Planning and Incentivizing Native Olympia Oyster Restoration in Southern California

This report was submitted in partial fulfillment of the requirements for the degree of Master of Environmental Science and Management at the Bren School of Environmental Science & Management, University of California, Santa Barbara.

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Signature Page

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In Southern California

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The Group Project is required of all students in the Master of Environmental Science and Management (MESM) Program. The project is a year-long activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Group Project Final Report is authored by MESM students and has been reviewed and approved by:

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Abstract

The Olympia oyster, *Ostrea lurida*, is the only oyster native to the west coast of the United States. Populations have declined over the last 150 years due to coastal development, overharvest, and pollution. Through visiting natural history museums and surveying in Southern California, we discovered that small populations of Olympia oysters still exist, though they do not resemble the historic populations they once formed. Oysters are habitat engineers that provide ecosystem benefits such as erosion control, water quality improvement, and habitat for fish and invertebrates. To incentivize oyster restoration, we quantified some of these ecosystem services through a bioeconomic model and cost-benefit analysis. Results revealed that restoring one hectare of oyster reef could increase the kelp bass fishery by 39,304 additional grams in biomass over 30 years and increase the California halibut fishery by $24,411 per cohort. Furthermore, this study suggests that restoring Olympia oysters in the Batiquitos Lagoon could decrease ecosystem maintenance costs by up to $2 million. This project provides a framework for successful collaboration between experts, researchers, and the community to further restoration efforts. We also provide key questions that should be addressed with further research, especially those concerning economic benefits and incentives for restoring an important west coast estuarine ecosystem engineer.

Executive Summary

Almost 40 million people live in California today, and nearly 70% of the population lives within coastal communities. This high density of people has put a significant amount of stress on coastal ecosystems through increased pollution, erosion, and habitat destruction. As a result, over 90% of California's wetlands have been destroyed over the last 150 years. It is now not only imperative to conserve remaining natural habitat, society needs to begin to restore coastal ecosystems. One restoration method is to reestablish ecosystem engineers that can create new habitat and resources for other species. An example of an ecosystem engineer is the oyster, which forms reefs in temperate estuaries and bays. Oysters improve the health of these coastal ecosystems by providing a number of ecosystem services to both people and wildlife. These services include water quality improvement, shoreline stabilization, and the production of important habitat for invertebrates and fish. Oyster restoration has been widespread and successful on a large scale on the U.S. Atlantic and Gulf of Mexico coastlines, and many ecosystem services have been recovered.

The Olympia oyster, *Ostrea lurida*, is the only native oyster inhabiting the west coast of the United States. Historical evidence suggests that California's bays and estuaries were once teeming with native oysters. However, due to pollution, overharvesting, and habitat modification, populations were drastically reduced by the 1950's. The Olympia oyster is much smaller than the Eastern oyster, *Crassostrea virginica*, but under the right conditions can form low-lying reefs that provide similar ecosystem services.

Olympia oysters still exist throughout the west coast. Restoration groups have documented thriving Olympia reefs in Canada, recovering reefs in San Francisco Bay, and many small populations in Southern California that have not formed reefs. Society today is generally unaware of the historic abundance of Olympia oysters on the West Coast and the ecosystem services they provide. As a result, Olympia oysters are typically not included in most restoration or management plans and are not sold for consumption in California. The purpose of our research is to provide useful tools and incentives for future Olympia oyster restoration efforts in Southern California by addressing the following objective questions:

1. Where are Olympia oysters in Southern California?
2. What are the economic incentives for Olympia oyster restoration?
3. How do we foster successful restoration?

We discovered small Olympia oyster populations in many of the bays, estuaries, and lagoons throughout Southern California through an extensive literature review and data collection. However, oyster populations have not formed reefs at these locations. Additional research is needed to identify the ecological or restoration bottlenecks at each site that are preventing survival and the formation of reefs. These bottlenecks may include poor recruitment as a result of poor water quality, low larval settlement resulting from a lack of hard substrate, or a shortage of adult broodstock for larval production. Similarly, further monitoring of chlorophyll concentrations, Olympia oyster population demographics, and sedimentation rates is needed to determine the state of these specific sites for suitable oyster habitat. Preliminary analysis suggests that some sites throughout Southern California may contain suitable habitat for successful oyster restoration.

Three Olympia oyster restoration projects have been completed in Southern California, at Mugu Lagoon, Alamitos Bay, and Newport Bay. Projects focused on addressing larval settlement as the key bottleneck at each site. Results showed that Olympia oyster larvae prefer to settle on shells of their own species, a factor well recognized most oyster species. Further research efforts will be focused on analyzing other bottlenecks that could impact survival and reef formation at each site. An ongoing project in San Diego Bay is determining the magnitude of the Olympia oyster's shoreline stabilization capacity. This will be the first project incorporating fieldwork to test for the ecosystem services provided by Olympia oysters in Southern California. The quantification of these ecosystem services could provide economic incentives for future restoration efforts.

Shoreline stabilization and fish production were identified and quantified as critical ecosystem services provided by native oysters. We concluded that restoring Olympia oyster reefs in Batiquitos Lagoon could provide a cost-effective alternative to dredging for maintaining local wetland habitat, with a cost savings of about $1- $2 million over a 30-year period. Olympia oyster restoration could also alleviate shoreline stabilization costs for coastal homes bordering the Carpinteria Salt Marsh Reserve. In terms of fish production, we found that one hectare of restored oyster reef has the potential to increase the California halibut fishery by $24,411 per cohort and the kelp bass fishery by 39,304 +/- 4549 additional grams of biomass. These values provide insight into the economic incentives provided by Olympia oysters. Additional research and understanding of these ecosystem services in Southern California's embayments will be paramount to the success of Olympia oyster restoration projects in the future.

Economic incentives related to coastal shoreline management in a changing climate can be used to engage the public and foster a connection with their local marine ecosystems. Oyster restoration efforts regularly integrate community involvement and education into their restoration plans. Our project developed a strategic communications plan that uses film to engage the public and generate volunteer interest through a short public service announcement. In addition, a short documentary was developed to clearly depict how Olympia oyster restoration can benefit the coastal communities in Southern California.

While it is important to engage coastal communities in oyster restoration, it is essential to create an efficient flow of communication between scientists, managers, and other stakeholders. To spark collaboration amongst restoration stakeholders, we organized an Olympia oyster restoration forum at the Aquarium of the Pacific in Long Beach, California, sponsored by the Honda Marine Science Foundation held in March 2017. The forum gathered restoration experts across the country from the National Oceanic and Atmospheric Administration (NOAA), The Nature Conservancy (TNC), the Honda Marine Science Foundation, Billion Oyster Project, and other public and private organizations and academic institutions. Its purpose was to identify optimal conditions for Olympia oyster survival, sites with those conditions, incentives for Olympia oyster restoration, and the success metrics to be utilized in Southern California. This information, in addition, to lessons learned from previous oyster restoration projects across the country was analyzed to develop steps for fostering Olympia oyster restoration in Southern California. Our project provided a framework for successful collaboration between these various organizations to initiate discussion and a sharing of ideas and data, resulting in the formation of a campaign to streamline and initiate future efforts.

Project Significance

The Olympia oyster, *Ostrea lurida,* is the only native oyster species to the West Coast. Olympia oysters were once prominent along the western coast of the United States to Baja, Mexico. However, Olympia oyster populations were reduced to a mere fraction of their once historical numbers due to overharvesting, pollution, and habitat modification. As a result, society today faces a shifting baseline. Olympia oysters have been functionally absent from California's coastline since the early 1900's, thus people no longer consider Olympia oysters to be an integral component of California's coastal ecosystems, nor are they aware of the ecosystem services they once provided. Consequently, *O. lurida* is not included in any coastal restoration or management plan that we know of, and are they not sold for consumption in California.

As an ecosystem engineer that provides a number of ecosystem services to people and wildlife, Olympia oysters serve as a model organism for estuary and wetland restoration throughout Southern California. Oysters form reefs, which create habitat for commercially and recreationally important species, help reduce wave energy and erosion rates, and improve local water quality through water filtration. Oysters are a key component of our coastal ecosystems and help maintain the quality and health of these important ecosystems.

Along the Atlantic Coast and in Washington State, numerous large-scale oyster restoration projects have been implemented to restore populations for the fishery and ecosystem services they provide. In Southern California, small-scale restoration projects have been completed, and focused solely on providing hard substrate for larval settlement. Future projects and research aim to identify the ecological and restoration bottlenecks that prevent reef formation. They also plan to quantify the magnitude of these ecosystem services in Southern California. Our objectives were to provide the necessary tools and incentives to motivate and support future restoration efforts. We achieved this by completing the following:

Objectives:

- Compile historic and present Olympia oyster spatial data throughout Southern California and create an online database to store this data for future use.
- Provide economic incentives for Olympia oyster restoration through a shoreline stabilization cost benefit analysis and a bioeconomic model to explore changes in fish abundance with a restored oyster reef.
- Identify gaps in ecological knowledge and synthesize lessons learned from previous Olympia oyster restoration projects.
- Create a network of collaboration amongst scientists, managers, and other stakeholders by organizing an Olympia oyster forum at the Aquarium of the Pacific.
- Develop two short films that can be used as outreach materials to engage the public in restoration efforts.

Background

Historic and Present Locations

According to fossil records, *Ostrea lurida* was prevalent from Sitka, Alaska to Baja, Mexico (Polson and Zacherl, 2009). Olympia oysters were present historically throughout Southern California and served as an important food source for Native Americans as supported by their presence in shell middens (Zacherl, 2014; Laylander and Iversen, 2008). Multiple explorers such as Cabrillo and Viscaino logged Olympia oyster sightings throughout Southern California from the 1600's to the 1900's (Bonnet, 1935; Davidson, 1887; Gilbert, 1889; Zacherl, 2014). Unfortunately, historical records do not report numerical abundances of oyster populations. Despite the lack of numerical data, anecdotal evidence suggests that Olympia oyster populations declined in the early 1900's due to pollution, overharvesting, and habitat destruction. However, recent surveys found small Olympia oyster populations remaining in bays and estuaries in Southern California, though no reefs have been found (Polson and Zacherl, 2009). These areas include San Diego Bay, Mission Bay, Batiquitos Lagoon, Aqua Hedionda, Newport Bay, Alamitos Bay, and Mugu Lagoon (Polson and Zacherl, 2009).

Life Cycle of Olympia Oysters

The Olympia oyster is a hermaphroditic bivalve mollusk that switches between male and female after each spawning event (Baker, 1995; Bluesco, 1982). Olympia oysters are brooders, meaning the larvae develop inside of the female and are released in an advanced development stage into the surrounding water. Further metamorphosis occurs once released and the free swimming remain in the water column for about two weeks (Bulesco, 1982). When the larvae settle on hard substrate, they are considered spat and become sessile (Baker, 1995). Olympia oysters prefer to settle on shells of their own species, but will settle on other various types of hard substrate such as rip rap, pier pilings, and cement walls (Coe, 1931). They prefer to settle at mid-intertidal to shallow subtidal depths in bays and estuaries (Wasson et al., 2014).

Many factors influence oyster reproduction, development, growth, and survival, including water temperature, salinity, sedimentation, predation, disease, and competition (Shumway 1996; Burrell 1986, Baker 1995: COSEWIC 2011). Limited research has shown the temperature threshold minimum for Olympia oyster reproduction is 16^{o}C in Southern California (Hopkins, 1937). If the temperature is significantly higher or lower than this critical temperature, spawning may be inhibited (Bulesco, 1982). In addition, relatively warm seawater temperatures can impact physiological processes, such as metabolism, growth, and respiration rates. Cheng et al. (2015) found that juvenile Olympia oyster growth increased significantly at temperatures of 24^{o}C compared with 20^{o}C in Central California. Other factors that influence Olympia oyster survival depends on the availability of food, exposure and desiccations, competition with invasive species, and broodstock availability (Wasson et al., 2014). Olympia oysters can live up to 10 years under optimal conditions (Baker, 1995), and few studies have addressed the bottlenecks limiting oyster population growth in Southern California. Future projects aim to identify specific bottlenecks and if they vary geographically in Southern California.

Ecosystem Services

Biogenic Reef Habitat for Fish and Invertebrates

Oyster reefs create important habitat for juvenile fish, crustaceans, worms, foraging nekton, and birds (Lenihan & Peterson, 1998; Lenihan, 1999; Lenihan et al., 2001; Grabowski et al., 2012). Young fish and invertebrates are able to survive to later life stages because oyster reefs provide refuge from predation, increase food availability, and provide substrate for recruitment and settlement (Lenihan, 1999). Furthermore, oyster reefs diversify the seascape, create corridors between various habitats, and stabilize sediment. Numerous studies have been conducted along the Atlantic and northern pacific to quantify ecosystem benefits of oyster reefs in terms of the increased biomass of the species utilizing the reefs (Lenihan & Peterson, 1998; Harding & Mann, 1999; Lenihan et al., 2001; Ramsay, 2012). Studies have shown that oyster reefs enhance biodiversity. A comparative study of fish and invertebrate production has not yet been conducted for Olympia oysters in Southern California. However, monitoring is underway in San Diego Bay, Newport Bay, and San Francisco Bay to measure the changes in biodiversity and species biomass before and after Olympia oyster restoration. Data from San Francisco Bay and Newport Bay suggest that avian and invertebrate species are responding to oyster restoration positively (Boyer et al., 2012). This data can be used to better understand how Olympia oyster reefs can enhance habitat in marine ecosystems.

Shoreline Stabilization

Armored shoreline techniques, such as rip rap and seawalls, negatively impact the surrounding ecosystems (Hall & Pilkey, 1991; Ells & Murray, 2012). Studies are exploring the use of living shorelines as a more natural long term method for shoreline stabilization. High densities of oysters reduce shoreline erosion and increase sediment accretion (Scyphers, 2011; Piazza, 2005; Meyer, 1997; Manis, 2015). There is some debate as to the extent that oysters can protect against wave energy in estuarine areas (Piazza, 2005; Meyer, 1997). In addition, combining oyster and vegetation restoration can further enhance this shoreline stabilization benefit (Manis, 2015). Furthermore, these methods are more sustainable and have the potential to naturally expand over time (Manis, 2015). San Francisco's Living Shoreline monitoring report stated that restored oyster reefs and eelgrass plots absorb 28% more wave energy than a mudflat at the same location. In addition, these reefs accumulated between 20-40 m^3 of sediment compared to 0-17m^3 on a mudflat of the same size (Boyer et al., 2013). If successfully restored, Olympia oyster reefs can sustainably protect California's coastline.

Spatial Analysis

Introduction

Accurate oyster presence data and suitable habitat needs to be identified to ensure successful oyster restoration. According to historic data, Ostrea lurida was present from Sitka, Alaska to Baja, Mexico (Polson and Zacherl, 2009). However, due to pollution, habitat destruction, and overharvesting, Olympia oysters have severely declined. In Southern California, no reefs have been identified and only small populations exist in bays and estuaries (Polson and Zacherl, 2009). The remaining populations need to be identified in order to prioritize restoration sites. Additionally, environmental characteristics within bays and estuaries need to be analyzed in order to determine whether a site with oyster presence is suitable for restoration. Preliminary monitoring data of oyster presence and the identification of suitable sites is available but not centrally located. Therefore, we compiled all available Olympia oyster presence data and began the development of an oyster habitat suitability model to improve the restoration site identification process.

Oyster Presence Data Collection

Oyster presence dating from the year 1900 exists in museum records, scientific reports, and restoration plans. Prior to our research, this data was not centralized or easily accessible for use in restoration plans. We visited the Santa Barbara Museum of Natural History, Natural History Museum of Los Angeles County, and the Smithsonian Institution National Museum of Natural History to electronically catalogue previously collected oyster survey data. Olympia oyster specimens were collected from Morro Bay, CA to Northern Baja California, Mexico dating from 1910 to 2010. Records included geographic coordinates, date collected, year, length, and available habitat information. Length was measured in millimeters from the hinge of the shell with manual or digital calipers. Up to five specimens were recorded per collection from the same date and GPS location. Presence data in San Diego Bay, Alamitos Bay, Newport Bay, and Los Angeles Harbor were collected from Dr. Danielle Zacherl and Holly Henderson. Data included oyster density and geographic locations from surveys between 2010 and 2014 at these sites. To fill in data gaps, our group conducted oyster presence surveys in Marina del Rey, Batiquitos Lagoon, San Dieguito Lagoon, and the Carpinteria Salt Marsh Reserve. Square meter quadrats were used to record densities of Olympia and Pacific oysters in the Carpinteria Salt Marsh. We aggregated the data from museums, restoration projects, and surveys to create a map of oyster presence in Southern California from 2000-2017 (Figure 1). The data collected shows that there are only small oyster populations in remaining wetland habitats. We mapped historic and present wetland habitat with oyster distribution data to show how coastal development has impacted oyster abundance (Figure 2; Appendix A, Figures 3-5).

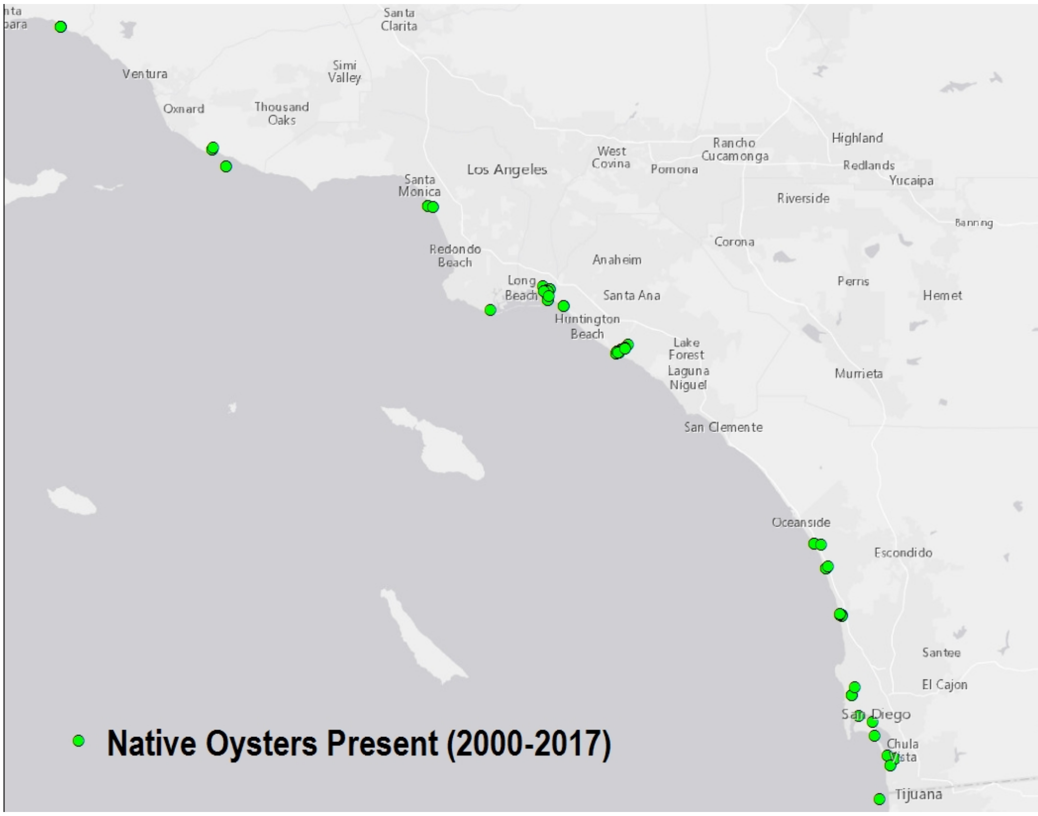

Figure 1. Map of Olympia oyster presence data in Southern California collected from 2000 to 2017. Data was collected from the Santa Barbara Natural History Museum, the Natural History Museum of Los Angeles County, Dr. Danielle Zacherl, Holly Henderson, and surveys by the SoCal Oyster Bren Group.

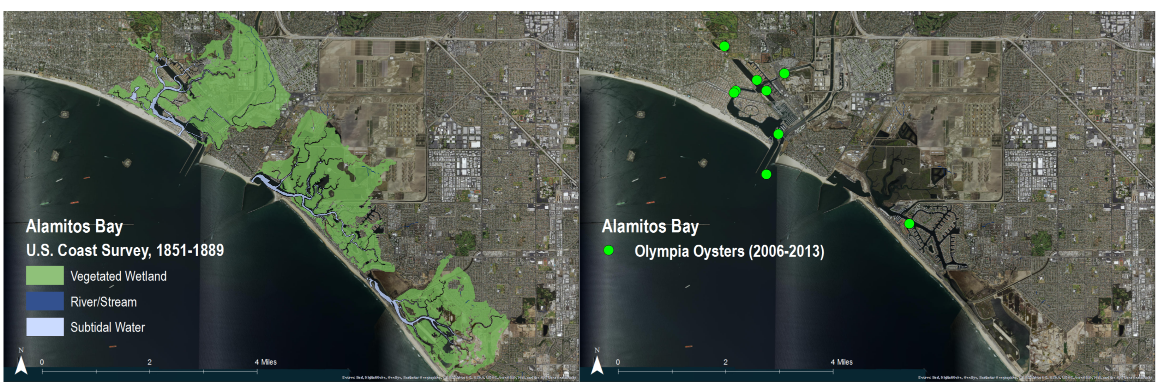

Figure 2. (Left) Historic vegetated wetland, river/stream, and subtidal water habitat in Alamitos Bay from the U.S. Coast Survey, 1851-1889. (Right) Olympia oyster presence points in Alamitos Bay collected by Dr. Danielle Zacherl and Dr. Maria Polson from 2006-2013.

Data Organization and Visualization

Presence data was recorded as coordinates in degrees, minutes, and seconds, converted to decimal degrees using an online conversion website, and loaded into ArcGIS (Figure 1). Valid data points were displayed in the World Geodetic System

1984 coordinate system and uploaded to ArcGIS online to create an interactive Story Map (Figure 2). Habitat, substrate, general location, and notes associated with the presence data were then sorted and also made visible in the Story Map. The map allows the public, restoration scientists, and managers to gain a better understanding of historical and present Olympia oyster populations in Southern California. This publicly viewable information can be updated by approved parties and used to prioritize restoration sites.

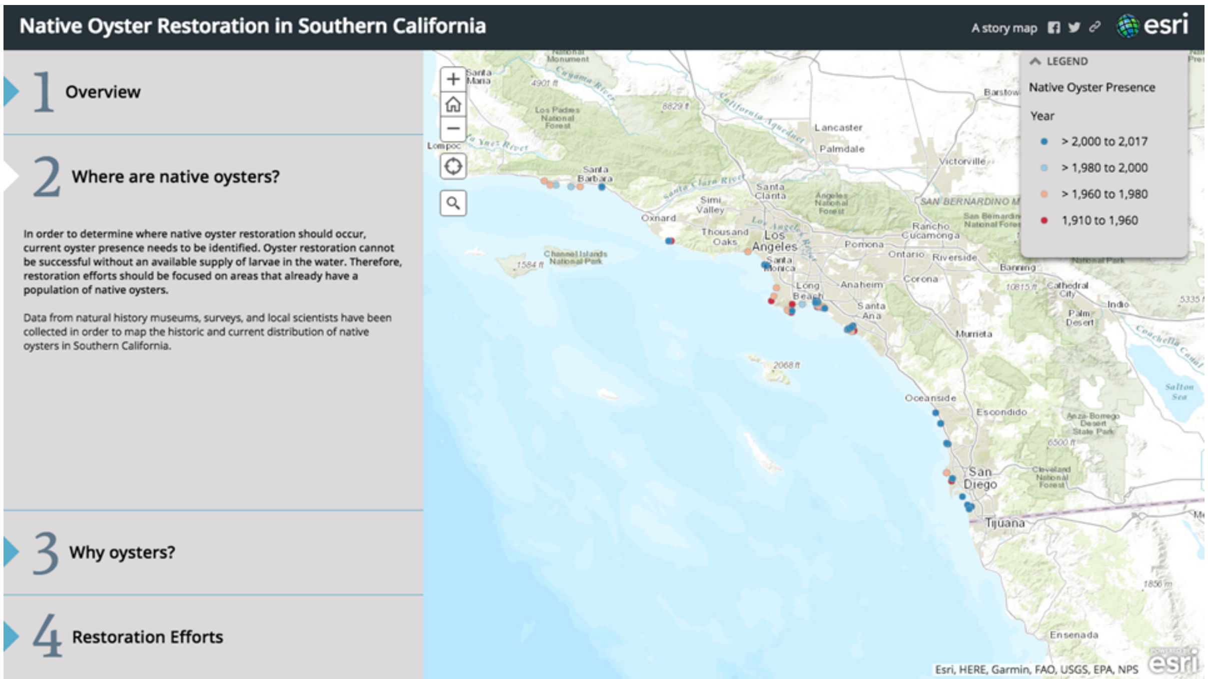

Figure 3. Esri story map of historic and present native oyster presence data collected. These data are available to the public online.

Suitable Habitat Modeling

Due to limitations in time and resources available to restoration managers, comprehensive monitoring of all potential restoration sites is not feasible. A model that incorporates environmental variables and existing oyster presence can highlight areas that should be prioritized. We created a species distribution model through MGET-Marine Geospatial Ecology Tools using habitat characteristics and oyster presence data to identify suitable restoration sites for Olympia oysters in Southern California (Young et al., n.d.).

Data Sources

- Presence and absence data collected by Dr. Danielle Zacherl, Holly Henderson, Emily Read, Colleen Grant, Desmond Ho, Brianna Group, and Erin Winslow between 2010 to 2017
- Eelgrass habitat layer from CA Fish & Wildlife updated 5/31/2016

- Estuary layer from CA Fish & Wildlife updated 3/26/2016
- Predicted Substrate layer from CA Fish & Wildlife updated 2/27/2015
    - Hard, soft, and unknown substrate with associated categorical depths

Data Transformation

A generalized linear model (GLM) from MGET in ArcGIS was used to model Olympia oyster distribution. The model required presence and absence data in vector form and habitat characteristic rasters to create a predictive distribution raster. For habitat characteristics, three layers were used: eelgrass habitat, estuaries, and substrate type. Each layer was converted from vector to raster format to be used in the model. A cell size of 0.001 by 0.001 (x,y) was used to capture the fine polygon features of each layer. All data layers were projected to WGS 1984.

Data Analysis

To begin the analysis, the oyster presence data was split into test and training data sets using the "Randomly Split Table into Training and Test Records" tool in MGET. A random portion of the data was then used to develop the model and the other data was used to test the accuracy of the model. Next, values of the three habitat rasters were assigned to the oyster presence dataset by extracting information underneath the presence points.

We then fit a GLM to the data set using a binomial response variable distribution and "logit" link function. Finally, we used the GLM to create a "predictive grid" over the study area to see which sites along the California coast were most likely to contain Olympia oysters. Site selection was based on the three predictor variables: eelgrass presence, location (estuary or open coastline), and substrate type.

Assumptions

- The presence and absence data used is an accurate representation of current oyster distribution in southern California
- All three habitat layers (2012, 2015, 2016) were from the same time period and experienced the same environmental conditions
- There was habitat variable data for each oyster presence and absence point
- Eelgrass habitat, estuaries, and substrate are the only factors in determining oyster presence

Results and Findings

Scientists identify oyster restoration sites through field surveying on foot or by boat. Application of the MGET model may make restoration site identification more time and cost efficient. The raster layer produced by this model highlighted predicted oyster presence from low to high probability along the coast of Southern California. The amount of deviance explained by the GLM model is only 13.9% indicating the MGET model needs more fine-grain habitat data. Other habitat variables that would improve the quality of this map include: sea surface temperature, pH, dissolved oxygen, elevation, mean lower low water levels, sedimentation rates, and water flow rates.

Conclusion

Coastal development has caused the destruction of over 90% of California's wetlands. The destruction of wetlands has dramatically reduced the amount of suitable habitat for Olympia oysters. It is important to understand the changes across the coastal landscape when planning an oyster restoration project. Similarly, knowledge of oyster distribution is needed to prioritize restoration sites. Small oyster populations remain in most bays and estuaries in Southern California, but no actual reefs have formed. Our analysis created the first centralized oyster distribution database. It is also necessary to analyze environmental conditions of an area before choosing a restoration site. Preliminary information allowed us to gain insight on the environmental conditions of Southern California's embayments. Additional fine-scale data is necessary to more accurately model suitable oyster habitat.

Bio-economic Model

Introduction

Restoring the Olympia oyster may help protect Southern California's remaining lagoons, estuaries, and wetlands. Oysters settle on hard substrate in brackish water environments and over time form biogenic reefs: reefs are formed because larvae prefer to settle on other oyster shells given the choice (Bulesco, 1982). Oyster reefs provide hard, complex structures with varying rugosity forming habitat for fish, mobile crustaceans, and many benthic invertebrates that act as a food source for many larger, commercially important fish (Wells, 1961; Bahr & Lanier, 1981; Peterson et al., 1989; Zimmerman et al., 1989; Lenihan et al., 1998; Breitburg, 1999; Coen et al., 1999; Lenihan et al., 2001). Peterson et al. quantified fish and invertebrate production per unit area of restored oyster reefs for *Crassostrea virginica* on the Atlantic Coast (2003). The Peterson et al. study calculated an index of reef exclusivity for each species studied and quantified the growth enhancement of oyster reefs in comparison to a sandy bottom or mudflat environment. Traditionally on the Atlantic Coast, oysters were largely restored for the value of the oyster fishery. However, recent studies have valued oysters at just under $100,000 per hectare per year of restored reef for ecosystem services (Peterson et al., 2003). In comparison, the value for human consumption over the same hectare is approximately $50,000 (Peterson et al., 2003). Similar to *C. virginica*, Olympia oysters are ecosystem engineers that could provide important habitat for juvenile fish in wetlands and estuaries. Restored reefs may also increase food availability for fish and invertebrates that feed in wetland areas.

In California, limited quantitative data exists to predict the degree to which oyster reefs enhance fish and invertebrate abundance. An increase in invertebrate abundance was quantified on restored Olympia oyster reefs in Newport Bay, but fish abundance and biodiversity were not quantified (Zacherl et al., unpublished data). Fish surveys were conducted both on and off restored oyster reefs in San Rafael, San Francisco Bay, however, there was not enough data to quantify fish enhancement (Stockmann, 2016).

Estuarine fish and invertebrates may benefit from oyster reef restoration in Southern California, however there are no current studies that test this hypothesis. We performed an exploratory analysis modeling the effects one hectare of restored oyster reef may have on two fisheries. Growth limited and recruitment limited fisheries can benefit from oyster reefs through different mechanisms (Peterson et al., 2003). Recruitment limited species depend on hard substrate such as oyster reefs to recruit to in their larval or juvenile phase. Oyster reefs provide an increase in food availability, leading to higher survivorship for growth limited species. We assumed species that recruit to rocky reefs may recruit to native oyster reefs in bays and estuaries. Through an extensive literature review and collaboration with fish experts, we identified two species that may benefit from Olympia oyster restoration: the California halibut and the kelp bass.

California Halibut

The California Halibut, *Paralichthys californicus*, is both a recreationally and commercially important fish in the Southern California Bight. In 2015, the yield from this fishery was valued at $2,226,593, making it the fifth most commercially important fishery behind the sablefish, swordfish, bigeye tuna, and chinook salmon (CADFW, 2015). The California halibut fishery has fluctuated in revenue over the last few decades, but in recent years it has steadily declined (Appendix B, Figures 2 and 3). Furthermore, California halibut fishery revenue from Los Angeles is quickly approaching zero (Appendix B, Figure 1). This decline may be associated with the impacts of coastal development in Southern California, resulting in the disappearance of important shallow water habitat (Kramer & Sunada, 1992).

Adult California halibut live in sandy bottom habitats, while juveniles are often found in estuaries and embayments (Allen, et al., 2006). Juvenile California halibut consume small fish and invertebrates, which have been shown to increase by over 300% on oyster reefs in comparison to sandy bottom habitats (Haugen, 1990; Boyer et al., 2013; Zacherl et al., unpublished data). California halibut are growth limited; juveniles do not require hard substrate to settle, but feed on organisms that live in reef like structures (Emmett et al., 1991; Love et al., 1996; Wertz & Domier, 1997).

Model Description

Using a stable-age structured model, we projected growth for California halibut with and without Olympia oyster restoration. We averaged the increased abundance of food sources on oyster reefs and rocky artificial reefs in comparison to sandy bottoms and found a 323% increase (Johnson et al., 1994; Zacherl et al., unpublished data). Assuming a 10% trophic transfer to the fish, we calculated an increase in the growth coefficient K, by 32.3%. We adjusted K from a value of 0.08 to 0.10584 in the von Bertalanffy equation used in our model accordingly (Appendix A, Table 1, 2, and 3).

Assuming an open fisheries model, we followed one individual cohort of 2,200 young of the year (YOY) California halibut over the course of 30 years. This cohort of 2,200 per hectare of restored oyster reef was based on an ecologically similar species, the Southern flounder, which was modelled with oyster restoration on the Atlantic Coast (Lenihan et al., 2001). We used matrix modeling to run 1000 iterations per gender for two scenarios of this model. This model assumed that increased food on oyster reefs leads to increased growth and survival of juvenile halibut.

California halibut have a 4.3:1 female to male sex ratio in Southern California and grow at different rates (Sunada et al., 1990). Using this ratio, 1,785 females and 415 males were modeled separately in each scenario. The sandy bottom habitat scenario used the standard K value of 0.08 for both sexes, and the restored oyster reef scenario used the adjusted K value of 0.10584. These scenarios were run for 30 years based on research conducted by Peterson et al. (2003).

Juvenile California halibut have a higher mortality rate than adults in a normal sandy bottom habitat. Under the CDFW fishery model, juvenile halibut grow large enough to reach adult mortality after reaching age 1 (Hobbs, Botsford, & Kope,1990). We assumed that on an oyster reef, juveniles grow faster due to the added food source and reach adulthood sooner. In this scenario, adult mortality was applied at an earlier life stage, year zero instead of year one.

Similarly, the fishing mortality rate was applied at a younger age in the restored oyster scenario. As a result, the fish were larger and fishable at an earlier age (Appendix B, Figure 5). The increase in fishery value was determined by using a discount rate of 4% and multiplying the biomass of added catch by the value per pound from 2015 in 2016 dollar value. The value of the fishery could increase by $24,411 per hectare per cohort of California halibut. This model only follows one cohort through time, thus the annual increase in value is variable and based on the age of the fish, the size of cohort, and fishing pressure (Appendix B, Figure 6). The fishery would reach its peak value in year 5 under the oyster restoration scenario and declines steadily until year 19 (Appendix B, Figure 5).

Kelp Bass

The kelp bass, *Paralabrax clathratus*, is one of the most important recreational fisheries in the Southern California Bight (CADFW, 2015). Kelp bass generally live at depths that range from 2-25m (Feder et al., 1974), though they become more pelagic as they age to maturity (Love, 2011). Kelp bass often associate with areas of hard substrate (Love et al., 1996, Bond et al., 1999), and juveniles are commonly found in estuarine and wetland areas (Allen et al., 2006). As a result, we identified the kelp bass as a recruitment limited species for this model.

Model Description

We assumed that restoration of oyster reefs increase suitable habitat for kelp bass to recruit (Anderson et al., 1989). We calculated that 740 YOY kelp bass would recruit to one hectare of restored oyster reef from a study conducted by Anderson et al., 1989. Since kelp bass require hard substrate to settle, we assumed zero recruitment to sandy bottom habitats.

The same growth parameters were used for both male and female kelp bass since they do not have sex-specific growth (Appendix A, Table 2). The total length at different ages was used to determine when kelp bass were large enough to be fished. We determined they are fishable starting at age 5, using the legal 14-inch size of harvestable kelp bass. From ages one to four, only natural mortality was applied in the model, after which both natural mortality and fishing mortality were incorporated (Appendix B, Tables 1 and 4). Total length was converted to age using the von Bertalanffy equation (Appendix B, Table 1). We assumed an open fishery model for kelp bass and ignored local recruitment.

Matrix modeling was used to run the oyster restoration simulation over a 30 year period. Each year we assumed a random influx of YOY kelp bass, ranging in value from 1 to 740. The simulation was run 1000 times and used to quantify the average increase in kelp bass fished per year (Appendix B, Figure 7). We converted this to biomass and determined that over the entire 30-year period, the total possible increase in fished biomass produced as a result of one hectare of restored oyster reef is 39,304 +/- 4549 grams.

Conclusion

Restoring oyster reefs increase taxonomic richness and the abundance of certain fishes that are limited by recruitment or growth. These complex living structures provide both nursery and foraging habitat to many important species. Data quantifying the effects of native oyster reefs on Pacific Coast aquatic communities is limited, but preliminary studies show increases in small invertebrates (Danielle et al., unpublished data). However, some invertebrates, such as polychaete worms, decreased on Olympia reefs in Newport Bay. Polycheates may not be the only species negatively affected by restored Olympia reefs, and further studies are needed to understand these relationships.

Both California halibut and kelp bass could benefit from native oyster restoration. The California halibut has experienced a significant decline throughout California in landings, particularly in Southern California. While data is unavailable for past trends in kelp bass abundance, anecdotal evidence suggests that this species comprises a significant portion of recreational catch in Southern California. Oysters provide important intertidal and subtidal habitat in bays and estuaries that can assist these species in overcoming life history bottlenecks and survive into adulthood. Through this population model, the expected increases in both California halibut and kelp bass were quantified to incentivize the inclusion of native oyster restoration in future management actions. These values are most likely underrepresented because we were unable to include local recruitment, reproduction, and production of additional fish and invertebrates that serve as a food source to important fish species.

Further research and experimentation is needed to better understand how the restoration of oyster reefs may impact our local fisheries. While we hypothesize that many fish and invertebrates would benefit from such restoration, some species may experience negative effects. Based on the many services provided by Olympia oysters as an ecosystem engineer, restoration of this animal could positively impact the health of California's coastlines and the many species that inhabit these critically important areas.

Cost Benefit Analysis

Introduction

Shoreline erosion is a persistent problem throughout Southern California's coastal communities. The coastline is almost entirely developed, and as a result, there has been a significant decrease in the natural wetlands and estuaries that once protected these areas from the impacts of wave action. Consequently, sand and sediment are constantly washed away, exposing homes and other coastal infrastructure to the open ocean. Erosion rates of shorelines increase with sea level rise, which is projected to increase over the next decade (Climate Central, nd). There is uncertainty regarding the extent of sea level rise in California, but it is expected to reach 11 inches by 2050, with high chances for a 100-year flood occurring before 2030 (Climate Central, nd). Thus, at least once before 2030, property damage due to storm surge is likely to take place in these coastal communities.

A long-term, natural solution to this problem is restoring Olympia oyster reefs in remaining wetlands and estuaries. Wave action is dissipated by the hard structure oyster reefs provide, minimizing erosion effects in that area. In addition, oyster reefs have been shown to accumulate some amount of sediment (SF Bay Living Shorelines Project). Large-scale restoration of Olympia oyster reefs could replace current forms of shoreline stabilization that are costly and environmentally damaging. Stabilization methods include beach nourishment, dredging, and rock revetment. We analyzed two sites to determine how Olympia oyster reefs might act as a cost-effective means for shoreline stabilization: the Batiquitos Lagoon, San Diego County, and the Carpinteria Salt Marsh Reserve, Santa Barbara County (Figures 3 and 4, respectively). The study sites were chosen based on their location, the stabilization methods currently used, and known costs at each site. Both sites are located in affluent areas with expensive coastal properties, which enabled us to maintain equal property assessment among sites. In addition, we assumed the cities where each site is located are more likely to continue to spend money on necessary shoreline armoring. Understanding how the costs and benefits compare between the Batiquitos Lagoon and Carpinteria Salt Marsh Reserve could offer an economic incentive for local entities to utilize Olympia oysters as a means of shoreline stabilization, instead of common, temporary solutions.

Figure 4. Restoration proposal for Batiquitos Lagoon, San Diego County, California; restoration site located at the mouth of Batiquitos Lagoon. Yellow lines indicate restoration sites. Map data ©2015 Google.

Figure 5. Restoration proposal for the Carpinteria Salt Marsh Reserve, Santa Barbara County, California; restoration site located at the mouth of the Carpinteria Salt Marsh Reserve. Yellow lines indicate restoration sites. Map data 2015 Google ©2015 Google.

Assumptions

1. Olympia oysters are biogenic reef forming invertebrates. The reef forming capability of oysters is what makes them an alternative to rock revetment or beach nourishment.
2. Oyster reefs grow faster than sea level rise is occurring (Grabowski et al., 2012).
3. There is enough oyster larvae naturally occurring in the water column to settle on substrate and survive to sustain the reef.
4. Selected restoration sites have suitable oyster habitat.
5. Value of property protection or damage per acre is constant among sites.

Our study covered a 30-year time frame spanning from 2017-2046 and used a discount rate of 4%. Additionally, the net present value (NPV) of costs and benefits for each site ignored the time cost of planning and consulting with relevant agencies for restoration. All values used were adjusted with inflation to the value of a US dollar in 2016. Below are the site-specific costs and benefits used in this study. It is important to note that oyster restoration cannot occur in open-water areas due to the habitat limitations of oysters. Olympia oyster restoration would take place in estuaries and wetlands, and could assist in absorbing storm surge as well as stabilizing sediment.

Methods: Batiquitos Lagoon
Batiquitos Lagoon is located in San Diego County close to the southernmost limit of our project area. Dredging and beach nourishment occur on an as needed basis (usually annually) and the costs are publicly available. There is some shoreline armoring in the form of rock revetment at this site. Batiquitos Lagoon was used as a comparison because of its known costs and use of stabilization methods similar to those in the Carpinteria Salt Marsh. Our analysis calculated the NPV of the costs and benefits for Batiquitos Lagoon in two scenarios: with Olympia oyster reef restoration and without restoration.

Benefits
Without restoration, the benefits included at Batiquitos Lagoon were flood control, water quality, wildlife habitat, and recreation. These benefits were taken from a California Sea Grant study conducted by Rager, Clifton, & Johnson (1995). In addition, Batiquitos Lagoon provides essential habitat for migratory waterfowl, birds, and fish species (Batiquitos Lagoon Foundation, 2017). Wetlands absorb wave energy and reduce the velocity of incoming surges. As a result, these living shorelines provide flood control to coastlines and property owners (Rager et al., 1995). The US Army Corps of Engineers valued flood control provided by

California's wetlands at $4,650 per acre (Allen, 1992). This value represents the amount of damages avoided with an intact wetland present. Wetlands also filter and treat water by removing nutrients, bacteria, and toxic chemicals. This water quality improvement by wetlands is valued at $6,600 per acre (Rager et al., 1995). Similarly wetlands provide important nursery and foraging habitat to fish and invertebrates. From a survey that assessed people's willingness to pay to preserve a California wetland, this benefit is valued at $3,337/acre for Batiquitos Lagoon (Allen, 1992). Finally, wetland ecosystems provide a recreational value to people through activities such as bird watching, hiking, and fishing. Stol et al. valued this recreational benefit at $3,347 per acre through a travel cost method in Batiquitos Lagoon (Allen, 1992). The annual dredging and beach nourishment that occur at this site maintains these benefits the wetland in Batiquitos Lagoon provides.

In the second scenario with restoration, our analysis examined the area of wetland habitat that would be protected by Olympia oyster reef restoration. Oyster reefs would protect this essential wetland habitat and therefore, maintain the benefits of the wetland (flood control, water quality, wildlife habitat, and recreation) without the need to dredge and nourish the beaches annually. We assumed this benefit is included in the analysis by reducing lagoon dredging and beach nourishment from annually to once every five years and is accounted for in the costs. Multiple groups would gain from these benefits including homeowners, the City of Carlsbad, recreational users of the lagoon and its wetlands, and the environment including wildlife that utilize the Lagoon and restored reefs as habitat. In both scenarios, the benefits of the wetland habitat are maintained, however, the costs to maintain that wetland habitat are different due to the two methods of shoreline stabilization.

Costs of Oyster Restoration

The oyster restoration costs taken into account at Batiquitos Lagoon included shell addition, initial construction, permitting, and periodic lagoon dredging and beach nourishment (Harrison et al., 2015). The costs of shell addition were taken from the San Diego Bay Native Oyster Restoration Plan (Harrison et al., 2015). We initially used both low and high cost estimates for shell addition (Harrison et al., 2015), but to remain conservative in our estimates of benefits relative to costs, we used the high-end estimates for our final analysis. Shell addition costs occurred twice at Batiquitos Lagoon due to the high sedimentation rates at this site. The costs of permitting were calculated using the proposed area for restoration of 0.2 hectares. Permitting prices calculated were taken from the California Department of Fish and Wildlife Mitigated Negative Impact Permit as well as the Coastal Development Permits from the California Coastal Commission. Lagoon dredging and beach nourishment would need to continue on an annual basis until the restored reefs become self-sustaining. There is uncertainty as to how long it would take for oyster reefs to become self-sustaining. A self-sustaining oyster reef no longer needs human maintenance to survive and grow. Therefore, three restoration analyses were conducted where it takes 5 years, 10 years, or 15 years for the reefs to become self-sustaining. During this time, beach nourishment and dredging take place on an annual basis. After the reefs become self-sustaining, we assumed that dredging and beach nourishment would only need to occur every five years. Groups that would incur the costs include groups funding the restoration such as the California State Coastal Conservancy, Batiquitos Lagoon Foundation (restoration, dredging, beach nourishment), and the City of Carlsbad.

Costs Without Restoration

Dredging and beach nourishment would continue to occur on an annual basis without oyster restoration. However, at the current spending rates, the Batiquitos Lagoon's dredging fund is expected to run out in 30 years (Sisson, 2016). Historic dredging costs have ranged from $256,000-$1,300,000 per year (Sisson, 2016). We included the low estimated dredging cost and the exhaustion of this fund in the analysis. Without restoration, the Batiquitos Lagoon Foundation would cover the costs of the dredging and beach nourishment annually until funding was exhausted. In addition, homeowners, wildlife, and recreational users of the lagoon would incur costs if the quality of the lagoon decreased over time without restoration.

Results and Implications

Without oyster restoration, the NPV of the net costs (costs minus benefits) is about $1 million more expensive than the most expensive oyster restoration scenario (15 years till self-sustaining) (Table 1). This indicates that lagoon dredging without restoration is the most costly option for the Lagoon foundation. If oyster restoration took place, savings to the lagoon over the next 30 years could alleviate dredging costs by $1-2 million. Although the costs outweigh the benefits in all scenarios, the costs associated with oyster restoration are much less than without restoration. These results also suggest that oyster restoration poses a possibility of alleviating the costs associated with annual dredging in other Southern California embayments.

Scenario	NPV Costs	NPV Benefits	Net Costs	Savings
5 years self sustaining	$835,822		$368,986	$1,815,779
10 years self sustaining	$1,199,413	$466,836	$732,577	$2,112,188
15 years self sustaining	$1,653,903		$1,187,067	$997,698
No restoration	$2,636,039	$451,274	$2,184,765	$0

Table 1. Net present value (NPV) of the costs and benefits for Batiquitos lagoon without restoration as well as 5, 10, and 15 years until oyster reefs become self-sustaining with restoration.

Methods: Carpinteria Salt Marsh

The Carpinteria Salt Marsh Reserve is close to the northern limits of our study area and our client, Dr. Andrew Brooks, is the Director of the reserve. The Carpinteria Salt Marsh utilizes dredging and rock revetment, though dredging occurs infrequently. The costs of rock revetment are unknown due to permitting and legal issues (Andrew Brooks, Personal Communication, November, 2016). We used available benefit and cost data to calculate the NPV of the costs and benefits associated with oyster restoration at this site. There is a private road adjacent to the marsh that could collapse if the rock revetment fails to protect against shoreline erosion. Two scenarios were analyzed; one where the private road adjacent to private property in the marsh withstands wave action, and one where it does not and needs to be rebuilt.

Benefits

Benefits included in Carpinteria were property values, potential road replacement costs, and water quality improvement. Cost estimates of property damage from storm surge were taken from Barbier et al. (2013) that provided an economic valuation for the protection in property loss associated with wetland restoration during storm surge events. The valuation was conducted in the New Orleans region where mean residential property value is approximately $170,000. The property values in Carpinteria are an order of magnitude higher, and range in value from $1 million - $26.5 million (Zillow, 2016). Due to these high property values, we used the study's high estimates for property protection. The avoided storm surge damages to the private coastal properties at this site as a result of oyster restoration were calculated as a benefit to this location. In addition, a road leading to the western properties could potentially collapse into the salt marsh with continued shoreline erosion (Elswick, 2016). We evaluated two scenarios: the road collapsing and the road not collapsing. Finally, water quality improvement values were taken from Grabowski et al and valued at $1,385 per hectare of restored oyster reef (2012). Groups that would gain from these benefits include homeowners, the City of Carpinteria, the Carpinteria Salt Marsh Reserve, recreational users of the reserve, and the environment including wildlife that utilize the salt marsh and the restored reefs.

Costs

Similar to Batiquitos Lagoon, costs at the marsh would include restoration costs, permitting costs, and hard armoring maintenance costs. However, due to restrictions on access to these values, costs for Carpinteria were not calculated. Groups funding the restoration project would cover costs for restoration. Homeowners, recreational users of the Carpinteria Salt Marsh, and wildlife would incur the costs if restoration did not take place, leading to road collapse or deterioration of the marsh. To calculate a conservative estimate of costs and benefits, these scenarios assumed that it would be 15 years until oyster reefs became self-sustaining and included one-time shell addition and permitting costs.

Results and Implications

Olympia oyster restoration may protect expensive coastal homes and surrounding infrastructure. Our analysis indicates that the estimated benefits of Olympia oyster restoration in the Carpinteria Salt Marsh is higher than the costs (Table 2). However, the costs of existing shoreline stabilization methods are not known for this area, because the local Homeowner's Association pays for the maintenance (Andy Brooks, personal communication, November, 2016). Based on the savings estimated in the Batiquitos Lagoon cost benefit analysis, it is possible that investing in Olympia oyster restoration could alleviate costs currently incurred by homeowners to maintain this hard armoring. Additionally, oyster restoration in the salt marsh could provide additional benefits such as increased habitat and food for important fish, invertebrates, and waterfowl species that live in the reserve. Further research would need to include the amount paid by the Homeowners' Association to maintain the rock revetment to determine if restoration is a more cost-effective method and to also quantify these other benefits.

Scenario	NPV Costs	NPV Benefits	Net Benefits
No Road Collapse	$18,983	$140,999	$122,016
Road Collapse		$228,297	$209,314

Table 2. Net present value (NPV) of benefits and present value of cost per year for Carpinteria Salt Marsh. Present value of benefits is for 50 years total years of restoration.

Conclusion

Olympia oyster restoration provides an opportunity to alleviate the costs associated with dredging, rock revetment, and other shoreline stabilization methods. In all three Batiquitos Lagoon restoration scenarios, the restoration costs are less than the current shoreline stabilization methods by $1 to $2 million. It is important to note that the high-end costs of restoration as well as the low-end costs of lagoon dredging were used to ensure that this is a conservative estimate. It is possible that oyster restoration could reduce the maintenance costs of the Batiquitos Lagoon for the Lagoon Foundation.

Additionally, the results of the Batiquitos Lagoon analysis can be used to determine if Olympia oyster restoration could be a cost-effective means of shoreline stabilization in the Carpinteria Salt Marsh Reserve. Currently, studies in San Francisco Bay, San Diego Bay, and Newport Bay are quantifying the potential for Olympia oyster reefs to stabilize shorelines. Further studies are needed to assess the feasibility of applying these results to other specific sites in Southern California.

Fostering Oyster Restoration in Southern California

Past and Present Projects

Early Olympia oyster restoration projects focused primarily on substrate addition to address the low densities of oysters in these areas. However, other factors may be limiting oyster growth and survival at these sites. Oyster restoration projects were completed at Mugu Lagoon, Alamitos Bay, and Newport Bay.

The largest project under development in Southern California is the San Diego Native Oyster Restoration Project, which will take place in San Diego Bay. Construction is estimated to begin in 2018, and pre-monitoring and site evaluations are already occurring. The San Diego project not only addresses the lack of suitable substrate in the area, but also explores the shoreline stabilization capability of Olympia oysters. A series of reef designs are being constructed in various places throughout the southern portion of the bay. Each reef element is trapezoidal in shape and consists of pilings of oyster shells. The lead researchers and consultants of this project will be able to analyze how successfully these reef elements prevent erosion from wave energy (San Diego Native Oyster Restoration Plan, 2015). The results could bolster our cost benefit analysis, by providing concrete evidence that Olympia oysters have the ability to stabilize our shorelines in Southern California.

Community Involvement

Large restoration projects such as the San Diego Native Oyster Restoration Project are typically expensive and labor intensive, and often must seek additional funding. One method of obtaining additional funding is to incorporate an element of community engagement and education into a restoration plan. Many funding agencies will not consider providing financial support for restoration projects unless this criterion is met. This type of strategy is utilized across the country for many different types of restoration projects. Additionally, community participants feel more connected to their environment and more invested in the overall future wellbeing of the coastal communities around them. Volunteers also are more likely to participate in this type of project in the future.

Strategic Communication Plan

Oyster restoration projects can benefit from local community involvement. By speaking with community members and showcasing the importance of this work, we can increase public involvement through volunteer programs. Volunteers improve their connection with the environment and the Olympia oyster through assisting in restoration. Volunteer activities include assisting with field work, outreach, and restoration coordination. We have produced videos to inform target audiences of ongoing oyster restoration projects and the benefits they can bring to Southern California coastal ecosystems.

PSA Video (2-3 min)
Audience: Coastal communities near Orange County, CA

Purpose: The oyster restoration efforts of Orange County Coastkeeper are dependent upon the participation community volunteers. We created a public service announcement to bring awareness to the ongoing restoration projects and encourage local involvement. The video incorporates footage from previous restoration projects and features a call to action by Katie Nichols, the OC Coastkeeper Marine Restoration Coordinator.

Oyster Restoration Short Documentary (5-10 min)
Audience: Coastal communities of Southern California

Purpose: A documentary was produced to explain how oyster restoration can be used as a natural way to mitigate the effects of development and climate change in coastal ecosystems. A graduate student, reserve director, and a restoration coordinator were showcased in the documentary to describe the ecosystem services provided by the Olympia oyster.

Native Oyster Restoration Forum
The success of oyster restoration is dependent upon collaboration between members of the oyster restoration community to streamline restoration efforts. Our group organized and co-hosted an Oyster Restoration Forum on March 16 & 17, 2017 with the Aquarium of the Pacific. This forum was sponsored by the Honda Marine Science Foundation, which launched February 2017 by the American Honda Motor Co., Inc. It is crucial to share best practices to overcome barriers to successful large scale Olympia oyster restoration. The overall goal of this forum was to develop a dialogue between oyster researchers and restoration managers. The forum participants included various agencies and institutions. These participants included:

- Bren School of Environmental Science & Management
- Honda Marine Science Foundation
- Aquarium of the Pacific
- University of California, Santa Barbara Marine Science Institute
- Carpinteria Salt Marsh Reserve
- The Nature Conservancy Global Marine Team
- California State Coastal Conservancy
- New York Harbor Foundation

- Billion Oyster Project
- Wild Oyster Project
- University of California, Davis – Romberg Tiburon Center
- California Coastal Commission
- Orange County Coast Keeper
- National Oceanic and Atmospheric Administration Restoration Center
- Seafood for the Future
- Elkhorn Slough National Estuarine Research Reserve
- University of California, Santa Cruz
- Smithsonian Environmental Research Center
- NOAA Fisheries West Coast Regional Aquaculture for California
- California State University, Fullerton

Our forum focused on the following objective questions:

1. Under what environmental and societal conditions is oyster restoration an effective strategy for ecosystem restoration?
2. Where are these conditions found in Southern California?
3. What are the appropriate incentives to trigger and sustain oyster restoration efforts in selected sites in southern California?
4. What are the key metrics for measuring success?

Public Presentation

Our group presented at the Aquarium of the Pacific Lecture event on the evening of March 16th .The public presentation was designed to inform the public of the history and significance of the Olympia oyster, and the incentives for restoring this species to Southern California. This presentation was streamed live on the Aquarium of the Pacific's website to reach a broader audience. We received valuable feedback from audience members regarding our research that we were able to incorporate in later presentations and this report. The link to this presentation is below.

http://www.aquariumofpacific.org/events/archive/planning_and_incentivizing_native_olympia_oyster_restoration_in_southern_ca

Forum Conclusions

Attendees of the forum concluded that the bottlenecks affecting Southern California's oyster populations differ from those in Central and Northern California, and are site specific. Recent research indicates there is a high abundance of larvae in the water column in Southern California. Most Olympia oyster restoration projects have addressed the lack of suitable substrate for settlement and oyster reef formation, however, other factors may exist that affect oyster growth and survival in

Southern California. Examples include poor water quality affecting survival, a lack of adult oysters for reproduction, and low recruitment of adult oysters. Additional research is needed to further explore these factors and their impacts on Olympia oysters at each specific site. Forum attendees also pinpointed potential sites for future restoration projects and discussed key traits of specific sites. The discussion incorporated present and past Olympia oyster restoration projects and their findings. Similarly, successful oyster restoration projects from the Atlantic Coast were discussed to apply the findings of these studies to the Olympia oyster. Participants also expressed the need to establish a set of standardized restoration monitoring protocols that could be adjusted for each location. Further monitoring and research is needed to identify the restoration bottlenecks at each site so that we can determine potential sites and best practices for future Olympia oyster restoration projects.

Participants also identified key incentives for restoring Olympia oysters throughout California. “Sato Umi” was an overarching theme throughout the forum; Sato meaning “the place where people live” and Umi, meaning, “where the sea is”. People living by the sea have a holistic obligation to protect the health of coastal ecosystems because their lives and homes depend upon it. Olympia oyster restoration embodies “Sato Umi” because it reconnects communities with their natural environment through education and community involvement. Volunteers develop a more conscious relationship with coastal ecosystems by participating in the restoration of their local coastline. Forum participants agreed that other incentives of Olympia oyster restoration include shoreline resilience to climate change, carbon sequestration in the form of blue carbon, increased habitat and food for fish and invertebrates, supportive interactions between oysters and other important or endangered species, improved water quality, and the possibility for an aquaculture-restoration partnership. Ecological and economic incentives support engineering healthier coastal ecosystems by restoring Olympia oysters. The link to the forum report is listed below.

http://www.aquariumofpacific.org/mcri/category/forums

Next Steps: “BC to Baja”

Forum participants agreed that a significant disconnect exists between oyster researchers, restoration managers, NGOs, and other stakeholders. Discussion and brainstorming led to the creation of an Olympia oyster restoration initiative. The overall goal of BC to Baja is to increase and motivate large-scale restoration efforts for the native Olympia oyster throughout its entire geographic range, British Columbia to Baja California. This initiative will develop a centralized location for restoration stakeholders to share data, ideas, and best practices. Centralizing this information replaces small, individual projects with large scale, collaborative restoration of the Olympia oyster along the entire western coast of North America. Our first step in establishing this initiative is to gauge interest and conduct an audience analysis to determine the most effective framework. BC to Baja will provide a platform for collaboration and information sharing that may significantly impact the success of future Olympia oyster restoration projects.

Project Summary

Olympia oyster restoration executed at a large scale in Southern California is a realistic objective. Our project gathered and compiled historic and present spatial data of Olympia oysters throughout Southern California to develop a better understanding of environmental bottlenecks preventing their survival. In addition, we utilized historical maps of estuaries and wetlands from the 1880's in order to visualize how oyster habitat has changed in the last century. We constructed maps to showcase potential restoration sites for future management plans.

We conducted an economic valuation of restored oyster reefs through a bioeconomic fish model and a cost-benefit analysis. Oyster reefs have the ability to host and provide food for many economically valuable fish species such as the California halibut and the kelp bass. Restored reefs may provide higher quality habitat and food for these species and thus, generate a greater economic value for the fisheries. Reefs may also have the ability to slow erosion rates because oysters in high densities can absorb wave energy and retain sediment.

Ongoing restoration projects in Southern California aim to address information gaps regarding Olympia oyster reefs and their ability to provide ecosystem services. With additional publicity and outreach, these projects can increase local community involvement so that people develop a stronger relationship with their coastal ecosystems. We have contributed to this communication process by generating videos to recruit volunteers in coastal communities.

To stimulate collaboration between restoration scientists, managers, and NGOs, organized an Oyster Restoration Forum. The forum sparked an Olympia oyster initiative to motivate restoration from British Columbia, to Baja, California. Through the results of this project and the collaboration of these stakeholders, we hope to incentivize future Olympia oyster restoration projects that restore these important ecosystem services to both people and wildlife in California's coastal communities.

References

Allen, L. G., Pondella, D. J., & Horn, M. H. (2006). *The ecology of marine fishes: California and adjacent waters*. Univ of California Press.

Anderson, T. W., DeMartini, E. E., & Roberts, D. A. (1989). The relationship between habitat structure, body size and distribution of fishes at a temperate artificial reef. *Bulletin of Marine Science*, *44*: 681-697.

Bahr, L. M., & Lanier, W. P. (1981). *The ecology of intertidal oyster reefs of the South Atlantic coast: a community profile* (No. 81/15). US Fish and Wildlife Service.

Baker, P. (1995). Review of ecology and fishery of the Olympia oyster, Ostrea lurida with annotated bibliography. *Journal of Shellfish Research*, *14*: 501-518.

Batiquitos Lagoon Foundation. (2017). The Batiquitos Foundation. *Batiquitos Lagoon Foundation*. Retrieved from http://www.batiquitosfoundation.org/foundation/

Barbier, E. B., Georgiou, I. Y., Enchelmeyer, B., & Reed, D. J. (2013). The value of wetlands in protecting southeast Louisiana from hurricane storm surges. *PloS one*, *8*(3), e58715.

Beck, M. W., Brumbaugh, R. D., Airoldi, L., Carranza, A., Coen, L. D., Crawford, C., ... & Lenihan, H. S. (2011). Oyster reefs at risk and recommendations for conservation, restoration, and management. *Bioscience*, *61*: 107-116.

Bond, A. B., Stephens, J. S., Pondella, D. J., Allen, J. M., & Helvey, M. (1999). A method for estimating marine habitat values based on fish guilds, with comparisons between sites in the Southern California Bight. *Bulletin of Marine Science*, *64*: 219-242.

Bonnot, P. (1938). Report on the California oyster industry for 1937. *Calif. Fish Game*, *24*: 191-195.

Bonnot, P. (1935). The California oyster industry. *California Fish and Game*, *21*: 65-80.

Botsford, L. W., Hobbs, R. C., & Kope, R. G. (1989). Bioeconomic evaluation of the culture/stocking concept for white seabass and California halibut: models and computer programs. Final Report. *OREHAP Project. Calif. Dept. Fish and Game. Mimeo*.

Breitburg, D. L. (1999). Are three-dimensional structure and healthy oyster populations the keys to an ecologically interesting and important fish community. *Oyster reef habitat restoration: a synopsis and synthesis of approaches. Virginia Institute of Marine Science Press, Gloucester Point, Virginia*, 239-250.

Bulseco, A. (1982). A synopsis of the Olympia Oyster (Ostrea lurida). *Aquaculture*, *262*: 63-72.

Burrell, V. G. (1986). Species profiles: Life histories and environmental requirements of coastal fishes and invertebrates (South Atlantic): American oyster.

California Department of Fish and Wildlife. (2003). 11. Sea Basses. *Annual Status of the Fisheries Report.*

Cheng, B. S., Bible, J. M., Chang, A. L., Ferner, M. C., Wasson, K., Zabin, C. J., ... & Grosholz, E. D. (2015). Testing local and global stressor impacts on a coastal foundation species using an ecologically realistic framework. *Global change biology*, *21*: 2488-2499.

Climate Central. *Facts and Findings: Sea level rise and storm surge threats for California*. nd.

Coast: a postmodern experience. Really Big Press.

Coe, W. R. (1931). Spermatogenesis in the California oyster (Ostrea lurida). *The Biological Bulletin*, *61*: 309-315.

Coen, L. D., Luckenbach, M. W., & Breitburg, D. L. (1999). The role of oyster reefs as essential fish habitat: a review of current knowledge and some new perspectives. In *American Fisheries Society Symposium*, 22: 438-454.

Davidson, George. Voyages of Discovery and Exploration on the Northwest Coast of America from 1539 to 1603. US Government Printing Office, 1887.

Economics, N. (2009). Valuation of ecosystem services from shellfish restoration, enhancement and management: a review of the literature. *Prepared for Pacific Shellfish Institute*.

Ells, K., & Murray, A. B. (2012). Long-term, non-local coastline responses to local shoreline stabilization. *Geophysical Research Letters*, *39*.

Emmett, R. L., Stone, S. L., Hinton, S. A., & Monaco, M. E. (1991). *Distribution and abundance of fishes and invertebrates in west coast estuaries. Volume II: Species life history summaries*. NOAA.

Feder, H. M., Turner, C. H., & Limbaugh, C. (1974). *Observations on fishes associated with kelp beds in southern California*. State of California, Resources Agency of California, Department of Fish and Game.

Froese, R., Palomares, M. L. D., & Pauly, D. (2007). Estimation of life history key facts of fishes. *FishBase World Wide Web electronic publication version (02/2007)[available on internet at www. fish base. Org]*.

Froese, R., & Pauly, D. (2012). FishBase.

Gilbert, C. H. (1889). Report on certain investigations regarding the planting of oysters in southern California: Alamitos Bay and Newport Bay, California. *US Fish Comm. Bull*, *9*: 95-97.

Gillespie, G. E. (2009). Status of the Olympia oyster, Ostrea lurida Carpenter 1864, in British Columbia, Canada. *Journal of Shellfish Research*, *28*: 59-68.

Grabowski, J. H., Brumbaugh, R. D., Conrad, R. F., Keeler, A. G., Opaluch, J. J., Peterson, C. H., ... & Smyth, A. R. (2012). Economic valuation of ecosystem services provided by oyster reefs. *BioScience*, *62*: 900-909.

Haaker, P. L. (1975). The biology of the California halibut, Paralichthys californicus (Ayres) in Anaheim Bay. *Lane & CW Hill (eds.). The marine resources of Anaheim Bay. Calif. Depart. Fish Game. Fish Bull*, *165*, 137-151.

Hall, M. J., & Pilkey, O. H. (1991). Effects of hard stabilization on dry beach width for New Jersey. *Journal of Coastal Research*, 771-785.

Harrison, H., Garrity, N., & Zacherl, D. (2015). San Diego Bay Native Oyster Restoration Plan.

Harding, J. M., & Mann, R. (1999). Fish species richness in relation to restored oyster reefs, Piankatank River, Virginia. *Bulletin of Marine Science*, *65*: 289-299.

Haugen, C. W. (Ed.). (1990). *The California Halibut, Paralichthys Californicus, Resources and Fisheries*. State of California, Resources Agency, Department of Fish and Game.

Hobbs, R. C., Botsford, L., & Kope, R. G. (1990). Bioeconomic evaluation of the culture/stocking concept for California halibut. *Fish Bulletin (California Department of Fish and Game)*, *174*, 417-449.

Hopkins, A. E. (1937). *Experimental Observations on Spawning: Larval Development, and Setting in the Olympia Oyster Ostrea Lurida*. US Government Printing Office.

Jackson, J.B.C., Kirby, M.X., Berger, W.H., Bjorndal, K.A., Botsford, L.W., Bourque, B.J., Bradbury, R.H., Cooke, R., Erlandson, J., Estes, J.A., Hughes, T.P., Kidwell, S., Lange, C.B., Lenihan, H.S., Pandolfi, J.M., Peterson, C.H., Steneck, R.S., Tegner, M.J., Warner, R.R., (2001). Historical overfishing and the recent collapse of coastal ecosystems. *Science* 293: 629–638.

Johnson, T. D., Barnett, A. M., DeMartini, E. E., Craft, L. L., Ambrose, R. F., & Purcell, L. J. (1994). Fish production and habitat utilization on a southern California artificial reef. *Bulletin of Marine Science*, *55*: 709-723.

Kramer, Sunada. (1992). The overall decline in California halibut landings corresponds to a decline in shallow water habitats in southern California associated with dredging and filling of bays and wetlands. *California Fish and Game.*

Laylander, D. and Iversen, D. (2008). SDI-4553, Major Shellfish Genera and Prehistoric Change on the San Diego County Coast. Pacific Coast Archaeological Society Quarterly, Volume 39: 39-48.

Lenihan, H. S., Grabowski, J. H., & Thayer, G. W. (1998). *Recruitment to and utilization of oyster reef habitat by commercially and recreationally valuable crabs and fishes: an experiment with economic analysis* (No. 1-97). Final Report.

Lenihan, H. S., & Micheli, F. (2000). Biological effects of shellfish harvesting on oyster reefs: resolving a fishery conflict by ecological experimentation. *Fishery Bulletin*, *98:* 86-95.

Love, M. S. (2011). *Certainly more than you want to know about the fishes of the Pacific Coast: a postmodern experience*. Really Big Press.

Love, M. S., Brooks, A., Busatto, D., Stephens, J., & Gregory, P. A. (1996). Aspects of the life histories of the kelp bass, Paralabrax clathratus, and barred sand bass, P. nebulifer, from the southern California Bight. *Fishery Bulletin*, *94*: 472-481.

Peterson, C. H., Grabowski, J. H., & Powers, S. P. (2003). Estimated enhancement of fish production resulting from restoring oyster reef habitat: quantitative valuation. *Marine Ecology Progress Series*, *264*, 249-264.

Polson, M. P., & Zacherl, D. C. (2009). Geographic distribution and intertidal population status for the Olympia oyster, Ostrea lurida Carpenter 1864, from Alaska to Baja. *Journal of Shellfish Research*, *28:* 69-77.

PWA, E., & George, D. San Francisco Bay Living Shorelines: Near-shore Linkages Project 8 month Progress and Preliminary Monitoring Results Covering Activities July 2012-February 2013 Submitted: March 6, 2013 Marilyn Latta, Project Manager, State Coastal Conservancy (510-286-4157, mlatta@ scc. ca. gov).

Rager, K. A., Clifton, C. B., & Johnson, L. T. (1995). *San Diego County Wetlands: History, Inventory, Ecology, and Economics Valuation with Special Reference to Agricultural Nonpoint Source Pollution*. University of California Cooperative Extension, County of San Diego Farm & Home Advisor Department, Sea Grant Extension Program.

Ramsay, J. (2012). Ecosystem services provided by Olympia oyster (Ostrea lurida) habitat and Pacific oyster (Crassostrea gigas) habitat; Dungeness crab (Metacarcinus magister) production in Willapa Bay, WA.

Shumway, S. E. (1996). Natural environmental factors. *The eastern oyster Crassostrea virginica*, *467513*.

Sisson, P. (August 2016). Carlsbad: Lagoon maintenance fund is drying up. *San Diego Union Tribune*.

Southern California Halibut Stock Assessment (pp. B1-B84, Tech.). (n.d.). California Department of Fish and Wildlife.

Stockmann, K. (2016). *Assessing fish presence at eelgrass and oyster restorations in San Francisco estuary.* Master's Thesis. San Francisco State University.

Sunada, J. S., Velez, P. V., & Pattison, C. A. (1990). Age, size, and sex eomposition of California halibut fi'om southem Califomia commercial fishery landings, 1983-1988. *Fish. Bull. Calif. Dep. Fish Game*, *174*, 303-320.

Von Bertalanffy, L. (1938). A quantitative theory of organic growth (inquiries on growth laws. II). *Human biology*, *10*: 181-213.

Wasson, K., Zabin, C., Bible, J., Briley, S., Ceballos, E., Chang, A., ... & Latta, M. (2015). A guide to Olympia oyster restoration and conservation. *Elkhorn Slough National Estuarine Research Reserve. JT, Litho*.

Wells, H. W. (1961). The fauna of oyster beds, with special reference to the salinity factor. *Ecological Monographs*, *31*: 239-266.

Wertz, S. P., & Domeier, M. L. (1997). Relative importance of prey items to California halibut. *California Fish and Game*, *83*: 21-29.

Young, P. H. (1963). *The Kelp Bass, Paralabrax Clathratus, and Its Fishery, 1947-1958*. Department of Fish and Game, the Resources Agency, State of California.

Young, Mary, Lisa Wedding , Ben Best, Jason Roberts. Species Distribution Modeling Lab. Deakin University, Center for Integrative Ecology, Stanford University, Center for Ocean Solutions, National Center for Ecological Analysis and Synthesis, Duke University, Marine Geospatial Ecology Lab.

Zacherl, D. (2014). *San Diego Oyster Restoration: Preliminary Literature Survey* (Rep.).

Zillow. (2016). https://www.zillow.com/homes/for_sale/Carpinteria-CA_rb/?fromHomePage=true&shouldFireSellPageImplicitClaimGA=false&fromHomePageTab=buy

Zimmerman, R., Minello, T. J., Baumer, T., & Castiglione, M. (1989). Oyster reef as habitat for estuarine macrofauna. *NOAA Tech. Memo. NMFS-SEFC-249*, *16*.

Appendix A. Spatial

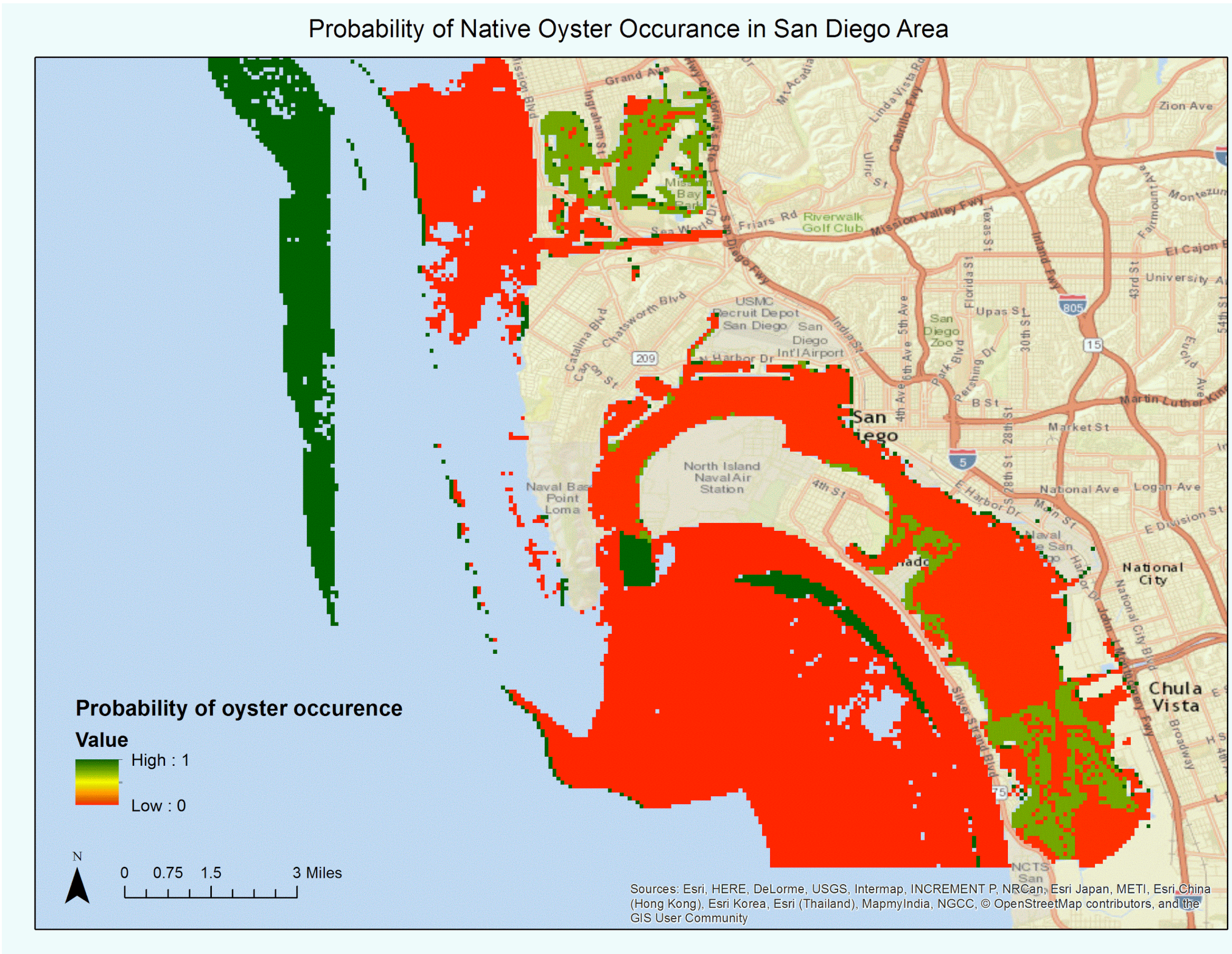

Figure 1. MGET raster output depicting the probability of native oyster occurrence in the San Diego Area ranging from low (0=red) to high (1=dark green).

Figure 2. Oyster presence data collected from multiple surveys in 2017 in the Carpinteria Salt Marsh Reserve. Red dots indicate that no oysters were found, green represent only Olympia oysters presence, yellow represent both Olympia and Pacific oysters presence, and orange represents only Pacific oyster presence.

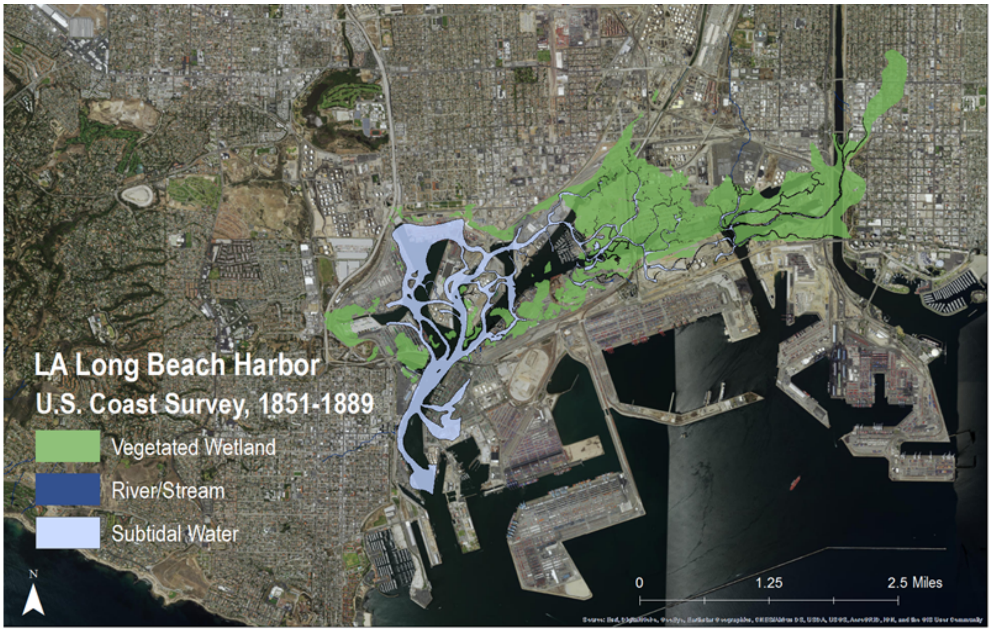

Figure 3. Historic wetland habitat in the LA Long Beach Harbor (1851-1889) as analyzed by the San Francisco Estuary Institute & The Aquatic Science Center. Green area represents historic vegetated wetland, dark blue represents historic rivers and streams, light blue represents historic subtidal water.

Figure 4. Historic wetland habitat in Newport Bay (1851-1889) as analyzed by the San Francisco Estuary Institute & The Aquatic Science Center. Green area represents historic vegetated wetland, dark blue represents historic rivers and streams, light blue represents historic subtidal water.

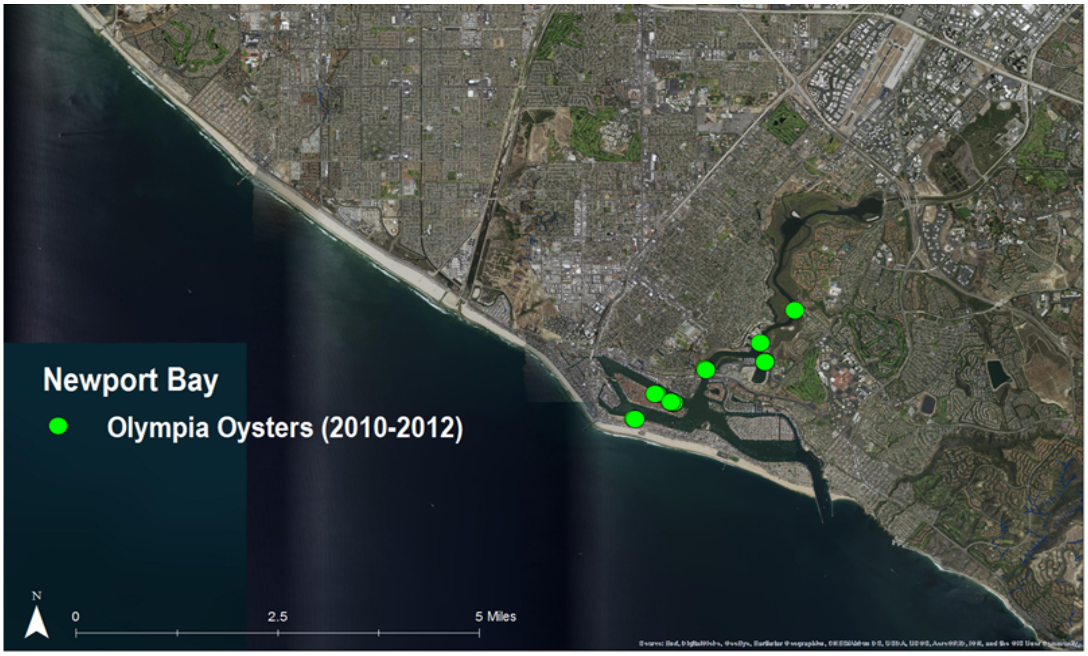

Figure 5. Locations where Olympia oyster density data was recorded in Newport Bay by Dr. Danielle Zacherl from 2010 to 2012.

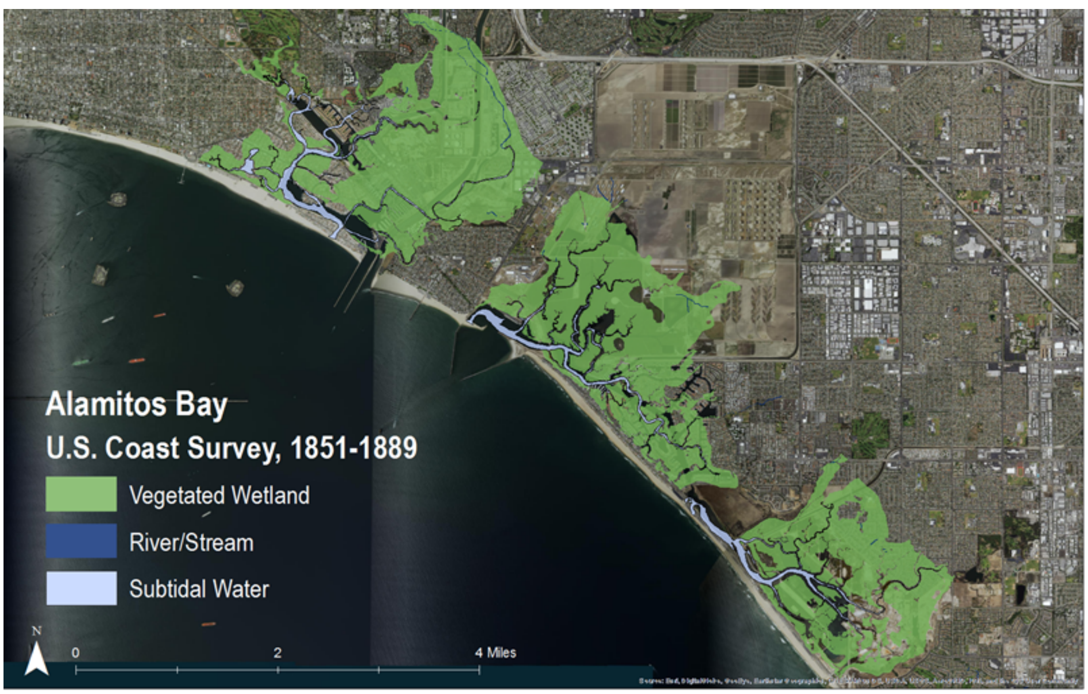

Figure 7. Historic wetland habitat in Alamitos Bay (1851-1889) as analyzed by the San Francisco Estuary Institute & The Aquatic Science Center. Green area represents historic vegetated wetland, dark blue represents historic rivers and streams, light blue represents historic subtidal water.

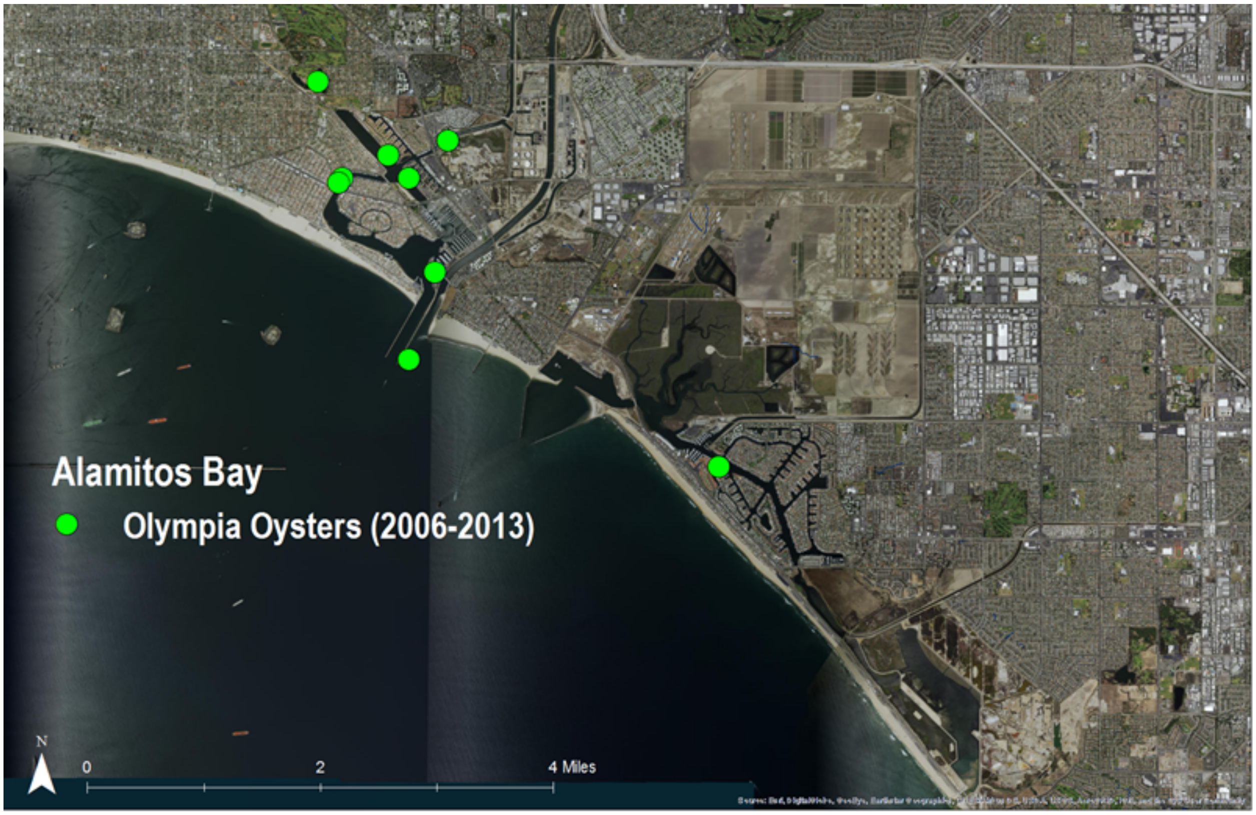

Figure 5. Locations where Olympia oyster density data was recorded in Alamitos Bay by Dr. Danielle Zacherl from 2006 to 2013.

Appendix B. Bioeconomic Model

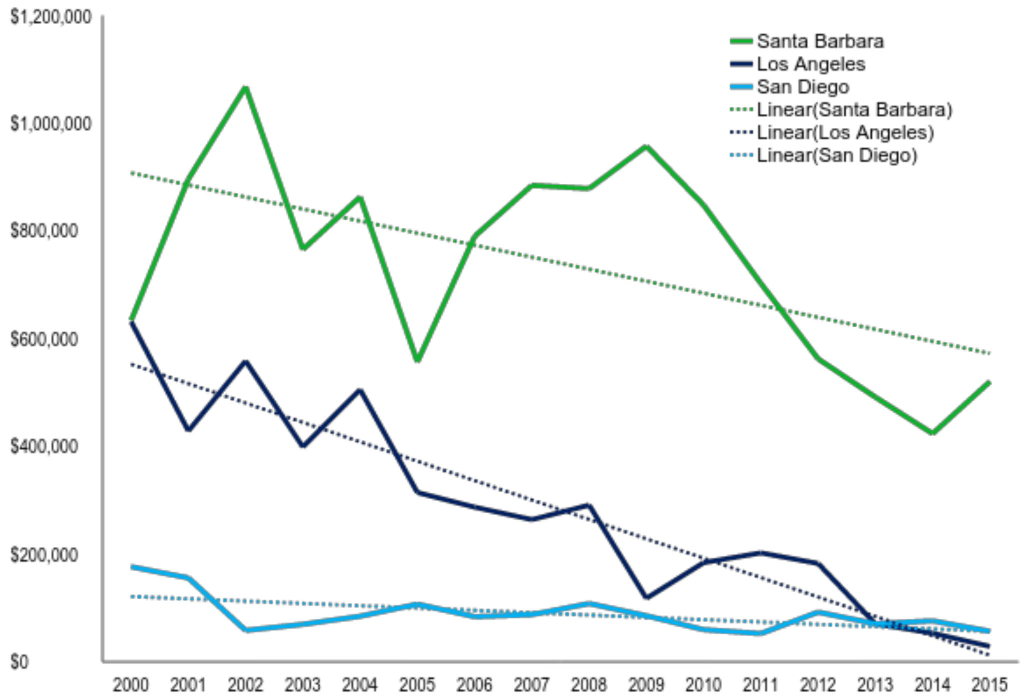

Figure 1. Fishery Revenue (USD) of California Halibut from 2000-2015 in Santa Barbara, Los Angeles, and San Diego; data from CADFW 2015.

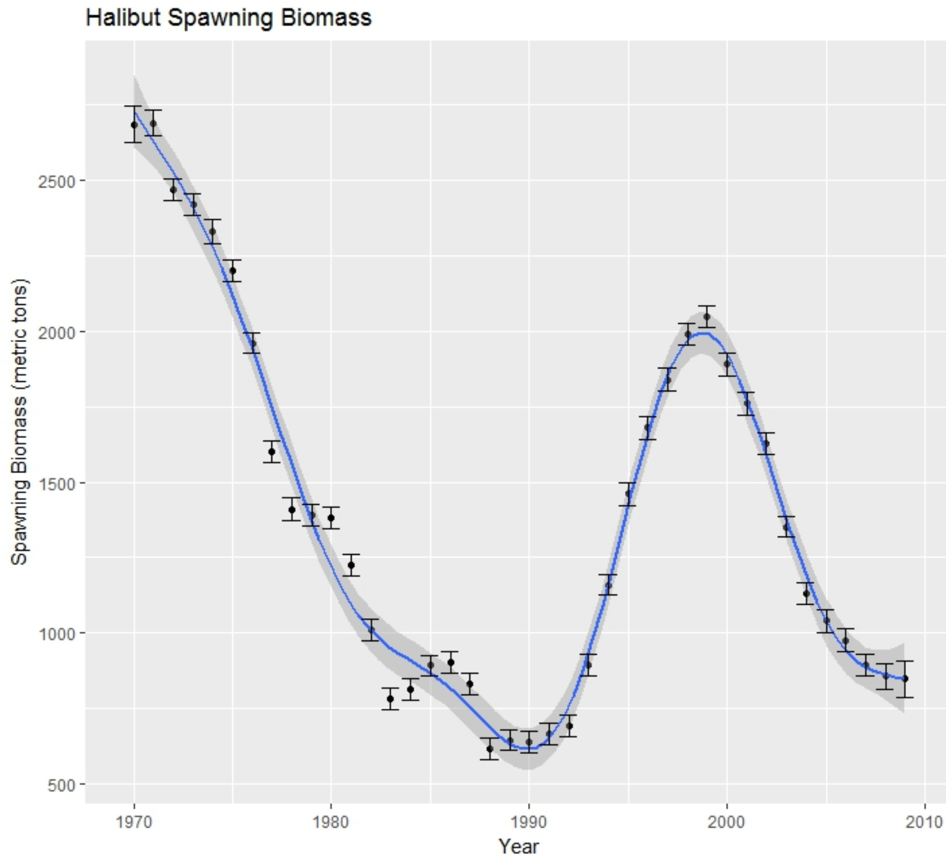

Figure 2. Halibut spawning biomass from 1970 to 2012; data from Southern California halibut stock assessment. Error bars represent +/- 1 standard deviation from the mean.

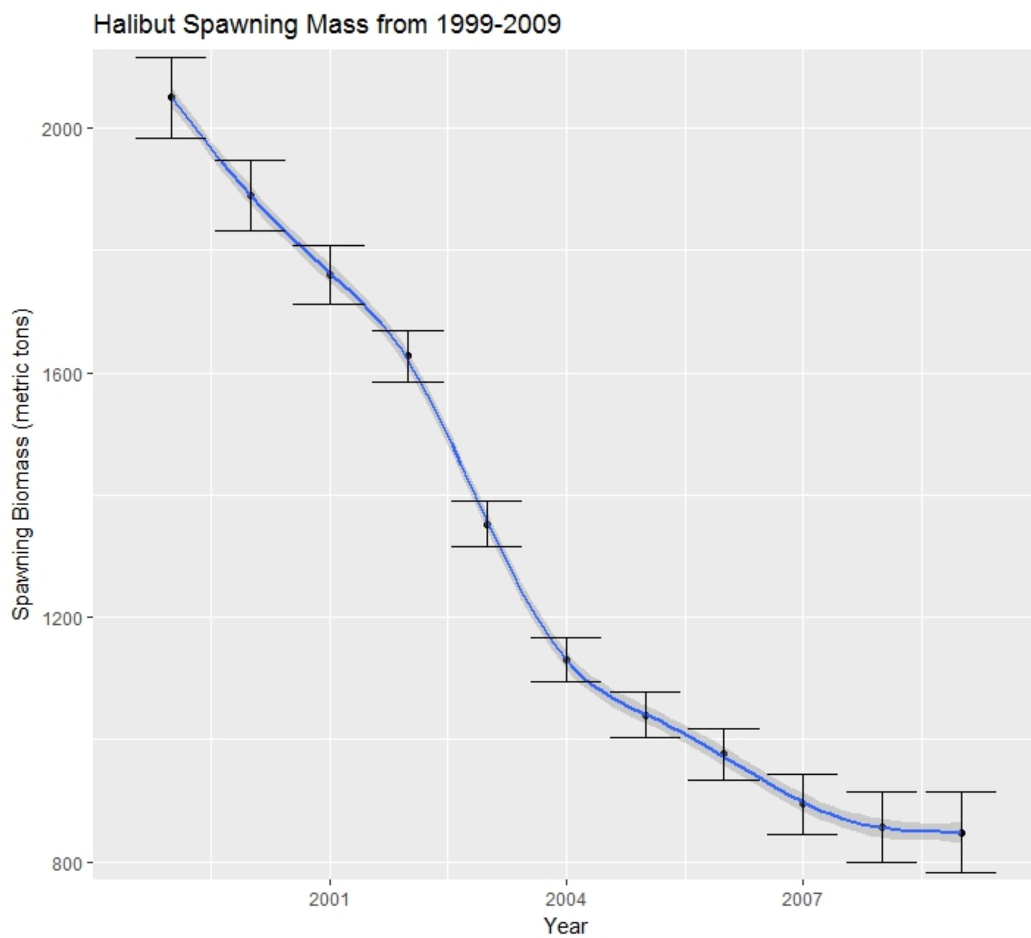

Figure 3. Halibut spawning biomass from 1999-2009. Error bars represent 95% confidence interval +/- 1 standard deviation from the mean. A linear regression was run to develop a model for this trend ($F(1,9)= 135.9$, $p<0.001$, $R^2= 0.931$)

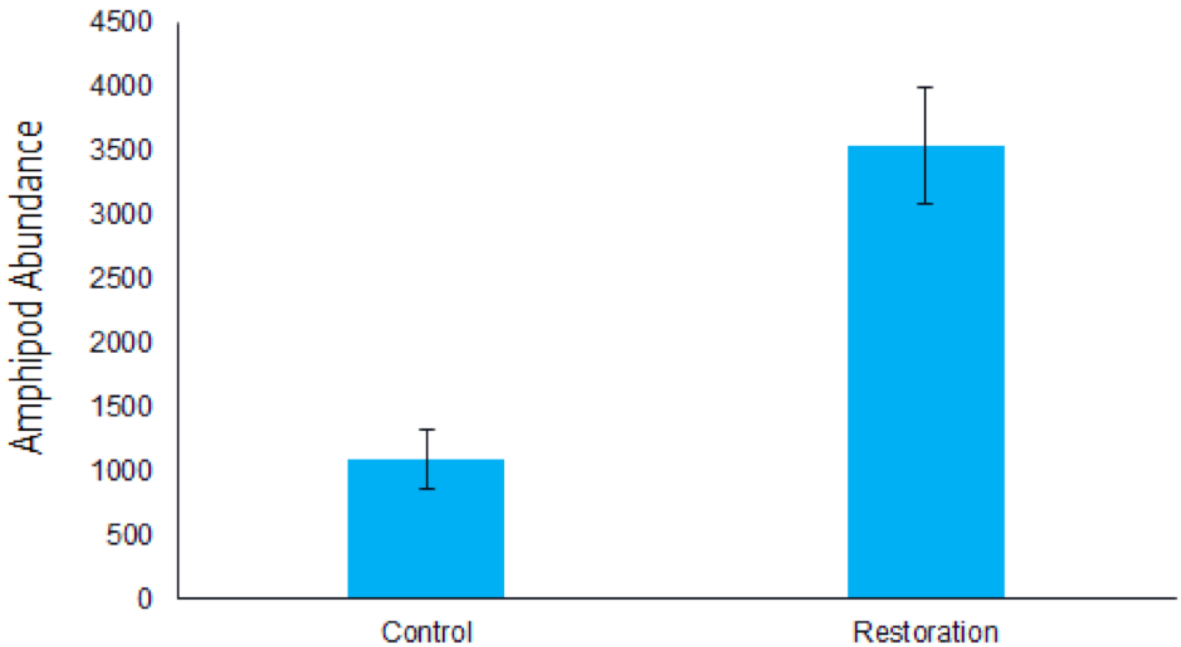

Figure 4. Amphipod abundance on sandy bottom habitats (control) and restored oyster reefs (restoration); data from Zacherl et al., unpublished data; error bars represent standard deviation.

Von Bertalanffy Equations	
Total length to age	Age to size
$l_t=l_i(1-e^{-k(t-to)})$	$w_i= a* L_i^b$

Table 1. Von Bertalanffy equations used to convert between length, age, and size of fish.

Parameter	Value
M (natural mortality rate)	0.2F, 0.28M (adults)
F (fishing mortality rate)	0.265(F), 0.375(M)
r (age at first harvest)	6years(F), 10 years(M)
L (asymptotic max length)	925.3 cm (M), 136.77 cm (F)
K (body growth coefficient)	0.08
K (with enhancement)	0.10
T_o (age at zero length)	0.4073
a	0.00692
b	3.13

Table 2. Von Bertalanffy growth parameters for California halibut under normal conditions.

Parameter	Value
M (natural mortality rate)	0.287
F (fishing mortality rate)	0.257
r (age at first harvest)	5years
L (asymptotic max length)	69.8 cm
K (body growth coefficient)	0.06
T_o (age at zero length)	-3.5
a	0.00813
b	3.03

Table 3. Von Bertalanffy growth parameters for kelp bass under normal conditions.

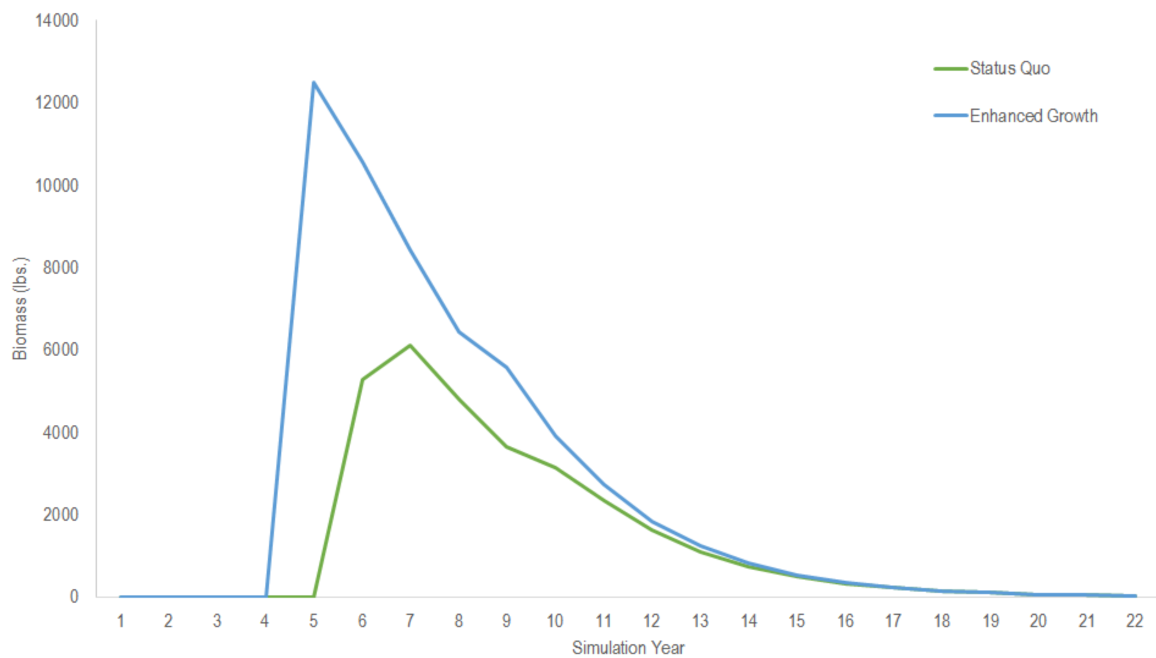

Figure 5. Biomass of fished halibut (lbs) per year of the simulation. The blue line represents fish enhanced by a restored oyster reef, while the green line represents fish on a sandy bottom

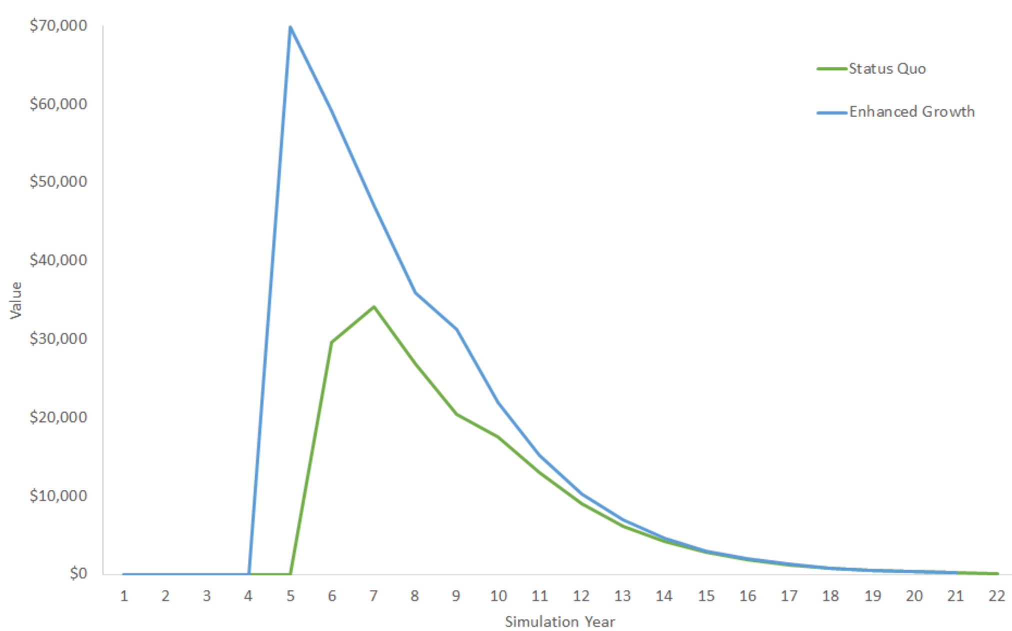

Figure 6. Net present value of fished halibut per simulation year. The blue line represents fish enhanced by a restored oyster reef, while the green line represents fish on a sandy bottom.

Parameter	Value
M (natural mortality rate)	0.287
F (fishing mortality rate)	0.257
r (age at first harvest)	5
L (asymptotic max length)	69.8 cm
K (body growth coefficient)	0.06
T_o (age at zero length)	-3.5
a	0.00813
b	3.03

Table 4. Von Bertalanffy parameters used in the kelp bass model.

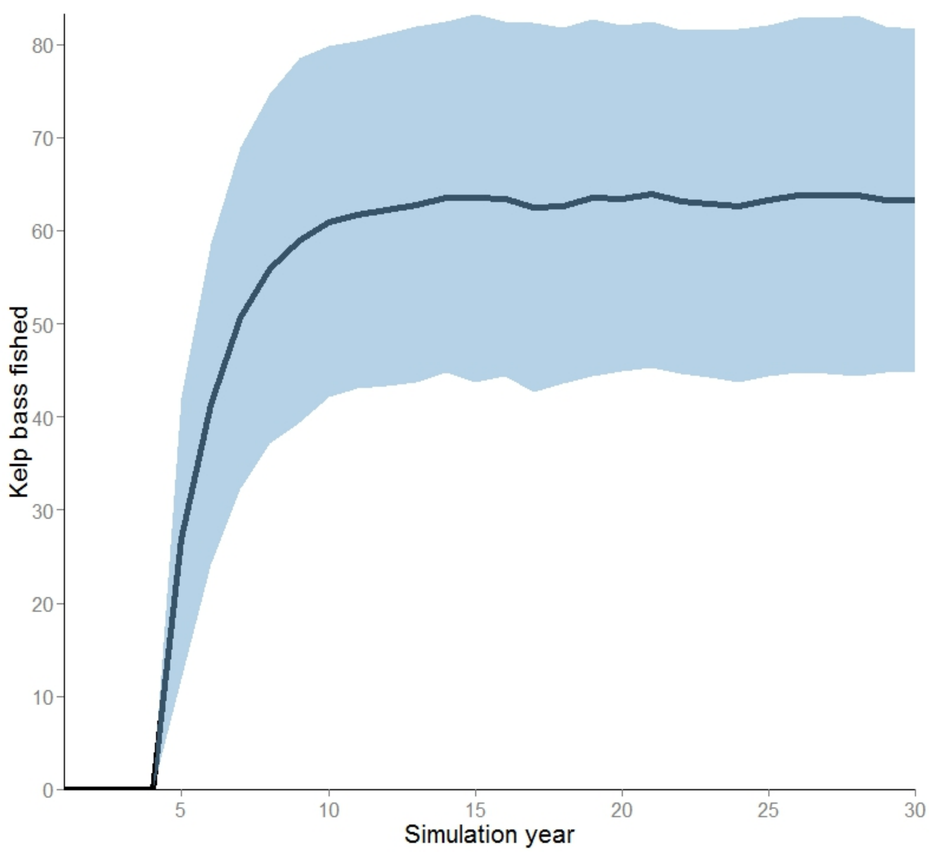

Figure 7. Kelp bass fished each simulation year as a result of the restored oyster reef; blue bands indicate the mean plus or minus the standard deviation.

Appendix C. Cost Benefit Analysis

Table 1. Costs of lagoon dredging and lagoon benefits for Batiquitos Lagoon without restoration.

	Costs	Benefits			
	No Restoration	No Restoration			
Year	Lagoon Dredging & Beach Nour	Flood Cont	Water Qual	Wildlife Habi	Recreatio
2017	$294,818	$15,715	$22,305	$11,278	$1,173
2018	$294,818	$15,715	$22,305	$11,278	$1,173
2019	$294,818	$15,715	$22,305	$11,278	$1,173
2020	$294,818	$15,715	$22,305	$11,278	$1,173
2021	$294,818	$15,715	$22,305	$11,278	$1,173
2022	$294,818	$15,715	$22,305	$11,278	$1,173
2023	$294,818	$15,715	$22,305	$11,278	$1,173
2024	$294,818	$15,715	$22,305	$11,278	$1,173
2025	$294,818	$15,715	$22,305	$11,278	$1,173
2026	$294,818	$15,715	$22,305	$11,278	$1,173
2027	$294,818	$15,715	$22,305	$11,278	$1,173
2028	$294,818	$15,715	$22,305	$11,278	$1,173
2029	$294,818	$15,715	$22,305	$11,278	$1,173
2030	$294,818	$15,715	$22,305	$11,278	$1,173
2031	$294,818	$15,715	$22,305	$11,278	$1,173
2032	$294,818	$15,715	$22,305	$11,278	$1,173
2033	$294,818	$15,715	$22,305	$11,278	$1,173
2034	$294,818	$15,715	$22,305	$11,278	$1,173
2035	$294,818	$15,715	$22,305	$11,278	$1,173
2036	$294,818	$15,715	$22,305	$11,278	$1,173
2037	$294,818	$15,715	$22,305	$11,278	$1,173
2038	$294,818	$15,715	$22,305	$11,278	$1,173
2039	$294,818	$15,715	$22,305	$11,278	$1,173
2040	$294,818	$15,715	$22,305	$11,278	$1,173
2041	$294,818	$15,715	$22,305	$11,278	$1,173
2042	$294,818	$15,715	$22,305	$11,278	$1,173
2043	$294,818	$15,715	$22,305	$11,278	$1,173
2044	$294,818	$15,715	$22,305	$11,278	$1,173
2045	$294,818	$15,715	$22,305	$11,278	$1,173
2046	$294,818	$15,715	$22,305	$11,278	$1,173
Total	$8,549,722	$455,741	$646,858	$327,055	$34,009
Total P	$2,636,039	$140,513	$199,438	$100,837	$10,486

Table 2. Costs of lagoon dredging and lagoon benefits for Batiquitos Lagoon with restoration. Benefits are calculated for 5 years until reef becomes self-sustaining.

	Costs				Benefits			
	5 Year Self-Sustaining				5 Year Self-Sustaining			
Year	Lagoon Dredging & Beach Nourishment	Shell Permitting	Shell Placement (Low)	Shell Placement (High)	Flood Control	Water Quality	Wildlife Habitat	Recreation
2017	$294,818	$26,003	$15,769	$70,959	$15,715	$22,305	$11,278	$1,173
2018	$294,818	$0	$15,769	$70,959	$15,715	$22,305	$11,278	$1,173
2019	$294,818	$0	$0	$0	$15,715	$22,305	$11,278	$1,173
2020	$294,818	$0	$0	$0	$15,715	$22,305	$11,278	$1,173
2021	$294,818	$0	$0	$0	$15,715	$22,305	$11,278	$1,173
2022	$0	$0	$0	$0	$15,715	$22,305	$11,278	$1,173
2023	$0	$0	$0	$0	$15,715	$22,305	$11,278	$1,173
2024	$0	$0	$0	$0	$15,715	$22,305	$11,278	$1,173
2025	$0	$0	$0	$0	$15,715	$22,305	$11,278	$1,173
2026	$0	$0	$0	$0	$15,715	$22,305	$11,278	$1,173
2027	$294,818	$0	$0	$0	$15,715	$22,305	$11,278	$1,173
2028	$0	$0	$0	$0	$15,715	$22,305	$11,278	$1,173
2029	$0	$0	$0	$0	$15,715	$22,305	$11,278	$1,173
2030	$0	$0	$0	$0	$15,715	$22,305	$11,278	$1,173
2031	$0	$0	$0	$0	$15,715	$22,305	$11,278	$1,173
2032	$0	$0	$0	$0	$15,715	$22,305	$11,278	$1,173
2033	$294,818	$0	$0	$0	$15,715	$22,305	$11,278	$1,173
2034	$0	$0	$0	$0	$15,715	$22,305	$11,278	$1,173
2035	$0	$0	$0	$0	$15,715	$22,305	$11,278	$1,173
2036	$0	$0	$0	$0	$15,715	$22,305	$11,278	$1,173
2037	$0	$0	$0	$0	$15,715	$22,305	$11,278	$1,173
2038	$0	$0	$0	$0	$15,715	$22,305	$11,278	$1,173
2039	$294,818	$0	$0	$0	$15,715	$22,305	$11,278	$1,173
2040	$0	$0	$0	$0	$15,715	$22,305	$11,278	$1,173
2041	$0	$0	$0	$0	$15,715	$22,305	$11,278	$1,173
2042	$0	$0	$0	$0	$15,715	$22,305	$11,278	$1,173
2043	$0	$0	$0	$0	$15,715	$22,305	$11,278	$1,173
2044	$0	$0	$0	$0	$15,715	$22,305	$11,278	$1,173
2045	$294,818	$0	$0	$0	$15,715	$22,305	$11,278	$1,173
2046	$0	$0	$0	$0	$15,715	$22,305	$11,278	$1,173
Total	$2,653,362	$26,003	$31,537	$141,917	$471,456	$669,163	$338,333	$35,182
Total PV	$818,081	$8,017	$9,724	$43,756	$145,359	$206,316	$104,314	$10,847

Table 3. Costs of lagoon dredging and lagoon benefits for Batiquitos Lagoon with restoration. Benefits are calculated for 10 years until reef becomes self-sustaining.

	Costs				Benefits			
Year	Lagoon Dredging & Beach Nourishment	Shell Permitting	Shell Placement (Low)	Shell Placement (High)	Flood Control	Water Quality	Wildlife Habitat	Recreation
2017	$294,818	$26,003.25	$15,768.60	$70,958.68	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2018	$294,818	$0	$15,768.60	$70,958.68	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2019	$294,818	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2020	$294,818	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2021	$294,818	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2022	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2023	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2024	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2025	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2026	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2027	$294,818	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2028	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2029	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2030	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2031	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2032	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2033	$294,818	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2034	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2035	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2036	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2037	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2038	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73

2039	$294,818	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2040	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2041	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2042	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2043	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2044	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2045	$294,818	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2046	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
Total	$3,832,634	$26,003	$31,537	$141,917	$471,455.70	$669,163.20	$338,332.80	$35,181.90
Total PV	$1,181,673	$8,017	$9,724	$43,756	$145,359	$206,316	$104,314	$10,847

Table 4. Costs of lagoon dredging and lagoon benefits for Batiquitos Lagoon with restoration. Benefits are calculated for 15 years until reef becomes self-sustaining.

	Costs				Benefits			
Year	Lagoon Dredging & Beach Nourishment	Shell Permitting	Shell Placement (Low)	Shell Placement (High)	Flood Control	Water Quality	Wildlife Habitat	Recreation
2017	$294,818	$26,003.25	$15,768.60	$70,958.68	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2018	$294,818	$0	$15,768.60	$70,958.68	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2019	$294,818	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2020	$294,818	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2021	$294,818	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2022	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2023	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2024	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2025	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2026	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2027	$294,818	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73

2028	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2029	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2030	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2031	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2032	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2033	$294,818	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2034	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2035	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2036	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2037	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2038	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2039	$294,818	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2040	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2041	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2042	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2043	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2044	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2045	$294,818	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
2046	$0	$0	$0	$0	$15,715.19	$22,305.44	$11,277.76	$1,172.73
Total	$5,306,724	$26,003	$31,537	$141,917	$471,456	$669,163	$338,333	$35,182
Total PV	$1,636,162	$8,017	$9,723	$43,756	$145,359	$206,316	$104,314	$10,847

Table 5. Costs and Benefits of Oyster Restoration in the Carpinteria Salt Marsh; Olympia oyster restoration scenario assumes 15 years until self-sustaining and includes one-time shell placement and permitting fee.

	Costs			Benefits	
	No Road Rebuilt				
Year	Permitting	Shell Placement (Low)	Shell Placement (High)	Avoided Property Damages	Water Quality
2017	$31,668	$6,645	$29,901	$0	$0
2018	$0	$0	$0	$0	$0
2019	$0	$0	$0	$0	$0
2020	$0	$0	$0	$0	$0
2021	$0	$0	$0	$0	$0
2022	$0	$0	$0	$0	$0
2023	$0	$0	$0	$0	$0
2024	$0	$0	$0	$0	$0
2025	$0	$0	$0	$0	$0
2026	$0	$0	$0	$0	$0
2027	$0	$0	$0	$0	$0
2028	$0	$0	$0	$0	$0
2029	$0	$0	$0	$455,196	$0
2030	$0	$0	$0	$0	$0
2031	$0	$0	$0	$0	$0
2032	$0	$0	$0	$0	$141
2033	$0	$0	$0	$0	$141
2034	$0	$0	$0	$0	$141
2035	$0	$0	$0	$0	$141
2036	$0	$0	$0	$0	$141
2037	$0	$0	$0	$0	$141
2038	$0	$0	$0	$0	$141
2039	$0	$0	$0	$0	$141
2040	$0	$0	$0	$0	$141
2041	$0	$0	$0	$0	$141
2042	$0	$0	$0	$0	$141
2043	$0	$0	$0	$0	$141
2044	$0	$0	$0	$0	$141
2045	$0	$0	$0	$0	$141
2046	$0	$0	$0	$0	$141
Total	$31,668	$6,645	$29,901	$455,196	$2,119
Total PV	$9,764	$2,049	$9,219	$140,345	$653

Table 6. Costs and Benefits of Oyster Restoration in the Carpinteria Salt Marsh; benefits include benefits of avoided private road loss; Olympia oyster restoration scenario assumes 15 years until self-sustaining and includes one-time shell placement and permitting fee.

	Costs			Benefits		
	Road Rebuilt					
Year	Permitting	Shell Placement (Low)	Shell Placement (High)	Beach	Avoided Property Damages	Water Quality
2017	$31,668	$6,645	$29,901	$1,438	$0	$0
2018	$0	$0	$0	$1,438	$0	$0
2019	$0	$0	$0	$1,438	$0	$0
2020	$0	$0	$0	$1,438	$0	$0
2021	$0	$0	$0	$1,438	$0	$0
2022	$0	$0	$0	$1,438	$0	$0
2023	$0	$0	$0	$1,438	$0	$0
2024	$0	$0	$0	$1,438	$0	$0
2025	$0	$0	$0	$1,438	$0	$0
2026	$0	$0	$0	$1,438	$0	$0
2027	$0	$0	$0	$1,438	$0	$0
2028	$0	$0	$0	$1,438	$0	$0
2029	$0	$0	$0	$1,438	$455,196	$0
2030	$0	$0	$0	$1,438	$0	$0
2031	$0	$0	$0	$1,438	$0	$0
2032	$0	$0	$0	$1,438	$0	$141
2033	$0	$0	$0	$1,438	$0	$141
2034	$0	$0	$0	$1,438	$0	$141
2035	$0	$0	$0	$1,438	$0	$141
2036	$0	$0	$0	$1,438	$0	$141
2037	$0	$0	$0	$1,438	$0	$141
2038	$0	$0	$0	$1,438	$0	$141
2039	$0	$0	$0	$1,438	$0	$141
2040	$0	$0	$0	$1,438	$0	$141
2041	$0	$0	$0	$1,438	$240,000	$141
2042	$0	$0	$0	$1,438	$0	$141
2043	$0	$0	$0	$1,438	$0	$141
2044	$0	$0	$0	$1,438	$0	$141
2045	$0	$0	$0	$1,438	$0	$141
2046	$0	$0	$0	$1,438	$0	$141
Total	$ 31,668.25	$ 6,644.63	$29,900.83	$43,141	$695,196	$2,119
Total PV	$9,763.91	$2,048.66	$9,218.98	$13,301.24	$214,341.98	$653.39