**Practitioner’s Guide to setting Oyster Restoration Objectives**

Authors: , Boze Hancock, Bryan DeAngelis, Mark Spalding, Rob Brumbaugh, Jenn Greene, Elisabeth Schuster.

Table of Contents

Preface 2

Introduction: Making the case for oyster restoration 4

What is an oyster reef? 4

Historic decline 6

Ecosystem services 8

Water clarity 8

Nitrogen removal 8

Fisheries enhancement 9

Coastal protection 9

Oyster harvest 9

Biodiversity 10

Cultural value 10

Does restoration work? 10

Setting ecosystem service goals(objectives?) 10

Determining what is of importance to stakeholders 10

Rapid Stakeholder Assessment 12

Implementing the results of a rapid stakeholder assessment 14

Revising the role of historic abundance in restoration goal setting 15

Restoring for improved ecosystem services 17

Water clarity 17

The eastern oyster 17

The Olympia oyster 22

Nitrogen removal 23

Quantifying nitrogen assimilation in tissues 23

Quantifying nitrogen burial 24

Quantifying nitrogen removal by denitrification 24

The relative roles of oyster habitat restoration and aquaculture 25

Using nitrogen removal to set restoration goals 25

Non-oyster fisheries 26

Quantifying fish enhancement by oyster reefs 26

Using fish enhancement estimates in oyster restoration goal setting 32

Coastal protection 34

Coastal Resilience 34

Coastal Defense 35

Factors affecting ecosystem service provision 35

Appendix: 36

Appendix 1 Estuary scale data summaries 36

Appendix 2 Shell height biomass conversion 36

Appendix 3 Detailed fisheries methods 36

References: 37

Appendix 4 43

# Preface

Oyster restoration for conservation purposes is becoming commonplace along US coasts. The number of projects implemented have increased over recent years, with a growing number of larger scale projects. Both large and small scale restoration projects contribute to countering historic habitat loss and to the delivery of ecosystem services. As oyster restoration efforts become increasingly successful, it is increasingly important that the contribution of individual projects to the larger scale restoration objectives also be recognised. These large scale restoration objectives therefore need to be defined.

At present there is little guidance available to managers seeking to set long term, large-scale management and restoration objectives. Such objectives should be more tangible than aspirational goals, and should incorporate the factors that have motivated stakeholders to undertake the restoration project in question. Ecological restoration of oyster reefs and beds may be motivated by a number of perceived benefits including the enhancement of oyster and non-oyster (e.g. finfish, shrimp and crab) fisheries, water quality improvements, coastal defence, and the biodiversity and cultural value associated with oyster habitat. It is primarily an improved understanding of these values over the past decade that has resulted in the rapid growth and interest in oyster restoration projects. To ensure that restoration maintains its current momentum, it is essential that restoration practitioners, stakeholders and funding agencies are able to envisage how their efforts are contributing to these wider perceived or projected benefits.

This guide is intended to assist natural resource mangers and restoration practitioners in making the case for oyster restoration and in setting appropriate goals for restoring and managing oyster reefs and beds at an estuary or bay wide scale. Determining the area of oyster restoration required to achieve long term large scale goals has numerous applications; from being better able to incorporate restoration into spatial and conflict user group planning, to better articulating long term goals and benefits when fundraising. In formulating this guide we have drawn on the latest science and information on historical extent of these habitats. We focus on the potential benefits that restored or enhanced reefs may provide through four key ecosystem services: water filtration, denitrification, the enhancement of non-oyster fisheries, and shoreline protection. The information provided here allows for planning restoration at an estuary scale.

Where possible, we provide details for specific locations, but it must be recognised that such data are not equally available for all locations and may be interpolated from adjacent regions. These data will therefore not always account for local features and processes. They also necessarily represent an estuary wide mean, and are therefore not representative of all locations within an estuary. Furthermore, while this document uses science-based evidence to assist practitioners in defining their objectives and the approximate amount of restoration required to achieve them, the true amount of ecosystem services restored will be influenced by a multitude of factors on a smaller scale, including but not limited to: reef location, landscape, project success, and many other abiotic factors.

This guide ***does not*** intend to be a replacement for post-project monitoring to assess project performance or quantify the actual ecosystem services delivered as a result of a project. This document serves to act as a guide to help set science-based *targets* for the amount of restoration required to achieve the approximate level of ecosystem services that originally motivated the restoration efforts. Monitoring of the intended goal and adaptive management must also play a role in both setting goals and assessing progress.

This guide ***does not*** seek to assist restoration practitioners in determining suitable sites within an estuary to undertake restoration.

For further information on starting and locating a restoration project, please see Brumbaugh et al. (2006), and for further information on restoration design and monitoring please see Baggett et al. (2014).

# Introduction: Making the case for oyster restoration

Support for oyster restoration primarily arises as a result of the unequivocal evidence of large scale and dramatic loss of this critical coastal habitat (zu Ermgassen et al., 2012), and the ecosystem services it provides (Coen et al., 2007, Grabowski et al., 2012). This report seeks to summarise the current state of knowledge regarding the benefits of oyster restoration in a readily accessible format. In this section we outline evidence of the declines in oyster habitat in the United States, as well as the ecosystem services these habitats provide. We also set out the evidence that these services can be regained following restoration.

## What is an oyster reef?

Oysters are marine and estuarine bivalve molluscs in the Family Ostreidae. The most common species of oyster in the US are the eastern oyster (*Crassostrea virginica*) on the Atlantic and Gulf coasts, and the Olympia oyster (*Ostrea lurida*) on the Pacific coast. Both of these species are commercially valuable. Oysters can be extremely long lived, with individual eastern oysters as old as 18 years recorded (Bleakney and David, 1983). A life span of just 3-5 years is, however, more typical in today’s environment.

Oysters start life as planktonic veliger larvae before seeking out hard substrate on which to attach and grow. In the case of reef building species, young oysters preferentially attach to living oysters, although any hard substrate can be colonised. The successive generations of oysters grow on top of one another, forming a complex, raised, three-dimensional structure. This structure is typically called a reef if formed by the eastern oyster. Olympia oyster individuals more easily chip away from one another and therefore typically form less massive structures commonly referred to as beds (see box 1).

There are numerous challenges to delineating the area of an oyster reef or bed. The structure of reefs differs substantially depending on the direction and speed of flow, the nature of the underlying substrate, and whether the reefs are subtidal or intertidal (fig X). Furthermore, the fractal nature of reefs means that the area considered “reef” may differ with the scale considered and the purposes for which an area of reef has been defined (box 1). For further information regarding how to determine the area of an oyster restoration project, please refer to Baggett et al. (2014).

Figure X: Images of oyster reefs in a variety of settings.

**Box 1:What is meant by an oyster reef or bed?**

*“Very few people know what is and what constitutes a “natural bed”. Indeed it is only a matter of opinion at the best” (Winslow, 1889).*

*A comprehensive definition of an oyster reef or bed has challenged biologists for over a century. Yet it is essential to have a definition of the habitat, as this determines the goals and the monitoring required for each restoration project. Simplistically, oyster habitat refers to substrates with a veneer of live oysters, with the edge of the habitat defined by the density of living oysters, at an appropriate spatial scale. Practically, determining the minimum threshold that constitutes oyster habitat at different scales is fraught with difficulties.*

*We provide the following definitions at three different spatial scales.*

Oyster reefs and beds

*Oyster reefs and beds are biogenic structures formed by oysters that occur at high densities and provide the dominant structural component and significant vertical relief through their accumulated physical structure on otherwise unstructured bottom. Beck et al. (2009) identify reefs having significant vertical relief (>0.5m), while beds have lower relief (sensu Coen and Grizzle, 2007). Overall such structures are accreting through the continuing deposition of shell matter at rates sufficient to keep up with sedimentary dynamics (Mann et al., 2009) although there is likely to be small scale (meters) patchiness in oyster cover. In some places it is likely that vertical accretion may be restricted by tidal exposure, leaving a non-accreting reef flat.*

Oyster reef systems

*Oyster reef systems represent wider ecological network of which reefs and beds are the core structures – in many estuaries beds and reefs are found with an apparently natural level of fine-scale patchiness: areas of dense growth interspersed with areas of non-oyster substrate at scales of one to tens of metres. These larger reef systems may include areas of bare substrate, submerged or intertidal vegetation, but with a likely high degree of connectivity with the dominant oyster reefs or beds. By contrast, small or isolated oyster beds or reefs may not form part of a reef system. There are parallels with coral reef ecology here: many coral reef ecologists include reef flats, lagoons, coral cays and even small areas of contiguous seagrass and mangrove within their definitions of coral reef ecosystems, while isolated reef patches or bommies may not form part of any larger reef system (Spalding et al., 2001).*

Oyster grounds

*Oyster grounds encompass the wider community complex of which oyster reefs and beds are clearly an important part, but which also may include large areas of sediments, submerged aquatic vegetation and shell rubble. Such areas would broadly equate with “fishable areas” and are used here to broadly capture the more generic oyster grounds of many historic studies.*

*It is critical that the definition used in any restoration project is in line with the expectations of the reporting for any funding body. The definitions put forward here are inline with those proposed in Baggett et al. (2014), who set out preferred metrics for monitoring restoration efforts. Baggett et al. (2014) should be referred to for further information, specifically with regards to minimum densities.*

## Historic decline

Oyster reefs and beds have been an important feature of estuaries in the United States over at least the past 10,000 years, since the late Pleistocene. Early European explorers described oyster reefs as navigational hazards, in particular on the Atlantic and Gulf coasts where the reef building species *Crassostrea virginica* is found (see Box 2).

Oysters were a dietary staple in the early years of European settlement along the coasts of the United States. At first they were abundant and easily collected from the shallows and intertidal areas, but harvesting pressure quickly led to declines. Hand harvesting was supplemented by the use of boats and tongs, and as densities declined and accessible areas became depleted, this was followed by an increase in mechanical dredging. Dredging allowed the exploitation of deeper beds and more remote locations. Without adequate regulation to protect the beds and reefs, their decline soon followed (see Box 3). Both living and dead oysters contribute to the growth and persistence of oyster reef or bed habitats, therefore the large-scale removal of oysters and shell matter led to a loss of habitat, as well as a decline in living individuals. This pattern of over exploitation spread rapidly down the coast of the US away from major urban centres (Kirby, 2004).

While there is little doubt that overexploitation has been the primary driver of decline in oyster abundance throughout the US, pollution, coastal engineering and disease have also contributed to the loss of habitat. It is estimated that around 88% of the living biomass of oysters has been lost from US estuaries over the past 120 years alone (zu Ermgassen et al., 2012), and it is clear that losses may greatly exceed this estimate, as many of the mapped areas on which this assessment was based were already heavily before the areas were mapped and could be assessed (see box 3). It is therefore not possible to accurately quantify the original, natural, oyster abundance in most bays and estuaries. In particular, we know that exploitation was intense on the northeastern Atlantic from Connecticut to the Chesapeake, and on the West coast spreading out from San Francisco (box 3; Kirby, 2004).

Oyster reefs were not only physically dominant in many estuaries, but their presence in such great numbers would have provided a range of ecosystem services (Coen et al., 2007, Grabowski et al., 2012), including the maintenance of clear water and enhancement of fish populations that benefit from oyster habitat. Today their contribution to such ecosystem services has likely declined along with the habitat.

**Box 2: The historic magnificence of oyster reefs before they were impacted**

*It is challenging to envisage the importance and magnitude of oyster reefs and beds historically, primarily because much of the decline has taken place outside of living memory. Fortunately there are a number of descriptions of oyster habitat from the early explorers of the US coasts. A handful of examples are given below to provide context to the documented declines.*

Massachusetts

*“[The Oyster] often measures 12 or 15 inches in length, but seldom more than 3 inches in breadth.” (Gould, 1841).*

*“In 1637 Thomas Morton, writing of the Plymouth Colony, says: " There are great stores of oysters in the entrances of all rivers; they are not round as those of England, but excellent, fat and all good. I have seen an oyster bank a mile at length."” (Brooks et al., 1884)*

Virginia

*“The abundance of oysters is incredible. There are whole banks of them so that the ships must avoid them. A sloop, which was to land us at Kingscreek, struck an oyster bed, where we had to wait about two hours for the tide. They surpass those in England by far in size, indeed they are four times as large. I often cut them in two, before I could put them into my mouth.”(Michel 1702, translated in Hinke, 1916)*

Florida

*“Through many a shallow and barrier, the latter made up of oyster banks, the Caloosahatchee River is ascended” (The New York Times, Anon, 1884)*

*“There is a luxuriant growth of oysters in parts of Biscayne Bay…growing in dense reefs or beds in the open bay, and on the roots and submerged limbs of mangroves and other trees along the shore.” (Smith, 1896)*

Louisiana

*“The shoals and oyster banks extending out to sea between four and five leagues [~30km], and leaving only a very narrow and intricate channel” (Dumain, 1832)*

Washington

*“Natural oyster-beds stretched over a distance of thirty miles in length and from four to seven in width.” (Bancroft, 1890, speaking of Willapa Bay in ca.1850)*

*“Oystering as an industry dates back to the middle of the last century… In those times a much larger area than now was covered with natural beds of oysters.” (Bush, 1900)*

## Ecosystem services

The scale of loss of oysters in many bays is such that restoration to historical abundance may be a practical impossibility. Moreover it is important to recognise that conditions in many bays and estuaries are different now from when oysters were abundant 100 to 200 years ago. Thus in many settings it may be ecologically impossible or irrelevant to restore towards historical baselines. Another major target, however, is to restore elements of ecosystem function, and the associated benefits that oyster habitat can provide. These ecosystem services arise both as a result of the physical structure of oyster reefs and beds, and from the biological processes of living oysters. They include providing fisheries habitat, filtering the water column, enhancing denitrification in surrounding sediments, coastal protection, and enhancing benthic biodiversity (Grabowski and Peterson, 2007, Coen et al., 2007, Piehler and Smyth, 2011, zu Ermgassen et al., 2013a, zu Ermgassen et al., 2013b). These ecosystem services have been valued between $5500 and $99,000 per ha per year (Grabowski et al., 2012).

This list of services is not exhaustive, but seeks to provide an overview of the range of services provided by oyster habitats. While each of the services listed may be important, only filtration, enhancement of denitrification, non-oyster fisheries enhancement and shoreline protection will be revisited in the following chapters.

### Water clarity

Oysters are filter-feeding bivalves. Small particles of plankton and non-living matter that are suspended in the water (greater than 5 µm in diameter) are filtered by oysters with high efficiency. Selected particles are ingested, while the remaining particles are bound together in mucus pellets termed *pseudofaeces* and ejected. These pellets sink and particles are thus removed from the water column and deposited on the seafloor. This drawdown of suspended particles through the filter feeding activity of oysters (and associated fauna) can lead to enhanced water clarity, which results in greater penetration of sunlight through the water to the sea bed, with the potential of facilitating improved growth of submerged aquatic vegetation (Wall et al., 2008). The amenity value of the water body may also be improved through greater water clarity.

### Nitrogen removal

The production of waste matter by oysters, including both faeces and the pseudofaecal pellets, or *biodeposition*, enriches the bottom sediments with organic matter. This enrichment alters the microbial community (Richardson et al., 2008), and loads the sediments with organic nitrogen. One important outcome of these changes, also facilitated by the complex structure of oyster reefs and beds, is that denitrification rates can be greatly enhanced in the sediments (Newell, 2004, Newell et al., 2005, Kellogg et al., 2011). Denitrification is a microbe mediated process by which organic nitrogen is transformed into inert nitrogen gas (see Figure XX). “Reactive” nitrogen is thus permanently removed from the system. Given that reactive nitrogen from anthropogenic sources is a major driver of organic pollution, eutrophication and low oxygen levels in many US estuaries, this service could become one of considerable value with the restoration of additional oyster habitat.

### Fisheries enhancement

Oyster reefs and beds typically have vertical relief and a higher habitat complexity than the surrounding seafloor (see definitions in Box 1), and as such provide valuable structured habitat for juvenile fish and crustaceans. Numerous studies have shown that restored oyster reef supports higher densities of juvenile fish and crustaceans than unrestored sites (Tolley and Volety, 2005, Stunz et al., 2010). Juvenile fish benefit from the higher habitat complexity, which reduces predation and increases prey density (Boesch and Turner, 1984). There have been significant losses of complex habitat in estuaries worldwide (Waycott et al., 2009, Airoldi and Beck, 2007), therefore restoration may have a substantial impact, increasing not only the abundance, but also the diversity of associated fish and benthic fauna (Tolley and Volety, 2005, Shervette and Gelwick, 2008).

### Coastal protection

Three-dimensional structures in shallow areas may provide coastal protection – attenuating waves, reducing coastal erosion, and encouraging accretion (Borsje et al., 2011). Oyster reefs have been shown to have this effect in a number of locations (Piazza et al., 2005, Scyphers et al., 2011). While the provision of this service may be variable from location to location and with changes in reef structure (Stricklin et al., 2010, Scyphers et al., 2011, Meyer et al., 1997), it may play a critical role in some systems. Oyster reefs are already being used successfully in a growing number of locations to reduce erosion or enhance accretion of saltmarshes behind restored reefs. The coastal protection capacity of oyster reefs has been described as an alternative to the fully engineered solutions such as bulkheads (see CoastalResilience.org ), with the added benefit that the oyster habitat provides a suite of other ecosystem services in addition to the shoreline protection function.

### Oyster harvest

Restoration may be undertaken in order to enhance the direct harvest of oysters. While oyster reefs are widely restored for oyster harvest, it will not be dealt with further in this report. The harvest of oysters from an oyster reef is directly at odds with the aims of enhancing other ecosystem service provision from the reef. While it is theoretically possible to sustainably harvest oyster reef and simultaneously derive many of the other ecosystem service benefits, current evidence suggests that harvest reduces the provision of other valuable services to the extent that the total economic benefit of the reef is lower when harvest is allowed as opposed to when harvest is banned (Grabowski et al., 2012). Harvest of restored oyster reefs has been implicated in reducing the life-time success of the reef. Reefs with high relief often attract greater densities of oysters, while harvest by dredges reduces the height of the reef (Lenihan, 1999). Economic valuation of oyster reef ecosystem services indicates that the costs of habitat restoration are unlikely to be recouped where oyster harvesting is undertaken (Grabowski et al., 2012).

### *Biodiversity*

Oyster reefs support a higher biodiversity of invertebrates and fish than surrounding unstructured habitats (e.g. Rodney and Paynter, 2006). This is primarily because these small animals benefit from the three-dimensional structure provided by the oyster shells, either by avoiding predators, or because they form a surface to attach to (Tolley and Volety, 2005, Gedan et al., 2014). The biodepostion by oysters enriches the surrounding sediments with organic matter and also provides an abundant food source to a host of important prey species, further enhancing the biodiversity supported by this habitat.

### Cultural value

Oysters have been a significant feature of coastal communities for millennia. As such, the culture associated with harvesting and consumption of oysters is deeply rooted and highly valued. While it is challenging to quantify such values, it is important that these values are nevertheless not overlooked.

## Does restoration work?

The evidence that oyster reefs have been in decline and that they provide a large and valuable suite of services, is not on its own enough to justify significant investment. It is also critical to demonstrate that oyster restoration can successfully address both of these underlying issues. Thankfully it has been unequivocally demonstrated by previous restoration projects that oyster restoration can be successfully undertaken; that oysters can successfully recruit to planned structures, and that the restored reefs also provide the ecosystem services associated with natural oyster habitat such as fisheries enhancement (Scyphers et al., 2011, Gregalis et al., 2009), improved water transparency (Grizzle et al., 2008), enhanced denitrification (Kellogg et al., 2011) and effective shoreline protection (Piazza et al., 2005, Scyphers et al., 2011).

# Setting ecosystem service goals(objectives?)

## Determining what is of importance to stakeholders

The motivation to restore oyster reefs may arise from any of the many potential benefits oyster reefs provide (see Chapter 1). In order to select an appropriate restoration goal, it is necessary first to identify the relevant stakeholders at the restoration site, and to determine which of the numerous services are of greatest importance to them.

The success of restoration projects is heavily dependent on gaining and maintaining the support of stakeholders. It is therefore important to provide the opportunity for stakeholders to communicate effectively what they hope to gain from restoration before the start of the restoration activity and ideally from its very conception. The provision of ecosystem services may vary spatially and with the design of the restoration project, therefore early engagement can allow for stakeholder engagement to feed into restoration design and implementation. In order to maintain the support of stakeholders, it is important that the status of the restoration project, both generally and with respect to the ecosystem service(s) of interest, is reported back to them throughout the restoration and monitoring process. Some further guidance on stakeholder engagement is outlined in Brumbaugh et al. (2006).

Also ISSC report Leonard and Macfarlane

The following chapter provides information on low-cost methods for identifying stakeholders and understanding which ecosystem services matter most to them.

Stakeholder engagement: Identifying ecosystem service benefits

Stakeholder engagement is more than simply asking stakeholders about their preferences and concerns. Stakeholder engagement also encompasses understanding the socio-cultural context and building relationships with communities. Engaging stakeholders early in the process has several important advantages, including reducing conflict and increasing support for restoration projects. The NOAA Coastal Services Center has a report, Introduction to Stakeholder Participation (2007), which succinctly highlights a full suite of reasons why engaging communities before beginning a restoration project makes sense:

* Produce better outcomes or decisions
* Garner public support for agencies and their decisions
* Bring to light important local knowledge about natural resources
* Increase public understanding of natural resource issues or management decisions
* Reduce or resolve conflicts between stakeholders
* Increase compliance with natural resource laws and regulations
* Help agencies understand flaws in existing management strategies
* Create new relationships among stakeholders

*Source*: NOAA Coastal Services Center 2007

If resources are available, it is often worthwhile to conduct a more in-depth analysis of the degree of stakeholder support in the region surrounding the upcoming restoration project. This is particularly true for large-scale restoration projects, restoration projects with potential negative impacts on certain stakeholder groups, and/or restoration projects that have the potential to be politically controversial. The NOAA Coastal Services Center report (2007) provides valuable information on identifying and analyzing stakeholders.[[1]](#footnote-1) Chapter 3 of The Nature Conservancy’s guidebook on Strengthening the Social Impacts of Sustainable Landscapes Programs (2014) is a also good reference for engaging stakeholders.[[2]](#footnote-2) Although aimed at indigenous communities in developing countries, most of the process is still relevant to the United States, particularly when working with communities that are relatively dependent upon natural resources.

## Rapid Stakeholder Assessment

If resources are scarce and time constraints exist, it is worth conducting a rapid stakeholder assessment. Although the intent of a rapid stakeholder assessment is to be efficient and low-cost, we recommend that you allow for at least two to three months to conduct the analysis. The goal of the assessment is twofold, 1) understanding how stakeholder groups interact with natural systems in the region, particularly those aspects of the natural system that will be improved by the restoration project, so that we can engage these stakeholders to gain support for a given issue, and 2) to better match conservation goals with community needs.

**To conduct a rapid stakeholder assessment for a given ecological restoration project, follow these simple steps**:

1. Define the geography boundaries and scale of interest. This will vary depending upon biophysical aspects of the restoration project, hydrology, jurisdiction, and location of stakeholders who are benefiting or impacted by the project. Examples include a municipality, county, watershed, estuary, or state.
2. List the ecosystem service benefits that will result from the upcoming restoration/protection project(s). Consult with subject experts as needed.
3. Understand and be able to effectively communicate potential trade-offs in ecosystem service delivery.
4. List all relevant stakeholders to the project, including beneficiaries and those who may be impacted negatively, and those who have the power to influence the success or failure of the project.

A rapid assessment will not answer all research questions, but can help to highlight information and data gaps, as well as to establish next steps. Note that while steps one through four are listed chronologically, the process is iterative and may involve circling back to previous steps as additional information is gained.

When listing expected ecosystem service benefits for a project, it is recommended to list all potential benefits from the full project, not just those directly resulting from the oyster reef restoration. For instance, the full project budget for an oyster restoration project may also include renovations to a marina, or construction of an education center or boat ramp. It is advantageous to list the full suite of benefits that may result from the upcoming restoration project for two reasons, first because it will lead to more effective stakeholder engagement, and second, because the multiple benefits from a project can often enable you to access additional funding.

For those coastal restoration practitioners on a shoe-string budget, the most efficient way to collect information on relevant ecosystem service benefits is through expert and key informant interviews and/or focus groups. Next, list stakeholders who are likely to support, likely to impede, or able to influence the success of the restoration project. Stakeholders may for instance include, any number of individuals (homeowners, voters, tourists, etc.); federal, state or local government officials; non-profit organizations; or business owners. We expect each of these stakeholder groups will have different needs, values and risks which they are facing and thus, they are likely to have different priorities in terms of key ecosystem service benefits of interest.

Background research to answer the questions in the rapid stakeholder assessment can include but is not limited to the following:

* Reviewing organizational websites from local groups,
* Searching for relevant reports and grey literature,
* Reading relevant newspaper articles,
* Reviewing data from the region (for instance, USDA Agricultural census data or agricultural statistics which are provided by state and by county, US Census data, GIS data or NOAA storm surge data),
* Reviewing published academic articles when available and relevant to the local context and conditions. These are especially useful when they contain survey data from your geography of interest.
* For a good list of data sources, refer to the “Watershed Approach Handbook: Improving Outcomes and Increasing Benefits Associated with Wetland and Stream Restoration and Protection Projects” to their section on data sources.[[3]](#footnote-3)

Next, proceed with key informant interviews. Key informants are individuals in a community who are knowledgeable about the community or a specific stakeholder group. Key informants may include governmental officials, business owners, extension agents, non-profit leaders, health care employees, residents, or religious groups, among others. Key informants can either be identified through the background research or through word of mouth. It is recommended to set a predetermined list of eligibility criteria, such as a minimum number of years living in the region, criteria on certain areas of expertise, or demonstration of other relevant characteristics. Unlike surveys, these interviews can be fairly unstructured, without a formal list of questions. Nonetheless, it helps to identify a small list of informal questions through background research before beginning. One important question to ask is always, “Who else would you recommend that I interview on this subject?” Social scientists refer to this as *snowball sampling*, where each interview leads to more contacts and more interviews.

If time permits, focus groups can be an additional source of information on a community or issue. A focus group consists of approximately 6-12 individuals. The focus group may include individuals from the same stakeholder group or may include a diverse mix of stakeholders, depending upon the specific research questions. Focus groups are an efficient way of gaining additional information because it allows a researcher to obtain answers from multiple individuals in a single setting. Focus groups can also be useful because the cross-dialogue can inspire additional conversation. However, focus groups are not recommended in situations where the subject matter is controversial or sensitive and could result in privacy concerns.

If you intend to conduct multiple interviews, lead focus groups, or implement surveys during the stakeholder engagement phase, it is worth investigating if your institution has a standard operating procedure regarding research involving human subjects. Typically, the researcher must submit a proposal to their institution’s human subject review committee. The committee is designed to ensure proper respect and ethics related to those who are being asked to participate.

## Implementing the results of a rapid stakeholder assessment

In summary, stakeholder engagement can lead to more successful projects and a rapid stakeholder assessment is the first step to good stakeholder engagement. The rapid stakeholder assessment process itself also can serve as stakeholder engagement. When stakeholders are interviewed, they are more likely to feel that their voice has been heard and thus, the interview process itself can lead to greater buy-in for the project. The rapid stakeholder assessment may help in early identification of potential conflicts. And in the context of goal setting for an oyster reef restoration project, a rapid stakeholder assessment can help the project manager to understand and prioritize potential benefits from restoration that resonate most with stakeholders.

## Revising the role of historic abundance in restoration goal setting

Given that the roots of habitat restoration lie in regaining habitats that have become lost or degraded, restoring the full or a proportion of historic extent is frequently a cited aim of restoration efforts. We caution against the sole use of historic extent in setting restoration goals. Conditions within the bay or estuary may no longer be conducive to supporting the full historic extent of oyster reef habitat. The interaction between coastal user groups and oyster reef is also likely to have changed over time. Historic extent can, nevertheless, play an important role in a) informing stakeholders about the potential of the system and, b) setting restoration into an ecological and historical context. When considering historic data as one element in restoration decision making, it is critical to be aware that the known baseline may be shifted (see boxes 3 and 4). A lack of quantitative historic data should not preclude restoration.

While goals based purely on historic extent should be avoided, goals may be set on the basis of ecosystem service provision, but reported out as a proportion of historic. This can be a useful messaging tool, and can set the aims of restoration into context. Historic data can be a powerful tool for informing restoration efforts. It is, however, important to be aware that baseline data may not represent pristine conditions (see boxes 3 and 4). Historic data should therefore be used with recognition of its limitations.

**Box 3: Oyster reefs were impacted before comprehensive surveys were undertaken**

“As man has uprooted the greatest forests, so can he also annihilate the richest oyster beds.” (Moebius, 1883)

*Already at the turn of the century there was extensive evidence of the degraded status of oyster reefs throughout much of the US. This was particularly true of the northeastern Atlantic and the Pacific coast. A number of historic citations highlight the status of oyster reefs from a number of locations throughout the US, in some instances as “baseline” surveys were undertaken.*

Massachusetts: *“The early settlers of New England continually refer to the abundance of oysters at points where not a single oyster can now be found….The oyster beds in these two rivers [Mystic and Charles Rivers] are spoken of by many of the early writers, but they are now gone so completely that there is not even a tradition to mark the place where in 1634, according to Wood, " the oyster bankes do barre out the bigger ships.”(Brooks, 1884)*

New York: *“A good instance of this deterioration is found in the famous Saddle Rock beds (area 639 acres) near Great Neck, L. I. Years ago this bed produced large quantities of marketable oysters of excellent quality. The record of my recent investigation of the bed shows: “Dredged seventy-five yards, found a roller skate, bottles, ashes, pasteboard, refuse, eight large oysters and a peck of small seed.” (Blackford, 1887)*

New Jersey: *“The natural beds along the coast are numerous and valuable, and they formerly abounded in large, fine oysters, but for many years they have furnished scarcely any oysters large enough for food” (Brooks, 1884)*

Maryland: *“The area of oyster grounds which were formerly productive, but which are now practically barren and without the ability to be restocked through natural means, aggregates about 100,000 acres.” (Grave, 1912)*

South Carolina:  *“Many regions appear to have become depleted from overfishing.” (Battle, 1891)*

Georgia: *“In regard to the condition of the natural oyster beds of the State of Georgia, it was observed that there was a general depletion caused by the excessive fishing, and that the nearer the market the more were the beds depleted. In fact, the area which I have indicated on the charts as natural oyster beds really include all that area where oysters have grown, and practically nothing but shells now remain.” (Drake, 1891)*

Louisiana: *“Barataria Bay, Jefferson Parish, at one time contained large natural oyster reefs, but these are now extinct, as a result of increased salinity after improvement of the levee system.” (Schlesselman, 1955)*

Texas: *“Galveston bay has a greater area of natural oyster beds than any other bay in Texas, but the reefs are not so plentifully supplied with oyster as in some others in the State. This is to some extent due to overfishing.” (Stevenson, 1893)*

Washington: *“The 1870’s ushered in the peak of Oysterville’s prosperity….Then started the decline. A mysterious oyster malady, slight at first, began to gain headway, starting in 1881.” (Tompkins, 1932)*

*Please see appendix for further examples.*

This text is just separating these two boxes and can be deleted later.

***Box 4: Shifted baselines***

*Human exploitation of coastal seas has a long history, as evidenced by middens and other archaeological sites (Rick and Erlandson, 2009). From studies of such sites it is clear that exploitation may have impacted populations long before modern extraction techniques. As the seas were generally historically viewed as being too vast to impact, and the resources were therefore also considered to be limitless, no surveys were made of marine resources until the 1800’s, when it become clear that exploitation was indeed impacting supply. As a result there are virtually no quantitative baseline data for pristine marine and coastal systems (Roberts, 2007). Under these circumstances it is important to be aware of the risk of assessing all subsequent change relative to a shifted baseline. The shifting baseline syndrome refers to situations when assessments of change are made relative to a baseline that may itself represent substantial change from pristine. Shifting baselines are frequently encountered in fisheries due to the late start in collecting relevant biological data, and has been shown to be present even over the period of a life time. Even quantitative baselines should therefore be utilised with caution and an understanding of the limitations the baseline presents.*

*In the case of oysters, early surveys represent perhaps the best historic record of any marine habitat (zu Ermgassen et al., 2012). The available records, however, are not complete, neither do they represent habitat at a universal stage of exploitation. As the overexploitation of oysters appeared to spread down the coasts away from major urban centres (Kirby, 2004), estuaries in the northeastern Atlantic and near San Francisco on the West coast in particular clearly represent an already shifted baseline (zu Ermgassen et al., 2012). This is because the oyster populations were already heavily exploited at the time the surveys were undertaken. Care should therefore be taken in interpreting the historic data available in these estuaries. The likely degree of exploitation at the time historic surveys were undertaken is illustrated by estuary in the Appendix.*

## Restoring for improved ecosystem services

Recovery of ecosystem services is frequently the primary motivation to restore oyster reef habitats. It follows that the established goal of restoration should reflect this motivation. This section outlines the methods for setting a restoration goal on the basis of one of the following ecosystem services: water filtration, non-oyster fisheries, nitrogen removal, and shoreline protection. Using the methods outlined it is possible to estimate what a subset of these services a given area of restoration is predicted to provide, or to estimate the area of restoration needed to achieve a set ecosystem service goal.

### Water clarity

Oysters are filter feeding bivalves. Like most bivalves, they draw in a current of water by beating a series of small hairs, or cilia, along their gills, which they then use to sort particles encountered in the water column. Particles are efficiently sorted by the cilia and either passed to the mouth or bound in mucus and expelled as pseudofaeces. By removing small particles from the water column and ejecting them as larger faeces or pseudofaeces, oysters can improve water clarity (Wall et al., 2011). The volume of water cleared by an oyster is determined by the species (Moehlenberg and Riisgaard, 1979), the size of the oyster (Gerdes, 1983), the temperature (Haure et al., 1998), the sediment load (Barille et al., 1997), and salinity (Hutchinson and Hawkins, 1992). The potential for oyster filtration to have a marked effect on water clarity is therefore dependent both on the abundance of oysters and on local conditions.

### The eastern oyster

Numerous equations quantifying the volume of water filtered by an oyster per unit time have been derived for the eastern oyster (e.g. Haven and Morales-Alamo, 1970, Tenore and Dunstan, 1973, Riisgaard, 1988). Few of these, however, have been truthed in the field. Adapting laboratory estimates of filtration to the field can be very data intensive, as a large number of variables can influence the rate of filtration. Laboratory measurements may furthermore, not reflect filtration *in situ*, where oyster populations may spend a different proportion of time with their valves shut, there is the potential for synergistic population-level influences and re-filtration, and physical attributes of the reef may influence flow dynamics and hence the uptake of particles (Dame et al., 1984, Harsh and Luckenbach, 1999). We therefore recommend that practitioners use the equation derived by zu Ermgassen et al. (2013a), which is fitted to data collected on oyster reefs *in situ*. Equation 1 (below) can be used to estimate the volume of water filtered by eastern oysters under known water temperature conditions and where the mean mass and density of oysters is known. Where oyster lengths are known, they can be converted to mass using the conversions outlined in Appendix 2.

Equation 1, filtration rate of the eastern oyster:

Filtration rate (L hr-1 m-2)=

where *N* is the density of oysters per m2, W is the dry tissue weight in g and T is temperature in °C.

#### Estimating population level filtration

Population level filtration can be estimated with as little information as mean oyster size, density and water temperature. Where oyster population size class and density information is available, more accurate estimates of the volume of water filtered per unit time can be determined by deriving size class specific estimates using equation 1, and summing the total volume filtered. A worked example is given below. For details on how best to determine the oyster population metrics necessary to estimate population level filtration see Baggett et al. (2014).

Case study: Great Bay, New Hampshire

Current mapping efforts in Great Bay New Hampshire have identified 87ha of oyster reefs with a mean density of 287 oysters per m2 and an average size of 55mm shell height (SH) (Grizzle and Brodeur, 2004, Grizzle and Ward, 2009). The shell height to biomass conversion with the nearest geographical location is 0.00003 x SH2.45 (Bushek et al. unpublished data) from Delaware Bay, NJ (Appendix 2). The mean June water temperature in Great Bay is 18.2°C, as recorded by the National Estuarine Research Reserve network. The population level filtration rate in June can therefore be calculated as follows

Where the mean dry tissue mass of each oyster is equal to 0.00003x552.45 =0.55g

Therefore the whole population filters approximately:  = 4.3 x 108 litres per hour

#### Setting goals based on filtration

Restoration goals can be set on a number of scales. Using equation 1 it is possible to estimate the volume of water filtered by an existing or planned restoration effort, as long as the actual or expected oyster density, size and water temperature is known in addition to the area of oyster reef restored. A small scale goal can be established with the aim of restoring an oyster population capable of filtering a given volume of water at a given time of year. Water temperature has a strong influence on filtration rate. The appropriate seasonal temperature should therefore be used in this calculation. Mean monthly water temperatures representative of large bay units can be found in the appendix. Water temperature can, however, vary substantially within an estuary and at varying depths. Where possible, therefore, temperature at the restoration site should be used to derive estimates of volume filtered.

Larger scale goals can be set on the basis of achieving full estuary filtration (see below for details). Where as this approach is not appropriate for small restoration activities within a large estuary (although it can form the long term goal for many smaller restoration activities), it may be appropriate for smaller restoration efforts in more contained settings, such as a creek. Estimating the degree of restoration necessary to achieve full estuary filtration relies on knowledge of the residence time of the water in the waterbody. Where the relevant data are known, it is possible to derive your own estimate of residence time at the scale most appropriate to you using the methodology outlined in <http://ccrm.vims.edu/research/water_sediments/tidal_flushing/TidFlush_final.pdf>. Residence times of whole estuaries can be found in Appendix X.

#### Full estuary filtration as a goal

Full estuary filtration is defined as “filtering a volume equivalent or larger than the entire estuary volume within the residence time of the water”. Eastern oyster populations were historically capable of achieving full estuary filtration throughout much of their range (zu Ermgassen et al., 2013a). Full estuary filtration does not actually equate to complete filtration of all estuarine waters as this rough calculation assumes that the estuary is perfectly mixed, which is never the case. Furthermore, it does not account for phytoplankton production. Full estuary filtration nevertheless provides a useful indicator of the rate of filtration relative to water flow, which in turn is an indicator of the potential for filtration to have a large scale impact on the ecology of the estuary (Smaal and Prins, 1993, Dame, 2011). It should be noted that increasing oyster populations to the point at which they achieve full estuary filtration is unlikely to resolve the water quality concerns of many US estuaries on its own (Cerco and Noel, 2007), but could meaningfully contribute to a system wide approach.

Restoring the capacity to once again achieve full estuary filtration may represent a suitable long term large scale goal in many estuaries. To determine the area and density of oyster required to achieve full estuary filtration the rate of filtration required on the estuary scale must be calculated. This is estimated by assuming a well mixed estuary, then by dividing the volume by the residence time. Residence time is usually reported in days. This calculation therefore yields the total volume that needs to be filtered within a 24 hour period in order to achieve full estuary filtration. This volume can be achieved by a) increasing the area of oyster reef, b) increasing the density of oysters or c) increasing the mean size of oysters. Options a and b will yield far greater returns as regards total filtration than option c. To set a goal, one can therefore either use the known or planned density of oysters on the restored site to calculate the volume filtered per unit area, then divide the total volume by the calculated volume filtered to get an estimate of the area required. Or one can assume a fixed area of oyster reef and determine what the target density should be in order to achieve full estuary filtration. In either case it is necessary to decide in advance in which season full estuary filtration is most desirable. The season or monthly average temperature can then be used in equation 1.

The volume of water that passed through (is filtered by) oysters does not equal the volume of water cleared of particles. Oysters do not filter efficiently across all size classes, and their efficiency can vary with under suboptimal conditions, such as high sediment loads. As the filtration rate in equation 1 was derived from the volume of water cleared *in situ* it can, however, be used as a good estimate of the potential volume of water cleared. Particles may nevertheless become resuspended by water movement and wave action. It can therefore not be assumed that full estuary filtration will necessarily result in clear water across the whole of the bay or estuary. This approach provides a conceptual framework for estimating when a system-wide effect may be expected, and hence how much restoration may be necessary to see large scale impacts on water clarity.

Case study: Matagorda Bay, Texas

Historically Matagorda Bay was home to around 16679ha of oyster reef with a mean density of 58 oysters m-2. Current estimates suggest that only 2229ha remain with an average density of 10 oysters m-2 (zu Ermgassen et al., 2012). Using the equations outlined above, it was determined that the population was historically capable of filtering fifty times the volume of the estuary (1.6 x 109 m3) within the estuary’s 38 day residence time during summer months (zu Ermgassen et al., 2013a). In other words, the historic population was more than ample to achieve full estuary filtration. The current population only has the capacity to filter around one third of the estuary’s volume within its residence time. Full estuary filtration may therefore be a suitable long term restoration goal in this case.

In order to determine how much restoration may be necessary to achieve full estuary filtration, the following steps must be taken.

The following data are required for the calculation:

Estuary related data:

|  |  |  |  |
| --- | --- | --- | --- |
| Data type | Value | Unit | Reference |
| Estuary volume | 1572150 (J) | 1000xm3 | (Bricker et al., 2007) |
| Estuary residence time | 38 (K) | days | (Bricker et al., 2007) |
| Mean summer temperature\* | 30.7 (AN-AP) | °C | NOAA |

\*NB. The temperature does not need to be mean summer temperature, but should be selected based on when the stakeholders most value the filtration service. This is being used for illustrative purposes only.

Oyster data:

|  |  |  |  |
| --- | --- | --- | --- |
| Data type | Value | Unit | Reference |
| Extent oyster habitat | 2229 (S) | ha | (zu Ermgassen et al., 2012) |
| Mean market oyster density | 1 (U) | Ind m-2 | TPWD dredge survey data \* |
| Mean cull oyster density | 4 (V) | Ind m-2 | TPWD dredge survey data \* |
| Mean market oyster size | 94 (X) | mm | zu Ermgassen et al., 2012) |
| Mean cull oyster size | 45 (Y) | mm | zu Ermgassen et al., 2012) |

\* Dredge survey data examined and a 15% dredge efficiency applied to give a rough estimate of current oyster abundance.

A *SH* to biomass relationship is also needed. In this case, the relationship drawn from the nearest geographical location available in the literature is:

 (Beseres Pollack et al., 2011) (AF)

Please see Appendix 2 for further suggested relationships.

1. The current filtration capacity of the population must be derived as outlined in “*Estimating population level filtration*”. In Matagorda Bay, we have data relating to two size classes, this is calculated as follows:

Therefore the volume filtered by the current oyster population = 4.99x108 litres an hour

1. The volume of the estuary must be divided by the residence time, and adjustments to the unit must be made in order to make the figures from step 1 and 2 comparable. In this case, the estuary volume is 1.57 x 1012 litres, therefore assuming a residence time of 38 days, 4.14 x 1010 would have to be filtered a day, equating to 1.72 x109 litres an hour.
2. Subtract the values derived in step 1 from step 2 to determine the “missing” filtration. In this case 1.72 x109 - 4.99x108 = 1.22x109.
3. Determine how many oysters of mean size are required to filter the missing volume. This number of oysters is the “goal”. The mean size of oysters in Matagorda is currently 54mm, therefore one oyster in summer months filters 

Therefore 1.22x109/3.97=3.1x108 additional oysters are needed in the estuary to approach full estuary filtration.

1. The required number of oysters can be achieved either by increasing the area of oyster reefs, or by increasing the density of oysters on existing reefs. The goal should therefore be reported both as an area and as a target density. In the case of Matagorda Bay, this may therefore translate to: 2049ha (5063acres) of oyster reef with an average density of 15 oysters m-2.

### The Olympia oyster

The Olympia oyster is morphologically and physiologically distinct from the eastern oyster (Kellogg, 1915, Elsey, 1935). It is also significantly less well studied. Estimates of Olympia oyster filtration rates have yet to be derived in the field. We therefore suggest that filtration by Olympia oyster populations be derived based on the only currently published laboratory derived filtration rate (zu Ermgassen et al., 2013b). Equation 2 (below) can be used to estimate the volume of water filtered by an Olympia oyster under known water temperature conditions and where the mean mass and density of oysters is known. Where oyster lengths are know, they can be converted to mass using the shell height (SH) to dry tissue weight (DTW) conversion as follows DTW=6 x 10-6 SH3.06 (M. Gray unpublished data cited in Blake and zu Ermgassen in review).

Filtration rate (L hr-1 m-2)=

where *N* is the density of oysters per m2, W is dry tissue weight in g and T is temperature in °C.

#### Estimating population level filtration

As for the eastern oyster, population level filtration can be estimated with as little information as mean oyster size, density and water temperature, using equation 2. Where oyster population size class and density information is available, more accurate estimates of the volume of water filtered per unit time can be determined by deriving size class specific estimates using equation 2, and summing the total volume filtered. For details regarding how best to determine the oyster population metrics necessary to estimate population level filtration see Baggett et al. (2014).

#### Setting goals based on filtration

While the Olympia oyster was historically much more abundant than present (zu Ermgassen et al., 2012), it is unlikely that it ever played a significant large scale role in filtering seston from the water (zu Ermgassen et al., 2013b). This is primarily a product of the low water temperatures and low residence times of Pacific coast estuaries. Full estuary filtration, unlike for the eastern oyster, is therefore not an appropriate long term, large scale goal (zu Ermgassen et al., 2013b).

While Olympia oyster restoration is unlikely to lead to large-scale regulation of seston at whole-estuary scales, restoring oyster beds may nevertheless result in significant local impacts on sea grasses (Smith et al., 2009, Wall et al., 2008, Booth and Heck Jr., 2009), or in high residence time locations within estuaries (Banas et al., 2007, zu Ermgassen et al., 2013b). It is challenging to set goals on the basis of these potential benefits, as the local flow rate, direction and sediment load all influence the impact of filtration on a local scale. Small scale goals based on filtration must therefore be formulated around the volume of water filtered. Where flow rate, direction and water depth are known it may be possible to inform goal setting by calculating the filtration rate required to process the volume of water passing over the reef. This can be done by using the flow rate and water depth to determine the volume of water passing over the oyster reef in a given unit time, and then determining what density and size class of oysters would be necessary to filter the equivalent volume of water for that same unit of time. Given local variation and the large uncertainty in using this approach, however, it should be used with caution. Goals may more practically be set simply by determining what volume of water can be expected to be processed by a given area and density of oysters.

## Nitrogen removal

Restoration of oyster reefs may result in a positive net effect on the removal and retention of biologically active nitrogen from overlying waters relative to unrestored sites. The nitrogen (N) is removed via three pathways (see figure x). The first of these is through assimilation of N in the shell and tissues of the oysters and associated biota, the second is through the enhanced burial of N into the sediments surrounding oyster reefs, and the third is through the enhancement of biochemical pathways, in particular microbe mediated denitrification. Each of these pathways may be locally important. Estimates of net nitrogen removal and retention should take each of these pathways into account, however, only denitrifcation definitively permanently removes biologically active nitrogen from the system. Nevertheless, all three pathways should be considered when estimating net nitrogen removal resulting from oyster restoration.

### Quantifying nitrogen assimilation in tissues

Nitrogen from phytoplankton is assimilated into the shell and soft tissue of oysters as they grow. By promoting their growth through restoration, it is therefore possible to enhance the storage of N in the oysters themselves. Oyster reefs also support a host of other species, each of which also assimilate N into their tissues. In one study in the Choptank River, MD, restoration was found to enhance the standing stock of N by 95g N m-2 (Kellogg et al., 2013). The degree of enhancement varies, however, with oyster density and size and with the composition and abundance of the associated community.

The concentration of N in eastern oyster tissues remains relatively constant at around 9% of the dry tissue weight even where environmental N concentrations vary (Carmichael et al., 2012a). N concentrations in shell range between 0.2-0.26% of shell weight (Kellogg et al., 2014). Both tissue and shell N concentrations have been found to be higher in the Gulf of Mexico compared to the Atlantic coast, and concentrations may also vary with oyster size (Kellogg et al., 2014). We are unaware of any similar estimates for N content of Olympia oyster shell or tissues.

While harvesting the oysters permanently removes the assimilated N from the estuary, is not recommended as it significantly reduces the longevity of the reef and the potential for success, as well as reduces the delivery of other key ecosystem services (Grabowski et al., 2012). Furthermore, harvesting of the oysters is very likely to reduce the N removal via the two other oyster-enhanced pathways.

### Quantifying nitrogen burial

Oysters are filter-feeding bivalves. They filter particles from the water column and sort them, ingesting the edible particles and binding the undigested particles in mucus before ejecting them. These relatively large mucus-bound bundles are referred to as pseudofaeces. Because of their large size and relatively high density, both pseudofaecal and faecal particles tend to settle on the bottom, concentrating organic matter in the vicinity of the reef resulting in sediments are relatively rich in N. In the absence of resuspension of these sediments, some of these deposits and their associated N may become buried. The rates of burial and which factors affect it are currently unknown. Once buried, the permanence of burial is also unknown, as passing storm events can resuspend sediments at depth. Nevertheless, it is possible that burial by oyster reefs may be a locally important nitrogen sink.

### Quantifying nitrogen removal by denitrification

Oyster reefs modify biogeochemical cycles by concentrating organic matter from the water column around the reef system (Kellogg et al., 2013). Denitrification, the microbally mediated conversion of biologically active nitrogen into inert dinitrogen gas, is one such process (See Fig ??). Denitrification results in the permanent removal of nitrogen from the water body and is therefore a highly desirable process in today’s often eutrophic estuaries.

Our understanding of the role of marine and estuarine habitats in enhancing denitrification is evolving rapidly. It is now well established that oyster reefs enhance rates of denitrification *in situ* (Kellogg et al., 2013, Piehler and Smyth, 2011, Smyth et al., 2013). Indeed, some of the highest recorded values have been made in subtidal oyster reefs (Kellogg et al., 2013), and oyster reefs have been shown to stimulate higher rates of denitrification than many other coastal habitats (Piehler and Smyth, 2011). Denitrification around intertidal oyster reefs in North Carolina have been measured to be 14-96µM N m-2 h-1 higher than background rates (Piehler and Smyth 2011), and rates on subtidal reefs in Maryland have been found to be 200-610µM N m-2 h-1 higher than background (Kellogg et al. 2013).

While it is not yet possible to estimate the likely denitrification enhancement from any restoration site prior to restoration, the potential benefits arising from oyster restoration may be significant, and are therefore worthy of consideration. Indeed even conservative estimates of denitrification enhancement by oyster reefs may represent a large proportion of the total ecosystem services delivered by oyster reefs (Grabowski et al., 2012). Grabowski et al. (2012) estimated that one hectare of intertidal oyster reef in North Carolina removed $1385-$6716 worth of nitrogen per year. While this example is geographically specific to the site at which the denitrification enhancement measurements were made, it provides us with some insight into the potential value of this oyster reef ecosystem service.

In order to build a general model capable of quantifying the denitrification enhancement resulting from a restoration project, it is necessary to collect more data on the role of seston concentration, light intensity, temperature, salinity, oyster size, density and habitat quality, as well as the role of the associated community among other factors. Further information about sampling protocols can be found in Baggett et al. (2014). It should eventually be possible to build a general model to estimate the denitrification enhancement by oyster reefs. A preliminary model already exists for Harris Creek, a well studied river in Maryland (see Box XX). Ongoing research in Harris Creek seeks to both test the current model predictions and collect additional data to better parameterize the model.

### The relative roles of oyster habitat restoration and aquaculture

It should be noted that the ecosystem service benefits of oyster restoration are not necessarily equal to the ecosystem service benefits of oysters under aquaculture conditions. In the case of denitrification, no studies have found net annual enhancement of denitrification in sediments under oysters grown in aquaculture floats (Higgins et al., 2013, Kellogg et al., 2014). To date, no data have been published for denitrification rates associated with other forms of aquaculture.

### Using nitrogen removal to set restoration goals

The state of knowledge is not yet advanced enough to use nitrogen removal as a quantitative goal for oyster restoration. Nevertheless, it is useful to consider the positive contribution that oyster restoration is likely to make to net nitrogen removal from restored estuaries.

If restoration takes place near a site for which habitat and biomass specific denitrification values are already available, the contribution of restoration can be estimated by multiplying the amount by which the rate is enhanced (the oyster habitat less the control rate of denitrification) and multiplying it by the area of restoration. While the current data do no allow for an estimate of this service at any given site, the available values in the literature provide some indication of the range of enhancement which might be expected (see text above and Kellogg et al., 2014 for further detail on exisiting values).

Where measurements of denitrification are available, the contribution of oyster restoration can be put into context not only in terms of the mass of nitrogen removed from the system, but it may also be useful to consider the number of people “offset” by restoration (by which we mean the amount of denitrification necessary to mitigate the excretion of N from one person), the value of the denitrification service in monetary terms (see Box X), or the % of anthropogenically derived N removed (Carmichael et al., 2012b). These alternative units can be useful in setting goals.

Box XX: Using denitrification estimates to set restoration goals

While it is not currently possible to set goals where denitrification data are absent, a model has been developed by Drs. Mark Brush and Lisa Kellogg for Harris Creek, Maryland. This web based model can be found at:

<http://netsim.vims.edu/netsims/brush/harris_creek_model/index.html>

The model allows the user to specify the area of restoration planned within each of 5 areas within the creek along with the oyster density and mean weight. The outputs of the proposed restoration can then be viewed. These include, N denitrified, N in tissue, N in shell and N buried, among a host of other values.

NB: It should be noted that this is intended as a case example. The Harris Creek model is still being refined and should not be applied to other areas.

## Non-oyster fisheries

The complex three-dimensional habitat formed by oyster reefs can provide refuge for juvenile fish and invertebrates, and provide important fish foraging grounds. When practitioners, stakeholders and communities are motivated to implement restoration to augment the production of juvenile fish and invertebrates, it’s critical to be able to envision approximately how many more fish an area of oyster reef is likely to provide. Zu Ermgassen et al. (2014) undertook a review of 12 studies on the South and Mid Atlantic coast and 19 studies on the Gulf of Mexico coast of the US in order to determine how many more juvenile fish recruit to oyster reef than nearby mud or sand areas. They then estimated the final biomass of fish and mobile crustaceans resulting from the enhancement of juvenile abundance. We summarize their finding here, and suggest a framework for using their results to predict how many fish and mobile crustaceans a given restoration project may expect to “produce”.

It should be noted that the values presented here represent the mean enhancement across all of the studies included in the initial literature review conducted by zu Ermgassen et al 2014. Individual sites are expected to differ not only because not all species are present at all sites, but also because there is great natural variability in recruitment both across space and time. As such, these values represent a *predicted* enhancement, and are meant to be used when planning restoration and envisioning restoration targets and objectives. The biomass that restoration projects actually contribute can only be determined through appropriate sampling of fish populations on and off the reef in the years following restoration. Further information about appropriate sampling techniques for juveniles can be found in Baggett et al. 2014.

### Quantifying fish enhancement by oyster reefs

Fifteen fish species and four crustacean species were found at greater densities on oyster reef habitat as opposed to unstructured habitat in the Gulf of Mexico, whereas eleven fish species and one crustacean species were enhanced on the Atlantic coast. The mean increase in juvenile individuals quantified per unit area is given in table X. This represents how many more individuals were found on oyster reef, over and above what was found on the unrestored/unstructured sites. It is believed that these numbers should scale linearly with area, hence the number of additional individuals recruiting to an area of restoration can be determined by multiplying the density per m2 or acre, by the area restored. For further information regarding how to measure the restored area, please see chapter 3 in Baggett et al. 2014.

In order to calculate how many more fish and mobile crustaceans might be expected as a result of restoration efforts, this list can be cross-checked with the species known to exist in the area where restoration is being undertaken. Species that are not present in the area should be excluded. For guidance as to which species can be expected in your region of interest, NOAA’s Estuarine Living Marine Resources Program publications can be referred to. See index for web resources.

Table X: Mean enhancement in fish and mobile crustacean species as determined by an extensive literature review for the Gulf of Mexico and Atlantic coasts of the US. The standard deviation of the mean is given in brackets. Means represent the number of additional individuals recruiting per m2 or acre, and the number per acre at the age at which they attain fishable size (r; fishery species only).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Coast** | **Species** | **Common name** | **Mean number of juvenile ind m-2 (stdev)** | **Mean number of juvenile ind acre (stdev)** | **Mean number ind per acre at age=r** |
| Gulf of Mexico | **Fish** |  |  |  |  |
|  | *Archosargus probatocephalus* | Sheepshead | 0.139  (0.101) | 562.5 | 417.4 |
|  | *Bairdiella chrysoura* | Silver Perch | 0.501  (0.481) | 2024.5 | NA |
|  | *Bathygobius soporator* | Frillfin Goby | 0.024  (0.009) | 97.1 | NA |
|  | *Chaetodipterus faber* | Spadefish | 0.006  (0.004) | 24.3 | NA |
|  | *Chasmodes bosquianus* | Striped Blenny | 0.062  (0.032) | 250.9 | NA |
|  | *Ctenogobius boleosoma* | Darter Goby | 0.192  (0.138) | 777.0 | NA |
|  | *Gobiesox strumosus* | Skilletfish | 0.788  (0.345) |  | NA |
|  | *Gobiosoma bosc* | Naked Goby | 1.547  (0.393) | 6260.5 | NA |
|  | *Hypsoblennius hentz* | Feather Blenny | 0.057  (0.015) | 230.7 | NA |
|  | *Hypsoblennius ionthas* | Freckled Blenny | 0.303  (0.207) | 1226.2 | NA |
|  | *Lagodon rhomboides* | Pinfish | 0.415 (0.209) | 1679.4 | NA |
|  | *Leiostomus xanthurus* | Spot | 0.342 (0.167) | 1384.0 | NA |
|  | *Opsanus beta* | Toadfish | 0.635 (0.253) | 2569.8 | NA |
|  | *Orthopristis chrysoptera* | Pigfish | 0.044 (0.018) | 178.1 | 131.5 |
|  | *Prionotus spp.* | Sea Robin | 0.012 (0.015) | 48.6 | NA |
|  | **Crustaceans** |  |  |  |  |
|  | *Callinectes sapidus* | Blue Crab | 7.418 (6.731) | 30,019.6 | 11680.7 |
|  | *Farfantepenaeus aztecus* | Brown Shrimp | 1.043 (0.627) | 4220.9 | 6.4 x 10-5 |
|  | *Litopanaeus setiferus* | White Shrimp | 4.640  (2.726) | 18777.4 | 208.6 |
|  | *Menippe mercenaria* | Stone Crab | 1.936 (0.214) | 7834.7 | 1361.4 |
| Atlantic | **Fish** |  |  |  |  |
|  | *Archosargus probatocephalus* | Sheepshead | 0.072 (0.048) | 290.2 | 215.0 |
|  | *Chasmodes bosquianus* | Striped Blenny | 4.790  (1.177) | 19385.1 | NA |
|  | *Fundulus majalis* | Striped Killifish | 0.016  (0.020) | 66.4 | NA |
|  | *Gobiesox strumosus* | Skilletfish | 5.618  (1.795) | 22735.6 | NA |
|  | *Gobiosoma bosc* | Naked Goby | 20.037  (5.542) | 81087.6 | NA |
|  | *Lagodon rhomboides* | Pinfish | 0.009 (0.046) | 35.3 | NA |
|  | *Lutjanus griseus* | Gray Snapper | 0.010 (0.007) | 40.5 | 15.6 |
|  | *Mycteroptera microlepis* | Gag | 0.014 (0.009) | 57.3 | 30.5 |
|  | *Opsanus tau* | Toadfish | 0.955 (0.322) | 19385 | NA |
|  | *Orthopristis chrysoptera* | Pigfish | 0.026 (0.027) | 103.9 | 76.9 |
|  | *Paralichthys lethostigma* | Southern Flounder | 0.001 (0.008) | 5.1 |  |
|  | **Crustaceans** |  |  |  |  |
|  | *Farfantepenaeus aztecus* | Brown Shrimp | 0.034  (0.008) | 138.3 | 2.1 x 10-6 |

#### Estimating fish and mobile crustacean biomass production

Once the number of additional individuals recruiting to an area is known, it is possible to estimate the resulting increase in biomass using established life history and mortality estimates. Details of the growth and mortality models applied can be found in Appendix 2.

Zu Ermgassen et al. 2014 applied known growth and mortality relationships to the mean juvenile density values listed in table X, using the species specific life history constants in Appendix 3, the results of which can be found in table XXX. These values represent the annual enhancement in biomass of each fish or crustacean species which can be attributed to oyster reef over the lifetime of the species (tmax), assuming that individuals recruit to the restored reef each year. Alternatively this can be considered to be the annual enhancement summed across all year classes once the restored reef exceeds tmax in age (with the assumption that the reef enhanced recruitment every year following construction).

There is strong evidence that restored oyster reefs support fish and mobile crustaceans very soon after restoration has taken place (La Peyre et al., 2014). Fish and mobile crustacean biomass can therefore be assumed to be enhanced from the first season of recruitment following restoration. While the full biomass enhancement benefits for each species will not be fulfilled until tmax, a significant proportion of the biomass can be attributed from just 1 year in the Gulf of Mexico (66%) and three years on the Atlantic coast (58%). These values will vary depending on which species are present at the location of the restoration project.

It should be noted that the values given in table XXX represent the mean enhancement across all of the studies included in the initial literature review on which table X is based. Individual sites are expected to differ not only because not all species are present at all sites, but also because there is great natural variability in recruitment both across space and time. As such, these values represent a predicted enhancement. The variability in each value is expressed as standard deviations calculated for each species, and should be considered when setting restoration objectives.

Restoration practitioners must bear in mind that the values given here represent a mean, and the biomass their restoration efforts are actually contributing can only be determined through appropriate sampling of fish populations on and off the reef in the years following restoration. Further information about appropriate sampling techniques for juveniles can be found in Baggett et al. 2014.

Table XXX Estimated biomass enhancement per m2 per year of oyster reef restored per year on the Gulf of Mexico and Atlantic coasts. These numbers are derived from applying known mortality and growth estimates to the observed enhancement in juvenile fish and mobile crustacean density on oyster reefs over unstructured controls.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Coast** | **Species** | **Common name** | **Mean *Pg***  **g m-2 y-1 (stdev)** | **Mean *Pn***  **g m2 y-1**  **(stdev)** |
| Gulf of Mexico | **Fish** |  |  |  |
|  | *Archosargus probatocephalus* | Sheepshead | 116.4  (84.0) | 105.6  (76.3) |
|  | *Bairdiella chrysoura* | Silver Perch | 28.0  (26.9) | 15.5  (14.9) |
|  | *Bathygobius soporator* | Frillfin Goby | 1.9  (0.7) | 1.2  (0.4) |
|  | *Chaetodipterus faber* | Spadefish | 4.2  (3.1) | 3.2  (2.4) |
|  | *Chasmodes bosquianus* | Striped Blenny | 1.0  (0.5) | 0.4  (0.2) |
|  | *Ctenogobius boleosoma* | Darter Goby | 0.4  (0.3) | 0.2  (0.1) |
|  | *Gobiesox strumosus* | Skilletfish | 2.6  (1.1) | 1.1  (0.5) |
|  | *Gobiosoma bosc* | Naked Goby | 1.8  (0.5) | 1.2  (0.3) |
|  | *Hypsoblennius hentz* | Feather Blenny | 0.2  (0.1) | 0.1  (0.03) |
|  | *Hypsoblennius ionthas* | Freckled Blenny | 1.1  (0.8) | 0.7  (0.5) |
|  | *Lagodon rhomboides* | Pinfish | 35.0  (17.6) | 24.4  (12.3) |
|  | *Leiostomus xanthurus* | Spot | 18.4  (9.0) | 11.6  (5.7) |
|  | *Opsanus beta* | Toadfish | 43.0  (26.4) | 32.3  (19.9) |
|  | *Orthopristis chrysoptera* | Pigfish | 5.3  (2.1) | 4.0  (1.6) |
|  | *Prionotus spp.* | Sea Robin | 5.0  (4.1) | 2.9  (3.6) |
|  | **Crustaceans** |  |  |  |
|  | *Callinectes sapidus* | Blue Crab | 1261.9  (814.6) | 825.4  (534.2) |
|  | *Farfantepenaeus aztecus* | Brown Shrimp | 7.3  (5 x 10-2) | NA |
|  | *Litopanaeus setiferus* | White Shrimp | 25.1  (0.2) | NA |
|  | *Menippe mercenaria* | Stone Crab | 232.3  (36.3) | 167.3  (26.1) |
|  |  | **TOTAL** | **1789.8**  **(820.8)** | **1199.3**  **(541.1)** |
| Atlantic | **Fish** |  |  |  |
|  | *Archosargus probatocephalus* | Sheepshead | 71.5  (47.7) | 64.9  (43.3) |
|  | *Chasmodes bosquianus* | Striped Blenny | 75.7  (18.5) | 31.0  (7.6) |
|  | *Fundulus majalis* | Striped Killifish | 3 x 10-2  (3 x 10-2) | 0.01  (0.01) |
|  | *Gobiesox strumosus* | Skilletfish | 18.6  (6.0) | 8.1  (2.6) |
|  | *Gobiosoma bosc* | Naked Goby | 23.8  (6.6) | 15.1  (4.1) |
|  | *Lagodon rhomboides* | Pinfish | 0.7  (19.3) | 0.5  (13.5) |
|  | *Lutjanus griseus* | Gray Snapper | 10.9  (7.4) | 9.8  (6.7) |
|  | *Mycteroptera microlepis* | Gag | 79.6  (49.8) | 73.0  (45.6) |
|  | *Opsanus tau* | Toadfish | 110.3  (26.2) | 89.3  (21.2) |
|  | *Orthopristis chrysoptera* | Pigfish | 3.1  (3.3) | 2.3  (2.5) |
|  | *Paralichthys lethostigma* | Southern Flounder | 0.5  (2.3) | 0.4  (1.8) |
|  | **Crustaceans** |  |  |  |
|  | *Farfantepenaeus aztecus* | Brown Shrimp | 0.2  (1 x 10-3) | NA |
|  |  | **TOTAL** | **395.1**  **(79.3)** | **294.2**  **(68.6)** |

#### Utilisation enhanced fish species

A number of species do not recruit to oyster reefs, but do preferentially utilize the habitat at later life history stages. While there is not yet sufficient knowledge to quantify the biomass enhancement to these species resulting from the use of oyster reef habitats, there is sufficient evidence to suggest that species which preferentially use oyster reef habitat are likely to gain from this habitat usage. These benefits primarily arise as a result of greater prey abundance and enhanced predator avoidance, provided by the structured shell habitat.

Zu Ermgassen et al. 2014 used the same literature review referred to in the section on recruitment enhancement to determine the degree to which larger individuals preferentially utilized oyster reef habitat over unstructured / unrestored reefs. Five species on the Gulf of Mexico coast and two species on the Atlantic coast were found to preferentially use oyster reef as adults (Table XXXX). Once it was established which species were consistently found in greater abundance on as opposed to off oyster reef, they were able to determine what percentage of individuals sampled were caught over reef habitat as opposed to off. The resulting percentage can be used as an indicator of how important oyster reefs might be to the identified fish species as adults.

While we are unable to determine the biomass enhancement resulting from the preferential use of oyster reefs, it is clear that a number of recreationally and commercially important species have a strong preference for oyster habitat as adults, and are likely to benefit from the presence of healthy reef systems.

Table XXXX Species identified to be found most commonly in higher abundance on oyster reef than unstructured controls.

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Species** | **Common name** | **Proportion of individuals caught on oyster** |
| **Gulf Coast** | *Menticirrhus americanus* | Southern Kingfish | 52% |
|  | *Paralichthys lethostigma* | Southern Flounder | 82% |
|  | *Pogonias cromis* | Black Drum | 75% |
|  | *Rhinoptera bonasus* | Cownose Ray | 82% |
|  | *Sciaenops ocellatus* | Red Drum | 69% |
| **Atlantic Coast** | *Centropristis striata* | Black Sea Bass | 63% |
|  | *Morone saxatilis* | Striped Bass | 93% |

### Using fish enhancement estimates in oyster restoration goal setting

Oyster restoration has the potential to significantly enhance fish production by providing habitat to juvenile fish and mobile crustaceans. This is important both from a biodiversity perspective and from a fisheries perspective.

Restoration may be undertaken with the whole fish community in mind, or may be aimed at a few fish or crustacean species of greatest interest to the stakeholders. Using the tables presented in this section it is possible to predict how much fish, on a community or single species level, one can hope to attain from a given area of restoration. Goals can therefore be set on the basis of expected fish biomass enhancement.

For example, if Gray Snapper is the species of interest in an Atlantic site, the stated aim of the goal could be to have 1000 additional fish recruiting to the area per annum. At 0.01 additional Gray Snapper recruiting per m2 of oyster reef (Table X), it can be expected that this degree of enhancement may be achieved from restoring 24.7acres (10ha) of oyster reef. The same approach could be taken, but basing the restoration target on the number of fish entering the fishery. In this case, we would expect an additional 15.6 Gray Snapper to enter the fishery every year for every acre of oyster reef restored, therefore to enhance the fishery by 1000 individuals a year, the restoration target should be 64 acres (1000/15.6). Alternatively the goal could be biomass based, and the area could be determined using the biomass estimates in table XX.

If the stakeholders wish to undertake restoration for the sake of the whole fish community as opposed to a single species, a target can be set based on the biomass of the whole community. In order to estimate the biomass that can be attributed to the planned oyster restoration, it is necessary to determine which of the species listed in table XX are present at the site. Once this is known, the predicted biomass for species deemed to be present can be totaled in order to provide a per unit area prediction of fish and mobile crustacean biomass.

For example, if the restoration is planned to take place in Charlotte Harbour FL, the first step is to ascertain which of the listed fish species are common in that estuary. This list can be determined by your own knowledge of the site, or by referring to published resources. Using Patillo et al. 1997 (See web resources at the end of this section), we can determine that Brown Shrimp, Blue Crab, Stone Crab, Sheepshead, Pinfish, Silver perch and Spot are all present, with Brown Shrimp and Sheephead listed as “rare”. Of the utilization enhanced species, Southern Flounder, Black Drum and Red Drum are all present.

The expected biomass enhancement of the fish and mobile crustacean community can be estimated by totaling the predicted biomass enhancement for the appropriate species in table XXX. For species listed as rare, it is appropriate to assume that they are not important contributors, and therefore to be conservative and not represent them in the enhancement estimates. For those listed as common or abundant, the mean enhancement could be assumer, whereas for those species listed as highly abundant, it is appropriate to assume the upper values of biomass enhancement are applicable. The upper and lower bounds are given by adding or subtracting the standard deviation (given in brackets) from the mean. If the relative abundance is unknown, the mean should be used. The case for Charlotte Harbour is presented in the table below as an example.

Table XXXXX: The predicted biomass enhancement per unit area or oyster restoration undertaken in Charlotte Harbour, FL. Abundance as listed by Patillo et al. 1997.

|  |  |  |  |
| --- | --- | --- | --- |
| Species name | Abundance | Biomass enhancement per m2 restoration (g) | Biomass enhancement per acre restoration (kg) |
| Sheepshead | Rare | NA | NA |
| Silver perch | Abundant | 37.42 | 151 |
| Pinfish | Highly abundant | 41.74 | 169 |
| Spot | Common | 12.74 | 52 |
| Blue crab | Abundant | 1592.86 | 6446 |
| Brown shrimp | Rare | NA | NA |
| Stone crab | Common | 167.67 | 679 |
|  |  |  |  |
|  |  |  |  |
|  |  |  |  |
| Total | NA |  |  |

**Web resources:**

NOAA’s Estuarine Living Marine Resources Program Publications:

North East Coast

<http://www.biodiversitylibrary.org/item/24461#page/3/mode/1up>

Mid Atlantic

<http://www.biodiversitylibrary.org/item/23780#page/16/mode/1up>

South East Coast <http://ccma.nos.noaa.gov/publications/biogeography/ELMR_SE_report.pdf>

Gulf of Mexico

<https://ia600309.us.archive.org/12/items/distributionabun02nels/distributionabun02nels.pdf>

## Coastal protection

Erosion is one of the most persistent threats affecting many of the world’s coastlines. Wind-generated waves generally become unstable and break as they enter shallower waters, dissipating some of their energy. However, the remaining energy still has the capacity to cause significant coastal erosion and suspend bottom sediment, which degrades water quality.

The loss of many nearshCore habitats has exacerbated rates of coastal erosion. These habitats help absorb the constant energy of wind and waves and thereby provide a coastal protection ecosystem service. This reduction of wind and wave energy, or attenuation, provided by the structure of many habitats including oyster and coral reefs, wetlands, seagrasses and dunes is now being regarded as a co-benefit ecosystem service alongside fishery, tourism and biodiversity (ref).

To demonstrate the coastal protection benefits from nearshore habitats, The Nature Conservancy, Natural Capital Project, US Geological Survey, the University of California at Santa Cruz, and the University of Southern Mississippi has teamed up to build an online application (“app”) called Coastal Defense. The Coastal Defense app is a module of the Coastal Resilience decision support tool.

### Coastal Resilience

[Coastal Resilience](http://www.coastalresilience.org/) is a web-based decision support tool that provides local, state and national planners a step-wise process to guide decisions to reduce the ecological and socio-economic risks of coastal hazards. The Coastal Resilience [tool](http://maps.coastalresilience.org) works US nationwide and globally to assess risk and identify risk reduction solutions, and operates at multiple scales for more detailed planning in more than a dozen states and numerous communities. The Coastal Resilience tool is expanding across the US and internationally and includes 12 U.S. coastal states, (Alabama, California, Connecticut, Florida, Louisiana, Mississippi, New Jersey, New York, North Carolina, Texas, Virginia, Washington), four countries in Latin America (Mexico, Belize, Guatemala, Honduras) and in three island nations in the Caribbean (Grenada, St. Vincent and the Grenadines, U.S Virgin Islands). It includes an approach to help communities take the next step beyond assessing their risk:  finding innovative ways to protect their communities by exploring the use of natural solutions.

### Coastal Defense

A core feature of the tool is the open source apps that integrate coastal hazards with social, ecological, economic and coastal engineering to identify solutions. [Coastal Defense](http://coastalresilience.org/our-approach/identify-solutions/coastal-defense/) is an app within Coastal Resilience that identifies the coastal protection value of existing reef and wetland habitats and allows users to design restoration solutions.  The Coastal Defense app uses standard engineering techniques to calculate the reduction of wave height and wave energy in the presences of these habitats. A coastal protection from the Natural Capital Project’s Marine Integrated Valuation of Environmental Services and Tradeoffs (InVEST) program runs the app. The app helps support decisions to: (1) identify areas that may be at risk of coastal erosion and inundation from wave action and storm surge; (2) interactively examine the role of coastal habitats in attenuating wave height and energy; and (3) determine appropriate adaptation strategies that incorporate green (habitats) and grey (seawalls and other man-made structures) infrastructure trade-offs.  Nature-based approaches like these are changing the perception that only hard infrastructure solutions provide effective coastal defense.

To date the app has been deployed in Puget Sound, Washington (tidal marshes), Mobile Bay, Alabama (oyster reefs), and the Florida Keys (coral reefs and mangroves).  The app lets users specify offshore forcing conditions (wave and surge characteristics), a sea-level rise value, the location of restored or degraded coastal habitats, and the location of built infrastructure for exploring hybrid green (habitat) and gray (seawalls, dikes, etc.) solutions.  Coastal Defense has been used with diking districts in Puget Sound to examine hybrid green/gray infrastructure solutions, and in Alabama and Florida to site oyster restoration projects.  The Coastal Resilience tool platform and Coastal Defense app help make complex social-ecological models more accessible to non-technical audiences, giving stakeholders the power to make more informed adaptation and restoration decisions.

## Factors affecting ecosystem service provision

The models set out above are highly stylised, and represent a realistic, but not guaranteed level of ecosystem service provision. A number of factors may either positively or negatively affect the true values at any given site.

Insights into the impact of habitat setting: Project placement to maximise on the provision of your target ecosystem service; a summary of factors affecting the rate of ecosystem service delivery and factors to trade off- link to decision support tool in the Gulf of Mexico.

# Appendix:

## Appendix 1 Estuary scale data summaries

This section contains a compilation of estuary level data, including information on the historic presence and, where possible, extent of oyster reef systems in each estuary, as well as a range of physical attributes of each estuary which may be of use in goal setting.

Data on the historic and present extent should be attributed to zu Ermgassen et al. (2012) unless otherwise stated. The publication by zu Ermgassen et al. (2012) can be found at (WEBLINK), and provides more information about the source and methods used to determine the historic and present data extent presented. When using historic data such as those provided, it is important to be aware that baseline data may not represent pristine conditions (see box 3 and 4). The values given to describe oyster extent in the bay summaries presented in the appendix refer to reef systems (see Box 1).

Estuary overview – see proforma. Include bays for which no quantitative historic data exist, but where qualitative statements can assist with promoting restoration.

(Estimate 20 pages)

Total 23-32 pages without figures/pictures or references

## Appendix 2 Shell height biomass conversion

## Appendix 3 Detailed fisheries methods

The number of individuals surviving over time decreases by *M*, the natural mortality rate. The number of individuals surviving to each age class can therefore be estimated by applying:



where *Ni* is the density enhancement for age class *i* and *M* is the natural mortality of the fish species.

For each age class the expected growth can be determined by von Bertalanffy growth curves:



where *L∞* is the asymptotic maximum length (in cm), *K* is the Brody growth coefficient and *t0* is the age at zero length.

The average weight for each age class (*Wi*) can then be calculated from the length using the length-weight relationship:



where *a* and *b* are species-specific constants. The increase in weight of an average fish between age classes (*Pi*) was calculated:



The total annual enhancement of a species (gm-2) can be calculated by summing the incremental increase in weight each year for an average fish (*Pi*), multiplied by the number (density) of fish (*Ni*) for each age class.

# References:

Airoldi, L., Beck, M.W. (2007) Loss, status and trends for coastal marine habitats of Europe. *Oceanography and Marine Biology Annual Review* **45,** 345-405.

Anon (1884) The cowboys of Florida. In: *The New York Times*. New York.

Baggett, L.P., Powers, S.P., Brumbaugh, R.D.*, et al.* (2014) Oyster habitat restoration monitoring and assessment handbook. 96.

Banas, N.S., Hickey, B.M., Newton, J.A., Ruesink, J.L. (2007) Tidal exchange, bivalve grazing, and patterns of primary production in Willapa Bay, Washington, USA. *Marine Ecology-Progress Series* **34,** 123-139.

Bancroft, H.H. (1890) *History of Washington, Idaho and Montana 1845-1889,*  (The Works of Hubert Howe Bancroft, Vol., The History Company, Publishers, San Francisco CA.

Barille, L., Prou, J., Heral, M., Razet, D. (1997) Effects of high natural seston concentrations on the feeding, selection, and absorption of the oyster Crassostrea gigas (Thunberg). *Journal of Experimental Marine Biology and Ecology* **212,** 149-172.

Battle, J.D. (1891) An investigation of the coast waters of South Carolina with reference to oyster-culture. *Bulletin of the United States Fish Commission* **10,** 303-330.

Beck, M.W., Brumbaugh, R.D., Airoldi, L.*, et al.* (2009) Shellfish Reefs at Risk: A Global Analysis of Problems and Solutions., 52.

Beseres Pollack, J., Kim, H.-C., Morgan, E.K., Montagna, P.A. (2011) Role of flood disturbance in natural oyster (Crassostrea virginica) population maintenance in an esturay in South Texas, USA. *Estuaries and Coasts* **34,** 187-197.

Blackford, E.G. (1887) Second report of the oyster investigation and of survey of oyster territory, for the years 1885 and 1886. 48.

Bleakney, J.S., David, D. (1983) Discovery of an undisturbed bed of 3800 year old oysters (*Crassostrea virginica*) in Minas basin, Nova Scotia. *Proceedings of the Nova Scotian Institute of Science* **33,** 1-6.

Boesch, D.F., Turner, R.E. (1984) Dependence of fishery species on salt marshes: The role of food and refuge. *Estuaries* **7,** 460-468.

Booth, D.M., Heck Jr., K.L. (2009) Effects of the American oyster Crassostrea virginica on growth rates of the seagrass Halodule wrightii. *MARINE ECOLOGY PROGRESS SERIES* **389,** 117-126.

Borsje, B.W., van Wesenbeeck, B.K., Dekker, F.*, et al.* (2011) How ecological engineering can serve in coastal protection. *Ecological Engineering* **37,** 113-122.

Bricker, S., Longstaff, B., Dennison, W.*, et al.* (2007) *Effects of nutrient enrichment in the nation's estuaries: A decade of change,*  (NOAA Coastal Ocean Program Decision Analysis Series, Vol. 26), National Centers for Coastal Ocean Science, Silver Spring, MD.

Brooks, W.K. (1884) *The development and protection of the oyster in Maryland By W. K. Brooks ... Being the report written by him as chairman of the Oyster Commission of the state of Maryland and presented to the General Assembly, February, 1884,*  Vol., Publication Agency of the Johns Hopkins University, Baltimore.

Brooks, W.K., Waddell, J.I., Legg, W.H. (1884) Report of the oyster commission of the state of Maryland January 1884. 183.

Brumbaugh, R.D., Beck, M.W., Coen, L.D., Craig, L., Hicks, P. (2006) A practitioners guide to the design and monitoring of shellfish restoration projects. 32.

Bush, L.L. (1900) The oyster industry. In: *Pacific County Edition of the South Bend Journal*. South Bend, WA.

Carmichael, R.H., Shriver, A.C., Valiela, I. (2012a) Bivalve Response to Estuarine Eutrophication: The Balance between Enhanced Food Supply and Habitat Alterations. *Journal of Shellfish Research* **31,** 1-11.

Carmichael, R.H., Walton, W., Clark, H. (2012b) Bivalve-enhanced nitrogen removal from coastal estuaries. *Canadian Journal of Fisheries and Aquatic Sciences* **69,** 1131-1149.

Cerco, C.F., Noel, M.R. (2007) Can oyster restoration reverse cultural eutrophication in Chesapeake Bay? *Estuaries and Coasts* **30,** 331-343.

Coen, L.D., Brumbaugh, R.D., Bushek, D.*, et al.* (2007) Ecosystem services related to oyster restoration. *MARINE ECOLOGY PROGRESS SERIES* **341,** 303–307.

Coen, L.D., Grizzle, R.E. (2007) The Importance of Habitat Created by Molluscan Shellfish to Managed Species along the Atlantic Coast of the United States. Habitat Management Series No. 8, 115.

Dame, R.F. (2011) *Ecology of Marine Bivalves: an ecosystem approach,*  Vol., CRC Press, Boca Raton, FL.

Dame, R.F., Zingmark, R.G., Haskin, E. (1984) Oyster Reefs as Processors of Estuarine Materials. *Journal of Experimental Marine Biology and Ecology* **83,** 239-247.

Drake, J.C. (1891) On the sounds and estuaries of Georgia, with reference to oyster culture. *United States Coast and Geodetic Survey Bulletin* **19,** 179-209.

Dumain, L. (1832) Survey of the Coast of Louisiana [1806-1807, communicated to the Senate 1811]. Class IV, Commerce and Navigation. In: *Document No. 158 in the American State Papers.* Vol. 7. (Eds. W. Lowrie, M. St. Clair Clarke), Gales and Seaton, Washington, pp. 839-842.

Elsey, C.R. (1935) On the structure and function of the mantle and gill of *Ostrea gigas* (Thunberg) and *Ostrea lurida (*Carpenter). *Transactions of the Royal Society of Canada* **29,** 131-158.

Gedan, K.B., Kellogg, L., Breitburg, D.L. (2014) Accounting for multiple foundation species in oyster reef restoration benefits. *Restoration Ecology* **22,** 517-524.

Gerdes, D. (1983) The Pacific oyster Crassostrea gigas: Part I Feeding behaviour of larvae and adults. *Aquaculture* **31,** 195-219.

Gould, A.A. (1841) *Report on the invertebrata of Massachusetts comprising the mollusca, crustacea, annelinda and radiata,*  Vol., Folsom, Wells, and Thurston, Cambridge MA.

Grabowski, J.H., Brumbaugh, R.D., Conrad, R.F.*, et al.* (2012) Economic Valuation of Ecosystem Services Provided by Oyster Reefs. *BioScience* **62,** 900-909.

Grabowski, J.H., Peterson, C.H. (2007) Restoring oyster reefs to recover ecosystem services. In: *Ecosystem engineers*. (Eds. K. Cuddington, J.E. Byers, W.G. Wilson, A. Hastings), Elsevier Academic Press, Burlington MA, pp. 281-298.

Grave, C. (1912) *Notes on the history of the oyster in Maryland and the physical valuation of her oyster properties,*  Vol., Baltimore.

Gregalis, K.C., Johnson, M.W., Powers, S.P. (2009) Restored Oyster Reef Location and Design Affect Responses of Resident and Transient Fish, Crab, and Shellfish Species in Mobile Bay, Alabama. *Transactions of the American Fisheries Society* **138,** 314-327.

Grizzle, R.E., Brodeur, M. (2004) Oyster (*Crassostrea virginica*) reef mapping in the Great Bay Estuary, New Hampshire - 2003. 19.

Grizzle, R.E., Greene, J.K., Coen, L.D. (2008) Seston Removal by Natural and Constructed Intertidal Eastern Oyster (Crassostrea virginica) Reefs: A Comparison with Previous Laboratory Studies, and the Value of in situ Methods. *Estuaries and Coasts* **31,** 1208-1220.

Grizzle, R.E., Ward, K. (2009) Video-Based Mapping of Oyster Bottom in the Upper Piscataqua River, Sturgeon Creek, and Spruce Creek. 10.

Harsh, D.A., Luckenbach, M.W. (1999) Materials processing by oysters in patches: Interactive roles of current speed and seston composition. In: *Oyster reef habiatat restoration: A synopsis and synthesis of approaches*. (Eds. M.W. Luckenbach, R. Mann, J.A. Wesson), Virginia Instiute of Marine Science, School of Marine Science, College of William and Mary, VIMS Press, pp. 251-265.

Haure, J., Penisson, C., Bougrier, S., Baud, J.P. (1998) Influence of temperature on clearance and oxygen consumption rates of the flat oyster Ostrea edulis: determination of allometric coefficients. *Aquaculture* **169,** 211-224.

Haven, D.S., Morales-Alamo, R. (1970) Filtration of particles from suspension by the american oyster Crassostrea virginica. *Biological Bulletin* **139,** 248-264.

Higgins, C.B., Tobias, C., Piehler, M.F.*, et al.* (2013) Impact of aquacultured oyster biodeposition on sediment N2 production in Chesapeake Bay. *MARINE ECOLOGY PROGRESS SERIES*.

Hinke, W.J. (1916) Report of the Journey of Francis Louis Michel from Berne, Switzerland, to Virginia, October 2, 1701-December 1, 1702. Part II. *The Virginia Magazine of History and Biography* **24,** 113-141.

Hutchinson, S., Hawkins, L.E. (1992) Quantification of the physiological responses of the European flat oyster Ostrea edulis L. to temperature and salinity. *Journal of Molluscan Studies* **58,** 215-226.

Kellogg, J.L. (1915) Ciliary mechanisms of lamellibranchs with descriptions of anatomy. *Journal of Morphology* **26,** 625-701.

Kellogg, L., Cornwell, J.C., Paynter, K.T., Owens, M.S. (2011) Nitrogen removal and sequestration capacity of a restored oyster reef. 65.

Kellogg, M.L., Cornwell, J.C., Owens, M.S., Paynter, K.T. (2013) Nitrogen removal and nutrient sequestration of a restored oyster reef. *MARINE ECOLOGY PROGRESS SERIES* **480,** 1-19.

Kellogg, M.L., Smyth, A.R., Luckenbach, M.W.*, et al.* (2014) Use of oysters to mitigate eutrophication in coastal waters. *Estuarine, Coastal and Shelf Science*.

Kirby, M. (2004) Fishing down the coast: Historical expansion and collapse of oyster fisheries along continental margins. *Proceedings of the National Academy of Sciences* **101,** 13096-13099.

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.

Lenihan, H.S. (1999) Physical-Biological Coupling on Oyster Reefs: How Habitat Structure Influences Individual Performance. *Ecological Monographs* **69,** 251-275.

Mann, R., Harding, J.M., Southworth, M.J. (2009) Reconstructing pre-colonial oyster demographics in the Chesapeake Bay, USA. *Estuarine, Coastal and Shelf Science* **85,** 217-222.

Meyer, D.L., Townsend, E.C., Thayer, G.W. (1997) Stabilization and Erosion Control Value of Oyster Cultch for Intertidal Marsh. *Restoration Ecology* **5,** 93-99.

Moebius, K. (1883) The oyster and oyster-culture. Report of commissioner of fish and fisheries, 683-747.

Moehlenberg, F., Riisgaard, H.U. (1979) Filtration rate, using a new indirect technique, in thirteen species of suspension-feeding bivalves. *Marine Biology* **54,** 143-147.

Newell, R.I.E. (2004) Ecosystem influences of natural and cultivated populations of suspension-feeding bivalve molluscs: A review. *Journal of Shellfish Research* **23,** 51-61.

Newell, R.I.E., Fisher, T.R., Holyoke, R.R., Cornwell, J.C. (2005) Influence of Eastern Oysters on Nitrogen and Phosphorus Regeneration in Chesapeake Bay, USA. In: *The Comparative Roles of Suspension-Feeders in Ecosystems*. pp. 93-120.

Piazza, B.P., Banks, P.D., La Peyre, M.K. (2005) The Potential for Created Oyster Shell Reefs as a Sustainable Shoreline Protection Strategy in Louisiana. *Restoration Ecology* **13,** 499-506.

Piehler, M.F., Smyth, A.R. (2011) Habitat-specific distinctions in estuarine denitrification affect both ecosystem function and services. *Ecosphere* **2,** art12.

Richardson, N.F., Ruesink, J.L., Naeem, S.*, et al.* (2008) Bacterial abundance and aerobic microbial activity across natural and oyster aquaculture habitats during summer conditions in a northeastern Pacific estuary. *Hydrobiologia* **596,** 269-278.

Rick, T.C., Erlandson, J.M. (2009) Coastal exploitation. *Science* **952,** 325-326.

Riisgaard, H.U. (1988) Efficiency of particle retention and filtration rate in 6 species of Northeast American bivalves. *Marine Ecology-Progress Series* **45,** 217-223.

Roberts, C.M. (2007) *The Unnatural History of the Sea. The past and future of humanity and fishing,*  Vol., Gaia, London.

Rodney, W.S., Paynter, K.T. (2006) Comparisons of macrofaunal assemblages on restored and non-restored oyster reefs in mesohaline regions of Chesapeake Bay in Maryland. *Journal of Experimental Marine Biology and Ecology* **335,** 39-51.

Schlesselman, G.W. (1955) The Gulf coast oyster industry of the United States. *Geographical Review* **45,** 531-541.

Scyphers, S.B., Powers, S.P., Heck, K.L., Byron, D. (2011) Oyster reefs as natural breakwaters mitigate shoreline loss and facilitate fisheries. *PLoS ONE* **6,** e22396.

Shervette, V.R., Gelwick, F. (2008) Seasonal and Spatial Variations in Fish and Macroinvertebrate Communities of Oyster and Adjacent Habitats in a Mississippi Estuary. *Estuaries and Coasts* **31,** 584-596.

Smaal, A.C., Prins, T.C. (1993) The uptake of organic matter and the release of inorganic nutrients by bivalve suspension feeder beds. In: *Bivalve filter feeders in estuarine and coastal ecosystem processes*. (Ed. R.F. Dame), Springer-Verlag, Heidelberg, pp. 273-298.

Smith, H.M. (1896) Notes on Biscayne Bay, Florida, with reference to its adaptability as the site of a Marine Hatching and Experiment Station. In: *United States Commission of Fish and Fisheries Report of the Commissioner for the year ending June 30, 1895.* Vol. 21. Government Printing Office, Washington D.C., pp. 169-191.

Smith, K.A., North, E.W., Shi, F.Y.*, et al.* (2009) Modeling the Effects of Oyster Reefs and Breakwaters on Seagrass Growth. *Estuaries and Coasts* **32,** 748-757.

Smyth, A.R., Geraldi, N.R., Piehler, M.F. (2013) Oyster-mediated benthic-pelagic coupling modifies nitrogen pools and processes. *MARINE ECOLOGY PROGRESS SERIES* **493,** 23-30.

Spalding, M., Ravilious, C., Green, E.P. (2001) *World Atlas of Coral Reefs,*  Vol., University of California Press, Bekeley, CA.

Stevenson, C.H. (1893) Report on the Coast Fisheries of Texas. In: *United States Commission of Fish and Fisheries. Report of the Commissioner for 1889 to 1891.* Vol. 17. Government Printing Office, Washington D.C., pp. 373-420.

Stricklin, A.G., Peterson, M.S., Lopez, J.D., May, C.A., Mohrman, C.F., Woodrey, M.S. (2010) Do small, patchy, constructed intertidal oyster reefs reduce salt marsh erosion as well as natural reefs? *Gulf and Caribbean Research* **22,** 21-27.

Stunz, G.W., Minello, T.J., Rozas, L.P. (2010) Relative value of oyster reef as habitat for estuarine nekton in Galveston Bay, Texas. *MARINE ECOLOGY PROGRESS SERIES* **406,** 147-159.

Tenore, K.R., Dunstan, W.M. (1973) Comparison of rates of feeding and biodeposition of the American oyster, *Crassostrea virginica* Gmelin, fed different species of phytoplankton. *Journal of Experimental Marine Biology and Ecology* **12,** 19-26.

Tolley, S.G., Volety, A.K. (2005) THE ROLE OF OYSTERS IN HABITAT USE OF OYSTER REEFS BY RESIDENT FISHES AND DECAPOD CRUSTACEANS. *Journal of Shellfish Research* **24,** 1007-1012.

Tompkins, W.A. (1932) Oysterville, 1840-97. *Oregon Historcial Quarterly* **33,** 160-163.

Wall, C., Peterson, B., Gobler, C. (2011) The Growth of Estuarine Resources (*Zostera marina*, *Mercenaria mercenaria*, *Crassostrea virginica*, *Argopecten irradians*, *Cyprinodon variegatus*) in Response to Nutrient Loading and Enhanced Suspension Feeding by Adult Shellfish. *Estuaries and Coasts* **34,** 1262-1277.

Wall, C.C., Peterson, B.J., Gobler, C.J. (2008) Facilitation of seagrass Zostera marina productivity by suspension-feeding bivalves. *MARINE ECOLOGY PROGRESS SERIES* **357,** 165-174.

Waycott, M., Duarte, C.M., Carruthers, T.J.B.*, et al.* (2009) Accelerating loss of seagrasses across the globe threatens coastal ecosystems. *Proceedings of the National Academy of Sciences* **106,** 12377-12381.

Winslow, F. (1889) Report on the sounds and estuaries of North Carolina with reference to oyster culture. *United States Coast and Geodetic Survey Bulletin* **10,** 53-132.

zu Ermgassen, P.E., Spalding, M., Grizzle, R., Brumbaugh, R. (2013a) Quantifying the Loss of a Marine Ecosystem Service: Filtration by the Eastern Oyster in US Estuaries. *Estuaries and Coasts* **36,** 36-43. [In English].

zu Ermgassen, P.S.E., Gray, M.W., Langdon, C.J., Spalding, M.D., Brumbaugh, R.D. (2013b) Quantifying the historic contribution of Olympia oysters to filtration in Pacific Coast (USA) estuaries and the implications for restoration objectives. *Aquatic Ecology* **47,** 149-161. [In English].

zu Ermgassen, P.S.E., Spalding, M.D., Blake, B.*, et al.* (2012) Historical ecology with real numbers: Past and present extent and biomass of an imperilled estuarine ecosystem. *Proceedings of the Royal Society B* **279,** 3393-3400.

## Appendix 4

Appendix 4: Table of Life history parameters of recruitment enhanced species.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Species** | **Common name** | **M** | **L∞** | **K** | **t0** | **a** | **b** | **tmax** | **r** | **References** |
| **Fish** |  |  |  |  |  |  |  |  |  |  |
| *Archosargus probatocephalus* (Gulf of Mexico) | Sheepshead | 0.20 | 38.1 | 0.39 | -1.13 | 0.0343 | 2.91 | 16 | 2 | Murphy and MacDonald 2000 |
| *Archosargus probatocephalus* (Atlantic) | Sheepshead | 0.20 | 45.1 | 0.24 | -1.17 | 0.0237 | 3.07 | 16 | 2 | Murphy and MacDonald 2000 |
| *Bairdiella chrysoura* | Silver Perch | 1.39 | 27.0 | 0.69 | -0.24 | 0.0114 | 3.00 | 6 | NA | Ayala-Perez et al. 2006, Welsh and Breder 1923 |
| *Bathygobius soporator* | Frillfin Goby | 1.08 | 26.5 | 2.56 | 0.04 | 0.0091 | 2.84 | 4 | NA | Hernaman and Munday 2005 (*Valenciennea muralis* [M] as a proxy) |
| *Chaetodipterus faber* | Spadefish | 0.55 | 49.0 | 0.34 | -0.18 | 0.0373 | 2.96 | 8 | NA | Hayse 1990, Vianna et al. 2004 |
| *Chasmodes bosquianus* | Striped Blenny | 2.14 | 15.9 | 2.56 | 0.04 | 0.0091 | 2.84 | 2 | NA | Robins and Ray 1986, Hernaman and Munday 2005 (*Valenciennea muralis* [M] as proxy) |
| *Ctenogobius boleosoma* | Darter Goby | 2.14 | 8.0 | 1.46 | 0.02 | 0.0094 | 3.06 | 2 | NA | Robins and Ray 1986, Hernaman and Munday 2005 (*Amblygobius bynoensis* [F] as proxy) |
| *Fundulus majalis* | Striped Killifish | 2.14 | 15.9 | 0.28 | -0.24 | 0.0132 | 3.03 | 2 | NA | Clemmer and Schwartz 1965, Kneib and Stiven 1978 (*F. heteroclitus* as proxy) |
| *Gobiesox strumosus* | Skilletfish | 2.14 | 8.6 | 1.46 | 0.02 | 0.0128 | 3.04 | 2 | NA | Smith 1997, Bohnsack and Harper 1988, Hernaman and Munday 2005 (*Amblygobius bynoensis* [F] as proxy) |
| *Gobiosoma bosc* | Naked Goby | 1.08 | 6.5 | 1.10 | -0.03 | 0.0105 | 2.99 | 4 | NA | Robins and Ray 1986, Boschung, H.T., Jr., and R.L. Mayden. 2004, Hernaman and Munday 2005 (*Istigobius goldmanni* [M] as proxy) |
| *Hypsoblennius hentz* | Feather Blenny | 1.08 | 10.7 | 0.62 | -0.39 | 0.0110 | 2.96 | 4 | NA | Robins and Ray 1986, Azevedo and Homem 2009 (*Parablennius ruber* as proxy) |
| *Hypsoblennius ionthas* | Freckled Blenny | 1.08 | 10.7 | 0.62 | -0.39 | 0.0110 | 2.96 | 4 | NA | Robins and Ray 1986, Azevedo and Homem 2009 (*Parablennius ruber* as proxy) |
| *Lagodon rhomboides* | Pinfish | 0.78 | 22.0 | 0.33 | -1.10 | 0.0316 | 3.03 | 7 | NA | Nelson 2002 |
| *Leiostomus xanthurus* | Spot | 1.08 | 23.9 | 0.89 | -0.04 | 0.0092 | 3.07 | 4 | NA | Sundaraj 1960, Dawson 1965, Hugg 1996, Florida Fish and Wildlife Conservation Commission |
| *Lutjanus griseus* | Gray Snapper | 0.21 | 89.0 | 0.10 | -0.32 | 0.0232 | 2.88 | 21 | 5 | Manooch and Matheson 1983, Bohnsack and Harper 1988, Manooch 1987 |
| *Mycteroperca microlepis* | Gag Grouper | 0.18 | 118.0 | 0.17 | -0.74 | 0.0093 | 3.059 | 17 | 4 | Hood and Schlieder 1992, McGovern et al. 2005 |
| *Opsanus beta* (Female) | Toadfish | 0.60 | 20.1 | 0.79 | 0.47 | 0.0063 | 3.28 | 5 | NA | Malca et al. 2009 |
| *Opsanus beta* (Male) | Toadfish | 0.60 | 39.4 | 0.30 | 0.36 | 0.0063 | 3.28 | 6 | NA | Malca et al. 2009 |
| *Opsanus tau* (Female) | Toadfish | 0.49 | 27.2 | 0.39 | -0.41 | 0.0100 | 3.22 | 9 | NA | Swartz and van Engle 1968, Radtke et al. 1985 |
| *Opsanus tau* (Male) | Toadfish | 0.40 | 40.7 | 0.15 | -0.33 | 0.0100 | 3.22 | 11 | NA | Swartz and van Engle 1968, Radtke et al. 1985 |
| *Orthopristis chrysoptera* | Pigfish | 0.60 | 47.5 | 0.16 | -1.14 | 0.0128 | 3.06 | 4 | 1 | Peterson et al. 2003, Darcy 1983 |
| *Paralichthys lethostigma* (Female) | Southern Flounder | 0.55 | 66.0 | 0.21 | -1.32 | 0.0043 | 3.30 | 8 | 1 | Stunz et al. 2000, Fischer and Thompson 2004 |
| *Paralichthys lethostigma* (Male) | Southern Flounder | 1.08 | 33.3 | 1.03 | -0.25 | 0.0043 | 3.30 | 4 | 1 | Stunz et al. 2000, Fischer and Thompson 2004 |
| *Prionotus sp.* | Sea Robin | 0.73 | 36.6 | 0.39 | 0.00 | 0.0097 | 3.48 | 6 | NA | Richards et al. 1979, Robins & Ray 1986 |
| **Crustaceans** |  |  |  |  |  |  |  |  |  |  |
| *Callinectes sapidus* (Female) | Blue Crab | 1.00 | 17.6 | 1.45 | 0.13 | 1.1474 | 1.86 | 6 | 0.75 | Murphy et al. 2007, Smith 1997 |
| *Callinectes sapidus* (Male) | Blue Crab | 1.00 | 17.6 | 1.45 | 0.13 | 0.7634 | 2.10 | 6 | 0.75 | Murphy et al. 2007, Smith 1997 |
| *Farfantepenaeus aztecus* | Brown Shrimp | 18.00 | 19.1 | 1.14 | -0.29 | 0.0071 | 3.07 | 2 | 0.5 | Arreguin Sanchez 1999, Minello et al. 2008. |
| *Litopanaeus setiferus* | White Shrimp | 18.00 | 19.1 | 1.14 | -0.29 | 0.0065 | 3.00 | 2 | 0.5 | Arreguin Sanchez 1999 (*F. aztecus* as proxy), Minello et al. 2008 |
| *Menippe mercenaria* (Female) | Stone Crab | 0.70 | 12.6 | 0.456 | 0.255 | 0.2885 | 3.048 | 8 | 3 | Restrepo 1989, Sullivan 1979, Gerhart and Bert 2008 |
| *Menippe mercenaria* (Male) | Stone Crab | 0.70 | 12.6 | 0.456 | 0.255 | 0.1941 | 3.290 | 7 | 3 | Restrepo 1989, Sullivan 1979, Gerhart and Bert 2008 |

1. http://www.csc.noaa.gov/digitalcoast/publications/stakeholder [↑](#footnote-ref-1)
2. http://www.conservationgateway.org/ConservationPractices/PeopleConservation/SocialScience/Pages/strengthening-social-impacts.aspx [↑](#footnote-ref-2)
3. http://www.conservationgateway.org/ConservationPractices/Freshwater/HabitatProtectionandRestoration/Pages/habitat-protection-and-re.aspx [↑](#footnote-ref-3)