OIL SPILL SCIENCE

SEA GRANT PROGRAMS OF THE GULF OF MEXICO

FROM THE OCEAN TO HUMANS: INTEGRATED MODELING OF OIL SPILL IMPACTS

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Since the Deepwater Horizon oil spill, scientists have gained a wealth of new knowledge about the oil spill's impacts to the ocean environment and its ecosystems in addition to humans living near the shore. Understanding a wider range of possible effects has greatly improved scientists' ability to model impacts of future spills. Scientists examined existing models and stakeholder needs to enhance efforts towards integrating models of oil spill impacts to help inform plans and decisions for future oil spill response.

SYNTHESIS SERIES

The purpose of this publication is to exclusively reflect findings from synthesis activities supported by the Gulf of Mexico Research Initiative (GoMRI). GoMRI synthesis documents are the primary references for this publication. The summary may also include peer-reviewed publications and other reports cited in the GoMRI synthesis activities that help to provide foundation for the topic.

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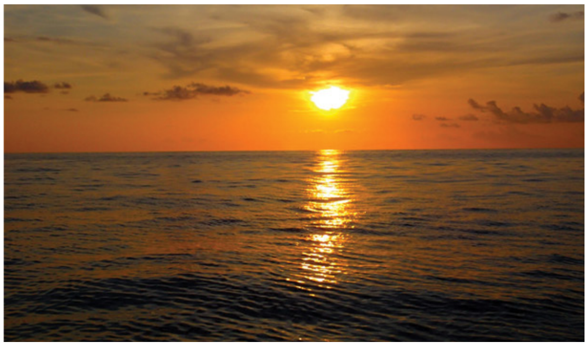
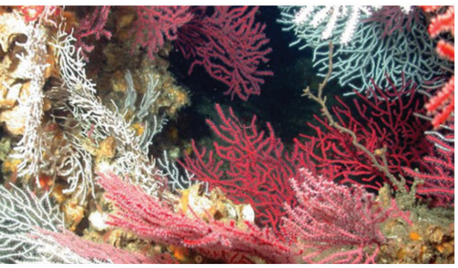
Gulf of Mexico Research Initiative

EVERYTHING IS CONNECTED

The Gulf of Mexico's ocean and coastal environments and the lifestyles and economies associated with them are deeply connected. The region is known for seafood, recreational fishing, beach destinations, and is a highway for marine vessels. It also produces much of the oil used and exported by the United States. The Gulf is a marine system that often has to cope with multiple stressors, such as oil spills, hurricanes, stormwater and agricultural runoff, and industrial pollution. Because of its ability to withstand adversity and recover from disasters or stress is greatly affected by the interactions of humans and nature, people can play a key role in helping find solutions to keep the Gulf healthy.[1] A 10-year period of research funded by the Gulf of Mexico Research Initiative (GoMRI) that followed the Deepwater Horizon (DWH) oil spill produced more knowledge about the Gulf than ever before, knowledge that can help us find those solutions.





Scientists continue to assess the impacts of oil spills on the ocean environment, biological ecosystems, socioeconomics, and human health. (Top left, Carol Highsmith; top right, Jaishree Beedasy; bottom left, NURC/UNCW ; bottom right, GiSR/Laura Spencer)

SYSTEM INTERACTIONS

The Gulf of Mexico is a complex system made up of physical, biological, geological, chemical, ecological, and human components. These components are interconnected—they all affect and are affected by the environment and each other. Because these connections are complex, some of their links are only now being understood. Much is still unknown. Computer models are tools that can help tease out these connections. Scientists need to better understand the interactions within the Gulf of Mexico before they can create models useful for oil spill planning and response. However, this is no simple task.

The ocean environment is dominated by physical processes, like circulation and mixing, that move materials, such as oil or pollutants, throughout the water. Those materials are then changed through biological and chemical processes to help make them available as a potential food or energy source to living organisms. Living organisms provide food, energy, transportation, and recreation to humans living nearby, supporting the lifestyles and economies of coastal communities. The social and economic condition of coastal communities ultimately influence the physical and mental health of residents. Both can affect how people use living resources, creating interconnections (also called feedback loops) among the ecosystems of the Gulf of Mexico as well as human health and **socioeconomic** systems. Scientific understanding of how these systems interact directly affects people's ability to effectively manage responses to future disasters.[1]

TACTICAL VERSUS STRATEGIC MODELING

Scientists develop some models for tactical reasons and others for more strategic reasons. As the names imply, tactical models focus on specific short-term actions while strategic models focus on the big picture with a long-term goal in mind. The difference between tactical and strategic models is most relevant in terms of the purpose of the model and user perspective. Tactical models run over short time scales (hours or days), when circulation and mixing dominate, making them great tools for response planners to predict the oil's path in the near future.

Strategic models offer a plan to merge many different types of information, which often comes from two or more research disciplines. They operate on times scales of weeks, years, or decades and are used for damage assessment and recovery planning. These tools are best suited for resource managers and scientists.[a]

INTEGRATED MODELING

Integrated modeling is based on information shared between two or more modeling systems that generates an understanding of how they are connected. In the past decade, scientists have learned about the interactions between ocean physics, chemistry, biology, and human socioeconomic systems by developing integrated models.[a,1] For example, scientists paired models that simulate the speed of water currents with deep-sea oil and gas spill models to track the movement of oil underwater after the DWH spill. They also coupled different models that included the movement of **larvae**, impacts of oil on marine organisms, and **population dynamics** to study the fate of oil. In some cases, scientists used models to link marine populations and humans through effects such as job loss and services like tourism and commercial fishing.[a,1]

As part of a final analysis of the GoMRI program, scientists combed through peer-reviewed publications, websites, technical reports, book chapters, and conference proceedings for advancements in integrated modeling. In sources published between 2010 and 2020, scientists found 330 DWH oil spill models funded by many sources, including GoMRI and the Natural Resource Damage Assessment (NRDA) program. They categorized the models into the following four domains:

- Ocean environment—includes models of ocean, atmosphere, biology, chemistry, temperature, and water movement, and processes that control the movement of oil.
- Biological ecosystems—includes models that connect organisms geographically and by their place on the food web.
- Socioeconomics—includes models of economic impacts across different regions as well as non-economic impacts on society.
- Human health—includes models of acute and persistent physical and mental health impacts, as well as the consequences of prolonged and growing stress.

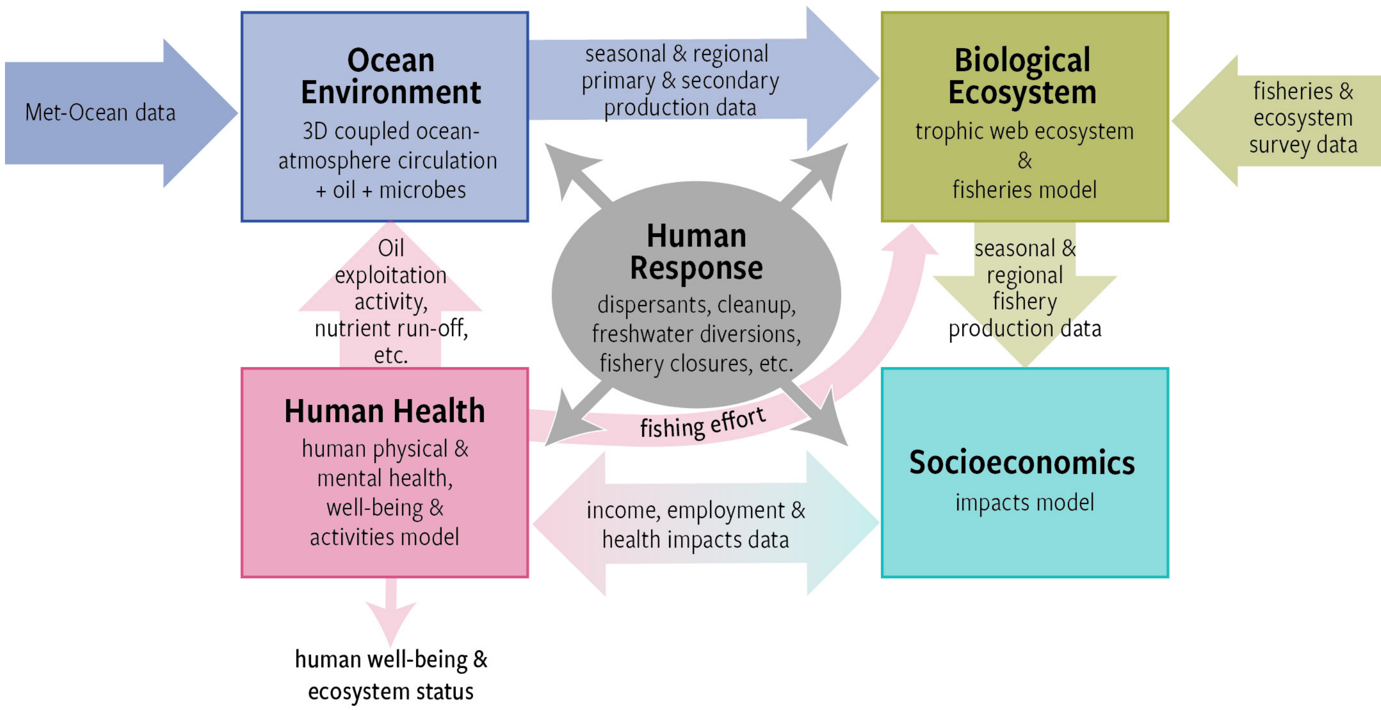


FIGURE 1. This schematic outlines the four domains that address questions relating to oil spill science to help develop a diagram to visualize connections between fields to be linked. The arrows show the connections between spill response and the four domains as well as how the four domains interact with one another.[b] (Reprinted from Solo-Gabriele et al., 2021)

These domains were used as an initial step to identify the areas of science needed to address the impacts and effects of oil spill response (**Figure 1**).[a,b]

Most of the DWH research (65%) used models to study water circulation, mixing, oil plume dynamics, and particle movement. Many included chemistry. Twenty-two percent of the studies used models coupling physics and biology, including ocean circulation models, to track fish eggs and larvae. Studies that used biological models (5%) included population and individual-based models for marine animals. The remaining studies (5%) used a combination of models for ocean physics, biochemistry, and human socioeconomic systems. Some (or most) of these studies paired oil fate models with an ecosystem model to include oil spreading, burial, evaporation, and breakdown by organisms. Results from these models estimate potential impacts on human beings, seafood markets, food security, toxin levels, environmental services, and some shore-based industries.[a]

Natural and human systems

Some studies address the overlap between natural and human systems. Although scientists often base socioeconomic impacts from disasters on fisheries and shore-based industries like ports and shipyards, recreational facilities should also be considered. However, models that include these factors are scarce, suggesting that connecting ocean-ecosystem models to human system models should be a high priority for future research. To help, scientists came up with strategies to improve future studies. The first strategy pairs existing ocean-ecosystem and economic models. The second creates new health and socioeconomic models that address important feedback loops between mental and physical health and socioeconomic activity. The third strategy incorporates socioeconomics and human health to assess potential impacts from decisions made during and after oil spill cleanup efforts and possible long-term effects.[a]

GoMRI-funded modeling efforts have focused on developing and exploring a useful structure for response decision making to minimize long-term impacts to society from oil spills.[2] This approach allows scientists to consider how an oil spill affects the entire Gulf of Mexico, nature and humans. Scientists explored interactions among these domains by gathering information from stakeholders, including input from experts about existing models, and combining information through a system dynamics approach.[b]

SYSTEM DYNAMICS

System dynamics is a modeling technique used to understand and discuss complex systems, issues, or procedures. It ignores the fine details to focus on how the system works overall. It specifically focuses on modeling series of cause and effect, also known as feedback loops. System dynamics works to place real-life scenarios into computer models to show how decision-making policies influence structure and performance.[3]

CAUSAL LOOP DIAGRAM

Building a system dynamics model often includes the development of a Causal Loop Diagram (CLD). A CLD helps visualize the connections among the systems or fields to be linked. Displayed as flow diagrams, they have arrows that show how different factors influence and interact with each other. CLDs provide a high-level overview of the system, making them ideal for looking at complex systems in a way that is easy to understand. GoMRI-funded scientists developed a CLD for impacts of marine oil spill response tactics to view, link, and identify data gaps in hopes that they will apply to oil spills in general (**Figure 2**).[b]

The CLD also helps assess damages to the environment, ecosystems, and human health systems and explores the financial consequences of those damages. The four domains—ocean environment, biological ecosystems, socioeconomics, and human health—provide a starting point to identify the fields of science needed to address oil spill impacts as well as effects of response actions. These four domains help to separate the modeling of oil spill impacts into distinct sets of related and overlapping disciplines (**Table 1**).[b]

The Gulf of Mexico system naturally separates into two groups, the domains for ocean environment (blue arrows) and biological ecosystems (green arrows) and the domains for socioeconomics (teal arrows) and

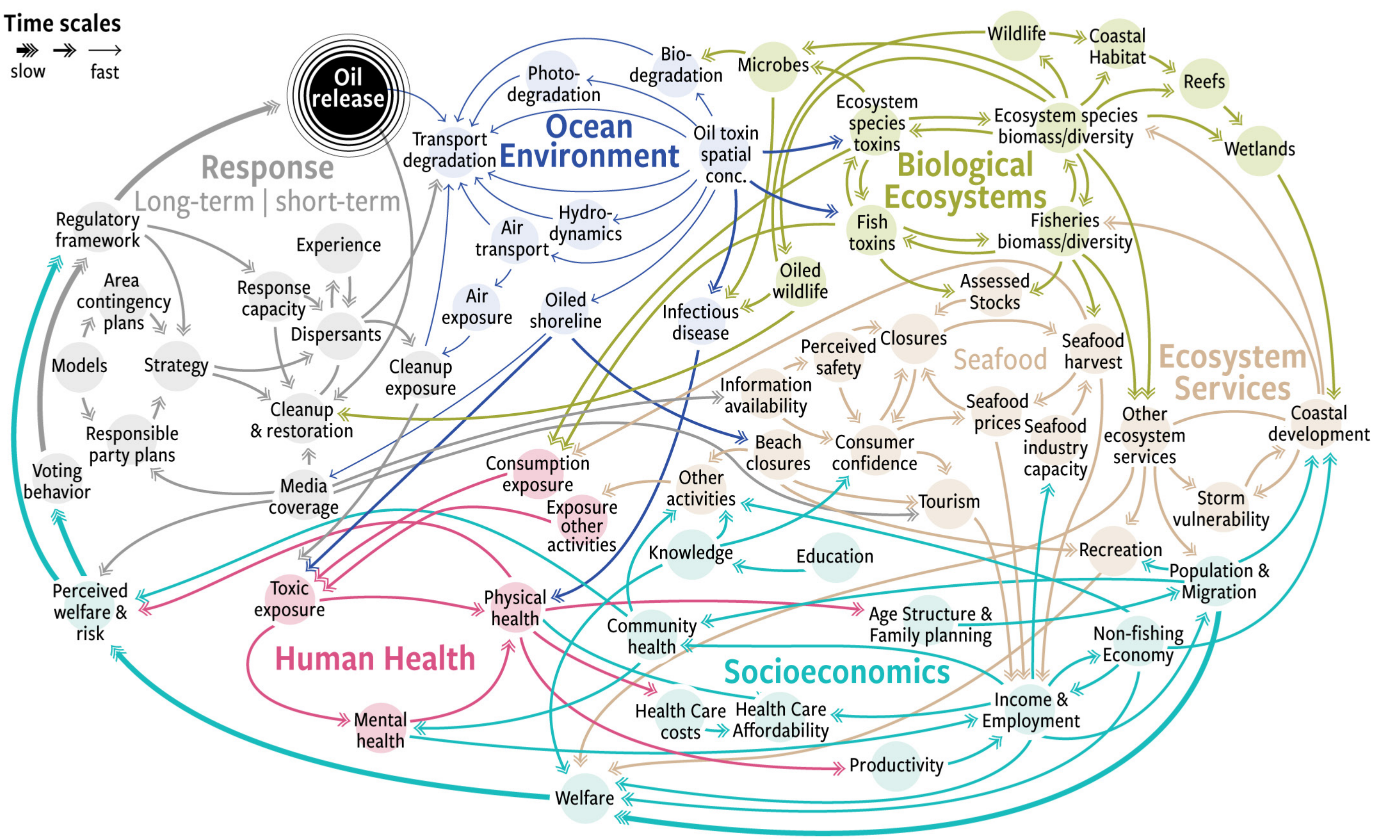


FIGURE 2. This diagram depicts the interconnections among the ocean environment (blue arrows), biological ecosystems (green arrows), socioeconomics (teal arrows), and human health (pink arrows) that can help inform the response community when they prepare and plan for oil spills. The number of arrowheads and line thickness represent time scales of impacts. Three arrowheads with thicker lines represent long/slow time scales, two arrowheads represent medium timescales, and one arrowhead with thin lines represent short/fast timescales.[b] (Reprinted from Solo-Gabriele et al., 2021)

TABLE 1. Each area of study in an integrated model requires a different set of expertise and knowledge.

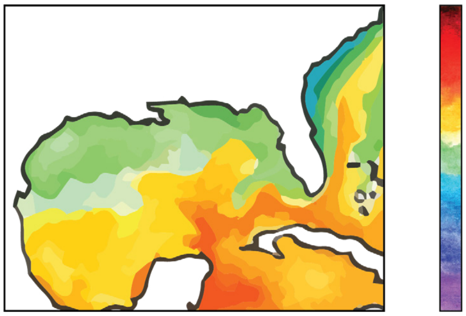
MODEL	EXPERTISE NEEDED
Ocean Environment	Oceanography, climate science, pollution movement, physics, geology chemistry, and biology
Biological Ecosystems	Ecology, microbiology, marine sciences, zoology, botany, fisheries, and veterinary sciences
Socioeconomics	Economics, anthropology, sociology, psychology, and communication studies
Human Health	Environmental health science, public health, medicine, physiology, as well as the study of genes and the use of statistics to map risk factors and health trends

human health (pink arrows) (**Figure 2**). The ocean environment and ecosystem models could be used to provide input to the human health and socioeconomic systems and vice versa. The CLD also shows how human systems link to government regulations related to spill response efforts. Because connections between physics and biology are fairly well understood, advancements in modeling the ocean environment and biological ecosystems have greatly outpaced advancements for the socioeconomic and human health domains. The latter are still in the early stages of development.[b]

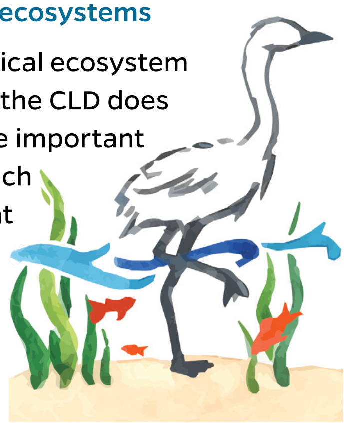
Causal Loop Diagram observations

Ocean environment

The CLD illustrates a number of connections between the ocean environment and oil spill response (gray arrows) (**Figure 2**). Short-term links would include immediate preparedness and cleanup efforts in oil spill response. Long-term links would show how the ocean environment connects with the larger socio-ecological system. Most people understand that forecasts from short-term operational models inform immediate response actions such as protecting sensitive resources. However, operational model forecasts and the actions based upon them can also influence socioeconomics and human health domains. These outcomes, in turn, influence regulations through public perceptions of impacts, which can further affect operational responses. The CLD also illustrates that media coverage can influence human perceptions, and these perceptions can impact planning, response capacity, and cleanup efforts. All of these interactions can affect the amount of oil that remains in the ocean.[b]



Biological ecosystems



The biological ecosystem portion of the CLD does not include important aspects such as different positions on the food web or the many connections between species. By keeping the illustrations uncomplicated, the focus is on the links between oil and living organisms. It also shows connections between biological ecosystems and socioeconomics, for example, through seafood safety or human contact with oil on the beach. The CLD also shows that oil contamination can be ongoing due to oil-based toxins entering the water when freed from **sediments** containing sunken oil. Scientists explained the importance of seeing these connections as a means to improve knowledge and inform actions in several areas:

- Those who are interested can have a better understanding about the flow of effects triggered after a spill.
- The response community can make better estimates of short- and long-term effects that inform injury assessments and restoration planning.
- Resource managers can better identify effects on non-market **ecosystem services**, such as protection from storm surges and access to recreation.

Although the ocean environment and biological ecosystems have many significant feedback loops within their individual domains, processes between the domains influence them both. For example, ocean currents impact how oil circulates, causing the oil to spread and affect marine life. Biological ecosystems that spread oil even further within the ecosystem can also influence oil's path in the ocean environment. An example of this would be when microbes break down oil in the water, changing how the oil floats and moves.[b]

Socioeconomics

Oil spills and response can affect various components within the socioeconomic domain, including ecosystem services (tan arrows) (**Figure 2**), seafood harvest, seafood prices, seafood industry capacity, and people's income and employment. When oil hits a shoreline, it may cause beach closures, which impact tourism, employment, and income. Beach oiling and subsequent closures are linked to human physical and mental health, which can directly impact people's productivity. Other spill response actions such as the closure of fishing grounds could lead to less seafood caught, loss of jobs in the charter fishing industry, and the closure of beaches, affecting tourism. The information that the public receives related to seafood safety can lower consumer confidence, market demands, and seafood prices. All of these impacts are tied to human welfare, affecting the productivity and the health of individuals and the community as a whole. The diagrams show the links between socioeconomics and human health can be very complex after an oil spill.[b]

Human health

Information from operational models that simulate short-term or serious effects from oil spills can influence the forecasts for longer-term impacts on individual and community health. Typically, direct exposure to oil spill toxins occurs during cleanup efforts, eating contaminated seafood, and using oiled beaches.[b] However, impacts to human health are not limited to physical illnesses. Physical and mental health effects have been reported to be closely related to disasters due to the stress they put on the environment and communities.[4] Activities that can impact physical health may lead to losses in productivity, income, and employment. When income and employment are affected, then healthcare affordability can become an issue. Employment status and income are strongly linked with mental health. When the economy is not doing well, stress increases, negatively impacting overall human health.[b,4]

The fear of being exposed to toxins or being unable to use community places affected by oil spill toxins can cause mental health strain. The CLD illustrates many linkages between people's physical and mental health and socioeconomic factors.[b] The links between socioeconomics and human health are so strong that these two domains should not be separated. Six factors linked to community **resilience**[5] can potentially be impacted by an oil spill:

- Human and cultural
- Social
- Political
- Natural
- Infrastructural
- Financial

To learn more about the impacts of oil spills on socioeconomics and human health, read the Sea Grant publication ***Understanding the human health and socioeconomic impacts from the Deepwater Horizon oil spill***.

Progress has been made in integrated modeling for ocean environment, ecosystems, and socioeconomic domains, although there is much more to do, especially in integrating human health. Ideally, building more intricate models within the socioeconomic and human health domains would provide scientists with more knowledge about the complexities of these domains.[b] Scientists need many types of social data to adequately support modeling needs.[a]

CONCLUSION

The Gulf of Mexico sits in a region subject to a variety of natural and human-caused threats. Gulf-area disasters impact not only its many marine ecosystems but also the people who depend on them for their livelihoods and culture. GoMRI-funded research that included integrated modeling has greatly expanded knowledge about the interconnections among ecosystems. Additionally, integrated modeling can reveal where user interests align and where trade-offs between competing interests exist.[a] This research has also raised awareness of the risks associated with oil spills, the vulnerabilities of the natural and human systems connected to the Gulf, and the costs and benefits of oil exploration.[a]

Additionally, integrated modeling can show where stakeholder interests align and where trade-offs between competing interests exist. During and after an oil spill like DWH, response efforts and energies need to be directed toward public health and safety, environmental cleanup, and eventually quantifying the extent of the damage.[a] The GoMRI-funded CLD provides the concept for integrated models whose outputs and forecasts can help answer the many questions related to oil spills and subsequent damage assessments. These advancements provide big picture views of likely short-term oil spill impacts as well as the potential for a wide range of long-term indirect effects.[b]

FUTURE WORK

Considerable work is needed to address research gaps and create comprehensive integrative models to help decision makers respond to and improve recovery from oil spills. Future versions of CLDs would benefit from inclusion of the most disadvantaged members of affected communities as well as cultural and artistic elements. Socioeconomic modeling efforts could benefit from focused efforts to understand how societies change after oil spills, to develop best practices related to data collection, and to create regional economic frameworks that include a broad range of community health and socioeconomic impacts.[b] Such efforts will help scientists better understand the interactions between socioeconomic conditions and human health to be ready for future oil spills.[1]

Shrimping is an integral part of the seafood industry. Oil spills impact the industry by causing contamination, which can lead to closing of fishing zones, resulting in a reduction in work and employment for coastal residents. (UF/IFAS/Tyler Jones)

GLOSSARY

Ecosystem service — The direct and indirect contributions of the environment and wildlife to human wellbeing (such as food, clean water and air, flood control, and employment).

Larvae — The immature form of an animal that undergoes physical changes during its life.

Population dynamics — The study of how the size and age of a species changes over time.

Resilience — The ability to withstand adversity and recover quickly from disasters or stress such as oil spills and hurricanes.

Sediment — Naturally occurring material that is broken down by weathering and/or erosion and transported by wind, water, or ice. It can consist of rocks, boulders, sand, and/or the remains of plants and animals.

Socioeconomics — Science that studies how the economy affects social processes and vice versa. This includes the social (or cultural) and economic components of individuals, families, or communities.

REFERENCES

Publications resulting from the GoMRI-supported synthesis activities serve as the primary references for this work. Additional supporting literature, either cited in GoMRI synthesis papers or necessary for foundational information about the subject, is also included.

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The GoMRI Research Board established Synthesis & Legacy committees to review 10 years of oil spill science findings. Look for Sea Grant extension publications on these GoMRI synthesis topics:

- Observing and modeling oil plumes and circulation
- Combined ecosystem modeling
- Combined oil spill modeling
- How oil weathers and degrades
- Ecological/ecosystem oil spill impacts
- Human health and socioeconomic oil spill impacts
- Microbiology, genetics, and oil spills
- Dispersant-related impacts from oil spill response

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