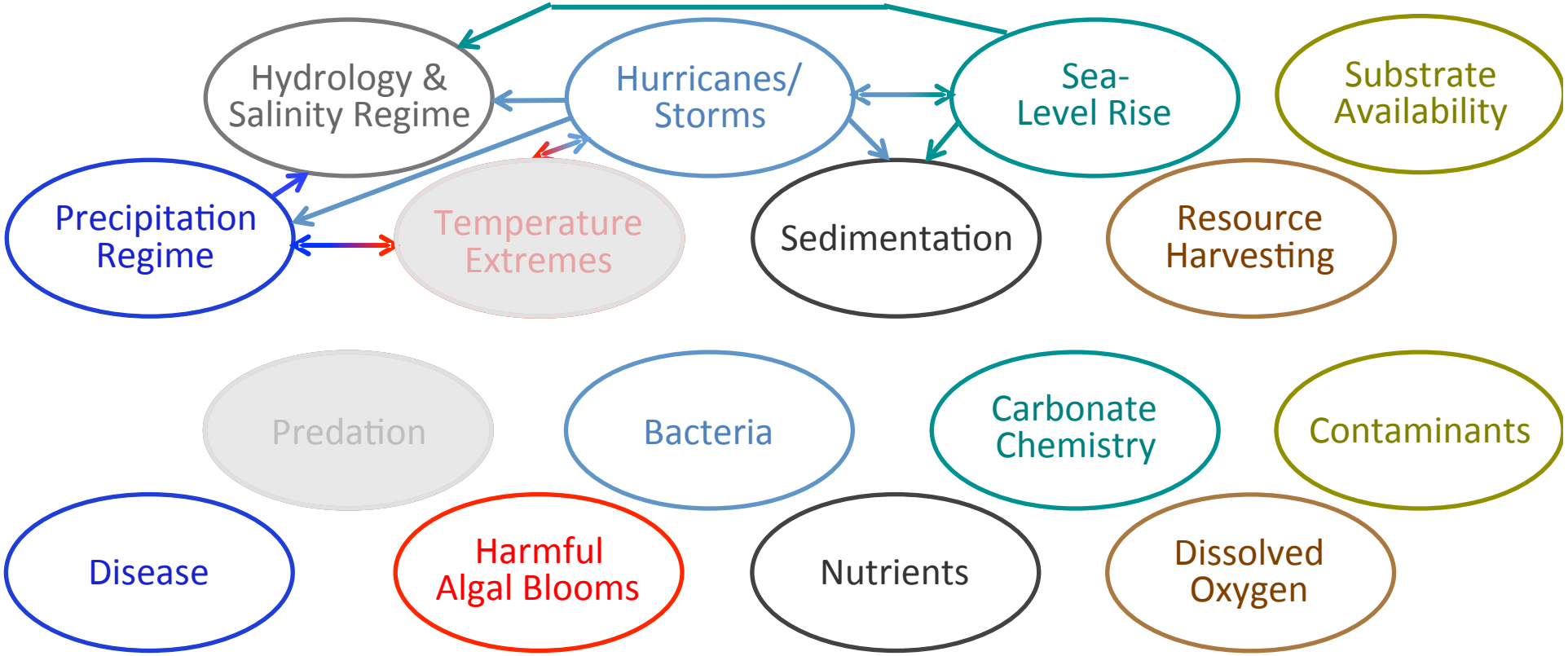
Texas Oyster Reefs

Coastal Development | Commercial & Rec Fishing | Oil/Gas Activities | **Dams & Dikes** | Water Management | Navigation & Dredging



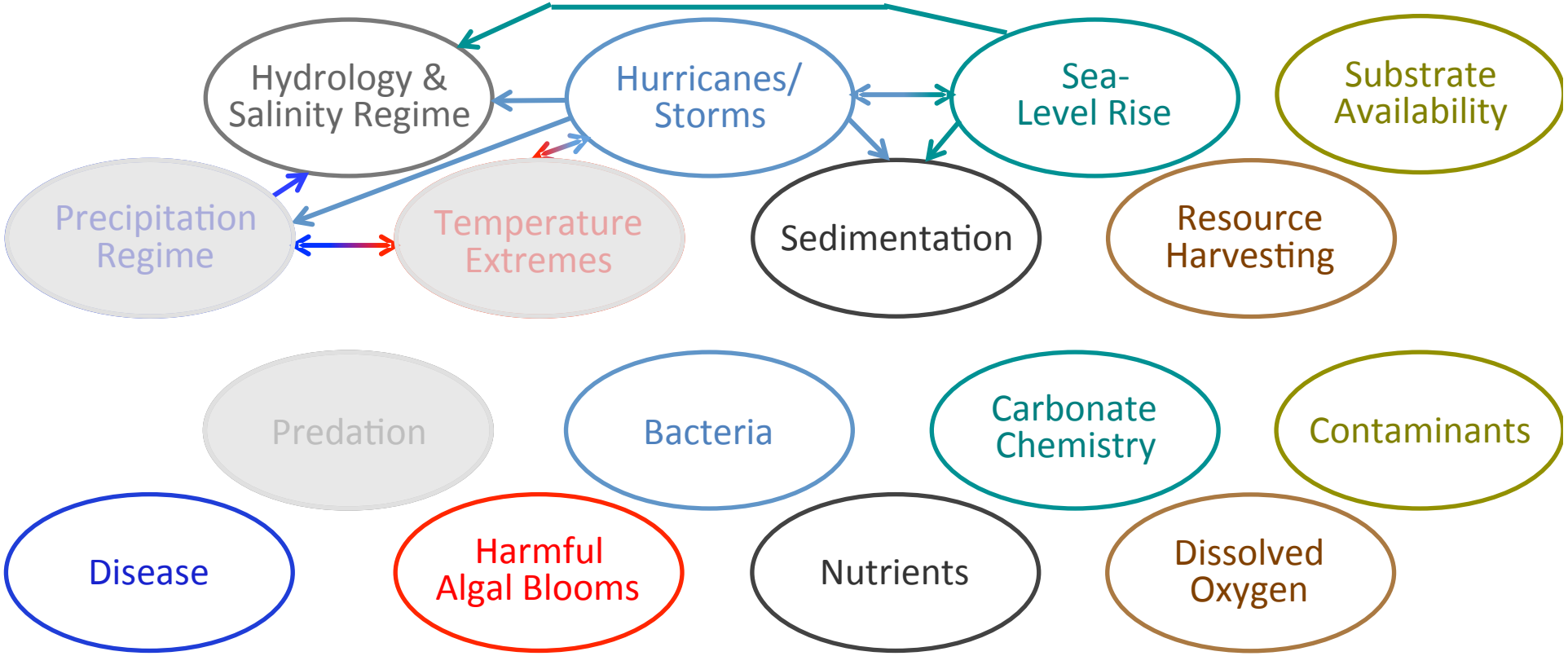
Texas Oyster Reefs

Coastal Development | Commercial & Rec Fishing | Oil/Gas Activities | Dams & Dikes | **Water Management** | Navigation & Dredging

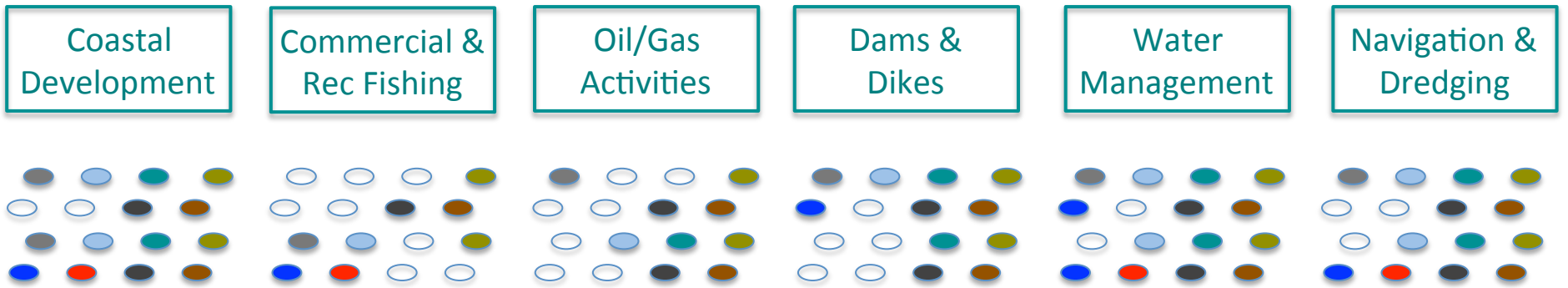


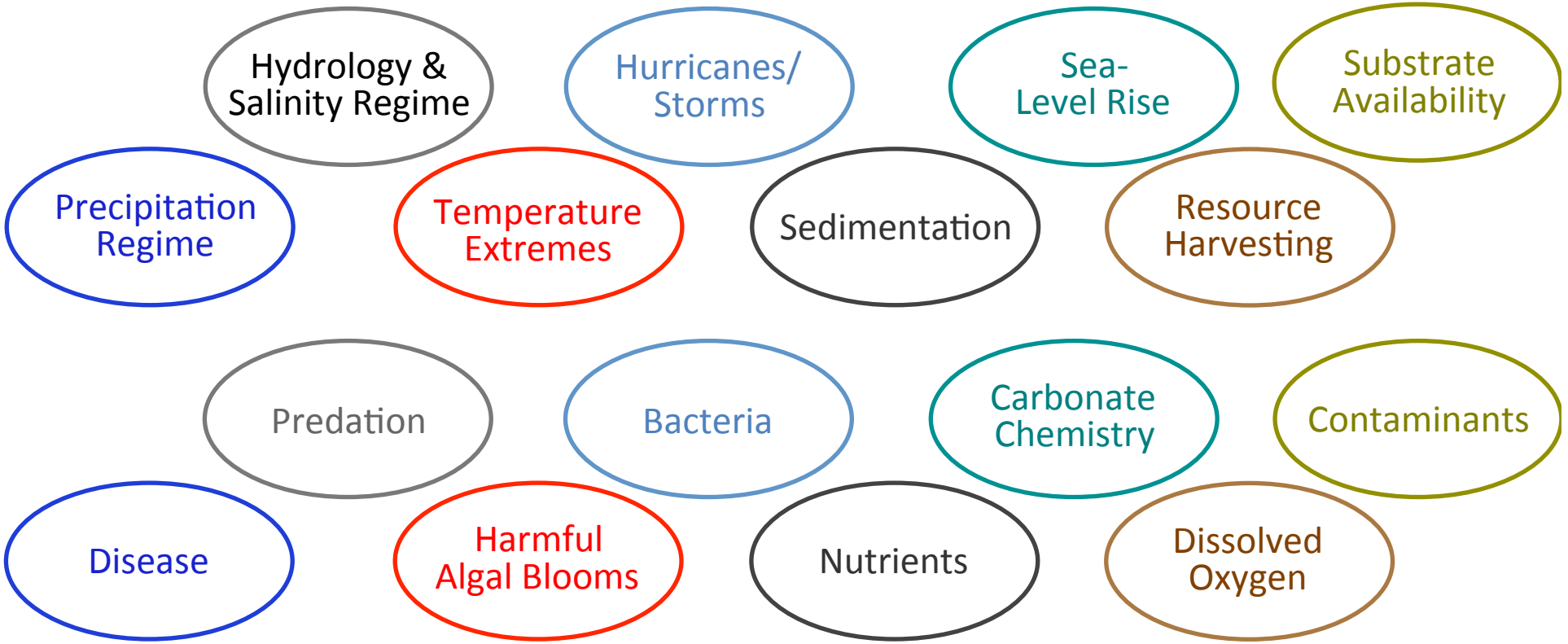
Texas Oyster Reefs

Coastal Development | Commercial & Rec Fishing | Oil/Gas Activities | Dams & Dikes | Water Management | Navigation & Dredging

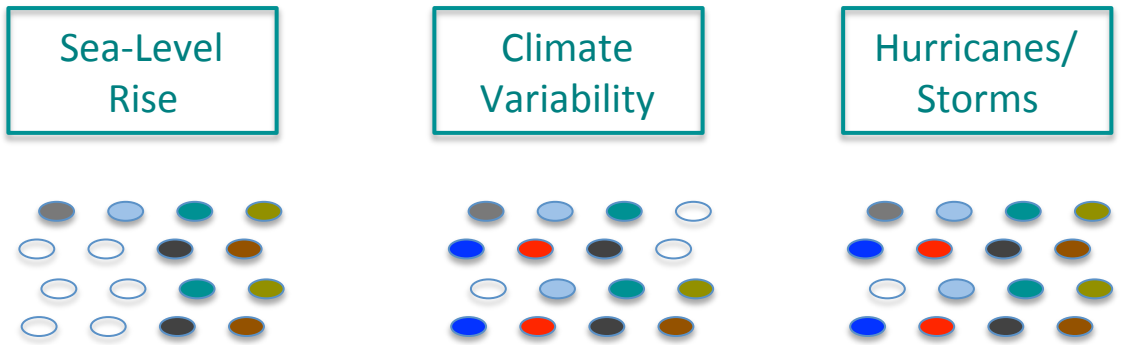


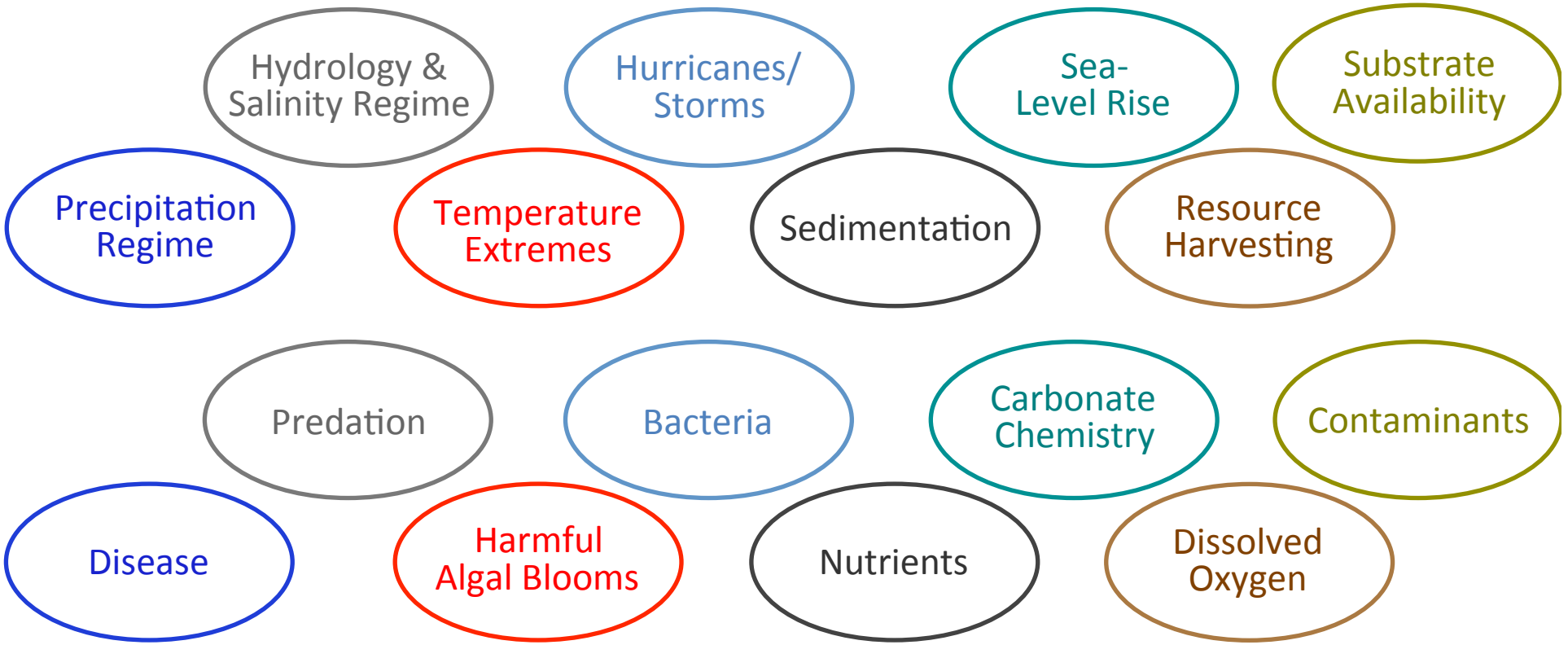
Texas Oyster Reefs – Human Activities





Texas Oyster Reefs – Climate Change

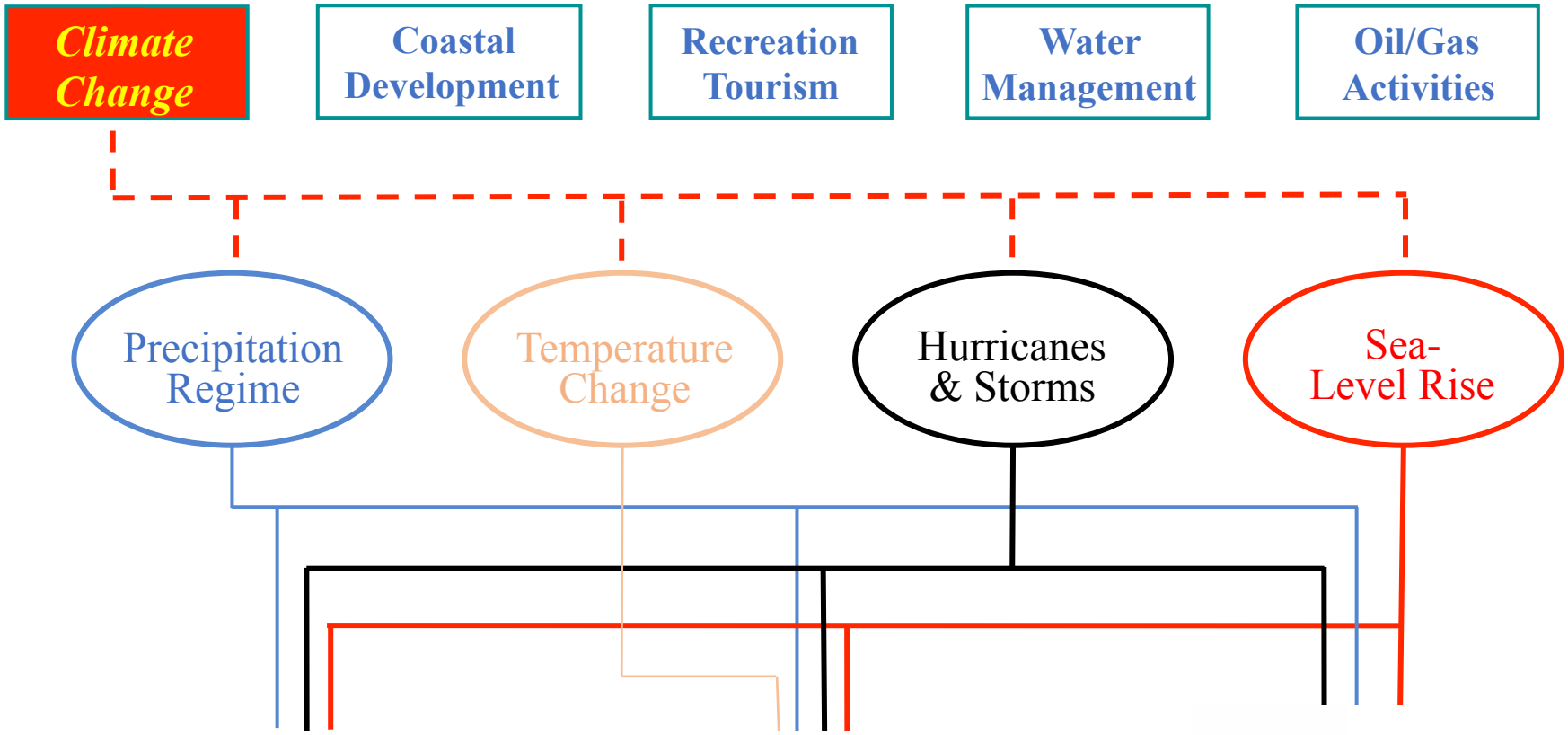




IV-4. Bird Health Data Conceptual Ecosystem Models

Texas Coastal Breeding Resident Birds

Climate Change Stressors



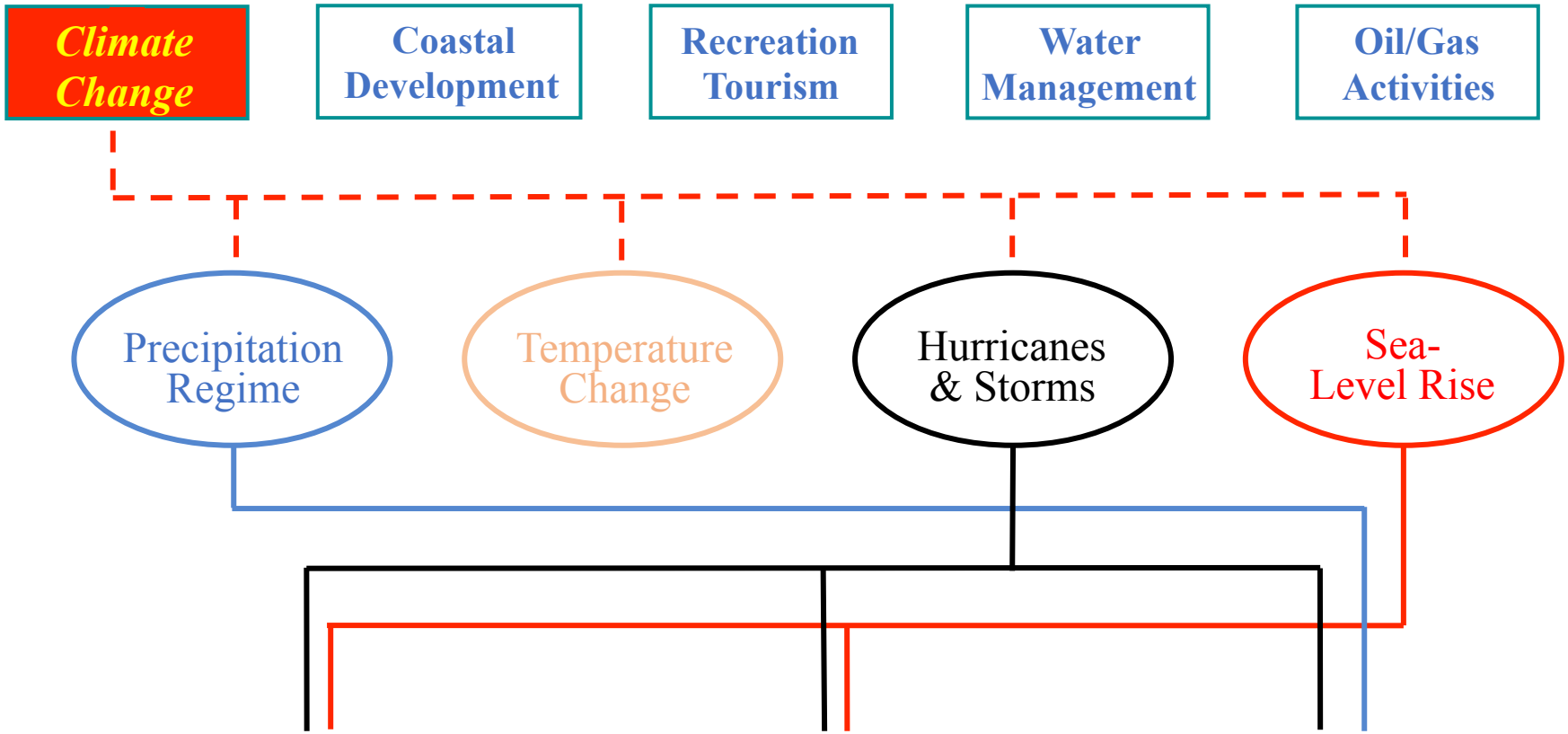
Forster's Tern

Great Egret

Mottled Duck

Texas Coastal Migratory - Wintering Birds

Climate Change Stressors



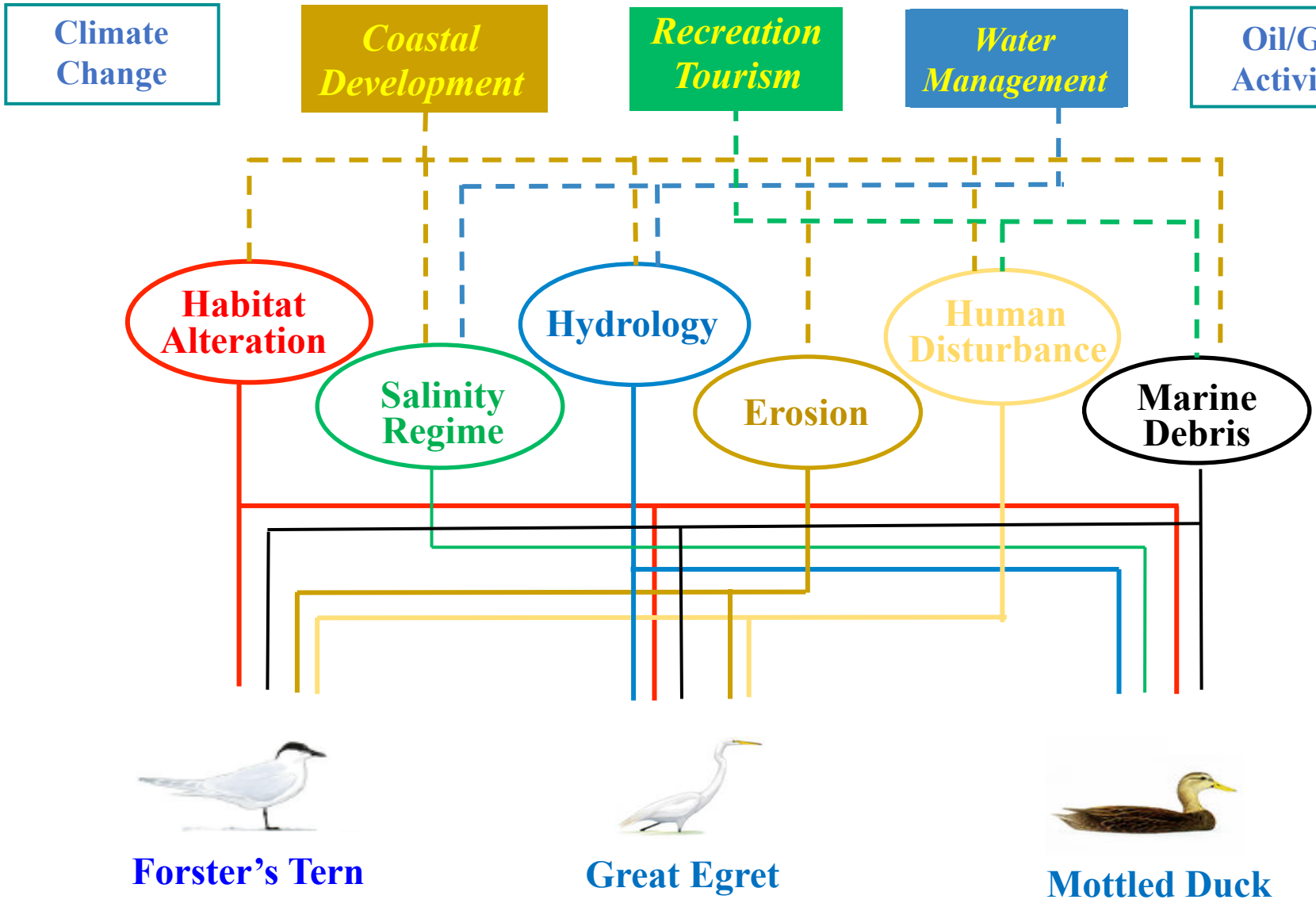
Piping Plover

Least Sandpiper

Lesser Scaup

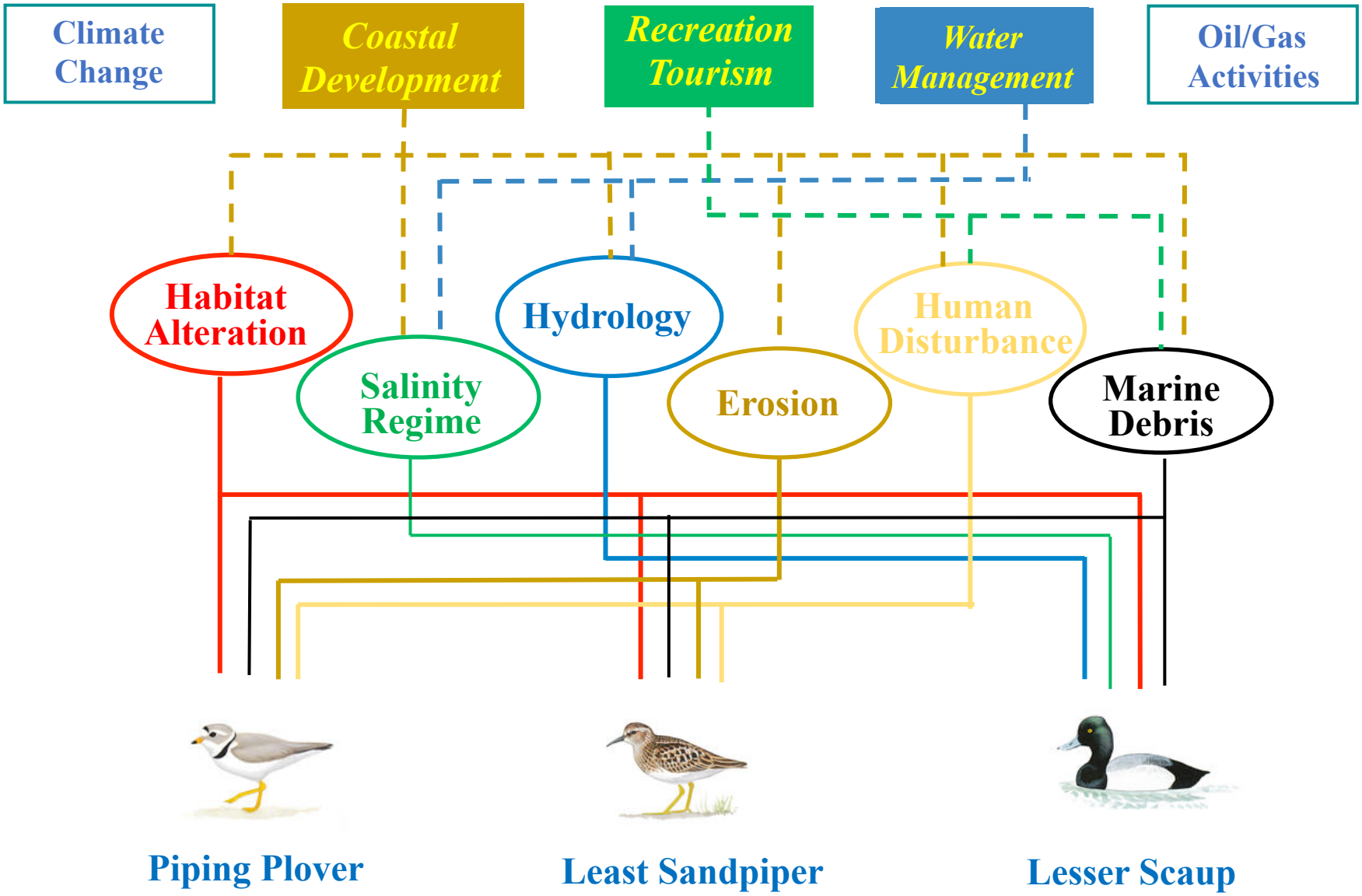
Texas Coastal Breeding Resident Birds

Physical Stressors



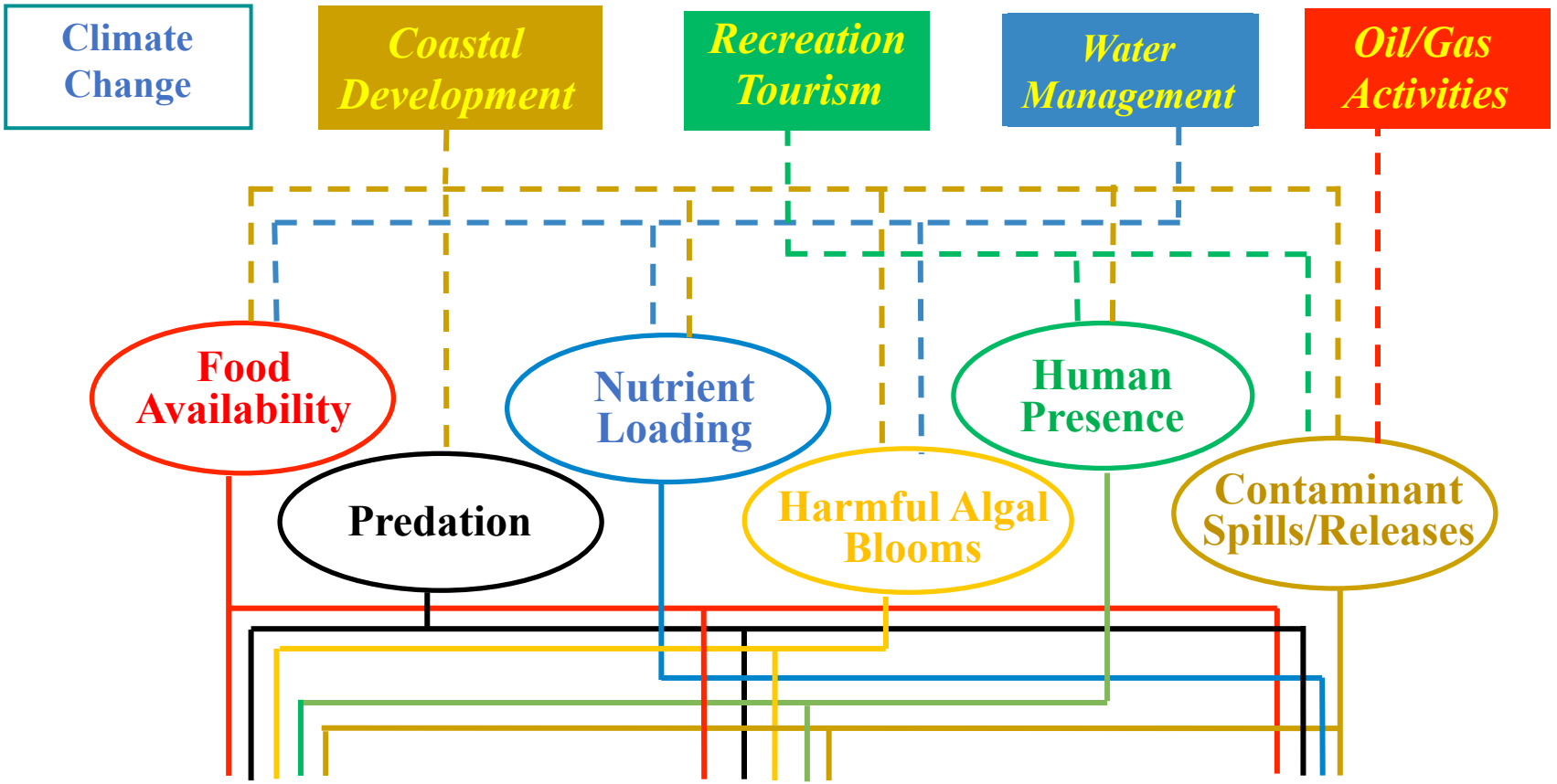
Texas Coastal Migratory - Wintering Birds

Physical Stressors



Texas Coastal Breeding Resident Birds

Biological & Chemical Stressors



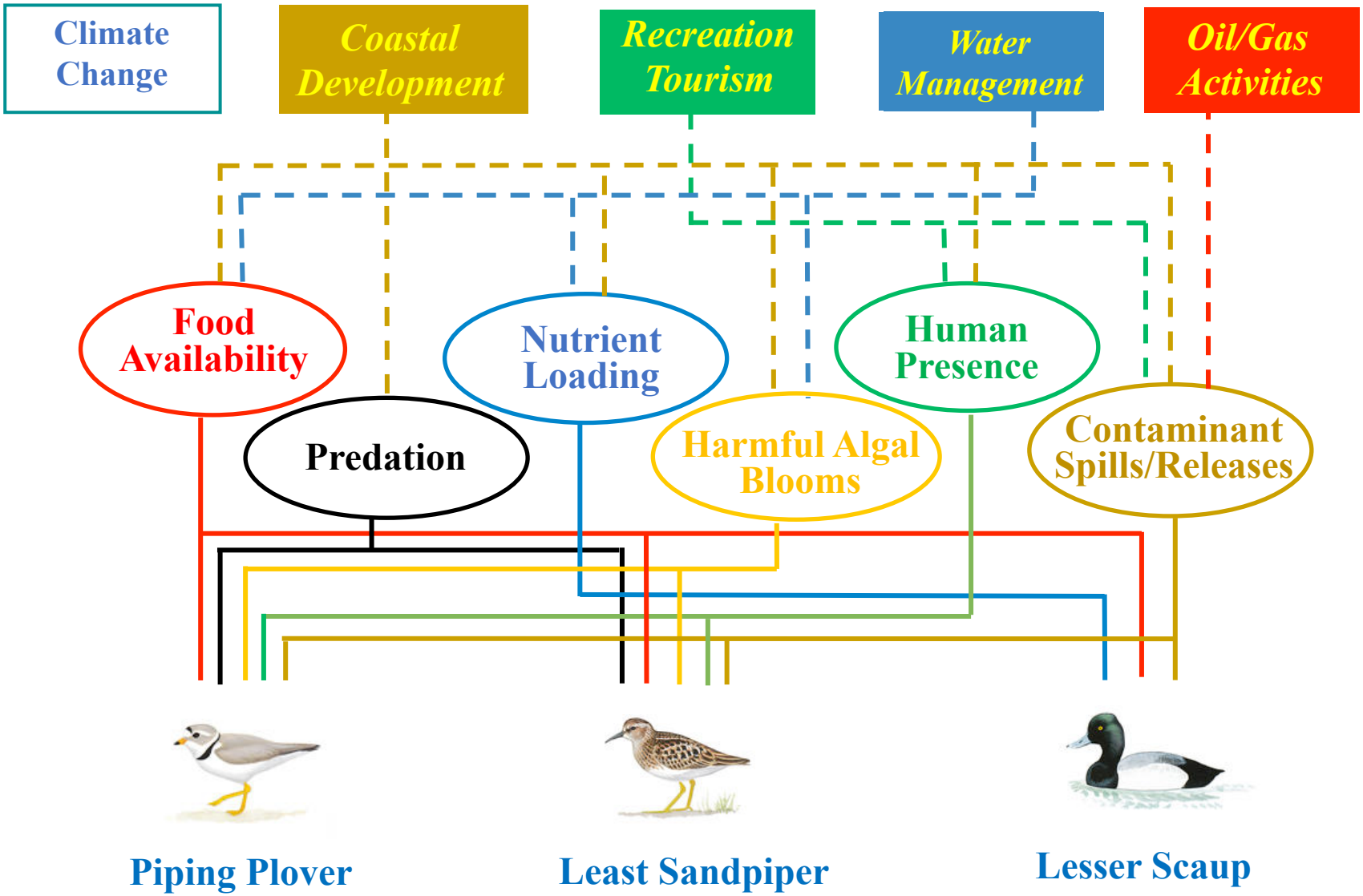
Forster's Tern

Great Egret

Mottled Duck

Texas Coastal Migratory - Wintering Birds

Biological & Chemical Stressors

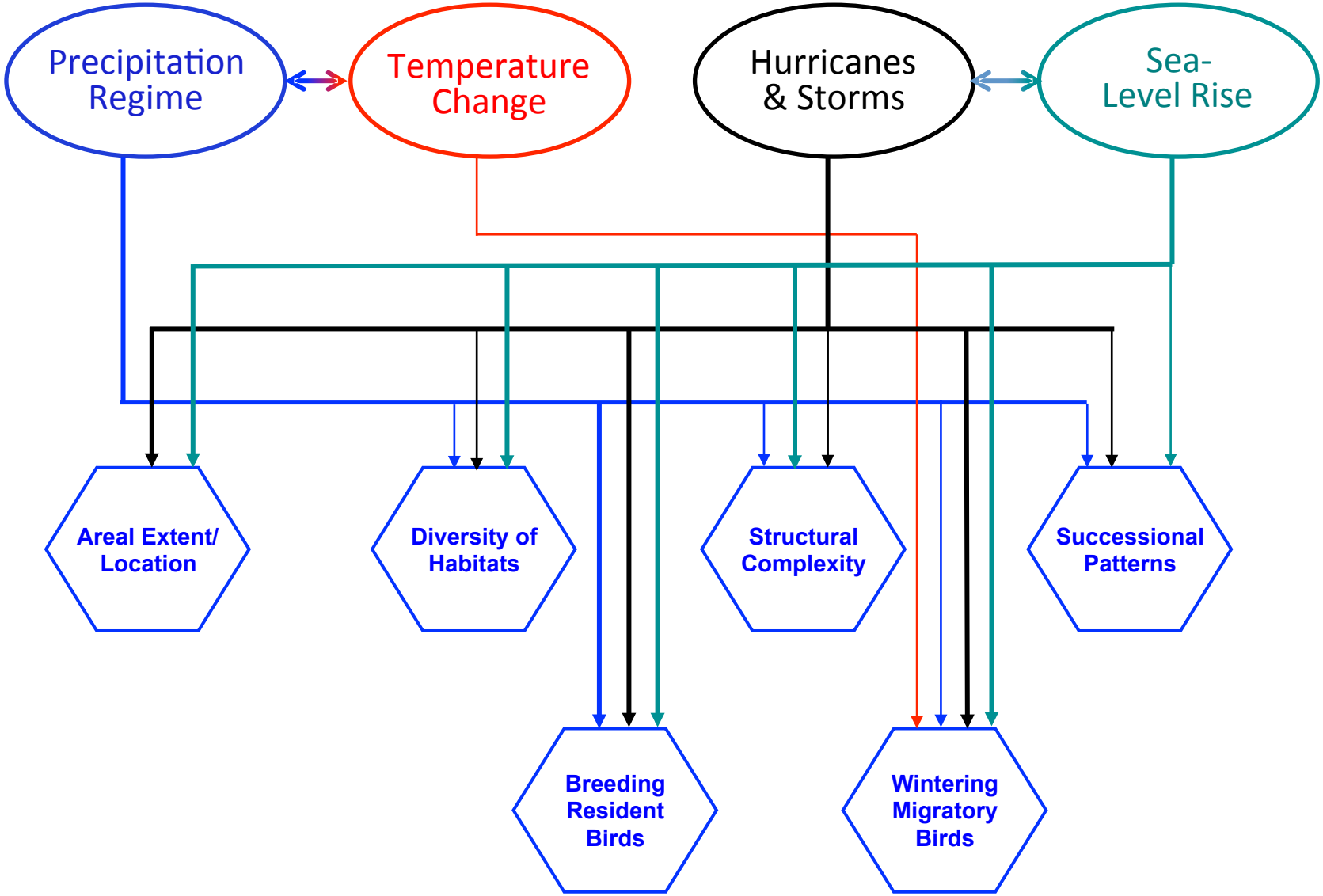


IV-5. Rookery Islands Conceptual Ecosystem Models

Rookery Islands

Climate Change Stressors

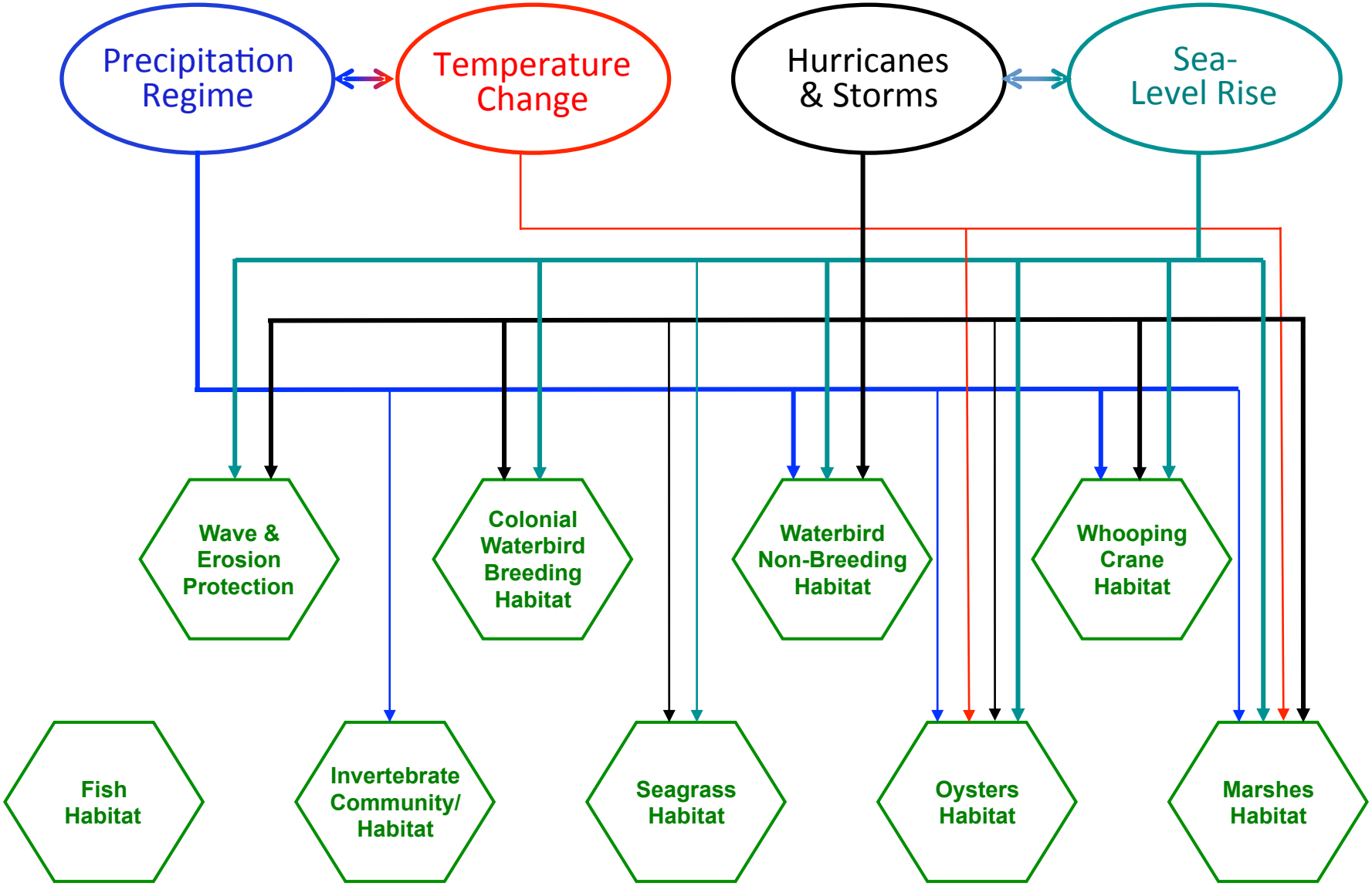
Structural Indicators



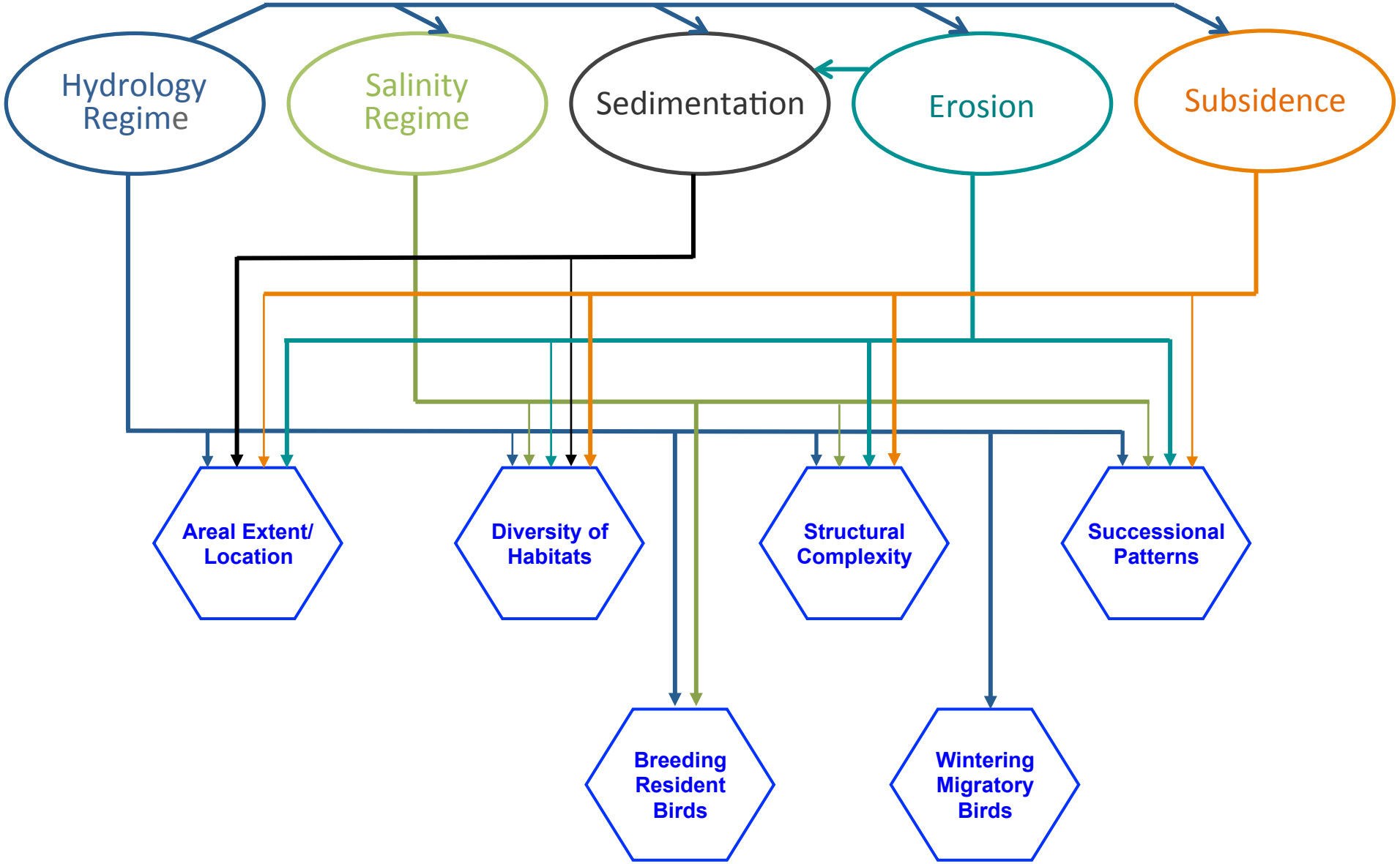
Rookery Islands

Climate Change Stressors

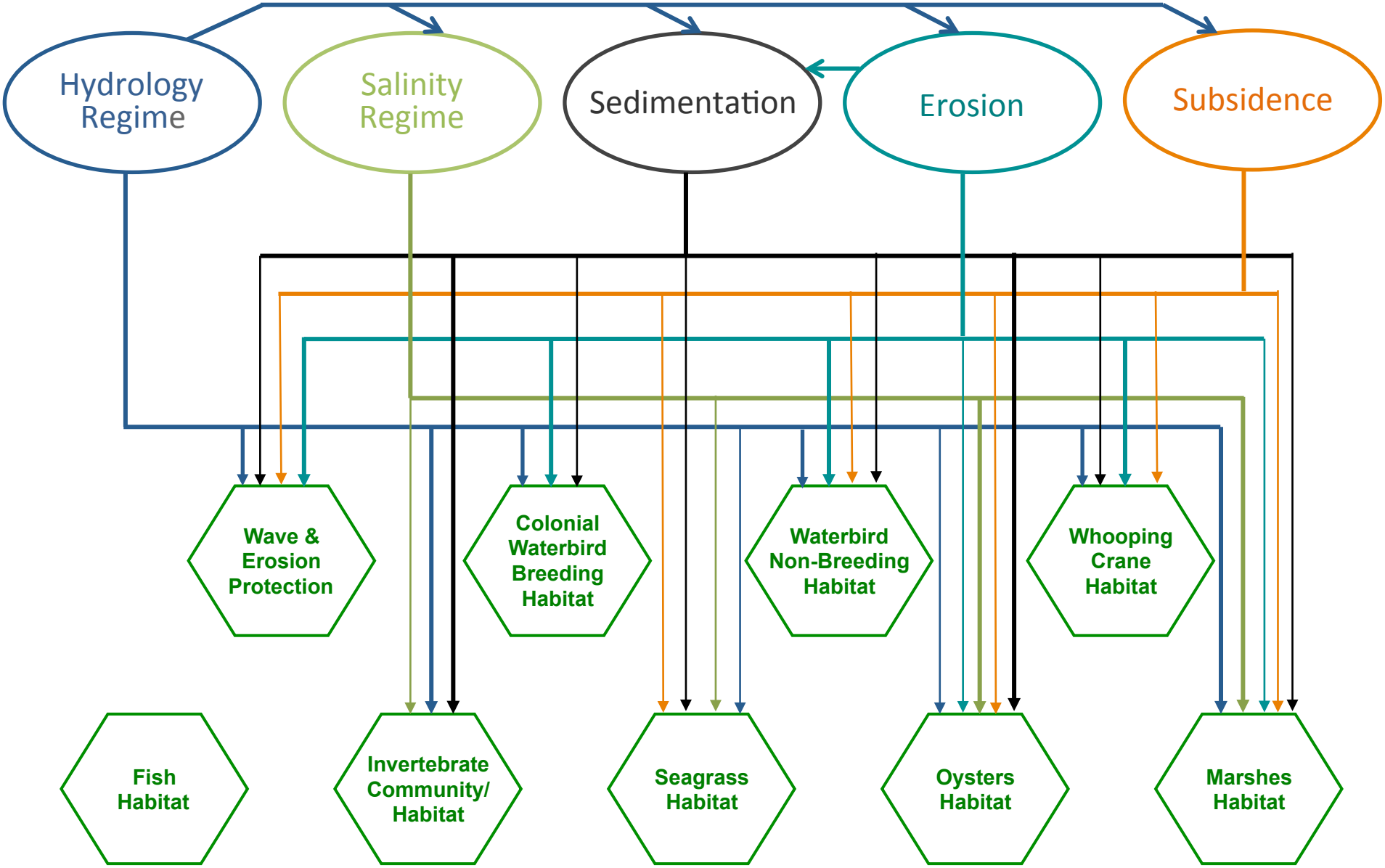
Functional Indicators



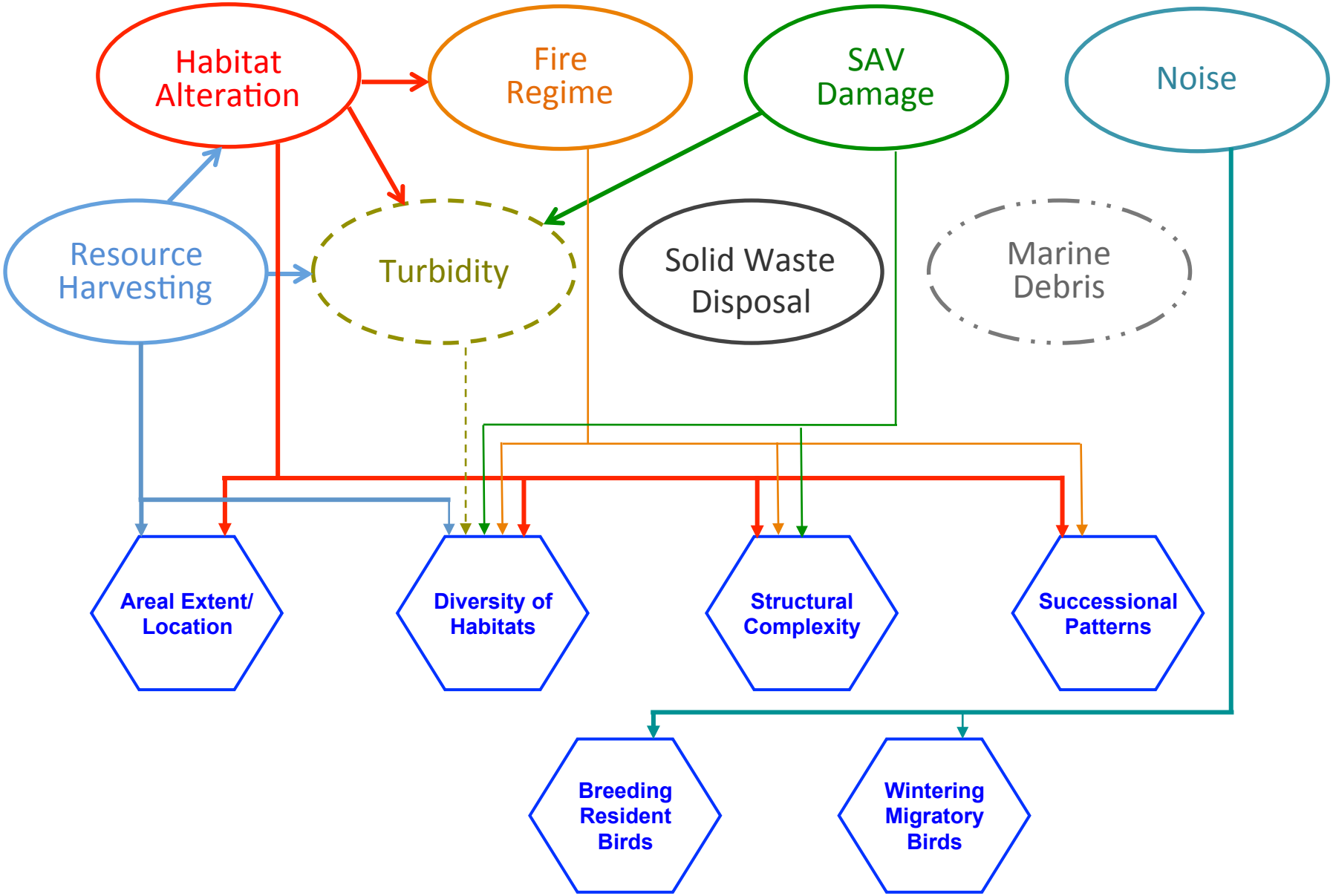
Rookery Islands



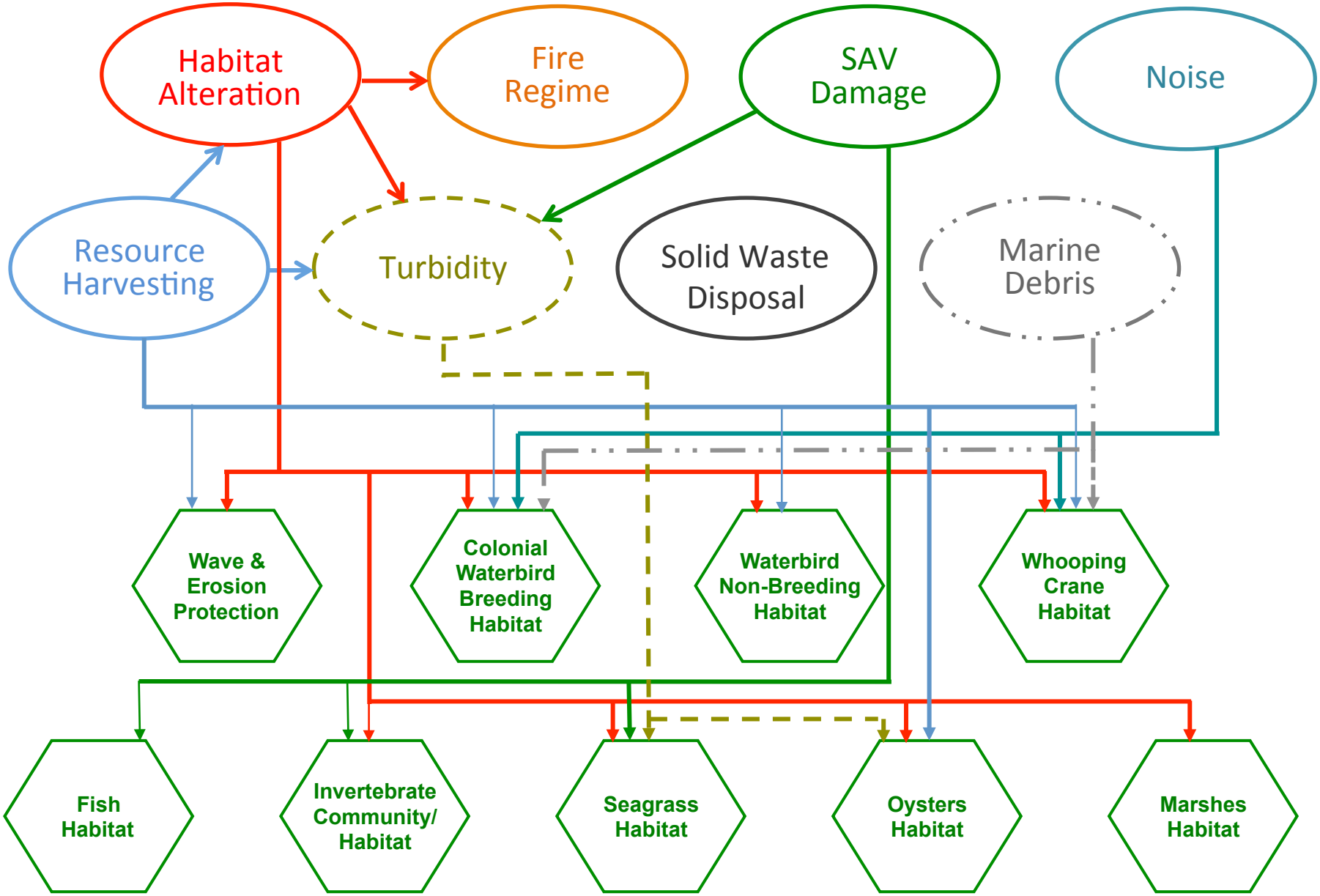
Rookery Islands



Rookery Islands



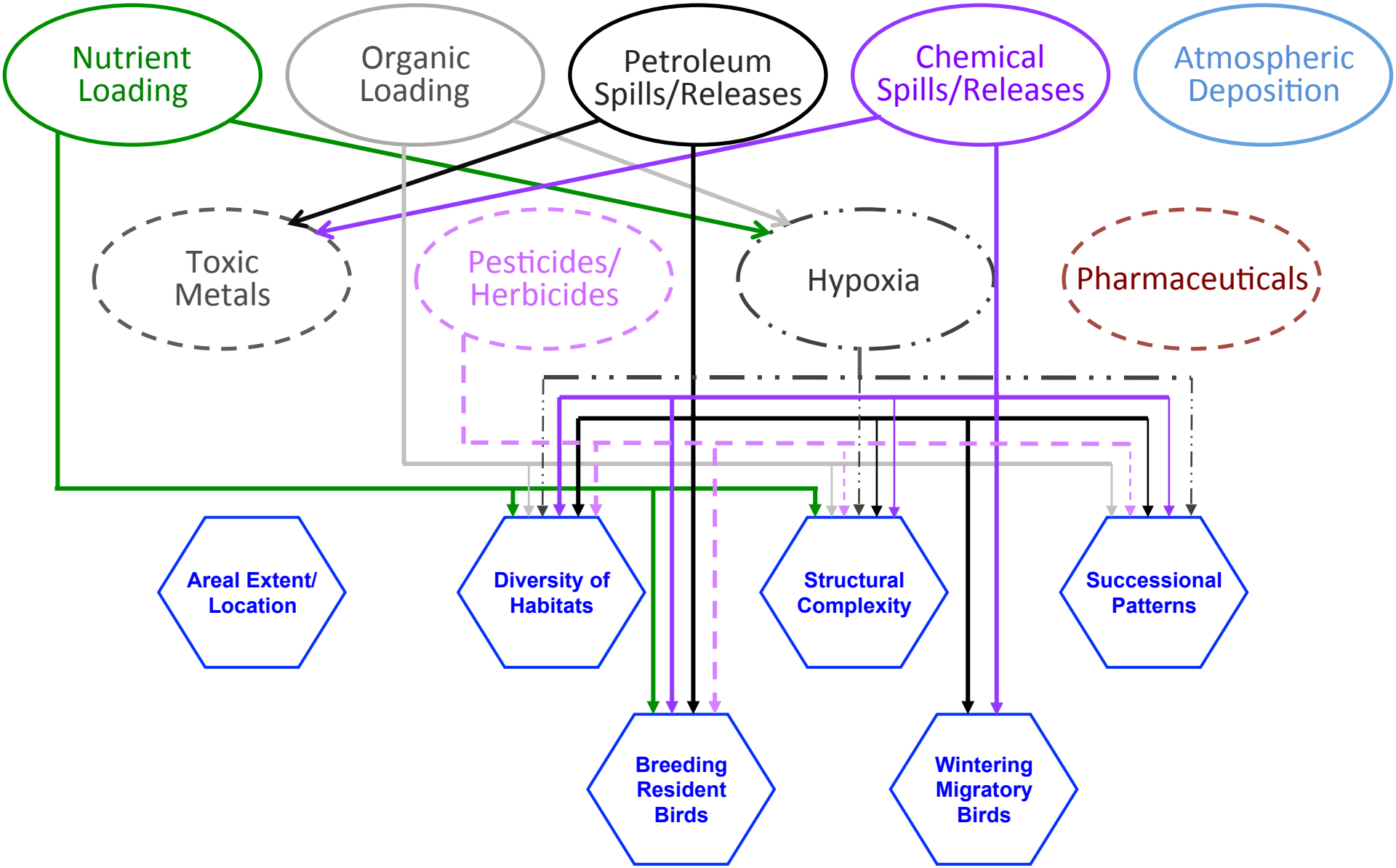
Rookery Islands



Rookery Islands

Chemical Stressors

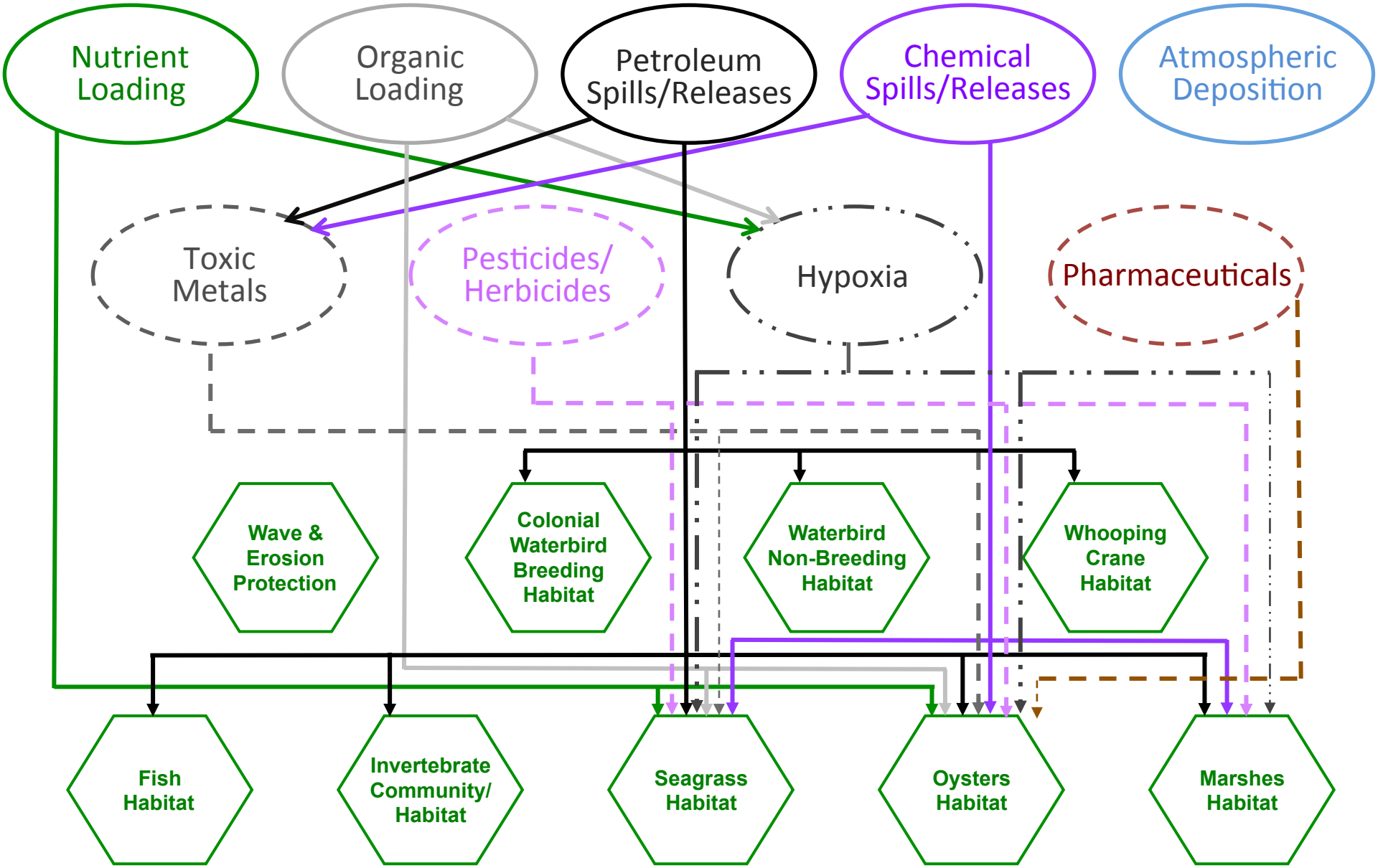
Structural Indicators



Rookery Islands

Chemical Stressors

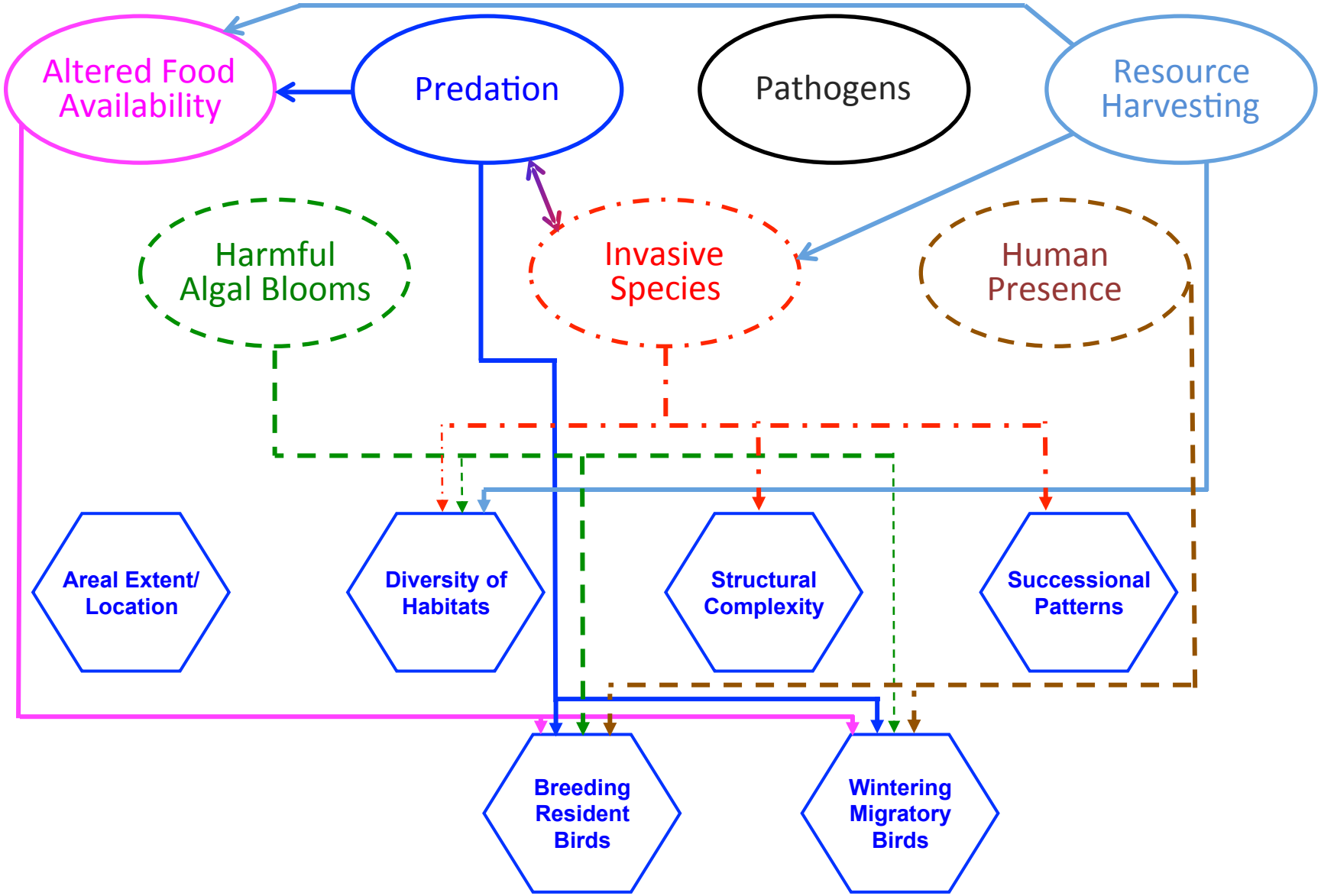
Functional Indicators



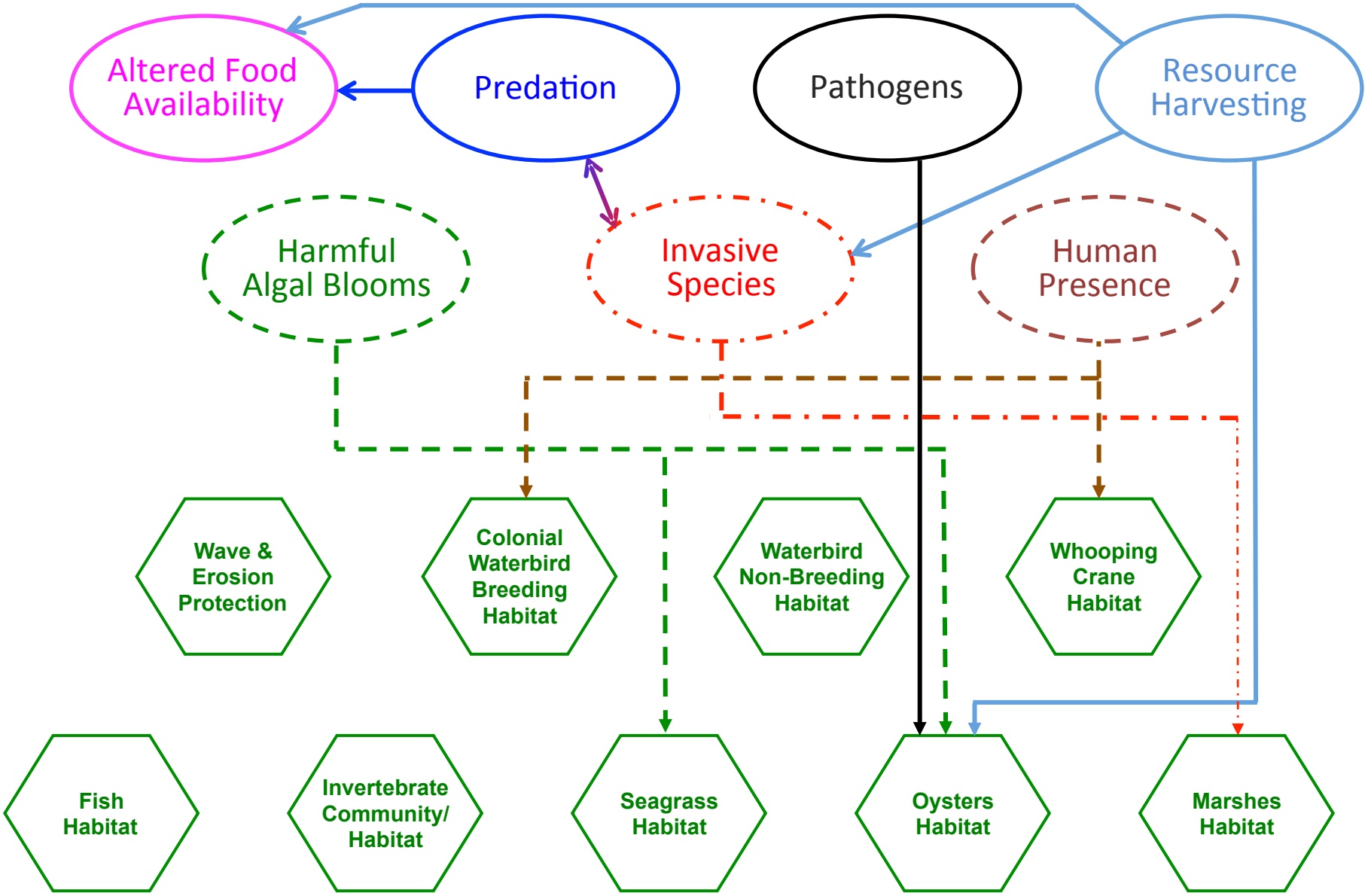
Rookery Islands

Biological Stressors

Structural Indicators



Rookery Islands

Biological Stressors

Functional Indicators