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Evidence Library for Oyster Reef Restoration in North Carolina

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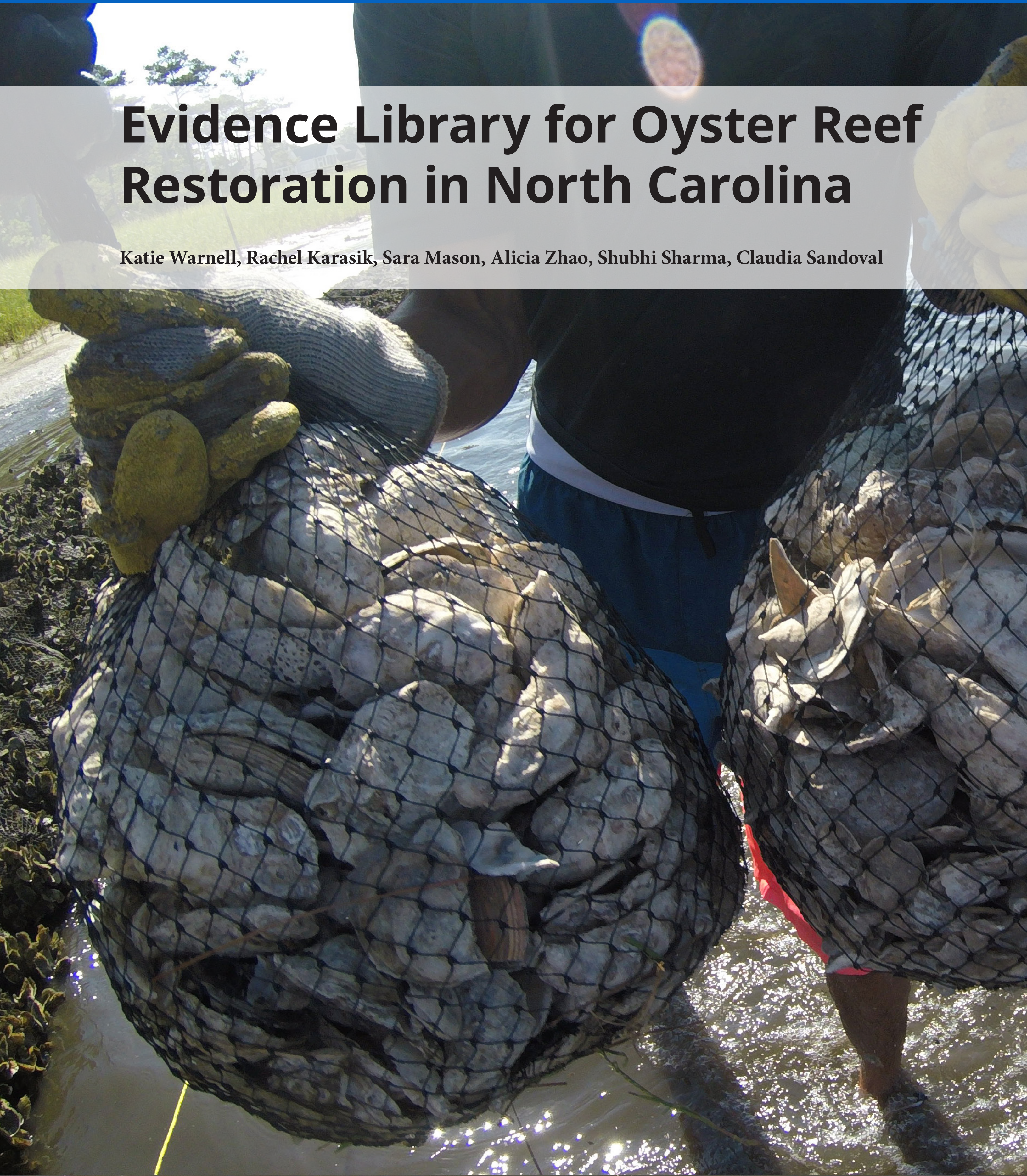

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http://bit.ly/NI-ES

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INTRODUCTION

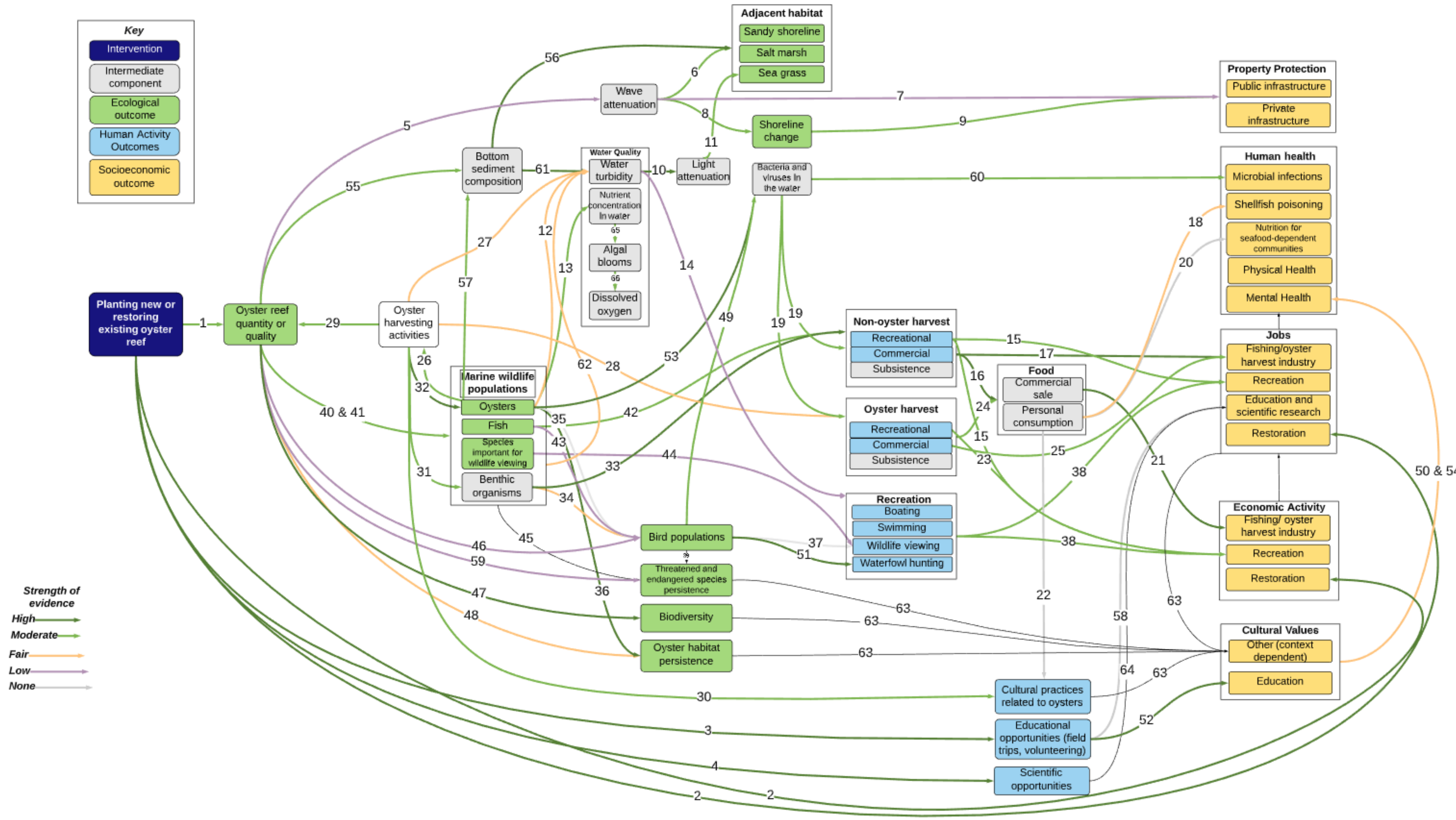
This evidence library contains summaries of the evidence for the links in the oyster reef restoration ecosystem service conceptual model (ECSM) (Figure 1, next page). It is largely adapted from the evidence library developed for an oyster reef restoration ECSM for the Gulf of Mexico Ecosystem Service Logic Models & Socio-Economic Indicators (GEMS) project. As a result, many links include resources and evidence from the Gulf region. For most links, the relationship demonstrated by the evidence is easily transferable to oyster reef sites in North Carolina. For other links, the relationship described is affected by conditions specific to the Gulf of Mexico, such as cultural values or regional-level regulation and management. In this situation, we advise the readers to do additional research to see if the relationship described applies in a North Carolina context.

The summaries of each link include an assessment of the strength of evidence for each link. Each link in the model has an identification number. To find the evidence library entry for a particular link, use the search function (keyboard shortcut Control + F) and search for "Link #" (e.g., "Link 3").

This document was created as part of a collaboration with NERRS Science Collaborative work entitled "Exploring Applications of Ecosystem Service Conceptual Models for Coastal Habitats. For more information on this project, please visit the project website, https://nerrssciencecollaborative.org/project/Olander18.

Cover Photo: Natalie Rodriguez

Figure 1. Ecosystem service conceptual model for oyster reef restoration, links color-coded by strength of evidence rating. Numbers correspond to sections below.



Link 1: Planting new or restoring existing oyster reef → Oyster reef quantity or quality

Description of relationship

Most oyster reef restoration projects directly change the quantity or quality of oyster reefs by adding substrate material. Projects aimed at protecting and enhancing existing reefs may add material or protect reefs so that natural processes that cause reef expansion and other attribute changes can occur.

Summary of evidence

We discuss four major oyster restoration project categories in terms of their effect on oyster reef quantity or quality in this summary.

Placement of oyster substrate to create structurally simple reefs: These projects place loose cultch material (usually oyster shells, relic shells, crushed limestone, or crushed concrete) on the estuary floor to create a flat or 'two-dimensional' structure on which oysters can grow. Monitoring reports from oyster restoration sites in Louisiana and Florida confirm that cultch placement projects increase the extent of oyster substrate (Louisiana Natural Resource Trustees 2016, NRDA 2017). However, these reefs are designed to recruit a single age class of oysters; when these oysters are harvested, the majority of oysters on the reef are removed and the reef structure is substantially damaged (for more detail on the effects of harvesting on oyster reef quantity and quality, see link 29). Field research and modeling show that low reefs expose oysters to poor environmental conditions, resulting in a less healthy oyster community, and are susceptible to burial by sediment, decreasing their long-term viability (Jordan-Cooley et al. 2011, Schulte et al. 2009).

Placement of oyster substrate to create structurally complex reefs: These projects place large, durable materials (e.g. oyster balls, precast concrete structure, large pieces of limestone) to create a three-dimensional structure to which oysters can attach. The resulting oyster reef has a significant vertical component, resulting in a healthier oyster community due to exposure to better environmental conditions, and is less likely to be buried by sediment (Jordan-Cooley et al. 2011, Schulte et al. 2009). These projects can be placed in subtidal or intertidal areas and can be open or closed to harvest (see link 29 for discussion of harvesting effects on oyster reef quantity and quality). Metrics related to reef height and structural complexity are not often collected or made available, making it difficult to assess the long-term influence of projects on reef quantity and quality (La Peyre et al. 2014, appendix A). A field survey of subtidal oyster restoration projects in the Gulf of Mexico found that rock reefs had greater volumes (liters/m^2, indicating higher vertical relief or more complexity) than shell or historic reefs (La Peyre et al., 2014). Intertidal projects, often referred to as 'living shoreline' projects, often use vertical relief of the reef as a key monitoring metric (e.g. NOAA Restoration Center 2016).

Protection or enhancement of existing reefs: Protection of existing reefs (preventing intensive oyster harvest) does not directly change reef extent or structure. Depending on system dynamics (including oyster growth rates, disease, and other stressors), protected reefs may accumulate material and grow in extent, height, and complexity. An analysis of oyster stock assessment data in the Delaware Bay estimated the minimum doubling time of oyster shell material on oyster beds at 10-25 years, assuming zero shell loss (Powell et al. 2006). This indicates that oyster reefs can grow naturally when shell loss (caused either by environmental conditions or anthropogenic actions) is low, although the authors note that there are few documented examples of reef vertical or lateral expansion. A model of shell accumulation in Mid-Atlantic estuaries showed that reef accretion only occurs when oyster populations are high and harvest rates are low (Powell et al. 2012). When protection of existing reefs is combined with habitat enhancement by placing substrate material (e.g. Walton Lab, n.d.), the effect on reef extent and structure depends on the material used, as described above for the creation of structurally simple and structurally complex reefs.

Oyster aquaculture projects: The oyster aquaculture methods used in the Gulf of Mexico are 'off-bottom' – oysters are grown in baskets or cages suspended in the water column (Walton n.d.). Therefore, oyster aquaculture does not create a natural reef structure, but it does create a new population of oysters in the estuary system that perform certain ecological functions similar to natural oyster populations (see link 40 and links resulting from oyster population).

Strength of evidence

Placement of oyster substrate to create structurally simple reefs or structurally complex reefs: **Moderate.** While the short-term effect of a project on the extent and structure of oyster reefs is evident from project plans, longer-term persistence of the created reefs is uncertain, and there is limited monitoring data available for established reef projects.

Protection or enhancement of existing reefs: **Low.** There is little evidence to support the idea that reef protection alone will result in reef accretion or lateral expansion, and environmental factors play a strong role in determining shell accretion rates (Powell et al. 2012). When protection is combined with reef enhancement by substrate placement, the short-term effect on reef size and structure is straightforward, but persistence of this effect is uncertain.

Oyster aquaculture: **High.** Oyster aquaculture creates and maintains oyster populations in baskets or cages with known dimensions and locations.

Other factors

Environmental factors (salinity, dissolved oxygen, sedimentation rates) that influence the health and growth of oyster populations affect the timeframe on which the oyster reefs created by restoration projects persist.

Oyster disease: Modeling of oyster shell budgets in the Mid-Atlantic suggests that oyster reef accretion is not possible in areas where dermo and other oyster diseases are prevalent (Powell et al. 2012).

Predictability

The immediate effect of restoration projects that involve placing substrate on oyster reef quantity and quality is described in project planning documents (extent, shape, and relief of substrate). Longer term effects of these projects, as well as protection of existing reefs, is dependent on a variety of factors and difficult to predict.

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Link 2: Planting new or restoring existing oyster reef → Economic activity (restoration)

Description of relationship

Oyster restoration directly supports jobs related to project planning and construction.

Summary of evidence

Restoration projects that involve placing oyster substrate or constructing oyster aquaculture facilities involve many types of jobs, from project planning and materials preparation to construction and piloting vessels. An extensive list of more than 40 jobs essential to oyster reef restoration, drawn from the Bureau of Labor Statistics list of job titles, was developed through conversations with contractors who oversee oyster restoration projects (Stokes et al. 2012).

Not every oyster restoration project will require all of these jobs, and a single oyster restoration project may not create enough work that new hiring is required. Many of the businesses involved in oyster reef restoration are small and use short-term workers or subcontractors to meet project requirements rather than hiring new permanent staff, but this may change as the magnitude of oyster reef restoration increases (Stokes et al. 2012). Some jobs needed for restoration projects require a certification or license, which can make it difficult to find qualified employees; this highlights a need for workforce training (Oxfam America and The Nature Conservancy, 2012).

A 2015 review of the economic impact of ecological restoration examined 14 case studies of restoration projects and found that for every $1 million invested in restoration, between 6 and 40 jobs were created. Two of the case studies were for oyster reef restoration projects; they created 16.6 and 20.5 jobs per $1 million invested (BenDor et al. 2015a). One of these case studies, an economic assessment of two oyster restoration projects in Mobile Bay, Alabama, estimated that 88 part- and full-time jobs would be supported by reef construction activities during the construction period (approximately 1 year): 9 in project design and management, 68 in construction, 8 in monitoring, and 2 in community outreach, workforce development, and marketing (Kroeger 2012). A study of the economic impact of American Recovery and Reinvestment Act projects administered by NOAA found that habitat restoration projects created 17 jobs for every $1 million invested (Edwards et al. 2012). Five oyster restoration projects were included in the analysis and created an average of 16.6 jobs for every $1 million invested.

A national assessment of the economic impact of restoration activities in the United States, carried out by surveying businesses engaged in restoration work, estimated that restoration activity directly employs about 126,000 people (BenDor et al. 2015b). This study did not report employment by businesses engaged in oyster reef restoration separately.

Strength of evidence

High. There is clear evidence that oyster reef restoration projects support a variety of jobs during the planning and construction phases. Economic assessments, including several assessments of oyster restoration projects in the Gulf of Mexico, have estimated the number of jobs directly supported by individual projects.

Other factors

The specific plans for individual projects determine the types of jobs that are needed and the time frame over which jobs are supported.

Predictability

General predictions for the number of jobs supported by a particular project could be made based on the total project cost, using the numbers provided above for job creation from restoration projects; however, there are few estimates available for oyster restoration specifically, so any such predictions would be highly uncertain.

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Link 3: Planting new or restoring existing oyster reef → Educational Opportunities (field trips, volunteering)

Description of relationship

Oyster reef restoration projects engage many volunteers and create new opportunities for educational activities focused on oyster reefs.

Summary of evidence

Oyster restoration projects provide excellent volunteer opportunities because the work is hands-on and can be divided among many people. Since oyster restoration is labor-intensive, volunteers are essential for many projects, and volunteers often learn about oysters and coastal ecosystems while they work (DeAngelis et al. 2018). Since 1995, more than 68,000 people have volunteered at restoration projects through NOAA's Community-based Restoration Program, and many organizations involved in oyster restoration in the Gulf of Mexico, including The Nature Conservancy, Galveston Bay Foundation, Florida State University Coastal and Marine Laboratory, Texas A&M University, and Florida Gulf Coast University, engage volunteers in building and monitoring oyster reefs. Specific tasks often done by volunteers include bagging oysters, creating oyster mats, transporting reef material, and placing reef material (DeAngelis et al. 2018; Florida Gulf Coast University, n.d.; Florida State University, n.d.; Galveston Bay Foundation, 2019; Texas A&M University, 2015). One oyster restoration project led by The Nature Conservancy in Charlotte Harbor, Florida, had volunteers help construct the reefs and set up a volunteer monitoring program for continued community engagement after construction was completed. This facilitates project monitoring, which is often limited by funding, and gives volunteers an opportunity to work alongside marine scientists. Students can be involved in oyster reef restoration through volunteer work, field trips, or even in-class activities, such as attaching shells to oyster mats, that allow classes to learn about oysters in a hands-on way when a field trip is not possible (DeAngelis et al. 2018).

Strength of evidence

High. Oyster reef restoration projects commonly use volunteers. Community education about oyster reefs occurs through interactions with volunteers and projects with local schools.

Other factors

The type of oyster reef restoration project will determine the specific tasks with which volunteers can assist. The size and composition of the local community may influence how many volunteers and students engage with the project.

Predictability

No way to predict the magnitude of volunteer or educational engagement with a particular oyster restoration project was found.

Sources

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Link 4: Planting new or restoring existing oyster reef → Scientific opportunities

Description of relationship

Planting new or restoring existing oyster reef facilitates scientific research and promotes productivity in the field.

Summary of evidence

It can be reasonably inferred that planting new or restoring existing oyster reef requires careful consideration, organization, and planning in order to be effective. This logically requires extensive background on the topic and therefore facilitates scientific activities.

In an article that looks at the extent, methods, and outcomes of oyster reef restoration in the Gulf of Mexico, researchers found that maximizing restoration benefits and increasing efficiency of shellfish restoration activities would greatly benefit from understanding and measurement of system responses to management activities (La Peyre et al., 2014).

According to the Smithsonian Environmental Research Center, research on methods, application of active interventions and evaluations are important tools used to restore ecosystems for their inherent value and the ecosystem services they provide humans. The ability to apply a broad range of scientific disciplines is needed to understand the outcomes of restoration practices that can include reforestation of cleared land, dam removal, oyster restoration, and many others.

It has also been shown in other links of the Gulf of Mexico ESLM evidence library that oyster reef restoration is facilitating scientific activities. For example, the links connecting planting new or restoring existing oyster reef to oyster reef quantity or quality, educational activities, and restoration jobs all demonstrate this relationship.

Strength of evidence

High. Many academic studies/articles have addressed the benefits, economics, and outcomes of oyster reef restoration efforts, among other things. This, in and of itself, demonstrates that planting new or restoring existing oyster reef promotes scientific activities.

Other factors

The amount of available funding for scientific activities can have an effect on the frequency and extent of the activity. The less funding a topic receives, the less research into that topic will be conducted.

Predictability

While restoration outcomes are difficult to predict, experimental approaches to restoration and post-restoration monitoring can improve understanding of outcomes, and identify best practices. Rigorous evaluation of restoration practices is critical to ensuring that the limited resources available for restoration are used wisely (Smithsonian Environmental Research Center).

Sources

La Peyre, M., Furlong, J., Brown, L. A., Piazza, B. P., & Brown, K. (2014). Oyster reef restoration in the northern Gulf of Mexico: extent, methods and outcomes. Ocean & Coastal Management, 89, 20-28.

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Link 5: Oyster reef quantity or quality → Wave attenuation

Description of relationship

Oyster reefs may act as physical barriers to incoming waves, resulting in smaller waves on the landward side of reefs, but there is limited evidence that this occurs around restored oyster reefs in the Gulf of Mexico.

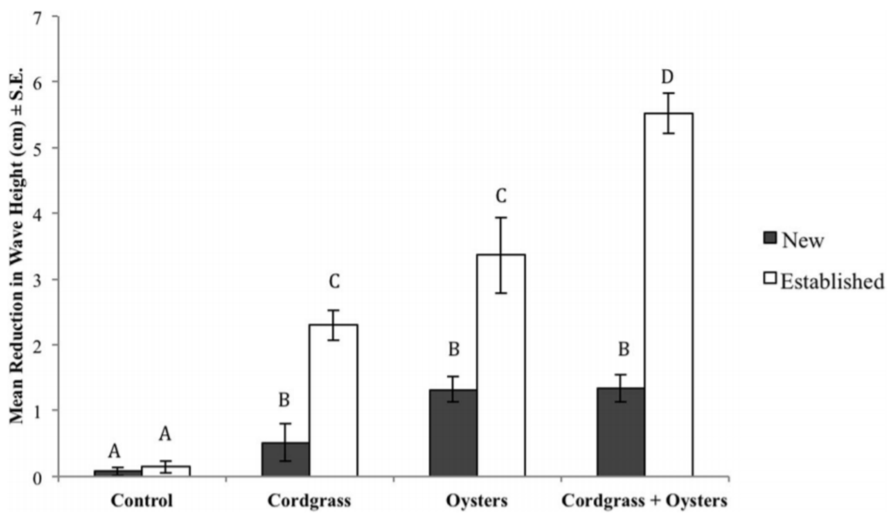
Summary of evidence

As rigid structures in the water column, oyster reefs may be able to attenuate waves (Bouma et al. 2013). In some cases, oyster reefs are assumed to function as well as engineered breakwaters

(Grabowski et al. 2012). However, there is little evidence to support oyster reefs' influence on wave height or energy, especially from field studies. Several related papers note the lack of publications on wave attenuation by oyster reefs and suggest that more research is needed (Bouma et al. 2013, Myszewski & Alber 2016).

Two laboratory studies using wave tanks showed wave height reductions from restored oyster reef structures, but both only assessed attenuation for relatively small waves. The first study investigated the ability of eastern oysters and cordgrass to attenuate waves from recreational boat wakes (wave height was set at 0.127 meters); both oysters (on oyster mats) and cordgrass reduced wave height and energy, especially after they had been established for a year (Manis et al. 2015). The observed increase in wave attenuation by established oysters was attributed to the larger vertical height of the oysters after one year. The combination of established oysters and cordgrass together was the most effective treatment, reducing wave energy by 67.3%.

Reduction in wave height from new and established oysters and cordgrass (Manis et al. 2015).



The second study focused on wave attenuation by oyster bag breakwaters of various heights and found that longer and higher reef structures were more effective in reducing wave height. This study used very small waves (0.1 meters). (Allen & Webb 2011).

There are few field studies of wave attenuation by restored oyster reefs. Subtidal reefs in Mobile Bay, Alabama constructed from loose shell contained in a mesh cover were designed as breakwaters, but did not effectively attenuate waves (Scyphers et al. 2011). The mesh was not sufficient to hold the reef together until oyster recruitment stabilized it, so the reef flattened over the study period. The researchers recommended the use of a more rigid structure for future oyster restoration projects to maintain the structural integrity of the reef. Another experimental field study of shell cultch oyster reefs, using intertidal reefs in Sister Lake, Louisiana, did not directly measure wave height or energy around reefs, but calculated an index of wave exposure, which showed reduced exposure to waves behind oyster reefs compared to mud bottom (La Peyre et al. 2014).

Several models of wave attenuation by breakwaters, including oyster reefs, are available. A study of an oyster breakwater constructed from Reef Balls in the Grand Cayman islands used several of these models to calculate expected wave transmission across the reef, based on reef attributes (height, cross-sectional area, and freeboard) and hydraulic characteristics (water depth, wavelength, and wave height) (Arnouil 2008). Results varied by the model used, but generally showed that wave transmission decreased with wave height up to the normal expected wave height (during non-storm conditions). When wave height increased above this maximum under storm surge conditions, wave transmission increased with wave height. This study did not directly measure wave attenuation by the restored reef, so the models could not be validated with field data.

Strength of evidence

Low. While models suggest that oyster reefs may be able to attenuate waves, evidence to support this idea is currently lacking. Laboratory studies have shown changes in wave height across oyster reefs, but these are at small spatial scales and for very small waves. The two field studies we found investigated the effects of cultch shell reefs; one did not directly measure wave height, and the other's experimental reefs were not structurally sound.

Other factors

Reef height relative to the water depth is frequently identified as a critical factor in the reef's ability to attenuate waves. Larger reef height to water depth ratios are associated with greater wave attenuation. For this reason, intertidal reefs are generally expected to be more effective at attenuating waves than subtidal reefs (Bouma et al. 2013).

Longer oyster reefs are generally more effective at wave attenuation than shorter reefs (Allen & Webb 2011).

It is difficult to restore oyster reefs in areas of high wave energy, where wave attenuation is most needed, so the overall potential for oyster reefs to act as breakwaters is limited (Borsje et al. 2011).

The presence of other habitat types behind an oyster reef may enhance wave attenuation compared to the reef alone (Manis et al. 2015).

Predictability

Several empirical models of wave attenuation from breakwaters are available (see Arnouil for a comparison), but they have not been validated for the multiple techniques for oyster reef restoration in use in the Gulf of Mexico.

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Link 5-8: Oyster Reef Quantity or Quality→ Shoreline Erosion or Accretion[1]

Description of relationship

The presence of oyster reefs contributes to accretion along the oyster reef. This may be affected by characteristics of oyster reefs such as height. External factors also influence this relationship.

Summary of evidence

The hard substrate of oyster reefs slows down wave and wind energy (Oyster-restoration.org. n.d.) which allows oysters on those reefs to both ingest and egest sediment. Some experimental studies have found that this process contributes to accretion, while preventing erosion (de Paiva et al., 2018), while others have found that erosion is not prevented by oyster reefs.

One such study in Mobile Bay Alabama in the Gulf of Mexico, developed two breakwater reef sites (each one comprised of three 5m X 25 m rectangular trapezoids) made of oyster shells to determine their efficacy of preventing erosion and protecting eroding shorelines. In the experiment, constructed pairs of subtidal breakwater reefs were constructed along stretches of eroding shoreline. One site was able to mitigate shoreline retreat by over 40%, while the other one was unable to slow erosion relative to the control site. Overall, both sites had increased rates of erosion, indicating that oyster reefs alone cannot prevent shoreline erosion, though they may have some local impacts (Scyphers et al., 2011).

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[1] This entry addresses the combined effects of link 5 (oyster reef quantity or quality → wave attenuation) and link 8 (wave attenuation → shoreline change). It includes evidence for the effect of oyster reef restoration on shoreline change that does not measure the reason for that change (e.g. via an effect on wave attenuation).

In Louisiana, experimental eastern oyster reefs were created in low- and high-energy shorelines on 12 sites (25 meter X 1 m X 0.7 m). The study found that the reefs were able to reduce shoreline retreat in low-energy shorelines, but did not have significant effects on high-energy shorelines, indicating that there are external factors that may limit the ability of reefs to stabilize sediment in their habitat (Piazza et al, 2005).

In one experiment in North Carolina, oyster cultch was added to the intertidal fringe of three marshes (1.5 m wide by 0.25 m deep), and non-cultched sites at marshes were selected as the control. The sites were influenced by varying factors; some were facing north, while others south, and some had disturbances due to storms, while others were exposed to boat wakes and dredge effluent pipes. Despite these external factors, the presence of oyster cultch, on average, resulted in accretion while non-cultched sites experiences a loss of sediment (erosion) on average. (Meyer et al., 1997).

In Bangladesh, an oyster farming pilot was tested to determine the capacity of reefs to combat coastal erosion, finding that the presence of oyster reefs can result in accretion on the lee side of the reef (Gracia et al., 2018). Similarly, a pilot program in the Grand Cayman Islands deployed over 200 artificial reef structures known as "Reef Balls" that could stimulate oyster growth, mangrove rehabilitation and shoreline stabilization (Arnouil, 2008). The results of this experiment demonstrated that the shoreline fluctuated throughout the year, but the presence of the Reef Ball resulted in the largest amount of accretion documented between seasons (average of 50 feet during 3-months after installation), and that even during seasons where tropical storms could normally result in erosion, reef balls were able to prevent or reduce erosion and yield some accretion.

These experimental studies do not demonstrate every type of oyster reef restoration, and most of the experimental sites (except for the Reef Ball experiment) are small; they do not provide comprehensive reef structure coverage across an entire body of water that could have cumulative impacts on erosion or accretion.

Strength of evidence

Moderate. Many studies have looked explicitly at the role of oyster reefs, oysters, and benthic organisms on accretion and erosion, though there is limited detail explaining the process. Experiments are relevant and repeatable, but may not be at a large enough scale to demonstrate the potential of oyster reefs to prevent or induce erosion. Likewise, there has not been consensus on the effect (possibly owing to many external factors), which reduces predictability regarding the relationship between oyster reefs and shoreline accretion/erosion rates.

Other factors

Wave energy, water quality, sediment size, and hydrodynamic forcing are all mentioned as external factors that affect rates of accretion surrounding oyster reefs. (de Paiva et al., 2018; Black, 2011; Gregalis et al., 2008; Piazza et al., 2005, Scyphers et al., 2011)).

Predictability

Despite strong consensus among the scientific community that oyster reefs can result in increased accretion, there do not appear models that can predict or characterize this relationship, or account for external factors.

Sources

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Link 6: Wave attenuation → Adjacent habitat (salt marsh, sea grass, mangrove)

Description of relationship

Wave attenuation by oysters may promote growth and expansion of adjacent habitats, including salt marsh, seagrass, and mangroves.

Summary of evidence

Salt marsh

Salt marshes are susceptible to wave-driven erosion (Leonardi & Fagherazzi 2014). At eight salt marshes in the United States that are affected by hurricanes, analysis of twenty years of data showed that salt marsh erosion was driven by frequent, moderate storms rather than high-energy hurricane events (Leonardi et al. 2016). Overall, marsh erosion was more sensitive to mean wave energy than extreme wave energy, and there was a linear relationship between wave power and erosion. There was no critical threshold of wave energy below which no marsh erosion was expected or above which erosion rates became exponential. Any decrease in mean wave energy at a site is expected to decrease marsh erosion rates. A model of wave-driven erosion in salt marshes suggested that high wave energy causes many moderate erosion events and results in uniform erosion across the marsh, while lower wave energy allows local marsh characteristics (e.g. vegetation root tensile strength) to play a larger role in determining erosion rates (Leonardi & Fagherazzi 2014). Lower wave energy was therefore linked to frequent small erosion events and few large erosion events and resulted in more complex marsh edge.

A project in Grand Bay National Estuarine Research Reserve measured the rate of marsh erosion behind created (shell bag) and natural oyster reefs; mean erosion rates were lower and less variable at constructed reefs than natural reefs (Stricklin et al. 2010). This study did not measure marsh erosion rates in areas without reefs. Oyster reef breakwaters are sometimes included in salt marsh restoration projects to achieve target wave energies for salt marsh plants (as in Douglass et al. 2012), but no studies that measured marsh restoration success with and without oyster reefs were found.

Seagrass

High wave energy can inhibit seagrass growth, although the flexible leaves of most seagrass species allows them to move with waves with minimal stress to their root systems. In addition, waves can have positive effects on seagrasses by increasing nutrient flows to leaves and reducing self-shading (Koch 2006). While there are few studies comparing seagrass restoration across wave energy regimes, restoration success may be limited in high energy areas due to mechanical removal of plant material (Heise & Bortone 1999). Experimental loose shell reefs in Portersville Bay, AL did not have a discernable effect on any of the measured water quality or sediment parameters (including total suspended solids, particulate organic matter, and chlorophyll-a), but there was an overall increase in seagrass abundance across the study area in the five years after the reefs were installed (Sharma 2016). No such increases in seagrass abundance were seen in nearby areas without reefs, suggesting that the presence of reefs may benefit seagrass in the local area beyond the portion of the estuary immediately behind the reef, but the observed increase cannot be definitively attributed to the reefs. A study of seagrass planting with and without experimental reefs in Choctawhatchee Bay, Florida, saw no difference in seagrass survival or coverage due to the presence of the reefs, but the reefs were relatively small plastic crates (26 cm tall) and had limited recruitment of oysters (Heise & Bortone 1999). A project in Florida that simultaneously restored oysters and red mangroves saw an increase in both of those habitat types as well as seagrass abundance, suggesting that seagrass benefitted from the restoration of other habitat types (Milbrandt et al. 2015).

Mangroves

Wave action is also thought to be an important factor in mangrove restoration success (Kamali & Hashim 2011). A restoration project in Malaysia that used a breakwater to reduce wave energy saw significant natural regeneration of mangroves in the sheltered area about a year after the breakwater was installed; regeneration was attributed to sediment buildup and a calm environment behind the breakwater (Kamali & Hashim 2011). This suggests that mangroves may be able to regenerate naturally behind oyster reefs where conditions are suitable. No studies of mangrove restoration success in areas with different wave energies or with and without oyster reefs were found.

Strength of evidence

Salt marsh **High.** Models and analysis of field data support a strong linear relationship between wave energy and salt marsh erosion.

Seagrass and mangroves **Low.** Wave attenuation may facilitate seagrass and mangrove restoration efforts and natural regeneration, but no studies comparing growth or restoration success of these habitats in different wave energy environments were found. Experimental breakwater installations give some support for seagrass and mangrove growth in sheltered areas, but lacked true controls to show that the observed changes were due to the breakwaters.

Other factors

Other environmental factors that determine habitat suitability for salt marsh, seagrass, and mangroves (e.g. light availability, nutrient concentrations, sediment stability) will influence the relationship between wave attenuation and those habitat types. Some of these are discussed in link 11.

Predictability

The effect of a change in wave attenuation on salt marsh erosion rates can be calculated from the equation included in Leonardi et al. 2016. There is not enough supporting evidence to predict changes in mangroves or seagrass due to wave attenuation.

Sources

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Link 7: Wave attenuation → Public and private property protection

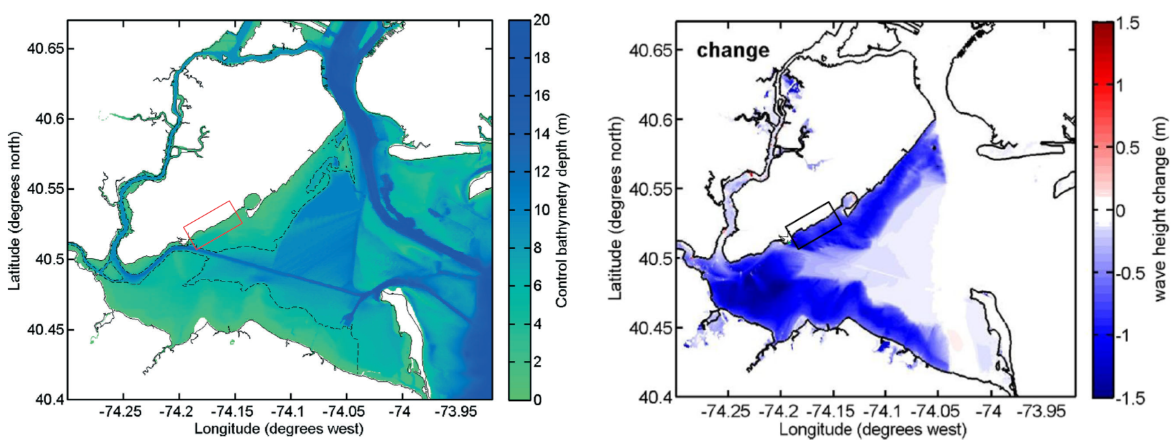
Description of relationship

Reduced wave energy can limit wave travel over land and reduce overtopping of beaches, dunes, and other barriers.

Summary of evidence

Wave attenuation can reduce the extent of overwash, which occurs when waves are higher than beach or dune crests, causing water and sediment to wash over the crest (Donnelly 2004). Overwash is common on barrier islands and low-profile shorelines, and can cause damage from flooding or sedimentation of infrastructure, including roads. As noted in link 5, there are few studies showing the impact of oyster reefs on wave attenuation. This is also true of subsequent effects of oyster-induced wave attenuation on infrastructure damage. Studies that do exist are limited in both spatial and temporal scale and focus on oyster cultch placement projects (Brandon et al. 2016). Therefore, they are not likely to show the full potential of large, established oyster reefs on shoreline protection. One study that did attempt to capture the effect of established oyster reefs used sediment analysis to assess the frequency of storm-induced overwash in New York Harbor during the period of oyster reef destruction in the area (1600-1800 CE) (Brandon et al. 2016). Sediment cores showed an increase in overwash deposition that corresponded with oyster reef destruction and could not be explained by other natural or anthropogenic causes. The study also used hydrologic modeling to quantify the expected difference in wave height and flood extent during two recent storms (a 1992 Nor'easter and 2012 Hurricane Sandy) if historic oyster reefs were intact.

Left: present-day bathymetry, oyster reef extent included in models is shallow water bounded by the dashed line. Right: Modeled change in wave height for the 1992 Nor'easter with 3m high oyster reefs.



The models showed that oyster reefs significantly reduced wave height and wave energy for both storms. Wave height reduction was very sensitive to reef height, but not to reef roughness. Peak average flood level was only changed by a very small amount by the presence of reefs, and the direction of change varied by storm. Together, the sediment analysis and modeling indicate that large, well-established oyster reefs can provide protection for storms by decreasing the height and energy of waves that cause overwash on land, but are not likely to have a meaningful influence on the depth or extent of flooding.

Strength of evidence

Low. No evidence was found that directly connected wave attenuation from restored oyster reefs to decreased infrastructure damage from reduced overwash or flooding. The historical analysis and modeling by Brandon et al. (2016) show that oyster reefs can reduce overwash even under severe storm conditions, but the extent and vertical height of the modeled reefs is much greater than most restoration projects.

Other factors

The location of an oyster reef restoration project relative to public infrastructure and shorelines determines what infrastructure may be protected by the reef.

Site-specific wave conditions and particular storm events determine the characteristics of waves and storm surge experienced by a given area, which influence the ability of oyster reefs to decrease wave energy and overwash (Brandon et al. 2016).

Besides storm surge and wave height, the likelihood of overwash also depends on the tidal phase during the storm, nearshore bathymetry, beach topography (width and height of beach or dune crest), and dune vegetation (Donnelly 2004).

Predictability

Circulation and wave simulation models can be used to estimate the effect of oyster reefs on wave height, wave energy, and flood level, as in Brandon et al. 2016.

Sources

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Link 8: Wave attenuation → Shoreline change (erosion/accretion)

Description of relationship

Decreased height and energy of waves decreases shoreline erosion rates.

Summary of evidence

Waves move sediment and can cause erosion; a decrease in wave height and energy may result in lower erosion rates or higher accretion rates. The relationship between wave characteristics, sediment characteristics, and erosion or accretion events has been studied in laboratory experiments and via field studies of exposed ocean beaches (Jackson 1999). A model of erosion vulnerability on Oregon beaches found that wave height interacts with wave length and beach slope to determine the wave run-up height on a beach, and therefore the beach's susceptibility to wave-driven erosion (Ruggiero et al. 2001). A model of shoreline responses to breakwaters showed that the wave transmission parameter (a measure of wave attenuation by the breakwater) was a key driver of shoreline movement due to erosion and sediment distribution. The study also pointed out that since longshore sediment transport is proportional to $H^{5/2}$ (where H is wave height), a given reduction in wave height would have a greater influence on shoreline change at larger initial wave heights (Wamsley et al. 2003).

These may not apply to sandy beaches in estuaries, which have lower wave energy. Several proposed numerical models that use wave and sediment parameters to determine whether a beach is undergoing erosion or accretion were assessed with field data from a sandy estuary beach in New Jersey to see if they were applicable to this environment. The study confirmed the effect of wave height on shoreline changes; higher wave heights were associated with erosion events, and lower wave heights with accretion events. Wave height was usually combined with another wave parameter, such as wave length or period, to derive a single parameter representing waves' influence on erosion. However, the predictive models tested were not very accurate for estuarine beaches due to large differences in model parameters from estuarine beaches to exposed ocean beaches or field experiments (Jackson 1999).

A review of 'low-energy' estuarine environments describes sediment processes occurring on low-energy beaches (Jackson et al. 2002). Beach erosion resulting in a change to the beach profile is caused by wave energy higher than background levels. At low-energy beaches, erosion can occur at wave heights that would be considered small at higher-energy beaches (0.35 meters or greater). While the beach profile usually recovers quickly after wave heights decrease, larger storm waves can result in greater off-shore sediment transfer and slow recovery. Low background wave energy can also limit sediment availability to rebuild beach profiles after storms (Jackson et al. 2002). An overview of coastal change processes in Louisiana noted that there are few direct measurements of sediment transport, but both longshore and cross-shore sediment transport occur, and there are some examples of sediment accretion behind breakwaters (Georgiou et al. 2005).

Strength of evidence

Moderate. The relationship between larger waves and increased erosion is intuitive; field studies and modeling of sediment transport processes in estuaries and beaches show that larger waves are generally associated with more erosion events, and smaller waves with more accretion events. However, the influence of other factors means that wave attenuation may not always lead to decreased erosion.

Other factors

Shoreline sediment composition: Larger sediment requires higher wave energy to move and moves more slowly than smaller sediment (Yates et al. 2011).

Wave period and source: Long-period ocean waves can return sediment to beaches, while short-period waves cause erosion (Leatherman et al. 2011). The wave climate in a given area influences how wave attenuation will influence shoreline change processes.

Predictability

The many other wave, shoreline, and sediment characteristics that drive shoreline change processes make it difficult to predict shoreline change response to wave attenuation. Several models are mentioned in the summary of evidence, but they only apply to certain contexts, and no examples of their application in the Gulf of Mexico were found.

Sources

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Link 9: Shoreline change (erosion/accretion) → Public infrastructure and shoreline protection

Description of relationship

Decreased shoreline erosion (or increased accretion) can protect public infrastructure from damage and reduce the need for shoreline repair such as beach nourishment.

Summary of evidence

Shoreline erosion poses a direct threat to coastal areas. A FEMA-commissioned study of property vulnerability to erosion in the United States estimated property damage within a 60-year erosion hazard area, which represents the land expected to be lost to erosion by 2060 (Merrell et al. 2000). This analysis is based on in-depth study of 18 selected counties, extrapolated to the national scale using a lower-resolution, national-scale erosion rate dataset (Friedman et al. 2002). In the Gulf of Mexico, 13,000 structures are within the erosion hazard area (29% of all structures within 500 feet of the shoreline). If structures were built on all lots vacant as of 2000, the number of structures at risk to erosion in the region could reach 22,000. These estimates do not specifically identify public infrastructure within the erosion hazard areas, but there is certainly public infrastructure (roads, bridges, utilities) providing access and services to these structures, even if many of them are privately owned. This analysis does not include structures in major urban areas, as they are assumed to be protected from erosion risk.

While it is clear that shoreline erosion is a significant threat to coastal properties in the Gulf of Mexico, the properties most at risk from erosion (which would benefit most from reduced shoreline erosion) may not be fully spatially aligned with areas where oyster reef restoration is possible. The erosion hazard area has not been mapped at a broad geographic scale, so the spatial overlap of areas vulnerable to erosion and areas suitable for oyster reef restoration cannot be assessed.

Beach nourishment—placing sand on beaches to replace sand lost to erosion—occurs in every Gulf coast state. The volume of sand and amount spent on beach nourishment projects in the Gulf coast increased from 1950 to 1995; no comprehensive data since 1995 was found (Trembanis & Pilkey 1998). Nourishment projects are expensive (the average cost for nourishment sand is $5 per cubic yard, and the cost per mile for the Florida Gulf coast was estimated at $2.5 million) and must be done repeatedly as the new sand is redistributed and erodes over time (Trembanis et al. 1999, Smith et al. 2009). Nevertheless, beach nourishment is gaining popularity as an alternative to structural erosion control in the Gulf of Mexico (Morton et al. 2004). An economic model of the optimal frequency of beach nourishment showed that nourishment can be done less frequently when the baseline erosion rate is decreased (Smith et al. 2009). However, it is unclear whether any beach nourishment is done in the lower-energy estuaries where most oyster reef restoration projects are placed. Many of the specific beach nourishment projects cited appear to be on exposed ocean beaches, which are likely less suitable for oysters. Therefore, oyster reef restoration may not always result in reduced frequency of beach nourishment.

Strength of evidence

Moderate. Coastal erosion causes damage to infrastructure and shorelines; lower erosion rates will reduce infrastructure damage and the frequency of shoreline repair activities. However, the evidence summarized above does not show the spatial overlap of erosion-vulnerable infrastructure or beach nourishment activities with areas suitable for oyster reef restoration, so the magnitude of this effect is uncertain.

Other factors

As discussed above, the location of oyster reef restoration projects relative to areas vulnerable to erosion determines the effect of reefs on infrastructure and shoreline protection via reduced erosion.

Predictability

The FEMA study estimates property damage from shoreline erosion, but is extrapolated from data for a small number of counties and contains many assumptions about the effects of erosion (Friedman et al. 2002).

Sources

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Link 10: Water turbidity → Light attenuation[2]

Description of relationship

A change in turbidity will change light attenuation into the water column (which changes the amount of light reaching through the water). Lower turbidity reduces the scatter of light entering estuary water, which will increase the amount of light able to penetrate the water column (corresponding to a decrease in light attenuation).

Summary of evidence

Turbidity is an optical determination of water clarity and is a measure of the amount of light scattered by suspended particles in water. The more suspended particles in the water, the more those particles will scatter incoming light. Light attenuation represents the reduction of intensity of a beam of light traveling through a medium, such as water. Therefore, with less turbidity (scatter of light from suspended particles), light attenuation will correspondingly decrease, resulting in more available light to reach the water column.

There is an understood connection between measurements of turbidity (using a Secci disk) and light attenuation of water (measured by the light attenuation coefficient, K_d). Predictions of K_d from Secci depth measurements can be made using an index, represented by the equation below.

$$K_d = a / Z_{secchi}$$

Where a is a constant derived from reflectance properties, and Z_{secchi} is the Secchi depth, measured in meters. The constant a is often considered to be 1.7 (Padial and Thomaz 2008); however, it has been shown to vary on the basis of site characteristics. Smith et al. (2006) used a values of 1.0, 1.4, and 1.7 for

[2] This entry is from Mason, Sara, Lydia Olander, and Katie Warnell. 2018. "Ecosystem Services Conceptual Model Application: NOAA and NERRS Salt Marsh Habitat Restoration." National Ecosystem Services Partnership Conceptual Model Series No. 3. Durham, NC: Duke University, Nicholas Institute for Environmental Policy Solutions. https://nicholasinstitute.duke.edu/conceptual-model-series

naturally turbid, moderately turbid, and clear water estuaries, respectively (see Smith et al. 2006 formulas 2 and 3 for further detail). Liu et al. (2005) did a literature review of *a* values and found them to range between 1.1 and 2.02. If both Secchi depths and light meter readings with resulting K_d values are available for a site, statistical models relating Secchi depth and K_d can be developed. These models enable the user to predict K_d values from known Secchi depths. Such models can be seen in Padial and Thomaz (2008), Devlin et al. (2008), and Liu et al. (2005).

Strength of evidence

High. The literature shows that there is general consensus about the relationship between turbidity and light attenuation as well as about the relationship between Secchi depth and the light attenuation coefficient, K_d. Using common values of the constant *a*, it is possible to calculate K_d from known Secchi depths; however, local data that can provide specific values of *a* or generate a local model are preferred.

Other factors

Water flow and weather are other factors. Water with a high flow rate will prevent suspended particles from settling on the bottom and maintain higher levels of turbidity. Weather events that result in higher stream flows will often be associated with temporary higher turbidity levels due to increased flow as well as particle runoff.

Predictability

Using local data on Secchi depth and light meter readings to generate a statistical model that links these two variables has been shown to be successful, enabling the user to predict K_d values on the basis of Secchi depths.

Sources

Devlin, M.J., J. Barry, D.K. Mills, R.J. Gowen, J. Foden, D. Sivyer, and P. Tett. 2008. "Relationships between Suspended Particulate Material, Light Attenuation and Secchi Depth in UK Marine Waters." Estuarine, Coastal and Shelf Science 79 (3): 429–439.

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Smith, Lisa M., Virginia D. Engle, and J. Kevin Summers. 2006. "Assessing Water Clarity as a Component of Water Quality in Gulf of Mexico Estuaries." Environmental Monitoring and Assessment 115 (1): 291–305.

Link 11: Light attenuation → Seagrass

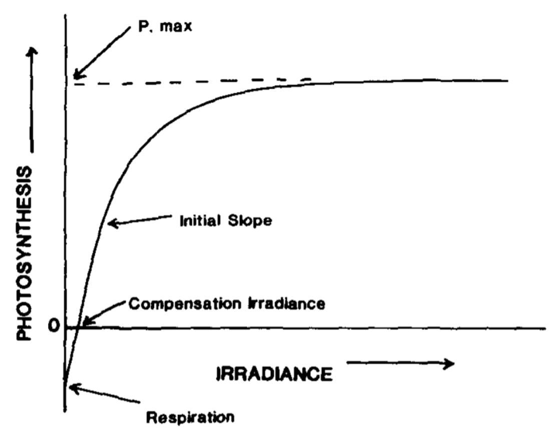
Description of relationship

Decreased light attenuation enhances seagrass growth, leading to an increase in the extent and health of seagrass habitat.

Summary of evidence

Seagrass requires light for photosynthesis, so a change to light availability can influence seagrass extent and density (Ralph et al. 2007). Light attenuation determines the maximum depth at which seagrass can grow; decreased light attenuation associated with an increase in water clarity can allow seagrass to colonize deeper areas where other environmental conditions permit. Because self-shading (leaves shading other leaves lower in the canopy) results in less light available near the bottom of the seagrass canopy, seagrass density tends to decrease in low-light conditions to reduce the self-shading effect. Therefore, seagrass density can also be influenced by a change in light attenuation (Ralph et al. 2007). Field and laboratory studies show that Gulf of Mexico seagrass species are sensitive to and often limited by light availability.

In general, the relationship between irradiance (amount of light reaching the seagrass) and photosynthetic activity has a light-limited phase where photosynthesis increases linearly with irradiance and a light-independent region where irradiance is sufficient for photosynthesis and other factors determine photosynthetic rate. At very high light levels, the plant can receive too much irradiance, causing a decrease in photosynthesis (Lee et al. 2007).



Source: Bulthuis 1987

This relationship, and the minimum irradiance necessary for an organism to survive, varies by species (Lee et al. 2007, Choice et al. 2014). Light requirements for common Gulf of Mexico seagrass species were derived from field sampling of seagrass coverage and density, light penetration, and other environmental variables (Choice et al. 2014):

Estimated threshold light requirements for seagrasses and results of *t*-tests assessing differences in percentage covers and shoot densities. % SI = percent of surface irradiance; SE = standard error; * = significant at $0.01 < p \leq 0.05$; ** = significant at $p \leq 0.01$; *T. testudinum* = *Thalassia testudinum*; *H. wrightii* = *Halodule wrightii*; *S. filiforme* = *Syringodium filiforme*; *H. engelmannii* = *Halophila engelmannii*.

Species	Portion of moving window	Cover			Density		
		Threshold (% SI)	Mean (%)	SE (%)	Threshold (% SI)	Mean (shoots m^{-2})	SE (shoots m^{-2})
T. testudinum	Below threshold	18–23	0.20**	0.02	20–25	0.40**	0.36
	Above threshold		22.00**	4.25		393.00**	65.20
H. wrightii	Below threshold	25–27	2.00	0.68	25–27	32.40*	13.66
	Above threshold		7.10	2.29		400.10*	141.73
S. filiforme	Below threshold	8–16	0.00**	0.00	8–16	0.00**	0.00
	Above threshold		17.30**	5.13		525.50**	140.72
H. engelmannii	Below threshold	8–10	0.10*	0.05	8–10	1.90	1.86
	Above threshold		3.50*	1.52		142.80	65.93

An EPA water quality monitoring report rated 10% of Gulf coast estuaries as 'poor' and 53% as 'fair' for water clarity, which was determined by light penetration measurements (EPA 2012). The light penetration classes to determine water clarity ratings were not uniform across the Gulf (estuaries considered 'naturally turbid' were rated 'good' at lower light penetration measurements). Since the underlying data are not available, the actual light penetration in Gulf estuaries cannot be assessed. However, several pieces of evidence support the idea that seagrasses in the Gulf of Mexico are often limited by available light. A study of seagrass in the Florida Gulf coast that combined field measurements of water quality and seagrass density with laboratory measurements of seagrass growth under different light conditions found that light was an important limiting factor in seagrass distribution when salinity and temperature do not preclude seagrass growth (Livingston et al. 1998). The data used to calculate minimum light requirements for Gulf of Mexico seagrasses, as described above, show that light was often a limiting factor in seagrass coverage and density (Choice et al. 2014). Concerns about seagrass losses from increased turbidity prompted researchers to propose light penetration targets for Charlotte Harbor, Florida (Corbett & Hale 2006).

Strength of evidence

Moderate. Many field and laboratory research studies, in the Gulf of Mexico and around the world, show that seagrass growth is dependent on light availability and explain the relevant mechanisms. Several studies in the Gulf of Mexico suggest that light is a common limiting factor among seagrasses. However, the many other factors that control seagrass growth mean that a change in light attenuation will not always result in a change in seagrass populations.

Other factors

Salinity and water temperature limit seagrass growth and can inhibit seagrass response to changing light conditions (Livingston 1998). Salinity can also modify light requirements; some species have higher light requirements in non-optimal salinity (Choice 2014).

Seagrasses can photo-acclimate to low light areas (e.g. deep or high-turbidity) (Lee et al. 2007, Leoni 2008).

Light requirements vary by species (Lee 2007).

Predictability

External factors make predicting the effect of a change in light attenuation on seagrass extent or growth difficult. While no predictive models for seagrass growth in the Gulf of Mexico were found, a model for seagrass growth (as influenced by bivalve effects on water turbidity) in the Chesapeake Bay could be used as an example for future modeling efforts (Newell and Koch 2004).

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Link 12: Oyster population → Water turbidity

Description of relationship

Oysters reduce water turbidity by removing suspended particles from the water column.

Summary of evidence

As filter feeders, oysters remove particulates from the water column. After ingestion by oysters, particulates can be assimilated or deposited in sediments (Cerco & Noel 2007). Evidence from laboratory experiments and models supports the fact that oysters efficiently filter particulates from the water column. One laboratory study of oysters' influence on suspended solids (groups of oysters were placed in a 1,000-liter tank and water clarity monitored) found that on average, a one-gram oyster filtered 6.4 liters of water per hour (Newell and Koch 2004). A synthesis study based on three existing oyster filtration models used an individual maximum filtration rate for a 1-gram oyster (0.17 m^3/gram dry weight/day) and the influences of temperature, salinity, and total suspended solids on filtration rates to develop a new filtration model (Ehrich & Harris 2015). When empirically derived equations for oyster filtration were incorporated into the Chesapeake Bay Environmental Model Package as part of an effort to examine benefits of nutrient load reductions and oysters' role in nutrient reduction, increased oyster populations were associated with increased clearing of suspended solids from the water column (Cerco & Noel 2007). There is also evidence that oysters grown in aquaculture facilities have a similar influence on suspended particulates in the water column, as reviewed by Forrest et al. 2009 and by Gallardi et al. 2014.

While it is clear that oyster remove particulates from the water column, the influence of this activity on water turbidity or the concentration of total suspended solids is more difficult to assess because it is determined by local factors, including freshwater inflows and hydrodynamics. A field study of restored oyster reefs in North Carolina tidal creeks found some evidence of decreased suspended sediments concentration downstream of the reefs, but the effect was inconsistent (Nelson et al. 2004). A similar study of water quality around restored oyster reefs in Alabama suggested that the lack of consistent effects was because measurements were taken too far from the reef (50 cm) or because local hydrodynamics kept much of the water column from coming into contact with the reefs (Plutchak et al. 2010). A spatially explicit model of oyster filtration services in Yaquina Bay, Oregon, which accounted for hydrodynamics, found that Pacific oysters could clear up to 12.7% of the estuary volume during the wet season at historic distributions, and that the same clearance could be achieved at much smaller distributions if oyster restoration were targeted to areas with the greatest potential for filtration services (Gray et al. 2019).

Strength of evidence

Fair. There is strong evidence that oysters remove suspended solids from water via filter-feeding, but very little evidence to connect that removal to an observable change in water turbidity or suspended solid concentrations. Field studies that measured turbidity around oyster reefs have found inconsistent effects, and modeling suggests that local hydrodynamics play a large role in determining oysters' effect on turbidity.

Other factors

Temperature, salinity, and total suspended solids influence oyster filtration rates (Ehrich & Harris 2015).

Hydrodynamics determine what portion of the water column is exposed to oysters, and could potentially be influenced by the removal of particulates, at a particular reef (Plutchak et al. 2010).

Predictability

No generally applicable models to predict oysters' effects on turbidity are available. Gray et al. 2019 is an example of predictions in a specific estuary using oyster filtration models combined with a hydrodynamic model.

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Link 13: Oyster population → Water quality: Nutrient concentration

Description of relationship

Oysters remove nitrogen from the water via storage in tissue, which is permanently removed when oysters are harvested, excretion of biodeposits that are buried in sediments, and increased denitrification.

Summary of evidence

Oysters remove nitrogen from the water in several ways: they store it in their tissues and shells, where it is physically removed from the water during oyster harvest; they excrete nitrogen-containing waste that is buried in sediments, and they facilitate denitrification (Carmichael et al. 2012). A variety of studies has demonstrated oysters' ability to remove nitrogen from water and estimated the magnitude of this effect.

A field study in five Massachusetts estuaries measured nitrogen assimilation in oyster tissue and used stable isotope ratios to identify the source of assimilated nitrogen (Carmichael et al. 2012). The study confirmed that oysters are able to assimilate anthropogenic nitrogen and estimated that for typical oyster restoration project scales for the US (oyster densities between 75 and 150 oysters/m^2 and covering <5% of the total estuary area) would remove less than 30% of land-derived nitrogen loading and less than 1% of total phytoplankton N each year. At higher densities, such as those in oyster aquaculture facilities (400-1650 oysters/m^2), oysters removed up to 100% of land-derived nitrogen and

0-12% of phytoplankton nitrogen (assimilation varied by estuary; see 'other factors'). The study concluded that oysters have the greatest potential for mitigating nitrogen loading in estuaries with low nitrogen loading and high-quality oyster habitat.

A predictive eutrophication model developed for the Chesapeake Bay included the effects of oyster reef restoration and found that the restoration of oyster reefs to 10x their current distribution in the bay would reduce surface total nitrogen concentrations by 10-15% (Cerco & Noel 2007).

Field data on oyster size parameters and environmental variables were used to estimate oyster nitrogen removal in Mission-Aranas Estuary (Texas) through a series of empirical equations (Pollack et al. 2013). Annual nitrogen removal rates were estimated per square kilometer of oyster reef at the mean oyster density for the estuary (408 oysters/m^2): 502.5 kg nitrogen denitrified, 251.25 kg nitrogen buried in biodeposits, and 1196.3 kg nitrogen physically removed from the estuary via oyster harvest (7% of tissue mass and 0.3% of shell mass on a dry weight basis) (Pollack et al. 2013). This study did not estimate changes in nitrogen concentrations in the estuary due to these removal rates.

Note:

Nitrogen removal by oysters could influence additional ecological components, such as algal biomass and the occurrence of toxic algal blooms. These changes are not included in the ecosystem services conceptual model because there is little evidence to support them. Besides the relatively small changes in nitrogen concentrations expected to be caused by oysters, as discussed above, many factors influence algal blooms, so it is not clear that a reduction in nitrogen concentration will result in a change in algal biomass or bloom frequency. This is especially true of toxic algal blooms, which are poorly understood and thought to be influenced by a variety of factors including currents, inflow, stratification, and salinity (Roelke & Pierce 2011). Research emphasizes that "neither the quantity nor the ratio of inorganic nutrients can explain blooms" and that potential nutrient effects are often overridden by hydrodynamics (Heisler et al. 2008, Davidson et al. 2014).

Strength of evidence

Moderate. There is clear evidence from a variety of sources, including large field-based research studies and empirically derived models, that oysters are capable of removing anthropogenic nitrogen from water bodies. However, there is consensus that while oysters can remove large amounts of nitrogen, in most cases oysters do not substantially change nitrogen concentrations due to high nitrogen loading and relatively small oyster reef extent. In addition, nitrogen removal varies considerably due to environmental conditions (see 'other factors').

Other factors

Environmental parameters, including salinity, temperature, dissolved oxygen, and total nitrogen load, can influence oyster growth and nitrogen assimilation rates (Carmichael et al. 2012).

Nitrogen loading, which is influenced by land use and anthropogenic activities such as agriculture, can determine whether nitrogen removal by oysters results in a change in nitrogen concentrations in an estuary. In order to decrease nitrogen concentrations, oysters must entirely offset nitrogen loading (Pollack et al. 2013).

Harvest regulations influence whether nitrogen assimilated by oysters is removed from the system when oysters are harvested. In terms of nutrient removal, there is a trade-off between leaving oysters in the estuary to remove nitrogen on an ongoing basis (via denitrification and biodeposits) and harvesting them in a one-time nitrogen removal event (Pollack et al. 2013).

Predictability

There are models available to predict nitrogen removal by oysters, as exemplified in Cerco & Noel 2007 and Pollack et al. 2013. These are generally based on metabolic equations and estimate the amount of nitrogen removed, not the change in nitrogen concentration in the water body. Nitrogen concentrations are influenced by a variety of factors, including hydrologic processes, and are therefore very difficult to predict.

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Link 14: Water Turbidity → Recreation (Recreational Fishing, Oyster Harvest, Kayaking & Wildlife Viewing)

Description of relationship

Water quality issues, including turbidity, can impact demand for and use of recreational sites for activities such as recreational fishing, oyster harvest, kayaking, and wildlife viewing.

Summary of evidence

Academic literature states that water quality issues, including but not limited to turbidity, in the Gulf of Mexico affect tourism and recreation generally (Kennicutt, 2017). However, none of these studies provides details or experimental information that elaborate on how the presence or absence of turbidity affects recreation such as recreational harvest, kayaking, or wildlife viewing.

Turbidity can impact wildlife viewing in a number of ways. Clear water in bodies of water used for recreation is more visually attractive to recreationists and makes recreation safer by allowing people to estimate the depth of the water, see underwater hazards, and locate submerged people. Turbidity results in reduced visibility (Rovere et al., 2011) which may make it difficult to actually observe wildlife in bodies of water, either from above ground or in the water (i.e. snorkeling or diving).

A 2011 (Paudel et al.) study examined a visitor's decision to participate in coastal recreational activities in Louisiana based on in-person and internet survey data. Environmental quality of the site was an influential factor on visitors' decisions to participate in coastal recreation activities; visitors concerned about environmental quality were less likely to swim and go offshore fishing, but more likely to engage in surf-based fishing. The environmental quality attributes in this study did not specifically include turbidity or water quality. The only mention of turbidity in this study referred to coastal waters of Louisiana being less desirable for swimming due to turbidity.

A study in Finland used national recreational inventory data and water quality data to estimate the benefits of water quality improvement as measured by recreation participation (Vesterinen et al., 2005). The recreational activities included in this study were swimming, fishing, and boating. While water quality measurements incorporated turbidity, it was not isolated from the other indicators of water quality in the results. However, to the respondents, water quality was defined as water clarity in their home municipality, which is correlated with turbidity. The study found that increased water quality did not influence participation in swimming or boating, however it did have a significant positive effect on fishing.

A study in New Zealand (Nagels, 2001) surveyed 16 water quality experts to develop a water quality index for contact recreation in New Zealand fresh water bodies. Turbidity was included in the index because of its effect on aesthetics and swimming safety, though not necessarily for kayaking or wildlife viewing. Along with this, two studies by the same research group in New Zealand interviewed people at rivers and lakes about their perceptions of the water's suitability for bathing and clarity and conducted field measurements of water clarity (Smith et al., 1995; Smith et al., 1991). Increased water clarity was correlated with increasing suitability for bathing; overall, water was perceived as suitable for bathing when clarity was at least 1.2 m (as measured by horizontal black disc visibility; equivalent Secchi disc visibility of 1.5 m). At this clarity, about 75% (Smith et al., 1991) to 80% (Smith et al., 1995) of respondents thought that the water was suitable for bathing. A follow-up study that surveyed field staff who carry out water quality monitoring about their perception of suitability for bathing based on water clarity found similar results, with water considered marginally suitable when clarity exceeded 1.1 m and suitable when clarity exceeded 1.6 m (Smith et al., 1992).

In another study, researchers modeled the recreational use of 129 lakes in Iowa based on a survey of 1,286 households and field measurements of water quality parameters including clarity (Secchi depth) (Egan et al., 2009). Lake clarity was positively correlated to the number of visits to the lake; the specific recreational activities in which visitors engaged at lakes was not investigated. Finally, a survey of water monitoring field crews in New York state found that low water clarity was a significant predictor of impaired recreational use (as judged by the field crews) for both primary and secondary contact uses at 203 wadeable streams (Kooyoomjian et al., 1974).

These studies indicate that environmental quality issues can affect demand for recreation, particularly swimming, boating, and fishing. Further studies would need to be conducted to isolate turbidity's effect on oyster harvest, kayaking, and wildlife viewing recreation in the Gulf of Mexico.

Strength of evidence

Low. While there are a number of studies that examine the relationship between environmental quality and recreation, none focuses on the relationship between turbidity and recreational harvest, kayaking, or wildlife viewing in the Gulf of Mexico. Several studies in other regions suggest that recreationists prefer low-turbidity water, especially for primary contact activities such as swimming and diving. However, there are too few studies to discern a consistent relationship for any particular recreational activity.

Other factors

Socioeconomic factors: Race, income, gender, and urban versus rural areas are all factors in these studies that play important deterministic roles in demand for recreation activities.

Substitutability: The availability of alternate opportunities for outdoor recreation (water-related or not) can influence the effect that water clarity has on water-related recreation. In areas with many lakes and rivers that can be used for recreation, a reduction in water clarity of a few bodies of water may encourage people to shift their activities to other bodies of water rather than decrease total water-related recreation. In areas with a variety of other (non-water-related) outdoor opportunities, some people may respond to decreased water clarity by engaging in other types of recreation, therefore reducing the total recreational benefits lost due to decreased water clarity relative to areas without other types of recreational opportunities.

Predictability

No models or methods to predict this relationship were found.

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Link 15: Recreational non-oyster harvest → Economic activity (recreation)

Description of relationship

Recreational harvest of non-oyster species in the Gulf of Mexico generates economic activity, including jobs, via expenditures on trips and equipment.

Summary of evidence

Recreational non-oyster harvest generates economic activity through expenditures on trips and equipment, including permits, boat rentals, fishing tackle, and hiring guides. Several sources estimate expenditures related to recreational fishing.

The National Survey for Fishing, Hunting, and Wildlife-Associated Recreation (NSFHWAR) estimates recreational saltwater fishing expenditures by state every five years; the most recent year with state-level data available is 2011 (Table 1) (US DOI et al., 2011). More than 65% of expenditures on saltwater recreational fishing in the Gulf of Mexico occur in Florida.

Table 1. Expenditures for saltwater recreational fishing in 2011, thousands of dollars

State	Food and lodging	Transportation	Other trip costs	Equipment	Total
Alabama	26,656	10,002	33,832	N/A	74,012
Florida	732,014	430,437	1,178,031	778,754	3,119,236
Louisiana	100,312	39,068	96,270	N/A	264,998
Mississippi	28,022	22,213	74,507	115,144	239,886
Texas	239,063	114,357	208,540	328,596	890,556

NOAA's Fisheries Economics of the United States report includes estimates for several types of economic activity related to recreational fishing at the state level (Table 2). These are modeled using IMPLAN based on recreational harvest volume. Sales includes purchases by anglers and sales between businesses as a result of sales to anglers; value added is the contribution to gross domestic product (National Marine Fisheries Service 2017). The sales numbers reported in the FEUS are larger than total expenditures in the NSFHWAR; this is likely partly due to the temporal difference (2011 vs 2015) and partly due to difference in methodology (NSFHWAR is survey-based, while FEUS is modeled).

Table 2. Economic activity from saltwater recreational fishing in 2015, thousands of dollars

State	Sales	Value added
Alabama	1,244,884	888,904
Florida (west coast only)	6,947,889	4,184,808
Louisiana	1,285,974	784,385
Mississippi	656,407	354,185
Texas	1,937,753	1,202,300

Some of these costs, such as food and lodging and transportation, are incurred during each recreational fishing trip; therefore, they would be expected to increase as the number of recreational fishing trips increases. Other costs, such as annual permits and certain equipment, will not increase with the number of trips taken.

The Gulf coast states require licenses and permits for a variety of non-oyster recreational harvesting activity. Harvesting certain species requires an additional endorsement with a corresponding fee. Fees for licenses and permits vary by state and by the applicant's residency (fees are generally cheaper for state residents). These permit fees are included in the 'other trip costs' category in Table 1. The Gulf States Marine Fisheries Commission publishes an annual report on licenses and fees for saltwater fishing in the Gulf coast states (McIntyre 2018). The results for the most recent year available (2017) are summarized below (rounded to nearest $1,000).

Table 2. Total revenue from saltwater recreational fishing licenses and fees

State	Total revenue from recreational licenses and fees
Alabama	$3,094,681.85
Florida	$39,757,005.00
Louisiana	$8,903,490.00
Mississippi	$944,750.00
Texas	$65,605,340.00

In addition to revenue from license and permit fees, states can also receive funding from the Sport Fish Restoration Program, a federal program that provides grants for fishery improvement, boating access, and education projects. The formula to determine each state's award is partly based on the number of paid, licensed anglers (USFWS 2018). Awards for the Gulf coast states in 2017 are summarized in Table 3 (McIntyre 2018).

Table 3. Sport Fish Restoration Funds received by Gulf coast states, 2017 (rounded to nearest $1,000)

State	**Sport Fish Restoration Funds**
Alabama	$5,682,000
Florida	$11,249,000
Louisiana	$6,306,000

Mississippi	$3,694,000
Texas	$16,258,000

Because fishing licenses and permits are issued to individuals rather than by harvest volume, an increase in non-oyster harvest may not necessarily lead to increased revenue from permits. If the increased harvest activity is conducted by people who regularly purchase licenses or permits regardless of oyster reef restoration, then no additional revenue would be expected. If new anglers or harvesters who have not previously purchased licenses or permits, but do so in response to the better fishing experiences created by oyster reef restoration, then those new licenses and permits will generate additional revenue.

Recreational fishing creates jobs both directly (e.g. hiring fishing guides) and through expenditures on trips and equipment (e.g. boat rentals, fishing tackle, etc.). NOAA's Fisheries Economics of the United States (FEUS) tracks economic trends in marine-related sectors including the recreational fishing industry. This report gives an overall picture of the economic benefits provided by fisheries each year, including the number of jobs supported by recreational fisheries in each state, as modeled using IMPLAN (Table 1). These include part- and full-time jobs that are directly or indirectly supported by expenditures related to recreational fishing.

Table 1. Jobs supported by recreational fisheries in Gulf of Mexico states, 2015

State	# of jobs supported
Alabama	13,888
Florida (west coast only)	61,278
Louisiana	11,054
Mississippi	5,511
Texas	15,368

While recreational fishing clearly supports jobs, it is less clear whether an increase in recreational harvest of non-oyster species will support additional jobs. If the increase in harvest solely occurs through additional catch during the existing number of recreational fishing trips, additional equipment, guides, or boat rentals may not be necessary. If enhanced recreational fishing attracts new anglers or encourages existing anglers to take more fishing trips, this would be expected to support additional jobs through hiring fishing guides and purchasing or renting fishing equipment. A socioeconomic assessment of Half Moon Reef, an oyster reef restoration project in Matagorda Bay, Texas, found that increased recreational fishing at the reef generated more than a million dollars in economic activity and twelve new jobs (The Nature Conservancy and Texas Sea Grant, n.d.).

Strength of evidence

Moderate. Clearly, economic activity is generated from expenditures on recreational fishing trips and equipment. The amount of new economic activity from an increase in non-oyster harvesting is expected to increase with additional trips taken, but certain categories of expenditures may not be strongly influenced by additional trips.

Other factors

Extent of unlicensed/unpermitted fishing activity: Some people illegally harvest without the required licenses or permits; this weakens the link between harvest activity and permit revenue.

Region, species and type of recreational activity (e.g. saltwater recreational fishing/ private boat or commercial boat trips etc.) will influence the types of jobs supported by the specific recreational activity.

Predictability

Modeling, such as the IMPLAN model used by NOAA for the FEUS report, can estimate economic impacts including jobs from harvest volume.

Sources

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Link 16: Recreational, commercial, and subsistence non-oyster harvest → Food (for commercial sale & personal consumption)

Description of relationship

All three forms of harvest (recreational, commercial, and subsistence) result in personal consumption of food, but there is not enough information to determine exactly how a change in quantity harvested will lead to a change in food consumption.

Summary of evidence

Important forms of seafood harvest besides oysters in the Gulf of Mexico are red snapper, grouper-tilefish, blue crab, crawfish, menhaden, mullet, shrimp, stone crab, and tuna fisheries. Combined, the commercial fishery harvested 1.7 billion pounds of finfish and shellfish, with the overwhelming majority of harvest coming from the menhaden fishery (78%). In the recreational fishery, estimates of catch for the key species for 2016 are almost 50 million fish, about half of which were kept for harvest and the other half released. These estimates do not include every recreationally harvested species (National Marine

Fisheries Service, 2018). A significant proportion of non-oyster commercial harvest is sold as food. For example, in 2017, approximately 3,600 thousand metric tons of fishery landings were reported, out of which about 3,500 thousand metric tons (or approximately 94.4%) was sold for human consumption and 766 thousand metric tons were used for industrial purposes (including 131 thousand metric tons used for bait and animal food; NMFS, 2017). Therefore, an increase in commercial harvest of non-oyster species (fish and shellfish) is expected to result in an increase in the amount sold as food.

Seafood products are irrefutably an important contributor to food security on a global scale (Béné et al., 2016), with some three billion people relying on seafood as their main source of protein. A survey conducted in Australia by Christensen et al (2017) found that the leading drivers of seafood consumption are nutrition, taste, and convenience, and the barriers are price, availability, and concerns about quality. A survey study conducted in South Carolina and Kentucky, however, found that demographic characteristics and the desire to support local foods are determinants of seafood consumption behaviors (Ratliff et al., 2017). In the US, consumption and demand for seafood has increased, which has been met substantially by seafood imports. Likewise, a study found that recreational fishing harvest is an important contributor of food security globally. In the US in 2003, roughly 10% of total harvest came from recreational fishing, and provided, on average, an angler with 7,300 grams of edible fish per year. It is unclear whether or not these statistics are similar in the Gulf of Mexico region (Cooke et al., 2017).

After the BP Gulf Oil Spill, a survey was conducted to determine seafood consumption patterns of Gulf of Mexico residents and found that overall, shrimp consumption rates were higher than recommended by the FDA for safe exposure to oil-spill related contaminants. The survey also found that Vietnamese-Americans in the region had higher seafood consumption rates than the remainder of the respondents (Natural Resources Defense Council, 2010). Demand for Gulf of Mexico seafood declined drastically following the BP oil spill, but has since recovered (Kaplan-Levenson, 2017).

The Gulf of Mexico seafood supply chain reaches local and domestic markets, including grocery stores and high end restaurants, some of which is well traced, and some of which is not (Oceana, 2016). More details about the supply chain would illuminate more clearly the relationship between harvest and personal consumption of food, other than by noting that harvest does lead to consumption of food.

Similarly, there are no data and poor documentation describing subsistence harvest for non-oysters and therefore no reliable way to measure how much subsistence harvest leads to consumption of food. Undoubtedly, close to all of subsistence harvest is consumed as food, but there is no information on those quantities. Subsistence harvest is often part of an "informal economy." Subsistence harvest in the Gulf of Mexico includes shrimp harvesting (Hunter et al., 2009). Early subsistence harvest also included other finfish and shellfish (Hadden 2015).

Strength of evidence

High. There is a lot of data demonstrating the harvesting and sale of non-oyster harvest as food. There is less data demonstrating the quantities of commercial and recreational non-oyster harvest in the Gulf of Mexico, but there is consensus that the majority of this harvest is used for personal consumption of food.

Other factors

Manmade and natural disasters, such as the BP oil spill have reduced seafood consumption from the Gulf of Mexico. These reductions can be severe; in its settlement, subsistence fishermen submitted claims to BP so that they could potentially be reimbursed for the losses they accrued as a result of the spill.

Economic factors may influence the proportion of landings sold as food. Some of the species harvested in the Gulf of Mexico enter global market and are therefore subject to prices and demand that are decided by the global market. Harvesters of those species are subject to those prices and those supply chains, unless they are able to develop new markets that distinguish their product from its substitutes.

Predictability

While there is no question that commercial, recreational, and subsistence harvest of non-oyster species results in consumption of food, it is not possible to predict how quantities of harvest change personal food consumption on local, domestic, or global scales.

Sources

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Link 17: Commercial non-oyster harvest → Jobs (Fishing/oyster harvest industry)[3]

Description of relationship

The commercial harvest of non-oyster species creates a variety of jobs in the commercial harvest sector. (Note that other economic activity generated from the sale of commercially harvested seafood is summarized in link 21).

Summary of evidence

The commercial harvest of fish and other species supports a lucrative marine economy, producing a number of jobs from fishing to seafood packaging and processing to transport and support of marine operations. NOAA reports that commercial fisheries supported 1.18 million jobs and generated $39.7 billion dollars in income in the United States in 2015 (NMFS 2017). Table 1 summarizes the evidence for employment within these sectors in 2014 (NOAA 2015).

Table 1: Seafood sales and processing, transport, support and marine operations- employer establishments for Florida in 2014 (thousands of dollars; from Fisheries Economics of United States Report)

Sector	**Establishment**	**Employees**	**Payroll**
Seafood product prep & packaging	27	1,419	50,556
Seafood sales, wholesale	233	1,974	83,964
Seafood sales, retail	166	1,037	25,844
Coastal & Great Lakes freight transportation	62	1,743	175,366
Deep sea freight transportation	77	2,015	131,069
Deep sea passenger transportation	28	DS	DS
Marinas	464	5,421	168,185
Marine cargo handling	61	6,992	179,024
Navigational services to shipping	190	878	74,185

[3] This entry is adapted from Mason, Sara, Lydia Olander, and Katie Warnell. 2018. "Ecosystem Services Conceptual Model Application: NOAA and NERRS Salt Marsh Habitat Restoration." National Ecosystem Services Partnership Conceptual Model Series No. 3. Durham, NC: Duke University, Nicholas Institute for Environmental Policy Solutions. https://nicholasinstitute.duke.edu/conceptual-model-series

Port and Harbor operations	56	588	20,647
Ship and boat building	263	9,608	448,514

The number of fisheries jobs supported by a single restoration project will depend on how much wildlife populations change due to nursery habitat provided for commercial species. Multiple restoration projects would likely have a more noticeable impact on job creation than single projects in the fisheries industry, but one large project could have a measurable job outcome.

Strength of evidence

High. Clearly, commercial fishing supports jobs, and an increase in commercial fishing would support more jobs. Although the evidence for this particular link is high, it is unclear whether a single salt marsh restoration project will increase fisheries stocks enough to increase local jobs in the commercial fishing sector.

Other factors

Job location is another factor. Jobs created in the fisheries industry might not be local. If the commercial species supported by the nursery habitat of the marsh is migratory or wide ranging, the locations where these species are caught (and therefore the location of the jobs created) might not be close to the site of the restoration project.

Predictability

Using the National and coastal input/output model, economic impact on harvesters, seafood industry and retailers (including processors, wholesalers/distributors, grocers and restaurants) can be estimated (NMFS, 2011). The model generates estimates four types of impacts- employment, income, total value added, and output. Each of these impacts is expressed as direct, indirect and induced effects as well as the total of these effects. The model is an approximation of reality (like any model) and is limited by uncertainty. The most important source of uncertainty in the input/output model is associated with costs and earnings of commercial fish harvesters. There is uncertainty around data on product flow, movement of fish and seafood products between segments of the seafood industry that begin with harvesting and imports and end with final sales to domestic consumers or with exports. Data are available for a few states, there are no data for many states and for the nation as a whole or for movements between specific states.

Sources

National Marine Fisheries Service (2011), A User's Guide to the National and Coastal State I/O Model (https://www.st.nmfs.noaa.gov/documents/commercial_seafood_impacts_2007-2009.pdf)

NOAA (2015) Economic state of Fisheries in United States – (https://repository.library.noaa.gov/view/noaa/16121)

National Marine Fisheries Service. 2017. "Fisheries Economics of the United States 2015." NOAA Technical Memorandum MNFS-F/SPO-170. U.S. Department of Commerce, National Oceanic and Atmospheric Administration. https:// www.fisheries.noaa.gov/resource/document/fisheries-economics-united-states-report-2015.

Link 18: Food → Shellfish and fish poisoning[4]

Description of relationship

Consumption of seafood (oysters, other shellfish, and finfish) contaminated with toxins, usually from harmful algal blooms, can cause poisoning. Therefore, increased consumption of seafood from the Gulf of Mexico may lead to increases in shellfish and fish poisoning cases. However, harvest area closures are effective in preventing cases of shellfish and fish poisoning from commercially harvested seafood.

Summary of evidence

Seafood can contain toxins produced by harmful algae. There are several poisoning syndromes caused by different types of toxins produced by various algal species. The National Science and Technology Council Subcommittee on Ocean Science and Technology released a report on harmful algae blooms. including provide a summary of the toxins produced during different kinds of blooms; those associated with ingestion of contaminated seafood that are present in the Gulf of Mexico are shown in the table below.

Harmful algal bloom taxa	**Toxin**	**Human health effects**
Karenia	Brevetoxins	Neurotoxic shellfish poisoning (nausea, vomiting, diarrhea, numbness, muscle aches, fever, chills, reduced heart rate)
Dinophysis, Prorocentrum	Oxadaic acid, dinophysotoxins	Diarrhetic shellfish poisoning (nausea, vomiting, diarrhea, abdominal pain, chills, headache, fever)
Gambierdiscus; Fukuyoa	Ciguatoxins	Ciguatera fish poisoning (abdominal pain, nausea, vomiting, diarrhea, paresthesia, temperature dysesthesia, pain, weakness, brachycardia, hypotension)

Source: Adapted from National Science and Technology Council (2016)

The Gulf of Mexico is the area of the United States most commonly impacted by neurotoxic shellfish poisoning, which is caused by *Karenia brevis*, the organism that creates red tides (Smith & Swoboda 2018, Bhunia 2018). A 2015 study examined 24 confirmed cases of neurotoxic shellfish poisoning along the southwest Florida coast occurring during a red tide event; the majority of the cases were visitors to the area and reported eating clams (Reich et al. 2015). Ciguatera fish poisoning generally occurs in areas with high consumption of reef fish (southern Florida, the Caribbean, Hawaii), but there have been recent reports from the northwestern Gulf of Mexico. The organisms responsible for diarrhetic shellfish poisoning have been detected in waters off the coast of Texas, and oysters in the area have been found to contain okadalic acid, which causes diarrhetic shellfish poisoning (Grattan et al. 2016).

There are no diagnostic tests available for any of the poisoning syndromes, so diagnoses are not usually confirmed, and the frequency of occurrence is underreported (Grattan et al. 2016). The closure of shellfish and oyster harvest areas during red tide events is thought to be effective in preventing neurotoxic shellfish poisoning from commercially harvested shellfish (there have been no documented

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[4] Part of this entry is adapted from Mason, Sara, Lydia Olander, and Katie Warnell. 2018. "Ecosystem Services Conceptual Model Application: NOAA and NERRS Salt Marsh Habitat Restoration." National Ecosystem Services Partnership Conceptual Model Series No. 3. Durham, NC: Duke University, Nicholas Institute for Environmental Policy Solutions. https://nicholasinstitute.duke.edu/conceptual-model-series

cases from shellfish sold through seafood markets or restaurants). However, recreational and subsistence harvest of fish and shellfish still occurs in areas closed to harvest, resulting in cases of neurotoxic shellfish poisoning. This is attributed to a lack of public understanding about health risks of red tides and the complexity of available information about harvest closures (Reich et al. 2015).

Strength of evidence

Fair. It is clear that shellfish and fish poisoning can be caused by ingestion of contaminated seafood from the Gulf of Mexico. However, effective harvesting regulations make the risk of eating commercially harvested seafood very low, so an increase in consumption of commercially harvested seafood is unlikely to lead to increased poisoning cases. Recreational and subsistence seafood harvesters may be unaware of the risks of harvesting in closed areas, or uncertain about which areas are closed, leading to a possible rise in poisoning cases if recreational and subsistence consumption of seafood increases.

Other factors

Harvest regulations and public communication can influence the risk of eating seafood harvested from the Gulf if people avoid harvesting in areas contaminated with algal toxins. If communication about seafood risks to the public or enforcement of harvest closures among recreational and subsistence harvesters increases, the link from increased consumption to poisoning cases could be weakened.

Predictability

No tools to predict this relationship were found. The risk of eating seafood harvested from the Gulf of Mexico varies spatially and temporally based on the presence of toxic algal blooms such as red tide.

Sources

Bhunia, A. K. (2018). Fish and Shellfish Toxins. In A. K. Bhunia (Ed.), *Foodborne Microbial Pathogens: Mechanisms and Pathogenesis* (pp. 175–180). https://doi.org/10.1007/978-1-4939-7349-1_9

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Smith, M. E., & Swoboda, H. D. (2019). Shellfish Toxicity. In *StatPearls*. Retrieved from http://www.ncbi.nlm.nih.gov/books/NBK470225/

Link 19: Bacteria and viruses in the water → Oyster & Non-oyster Harvest

Description of relationship

Concentration of pathogens in the water can trigger state agencies to issue advisories or closures of harvesting areas which may lead to changes in harvesting.

Summary of evidence

Concentrations of certain pathogens such as vibrio are strongly positively correlated with water temperatures (Froelich and Noble et al., 2016). In North Carolina, predictive management tools can estimate how different environmental factors, including temperature and salinity, will affect concentrations of Vibrio in shellfish harvesting areas (Froelich et al, 2015). These tools inform managers who may or may not issue advisories or area closures for harvesting areas.

Each state has a control plan for managing the risk of vibrio and other pathogens in the water. Multiple state programs including the recreational water quality and shellfish sanitation programs in North Carolina monitor pathogens in swimming and harvesting areas. In cases where concentrations are above a certain thresholds, these agencies orders swimming or harvesting advisories and/or area closures when they believe that exposure to those bodies of water may cause harm to humans (NC-DEQ).

Water samples are collected six times a year from harvest sites and tested for fecal coliform. Along with other forms of annual testing, this information is used to classify harvesting sites anywhere from consistently open, to conditionally open, to permanently closed.

In addition, the sanitation and health program within each state provide guidelines to shellfish and seafood handlers as well as seafood consumers regarding their risk of exposure as it relates to harvesting.

Strength of evidence

Moderate. The evidence does not explicitly indicate what concentration of pathogens in the water yields closures of harvesting areas or motivates fishing behavior, but there are standardized guidelines for pathogens in the water guiding decision-making as it relates to oyster and non-oyster harvest.

Other factors

None.

Predictability

There are methods to predict concentration of Vibrio in North Carolina given other environmental factors that can dictate management of harvesting areas.

Sources

Froelich, B. A., & Noble, R. T. (2016). Vibrio bacteria in raw oysters: managing risks to human health. Philosophical Transactions of the Royal Society B: Biological Sciences, 371(1689), 20150209.

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NC DEQ http://portal.ncdenr.org/web/mf/shellfish-sanitation

Link 20: Personal Consumption of Food → Nutrition for Seafood Dependent Communities (Human Health)

Description of relationship

There is not enough information to determine the role that personal consumption of food from the Gulf of Mexico plays in nutrition for seafood dependent communities.

Summary of evidence

Restoration of oyster reefs can lead to increased quantities of oysters and non-oyster species that can be consumed as food (see links 16 and 24). Seafood in general offers many nutritional benefits such as high protein, omega-3 fatty acids, vitamin B12, zinc, and more (Hosomi et al., 2012, Thilsted et al., 2014). Over one billion people rely on seafood as their main source of protein in the world; it is unclear how many communities rely on shellfish as their main source of protein (FAO, 2018). Table 1 demonstrates some nutritional content associated with various oyster species across the world.

Table 1. Nutritional content of oysters (Source: Food and Agriculture Organization of the United Nations 2016)

Food name	State of Food	Energy (kcal)	Protein (g/100g)	Fat (g/100g)	Carbohydrates (g/100g)	Cholesterol (mg/100g)	Zinc (mg/100g)	Vitamin B12 (mcg/100g)	Total poly unsaturated fatty acids (g/100g)
Cupped oysters, flesh, raw	Raw	73	8.89	1.8	5.3	30	11.5	21	0.65
Cupped oysters, flesh, steamed	Cooked	93	11.4	2.3	6.7	39	14.7	22	0.87
American cupped oyster, flesh, raw (n.s.)	Raw	50	5.57	1.4	3.8	31	[38.6]	18	0.47
American cupped oyster, flesh, steamed (n.s.)	Cooked	64	7.1	1.8	4.8	39	[49.5]	19	0.64
American cupped oyster, flesh, farmed, raw (USA)	Raw	51	5.11	1.4	4.7	26	[37.9]	15	0.5
American cupped oyster, flesh, farmed, steamed (USA)	Cooked	66	6.6	1.8	6.0	33	[48.6]	16	0.69

American cupped oyster, flesh, wild, raw (USA)	Raw	48	5.95	1.2	3.4	32	[39.3]	21	0.36
American cupped oyster, flesh, wild, steamed (USA)	Cooke d	62	7.6	1.5	4.4	40	[50.4]	22	0.5

There are no studies that demonstrate how much personal consumption of seafood is concentrated in seafood-dependent communities in the Gulf of Mexico or elsewhere. Despite limited empirical evidence, there is consensus that there are regions in the Gulf of Mexico where seafood is used for local consumptive and subsistence purposes (Petterson et al, 2005).

Analysis and documentation of seafood-dependent communities suggests that they are concentrated in emerging economies therefore there may be few in the Gulf of Mexico (Hobday et al, 2016). While many communities in the Gulf of Mexico are “fishing-dependent” from a social and economic perspective, it remains unclear if they are seafood dependent in terms of nutritional status.

Strength of evidence

Low. While seafood is nutritious and there are communities in the Gulf of Mexico that consume locally harvested seafood, no specific evidence to support the idea that some communities in the Gulf of Mexico depend on seafood for nutrition was found.

Other factors

None.

Predictability

There is no method to predict how much personal consumption of food is contributing to nutrition for seafood dependent communities.

Sources

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Link 21: Food (commercial sale) → Economic activity (fishing/oyster harvest industry)

Description of relationship

Seafood harvested from the Gulf of Mexico and sold commercially generates economic activity.

Summary of evidence

Seafood harvested from the Gulf of Mexico has value and generates revenue when it is sold commercially. As part of its commercial fisheries database, NOAA has data on the dockside value (the amount for which the catch is sold to the initial buyer) of commercially landed seafood, by species and state, on an annual basis (NOAA 2018). Table 1 shows the dockside value of several species associated with oyster reefs (see link 41) landed in the Gulf of Mexico in 2017.

Table 1. Dockside value for landings of oyster reef-related seafood species in Gulf Coast states, 2017.

State	**Blue crab**	**Red drum**	**Eastern oyster**
Alabama	$1,519,503	-	$556,624
Florida West Coast	$6,824,752	-	$3,921,056
Louisiana	$54,147,538	-	$84,378,781
Mississippi	$790,412	$139,421	$344,078
Texas	$5,415,937	-	$20,403,679

Additional economic activity is generated when dockside seafood dealers (who purchase landings directly from commercial fishermen) sell seafood to other customers, such as retailers, seafood processors, or the public. A 2014 survey of Gulf of Mexico dockside seafood dealers found that more than half of these dealers sell to other dealers or distributors, almost half sell directly to the public, about one-third sell to retailers, and slightly less than one-third sell to seafood processors (Miller et al. 2014). This economic activity occurs locally (59% of gross seafood sales were made to buyers within the seafood dealer's own state), regionally (23% of gross seafood sales were made to buyers in other Gulf Coast states), and nationally (18% of gross seafood sales were made to buyers in the U.S. outside of the Gulf Coast).

Strength of evidence

High. Selling seafood harvested from the Gulf of Mexico clearly generates economic activity; state-level summaries of seafood value, by species, are available from NOAA.

Other factors

The specific route that seafood takes through the supply chain (e.g. sold by a dockside seafood dealer to a consumer vs. being processed into a value-added food item) determines the amount and location of economic activity generated by that harvest.

Predictability

Dockside value can be estimated directly from catch, as NOAA does for its NFMS data. Predicting revenue from subsequent sales is more difficult; no tools were found to predict total economic activity generated from commercial seafood sales.

Sources

Miller, A., Ogunyinka, E., & Isaacs, J. (2014). *An economic baseline and characterization of U.S. Gulf of Mexico dockside seafood dealers* (No. 226). Retrieved from Gulf States Marine Fisheries Commission website: https://www.gsmfc.org/publications/GSMFC%20Number%20226.pdf

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Link 22: Food (Commercial Sale and Personal Consumption) → Cultural Practices Related to oyster

Description of relationship

While there are many festivals across the Gulf of Mexico that celebrate oysters in the region, there is no method to predict how the commercial sale and personal consumption of food influences those festivals.

Summary of evidence

Oysters are a big part the way of life in the Gulf of Mexico, particularly when it comes to culinary cultural identity in Louisiana. Oyster festivals are part of the regions culinary tourism; tourists from outside of the region attend the oyster events along with people who are more local to learn about, eat, and vote on the quality of oyster recipe competitions.

There are a number of annual festivals celebrating oysters in the Gulf of Mexico where the sale and consumption of Gulf oysters (among others) as food takes place. Annual festivals include the Gulf Coast Oyster Cook-Off in Gulfport, Florida, the Hangout Oyster Cook-Off in Gulf Shores, Alabama, the Austin Oyster Festival in Austin, Texas, The Apalachicola Oyster Cook-Off in Apalachicola, Florida, and the Shrimp, Crab and Oyster Festival in Panama City, Florida. These offer opportunities to sample and compete over differently prepared oysters. Others focus on heritage and folk life in the Gulf and feature oysters. For example, oysters feature somewhat prominently in annual Croatian celebrations, including the St. Anthony Day Festival and an oyster concession at the Plaquemines Parish Orange Festival and Fair (LSU AgCenter Research Report #116., 2013)

There is no data that demonstrates if changes in the consumption of oysters as foods has impacted the quality or quantity of festivals as cultural practices related to oysters. Likewise, there is no publicly available data outlining how many oysters are consumed and sold at these festivals, or what the attendance numbers are.

Strength of evidence

Low. Oysters are sold and consumed at various festivals across the Gulf of Mexico, but no evidence related to changes in oyster harvest or consumption and the number, quality, or attendance of festivals was found.

Other factors

Oil spills appear to be the biggest threat to access to oysters which threaten the culinary heritage associated with oysters, though it may not affect the number of festivals (Courselle 2010).

Predictability

There is no method to predict the relationship between the sale and consumption of oysters as food and the prevalence of festivals in the Gulf of Mexico.

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Link 23: Recreational oyster harvest → Economic activity (Recreation)

Description of relationship

Recreational oyster harvest in the Gulf of Mexico generates economic activity via permit fees.

Summary of evidence

In each state in the Gulf of Mexico, different amounts of revenue are derived from application fees and annual rents from recreational oyster harvest. The revenue derived from these permits goes towards financing oyster fishery management. Individuals do not generate revenue from the sale or lease of fishing permits as they are mostly not transferable between owners (VanderKooy, S. 2012).

Both the application fees and rental dues vary by state and by type of rental agreement. There are differences in price between natural and artificial oyster reefs, water bottoms and water columns, near shore and offshore harvesting sites, and more.

Unlike recreational harvest of other species, recreational oyster harvest does not create economic activity through hiring guides or purchasing or renting specialized equipment. There is not a substantial charter industry that relies on recreational oyster harvesting like there is for recreational fishing. There is, however, some evidence suggesting that opportunities for recreational harvest can serve to attract tourists into certain regions. In Northwestern Florida, for example, an area known as the Big Bend Shellfish Trail boasts harvest areas where visitors can recreationally harvest oysters, among other marine wildlife (Online Resource Guide for Florida Shellfish Aquaculture, 2017). Likewise, Shellbank Select Oyster Farm (Entin, 2018) offers oyster charters and an oyster bar for visiting tourists, and is often cited as a go-to destination in Alabama.

Strength of evidence

Moderate. There is considerable research and data collection regarding the price of permits and the revenue that state agencies receive from them, however these quantities are not public. While funding from Sea Grant was intended to determine the ecosystem service value associated with regulatory fees, the results of this study have not been published.

Other factors

There is evidence that demonstrates that fishermen who choose to diversify their harvest portfolio may be better off and have more steady income. As such, opportunities presented in other fisheries may incentivize oyster harvesters to pay fees for permits from other fisheries (Kasperski and Holland, 2013).

Predictability

There is not yet a way to use quantity of harvested oysters to predict revenue from permits, however there are efforts to make ecosystem service valuations associated with regulatory fees from oyster permitting in the Gulf of Mexico. (Otts et al., 2014)

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Link 24: Commercial, recreational, and subsistence oyster harvest → Food (for commercial sale and personal consumption)

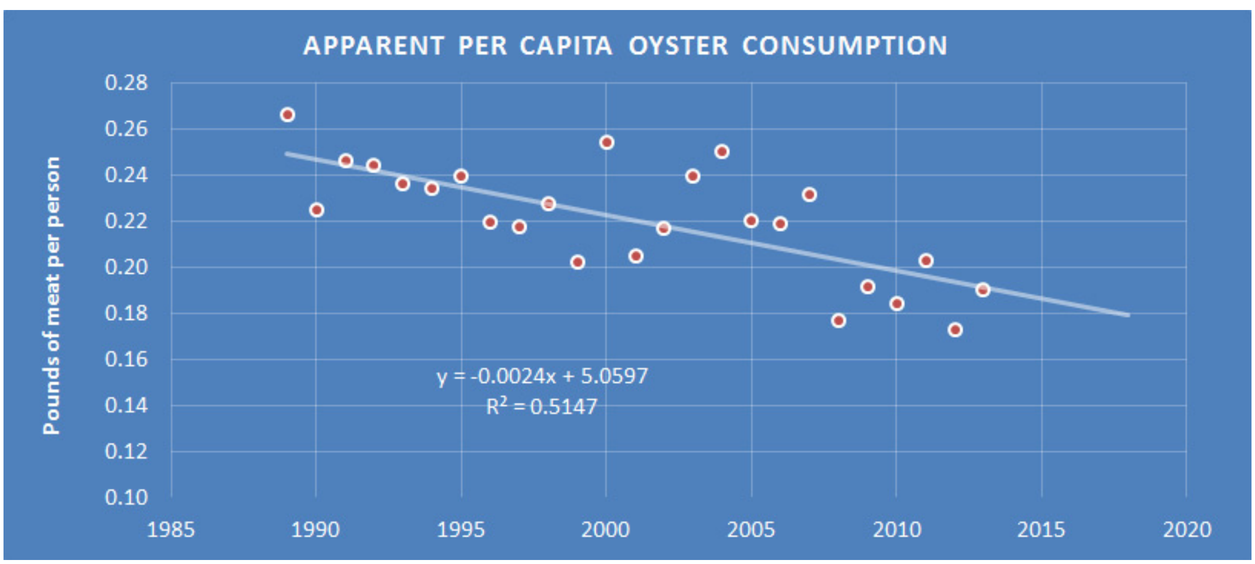
Description of relationship

All commercial oyster harvest in the Gulf of Mexico is sold for food consumption purposes, however it is unclear how much oyster harvest in the Gulf of Mexico explicitly links to larger food consumption patterns. Changes in oyster harvest quantities and/or marketing campaigns can lead to changes in price and demand for Gulf of Mexico oysters as well as their substitutes. Recreational and subsistence oyster harvest is intended for personal consumption of food.

Summary of evidence

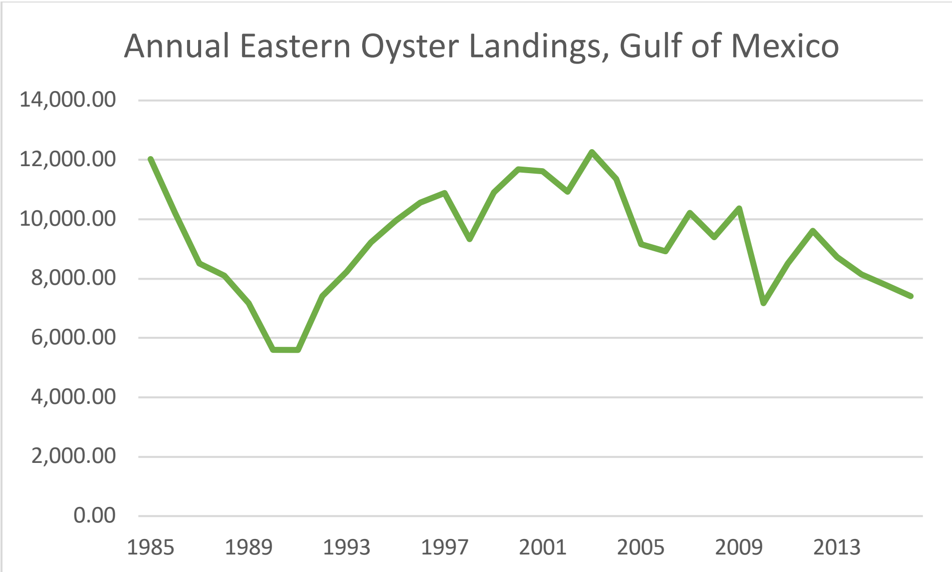
Seafood products–including oysters—are irrefutably an important contributor to food security on a global scale (Béné et al., 2016), with some three billion people relying on seafood as their main source of protein. It is unclear how much of that comes from oysters. Consumer demand for shellfish has increased, which has mobilized aquaculture operations to meet the demand (FAO, 2018). A survey conducted in Australia by Christensen et al (2017) found that the leading drivers of seafood consumption are nutrition, taste, and convenience, and the barriers are price, availability, and concerns about quality though it is unclear if that trend is also the same for oysters. A survey study conducted in South Carolina and Kentucky, however, found that demographic characteristics and the desire to support local foods are determinants of seafood consumption behaviors (Ratliff et al., 2017).

In the US, consumption and demand for seafood has increased, which has been met to some extent with imports of seafood, some of which are oysters. The Eastern oyster from the Gulf accounts for 75% of oysters that are harvested in the US, though it accounts for 54% of total market value (Petrolia et al., 2017). At the same time, however landings (domestic production) of oysters and per capita consumption of oysters in the US has decreased, and imports of oysters declined in 2016 and 2017 after steady growth. Furthermore, evidence demonstrates that per capita oyster consumption in the US is declining as imported oyster products are gaining market share (44% as of 2016) (Mississippi Market Maker, 2016). It is unclear if this trend is linked to declines in commercial harvest of oysters in the US. The figures below depict the decline in per capital oyster consumption between 1985 and 2016.



Source: Mississippi Market Maker, 2016

Figure 1. Declining per capita oyster consumption in the US, 1985 – 2016



Source: NOAA Commercial Landings Statistics

Figure 2. Oyster landings in the Gulf of Mexico, 1985 - 2016

Eastern oysters from the Gulf of Mexico tend to cost less on the market than other oysters consumed as food in the US. Oysters from the Gulf of Mexico are described as generic and without distinction, compared to oysters harvested from other regions such as Wellfleets (Cape Cod), Blue Points (Long Island Sound), and Chincoteagues (Virginia) (Petrolia et al., 2017). This may represent an opportunity to distinguish Gulf of Mexico oysters that are harvested and sold as food in a new way.

Unlike oysters harvested in other bodies of water, most oysters harvested from the Gulf of Mexico are sold and consumed as “shucked meat,” which means that they are removed from their shell and then packaged. This is largely attributed to the irregular shape and unappealing aesthetic associated with Gulf of Mexico oysters. Most oysters harvested in the Gulf of Mexico are not sold in restaurants and are not part of the live shell-stock market, which goes through a different supply chain, with different dealers and distributors. It is unclear how much of total commercial harvest of Gulf of Mexico oysters is sold as shucked meat or is intended for the live shell-stock market and how those trends have changed over time (Petrolia et al., 2017). In the Gulf, farm-raised oysters (which make up a very small portion of the commercial oyster sector) have more aesthetically appealing value and therefore tend to sell at a premium in high-end restaurants.

Changes in commercial harvest quantities of Gulf of Mexico oysters (due to closures from disease outbreaks or other disturbances) can, however, impact demand for substitute products from other regions, including imports. For example, nationwide commercial sale of oysters from the Gulf of Mexico as food suffered in the late 1990’s and early 2000’s as a result of *Vibrio* disease outbreaks which can threaten the lives of people with weakened immune systems, and their associated media coverage in California. Following the outbreak, California, Louisiana, Florida, and the FDA modified regulations and initiated awareness campaign to inform and prevent spread to at-risk populations (Dedah et al, 2011). This led to a decrease in Gulf of Mexico market share by 20%.

Subsistence harvest is often part of an "informal economy" (Hunter et al., 2008). Oyster harvesting activity leads to the exchange, bartering, and gifting of oyster resources between families and community members. It is very difficult to track this activity using empirical methods. Subsistence for oysters in the Gulf of Mexico has existed since only native populations occupied the region (Mercado-Allen and Goldberg, 2011). Ethnographic studies suggest that communities that participate in subsistence harvest of oysters in the Gulf of Mexico can be poor (Walton, 2018). They not only rely on subsistence to maintain cultural practices, but also to receive a substantial source of protein. As such, a decline in harvesting activity for subsistence can have important environmental justice consequences for communities reliant on subsistence oyster harvest (Walton, 2018). While empirical data does not exist to corroborate this claim, it seems that significant subsistence oyster harvest takes place in Louisiana. This oyster harvesting activity was negatively impacted by the Deepwater Horizon Oil Spill (Luton, 2011).

Because recreational oyster harvest is not conducted through catch and release programs, it is safe to assume that oysters harvested through recreational oyster harvest are used for personal food consumption. In fact, in the US in 2004, recreational fishing provides 7.3 kg of edible fish/angler/year (Cooke et al., 2017). However, disaggregated data by species or region could not be found, and it remains nebulous how changes in recreational oyster harvest impact food consumption.

Strength of evidence

Moderate. There is good data on commercial harvest of oysters in the Gulf of Mexico but very limited data or information documenting the supply chain and end-markets of Gulf of Mexico oysters. It is clear that there is some substitutability of oysters from different regions, which may influence the relationship between commercial harvest of oysters, commercial sale, and personal consumption of food, though that link is not explicitly clear based on the current suite of evidence. Data and studies on recreational or subsistence oyster harvest are limited, but there is consensus that those sectors are intended for personal consumption of food.

Other factors

Oil spills, disease outbreaks, changes in water quality, and regulations can all limit levels of commercial oyster harvest, which can impact commercial oyster sales as food. Public perceptions and marketing campaigns can also affect the publics' desire to purchase and consume oysters from the Gulf of Mexico.

Predictability

While commercial harvest of oysters is intended for commercial sale of food, it is not possible to predict how changes in commercial harvest will impact commercial sale of food. Likewise, changes in oyster harvest cannot predict changes in personal consumption of food.

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Link 25: Commercial Oyster Harvest → Jobs (fishing/oyster harvest industry)

Description of relationship

Jobs in the fishing and oyster harvest industry are determined by a number of social, economic, and environmental conditions, one of which may be harvest from commercial, recreational, and subsistence activities in the Gulf of Mexico. While some data exists that could suggest trends between the two nodes, there is not enough evidence to predict how oyster harvest will affect jobs in the oyster and fishing harvest industry.

(Note that other economic activity generated from the sale of commercially harvested seafood is summarized in link 21).

Summary of evidence

There are certain jobs in the fishing and oyster harvest industry that are explicitly linked to commercial oyster harvest. Jobs in the commercial oyster/fishing harvest industry include harvesters, shuckers, shellfish laborers, oyster packers, and deckhands (Haby, 2013).

Often in the Gulf of Mexico, a person with a job in the fishing/oyster harvest industry participates in and is employed by multiple fishing sectors, along with employment outside of the fishing industry. It is common, for example, for one fisher to have several licenses that allows them to switch between fisheries depending on changes in availability, price, season etc. (VanderKooy, S 2012; Riden 2003). (VanderKooy, S. 2012; Haby, 2013). As a result it is difficult to isolate the impact of commercial oyster harvest to changes in jobs in the fishing and oyster harvest industry. Descriptive data (figure 1, below) from NOAA's Fisheries Economics of the United States reports from 2008- 2016 does not suggest a clear causal impact between oyster harvest and jobs in the Gulf of Mexico.

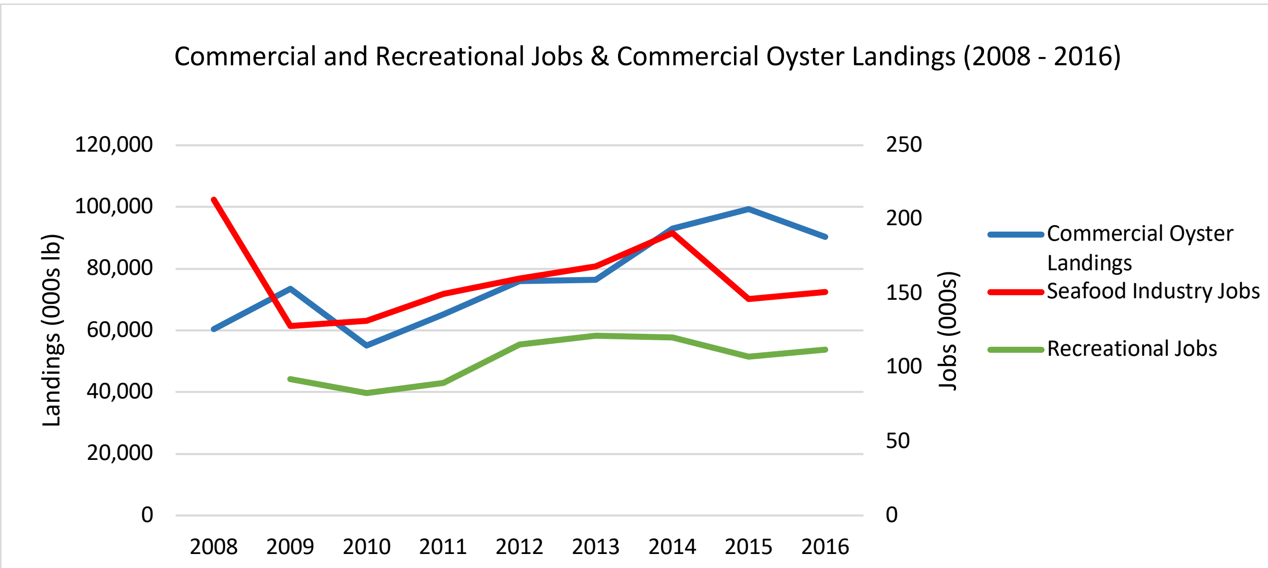

Figure 1. Commercial Oyster harvest plotted with commercial and recreational jobs (Source: NOAA FEUS 2008 -2016)

Regionally, there has been some anecdotal evidence linking oyster harvest to jobs in the industry. In Apalachicola Bay, Florida the number of licensed oyster harvesters has been stable despite fluctuations resulting from shifting demand and environmental disturbances that may reduce harvest quantities in the commercial sector (VanderKooy, S, 2012). In all of Florida however, the number of fishermen participating in the oyster fishery has declined in the past two decades. Florida's entire statewide oyster fishery includes both Gulf of Mexico and Atlantic oyster fisheries (VanderKooy, S, 2012).

Aquaculture through restoration and through other methods has the potential to serve as a new source of employment attained through oyster harvest, though this has not happened yet (Bendick et al, 2018).

Strength of evidence

Moderate. While there is good data on jobs in the fishing industry in the Gulf of Mexico, there are not sources of evidence that clearly illuminate the link between quantities of or changes in commercial oyster harvest and jobs in the fishing industry. Furthermore, there is no way to discern jobs in the oyster harvest industry from jobs in the fishing industry in general. The sources of evidence were strong, as they were up-to date government reports with a focus on the Gulf of Mexico.

Other factors

A number of other factors can influence the relationship between oyster harvest and jobs in the fishing industry. They are described below:

- Availability of additional employment opportunities in the region:
  - In Apalachicola Bay, limited employment opportunities are cited as one of the reasons that there is a stable number of oyster harvesters despite fluctuations that threaten the quantity of oysters harvested in the region. (VanderKooy, S. 2012)
  - Conversely, when there are other commercially viable fisheries, oyster harvest may be neglected in pursuit of more lucrative opportunities (VanderKooy, S, 2012)
- Closures
  - Natural disasters, water quality perturbations and anything that leads to closures that reduce oyster harvest has forced fishermen to leave the industry in pursuit of more stable opportunities (VanderKooy, S 2012)
- Demographic changes
  - Younger generations of harvesters in the Gulf of Mexico are exposed to more diverse career opportunities than those before them as a result of increasingly higher educational attainment. (Deseran and Riden 2000; GSAFF 2010)
  - In Texas, many people associated with the oyster/fisheries industry are foreign workers under the H-2B program. This may change the way jobs are counted and may correlate with traditional harvesters exiting the fishery. (Haby, 2013)
- Restrictions to entry
  - Restrictions on entry between fisheries make it difficult to move between fisheries and for new entrants to enter the fishery (VanderKooy, S. 2012)
  - Limited ability to move between fisheries resulting from limited-entry programs and moratoriums based on catch-based history VanderKooy, S. 2012; Deseran and Riden 2000)

Predictability

Many factors determine jobs in the oyster and fishing harvest industry beyond commercial, recreational, and subsistence oyster harvest, so there is limited capacity to predict the effect that oyster harvest will have on jobs in the industry.

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Link 26: Wild Oyster Population → Oyster Harvesting Activities

Description of relationship

While there have been general oyster population declines across the whole Gulf of Mexico, contemporary harvest of native oysters in the Gulf of Mexico remains among the highest in the world. Declines in wild oyster population may trigger closures for restrictions on oyster harvesting activity, including gear switches from dredging to tonging. Likewise, population declines serve as the catalyst for more aquaculture production of oyster and protected areas. Information regarding population of oysters is not formally utilized to manage harvest activity in the Gulf of Mexico.

Summary of evidence

Oysters are harvested for commercial and non-commercial (recreational and subsistence) purposes, using dredging, tonging, by hand, and from diving. There is a lot of variation regarding the ratio of dredging to tonging and the restrictions and provisions outlined for harvesting activity across the five

Gulf coast states. The catch efficiency of dredging may be impacted by the oyster reef consolidation, meaning that in localized settings, more densely populated reefs may make dredging activity less efficient, and vice versa (Marenghi et al 2017). Overall, average annual catch from 1995 to 2004 of relevant ecoregions demonstrates that oyster harvest from the Gulf of Mexico comprises the majority of global totals (Beck et al., 2011), though there is less data on harvest for non-commercial uses. This comes despite the condition of the oyster reefs in the region being described as poor or functionally extinct. The Gulf of Mexico ecoregion is one of six that has demonstrated at least a 90% loss in oyster reefs (Beck et al., 2011).

There is a lack of biological information regarding stock status (a proxy for population) of oysters. As a result, methods and models to measure population of oysters in the Gulf of Mexico that would otherwise be used for sustainable harvest are limited. While an annual survey of oyster abundance is conducted in most states in the Gulf, they have high variability between coverage and years. There is no assessment model that estimates fishing mortality and abundance of the fishable stock or helps determine the population reference points for any Gulf of Mexico oyster fishery (VanderKooy, S. 2012). Likewise, there is no model that can discern effects from harvesting, fluctuating environmental conditions, man-made perturbations, and natural mortality from disease and predation on mortality and population of oysters in the region. The literature does not show consensus on whether or not harvesting activity is the primary driver of population losses of oysters in the region. (VanderKooy, S. 2012). As a result, to date there is no clear method or model that could demonstrate any causal or inferential relationship between oyster population and oyster harvesting activity.

Management for oyster harvesting activity is not explicitly based on estimates of oyster population. There are limited plans for rebuilding oyster populations under fisheries management programs in the Gulf of Mexico. In other regions, sustainable oyster harvesting activity has been achieved through protected areas, cooperative management, access rights, and aquaculture (Beck 2011). These provisions are currently not widespread along the Gulf of Mexico (VanderKooy, S. 2012).

There have been instances where sharp population declines and collapses in the oyster stock can trigger immediate closures or restrictions on oyster harvesting activity in the region. Between 2011 and 2013, there was a collapse of near 80% of oyster biomass greater than 25 mm in length along the Gulf coast of Florida. Harvesting activities were not responsible for the collapse, external factors were (next section). This collapse led Florida Governor Rick Scott and the US Department of Commerce to declare a commercial fishery failure and enable federal funds to provide temporary relief for oyster harvesters (Florida Fish and Wildlife 2013). Likewise, closures and recommendations for closures in places with declining populations and collapses have occurred in the Gulf (Bendick et al., 2018). One such closure was announced in November 2018 for the entire state of Alabama as a result of population declines in Alabama. Though the population declines are not caused by harvesting activity, they result in prohibition of harvesting activity (Specker, 2018). It is unclear if this closure is also applied to non-commercial harvesters. Such closures –based on population changes— have a clear impact on harvesting activity in that they restrict or prohibit harvesting.

Another population decline in Calcasieu Lake, Louisiana may have been the result of dredging of oysters. In lieu of a closure of harvesting activities of the lake, state legislators decided in 2017 to mandate that tonging became the mechanism by which oysters could be harvested. This is an example in which oyster harvesting activities transition from one gear type to another in response to population declines.

Estimates of declining wild oyster populations can also serve as the catalyst for increased aquaculture of oysters (Bendick et al., 2018). There are currently limited plans for rebuilding oyster populations through fisheries management regimes, which are typically responsible for overseeing oyster harvesting activity (VanderKooy, S. 2012). Estimates of oyster populations can help establish baselines and goals for restoration and conservation programs, however those do not necessarily include provisions for oyster harvesting activity (Beck, et al., 2011). While such efforts have taken place in pilot locations throughout the region, their impacts on population or harvesting activity are not clear.

Strength of evidence

Moderate. While the evidence for this link includes peer reviewed journal articles, government reports, and white papers from NGOs who work in the Gulf of Mexico, the consistency across them is somewhat limited in that the reports do not build off of each other. Additionally, while some methods for assessing population are robust and replicable, there aren't models that can capture the relationship between oyster population and oyster harvesting activity.

Other factors

Many factors influence oyster population and oyster mortality. These include fluctuating environmental conditions (salinity, temperature, water flow, dissolved oxygen), man-made perturbations (e.g. habitat removal, coastal development), species composition on and around oyster reefs, impacts from natural and environmental disasters, and natural mortality from disease and predation. Individually and combined, these factors impact population of oysters in a way that can change the harvesting activity of oysters in the region.

Market forces may influence harvesting activity regardless of population effects, especially where population and science-based regulation of harvesting activity is not yet in place. Water quality issues may leave certain oyster reefs toxic for human consumption and therefore unable to be harvested (VanderKooy, S. 2012). Likewise, regulations on water quality, bacteria and toxins can close affected areas to oyster harvest. Changes in supply and demand for oysters in regional and global markets may lead to increases or decreases in effort for harvesting activity, which may also impact population of native oysters.

Major developments for certain kinds of aquaculture can potentially reduce pressure on wild harvest activity. In addition, innovations in the industry, for example transitioning to more selective gear, may impact harvest activity as well as populations of oysters.

Predictability

A change in harvesting activity resulting from changes in population is not easily predicted in the Gulf of Mexico. In some cases, population declines do not influence harvesting activity, while other times they do. In situations where population changes lead to harvest activity changes, an intervention from an authority dictates that change more explicitly by enabling restrictions on harvesting activity. Additionally, as long as management of the resource for harvesting does not have a standardized method to consider population or fluctuations in population, there is no way to quantify how much a change in population will impact harvesting activity

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Link 27: Oyster Harvesting Activity → Turbidity

Description of relationship

The effect of oyster harvesting activity on turbidity in the Gulf of Mexico is not precisely understood, though there is a breadth of literature on this topic for mollusk harvesting in general. Oyster reefs in the Gulf of Mexico display heterogeneity in initial sediment composition, environmental conditions, and efficiency and frequency of gear use. This obfuscates our understanding on the extent to which oyster harvesting activity impacts surrounding turbidity and sediment stability.

Summary of evidence

The literature reviewing mollusk harvesting activity, with a particular focus on dredging, indicates that such harvesting activity can alter sediment composition, increase turbidity, lead to sediment mobility and instability, and more (Mercado-Allen and Goldberg, 2011; DeGrave and Whitaker 1999). The current collection of evidence does not specifically apply to oyster harvesting activity in the Gulf of Mexico, and is described briefly below.

Where measurements have taken place (normally for clam harvesting), increased turbidity and plumes of sediment can extend from 75 to 100 feet beyond the dredge area and 98% of the sediment resettles within 50 feet of the dredged area several hours after dredging (Mercado-Allen and Goldberg 2011; Maier et al. 1998). It is unclear if the turbidity and sediment plumes resulting from dredging have long-term consequences on the surrounding environment. However, there is evidence demonstrating that long-term harvest does alter sediment composition in a given area (Tarnwoski, 2006). This can include the gradual replacement of one dominant grain size with another. These effects do, however, often depend on the type of original substrate (e.g. muddy sand) (Hauton et al. 2003; Ismail 1985). Estimating these long-term changes is also challenging because of high rates of resettlement after dredging.

Additionally, the literature suggests that hydraulic dredges and other oyster harvesting gear that use water jets on benthic areas will loosen and break up tightly packed sediment on the bottom, making it more porous, which can result in increased turbidity. Likewise, the more that a dredger passes over a given area, the more that it will loosen the sediment (Mercado-Allen and Goldberg 2011). Such effects can last for up to a year after dredging takes place (Mercado-Allen and Goldberg, 2011; Pfitzenmeyer 1972a, 1972b)

While there has been a comprehensive overview of mollusk harvesting activity in general, there is not a robust research focus specifically on oyster harvesting activity's impact on turbidity There are no models or studies that can comprehensively characterize or predict the condition of sediment stability with or without oyster harvesting. Studies that have explored sediment composition resulting from oyster harvesting activity are many decades old (Wilber and Clarke, 2010). Many factors contribute to sediment composition, and there does not seem to be a clear way to measure the contribution of oyster harvesting activity on sediment stability.

Strength of evidence

Fair. While there are multiples sources of evidence, the ones that include experimental methods are outdated (more than two decades old), and newer articles consist mostly of comprehensive reviews of the existing (and somewhat outdated literature). Likewise, a lot of the research exploring this link does not focus explicitly on oysters nor on the Gulf of Mexico.

Other factors

Many other factors contribute to turbidity both in the Gulf of Mexico as well as in other regions, and are outlined below:

- Sediment type (including grain size) affects dredging efficiency, turbidity, plume density and size, and plume dissolution (Mercado-Allen and Goldberg, 2011; Ruffin 1995; Tarnowski 2006)
- Likewise, environmental conditions such as wave activity and water column depth (Ruffin 1995; Tarnowski 2006).
- Petroleum industry drilling (Davis 2017)
- Sediment loading from non-point sources of pollution (Wilber and Clarke, 2010)
- Dredging for navigation purposes (Davis 2017; USEPA 1980).
- Natural fluctuations such as tidal cycles and storms (Wilber and Clarke 2010; Hinchey et al., 2006; Kniskern, 2001; Miller et al. 2002)

Predictability

The extent of turbidity resulting from oyster harvesting activity is not easily predicted in the Gulf of Mexico, though it can be expected to occur and for sediment to resettle in areas adjacent to harvested regions.

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Link 28: Oyster Harvesting Activity → Commercial, Recreational, & Subsistence Oyster Harvest

Description of relationship

Oyster harvesting directly begets commercial, recreational, and subsistence oyster harvest. There is far more data and knowledge regarding oyster harvesting activity as it relates to commercial oyster harvest than for subsistence or recreational oyster harvest. Based on this, it is very reliable to predict commercial oyster harvest using existing evidence streams for oyster harvesting activity.

Summary of evidence

Commercial oyster harvesting activity is often differentiated by gear type. The two most common gear types in the Gulf of Mexico region are dredges and tongs (VanderKooy, 2012). For oysters in Delaware Bay in the Northeast US, the catch efficiency of dredges is highly variable and dependent on attributes such as oyster size and reef consolidation (Marenghi et al 2017). Another study describes tonging efficiency at 100%, and dredging as highly variable, as low as 8% (zu Ermgassen. et al 2012, Chai et al 1992). This does not necessarily predict oyster harvest quantity from oyster harvesting activity without more information on effort.

The economic value of commercial harvest (e.g. ex-vessel prices) does not seem to be significantly impacted by the gear used. Between 1989 and 2009, there has been fluctuation in terms of which gear type dominated commercial harvest across the entire region. However, from 2000 to 2009, dredging has comprised the majority of landings across the region, despite Florida and Alabama having higher landings volumes from tonging activity (VanderKooy, 2012).

Commercial harvesting activity can also be differentiated by designation of harvest location, namely private or public harvest grounds. Private harvest grounds have excludability: they can only be accessed by rights holders with permits, leases, or licenses for harvestable grounds. On public harvest grounds, seed oysters are collected and transplanted to private grounds and market-sized oysters are harvested and sold commercially (VanderKooy, 2012). In this way, public ground harvesting activity indirectly leads to commercial oyster harvest as an input to private grounds, and directly leads to commercial oyster harvest through the market. In addition, public oyster reefs are seen as “wild” whereas private oyster beds are subject to anthropogenic modifications (Walton, 2016). Harvest from public seed grounds is regulated through limited entry programs such as vessel permits, quotas, and bag limits. These regulations vary by state (VanderKooy, 2012).

The majority of Louisiana’s commercial harvest comes through private ground oyster harvesting activity, despite the fact that there are 4.25 times as many public seed grounds than there are private lease grounds. The most recent data suggests that the proportion of yields from private and public grounds has fluctuated overtime, but as of 2015 only about 12% of harvest came from public grounds (VanderKooy, 2012, Banks, 2016). Texas tends to produce more harvest from public grounds than private leases, and more overall value is generated from public grounds. There is not a significant difference in terms of price-per-pound of harvest generated from private or public grounds (VanderKooy, 2012). Ex-vessel value data discerning between public grounds and private leases is not available for the other Gulf States. The National Marine Fisheries Service (NMFS) aggregates this data and makes most of it publicly accessible.

By-catch, unwanted catch, and discards do not appear to be a large portion of oyster harvesting activity and therefore do not obfuscate the inferences made about commercial oyster harvest. Based on the above, NMFS data and regional management plans for oyster harvesting activity are reliable sources for understanding commercial harvest of oysters in the region.

There is also oyster harvesting activity that yields recreational harvest in the Gulf of Mexico. Gulf wide, the recreational oyster fishery does not make up a substantial part of recreational harvest (e.g. oysters have not been considered in the top 25 caught or harvested species between 1990 and 2009), and is considered “not problematic” (Keithly and Roberts, 2017). Likewise, there are challenges to collecting viable data on catch and harvest quantity for all species across the recreational fishery in the Gulf of Mexico. Recreational oyster harvesting activity in the Gulf of Mexico is regulated on and varies by the state level. For example, in Florida, harvest is regulated with size limits, bag limits, temporal and spatial closures and more (Florida Fish and Wildlife, 2019). Likewise, an individual who chooses to harvest oysters commercially cannot also do so recreationally within the same day (and vice versa). This creates a somewhat rigid divide between commercial and recreational oyster harvesting activity in Florida. Recreational harvesting activity has can be commercial (or transactional) in nature in that it can require hiring or renting vessels, gear, and crew. It can also be done for personal reasons, such as for subsistence, which is described in more detail below.

Subsistence harvest is often part of an “informal economy” (Hunter et al., 2008). Oyster harvesting activity leads to the exchange, bartering, and gifting of oyster resources between families and community members. It is very difficult to track this activity using empirical methods. There is no data on how much oyster harvesting activity leads to subsistence oyster harvest, or discerning which gear type is utilized. Presumably the commons, rather than private oyster beds, provide grounds for oyster harvest activity for subsistence. NMFS data on catch and landings probably does not include oyster harvesting activity intended for subsistence. Furthermore, it is unclear if and when commercial and subsistence oyster harvest overlap spatially.

Subsistence for oysters in the Gulf of Mexico has existed since only native populations occupied the region (Mercaldo-Allen and Goldberg, 2011). Ethnographic studies suggest that communities that participate in subsistence harvest of oysters in the Gulf of Mexico can be poor (Walton, 2018). They not only rely on subsistence to maintain cultural practices, but also to receive a substantial source of protein. As such, a decline in harvesting activity for subsistence can have important environmental justice consequences for communities reliant on subsistence oyster harvest (Walton, 2018). While empirical data does not exist to corroborate this claim, it seems that significant subsistence oyster harvest takes place in Louisiana. This oyster harvesting activity was negatively impacted by the Deepwater Horizon Oil Spill (Luton, 2011).

In the future, it is possible that aquaculture in the region will be an additional source of oyster harvesting activity, yielding both commercial and subsistence oyster harvest. While aquaculture projects are currently underway, they do not appear to significantly contribute to either oyster harvesting activity or oyster harvest itself.

Strength of evidence

Commercial: **Moderate.** There is peer-reviewed evidence for commercial harvesting activity and oyster harvest. However, there are not strong methods or models to actually enumerate the link between oyster harvesting activity and commercial harvest, though the fishery management plan refers to some models that have been reliable in other oyster fisheries. Studies that measure efficiency for different oyster harvesting gears were consistent and applicable.

Recreational and Subsistence: **Fair.** The evidence linking oyster harvesting activity with recreational and subsistence oyster harvest tends to not come from peer reviewed sources, though it is clear that there is some anthropological research devoted to understanding certain groups that rely on subsistence harvesting in the Gulf of Mexico. In addition, there are almost no methods to determine the amount of recreational and subsistence harvest from oyster harvesting activity.

Other factors

Commercial oyster harvest results from oyster harvesting activity. Regulations that dictate utilization of gear can also impact oyster harvest resulting from oyster harvesting activity. Likewise, oil spills, natural disasters, changes in population, and other shocks can influence the capacity of harvesters in the region to engage in oyster harvesting activity or to yield oyster harvest, whether it be commercial or subsistence. For recreational oyster harvest, closures of harvesting areas are often dictated by water quality issues. These shocks are threats to the availability and reliability of commercial, recreational, and subsistence oyster harvest.

Predictability

A change in oyster harvesting activity will lead to a change in commercial and subsistence oyster harvest. This change can be much more easily predicted and tracked for commercial oyster harvest and its associated harvest activity. Existing knowledge on catch efficiency of dredges and tongs (~8%, and ~100% respectively) may not be able to forecast annual oyster harvest rates, however it can help predict oyster harvest from a particular harvest effort. Anecdotal evidence suggests that there have been fluctuations in oyster harvest activity for subsistence oyster harvest, though it is much more difficult to predict those changes using existing models and data streams.

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Link 29: Oyster Harvest Activity → Oyster Reef Quantity or Quality

Description of relationship

There is certainty a consensus that oyster harvesting activity, particularly dredging and tonging, leads to changes in oyster reef quality and quantity, including changes to wildlife habitat and population structure on reefs. Those changes come in the form of reductions in reef height and area, reef complexity and infrastructure, biodiversity, and biomass.

Summary of evidence

Oyster reefs develop and accumulate following generations of oyster growth and shell deposition in the same general area. Oyster reefs represent the creation of a type of substrate upon which habitat is created. Oyster reefs are where other species can grow, finding food and cover. Oyster reefs begin when free swimming larval oysters attach themselves to some substrate. From there, more larval oysters attach themselves to existing oyster shells. The accumulation of oysters and shelfs eventually develops into a reef area that reaches some height above the bottom. Metrics of oyster reef quality and quantity include height, complexity, area, density of oysters, and overall biomass (VanderKooy, 2012; Grabowski et al., 2007). Some oyster reefs in the Gulf of Mexico are permitted areas for harvest of oysters using tongs, dredges, and other harvesting equipment (VanderKooy, 2012). Oyster harvesting activity causes changes in the metrics of oyster reef quality and quantity.

Oyster harvesting activities are known to be one of several drivers of oyster reef damage and degradation, though its effect may not be discernable from the other drivers of change on oyster reefs (discussed briefly in "Other Factors" section). Lenihan and Peterson (2004) found that on American oyster (Crassostrea virginica) reefs in the Neuse River estuary of North Carolina, dredging reduced reef height by 34%, tonging reduced reef height by 23%, and diver hand-harvesting reduced reef height by 6%. Studies in the Chesapeake Bay and Pamlico Sound demonstrate the dredging and tonging have degraded oyster reefs and reduced oyster reef area (Rothschild et al., 2001). Likewise, there have been reductions in elevation resulting from oyster harvesting activity. Studies have yet to demonstrate whether transitioning to diver-hand oyster harvesting would have discernable impacts on oyster reefs (Grabowski et al., 2007). Conversely, one type of oyster harvesting activity (aquaculture) can potentially alleviate pressure from wild reefs (Beck, 2011).

A 2015 study (Beck and La Peyre, 2015) has measured the impacts of harvesting activity on oyster reefs in Louisiana, in the Gulf of Mexico. This study had replicable methods: two paired harvested and non-harvested sites (four in total) on public oyster grounds with similar salinity zones were chosen. Each site had three 10mX10m sample stations where measures of reef structure, water quality, and resident nekton communities were taken. The stations were sampled twice in the summer of 2010 and twice in the fall of 2010. The study determined that oyster harvesting impacts density of oysters, seed oysters, mussels, naked gobys, estuarine mud crabs, grass shrimp, other invertebrates, and other fish. The study also found that harvesting does not result in changes in the resident nekton community of oyster reefs, which could otherwise have trophic impacts.

One study in the Neuse River, North Carolina documented the impacts of oyster dredging on oyster reefs located in deep water. Oyster dredging shortens reef height, meaning that organisms living on reefs in deep water are moved farther down the water column after dredging activity takes place. Due to density stratification in the water column and anthropogenic eutrophication, there is less available dissolved oxygen (DO) in deeper water. Under such conditions, sessile organisms on shorter reefs are exposed to lower levels of dissolved oxygen than on taller reefs. Observations of these different kinds of reefs determined that there was higher abundance on taller reefs in deep water than on shorter reefs in deep water (Lenihan et al. 2001). In the study, oyster-reef dependent invertebrates and other sessile species died as a result of those conditions. This had a spatial and trophic cascading effect, in which mobile fish who preyed on the reef-associated invertebrates moved into new habitats. As a result, harvesting of oysters can have impacts on oyster reefs as well as cascading impacts on other wildlife habitats resulting from mobile species exploiting prey in new areas that serve as wildlife habitat.

Another study (deAlteris, 1998) provides a conceptual model and method for assessing the role of harvesting on oyster reefs. An analysis of the geomorphic history using bathymetric records between 1850 and 1980 in the James River estuary indicated that the area did indeed lose elevation in the study period. The study found that this reduction could be attributed to sea level rise, biodeposition from feces, and intense harvesting activity (deAlteris, 1998). This methodology provides the basis for a conceptual model for understanding the effect of harvesting activity on oyster beds, however, its relevance and transferability— the study is over three decades old—to reefs in the Gulf of Mexico is not clear.

Strength of evidence

Moderate. While there are multiple evidence types including government reports and peer-reviewed journal articles, many of the methods and experiments from the evidence are several decades old and do not focus on the Gulf of Mexico or oyster harvesting activity explicitly. One of the experimental methods did result in a conceptual model that can determine the impact of harvesting activity on reef height; other methods, however, were limited in their capacity to discern the impact of harvesting activity from other disturbances to oyster reef quality and quantity.

Other factors

There are other factors that may impact oyster reef recovery following harvesting activity. Studies of all kinds of mollusk harvesting activity note that these include: hydrodynamic energy, physical characteristics of the habitat, the characteristics of the resident species such as recruitment and reproduction , and the frequency of dredging activity, hydrological conditions, waves and currents, sediment stability, and other disturbances (Mercado-Allen and Goldberg, 2011).

Additional man-made disturbances to oyster reefs that have impacted their quality and quantity in the Gulf of Mexico include sewage and industrial pollution, channelization projects, petroleum exploration and production, and the development of shoreline housing (Kilgen and Dugas, 1989). Additional stressors on oyster reef health and habitat include diseases (e.g. dermo, nemaptosis, the burrowing clam) and predators (e.g. oystercatchers, sea anenomes, sea stars, etc.), and changes in physiochemical conditions (e.g. salinity, oxygen, and siltation) (Kilgen and Dugas, 1989).

Freshwater flow (and salinity) impact oyster reef productivity (Buzan et al 2009) and their capacity to regulate and process the chemical composition (carbon, nitrogen, and phosphorus) of the area (Dame et al 1989). Where freshwater flow is altered due to natural or anthropogenic causes, this can impact an oyster reefs capacity to be resilient against oyster harvesting activity's effect on wildlife habitat.

Predictability

The conceptual model provided by DeAlteris 1998 and the 2015 Beck study serves as a basis and starting point from which to create a model to better predict the impact of oyster harvesting activity on reef height over long periods of time. Aside from this, there are not methods that easily or actively account for or discern the impact of oyster harvesting activity's on oyster reefs in the Gulf of Mexico.

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Link 30: Oyster Harvesting Activity → Cultural practices related to oysters

Description of relationship

There is a link between oyster harvesting activity and some cultural and ethnic practices in the Gulf of Mexico. There are cultural practices such as art and festivals attributed to oysters and presumably oyster harvesting activity in the region. Ethnic groups, particularly Dalmatian oystermen have a strong history with oyster harvesting activity, though that may be waning presently.

Summary of evidence

There are a number of annual festivals celebrating oysters in the Gulf of Mexico, though they do not necessarily focus on oyster harvesting activity. Some are more focused on oysters as a food source. Others focus on heritage and folk life in the Gulf. For example, Croatians serve an important role in the development of oyster harvesting activity in the Gulf of Mexico (described below). As a result, oysters feature somewhat prominently in annual Croatian celebrations, including the St. Anthony Day Festival and an oyster concession at the Plaquemines Parish Orange Festival and Fair (LSU AgCenter Research Report #116., 2013)

The cultural tapestry of the Gulf of Mexico is quite diverse. Many groups have settled and made their living harvesting coastal resources in the region. Communities with Croatian, Yugoslavian, Vietnamese, Cambodian, Laotian, African-American, Native American and Hispanic ancestry have developed all over the region, many of them incorporating oyster harvesting activity into their livelihoods and cultural practices, while also enhancing and improving the activity (Courselle, 2010). Croatian men, in particular, stand out as having invested in and enhanced oyster harvesting activity since their arrival in the early 1800s from the Dalmatian coast (they are also known and identify as Dalmatians).

As of 2000, approximately 35 percent of the oyster harvesters in Louisiana self-identify as Croatian/Yugoslavian and many live in the Plaquemines Parish (Deseran and Riden 2000). Historically, male oyster harvesters in Plaquemines Parish were encouraged to and chose to stay in the industry, growing and expanding to include processing, canning, and distributing (LSU AgCenter). A tight-knit community, they were able to utilize social capital and networks to maintain steady employment in the oyster harvesting industry and elsewhere. A 2003 study observing social capital of oyster harvester in Plaquemines Parish, however, indicates that Croatian-American oystermen in Louisiana are now encouraging their children to pursue higher education and other career paths (Riden, 2003). The study attributes this shift to a number of changes in the oyster harvesting industry. Two of them, regulations and high operating costs, are directly linked to oyster harvesting activity. The other relevant considerations to this group are wetland area loss, pollution, water quality issues, and growing coastal populations. Interestingly enough, the respondents in the study declared that they themselves would not wish to exit the oyster harvesting industry, only that they do not want their children to enter it (Riden, 2003).

According to a 1968 report (Lovrich), Dalmatian oystermen produced three kinds of oysters using different techniques for harvesting and processing—steam canned, raw shop, and counter stock—that require different kinds of oyster harvesting activity. Steam canned oysters were harvested using dredges on natural reefs and then canned. Raw shop oysters were taken from natural reefs and then placed on bedding grounds to grow to a larger harvestable size, though it is unclear which gear was used. Lastly, stock oysters are those that are served at oyster and receive the highest prices, and it is also unclear how they were harvested. Furthermore, it is unclear if these oyster harvesting practices remain customary amongst Dalmatian oystermen in the Gulf of Mexico today.

There are many Gulf of Mexico based artists who are inspired and motivated by oysters. It is likely impossible to determine a causal link between oyster harvesting activity and this art in a meaningful way.

Strength of evidence

Moderate. There are multiple sources of evidence, and although few of them are peer-reviewed, this link may not necessitate peer reviewed literature to demonstrate the relationship between oyster harvesting activity and cultural practices in the Gulf of Mexico. Methods for measuring and understanding this link were qualitative surveys in communities. There was general consensus across the literature regarding the impact that oyster harvesting activity had on cultural practice, and which other disturbances posed as threats to cultural practices in the region.

Other factors

Factors that lead to closures of fishing grounds (such as oil spills or disruptions to water quality) impact the ability of ethnic groups who rely on the resource to continue to do so (or to want to continue to do so).

Predictability

There is no clearly predictable link between oyster harvesting activity and cultural practices related to oysters. Threats to the activity including overharvesting may serve as a motivation for ethnic groups who have historically relied on the activity for income to pursue other career paths, though there is likely no reasonable way to predict this outcome.

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Link 31: Oyster Harvest Activity → Benthic Organism Populations

Description of relationship

Oyster harvesting techniques, particularly dredging, impacts benthic populations, usually by leading to higher rates of mortality and destroying critical habitat. While dredging is known to do this, it is difficult to predict the exact impact of harvesting activity on benthic populations. There are many other factors that influence this relationship, described in the relevant section below.

Summary of evidence

A number of studies have examined the impact of oyster harvesting activity and mollusk harvesting activity in general on their respective benthic populations, with general consensus on the impacts and the caveats. Two studies have found no difference between dredged and non-dredged sites, but so far these are the anomaly. These studies and meta-analyses and their outcomes are described below.

A 2015 study (Beck and La Peyre, 2015) has measured the impacts of harvesting activity on oyster reefs in Louisiana, in the Gulf of Mexico. This study had replicable methods: two paired harvested and non-harvested sites (four in total) on public oyster grounds with similar salinity zones were chosen. The study determined that oyster harvesting impacts density of oysters, seed oysters, mussels, naked gobys, estuarine mud crabs, grass shrimp, other invertebrates, and other fish. The study also found that the trophic positions for certain species, including benthic species that reside on oyster reefs (e.g. hooked mussel, eastern oyster, grass shrimp, skilletfish, and naked goby) are generally higher in areas with oyster harvesting activity than on areas without. This may be because basal food source contributions from pelagic regions are also high in harvested sites for most organisms in the sample areas. While this study doesn't comment specifically on populations across regions, it does suggest that density, which can be seen as a proxy estimate for population, of benthic organisms (among others) does decrease as a result of oyster harvesting activity.

One study in the Neuse River, North Carolina documented the impacts of oyster dredging on oyster reefs located in deep water. Oyster dredging shortens reef height, meaning that organisms living on reefs in deep water are moved farther down the water column after dredging activity takes place. Due to density stratification in the water column and anthropogenic eutrophication, there is less available dissolved oxygen (DO) in deeper water. Under such conditions, sessile organisms on shorter reefs are exposed to lower levels of dissolved oxygen than on taller reefs. Observations of these different kinds of reefs determined that there was higher abundance on taller reefs in deep water than on shorter reefs in deep water (Lenihan et al. 2001). In the study, oyster-reef dependent invertebrates and other sessile species died as a result of those conditions. This had a spatial and trophic cascading effect, in which mobile fish who preyed on the reef-associated invertebrates moved into new habitats. As a result, harvesting of oysters can have impacts on oyster reefs as well as cascading impacts on other wildlife habitats resulting from mobile species exploiting prey in new areas that serve as wildlife habitat. While this study didn't determine population effects over time, it too can serve as a proxy demonstrating oyster harvesting activity on benthic populations.

Other studies have focused on other types of mollusk harvesting activity on benthic populations. For example, a 2000 meta-analysis (Collie et al 2000) on the effects of towed-bottom fishing gear on benthic communities in Southern and Northern Europe, Eastern and Western North America, South Africa, East and Northwestern Australia, and New Zealand demonstrated that dredges and similar gear types that penetrate through bottom initially harm benthic wildlife communities more than other modes of harvest, though the recovery rate can be quite rapid (Collie et al. 2000). While this study did not focus on oyster reef harvesting activity in particular, it was able to make predictions on how populations of certain taxa would be impacted by long-term versus one time-dredging activity. They estimate that chronic dredging in the same area could lead to 93% reductions for anthozoa (sea anenomes and corals), Malacostraca (crustaceans), ophiuroidea (echinoderms),and polychaeta (marine worms).Alternatively, a single dredge event could lead to 76% reductions for the same species groups. While these predictions are not directly relevant for estimating the impact of oyster harvesting activity in the Gulf of Mexico, they do suggest that it reduces benthic populations.

Aside from observing mortality and changes in population, other impacts of dredging on benthic wildlife include being removed, crushed, cut, injured, buried, exposed, scraped away, smothered, discarded, washed out in the gear, and having reduced respiratory and feeding function due to turbidity and hypoxic conditions (Mercado-Allen and Goldberg, 2011). All of these can also threaten long term resilience and viability of benthic organisms in areas susceptible to oyster harvesting activity.

Not every study is in accordance, however, with the outcomes mentioned above. In the Northeast US, a 1998 study (Langan, 1998) examined oyster dredging on two nearly identical sites, where one had been dredged, and the other had not for 30 years. The study found no significant differences in biomass, diversity, and species richness of epifaunal and infaunal (both benthic) invertebrates and oligochaetes (aquatic and terrestrial worms) between the two sites. The site with harvesting activity had more crustaceans and mollusks. Another study observed the impact of clam dredging on the benthic community along the Connecticut coast of Long Island Sound. The results showed no difference for ecological indices between dredged and not dredged plots, and the researchers concluded that environmental conditions such as seasonal settlement patterns and sediment grain size impacted the benthic community more than clam dredging. This may be attributable to the fact that a certain level of oyster harvesting activity can provide an appropriate amount of disturbance to oyster reefs to respond to over-growth on unharvested reefs which can lead to the smothering of crowded animals (Mercado-Allen and Goldberg 2011). Others have noted, too, that these types of experimental methods aren't ideal because reefs and harvestable areas used as sites are very dynamic systems that are difficult to control for variables and therefore hard to compare.

Strength of evidence

Moderate. While most of the evidence types are well cited peer reviewed journal articles or government reports, they focus on mollusk harvesting activity in general, which includes but is not limited to oysters and oyster reefs. Most of the sources of evidence were consistent in their findings that oyster harvesting activity impacted benthic populations, though two experimental studies in the Northeast US found that such activity had no effect on benthic populations. The methods included experimental studies comparing across sites. These are replicable methods though there are concerns that they are difficult environmental to control for all factors.

Other factors

Many factors that influence the relationship between oyster harvesting activity and benthic populations are mentioned in the Summary of Evidence section. Some are summarized below. **Note**: this is not an exhaustive list and doesn't pertain to oyster harvesting activity in the Gulf of Mexico, but rather the impact of dredging on benthic organisms (Powell et al., 2002; Mercado-Allen and Goldberg 201; Moschino et al. 2003).

Biological factors:

- Species' susceptibility to damage. Some benthic organisms are more resilient to damage than others

- Species' Recovery rate. After enduring damage from harvesting activity (particular dredges) some benthic species (such as clams) recover faster than others, influencing the effect of dredging on benthic populations.
- Biological community. Some communities/habitats have more biodiverse than others (including vegetation), which can impact resilience and how much population of benthic organisms is affected by dredging activity.

Physical factors

- Substrate type. Different substrates can impact dredge efficiency, which has varying effects on population of benthic organisms.
- Water Depth. Depending on the water depth, the dredge line (length) may have more intensive impacts on benthic habitats and organisms
- Water pressure. Increasing water pressure is known to lead to increased damage to clams in hydraulic dredge harvesting. It remains unclear if this also an impact in oyster harvesting areas.

Gear-related factors. Neither harvestable areas nor dredging attributes are homogenous across a given area; dredging isn't a precise science and some areas are dredged more efficiently and more intensely than others

- Time scale/frequency of dredging. Some areas with benthic wildlife are dredged once or rarely (i.e. given time to recover), while others are dredged very frequently, which leads to variable outcomes on benthic wildlife population.
- Gear attributes – Gear attributes (e.g. size, whether or not they are mechanized) are cited as having an impact on the severity of impact of dredging activity on benthic populations.
- Depth of gear penetrations – This is similar to water depth, but the depth of gear penetrations in the water column and on the seafloor impacts the magnitude of disruptions from harvesting activity

Mercado-Allen and Goldberg (2011) have more details and other factors that influence this relationship.

Predictability

While it is likely that oyster harvesting activity, particularly dredging, will lead to population declines of benthic organisms, there are so many other factors and considerations that influence this relationship that there are challenges to predicting the relationship between the two.

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Link 32: Oyster Harvesting Activity → Oyster Populations

Description of relationship

Oyster harvesting activity, particularly dredging, can lead to reductions in oyster biomass on a given oyster reef, however without better information and data on oyster stocks, it is difficult to discern the long-term relationship between oyster harvesting activity and oyster populations.

Summary of evidence

A 2015 study (Beck and La Peyre, 2015) has measured the impacts of harvesting activity on oyster reefs in Louisiana, in the Gulf of Mexico. This study had replicable methods: two paired harvested and non-harvested sites (four in total) on public oyster grounds with similar salinity zones were chosen. The study determined that oyster harvesting reduced the number of oysters, along with other organisms that reside in and rely on oyster reefs. However, it is not clear how this affects overall population, as oysters and oyster reefs that have been disturbed by harvesting activity can recover depending on the frequency and magnitude of the disturbance from oyster harvesting activity (VanderKooy, S. 2012).

To date there is no clear method or model that could demonstrate any causal or inferential relationship between oyster harvesting activity and oyster population. There is a lack of biological information regarding stock status (a proxy for population) of oysters in the Gulf of Mexico, and methods and models to measure population of oysters in the Gulf of Mexico are limited. While an annual survey of oyster abundance is conducted in most states in the Gulf, they have high variability between coverage and years. There is no assessment model that estimates fishing mortality and abundance of the fishable stock or helps determine the population reference points for any Gulf of Mexico oyster fishery (VanderKooy, S. 2012). Along with oyster harvesting activity, fluctuating environmental conditions, man-made perturbations, and natural mortality from disease and predation are all threats to oyster populations.

There is not consensus across the literature on whether or not harvesting activity is the primary driver of population losses of oysters in the region (VanderKooy, S. 2012). In regions within the Gulf of Mexico with fewer or milder environmental perturbations, low recruitment, and high predation and stress are high, oyster harvesting activity (overfishing, specifically) may be the primary driver of population declines. However, regions are not homogenous over space and time in this way in the Gulf of Mexico.

Oyster harvesting activity may indirectly impact oyster population by making oysters and oyster reefs more vulnerable to severe environmental perturbations, such as hurricanes, that are common in the Gulf of Mexico. In Galveston Bay, Texas, following Hurricane Ike in 2008, half of the public oyster reefs were lost after sediments settled on the reefs. Conversely, private oyster lease areas which are subject to less oyster harvesting activity were less disturbed following the hurricane (VanderKooy, S. 2012).

Strength of evidence

High. The two sources of evidence are from peer-reviewed journals and the fishery management plan for Gulf of Mexico oyster harvesters; both were published in the past decade, therefore making them strong types of evidence that were quite applicable to understanding the link. Across the evidence types there was consensus on the effects of harvesting on oyster population including some capacity to discern those affects from other threats to population. Methods are replicable though there are concerns that it is difficult to control using experimental methods comparing different sites.

Other factors

There are other factors that may impact oyster population recovery following harvesting activity. Studies of all kinds of mollusk harvesting activity note that these include: hydrodynamic energy, physical characteristics of the habitat, the characteristics of the resident species such as recruitment and reproduction , and the frequency of dredging activity, hydrological conditions, waves and currents, sediment stability, and other disturbances (Mercado-Allen and Goldberg, 2011).

Predictability

While it is likely the oyster harvesting activity, particularly dredging, will lead to population decline of oysters, there are many other causes that lead to population declines in oysters in the Gulf of Mexico. In addition, there remain insufficient methods for assessing and modeling population dynamics of oysters in the Gulf of Mexico to better understand and quantify the relationship between fishing mortality and population.

Sources

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Link 33: Benthic organism populations → Non-oyster harvest

Description of relationship

Populations of certain benthic species support the fishing industry. Maintenance of these populations will result in support of commercial, recreational and subsistence harvest.

Summary of evidence

This link will depend on the species or taxa being harvested. The benthic species that are of particular importance in Gulf of Mexico include blue crab and, brown shrimp, white shrimp. For example, the blue crab fishery has three components- residential, commercial and subsistence (Steele and Bert, 1998). Since 2000, annual Gulf hard crab landings have averages ~34% of total U.S. harvest, despite a reduction in effort for several of those years. In 2006, following hurricanes Katrina, Rita and Wilma of 2005, the Gulf's contribution reached an all-time high of 41.3% of the total US hard crab landings. The recreational fishery is thought to contribute significantly to total fishing pressure, with estimates of creational harvest equal to 4%-20% of reported commercial catch in different areas of the Gulf. Fishing effort, as measured by the no. of fisherman, has increased dramatically; from 1,516 in 1980 to 4,028 in 1991, an increase of 166% (GSMFC, 2015). The blue crab is an abundant, environmentally tolerate estuarine organism with year-round accessibility to the fishery.

The shrimp fishery in Gulf of Mexico was put under the management of The Gulf of Mexico Fishery Management Council and the National Marine Fisheries Service (NMFS) in 1981. Four species were included in the fishery management plan: brow shrimp *Farfantepenaeus aztecus,* pink shrimp *Farfantepenaeus duorarum,* white shrimp *Litoeus setiferus*, and royal red shrimp *Pleoticus robustus.* Since its commercialization, the shrimp fishery experienced economic losses primarily due to and reduced prices caused by competition with imports. In 2016 several issues were identified with the fisheries management plan. The number of permits issued for the shrimp fishery have been declining as maximum sustainable yield numbers are being recalculated for shrimp (Gulf of Mexico Fisheries Council, 2017).

From past evidence it is clear that harvesting beyond the limits fisheries can support leads to a critical crash in catch. Consumer demand, inadequate data and scientific information has led to overharvesting, reducing stocks and reducing species around the world (Fryxell *et al.,* 2017). In order to sustain commercial harvest of species, it is essential to maintain a balance between population regeneration times and catch size. As a result of this, the NOAA Sustainable Fisheries Division adopted the Magnuson-Stevens Fishery Conservation and Management Reauthorization Act. The act mandates the use of annual catch limits and accountability measures to end overfishing. For example, annual catch limits for Royal Red shrimp in the Gulf of Mexico is 337,000 lbs after which the fishery is closed. Spiny Lobster has a 6-month closed season. Such regulations indicate that there is a direct link between the wildlife population and commercial harvest (Gulf of Mexico Fisheries Council, 2019)

Strength of evidence

High. There is a strong link between size of wild population and size of harvest.

Other factors

Habitat destruction: The demand for waterfront properties in coastal regions of Florida resulted in loss of bay area due to dredging and other activities that led to blue crab habitat destruction. Other blue crab habitats such as wetlands, seagrasses, mangroves and tidal swamps have faced declines in area and quality of habitat. Alteration of freshwater flows and pollution by agricultural outflow have further impacted the Florida Bay (GSMFC, 2015).

Invasive species: Invasive species can be detrimental to blue crab populations through increased competition for food and space and alteration of the trophic structure of an ecosystem. Invasive species that occur in the Gulf of Mexico freshwater include ~480 microbes, invertebrates and aquatic vertebrates and ~200 aquatic plants (Battelle, 2000). These species have the potential to affect native populations and habitats.

Predictability

There are a number of stock assessment models that can be used to predict fish biomass. For example, the Food and Agriculture Organization (FAO) have a fish stock assessment model that can be applied to any fishery. The main objective of fish stock assessment models of exploited stocks is to predict what will happen in terms of future yields, biomass and value of catch, if the level of fishing effort remains the same. In an unfished stock the combined inputs are, on the average, equal to the removal of biomass by natural deaths. In a fished population, the relationship between fishing populations and recruitment size is given be a non-linear equation (refer to Sparre and Venema, 1998).

Sources

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Link 34: Benthic organisms → Bird populations

Description of relationship

Broadly speaking, benthic organisms serve as a primary or additional food source for birds. Therefore, changes in benthic populations should affect bird populations. However, there is limited evidence that can demonstrate the extent of this relationship.

Summary of evidence

Breeding bird populations are generally limited by resource availability (Newton, 1998). As such, bird species that feed primarily on benthic organisms will be affected most by changes in benthic organism populations (Molle et al., 2015). Bivalves can be important prey for generalist bird species as well (Griffiths et al., 2017; Sturbois et al., 2015). Shorebirds that consume benthic organisms have been shown to respond to prey availability by changing their distribution and behaviors (Colwell & Landrum, 1993; Garcia et al., 2016).

Some species, such as the red knot, are able to adapt their diet by using alternative prey – which means that they would be less affected by such fluctuations (Sturbois et al., 2015). American Oystercatchers feed primarily on benthic prey and have been demonstrated to select prey based on temporal and spatial availability (Garcia et al, 2016).

Strength of evidence

Fair. There is some evidence regarding the impact of changes in benthic organism populations on bird populations. Evidence is primarily taken from peer-reviewed journals; however, these studies do not take place in the Gulf of Mexico and thus may not be applicable.

Other factors

The location of the benthic organisms may affect the ability of birds to forage. Bird populations tend to prefer shallow and transition zones for feeding on benthic prey; deeper waters would greatly limit the availability of these benthic resources to birds (Griffiths et al., 2017). Therefore, intertidal oyster reefs may provide more food resources to birds than subtidal reefs do.

Biophysical features of the environment must be considered, as they can affect the distribution of bird populations as well (Colwell & Landrum, 1993).

Predictability

Although studies agree that changes in benthic populations will have an effect on shorebird populations, no models have been developed to predict this relationship.

Sources

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Link 35: Oyster populations → Bird populations

Description of relationship

Limited evidence suggests that changes in oyster populations can impact birds that feed on oysters.

Summary of evidence

Studies show that decreases in the availability of oysters can reduce overall food supply for shorebirds like the American oystercatcher (Markert et al., 2013). This can lead to changes in the birds' behavior – such as increased consumption of a different species or the switch to a different foraging location. For example, Tuckwell et al. (1997) found that after a decline in oyster populations due to harvesting, American oystercatchers increased their diet to include other species such as worms and were found foraging on sandy mudflats instead of oyster reefs.

The effect of oyster population change on bird populations will dependent upon the bird species. The American oystercatcher, for example, feeds primarily on oysters as well as other bivalves, and will likely be most affected by changes in oyster populations (Brush et al., 2016). Species that consume a broad range of food resources will be less affected than those that primarily feed on oysters (Waser et al., 2016). Additionally, although some bird species are not directly affected by changes in oyster populations, they may be indirectly affected through their associations with affected bird species (Waser et al., 2016).

Strength of evidence

Low. There are very few pieces of evidence that document the direct impact of oysters on bird populations. Evidence is taken from peer-reviewed journals; however, most of these studies do not take place in the Gulf of Mexico and thus may not be applicable.

Other factors

Tuckwell et al. (1997) have suggested seasonal differences in feeding patterns – American oystercatchers may seek out alternative prey during autumn to avoid competition and interference.

Biophysical features of the environment must be considered, as they can affect the distribution of bird populations as well (Colwell & Landrum, 1993).

Predictability

Little evidence documents the direct impact of oyster on bird populations, and no models have been developed to predict this relationship.

Sources

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Link 36: Population of Oysters → Oyster Habitat Persistence

Description of relationship

In oyster restoration projects, population of oysters is one of several indicators that determines oyster habitat persistence. Where there are consistently high rates of oyster populations in a restoration area, this is seen as a strong indicator of habitat persistence as well as restoration success.

Summary of evidence

Oyster habitat is comprised of oyster reefs, and therefore the presence or absence of oysters is expected to have an impact on habitat. One method for evaluating oyster restoration success is by determining oyster habitat persistence (Baggett et al 2015). According to a review article written by 20 frequently cited researchers on oysters and oyster restoration in the US, the metric to determine oyster habitat (reef) persistence is "reef areal dimension," and consists of five measurements taken at various frequencies (Table 1). Two of these metrics – oyster density and size-frequency distribution serve as proxies for population at a given moment in time; the research indicates that high population (high oyster density and size-frequency distribution) over time are indicators of oyster habitat persistence. These metrics are also proxies for recruitment and survivorship on the reef. While this does not numerically describe the relationship between population and persistence, it does provide guidance on methods to help predict that relationship.

Table 1. Reef Aerial Dimension Metrics (Source: Baggert et al. 2015)

Metric	Methods	Units	Frequency	Performance Criteria
Project Footprint	Measure maximal aerial extent of reef using GPS, surveyor's measuring wheel or transect tape, or aerial imagery; subtidal, use sonar or SCUBA.	m^2	Preconstruction, within 3 months post construction, minimum 1–2 years post construction; preferably 4–6 years.	None

			After events that could alter reef area.	
Reef Area	Measure area of each patch reef dGPS, surveyor's measuring wheel or transect tape, or aerial imagery; subtidal, use sonar or depth finder with ground truthing. Sum all patches to get total reef area.	m^2	Preconstruction, within 3 months post construction, minimum 1–2 years post construction; preferably 4–6 years. After events that could alter reef area.	None
Reef Height	Measure using graduated rod and transit, or survey equipment; subtidal, use sonar or depth finder	m	Preconstruction, within 3 months post construction, minimum 1–2 years post construction; preferably 4–6 years. After events that could alter reef area.	Positive or Neutral Change
Oyster Density	Utilize quadrats. Collect substrate to depth necessary to obtain all live oysters within quadrat, and enumerate live oysters, including recruits. If project involved the use of seed oysters, enumerate all seed oysters present in quadrat.	ind/ m^2	Immediately after deployment if using seed oysters. Otherwise, annually at the end of oyster growing season(will vary by region),1–2 years at minimum; preferably 4–6 years	Based on short- and long-term goals developed using available regional and project-type data, as well as current and/or historical local/regional densities.
Size-frequency distribution	Measure shell height of at least 50 live oysters per oyster density sample	mm (size), number or %per bin (size dist.)	Annually at the end of oyster rowing season (will vary by region) in conjunction with oyster density sampling, at a minimum.	None

In 2004, the US Army Corps of Engineers undertook an oyster restoration project–a 35-hectare area in the Great Wilmico River, Virginia (Schulte et al, 2009). Measurements and estimates of population were determined in 2007 and 2009 at 185 million oysters of various age classes. The researchers indicate that this thriving population measured three and five years after the restoration is a strong indicator of reef persistence.

Strength of evidence

High. Oyster populations are widely used as an indicator of persistence of oyster reefs and success of restoration projects. Oyster reefs are made of oyster shells, so a large oyster population directly creates and sustains the oyster reef habitat.

Other factors

In other regions, reef height is associated with oyster reef persistence (Taylor and Bushek, 2008).

Predictability

Consistently high populations of oysters are a strong indicator of oyster habitat persistence. However it is not clear which quantities/densities of oyster population indicate poor habitat persistence versus high habitat persistence.

Sources

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Link 37: Bird populations → Wildlife viewing

Description of relationship

Increases in bird populations can increase opportunities for bird-related recreation.

Summary of evidence

Birding is a popular activity for recreationists –according to the 2011 U.S. Census, birds attracted the most interest from wildlife viewers on trips, with about 18.9 million participating annually in the U.S. The most watched birds were waterfowl (13.3 million people), and other water birds such as herons attracted 10.6 million recreationists. Birding in Gulf of Mexico states is expected to generate between $2.88 billion to $11.5 billion annually (Table 1; Shepard et al., 2013).

TABLE 1. Estimated annual nonmarket values for selected recreational activities (nearest million $) that generate up to another $52 billion per year in nonmarket value of Gulf states' ecosystem services (from Kildow et al., 2009).

Activities	Alabama	Louisiana	Mississippi	Texas	Florida[a]
Beach	237–592	81–202	174–434	705–1,762	3,543–8,858
Swimming	164–410	92–230	135–337	592–1,480	3,222–8,055
Bird watching	118–472	228–911	181–725	401–1,605	1,949–7,795
Other wildlife	161–644	264–1,056	60–238	315–1,260	1,257–5,026
Fishing	253–422	749–1,249	280–466	986–1,643	3,377–5,629
Total—max. estimates	933–2,540	1,414–3,648	830–2,200	2,999–7,750	13,348–35,363

[a] Includes Gulf and Atlantic coasts of Florida.

Source: Shepard et al., 2013

Although no studies were found that link bird populations directly to recreation outcomes, an increase in bird populations will (most likely) increase birding opportunities. To determine this relationship, however, data on bird population sizes, number of people recreating or survey results on quality of recreation experiences are needed.

Participation in birding may depend more on the presence and predictability of different bird species, rather than the sizes of the populations (Duffus and Dearden, 1990). The diversity of the bird populations is also a major determinant that can drive these recreational activities. A study by Booth et al. (2011) found a positive relationship between rarity of birds seen at a site and the visitor numbers to the site.

Strength of evidence

Low. Though there are many logical connections to be made between bird populations and wildlife-based recreation, there are few studies that report data linking bird populations to recreational visits or tourist numbers. Site-specific information and data will be necessary to make estimates of recreational outcomes related to wildlife populations.

Other factors

Breeding versus Wintering Grounds: Bird populations may be more valued differently based on spatial differences. Mattson et al. (2018) found that viewing of the norther pintail was generally valued more in breeding regions than in wintering regions. Kolstoe and Cameron (2017) found that the marginal willingness to pay for an additional bird species was highest in June when birds are in their mating season plumage.

Laws, Permits, Permissions: Restrictions are sometimes applied to habitat or nesting areas for threatened or endangered species, so members of the public are not able to view them even if the population of that species is increasing.

Population Size Versus Visibility: For most species, visibility is a key aspect of wildlife-based recreation. If a species is particularly camouflaged, lives in dense habitat, is nocturnal, or is generally hard to see, it will be hard to link that species to wildlife-based recreation.

Facilities: A site may become more attractive for wildlife viewing if it provides facilities designed to provide services to visitors (Duffus & Dearden 1990).

Negative Feedbacks: Though increased populations of bird species can yield recreation or tourism benefits, increased recreational activities could negatively affect wildlife. Increased disturbance, noise, interactions with people, and facility construction can alter wildlife behavior and potentially decrease population numbers (Green & Giese 2004). If recreation negatively affects wildlife to the extent that populations die off or migrate, the original recreational benefits from those wildlife species will also disappear.

Predictability

InVEST models are convenient tools to predict ecosystem services-related outcomes; however, they inherently simplify certain processes and make assumptions (Natural Capital Project, n.d.). These assumptions are well described, and the user can run this model fully aware of its limitations. However, model limitations mean output limitations. The recreation model has been tested in multiple cases, and the natural capital project website links to practical applications of the model for reference. Spatial data on bird population presence or abundance are needed to use this model to predict bird population impacts on recreation person-days.

Other types of models can also be used to predict how visitation or recreation will change on the basis of bird species. Studies such as that performed by Booth et al. (2011) relating species rarity to the number of visitors to a site can provide site-specific data that will enable detailed descriptions of the connection between bird populations and recreation indicators. Though this study used species rarity as a predictor, it would be possible to also use data on population numbers, species diversity, or some other wildlife indicator as a predictor variable.

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Link 38: Recreation (boating, swimming, wildlife viewing, waterfowl hunting) → Economic activity (recreation)

Description of relationship

Engaging in recreational kayaking and wildlife viewing supports economic activity, including jobs, via expenditures on equipment, travel, and guides.

Summary of evidence

The National Survey for Fishing, Hunting, and Wildlife-Associated Recreation (NSFHWAR) estimates wildlife-watching expenditures by state every five years; the most recent year with state-level data available is 2011 (US DOI et al., 2011). Table 1 summarizes expenditures related to wildlife-watching for the Gulf coast states. These include all expenditures related to wildlife-watching in each state, not just for wildlife-watching activities along the Gulf coast.

Table 1. Trip and equipment expenditures for wildlife-watching, 2011, thousands of dollars

State	Trip expenditures	Equipment and other expenditures	Total expenditures
Alabama	41,191	693,014	734,204
Florida	1,732,652	1,308,682	3,041,334
Louisiana	222,145	320,607	542,752
Mississippi	90,493	251,928	342,422
Texas	478,080	1,345,678	1,823,758

Trip expenditures, including food, lodging, and transportation, would be expected to increase with the total number of wildlife-watching trips taken. However, equipment expenditures are likely not as tightly tied to the number of trips taken since equipment lasts for multiple trips.

The Bureau of Economic Analysis compiles outdoor recreation satellite accounts showing the contribution of the outdoor recreation economy to GDP. In 2016, real gross output for kayaking at the national level was estimated at $512 dollars (in 2012 dollars) (U.S. Bureau of Economic Analysis, 2018). No estimates for finer geographic areas within the United States were found. A survey of kayakers in Wales asked participants about the amount of time they spend kayaking and how much they spend on kayaking-related costs; the mean cost per day of about $40.86 (2013 dollars, calculated from the British pounds to dollars conversion rate in February 2013) (Ruiz-Frau et al., 2013). Again, certain expenditures related to kayaking would be expected to increase with the number of trips taken (food, lodging, and transportation), but equipment-related expenditures may not increase with the number of kayaking trips since durable equipment is used for multiple trips.

While no specific evidence related to jobs supported by kayaking or wildlife viewing was found, the expenditures (on travel and equipment) by participants in these activities make it reasonable to conclude that these recreational activities do support jobs. According to a report on wildlife tourism in the Gulf Coast economy, tourism supports 2.6 million jobs in Gulf Coast states and is concentrated in coastal counties, suggesting that tourism is associated with the coast (Stokes & Lowe, 2013). In addition, the report identified businesses (guides and outfitters) related to wildlife tourism in the Gulf (Table 1). These businesses clearly support jobs, but they may not exclusively depend on wildlife-watching. Some of them also support fishing, hunting, boating, and other tourist activities.

Table 1. Number of wildlife-related businesses by state (Stokes & Lowe, 2013).

State	Number of wildlife-related businesses
Alabama	26
Florida	97
Louisiana	24
Mississippi	22
Texas	60

A Google search for 'kayak outfitters Gulf of Mexico' finds many results for businesses providing guided kayak trips and rental equipment; these businesses also directly support jobs.

Strength of evidence

Moderate. While there is not as much evidence on economic activity from wildlife-watching and kayaking as there is for recreational fishing (link 15), participants in these activities spend money on travel and equipment. Based on expenditures related to kayaking and wildlife-watching and the number of businesses dedicated to these activities, it is clear that they support jobs in the Gulf of Mexico region.

Other factors

The specific type of activity determines the level of expenditures that support jobs and whether jobs are directly supported (e.g. via hiring guides).

Predictability

No tools or models to predict this relationship were found.

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Link 39: Bird population → Threatened and endangered species persistence

Description of relationship

Federally listed and state listed threatened and endangered bird species could be impacted by oyster reef restoration. Impacts on the American oystercatcher, bald eagle, red knot, and brown pelican can be found in links 34, 35, 43 and 46.

Link 40: Oyster reef quantity/quality → Oyster population

Description of relationship

Studies have observed immediate oyster recruitment to restored or new reefs. Reef characteristics such as height, size and amount of interior versus edge can also impact oyster populations.

Summary of evidence

The addition of oyster reefs has been associated with substantial oyster recruitment and growth (Blomberg et al., 2018; La Peyre et al., 2014). After restoring 260m^2 of oyster reef habitat in coastal Louisiana, La Peyre et al. (2014) found immediate oyster recruitment, with densities of oysters greater than 75mm exceeding 80 individuals/m^2 after 3 years. Blomberg et al. (2018) also found that oyster abundance and size were comparable to nearby natural and restored oyster reef habitats within the first year of building a reef in Copano Bay, Texas.

The effects of additional oyster reef habitat may be dependent upon the availability of oyster larvae. In Pamlico Sound, North Carolina, a study found that increasing oyster larvae did not enhance oyster populations due to the high natural recruitment of oysters. Therefore, in this case resources would be better used on creating additional substrate (Geraldi et al., 2013). However, in ecosystems where oyster recruitment is limiting or mortality is high, adding substrate may not have a large effect. While research in the Gulf of Mexico has suggested that the Gulf is also limited by substrate (Frederick et al., 2016), more evidence is needed to better predict the impacts of oyster reef restoration.

Reef characteristics such as reef height, size and amount of interior versus edge habitat impact oyster recruitment and densities. Oyster density was fourfold greater on high-relief reefs (25cm - 45cm above river bottom) compared to low-relief reefs (8cm - 12cm above river bottom) in a Great Wicomico River, Virginia study (Schulte et al., 2009). A Chesapeake Bay study found that reefs higher than 0.3m supported greater oyster density than reefs lower than 0.3m (Colden et al., 2017). Interior locations (near the center of the reef), intermediate sized reefs (5m-8m radius) and natural patch reefs have also been associated with greater oyster densities (Hanke et al., 2017).

Strength of evidence

Moderate. All types of evidence used were peer reviewed journal articles from the past decade. The studies on oyster recruitment took place in the Gulf of Mexico and were consistent in finding that the presence of oyster reefs increases oyster recruitment and density. The studies on reef characteristics took place in other areas in the U.S., though they did agree that high relief reefs tend to support greater oyster densities. Evidence for interior versus exterior location, reef size, and natural versus artificial reefs are limited.

Other factors

The suitability of oyster reefs as oyster habitat is affected by a host of environmental factors, such as temperature, salinity, water depth, dissolved oxygen and turbidity (Gregalis et al., 2009; Linhoss et al., 2016; Pollack et al., 2012; Wang et al., 2008). In particular, salinity and temperature have been cited as having the most dominant effects on oyster growth and mortality (La Peyre et al., 2016).

Hanke et al. (2017) emphasized the need to take into account both population and habitat characteristics when considering the impact of oyster reef change on oyster populations, as there are complex interaction effects and tradeoffs involved. For instance, habitats that observed high oyster densities also saw decreases in oyster size (Hanke et al, 2017).

Another study cited the importance of monitoring oyster densities over multiple years to capture multiple recruitment cycles and growth (Blomberg et al., 2018).

Predictability

While studies concur that changes in oyster reef availability and quality strongly impact oyster populations, no models exist yet to document the extent of this impact. There are habitat suitability models, (e.g. Linhoss et al., 2016; Pollack et al., 2012), population models (Wang et al., 2008), as well as bioenergetic models (Lavaud, et al., 2017), which can help predict oyster population response to environmental changes.

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Link 41: Change in oyster reef quantity/quality → Marine wildlife populations

Description of relationship

One of the goals of oyster reef restoration is to create and enhance critical habitat for fish and invertebrates, as oyster reefs can provide spawning substrate, a refuge from predation, and a food source for marine life. This results in increased populations of certain wildlife species.

Note: link 40 discusses the relationship between oyster reef extent/condition and oyster populations. This link focuses on non-oyster marine wildlife populations.

Summary of evidence

Oyster reefs are used as habitat by many marine species, and a variety of field studies shows increased abundance of certain marine wildlife species on oyster reefs. Generally, the addition of oyster reefs can lead to increased abundance of nekton (swimming aquatic animals)**.** In a review of six studies containing quantitative measurements of abundances of fish and crustaceans on oyster reefs in southeast United States, Peterson et al. (2003) estimated that 1 m^2 of restored oyster reef habitat creates an additional 260g of fish and large mobile crustacean production annually, and that a reef lasting 20-30 years would be expected to increase fish and crustacean population by 38-50 kg/10m^2. Using more advanced methodologies, zu Ermgassen et al.'s meta-analysis of 31 studies (2016) estimated a mean lifetime enhancement in annual production of 397g/m^2 in the Gulf of Mexico as a result of oyster reef restoration.

This relationship is supported by studies in Louisiana (Humphries & La Peyre, 2015; La Peyre et al., 2014), Texas (Stunz et al., 2010) and South Carolina (Kingsley-Smith et al., 2012). In coastal Louisiana, significantly more red drum and blue crab were observed in restored oyster reefs, although abundance did not continue to increase after the initial recruitment (La Peyre et al., 2014**).** Typically, new reefs are rapidly colonized by nekton and benthic macrofauna within the first year (Blomberg et al., 2018; La Peyre et al., 2014; Pierson & Eggleston, 2014; zu Ermgassen et al., 2016)**.** This initial colonization, however, may be partially due to the movement of fish from old to new reefs (Pierson & Eggleston, 2014) and therefore not necessarily indicative of a net increase in fish populations.

While higher benthic macrofaunal densities have been associated with oyster reefs compared to other habitats (Gain et al., 2017; Stunz et al., 2010), nekton densities are higher in marsh edge habitats than on oyster reefs (Nevins et al., 2014; Stunz et al., 2010). However, nekton abundance is significantly higher in oyster reefs than over unstructured bottom habitat (Kinglsey-Smith et al., 2012; Stunz et al., 2010).

Beyond the availability of oyster reefs, differing physical characteristics of the oyster reef can also influence wildlife abundance. Reef complexity has been characterized by parameters such as live oyster volume, reef height and rugosity. Complexity may increase predator foraging efficiency by reducing interference competition among predators. Grabowski and Powers' study (2004) observed that at high mud crab densities, foraging rates were higher for crabs in high-relief reefs (10-30cm) than those in low-relief reefs (<5cm), while foraging rates in both types of reefs were similar at low and intermediate crab densities (Grabowski and Powers, 2004). Benthic macrofaunal abundance has been positively associated with increased rugosity and live oyster volume in oyster reefs (Karp et al., 2018). Studies suggest that reef height and shell density do not affect nekton abundance; instead, the presence of oyster shells, or similar substrate, is the most important determining factor for nekton populations (Gregalis et al., 2009; Humphries et al., 2011).

Strength of evidence

High. Almost all of the studies cited were from peer-reviewed journals and specific to the Gulf of Mexico. The studies consistently found that the introduction of oyster reefs to unstructured bottom habitat increased recruitment and abundance of nekton. Methods are clearly described and replicable.

Other factors

The long-term effectiveness of oyster reefs as wildlife habitat can be influenced by biophysical characteristics such as water depth, temperature, salinity, turbidity and flow (Gregalis et al., 2009; Karp et al., 2018; Nevins et al., 2014; Stunz et al., 2010). For instance, in areas prone to stratification, deep water habitats are more likely to develop hypoxia, which can lead to mortality and other changes in abundance and distribution of species (Nevins et al., 2014).

The effectiveness of oyster reefs as habitat may also depend upon the habitat preferences of each species. In a study conducted on the central coast of Texas, red drum showed greater use of seagrass and oyster reef compared to unstructured bottom and were commonly associated with habitat edges or boundaries between habitat types. In contrast, spotted seatrout were commonly associated with unstructured bottom and seagrass compared to oyster reef. However, this finding may have been a reflection of preference for water depth rather than habitat type, due to the shallow nature of the oyster reefs (Moulton et al., 2017).

One study also stressed the importance of monitoring over multiple years, as changes in community assemblages occur gradually (Blomberg et al., 2018).

Predictability

Oyster reefs act as essential habitats by supporting a more abundant nektonic community. While zu Ermgassen et al. (2016) provides an example of a methodology that can be used to predict this relationship, they do not provide a model.

The interconnectedness between habitats clearly plays an important role in determining species abundance and richness; as a result, it can be difficult to determine the extent to which oyster reefs by themselves limit or support organisms (Humphries & La Peyre, 2015).

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Link 42: Fish populations→ Commercial harvest[5]

Description of relationship

Commercial harvest of fish depends directly on the population of fish

Summary of evidence

It can be assumed that with an increase in fish populations, fish landings will also increase. The National Marine Fisheries Service and state jurisdictions set fishing policy, and with healthy fish stocks, increased commercial fishing will be allowed to occur, up to a point. The National Marine Fisheries Service

[5] This entry is adapted from Mason, Sara, Lydia Olander, and Katie Warnell. 2018. “Ecosystem Services Conceptual Model Application: NOAA and NERRS Salt Marsh Habitat Restoration.” National Ecosystem Services Partnership Conceptual Model Series No. 3. Durham, NC: Duke University, Nicholas Institute for Environmental Policy Solutions. https://nicholasinstitute.duke.edu/conceptual-model-series

commercial fish landings database contains total data for fish species caught in the United States (http://www.st.nmfs.noaa.gov/commercial-fisheries/commercial-landings/annuallandings/index). Data can be organized by species and geography, and they can be used to estimate monetary value of fish caught in a certain area. Local governments or other fishery-related organized may host more specific data for a region of interest. To ensure sustainability of fishing effort, the fish stock sustainability index (FSSI) is used as a performance measure for the sustainability of ~200 fish stocks in the U.S. FSSI increases as stock status becomes known, overfishing is reduced and stocks increase to the level that provides maximum sustainable yield. FSSI are updated quarterly.

Fish stock predictions are used to guide fisheries management. Traditional fisheries models used estimates of population characteristics such as growth, maturity, fecundity, mortality and recruitment for each stock, but predictions need to be improved as knowledge of the marine environment improves (Brander 2003). From past evidence it is clear that harvesting beyond the limits fisheries can support leads to a critical crash in catch. Consumer demand and inadequate data have led to overharvesting, reducing stocks and reducing species around the world (Fryxell *et al.,* 2017). In order to sustain commercial harvest of species, it is essential to maintain a balance between population regeneration times and catch size. As a result of this, the NOAA Sustainable Fisheries Division adopted the Magnuson-Stevens Fishery Conservation and Management Reauthorization Act. The act mandates the use of annual catch limits and accountability measures to end overfishing. For example, the quota for Red Snapper is approximately 6 million pounds, the quota for Mangrove Snapper is 2 million pounds, and harvest and possession of Red Drum is banned as of 2019 (Gulf of Mexico Fisheries Management Council, 2019). Marine wild-capture fisheries in the United States are regionally managed and enforced under the Magnuson-Stevens Fishery Act. Management of fisheries is science-based and with the continuous scientific inputs used to ensure the improvement of fishery management plans in response to new information. This framework is designed to prevent overfishing or quickly end overfishing if it occurs and then to rebuild overfished stocks. Therefore, an increase in population of target species could also lead to higher quotas without raising the risk of a population crash.

Strength of evidence

Moderate. If fish stocks increase (and fishery policy allows it), commercial fishery catches will increase as well.

Other factors

State, local, regional, and national fishing policies can determine how much fish (and which fish species) the commercial fishing industry can harvest.

Predictability

The InVEST Fisheries model can estimate harvest volume of single-species fisheries. Model outputs include economic value of fish harvest. As a single-species model, this tool is best used for locations where a single species of fish is of high importance or interest and is known to rely on salt marsh as nursery habitat.

Sources

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Link 43: Fish populations → Bird populations

Description of relationship

The impacts of changing fish populations on bird populations will vary based on bird diet.

Summary of evidence

Studies agree that birds are generally limited by food availability (Newton, 1998; Vieyra et al., 2009). Therefore, increases in fish population should lead to an increase in piscivorous birds. In a study conducted in the Gulf of California, breeding performance, as well as hatching and reproductive success of Heermann's Gulls were found to be strongly influenced by the availability of sardines and anchovies (Vieyra et al., 2009). Another study examining 40 years of data in the Salton Sea observed that periods of high fish abundance were correlated with higher populations of piscivorous birds (Hurlbert et al., 2009). Birds are presumed to seek food elsewhere when fish are scarce. Some birds also have the ability to adapt their diets based on which species are available. Amirowicz & Gwiazda (2012) found that depending on the season, cormorants and pikeperch consumed fishes of different size ranges—perhaps to minimize dietary overlap with other piscivorous birds.

At the same time, fish and non-piscivorous water birds share food sources. Potential interspecies competition suggests a negative relationship between fish and non-piscivorous birds. Haas et al. (2007) found that biomasses of benthic macroinvertebrates, macroalgae and macrophytes as well as the densities of herbivorous, carnivorous and omnivorous water birds were reduced in ponds that were filled with carp when compared to fishless ponds.

Strength of evidence

Low. While studies have suggested changes in fish populations will affect bird populations, this relationship seems to be dependent upon the diet of the birds. There is not enough information to determine whether the dominant effect will be a net increase or decrease in bird populations. Furthermore, though the studies were mostly from peer-reviewed journals, they were all conducted outside of the Gulf of Mexico.

Other factors

While the abundance of fish populations certainly controls the availability of prey for piscivorous birds, biophysical properties such as temperature, turbidity and dissolved oxygen also play a role. In particular, dissolved oxygen was shown to best describe the abundance of piscivorous bird populations in one study (Pink & Abrahams, 2018). The authors suggest that low dissolved oxygen levels can encourage aquatic surface respiration in fish, which forces them to swim to the surface, increasing their risk of capture.

Predictability

Models that capture this relationship do not yet exist. Although several models that predict the impact of bird populations on fish populations exist, for the purposes of evaluating oyster reef restoration, we are only interested in looking at how fish populations affect bird populations.

Sources

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Link 44: Species important for wildlife viewing → Wildlife viewing

Description of relationship

Increases in populations important for wildlife viewing can increase opportunities for wildlife-related recreation.

Summary of evidence

Species important for wildlife viewing in the Gulf of Mexico include the dolphin, alligator and manatee. No studies were found that directly linked these species' populations to recreational outcomes.

Wildlife viewing is a popular activity for recreationists. In Gulf of Mexico states, wildlife viewing (excluding birding) is expected to generate between $2.06 billion to $8.22 billion annually (Table 1; Shepard et al., 2013).

Table 1. Estimated annual nonmarket values for selected recreational activities (nearest million $) that generate up to another $52 billion per year in nonmarket value of Gulf states' ecosystem services (from Kildow et al., 2009).

Activities	Alabama	Louisiana	Mississippi	Texas	Florida[a]
Beach	237–592	81–202	174–434	705–1,762	3,543–8,858
Swimming	164–410	92–230	135–337	592–1,480	3,222–8,055
Bird watching	118–472	228–911	181–725	401–1,605	1,949–7,795
Other wildlife	161–644	264–1,056	60–238	315–1,260	1,257–5,026
Fishing	253–422	749–1,249	280–466	986–1,643	3,377–5,629
Total—max. estimates	933–2,540	1,414–3,648	830–2,200	2,999–7,750	13,348–35,363

[a] Includes Gulf and Atlantic coasts of Florida.

Source: Shepard et al., 2013

Many factors can influence the decision to engage in wildlife-based recreation and satisfaction with that activity (more detailed explanations below). First, wildlife must exist for these recreational opportunities to be possible. Depending on the species available at the site of interest, recreational opportunities will differ. Further, according to Duffus and Dearden (1990), "Non-consumptive use of wildlife requires a predictable occurrence of the target species within a fairly small spatial area." Determining the relationship between wildlife populations and recreational opportunities requires data on wildlife population sizes and number of people recreating or survey results on quality of recreation experiences.

Strength of evidence

Low. Though there are many logical connections to be made between species important for wildlife viewing and wildlife-based recreation, no studies were found that report data linking these populations to recreational visits or tourist numbers. Site-specific information and data will be necessary to make estimates of recreational outcomes related to wildlife populations.

Other factors

Laws, Permits, Permissions: Restrictions are sometimes applied to habitat or nesting areas for threatened or endangered species, so members of the public are not able to view them even if the population of that species is increasing.

Population Size Versus Visibility: For most species, visibility is a key aspect of wildlife-based recreation. If a species is particularly camouflaged, lives in dense habitat, is nocturnal, or is generally hard to see, it will be hard to link that species to wildlife-based recreation.

Facilities: A site may become more attractive for wildlife viewing if it provides facilities designed to provide services to visitors (Duffus & Dearden 1990).

Negative Feedbacks: Though increased populations of wildlife species can yield recreation or tourism benefits, increased recreational activities could negatively affect wildlife. One study showed that as the numbers of swimmers and boats increased, manatees escaped to protected sanctuaries significantly more frequently (King & Heinen, 2004). If recreation negatively affects wildlife to the extent that populations die off or migrate, the original recreational benefits from those wildlife species will also disappear.

Predictability

The InVEST recreation model can be used to assess the relationship between wildlife populations and recreational use (using social media posts as a proxy). This model has been tested in multiple cases, and the natural capital project website links to practical applications of the model for reference (Natural Capital Project, n.d.). Spatial data on bird population presence or abundance are needed to use this model to predict bird population impacts on recreation person-days, and the many other factors that influence recreational activity are likely to obscure the relationship.

Other types of models can also be used to predict how visitation or recreation will change on the basis of bird species. Studies such as that performed by Booth et al. (2011) relating species rarity to the number of visitors to a site can provide site-specific data that will enable detailed descriptions of the connection between bird populations and recreation indicators. Though this study used species rarity as a predictor, it would be possible to also use data on population numbers, species diversity, or some other wildlife indicator as a predictor variable.

Sources

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Link 45: Marine wildlife populations → Threatened and endangered species persistence

Description of relationship

Federally listed and state listed threatened or endangered marine species could be impacted by oyster reef restoration. No studies were found that specifically document the impacts on threatened or endangered species, but the potential effects on marine populations in general are found in link 41.

Link 46: Oyster reef quantity or quality → Bird population

Description of relationship

Oyster reefs primarily benefit bird populations by acting as a feeding area – especially when surrounding areas are limited by food – and by providing additional substrate for foraging.

Summary of evidence

Overall, preference for oyster reefs will depend on species and their preferences for roosting/loafing and feeding sites. In Gulf of Mexico study, Frederick et al. (2016) found that although bird use was overall greater on sites with substrate, this effect may have been a result of elevation. When elevation was controlled for, most species—except for cormorants and bald eagles –preferred sandy control sites. As such, oyster reefs may be important because they provide additional elevation. Frederick et al. found that increase in elevation by substrate sites gives birds an hour more per rising or falling tide to forage than in lower control sites.

In a Colne Estuary, U.K. study, Herbert et al. (2018) found that oyster reefs can affect shorebird distribution and feeding behavior. While the reefs provided valuable supplementary feeding areas for some species, they were avoided by other species: oystercatchers and herring gulls were more commonly found on oyster reefs compared to uncolonized mudflats, and the black-tailed and bar-tailed godwits were found more frequently on mudflats.

Strength of evidence

Low. Of the three peer-reviewed studies found for this link, only one study took place in the Gulf of Mexico. No evidence was found on the relationship between the quality of oyster reefs and bird populations.

Other factors

Availability of prey: Since oyster reefs act as a feeding site for bird populations, the effects of oyster reef restoration on these populations may depend on the prey available at the reef. For instance, in Herbert et al.'s study, oystercatchers were found more frequently on oyster reefs over mudflats because they had greater success and biomass intake rates on oyster reefs.

Human Presence: The presence of tourists or commercial fishermen can deter bird populations from foraging or roosting on oyster reefs. For instance, red knots prefer to forage and roost where there are few or no people, and little or no activities (Burger et al, 2004).

Predictability

No models to predict this relationship were found.

Sources

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Link 47: Oyster reef quantity or quality → Biodiversity

Description of relationship

Oyster restoration increases species richness by providing structure. Limited evidence suggests that habitat complexity in oyster reefs may also increase species richness.

Summary of evidence

When compared to surrounding ecosystems such as seagrass and marsh edge, oyster reefs support a distinct community of nekton and benthic macrofauna (Gain et al., 2017; Nevins et al., 2014; Stunz et al., 2010). Oyster reefs also harbor more unique species than unstructured bottom, which suggests that reef restoration can increase overall diversity of estuarine fish assemblages (Humphries et al., 2011; Pierson & Eggleston, 2014).

The structure provided by oyster reefs may be the most important factor in defining nekton species assemblages (Brown et al., 2013; Humphries et al., 2011). A study in coastal Alabama found that habitats containing oyster reefs as well as intertidal marsh had more diverse fish species than control plots without oyster reef habitat. Particularly, blue crabs, spotted seatrout, drum and flounder were more abundant near oyster reefs than the control mudflats (Scyphers et al., 2011). Another 9-year study in the Indian River Lagoon in Florida found that restored oyster reefs accumulated as much genetic diversity in oysters as natural reefs as quickly as one month after restoration (Arnaldi et al., 2018).

In many ecosystems, structurally complex habitats have been associated with higher fish diversity; however, information for oyster reefs is limited (Gilby et al., 2018). In a study in Mosquito Lagoon, Florida, 40 sessile and 64 motile species of macroorganisms were found on oyster reefs, and the recruitment on live oyster was twice that on oyster-less shells. This richness in diversity found on reefs was comparable to other ecosystems in the Indian River Lagoon system (Boudreaux et al., 2006).

Strength of evidence

High. All studies cited are peer-reviewed journal articles from the past decade, and about half of the studies take place in the Gulf of Mexico. The findings from these studies are consistent in supporting the fact the oyster reefs harbor more unique species than unstructured bottom.

Other factors

The long-term effectiveness of oyster reefs as wildlife habitat can be influenced by biophysical characteristics such as water depth, temperature, salinity, turbidity and flow (Gregalis et al., 2009; Karp et al., 2018; Nevins et al., 2014; Stunz et al., 2010). For instance, salinity and rugosity are positively associated with macrofaunal diversity (Karp et al., 2018)

One study also stressed the importance of monitoring over multiple years, as changes in community assemblages occur gradually (Blomberg et al., 2018).

Predictability

Oyster reefs act as essential habitats by supporting a more diverse community. While models that predict the effect of oyster reefs on species abundance (e.g. zu Ermgassen et al., 2016) exist, no models predict its effect in terms of species diversity.

The interconnectedness between habitats clearly plays an important role in determining species abundance and richness; as a result, it can be difficult to determine the extent to which oyster reefs by themselves limit or support organisms (Humphries & La Peyre, 2015).

Sources

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Link 48: Oyster reef quantity or quality → Oyster habitat persistence

Description of relationship

Oyster reef quantity or quality can affect oyster reef persistence through its impacts on oyster recruitment and shell production.

Summary of evidence

Oyster reef restoration can lead to persistent and successful reefs. Persistence has been indicated by the size and structure of the oyster population: in the example of Lipcius and Burke's study (2018), the successful restored reef had high oyster biomass and was composed of four year classes, over half of which were of reproductive age.

Specifically, recruitment and shell production are strong determinants of oyster reef persistence (Walles et al., 2015). Because changes in oyster reef quantity or quality can increase oyster recruitment and shell density, as detailed in link 40, they can also affect oyster habitat persistence. The physical structure of oyster reefs can also influence reef persistence. High-relief reefs are associated with higher oyster density and recruitment, and they seem to be less susceptible to sedimentation and burial (Colden et al., 2017; Schulte et al., 2009). Colden et al. (2017) discovered that sediment deposition was significantly reduced in reefs higher than 0.3m, whereas reefs lower than 0.3m experienced heavy sediment deposition and were eventually buried.

Strength of evidence

Fair. All pieces of evidence used were peer reviewed journal articles from the past decade. None of the studies on oyster reef persistence took place in the Gulf of Mexico, though they were consistent in suggesting that changes in the quality and quantity of oyster reefs can impact persistence.

Other factors

Environmental factors: The ability of oyster reefs to persist can depend on a host of environmental factors, such as temperature, salinity, water depth, dissolved oxygen and turbidity (Gregalis et al., 2009; Linhoss et al., 2016; Pollack et al., 2012; Wang et al., 2008). In particular, salinity and temperature have been cited as having the most dominant effects on oyster growth and mortality (La Peyre et al., 2016).

Disease: Disease can increase oyster mortality and thus substantially weaken oyster reefs. Walles et al. (2015) predicted that disease would reduce shell addition rate by limiting the age up to which oysters survive.

Harvesting: Harvesting activity weakens the ability of oyster reefs to persist. Walles et al. (2015) calculated that harvesting certain year classes of oysters can decrease reef accretion rates by between 57 % to 89%. See link 29 for more information.

Predictability

No models were found that document the impact of oyster reef quality and quantity on persistence. However, there are habitat suitability models, (e.g. Linhoss et al., 2016; Pollack et al., 2012), population models (Wang et al., 2008), as well as bioenergetic models (Lavaud, et al., 2017), which can help predict oyster population response to environmental changes.

Sources

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Link 49: Bird Populations → Bacteria/viruses in the water

Description of relationship

Birds deposit feces into bodies of water, which carry and release pathogens into the water. However, other factors so heavily determine the amount of pathogens in the water it is unclear if an increase in bird population or feces affects the quantity of pathogens in the water.

Summary of evidence

Birds are vectors for bacteria and viruses through their feces (fecal coliform) (Jellison et al, 2007) which they deposit into bodies of water. While there are no studies that demonstrate the link between bird populations and/or feces amounts and quantity of pathogens in the water.

Despite empirical evidence demonstrating this link, experts indicate that in localized conditions with less water flow higher populations of birds may lead to localized increases of pathogens in the water. In addition, they mentioned that a nascent issue in oyster aquaculture is birds landing on floating cages. In those situations, birds deposit feces in very close proximity to oyster aquaculture sites which can lead to increases of pathogen concentrations in water as well as in oyster tissue, though this has not been tested.

Strength of evidence

Moderate. There has not been sufficient research exploring this link though there is high consensus that birds are vectors and transmitters of pathogens into bodies of water.

Other factors

Concentration of pathogens in the water is most commonly affected by water temperature and salinity. (Daniels et al., 2000). Likewise, other organisms concentrate pathogens in their tissue, such as abalones, corals fish, shrimp, sponges, squid, and zooplankton (Thompson et al, 2004)

Predictability

Bird populations cannot predict quantity of pathogens in the water.

Sources

Daniels, N. A., MacKinnon, L., Bishop, R., Altekruse, S., Ray, B., Hammond, R. M., ... & Slutsker, L. (2000). Vibrio parahaemolyticus infections in the United States, 1973–1998. The Journal of infectious diseases, 181(5), 1661-1666.

Jellison, K. L., Distel, D. L., Hemond, H. F., & Schauer, D. B. (2007). Phylogenetic analysis implicates birds as a source of Cryptosporidium spp. oocysts in agricultural watersheds. *Environmental science & technology*, *41*(10), 3620-3625. https://pubs.acs.org/doi/10.1021/es0626842

Thompson, F. L., Iida, T., & Swings, J. (2004). Biodiversity of vibrios. Microbiol. Mol. Biol. Rev., 68(3), 403-431.

Link 50: Cultural Values (Education & others) → Mental health & psychological well-being

Description of relationship

Engaging in educational activities related to oyster reef restoration, such as volunteering on restoration projects, may improve mental health and well-being through spending time in a natural environment, fostering social connections, and contributing to meaningful work.

Summary of evidence

In surveys and interviews, people engaging in environmental volunteer work often say that their work provides stress reduction and relaxation, as well as other benefits often linked to well-being such as meeting new people, feeling a sense of community, and feeling good about themselves (Grese et al. 2000, Guiney & Oberhauser 2010). However, attempts to measure the mental health benefits of environmental volunteer work are rare. One study involving observation, interviews, and surveys of volunteers at ten conservation groups in England and Scotland had volunteers complete an Emotional State Scale before and after their volunteer activity (O'Brien et al. 2010). A significant positive emotional shift took place during volunteering; positive changes were seen across all parameters of the emotional scale except for pain (some people were sore after physical work, but they saw this as a good thing). During interviews, the volunteers stated that the work keeps them active, provides socialization opportunities, and reduces stress and mental fatigue. This was especially important among groups with limited opportunities for social engagement and physical activity (e.g. people who are retired or not working due to disability).

In 2015, researchers attempted a systematic review of the health and well-being benefits of participation in environmental conservation activities (Lovell et al. 2015). The low number of studies on the subject, poor quality of many studies, and diversity of methods and metrics precluded a statistical meta-analysis. Instead, the authors used a narrative synthesis of existing studies and assessed the evidence for the various pathways from environmental conservation activities to well-being outcomes proposed in the studies they found. These pathways include physical activity, achievement and contribution to a worthwhile cause, social contact, and contact with the natural environment. Overall, the authors found that while there is little direct evidence available for the well-being benefits of environmental conservation activities, the proposed pathways seem plausible.

Strength of evidence

Fair. As summarized in the 2015 meta-analysis (Lovell et al.), there is little direct evidence for this relationship. However, the pathways by which environmental conservation activity can promote health and well-being are plausible and consistent with surveys and interviews with volunteers.

Other factors

None found.

Predictability

No method for predicting this relationship was found.

Sources

Grese, R.E., R. Kaplan, R.L. Ryan, & J. Buxton. (2000). Psychological benefits of volunteering in stewardship programs. In Gobster, P.H. & R.B. Hull (Eds.), *Restoring Nature*. Island Press. Washington, D.C.

Guiney, M. S., & Oberhauser, K. S. (2009). Conservation Volunteers' Connection to Nature. *Ecopsychology*, *1*(4), 187–197. https://doi.org/10.1089/eco.2009.0030

Lovell, R., Husk, K., Cooper, C., Stahl-Timmins, W., & Garside, R. (2015). Understanding how environmental enhancement and conservation activities may benefit health and wellbeing: a systematic review. *BMC Public Health*, *15*(1), 864. https://doi.org/10.1186/s12889-015-2214-3

O'Brien, L., Townsend, M., & Ebden, M. (2010). 'Doing Something Positive': Volunteers' Experiences of the Well-Being Benefits Derived from Practical Conservation Activities in Nature. *VOLUNTAS: International Journal of Voluntary and Nonprofit Organizations*, *21*(4), 525–545. https://doi.org/10.1007/s11266-010-9149-1

Link 51: Bird Populations → Waterfowl Hunting

Description of relationship

Some bird species' populations dictate amount of allowable waterfowl hunting but this is not true for all species.

Summary of evidence

All waterfowl hunting in North Carolina is regulated under the federal Migratory Bird Treaty Act (16 U.S.C. §§ 703–712) under US Fish & Wildlife Services. Waterfowl hunted in North Carolina include Tundra swan, Canada Geese, northern pintails, and American Wigeons, among others.

Population estimates or desired population levels dictate management for hunting of certain waterfowl species. For example, US Fish & Wildlife has a goal to maintain the Tundra Swan population at 80,000 birds as measured by the mid-winter survey in the Atlantic and Mississippi flyways. The management plan recommends that the sport harvest rate remain at or below 5% of the population. While the management does not have a quota, it limits the number of licenses permitted by states (12,000 across six states) for waterfowl hunting. An increase in the number of licenses allocated is fully contingent on an increase in population. Therefore, the population of tundra swan birds may have a direct impact on how much recreational waterfowl harvesting is permitted. (Tundra Swan Harvest FAQs, 2019)

Conversely, regulators want the population of Canada Geese to decrease, rather than increase in order to "reduce goose related damages" (50 CFR Parts 20 and 21, 2006). Management of Canada Geese is intended to reduce populations and consequently, increase hunting opportunities. As such, it is likely that any change in Canada goose populations will result either in an increase or no change in Canada goose hunting opportunities.

The Northern pintail and American Wigeon populations have decreased dramatically in the US due to loss of wetlands and nesting cover, though there is limited knowledge on what other factors affects population dynamics. The North American waterfowl management plan includes a goal to increase populations substantially, though it is not clear what limits or regulations are placed on hunting in order to achieve or delay such goals (Malecki et al., 2006; Mini et al, 2014).

While some waterfowl species are closely associated with oyster reefs, no studies have quantified how oyster habitat and/or reef restoration affects waterfowl populations or hunting in North Carolina or elsewhere. However, a study in central New York (funded by Ducks Unlimited) found that managed wetlands had 1.4 – 2.3 times more taxa of waterfowl than unmanaged land, and between 0.8 and 13.2 times more abundance. (Kaminski et al 2006). Similar outcomes have been observed on restored wetlands on private land in Illinois (O'neal et al 2008). Such findings may indicate that restored and perhaps more resilient or ecologically diverse ecosystems may attract more waterfowl suitable for hunting purposes.

Strength of evidence

High. In many cases, the population of birds dictates the level and type of waterfowl hunting and is supported and monitored by government programs.

Other factors

Management goals for individual species can dictate decisions and limits regarding allowances for waterfowl hunting regardless of population or population trends. In addition there is some evidence that waterfowl hunting is decreasing across the US, though it may not be clear if that is connected to declining breeding populations of waterfowls or shifting interests in younger generations. (Vritska et al., 2013; Watt 2017)

Predictability

If a particular species of waterfowl has a lower than desired population, management may regulate waterfowl hunting according to population estimates and population goals. However, sometimes population may not dictate allowances for waterfowl hunting. Additionally, waterfowl hunting trends may be changing regardless of bird population across the country, which reduces the predictability between bird population and hunting.

Sources

Kaminski, M. R., Baldassarre, G. A., & Pearse, A. T. (2006). Waterbird responses to hydrological management of wetlands reserve program habitats in New York. Wildlife Society Bulletin, 34(4), 921-926

Malecki, R., Sheaffer, S., Howell, D., & Strange, T. (2006). Northern Pintails in Eastern North America: Their seasonal distribution, movement patterns, and habitat affiliations. Atlantic Flyway Council, Technical Section.

Migratory Birds Treaty Act. 16 U.S.C. §§ 703–712

Mini, A. E., E. R. Harrington, E. Rucker, B. D. Dugger, and T. B. Mowbray (2014). American Wigeon (Mareca americana), version 2.0. In The Birds of North America (A. F. Poole, Editor). Cornell Lab of Ornithology, Ithaca, NY, USA. https://doi-org.proxy.lib.duke.edu/10.2173/bna.401

O'Neal, B. J., Heske, E. J., & Stafford, J. D. (2008). Waterbird response to wetlands restored through the conservation reserve enhancement program. The Journal of Wildlife Management, 72(3), 654-664.

Tundra Swan Harvest FAQs. (2019) North Carolina Resources Commission. https://www.ncwildlife.org/Portals/0/License/Documents/Permit%20Hunts/Swan-Harvest-FAQ.pdf).

Vrtiska, M. P., Gammonley, J. H., Naylor, L. W., & Raedeke, A. H. (2013). Economic and conservation ramifications from the decline of waterfowl hunters. Wildlife Society Bulletin, 37(2), 380-388

Watt, P. (2017) Looming Crisis: Falling waterfowl hunter numbers threaten the future of hunting and conservation. Delta Waterfowl Special Report. https://deltawaterfowl.org/wp-content/uploads/2017/03/LoomingCrisis.pdf

50 CFR Parts 20 and 21. (2006) Migratory Bird Hunting and Permits; Regulations for Managing Resident Canada Goose Populations; Final Rule. US Fish and Wildlife. https://www.ncwildlife.org/Portals/0/Hunting/Documents/Goose_final_rule.pdf

Link 52: Educational Opportunities→ Education

Description of relationship

Engagement in educational activities related to oyster reef restoration, such as volunteer work and field trips, can result in increased knowledge about oysters and coastal ecology as well as changes in volunteers' environmental attitudes and behaviors.

Summary of evidence

Educational experiences focused on natural ecosystems and environmental stewardship foster learning in participants, resulting in enhanced knowledge, attitudes, and behaviors about the environment. Several studies of specific environmental education programs have demonstrated increased knowledge and altered attitudes and behaviors when comparing pre- and post-program surveys.

Two evaluations of classroom-based environmental education programs – a 'hooked on fishing' program in 70 Montana public and private schools and a 'junior master gardener' program in Indiana third-grade classrooms – showed increases in knowledge (and skills, for students in the fishing program) over the course of the program among participating students (Flowers, 2010; Dirks & Orvis, 2005). A conservation stewardship program in Michigan targeted at adults also resulted in increased ecology and ecosystem-based management knowledge (Van Den Berg et al., 2011).

Some research has focused on differences in the type of educational experience – direct or indirect – on knowledge, attitude, and behavior outcomes. A study of middle- and high-school students enrolled in an exchange program that included both a preparatory classroom course (an indirect experience) and an international field-based trip (a direct experience) used tests at various points during the program to assess changes in knowledge, attitude, and behaviors (Duerden & Witt, 2010). Students gained environmental knowledge during both parts of the program, but the direct experience had a much greater influence on attitude change relative to knowledge change than the indirect experience. The authors suggested that direct experience helps to convert existing knowledge into attitude and behavior changes. Since many educational experiences related to oyster reef restoration provide the opportunity for direct interaction with the natural environment, they have the potential to influence participants' environmental attitudes and behaviors as well as increase their knowledge.

Strength of evidence

Moderate. While no research directly examining the influence of educational activities associated with oyster reef restoration projects was found, studies of other environmental educational experiences show that these types of educational activities, especially when they provide the opportunity for a direct experience with the environment, can facilitate knowledge gain as well as attitude and behavior changes.

Other factors

As described above, the type of educational experience (direct or indirect) can influence whether participants experience changes in attitudes and behaviors as well as knowledge gains (Duerden & Witt, 2010).

Predictability

No tools or models predicting this relationship were found.

Sources

Van Den Berg, H. A., Riley, S. J., & Dann, S. L. (2011). Conservation Education for Advancing Natural Resources Knowledge and Building Capacity for Volunteerism. *Society & Natural Resources*, *24*(3), 205–220. https://doi.org/10.1080/08941920902960404

Dirks, A. E., & Orvis, K. (2005). An Evaluation of the Junior Master Gardener Program in Third Grade Classrooms. *HortTechnology*, *15*(3), 443–447. https://doi.org/10.21273/HORTTECH.15.3.0443

Duerden, M. D., & Witt, P. A. (2010). The impact of direct and indirect experiences on the development of environmental knowledge, attitudes, and behavior. *Journal of Environmental Psychology*, *30*(4), 379–392. https://doi.org/10.1016/j.jenvp.2010.03.007

Flowers, A. B. (2010). Blazing an evaluation pathway: Lessons learned from applying utilization-focused evaluation to a conservation education program. *Evaluation and Program Planning*, *33*(2), 165–171. https://doi.org/10.1016/j.evalprogplan.2009.07.006

Link 53: Oyster Populations → Bacteria/viruses in the water

Description of relationship

Oysters, among other species, concentrate bacteria and viruses in their tissue. However, studies do not demonstrate whether this affects the quantity of bacteria or viruses in the water.

Summary of evidence

Oysters concentrate pathogens such as *Vibrio vulnificus* and *Vibrio parahaemolyticus* in their tissue during filtration. Concentrations of bacteria in oysters can sometimes be more than 100 times that in the overlying water (Froelich et al., 2017; Daniels et al, 2000). However, pathogens such as vibrio are naturally occurring in estuarine waters and may not be affected by oyster populations.

Experts that we spoke to indicated while it is possible that oyster filtration affects the amount of pathogens in the water, there are not tests that measure this and it is most likely other factors that influence the quantity of pathogens in a body of water, namely salinity and temperature of water. For this reason, experts warn that there are high abundances of pathogens in the water and in oysters during summer months.

Strength of evidence

Moderate. There is strong consensus and research demonstrating oysters ingestion of pathogens in the water, however almost no research has been dedicated to demonstrating if this changes the overall concentration of pathogens in the water. Experts suggest that it does not.

Other factors
Concentration of pathogens in the water is most commonly affected by water temperature and salinity. (Daniels et al., 2000). Likewise, other organisms concentrate pathogens in their tissue, such as abalones, corals fish, shrimp, sponges, squid, and zooplankton (Thompson et al, 2004)

Predictability
Oyster populations cannot predict quantity of pathogens in the water.

Sources
Daniels, N. A., MacKinnon, L., Bishop, R., Altekruse, S., Ray, B., Hammond, R. M., ... & Slutsker, L. (2000). Vibrio parahaemolyticus infections in the United States, 1973–1998. The Journal of infectious diseases, 181(5), 1661-1666.

Froelich, B. A., Phippen, B., Fowler, P., Noble, R. T., & Oliver, J. D. (2017). Differences in Abundances of Total Vibrio spp., V. vulnificus, and V. parahaemolyticus in Clams and Oysters in North Carolina. Appl. Environ. Microbiol., 83(2), e02265-16.

Thompson, F. L., Iida, T., & Swings, J. (2004). Biodiversity of vibrios. Microbiol. Mol. Biol. Rev., 68(3), 403-431.

Link 54: Cultural values (other) → Mental health and psychological well-being

Description of relationship
Cultural values support mental health and psychological well-being.

Summary of evidence
Several cultural values, including sense of place and livelihood option, support mental health and psychological well-being among people who hold these values. As explained in link 63, cultural values that can be supported by natural ecosystems are diverse, difficult to measure, and locally specific, so this section does not address all possible mental health and psychological well-being benefits of the full range of cultural values.

The option to support oneself through a livelihood that is strongly tied to one's sense of self and place in society can enhance well-being; the loss of such a livelihood can damage mental health (Brand, 2015). Commercial fishing and guiding recreational trips are two livelihoods that can be strongly tied to identity, as exemplified by oystermen in Apalachicola Bay (Reiley 2018).

Sense of place refers to individuals' attachment to and identification with their local area (Hausmann et al., 2015). Since this is a personal and emotional connection, it seems reasonable that enhancing sense of place can benefit psychological well-being. A study in Rigolet, an Inuit community in Canada, used interviews and an environmental distress survey to assess how climate-related changes to the land influence connection to the land and health outcomes (Cunsolo Willox et al., 2012). Survey respondents discussed how their mental health and enjoyment of the land were adversely affected by environmental changes.

Strength of evidence
Fair. The definition of sense of place makes clear that the concept is tied to psychological well-being, and a few studies show the connection between traditional livelihood options and mental health.

However, there are not many studies addressing these connections explicitly, and the many other cultural values that are likely linked to mental health and psychological well-being have not been examined.

Other factors

No other factors were described in the evidence found.

Predictability

No tools or models to predict this relationship were found.

Sources

Brand, J. E. (2015). The Far-Reaching Impact of Job Loss and Unemployment. *Annual Review of Sociology*, *41*(1), 359–375. https://doi.org/10.1146/annurev-soc-071913-043237

Cunsolo Willox, A., Harper, S. L., Ford, J. D., Landman, K., Houle, K., & Edge, V. L. (2012). “From this place and of this place:” Climate change, sense of place, and health in Nunatsiavut, Canada. *Social Science & Medicine*, *75*(3), 538–547. https://doi.org/10.1016/j.socscimed.2012.03.043

Hausmann, A., Slotow, R., Burns, J. K., & Minin, E. D. (2016). The ecosystem service of sense of place: Benefits for human well-being and biodiversity conservation. *Environmental Conservation*, *43*(2), 117–127. https://doi.org/10.1017/S0376892915000314

Reiley, L. (2018, April 11). Saving Florida’s oysters could mean killing a way of life. *Floridian*. Retrieved from http://www.tampabay.com/projects/2018/special-report/shell-game/panhandle-apalachicola-wild-oysters-aquaculture

Link 55: Oyster reef quantity/quality → Bottom sediment composition

Description of relationship

Oyster reefs trap sediment and oysters themselves deposit ingested matter onto the bottom, both of which affect bottom sediment composition. Other factors may impact whether or not these effects extend beyond the reef itself.

Summary of evidence

Oyster reefs affect the bottom sediment composition within and surrounding the reef in two ways. The 3-D structure of a reef traps sediment, which can reduce and stabilize the quantity and types of sediment in the water column. Because sediment tends to travel with currents, this effect usually results in sediment accumulation on the leeside of the reef, which may prevent erosion. At the same time, oysters and other filter feeders on an oyster reef ingest sediment and deposit fine particles, faeces, and pseudofaeces to the bottom (described in more detail in link 57) (Walles et al., 2015; Grabowski and Peterson 2007; Gutiérrez et al. 2011). The latter of these two processes (filtration) enable particular types of sediment to land along the bottom adjacent to the reef, affecting the composition of bottom sediment of an oyster reef.

In some cases, accretion and accumulation of sediment from the aforementioned processes can extend beyond the immediate area of the reef, into adjacent habitats. A field experiment in Bangladesh measured a number of morphological conditions and changes in and around a coastal area (link 56) following the installation of oyster breakwater reefs. Researchers found sediment deposition occurring seasonally in control and reef sites, but found higher sediment deposition at salt marsh areas of reef sites than at salt marsh areas of control sites (Chowdhury et al. 2019). This demonstrates that morphological conditions may affect bottom sediment composition both adjacent to and beyond an oyster reef.

While oyster reef structures are able to trap sediment in the water column, there are certain conditions (e.g. high sedimentation and particular tidal dynamics) which result in sediment burying the reef. Such situations may result in reduced oyster reef habitat, which can then also reduce their ability to affect bottom sediment composition (Walles et al., 2015).

Strength of evidence

Moderate. While the academic research around this topic is robust, recent, and consistent, none explicitly explores this relationship. There is little work to qualify and quantify bottom sediment composition around reefs as well as to discern how much of this phenomena can be attributed to the 3-D structure, and how much can be attribute to the process of ingestion/egestion.

Other factors

An oyster reef's capacity to trap and deposit sediment is contingent on other factors relating to hydrodynamic conditions (e.g. wave height and energy), sediment characteristics (e.g. quantity, sediment size), the presence or absence of storms, and reef height (Chowdhury et al., 2019).

Predictability

Bottom sediment composition is not often measured and there are no methods to discern between changes in sediment composition from the trapping of sediment by the structure or from the ingestion/egestion of particles of oysters and other filter feeders. However, the process of depositing particles from ingestion/egestion of live oysters on a reef is reliable.

Sources

Chowdhury, Mohammed Shah Nawaz, Brenda Walles, SM Sharifuzzaman, M. Shahadat Hossain, Tom Ysebaert, and Aad C. Smaal. "Oyster Breakwater Reefs Promote Adjacent Mudflat Stability and Salt Marsh Growth in a Monsoon Dominated Subtropical Coast." Scientific Reports 9, no. 1 (June 12, 2019): 8549. https://doi.org/10.1038/s41598-019-44925-6.

Walles, B., De Paiva, J. S., van Prooijen, B. C., Ysebaert, T., & Smaal, A. C. (2015). The ecosystem engineer Crassostrea gigas affects tidal flat morphology beyond the boundary of their reef structures. Estuaries and coasts, 38(3), 941-950.

Grabowski, J.H., and C.H. Peterson. 2007. Restoring oyster reefs to recover ecosystem services. In Theoretical Ecology Series, ed. K. Cuddington, J.E. Byers, W.G. Wilson and A. Hastings, 281-298.Academic Press.

Gutiérrez, J.L., C.G. Jones, J.E. Byers, K.K. Arkema, K. Berkenbusch, J.A. Committo, C.M. Duarte, S.D. Hacker, I.E. Hendriks, P.J. Hogarth, J.G. Lambrinos, M.G. Palomo, and C. Wild. 2011. Physical ecosystem engineers and the functioning of estuaries and coasts. In Treatise on estuarine and coastal science, ed. E.Wolanski and D. McLusky, 53–81. Amsterdam: Elsevier.

Link 56: Bottom sediment composition → Adjacent Habitat

Description of relationship

Oyster reefs influence bottom sediment composition and subsequently adjacent habitats through changing sedimentation both in the water column and on the benthos of surrounding habitats. In addition, nutrients deposited in bottom sediments of oyster reefs may affect adjacent habitats.

Summary of evidence

Oyster reefs trap and process incoming sediment from the water column, and deposit it to the benthos. A field experiment in Bangladesh measured a number of morphological conditions and changes in and around a coastal area following the installation of oyster breakwater reefs. Researchers found sediment deposition occurring seasonally in control and reef sites, but found higher sediment deposition at salt marsh areas of reef sites than at salt marsh areas of control sites (Chowdhury et al. 2019). In addition, sites with oyster reefs demonstrated seaward expansion of adjacent saltmarsh habitat, though the mechanism by which oyster reefs or bottom sediment composition influenced this outcome is not clear. This demonstrates that oyster reefs alter morphological conditions of coastal areas. These changes influence bottom sediment composition and habitat areas beyond an oyster reef. The process of how bottom sediment moves across and influences habitats is not entirely clear, however. It is possibly related to the redirection of sediment after a wave interacts with an oyster reef (Walles et al., 2015).

In addition, adjacent habitats are exposed to less turbid water because of oyster reefs' interacting with sediments and waves. One experimental study observed seagrass habitats adjacent to oyster reefs in the Gulf of Mexico (Sharma et al., 2016). The ability of seagrass to grow relies on access to sunlight in the water columns, and in many cases, oyster reefs reduce turbidity in the water column of adjacent habitats by trapping it in the bottom sediment. Whether or not the bottom sediment from oyster reefs remains on the benthos affects how much these habitats are able to grow and thrive. In some cases, when waves reach the sediment surface or there are strong bottom water currents, the deposited particles do not stay on the bottom and may re-enter the water column before reaching adjacent habitats, thereby increasing the turbidity in the water that is reaching adjacent habitats.

Lastly, the literature suggests that the nutrient inputs from oyster deposits may enhance seagrass growth, though there is not a clear demonstration of how this process works (Sharma et al., 2016; Newell & Koch 2004).

Strength of evidence

High. Academic journal articles on oyster reefs across the world demonstrate evidence of this link in addition to scientists who work specifically on the Gulf of Mexico. While the mechanism behind this link is murky, there is consensus that there is growth of adjacent habitats when there are oyster reefs.

Other factors

Conditions such as strong bottom currents can release sediment from the bottom and re-enter the water column before reaching adjacent habitats (Smith et al., 2009).

Predictability

While there is consensus among academics that this relationship exists, the details or process explaining the relationship remains nebulous. As a result, we cannot predict the relationship between bottom sediment composition and adjacent habitats.

Sources

Chowdhury, Mohammed Shah Nawaz, Brenda Walles, SM Sharifuzzaman, M. Shahadat Hossain, Tom Ysebaert, and Aad C. Smaal. "Oyster Breakwater Reefs Promote Adjacent Mudflat Stability and Salt Marsh Growth in a Monsoon Dominated Subtropical Coast." Scientific Reports 9, no. 1 (June 12, 2019): 8549. https://doi.org/10.1038/s41598-019-44925-6.

Newell, R. I., & Koch, E. W. (2004). Modeling seagrass density and distribution in response to changes in turbidity stemming from bivalve filtration and seagrass sediment stabilization. Estuaries, 27(5), 793-806.

Sharma, S., Goff, J., Moody, R. M., Byron, D., Heck Jr, K. L., Powers, S. P., ... & Cebrian, J. (2016). Do restored oyster reefs benefit seagrasses? An experimental study in the Northern Gulf of Mexico. Restoration Ecology, 24(3), 306-313.

Smith, K. A., North, E. W., Shi, F., Chen, S. N., Hood, R. R., Koch, E. W., & Newell, R. I. (2009). Modeling the effects of oyster reefs and breakwaters on seagrass growth. Estuaries and Coasts, 32(4), 748-757.

Walles, B., De Paiva, J. S., van Prooijen, B. C., Ysebaert, T., & Smaal, A. C. (2015). The ecosystem engineer Crassostrea gigas affects tidal flat morphology beyond the boundary of their reef structures. Estuaries and coasts, 38(3), 941-950.

Link 57: Oyster population → Bottom sediment composition

Description of relationship

Oysters impact bottom sediment composition through the process of biodeposition. While biodeposition rates fluctuate seasonally, in situ methods have been able to quantify those rates in oysters from the Chesapeake Bay and Pacific US.

Summary of evidence

Oysters and other filter feeders on an oyster reef ingest sediment and deposit fine particles, faeces, and pseudofaeces to the bottom. (Walles et al., 2015; Grabowski and Peterson 2007; Gutiérrez et al. 2011). This process enables particular types of sediment to land along the bottom adjacent to the reef and at times beyond it, affecting the composition of bottom sediment of marine habitats.

A study conducted in 1966 in the Chesapeake Bay demonstrates seasonal variability in terms of quantities of sediment deposited from oysters. The study attributes this variability to differing quantities of suspended solids found in the water column throughout the year. In addition, lab experiments testing ingestion and egestion rates in 30 cm circular troughs with eight 5 – 8 cm oysters in each trough determined that Chesapeake Bay oysters on 0.405 hectares of an estuarine bottom might produce up to 981 kg of feces and pseudofeces weekly, 95% of which are under 3 micrometers in diameter (Haven and Morales-Alamo, 1966). Similar experiments were conducted in Australia with pacific oysters in the late 1990s (Mitchell, 2006). The rates of biodeposition also varied seasonally, between 39.6 g m^{-2} day^{-1} in June and 180.5 g m^{-2} day^{-1} in November for 9.5 kilometers of oyster racks with a density of 360 oysters/m. This experiment demonstrates that not all deposits remained on the bottom adjacent to the oyster areas, and some were transported and deposited elsewhere. According to this study, variation in biodeposition was attributed to time of year and stocking density.

Strength of evidence

Moderate/High. Several studies demonstrate deposition rate and its variance across time, but few of them have recently been published. Many of the studies that measure deposition are in controlled environments and therefore may not be able to determine deposition rate in natural environments.

Other factors

Time of year, amount of sediment in the water column, the tidal cycle and wave energy can all impact bottom sediment composition from biodeposition from oysters (Mitchell, 2006).

Predictability

While rates of biodeposition have not been measured in oysters in the Gulf of Mexico, they have been on other oysters that grow naturally in the US. Those provide a reference point from which to determine whether changes in oyster populations result in changes to bottom sediment composition.

Sources

Grabowski, J.H., and C.H. Peterson. 2007. Restoring oyster reefs to recover ecosystem services. In Theoretical Ecology Series, ed. K. Cuddington, J.E. Byers, W.G. Wilson and A. Hastings, 281-298. Academic Press.

Gutiérrez, J.L., C.G. Jones, J.E. Byers, K.K. Arkema, K. Berkenbusch, J.A. Committo, C.M. Duarte, S.D. Hacker, I.E. Hendriks, P.J. Hogarth, J.G. Lambrinos, M.G. Palomo, and C. Wild. 2011. Physical ecosystem engineers and the functioning of estuaries and coasts. In Treatise on estuarine and coastal science, ed. E.Wolanski and D. McLusky, 53–81. Amsterdam: Elsevier.

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Link 58: Education Opportunities → Jobs

Description of relationship

Oyster reefs provide opportunities for research and outdoor education, which can lead to jobs in those sectors. Likewise, educational activities related to oyster reef restoration can improve individuals' skills and knowledge associated with the activity and enhance their ability to get jobs.

Summary of evidence

This link is context specific and dependent on nearby educational and research resources. For Natural Estuarine Research Reserve Sites (NERRS), it is likely that scientific and educational resources will be accessible. It is possible to educate students about coastal habitats including oyster reefs in a classroom setting as well as through experiential learning at the sites themselves. NOAA, for example, already provides resources such as the Bay Watershed Education and Training (B-WET) program, which funds "locally relevant, authentic experiential learning for K-12 audiences." Such programs serve as sources of employment through education.

Academic papers and studies have shown that educational activities, such as volunteering or job training, are beneficial to individuals looking to get a job after participating in a restoration effort. One paper examines the attitudes of several college students about environmental volunteering in order to back up the claim that volunteering is a useful mechanism to support Workplace Integrated Learning (WIL) (Scott & van Etten, 2013). The researchers surveyed roughly 100 students and asked them about what learning outcomes they think they achieved as well as what they gained from the volunteering experience. They received anecdotal evidence of considerable benefits to the students involved and found that many students felt that they gained useful knowledge and experience by volunteering in conservation work, among other efforts.

In another paper that examines past research on volunteers participating in multiple restoration and monitoring programs in Western Montana, the author found that volunteers felt that they gained valuable skills, felt more connected with local wilderness areas, and made an important contribution to wilderness management as a result of participation in volunteer projects (Yung, 2007). The author also found that volunteers feel that they are more likely to participate in public involvement processes related to wilderness management because of the volunteer experience, and that they would be better-informed participants.

In a case study conducted to analyze the experiences graduates gained from a green jobs training program, researchers found that there are benefits of urban conservation job training and employment (Falxa-Raymond et al., 2013). Graduates of the program work directly in arboriculture, ecological restoration, landscape design, and horticulture. They also found that individuals felt positive environmental attitudes and behaviors because of green jobs training and employment. They conclude that green job training and employment present real opportunities for intellectual stimulation and an increased sense of accomplishment, due in part to the uniqueness of environmental work.

Strength of evidence

None. Though many logical connections exist between oyster reef sites, research and education, and jobs, there is little to no published evidence that supports this generalized link. Site-specific data (perhaps economic impact reports) may be available at a local level to improve the evidence grade of this link for a particular site.

Other factors

None

Predictability

Strength of volunteer commitment can help predict whether individuals will gain a sufficient amount of knowledge/skills to get a job later on (Ryan et al., 2001). Additionally, more research and education opportunities may likely lead to more funding for employment but there is no way to predict this.

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Link 59: Oyster Reef Quantity and Quality → Threatened and Endangered Species

Description of relationship

Some threatened or endangered species interact with oyster reefs, but it is unclear how important oyster reefs are for supporting populations of threatened or endangered species in North Carolina or the Mid-Atlantic.

Summary of evidence

There are a number of threatened or endangered species that may be found in or around oyster reefs and restored reef sites in Pamlico Sound and the Neuse River. These include the shortnose sturgeon, the Atlantic sturgeon, the West Indian manatee, the smalltooth sawfish, and five species of sea turtle. Construction of restoration projects could potentially threaten these species (NC DMF, 2015). As a result, restoration projects must often demonstrate that they will not harm those species prior to being permitted to begin construction on the project.

While the presence of oyster reefs can increase abundance, size, and diversity of species (Peters, et al 2017), there is not research that explicitly demonstrates how reefs affect individual threatened or endangered species.

One report suggests that of the above mentioned species, only the Atlantic sturgeon may rely on oyster reef habitat, as they require hard substrate for the attachment of eggs. In addition, juvenile striped bass (considered overfished and experiencing overfishing) can be observed around oyster reef structures, with observations demonstrating an average of 15.4 individuals/m2 reef (Lowery et al, 2007 Breitburg 1999).

Strength of evidence

Low. There is little explicit mention in literature regarding the link between oyster reefs and endangered or threatened species, even though there is a lot of evidence to support that oyster reefs generally support wildlife.

Other factors

None

Predictability
There is no way to predict how the quantity and quality of oyster reefs can affect threatened or endangered species.

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Link 60: Bacteria/viruses in the water → Microbial infections

Description of relationship
There is a strong and proven positive correlation between pathogens in water and microbial infections in humans.

Summary of evidence
Pathogens in water, particularly enteric (fecal-oral) viral pathogens can infect humans who come into contact with them through recreational use of water and result in a number of symptoms or conditions (Griffin et al, 2003). Pathogens are often discharged into the water through untreated sewage.

To date, the occurrence of pathogenic human enteric viruses in marine water is not well understood, however as coastal water quality deteriorates as a result of increased inputs into the water, human health in negatively affected. Studies have demonstrates a positive correlation between concentration of pathogens and marine bacterial counts and incidence of infection by humans (Henrickson et al., 2003). These studies have taken place in the US, Egypt, Israel, South Africa, and more.

Strength of evidence
Moderate. There is strong consensus around the academic community and stakeholders that pathogenic organisms in the water results in microbial infections in humans and that an increase in concentration of pathogens in the water increases risk of infection. However there isn't a lot of literature on the subject that aims to quantify this link.

Other factors
The duration and type of exposure as well as the host immunity can also affect the risk of infection to humans. (Henrickson et al, 2003)

Predictability

For certain pathogens, there is sufficient evidence to determine risk of infection based on concentration or bacterial counts in the water. For others, it is fairly reliable that a change in amount of pathogens in the water will lead to a change in the

Sources

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Link 61: Bottom sediment composition → Turbidity

Description of relationship

Oyster reefs influence bottom sediment composition and turbidity by affecting sedimentation in the water column

Summary of evidence

Oyster reefs trap and process incoming sediment from the water column, and deposit it to the benthos. Oyster reefs affect the bottom sediment composition within and surrounding the reef in two ways. The 3-D structure of a reef traps sediment, which can reduce and stabilize the quantity and types of sediment in the water column. Because sediment tends to travel with currents, this effect usually results in sediment accumulation on the leeside of the reef, which may prevent erosion. At the same time, oysters and other filter feeders on an oyster reef ingest sediment and deposit fine particles, faeces, and pseudofaeces to the bottom (Walles et al., 2015; Grabowski and Peterson 2007; Gutiérrez et al. 2011). The latter of these two processes (filtration) enable particular types of sediment to land along the bottom adjacent to the reef, affecting both the composition of bottom sediment of an oyster reef. Oyster reefs are shown to affect quantity and quality of sediment in the water column and along the bottom, which contributes to turbidity regulation (Newell, 2004).

Studies on habitats that are adjacent to oyster reefs found that they are exposed to less turbid water because of oyster reefs' interaction with sediments and waves. One experimental study observed seagrass habitats adjacent to oyster reefs in the Gulf of Mexico (Sharma et al., 2016). The ability of seagrass to grow relies on access to sunlight in the water columns, and in many cases, oyster reefs reduce turbidity in the water column of adjacent habitats by trapping it in the bottom sediment. Whether or not the bottom sediment from oyster reefs remains on the benthos affects how much these habitats are able to grow and thrive. In some cases, when waves reach the sediment surface or there are strong bottom water currents, the deposited particles do not stay on the bottom and may re-enter the water column before reaching adjacent habitats, thereby increasing the turbidity in the water that is reaching adjacent habitats.

Strength of evidence

High. There is consensus amongst the scientific community that an oyster reefs' impact on bottom sediment composition will also affect turbidity, though it is difficult to predict how much it will affect turbidity.

Other factors

Conditions such as strong bottom currents can release sediment from the bottom and re-enter the water column before reaching adjacent habitats (Smith et al., 2009). Other factors regulate turbidity in and around oyster reef habitat, such as sedimentation in seagrass beds (Newell, 2004). The characteristics of the sediment in the water column itself can also affect how much of it is trapped and or digested in an oyster reef (Mitchell, 2006; Haven and Morales-Alamo, 1966).

Predictability

Without other information about the habitat surrounding an oyster reef, it is difficult to predict how the presence of oyster reefs of bottom sediment effects turbidity.

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Link 62: Water Turbidity → Marine Wildlife Populations

Description of relationship

Turbidity may affect certain species' habitat, resulting in migration or mortality (and subsequently, changes in population).

Summary of evidence

Turbid waters have varying effects on marine environments and wildlife. In some environments, particularly high-energy environments, turbid waters can circulate sediment and nutrients that feed oysters and other organisms living on and maintaining estuarine substrates that can help maintain populations living on and around oyster reefs. Conversely, turbid waters can bury benthic communities, inhibit filter feeders and block light for photosynthesis (Kennicutt, 2017). Turbidity can influence filtration rates of oysters, (VanderKooy, S, 2012; Galstoff, 1964) and can adversely affect or delay oyster-spawning (Cake Jr, 1983). Sometimes changes in turbidity are temporary (i.e. due to a storm event) and result in fewer long-term impacts for oysters. However, persistent levels of turbidity and sediment in the water column can cause permanent changes to the oyster reef community structure (Oyster-restoration.org, n.d.)

Turbidity can be a symptom of eutrophication, which is an excess of nutrients in the water (Bricker et al 1997). Input of nutrients and resulting eutrophication can lead to increases in algal toxins, low dissolved oxygen, and fish kills. Combined, fisheries habitats and populations are threatened by the presence of turbidity due to eutrophication.

Changes in turbidity impact habitat for recreationally significant species in other regions outside of the Gulf of Mexico, such as trout in the northeastern US (Englin et al., 1997) and striped bass in Chesapeake Bay (Lipton and Hicks, 1999). For example, a 1997 model of consumptive recreational demand (Englin et al., 1997) includes turbidity data and finds that turbidity is expected to influence total fish catch. Likewise, a model for striped seabass in Chesapeake Bay found changes in catch as they relate to nutrient content in the water, though not turbidity specifically. It is unclear if changes in fish catch is reflective of changes in population. In the Larto-Saline backwater complex of east central Louisiana, however, chronically high turbidity was a major factor limiting the production of gamefish in the early 90s (Ewing, 1991).

Strength of evidence

Fair. The evidence demonstrates that turbidity affects spawning and habitat for some species.

Other factors

Menhaden specifically may be affected by the combination of low winter temperatures, high salinities, and low turbidity ((Keithly Jr. and Roberts, 2017). Spotted sea trout may also be affected by changes in salinity associated with tropical storms or hurricanes (VanderKooy, 2001). Erosion, salinity, current patterns, temperature, sediment types, bottom conditions, and water depth (VanderKooy, 2012) all influence oyster reefs and oyster habitat in the presence of turbidity.

Predictability

While turbidity may threaten wild populations in a number of ways, no models or tools to predict this relationship were found.

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Link 63: (Various starting nodes) → Cultural values - other

Description of relationship

Many outcomes of oyster reef restoration have the potential to support cultural values, such as sense of place, existence value, livelihood option, traditional and local knowledge, and culinary heritage. The relationships between oyster reef restoration and cultural values, as well as the particular cultural values of interest, are very locally specific.

Summary of evidence

Cultural values that can be supported by natural ecosystems are diverse, ranging from knowledge systems, educational values, and aesthetics to cultural diversity and spiritual or religious values. These are difficult to measure, but often very important to communities (Reid et al., 2005). Due to the high local specificity in what is culturally valuable to a community and how oyster reef restoration can support these cultural values, the following sections provide an overview of some of the possible connections, but do not comprehensively address all possible cultural values or their connections to oyster reef restoration.

Sense of place (linked to educational activities, cultural practices related to oysters)

The term 'sense of place,' first used in the 1960s, has been variously defined but is generally understood to refer to a person's sense of belonging to particular places, incorporating attachment to the place and the meaning that the place holds for the person (Kudryavtsev et al. 2012). Ecopsychology, which integrates ecology and psychology to understand people's relationship with the environment, holds that the modern disconnection of people from the environment has adverse effects for both human and environmental well-being.

One possible solution to this problem is to engage communities in conservation efforts, which promotes a sense of connection and stewardship for the landscape (Leigh 2005). Thus, participation in educational activities related to oyster reefs can foster people's attachment to the landscape and their sense of place. Several studies of volunteers' motivations for working on conservation projects, and the benefits they derive from volunteer activity, support the idea that volunteering increases participants' knowledge about their local environment and builds their sense of connection to the landscape. Among volunteers at three Michigan conservation organizations, the strongest reported motivations for volunteering were helping the natural environment and learning more about the environment (Ryan et al. 2001). This study also attempted to measure the impact of volunteer work on the volunteers by asking about how their feelings and actions related to the natural world had changed over the last few years (the period of their volunteer work). Volunteers reported that they had become more attached to local natural areas and more interested in protecting local natural areas, as well as more appreciative of natural areas in general and more attached to their volunteer site. The strength of response for each of these outcomes suggests that volunteering may promote an attachment to local natural areas even more than attachment to the specific volunteer site (Ryan et al. 2001). In surveys and interviews, Minnesota Master Naturalist volunteers often cited learning more about nature, being close to nature, and giving back to the environment as reasons for their participation. Several volunteers mentioned an increased interest in and enjoyment of nature as they learned more about it through volunteering (Guiney & Oberhauser 2010). Prairie restoration volunteers in Chicago reported deriving satisfaction from learning how nature works, feeling they can play a role in nature, and acting responsibly toward the earth (Miles et al. 2000). A survey of volunteers at five ecological stewardship groups in Michigan and Ohio rated their reasons for participation; highly rated reasons included protecting natural places, learning new things, and feeling a sense of oneness with the natural world (Grese et al. 2000). While none of these studies focused on oyster reef restoration projects or even coastal ecosystems, it seems likely that volunteering in different types of ecosystems will have similar effects on participants' connection to the natural landscape as they learn more about it and work to restore it.

Cultural practices such as festivals and art with an oyster-related component may also help to foster a sense of place. A qualitative study of four community cultural festivals in New South Wales, Australia found that festivals can reflect the communities' sense of place and encourage the development of a deeper sense of place in residents (Derrett, 2003). Another study of an environmental art festival in the Noosa Biosphere Reserve, Australia, surveyed residents of the village in which the festival was held to assess the festival's influence on their sense of place. Survey respondents reported that the art festival made them feel more connected to their community and the local environment, and that they wanted to 'do more' for both their community and environment (Marks et al. 2016).

Existence value (linked to oyster habitat persistence, biodiversity, T&E species persistence)[6]

Existence value is the value people hold for the existence of a species or habitat without the intention to use, visit, or experience it.

A variety of studies have examined existence value for species by estimating willingness to pay (WTP) for conservation efforts targeting particular species, with various persistence-related outcomes including changes to population size, listing status, and probability of extinction within a certain timeframe. A meta-analysis of willingness-to-pay studies for endangered and threatened species in the United States found that people were willing to pay $0.101 more for each 1% increase in population size that a particular program created; this figure reflects the total value of those species (not just existence value) and only applies to threatened/endangered species (Richardson and Loomis 2009). Whether a species had only nonuse or both use and nonuse value was included as a factor in this analysis; species with only nonuse values were valued at about $39 lower than species with both use and nonuse values, when all other factors were equal. The USGS Benefit Transfer Toolkit provides estimates of total economic value for a variety of threatened, endangered, and rare species within the United States, based on a database of individual nonmarket valuation estimates. These estimates may include values other than existence value (e.g., recreational value), but they can provide a starting point for valuation of a particular species' persistence.

Few studies have attempted to estimate the non-use values (including existence value, option value, and bequest value) of intact habitats such as oyster reefs. A 2016 review of economic values of wilderness found six studies of wilderness values that included non-use values; annual household WTP was estimated at $0.01–$0.61/1000 acres (Holmes et al. 2016). The authors of the review article suggest that new studies are needed to update these estimates. It may also be difficult to separate non-use

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[6] Part of this section is adapted from Warnell et al. 2017 (BLM paper)

values for habitat existence from non-use values for the species dependent on that habitat; if these non-use values are not separated, double-counting may occur (e.g., the non-use value for a certain species may be counted towards the species non-use value and the habitat non-use value). Contingent valuation methods can be used to estimate the existence value that a population holds for a particular habitat area. An example of this method can be found in a study that assessed the existence value of a wilderness area in Vermont (Gilbert et al. 1992).

A report on the economic benefits of Chesapeake Bay oyster restoration assessed non-use (existence and option value) value of oyster reef restoration to the public (Hicks et al., 2004). Based on a phone survey, willingness to pay for a 1000-acre oyster reef restoration project was $55.45/year. Respondents who believed that oyster populations are in decline and that past restoration programs have been effective were willing to pay more. A more detailed mail survey estimated the non-use value of creating 1,000 acres of new oyster reefs in a new 10,000 acre oyster sanctuary, constructed over 10 years, as $179.61/year/household. Respondents to the mail survey self-selected to participate, and so may not be representative of the public.

Livelihood option (linked to jobs)

Livelihoods such as oyster harvesting, commercial fishing, and leading chartered recreational fishing trips are often strongly tied to identity, family, and community; this is exemplified by the oystermen of Apalachicola Bay (Reiley, 2018). When oyster reef restoration helps these livelihoods to remain viable options in an area, it supports these cultural values.

Traditional & local knowledge (linked to educational activities, oyster habitat persistence, jobs)

Traditional and local knowledge is knowledge that is generated through practical experience, tied to a particular location, and transmitted through demonstration or imitation rather than writing (Bicker et al. 2003). Because this knowledge is transmitted and reinforced through experience, the persistence of oyster reef habitat, availability of jobs supported by oyster reefs, and other engagement with oyster reefs such as volunteering can support traditional and local knowledge related to oyster reefs.

Culinary heritage (linked to food)

Culinary heritage and traditions related to consuming local oysters can be supported by oyster reef restoration.

Strength of evidence

None. The strength of evidence for these relationships was not rated since these are just examples of some of the ways oyster reef restoration can contribute to cultural values.

Other factors

The length of time that a person has been involved in restoration work may influence the strength of their attachment to local landscapes. One study found that the likelihood of a person engaging in environmental advocacy in response to a negative impact on their volunteer site increased with the duration of their volunteer work on the site (Ryan et al. 2001).

Predictability

No tools or models to predict this relationship were found.

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Link 64: Science Opportunities → Jobs (Education & Scientific Research)

Description of relationship

Oyster reefs provide opportunities for research and outdoor education, which can lead to jobs in those sectors.

Summary of evidence

This link is context specific and dependent on nearby educational and research resources. For Natural Estuarine Research Reserve Sites (NERRS), it is likely that jobs created by scientific and educational resources and needs will be accessible.

The process of developing a restoration project begets scientific expertise. According to the Smithsonian Environmental Research Center, research on methods, application of active interventions and evaluations are important tools used to restore ecosystems for their inherent value and the ecosystem services they provide humans. The ability to apply a broad range of scientific disciplines is needed to understand the outcomes of restoration practices that can include reforestation of cleared land, dam removal, oyster restoration, and many others.

Strength of evidence

None. Though many logical connections exist between oyster reef sites, research and education, and jobs, there is little to no published evidence that supports this generalized link. Site-specific data (perhaps economic impact reports) may be available at a local level to improve the evidence grade of this link for a particular site.

Other factors

The amount of available funding for scientific activities can have an effect on the frequency and extent of the activity. The less funding a topic receives, the less research into that topic will be conducted.

Predictability

While restoration outcomes are difficult to predict, experimental approaches to restoration and post-restoration monitoring can improve understanding of outcomes, and identify best practices. Rigorous evaluation of restoration practices is critical to ensuring that the limited resources available for restoration are used wisely (Smithsonian Environmental Research Center) and therefore it is somewhat likely that restoration projects that require scientific actives will lead to jobs.

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Link 65: Nutrient Concentration in Water → Algal Blooms

Description of relationship

Nutrient levels in estuary water can influence the likelihood that an algae bloom will occur. Algae blooms can occur because of "overfeeding" of algae by nutrient runoff (NOAA NOS 2017). This phenomenon occurs if phosphorus, nitrogen, and carbon levels are discharged to a waterbody at a rate that causes increased algae growth.

Summary of evidence

Algae blooms are a form of excessive primary production. Under the proper conditions, high levels of nutrients can stimulate explosive growths of algae, resulting in algae blooms (Howarth et al. 2000; NRC 2000; NOAA OSE 2017).

Some algal blooms can be categorized as harmful algal blooms (HABs) because of the damaging biotoxins they produce. Numerous studies from estuarine systems around the world find a positive correlation between nutrient runoff from anthropogenic activities to an increase in HAB frequency (Hallegaeff 1993; Sellner et al. 2003; Gilbert et al. 2007; Heisler et al. 2008). Harmful algae blooms have received a lot of attention in the United States, resulting in national-level assessments of trends in HAB occurrences (Bricker et al. 2008; Anderson et al. 2008) as well as government-funded working groups, committees, and preparedness plans for assessing, predicting, and handling HAB events (Ramsdell et al. 2005; Jewett et al. 2007; Jewett et al. 2008). In 2003, the U.S. Environmental Protection Agency held an expert roundtable discussion on the relationship between HABs and nutrients, and developed the following relevant consensus statements:

- Degraded water quality from increased nutrient pollution promotes the development and persistence of many HABs and is one of the reasons for their expansion in the United States and other nations.
- The composition—not just the total quantity—of the nutrient pool impacts HABs.
- High-biomass blooms must have exogenous nutrients to be sustained
- Both chronic and episodic nutrient delivery promote HAB development
- Management of nutrient inputs to the watershed can lead to significant reduction in HABs (Heisler et al. 2008).

Nuances in these statements should be considered when thinking about HABs at a site-specific level. More detail and supporting evidence for these statements can be found in Heisler et al. (2008).

Algae blooms are difficult to predict because a complex network of biotic and abiotic factors create conditions appropriate for a bloom. A neural network modeling approach has been used to attempt to predict coastal algal blooms, but this technique has primarily been used in freshwater systems (Lee et al. 2003). Research on specific bloom types, such as red tide in Florida, is progressing to the point that factors supporting bloom development are becoming well enough understood to support reasonable predictions. NOAA has developed models that form a HAB Monitoring System to forecast red tide occurrences in the Gulf of Maine, Gulf of Mexico, and Lake Erie. The monitoring system is meant to minimize HAB impacts on public health and coastal economies (Stumpf et al. 2003; NOAA 2013). By using HAB observational data from monitoring networks and linking them to optically based (remotely sensed) models, it is possible to predict where HABs may occur (Sellner et al. 2003; Stumpf et al. 2003; Stumpf et al. 2009). Linking general circulation models to algal biological models can also predict HAB distributions; however, developing these models is quite difficult (Sellner et al. 2003; Heisler et al. 2008). There are two general HAB model types: (1) models that predict general likelihood of occurrence, and (2) models that create explicit HAB predictions in time or space (Heisler et al. 2008). Models that have had relative success in predicting harmful algae blooms have been developed for the Gulf of Maine, Florida, the Gulf of Mexico, and several sites in Europe (Sellner et al. 2003; Heisler et al. 2008). These complicated simulation models have many inputs in addition to nutrient levels.

Strength of evidence

Moderate. There is strong evidence to suggest that links between nutrient levels and algal blooms exist; however, that evidence does not extend easily to predicting when or where those blooms will occur. Additionally, the literature suggests that these blooms are dependent on many factors, some of which are difficult to measure accurately, to model accurately, or both, and it is hard to predict when nutrients will reach a threshold level that would result in a bloom.

Other factors

Abiotic Factors: Algae blooms are not caused by nutrients alone. They can occur any time conditions are right for either micro or macroalgae to grow out of control (NOAA NOS 2017). Some estuarine systems are more susceptible to algae blooms than others due to hydrodynamic and other physical factors. Chief among these are light availability to support photosynthesis and frequency with which the estuary is flushed due to runoff, tidal flushing, or wind mixing (Howarth et al. 2000; Ferreira et al. 2005; Bricker et al. 2007). If flushing rates are high, algae growth cannot keep up with dilution, and cells are lost from the system limiting bloom development. Other hydrodynamic conditions such as development of salinity, temperature-driven frontal zones, or wind-driven accumulation of surface scums can also concentrate cells facilitating bloom development and maintenance. High temperatures also tend to favor blooms of cyanobacteria and certain toxic dinoflagellate species by promoting high growth rates (NOAA NOS 2017).

Nutrient Ratios and Speciation: A relationship between changing nutrient compositions and harmful algae blooms has been determined, though neither the quantity nor ratio of inorganic nutrients can explain fully when and where a harmful algae bloom will occur (see section 2.2 of Heisler et al. 2008 for more detail). The speciation of nutrients is also a factor as shown in the relationship of dissolved organic nitrogen (DON) and blooms of the brown tide organism, Aureococcus anophagefferens. This harmful algal bloom species preferentially uses dissolved organic nitrogen for its nutrient rather than inorganic nitrogen forms and thus is a symptom of organic- rather than inorganic-driven eutrophication (Glibert et al. 2007).

Algae Grazers: Algal grazing by zooplankton and benthic suspension feeders can help control explosive algae growth (Cloern 1982; Howarth et al. 2000).

Predictability

Models described in Lee et al. (2003), Sellner et al. (2003) and Heisler et al. (2008) have shown success in modeling and, in some cases, predicting different types of algae blooms. However, these are highly complex models that are likely inaccessible except to expert users. These models have numerous inputs, including nutrients, which are by no means the only predictive factor incorporated.

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Link 66: Algal Blooms → Dissolved Oxygen

Description of relationship

Algae blooms can deplete dissolved oxygen because of high respiration rates by algae, but most often oxygen depletion is due to bacterial respiration during decay of the bloom (Hallegraeff 1993; Howarth et al. 2000; Sellner et al. 2003).

Summary of evidence

As algae from a bloom dies, bacterial decomposition of the algae takes place and this decomposition process uses dissolved oxygen in the water. When the rate of oxygen consumption by bacteria exceeds the supply of oxygen provided by the environment, dissolved oxygen levels can drop and result in hypoxic conditions (Howarth et al. 2000; National Science and Technology Council 2016). Additionally, algal blooms can reduce water clarity to a level that prevents sunlight from reaching submerged aquatic plants, reducing their ability to photosynthesize and produce oxygen (Howarth et al. 2000; Bricker et al. 2008; National Science and Technology Council 2016). Jewett et al. (2010) provide a good overview of hypoxia in U.S. coastal waters.

Some models predict dissolved oxygen levels in relation to events such as algae blooms. Most models have been developed for specific locations, such as the ChesROMS model for the Chesapeake Bay (Wiggert et al. 2017). Dissolved oxygen is just one of many outputs of this model, and inputs include data on sediments, atmospheric deposition, nutrient and dissolved organic matter inputs, and benthic interactions. Algal blooms are not a singular predictor of dissolved oxygen, and the model’s complexity incorporates the various interactions between biotic and abiotic factors that result in dissolved oxygen levels (Wiggert et al. 2017). The model has been validated using fine-scale dissolved oxygen data, and it has been found to accurately represent dissolved oxygen fluctuations at various sites in the Chesapeake Bay.

Strength of evidence

Moderate. The literature strongly suggests that high biomass blooms will cause a reduction in dissolved oxygen. But it does not necessarily follow that the reduction will reach a critical threshold level with cascading ecological effects.

Other factors

Stratified layers of water will often have different levels of dissolved oxygen. Usually, deeper layers of water will contain less oxygen because of reduced oxygen exchange with the air.

Predictability

There is no good way to predict exactly how much high biomass algae blooms will reduce dissolved oxygen levels. Therefore, the magnitude of that effect cannot be predicted. Example. Models can predict dissolved oxygen levels for a specific estuary, but these models are often highly complex and are developed to work at a specific site. One such model is ChesROMS, applicable for the Chesapeake Bay (Wiggert et al. 2017). Transferability of such a model would be difficult, limiting the model's more generalized use.

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