San Francisco Bay Living Shorelines: Nearshore Linkages Project

Monitoring Summary Report through 2017

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Executive Summary

T he San Francisco Bay Living Shorelines: Nearshore Linkages Project was installed in July-August 2012 along the shoreline in San Rafael, California, in the north-central portion of San Francisco Bay. This installation entailed placing Pacific oyster shell bag mounds and eelgrass plantings, alone or together, in plots deemed large enough (10 x 32 m) to measure both habitat provision and physical processes such as wave attenuation and sedimentation. This first living shorelines project in the shallow waters of San Francisco Bay has a total footprint of about one acre, and is intended to pilot methods and provide guidance to inform scaling up to larger future projects along the bay's shores. In addition, an experiment testing different settlement substrates for native oysters was conducted both in San Rafael and along the Hayward shoreline just south of the San Mateo Bridge. Over the past five years (2012 through 2017), a multi-institution and interdisciplinary team of scientists who worked collaboratively to design the reefs, has been monitoring changes in species and processes developing over time at both sites, culminating in this final summary report.

Biological

responses to the large plots of shell bags or eelgrass were swift but variable over time. Eelgrass performed very well over the first few years, with numbers of vegetative shoots more than doubling relative to planted densities by summer 2015. Plants interspersed with oyster shell bag mounds performed less well than when planted alone, and plants originating from the donor site Point Molate tended to produce higher densities than those from Point San Pablo. We began to observe a decline in eelgrass densities at San Rafael in fall 2015, with roughly a third of the shoot numbers present relative to June 2015. A large algal bloom had formed a mat across the mudflat surface, but we do not know if this contributed to eelgrass losses as opposed to a water quality event or other causes. By early February 2016, all eelgrass in the treatment area had disappeared, as well as some earlier test plantings at the site that had been present for nine years. In April 2016, we transplanted eelgrass from Point Molate back into the original eelgrass-only plot as well as both shoreward and bayward of the former eelgrass + oyster plot. This effort was to test site suitability (i.e., whether the losses were due to a one-time event that did not have persistent effects) as well as the potential role of the oyster reefs in protecting shoreward eelgrass through a reduction in wave energy. We successfully established eelgrass through this planting and found exceptionally vigorous growth (higher shoot densities and heights) on the shoreward side of the oyster reefs. This suggests that the site is still suitable for eelgrass growth, and also leads us to recommend that oyster reefs as protection for eelgrass plantings be tested at additional sites. An extended low salinity period (four months <10 ppt) with the heavy rainfall of early 2017 again led to losses of eelgrass at the San Rafael site by the spring monitoring period. This was an extreme event that affected many marine organisms in the central bay portion of the estuary; e.g., native oysters also suffered total losses at the site as well as throughout the central bay. We have not replanted the eelgrass again, although we would do so in a future year given funding to plant and monitor.

This innovative pilot project has increased regional public awareness about the value of living shorelines and nature-based adaptation approached, including with resource agencies, landowners, scientists and consultants, and the general public. In general, we have seen multiple biological and physical benefits from this pilot living shorelines project and have also come to recognize that restoration of shallow subtidal habitats is likely to take sustained effort, with the benefit that we have extended periods in which the foundational habitats we have been targeting are present to provide habitat, accumulate sediment and carbon, and provide other valued ecosystem functions.

1 Introduction

Living shorelines projects utilize a suite of sediment stabilization and habitat restoration techniques to maintain or build the shoreline, while creating habitat for a variety of species, including invertebrates, fish, and birds (see National Oceanic and Atmospheric Administration [NOAA] 2015 for an overview). The term “living shorelines” denotes provision of living space and support for estuarine and coastal organisms through the strategic placement of native vegetation and natural materials. This green coastal infrastructure can serve as an alternative to bulkheads and other engineering solutions that provide little to no habitat in comparison (Arkema et al. 2013; Gittman et al. 2014; Scyphers et al. 2011). In the United States, the living shorelines approach has been implemented primarily on the East and Gulf Coasts, where it has been shown to enhance habitat values and increase connectivity between wetlands, mudflats, and subtidal lands, while reducing shoreline erosion during storms and even hurricanes (Currin et al. 2015; Gittman et al. 2014, 2015).

There have been fewer living shorelines projects along the US West Coast, with most occurring on small private parcels along Puget Sound in Washington state; however, recognition of the many potential benefits of this approach is growing in the region, in part because of increasing concerns about sea level rise and storm surge and the need to protect valuable residential, commercial, and industrial assets (Gallien et al. 2011; Heberger et al. 2011; McGranahan et al. 2007). In developing the California State Resources Agency Climate Change Adaptation Strategy (Natural Resources Agency 2015), California state agencies recommended the use of living shorelines as a climate change adaptation strategy to reduce the need for engineered hard shoreline protection while enhancing habitat functions as sea level rises. The California State Coastal Conservancy Climate Change Policy (State Coastal Conservancy 2011) and the California Coastal Commission Sea Level Rise Guidance (California Coastal Commission 2015) also recommended implementation of living shorelines because of their potential to reduce erosion and trap sediment while providing intertidal and subtidal habitat and helping to maintain and protect adjacent tidal wetlands. Further, the San Francisco Bay Subtidal Habitat Goals Project proposed piloting of living shorelines projects that test the roles and potential synergy of integrating restoration of multiple species for both habitat and shoreline protection benefits (State Coastal Conservancy 2010). In addition, a 2015 climate change update to the Baylands Ecosystem Habitat Goals Report (Goals Project 2015) recommended multi-habitat, multi-objective approaches and living shorelines to increase resiliency of San Francisco Bay tidal wetlands and associated habitats to climate changes such as sea level rise.

Concordant with these recommendations, the San Francisco Bay Living Shorelines: Near-shore Linkages Project was implemented in 2012 by the State Coastal Conservancy and an interdisciplinary team of biological and physical scientists. In this report, we review our objectives and project design, and evaluate outcomes after five years of monitoring post- installation, concluding with an assessment of lessons learned and design criteria for future projects in San Francisco Bay and elsewhere.

1.1 Focus on Eelgrass and Olympia Oysters

Although there are numerous options for species and materials to be utilized in living shorelines designs, this first living shorelines project in San Francisco Bay focused on restoration of two native species, eelgrass (*Zostera marina*) and Olympia oysters (*Ostrea lurida*). We selected these two species for several reasons. First, worldwide declines in both seagrasses and native shellfish species have made their restoration a major priority (Beck et al. 2009; Cunha et al. 2012; Kirby 2004; NOAA Fisheries National Shellfish Initiative 2011; Orth et al. 2006, 2010; Waycott et al. 2009), in part to recover the many associated species that utilize them as primary or critically important habitat (Coen et al. 2007; Hughes et al. 2009; Luckenbach et al. 1995; Ramsey 2012; Scyphers et al. 2011). Second, both seagrasses and shellfish have been shown to attenuate waves and accrete sediments, making them desirable for use in shoreline protection (Fonseca et al. 1982; La Peyre et al. 2015; Lenihan 1999; Meyer 1977; Piazza et al.

2005; Scyphers et al. 2011). Third, within San Francisco Bay, *Z. marina* and *O. lurida* have been identified as major targets for restoration, with increases of 3200 hectares/8,000 acres of each proposed over 50 years (State Coastal Conservancy 2010). Finally, incorporation of these two species in a living shorelines design was of interest because of the potential for positive interactions that could enhance establishment or growth of either species or increase the variety of organisms attracted to the complex habitat structure (e.g., Kimbro and Grosholz 2007; Wall et al. 2008).

Eelgrass provides valued ecological functions and services in San Francisco Bay (De La Cruz et al. 2014; Hanson 1998; Kitting 1993; Kitting and Wyllie-Echeverria 1992; Spratt 1981) but covers only ~1200 ha, or approximately 1% of submerged lands (Merkel and Associates 2004, 2009, 2015). Historic coverage and distribution are not well known (a few locations were noted by Setchell 1922, 1927, 1929), but many shallow areas that were likely to have been suitable for eelgrass growth were filled or dredged as commercial shipping and infrastructure around the Bay developed. Although submarine light levels in the Bay are relatively low and consequently limiting for eelgrass growth (Zimmerman et al. 1991), biophysical modeling indicates that 9490 ha of bottom area may be suitable habitat (Merkel and Associates 2005). Recent studies on restoration methodologies and donor source selection (Boyer et al. 2010), genetic diversity (Ort et al. 2012, 2014), invertebrate usage (Carr et al. 2011), trophic dynamics (Carr and Boyer 2014; Kiriakopolos 2013; Lewis and Boyer 2014; Reynolds et al. 2012), and abiotic effects on eelgrass (Santos 2013) have contributed to an understanding of the opportunities for eelgrass restoration within the Bay (reviewed in Boyer and Wyllie-Echeverria 2010). Further, declines in suspended sediment concentrations measured in the last decade indicate improving water clarity in San Francisco Bay (Schoellhamer 2011); restoration measures could proactively advance population expansion, taking advantage of improvements in water quality conditions.

Olympia oysters were historically an abundant part of the fauna in West Coast estuaries (Baker 1995); however, the popularity of the fishery that began in the 1850s as well as other impacts resulted in a collapse of native oyster populations in the region by the early 20th century (Baker 1995; Barnett 1963; Kirby 2004; Zu Ermgassen 2012). Little is known about the pre-European contact distribution and abundance of oysters in San Francisco Bay, much less the ecosystem services they provided; however, aggregations of native oysters were likely to have been habitat for numerous sessile and mobile animals (Ramsey 2012) and they are known today to increase invertebrate species richness even at small scales (Kimbro and Grosholz 2007). Because it has not been an important fishery since Gold Rush days, the Olympia oyster has been poorly studied compared to its larger cousins, the Atlantic (*Crassostrea virginica*) and Pacific oyster (*Crassostrea gigas*). Restoration of Olympia oysters, which began in Puget Sound in 1999, is still relatively new compared with efforts in the Atlantic and Gulf coasts and much remains to be learned about effective restoration for these oysters. Lessons learned from restoration on the East and Gulf Coasts are not directly transferrable for several reasons, including differences (1) between the species native to each coast in terms of life history and ecology; (2) in key limiting factors (such as disease, which is a major issue in many East Coast systems, but not on the West Coast); (3) in restoration goals, which, on the East and Gulf Coasts, frequently include restoring the commercial and recreational fishery as well as habitat, while West Coast restoration efforts have focused solely on oyster and eelgrass population and habitat enhancement; and (4) in the use of hatchery-reared oysters for population enhancement, which has not been used widely in West Coast projects to date because studies have confirmed that many estuaries such as San Francisco Bay are substrate-limited and not recruitment-limited.

Monitoring of oysters in SF Bay has resulted in detailed population data for more than 20 intertidal sites (presence/absence data for more than 80 sites), and an increased understanding of the factors that limit oyster populations today (e.g., A. Chang et al. 2016; Cheng et al. 2016; Deck 2011; Grosholz et al. 2008; Harris 2004; Polson and Zacherl 2009; Wasson et al. 2014; Zabin et al. 2010). This research, along with earlier recruitment studies and small-scale restoration projects, indicates the potential to restore oysters in many areas of the Bay through the placement of hard substrate at appropriate tidal elevations, relying entirely on naturally occurring recruitment (Abbott et al. 2012; Grosholz et al. 2008; Wasson et al. 2014; Welaratna 2008; Zabin et al. 2010), although enhancement with hatchery-reared oysters may improve success at some sites.

With these advances in our understanding of the dynamics of eelgrass and Olympia oyster populations and their restoration in San Francisco Bay, the timing was appropriate to increase the scale of restoration of both of these species to acreages large enough to permit evaluation of their effects on physical processes as well as habitat usage by highly mobile bird and fish species. The San Francisco Bay Living Shorelines: Near-shore Linkages Project endeavored to further test restoration techniques, restore critical eelgrass and oyster habitat, examine the individual and interactive effects of restoration techniques on habitat values, and test alternatives to hard/structural stabilization in a multi-objective pilot climate adaptation and restoration project.

1.2 Project Goal and Objectives

The overarching goal of the project was to create biologically rich and diverse subtidal and low intertidal habitats, including eelgrass and oyster reefs, as part of a self-sustaining estuary system that restores ecological function and is resilient to changing environmental conditions.

The objectives of the project are as follows:

1. Use a pilot-scale, experimental approach to establish native oysters and eelgrass at multiple locations in San Francisco Bay.
2. Compare the effectiveness of different restoration treatments in establishing these habitat-forming species.
3. Determine the extent to which restoration treatments enhance habitat for invertebrates, fish, and birds, relative to areas lacking structure and pretreatment conditions.
4. Determine if the type of treatment (e.g., oyster reefs, eelgrass plantings, or combinations of oyster reefs and eelgrass) influences habitat values differently.
5. Begin to evaluate potential for subtidal restoration to enhance functioning of nearby intertidal mudflat, creek, and marsh habitats, for example, by providing food resources to species that move among habitats.
6. Evaluate potential for living subtidal features intended for habitat to also reduce water flow velocities, attenuate waves, and increase sedimentation, and assess whether different restoration treatments influence physical processes differently.
7. Determine if position in the Bay, and the specific environmental context at that location, influences foundational species establishment, habitat provision, and physical processes conferred by restoration treatments.
8. Where possible, compare the ability to establish restoration treatments, habitat functions, and physical changes along mudflats/wetlands versus armored shores.

2 Siting and Design

The two locations for the project (Fig.1) were the San Rafael shoreline (parcel owned by The Nature Conservancy) and the Eden Landing Ecological Reserve in Hayward (owned by the California Department of Fish and Wildlife). The San Rafael site included a larger-scale and a small-scale study, while the Hayward site included only a small-scale study, as described below. Oyster treatments were constructed and eelgrass plantings were installed in mid July through early August 2012.

2.1 Larger-Scale Experiment to Test both Biological and Physical Effects (San Rafael Only)

This portion of the project included a larger-scale experimental design with four 32 × 10 m treatment plots situated parallel to the shore, approximately 200 m from shore. The scale of these four plots allowed for evaluation of the effects of native oyster substrate (mounds of bagged clean Pacific oyster half shell), eelgrass, and both together, in comparison to a control plot of the same size (Figs. 1 and 2). The experiment was designed to be large enough in scale to compare effects on physical factors such as wave attenuation and sediment accretion, as well as effects on biological properties that operate at larger scales (e.g., highly mobile invertebrate, bird, and fish utilization).

The Pacific oyster shell mound treatment plot, described in detail below, had a footprint of 1 × 1 m per element. These were laid out in sets of four elements to make larger units of 4 m^2 (Figs. 2 and 3). To minimize scour, the design included spaces of the same size (4 m^2) between these oyster shell mound units. There were three rows of eight units, for a total of 24 units per plot (96 elements).

Eelgrass was planted and seeded in the eelgrass treatment plot with the same spacing as the oyster reef units. The central 1.5 × 1.5 m (2.25 m^2) space within every other 4-m^2 space was planted with clusters of shoots and also seeded. The planting technique entailed using a bamboo stake to anchor each shoot in place until rooted (Fig. 3). Two donor beds were used for transplant material at each site: Point San Pablo and Point Molate (both on the Richmond shoreline) were the sources at San Rafael, while Eden Landing Ecological Reserve in Hayward (small patches offshore) and Bay Farm Island near Alameda were the sources planted at the Hayward small-scale project site (Fig. 1). Flowering shoots were only available from Point San Pablo at the time of project implementation in late summer 2012 and were collected for use in buoy-deployed seeding (Pickerell et al. 2005) at the San Rafael site only, with a mesh bag of 15 flowering shoots anchored by a PVC pipe at the center of each unit.

The combined oyster and eelgrass plot had an additive design, with eelgrass placed into the central 2.25 m^2 of the 4-m^2 spaces between oyster substrate features (Fig. 2). This design permitted us to maintain a spacing of oyster substrate that would minimize scour, while providing enough space around eelgrass plantings to permit access for sampling.

A treatment control plot of the same size, with no eelgrass or oyster substrates added, was also included (Figs.1 and 2). The four treatments were arranged randomly in the four possible positions, with 30 m between each plot. Adjacent to the overall treatment area, a large project control area of equal size to the four plots was monitored throughout the project period for certain measures (e.g., bird use of completely unstructured habitat relative to the whole treatment area containing structure).

2.2 "Substrate Element" Experiment to Examine Small-Scale Biological Effects (San Rafael and Hayward)

This smaller-scale experiment consisted of five replicate elements of different substrate (surface) types, intended to compare native oyster recruitment, growth, and survival to inform future restoration projects. At the San Rafael site, this experiment was situated in the 30-m spaces between and on either side of the line of larger-scale plots described above (Figs. 1-3). At San Rafael, the elements included reef balls, oyster ball stacks, oyster blocks, and a layer cake design all made of "baycrete," a mixture of roughly 20% marine-grade cement and a high proportion of materials (roughly 80%) derived from the Bay including dredged native sand and fossilized native oyster shell (Fig.3). These substrate types were replicated five times, for a total of 20 elements placed in groups (blocks), with each of the four substrate types represented in each block in randomized order.

The Hayward site also included 1-m^2 substrate elements made of baycrete, replicated in five blocks and aligned parallel with the shoreline at ~200 m from shore (Figs.1-3). However, there were five treatments (substrate types): reef balls, oyster ball stacks, oyster blocks, Pacific oyster shell mounds alone, and the latter placed along with adjacent eelgrass plantings. These substrate types were placed in randomized order within each block. The layer cakes were ultimately not included at this site due to concerns about structural integrity under higher wave action, and the oyster shell mounds were added since there was no large-scale project to test their effectiveness at this site as at San Rafael.

3 Brief Permitting Review

The State Coastal Conservancy coordinated with permit agencies before permit application submittals to discuss draft designs and regulatory mechanisms. Permitting discussions focused on project methods and resulting effects on Bay species, seasonal windows and construction methods for the work, and issues regarding the placement of clean Pacific oyster shell and baycrete structures as beneficial fill to create habitat. Permit applications were submitted in February 2012, and numerous follow-up meetings and correspondence occurred on particular aspects of each agency's requirements. Final permits were secured in July 2012, just before construction in mid July and August 2012. Permit applications and approvals included the following:

- US Army Corps of Engineers: Nationwide Permit 27 (Aquatic Habitat Restoration, Establishment, and Enhancement Activities).
- NOAA Fisheries consultation with US Army Corps of Engineers: Section 7 consultation relative to the Endangered Species Act, Essential Fish Habitat consultation relative to the Magnuson Stevens Fishery Conservation and Management Act and Fish and Wildlife Conservation Act.
- San Francisco Bay Conservation and Development Commission (BCDC): Administrative permit.
- California Department of Fish and Wildlife consultation with BCDC: Consultation to limit any impacts and maximize benefits to state-listed fish and wildlife; Scientific Collecting Permit for eelgrass donor collections; Letter of Authorization for transplanting eelgrass to restoration sites.
- San Francisco Bay Regional Water Quality Control Board: Section 404 Water quality certification.
- California State Lands Commission: Coordination to confirm that the project is not on state-leased lands.
- California Environmental Quality Act: the project was categorically exempt under Guidelines Section 15333 (14 Cal. Code Regs. §15333) as a small habitat restoration project, not exceeding five acres, to restore and enhance habitat for fish, plants, or wildlife and with no significant adverse impact on endangered, rare, or threatened species or their habitat, no known hazardous materials at or around the project site and, given the scale and methodology, no potential for cumulatively significant effects.

In addition to permits, agreements and letters of permission with the landowners (The Nature Conservancy for the San Rafael site and the California Department of Fish and Wildlife for the Hayward site) and local government (City of San Rafael) were obtained.

4 Key Findings, Five Years after Installation (through 2017)

4.1 San Rafael Site

4.1.1 Eelgrass

After replanting eelgrass in April 2013 (as the original late-summer planting in 2012 did not succeed), plants at the larger-scale San Rafael project site performed well through summer of 2015. By June 2015, more than 200% of planted shoot numbers occurred in the eelgrass-only plot and just over 100% in the eelgrass + oyster plot. Typically in nature and in planting efforts, we expect a 35-40% survival rate to indicate success, so our team was very pleased with the high survival rates and expansion of eelgrass. Although we did not detect seedlings from the buoy-deployed seeding effort in 2012, flowering shoots developed in the plots by summer each year (Fig. 4), suggesting the possibility of additional recruitment from seed; however, few seedlings were observed at the site over the course of the project. Maximum plant heights typically reached 160 cm or more during spring–fall, comparable to natural beds, with a marked decrease in height during winter most years (Fig. 5). Vegetative shoot heights also tended to be taller in the eelgrass-only plot over time. The trend of lower overall densities and heights in the eelgrass + oyster plot compared to the eelgrass-only plot may be attributed to abrasion of plants against the oyster shell bags, limited space for spread within the matrix of the mixed habitat plot, or other causes (increased organic matter among oyster reefs leading to reduced oxygen conditions is another hypothesis). During the period when the two donor sites could still be tracked (plants from the two donors began to grow together by summer 2014), plants originating from Point Molate tended to produce higher numbers of shoots than those from Point San Pablo, perhaps owing to better matching of site conditions between the Point Molate and San Rafael sites (finer sediments than Point San Pablo; Boyer and Wyllie-Echeverria 2010).

There was a precipitous decline in shoot numbers beginning with the fall 2015 sampling period (Fig. 4), with roughly a third of the shoot numbers present relative to June 2015. This decline was reflected to a lesser degree in shoot heights (Fig. 5). This decline may have been related to a large algal bloom that formed thick mats across the mudflat surface during this time, perhaps blocking light from eelgrass or drawing down oxygen as the mats decomposed. We also observed grazing by Canada Geese during this period. In addition, with the onset of winter rains, we speculate that there could have been a pollutant discharge to the area. We cannot be certain of the cause or combination of causes. By early February 2016, all eelgrass in the treatment area had disappeared, as well as the original eelgrass test plots (in the center gap of our large treatment plots), which had been present for nine years.

In April 2016, we transplanted eelgrass from Point Molate to the project site, but this time with a new experimental layout, with plantings inshore and offshore of the oyster + eelgrass plot as well as in the eelgrass only plot again, with a total of 240 shoots planted in each of the three new planting areas. This effort was to test site suitability (i.e., whether the losses were due to a one-time event that did not have persistent effects) as well as the potential role of the oyster reefs in protecting shoreward eelgrass through a reduction in wave energy. As early as July 2016, a striking pattern developed: the eelgrass inshore of the oyster reefs greatly exceeded the offshore and eelgrass-only plots in shoot numbers, and this trend became more pronounced in October 2016 and January 2017 (Fig. 6a). Heights of the tallest shoots were also greater in the shore-side than bay-side plots throughout the period (Fig. 6b). Eelgrass may experience reduced flows inshore of the oyster reefs, which may be beneficial to the plants directly (protection from higher wave energy) or indirectly (e.g., by affecting herbivory or other processes that feed back to eelgrass density). These results suggest that the site was still suitable for eelgrass growth; further, they suggest that oyster reefs placed bayward of eelgrass may be useful in promoting eelgrass growth, and thus we recommend this configuration of restoration treatments be tested at additional sites.

An extended low salinity period (four months at <10-15 PSU; see Physical Processes below) with the heavy rainfall atmospheric river events of early 2017 again led to losses of eelgrass at the San Rafael site by the spring monitoring period. This was an extreme event that affected many marine organisms in the central bay portion of the estuary; e.g., native oysters also suffered total losses at the site as well as throughout the central bay (see Olympia Oysters below). We did not replant the eelgrass again, although we hope to do so in a future year given funding to plant and monitor. In general, we have come to recognize that restoration of subtidal habitats is likely to take sustained effort, with the benefit that we have extended periods in which the foundational habitats we have been targeting are present to provide habitat, accumulate sediment and carbon, and provide other valued ecosystem functions. All restoration projects have basic maintenance needs, and also experience effects from weather events, seasonal influences, and natural baywide cycles of growth and dieback. As long as there is evidence that plantings will result in some amount of short term success (ie 2-3 years of growth and habitat benefits),The cost of replanting eelgrass intermittently can be a sound and cost-efficient maintenance action that helps to advance long-term success of eelgrass restoration at a site. In the case of oyster reefs, a lag period may be needed for oysters and other species to recruit and grow again after freshwater events, but if there are discrete periods of low presence within larger windows (ie 5-10 years) of generally good presence of habitat. Freshwater events that cause dieoff can be a relatively short term factor that would not necessarily cause the overall project to fail in the long term.

4.1.2 Olympia Oysters

Olympia oysters quickly recruited to the shell mound structures (by the first fall), with an estimate of more than two million present in the first year (Fig. 7). To be conservative, the population estimates included only the top layer of the oyster shell mounds (the upper third of the 1-m-tall structures), as the lower layers have accumulated sediment and may not support living oysters. The total population reached an estimated peak of three million in spring 2013, but has been in decline since fall that year. At the end of 2016, we estimated that ~288,000 oysters remained at the site. This may be attributable at least in part to lower recruitment to the site, which declined after 2013 at this site and at multiple locations along the Main shoreline and baywide, along with some expected mortality as oysters increased in size and overgrew one another. As with the eelgrass, the heavy rains in early 2017 led to losses of all of the macroinvertebrates and seaweeds at the site. No oysters were found in checks of the substrates or shorelines in April or July 2017, but new recruits appeared on settlement tiles in November and adult oysters were present on shellbags and baycrete elements in December 2017, with the total population estimated at ~57,600 oysters.

Over the course of the project we saw no differences in oyster performance in the oyster-only versus oyster + eelgrass plots (Fig. 7). Oysters also recruited in high numbers to the small baycrete structures made with concrete and mined sand and Olympia oyster shell (as measured with small quadrats, 100 cm^2). For most of the project period, baycrete structures did not support as many oysters as the shell-bag elements (Fig. 8). However, for reasons not known to us, oyster densities on bags of Pacific oyster shells declined more rapidly than on the baycrete elements, so that by our last time point, there was little difference between shell bags and baycrete structures. Measures of the baycrete structures showed that initially more oysters were present at lower and mid-level elevations (approximately -20 cm and 0 cm MLLW, respectively) than at the high elevation (~+50 cm MLLW) but these differences diminished over time with oyster densities declining at the low and mid-elevations. This may be the result of competition with other sessile species, which are more abundant at lower tidal elevations, or due to greater predation by non-native oyster drills at lower tidal elevations. The shell bag tops are at about the same tidal elevation as the "mid" level of the baycrete structures. It is possible that the decline on shell bags is due to the same causes as declines at the mid- and lower levels of the baycrete structures.

There were few differences in oyster sizes or densities between the various baycrete element structure types, with the exception of the layer cake configuration, which has more horizontal surface area, on which there were fewer oysters (Fig. 8). In addition, the stacked small oyster balls tended to collapse; hence, the larger reef balls and oyster blocks performed best overall in terms of structural integrity and oyster densities among the baycrete structures.

We measured very little sediment accumulation on the baycrete structures – never more than 4 mm – and saw no differences between the element types, although horizontal surfaces tended to have more sediment than vertical surfaces. Measurements by the Physical Processes team indicate no difference in scour or subsidence by element type. It is visually obvious that the shell bag substrates can accumulate large amount of sediment, both inside the bags and around the shell-mound structures. However, over the course of our project, sediment that built up around the shell-bag mounds over the first few years disappeared in time. Within our sample shell bags the amount of sediment varied greatly between bags and across sampling time points, and it is difficult to determine how much it impacted either recruitment or adult survival.

4.1.3 Epibenthic Invertebrate Response

Epibenthic invertebrates (those on the surface of sediments, oyster shell bag mounds, or eelgrass) were assessed quarterly using baited minnow and oval traps, suction sampling, and shoot collection (for detailed methods, see Pinnell 2016). A list of species collected with each trap type is in Table 1. Trapping with minnow and oval traps for 24 h each quarter indicated an early response of species reliant on physical structure, including shrimp (bay shrimp *Crangon franciscorum* and oriental shrimp *Palaemon macrodactylus*). Over time, several native crabs (the Pacific rock crab, *Romaleon antennarium*; the red rock crab, *Cancer productus;* and the Dungeness crab, *Metacarcinus magister*) as well as a few of the nonnative green crab (*Carcinus maenas*) tended to be more associated with physical structure, largely oyster reefs, than with mudflat. Dungeness crab sizes decreased with the added structure, with many more juveniles present following project installation, consistent with other studies indicating a nursery function of eelgrass and oyster reefs.

Suction sampling of epibenthic invertebrates (using a battery-powered aquarium pump on each type of structure or the sediment in the control or pretreatment sampling) indicated that community composition became distinct in plots with oyster reef present relative to the controls and pre-construction conditions as early as 2014 (Fig. 9). Further, the invertebrate assemblage in the eelgrass + oyster plot was intermediate between that in the eelgrass-only and oyster-only plots (although more similar to the oyster-only plot). Freshwater dips of eelgrass shoots to assess epifauna communities (Carr et al. 2011) showed epifauna assemblages on eelgrass at the San Rafael site remained distinct from those at Point Molate and Keller Beach, two natural beds just across the bay (Fig. 9). Notably, two native species known to remove epiphytes from eelgrass leaves to the benefit of eelgrass growth (Lewis and Boyer 2014) have been absent (the isopod *Pentidotea resecata*) or extremely rare (the sea hare *Phyllaplysia taylori*) at the restored site (only two individuals of the latter found, during July 2014).

4.1.4 Fish Response

Trapping of fish (the same oval and minnow traps described above for invertebrates, with deployment for 24 h once each quarter) showed much overlap in species composition among the treatments; however, a pattern of black surfperch (*Embiotoca jacksoni*) and bay pipefish (*Syngnathus leptorhynchus*) having a greater association with eelgrass habitat emerged early on. Seining results indicated early recruitment to eelgrass by bay pipefish (within one month of the April 2013 replant) and that eelgrass presence increased the occurrence of certain fish species among oyster reef structures, including bay pipefish, shiner surfperch (*Cymatogaster aggregata*) and saddleback gunnel (*Pholis ornata*).

Acoustic monitoring using an array of 69-kHz receivers to detect tagged fish showed that individuals of several species visited the vicinity of the site, including two white sturgeon (*Acipenser transmontanus*), a green sturgeon (*Acipenser medirostris*, a threatened species), a leopard shark (*Triakis semifasciata*), a steelhead (*Oncorhynchus mykiss)* smolt, and a striped bass (*Morone saxatilis*). Positional analysis found tagged fish only rarely occurred within the San Rafael site boundaries; these included a leopard shark visiting repeatedly over a period of eight days in March through June 2013 near the oyster + eelgrass plot and eelgrass only plots, and a steelhead smolt and a white sturgeon lingering near the oyster + eelgrass plot during a single period each of 20-40 minutes in March 2013. In general, the fish included in tagging programs in the region were found in deeper water offshore of the project site, perhaps suggesting that our project was too shallow to attract these species.

4.1.5 Bird and Infaunal Invertebrate Response

To evaluate bird and infaunal (in-sediment) invertebrate responses, the treatment area at San Rafael was subdivided into a zone encompassing the eelgrass and oyster treatment plots (zone B) as well as 150-m zones immediately inshore (zone A) and offshore (zone C) of the plots, and a nearby control (un-manipulated) area was divided in the same way; here, we focus on zone B. Avian density and behavior were surveyed at high tide (>0.8 m MLLW) and low tide (<0.25 m) from shore two times a month during the fall (September, October, and November), winter (December, January, and February), and spring (March, April, and May). Benthic cores (10 cm diameter) were collected during September and May of each year to sample infaunal invertebrates along transects that bisected each zone.

Results of the avian surveys indicate that the project enhanced habitat compared to pre-treatment and control areas, with both species richness and diversity increasing in the treatment area in years 2-5 (Fig. 10). Densities of black oystercatcher (*Haematopus bachmani*) increased in the treatment area in comparison to pre-installation and control densities, and Forster's terns (*Sterna forsteri*) and wading birds (herons and egrets) began using the treatment area only after installation. At low tide, avian densities appeared to be higher in Zone B of the treatment area in comparison to the control area for four years post-treatment; however, this difference was not significant. During low tide, diving duck densities in the treatment area have become increasingly greater than in the control area over time. Comparing behavior of all bird species during low tide, the treatment area was used more for foraging than was the control area (Fig. 11); non-foraging (resting, preening, etc.) behaviors were predominant at high tide. Average dive lengths of diving ducks (bufflehead *Bucephala albeola* and ruddy duck *Oxyura jamaicensis*) were longer in the control area compared with the treatment area, suggesting that invertebrate prey may have been more accessible, profitable, or both in the treatment area.

Benthic infauna community composition within Zone B of the treatment area was more complex than in the control area and included 6 phyla, 9 classes, 14 orders, 26 families and 20 distinct taxa identified to genus or species level, compared to 4 phyla, 6 classes, 10 orders, 18 families and 15 distinct taxa within the control area. While the number of taxa found in the treatment area was greater than in the control, we did not find significant differences in the overall densities or biomass of invertebrates. Amphipods and polychaetes were the densest taxa in both control and treatment Zone B in all years except the spring of year 5, when bivalves and cumaceans dominated. Polychaetes dominated benthic invertebrate biomass in Zone B until spring of year 5, when bivalves and cumaceans comprised the majority of biomass in both the control and treatment areas.

4.1.6 Physical Processes

Water quality was monitored from 2013 through 2017 using a multi-parameter sonde to collect ambient water temperature, salinity, dissolved oxygen (DO), pH, and turbidity data. The sonde was located on the bay side of the treatment area and submerged in 1 meter of water at low tide; a similar sonde at China Camp State Park to the north allowed for comparisons among measures. Of particular interest, salinity at both sites fell below 5 PSU for periods of weeks and in the range of 10-15 PSU for several months during the record rainfall of January-April 2017 (Fig. 12), coinciding with the large die-offs of eelgrass and oysters noted in the sections above.

Bathymetric surveys of the mudflat surface within 100 m of treatment plots at San Rafael prior to construction and again in 2014, 2016, and 2017 indicate that the treatment plots have little measurable impact on the overall pattern of erosion and sedimentation in the project area. The surveys showed a trend of erosion bayward of the plots and sediment deposition shoreward of the plots in all years except for the record rainfall year of 2017, which resulted in substantial sediment deposition across the entire area. Local sedimentation and erosion in and around the reef elements were monitored from 2013 to 2016. Surveys found that after an initial pulse of sedimentation in and around the shell mound units, sedimentation rates slowed and, in some areas adjacent to the units, an overall loss of sediment has been observed since construction. Note that local sedimentation surveys were not completed following the substantial sediment deposition that occurred early in 2017 with the record rainfall.

As of 2016, an average of 0.11 m of subsidence of the reef elements had been observed (average for shell bag mounds and four baycrete elements). As expected, the rate of subsidence was most rapid initially, and decreased over time. More than half of the total subsidence (0.06 m) occurred during the first three months of monitoring (Fig. 13). The baycrete elements subsided nearly four times as much as the shell bag elements since monitoring began, with subsidence of 0.15 m and 0.04 m, respectively. This may be a function of the relative weight of the elements, differences in buoyancy, or other factors.

The combination of shell bag settling, sediment accumulation around the reefs, and subsidence means that not all of the surface area of the individual elements is available to support oysters, and this area has varied over time (Fig. 13). When monitoring began in November 2012, the tops of the shell bag mounds were approximately 0.64 m above the sediment surface, but with subsidence and sedimentation in the first year, only 60-70% of the surface area was available to oysters. Subsequently, element subsidence slowed and previously-accumulated sediment eroded. By February 2017, as much as 90% of the shell mound surface area was once again available for oyster recruitment.

Wave monitoring was conducted in 2013 using two bottom-mounted acoustic doppler current profilers (ADCPs), with measurements taken in the lee (shoreward side) of a treatment plot and a control plot over a two-month period. Wave heights ranged from 0.06 m to 0.26 m in both locations, with fewer waves above 0.06 m in the lee of the oyster-eelgrass plot compared to the control (21 and 45, respectively) (Fig. 14). To further understand a larger range of wave conditions, the measured data were used to calibrate a numerical Boussinesq wave model. Results indicate that that the oyster-eelgrass plot dissipates approximately 30% of wave energy relative to the control plot at mean tide level and over a short distance (the width of the plot), adding to the much larger attenuation of the broad mudflat.

4.2 Hayward (ELER) Site

4.2.1 Eelgrass

Eelgrass at this smaller-scale project site reached 75% of planted densities by July 2013 (after a May 2013 replant) and survived through the fall months; however, major declines occurred during the next winter and only two shoots remained by summer 2014 across the 10 small plots. Eelgrass tended to be shorter at Hayward (~80 cm) than San Rafael, perhaps owing to shallower site conditions at Hayward. Plants at this site had high densities of the Eastern mud snail, *Ilyanassa obsoleta* (both adults and eggs) on their leaves and also appeared to experience substantial sediment movement and burial; either or both could have contributed to the observed eelgrass mortality.

4.2.2 Olympia Oysters

Oyster recruitment at Hayward did not occur until spring 2013 and then at a much lower rate than at San Rafael. In general, recruitment and survival were much lower at the Hayward site. Oysters were preyed upon by a non-native oyster drill, *Urosalpinx cinerea,* which is not present at the San Rafael site, and also settled heavily on top of barnacles, which later died and fell off of the restoration structures. At the height of the population at Hayward (summer 2013) we estimated ~2,000 oysters on our test elements; even this relatively modest effort increased the population by one order of magnitude. Experimental work indicates that predation by drills is a major cause of mortality at this site, with greater mortality at lower tidal elevations. Oysters survived longer on the baycrete structures (especially the oyster blocks) than on shell bags, particularly at the mid and high tidal elevations, but after fall 2015, there were few live oysters present.

4.2.3 Epibenthic Invertebrate Response

Trapping results at Hayward showed that shore crab (*Hemigrapsus oregonensis*) abundances increased within the treatment area relative to the control area and pre-project conditions. Eastern mud snails (*I. obsoleta*) were by far the most common invertebrates in traps, with hundreds found per trap in some seasons but no difference with added structure relative to the control area. Suction sampling of epibenthic invertebrates on the oyster shell mounds and eelgrass plots indicated that the mounds developed a distinct community relative to eelgrass when the eelgrass was still present, but in general, there was much overlap in assemblage characteristics with the control area and pre-project conditions, perhaps because of the small footprint of the added structure at this site (Pinnell 2016).

4.2.4 Fish Response

Trapping was conducted to assess fish use of this site in the treatment area versus control (unmanipulated) area. Besides leopard sharks (*T. semifasciata*), which were commonly caught in both control and treatment areas, only one to three individuals of other species were caught (barred surfperch [*Amphistichus argenteus*], Pacific staghorn sculpin [*Leptocottus armatus*], topsmelt [*Atherinops affinis*], jacksmelt [*Atherinopsis californiensis*], Pacific sand dab [*Citharichthys sordidus*], and sevengill shark [*Notorynchus cepedianus*]) over the course of the project to date, making it impossible to discern patterns relative to the addition of reef structure (and eelgrass before the end of 2013).

4.2.5 Bird and Infaunal Invertebrate Response

Although the footprint of the treatment area was substantially smaller at Hayward than at San Rafael, the same zone arrangement was used to assess bird and infauna responses to treatments and for consistency between the two sites. While avian diversity and richness were higher at San Rafael, both pre- and post-installation avian densities were higher at the Hayward treatment and control sites, where small shorebirds predominated. Even with the small project footprint, wader species increased substantially (ANCOVA, $F_{1,117} = 3.52$, $p = 0.063$) post-installation in the treatment area at Hayward. As at San Rafael, the Hayward treatment area was used primarily for foraging at low tide and non-foraging (resting, preening, etc.) behaviors at high tide. We observed a substantial increase in bivalves in the first post-installation sampling period. Several years of monitoring at this site established a baseline of avian and infaunal invertebrate characteristics that will be useful if larger-scale restoration projects go forward in the future.

4.2.6 Physical Processes

Subsidence of the individual elements at Hayward was similar to San Rafael initially, with an average of 0.05 m in the first 3.5 months for all element types. Over the full monitoring period, baycrete structures subsided approximately 37% more than shell bag structures (average of 0.14 m and 0.10 m, respectively). Monitoring of sediment accumulation/erosion was not conducted after 2014. The small-scale treatments did not allow for physical monitoring of wave attenuation and sediment accretion.

5 Progress toward Addressing the Project's Objectives

Objective 1: Use a pilot-scale, experimental approach to establish native oysters and eelgrass at multiple locations in San Francisco Bay

As this project is the first living shorelines design carried out in San Francisco Bay and one of few focused on native oyster and eelgrass habitats on the West Coast, it was important to start small to gain acceptance for such projects among regulators and the public. However, we recognized the need for the project to be large enough to allow assessment of physical effects along shorelines and to attract species that require a larger habitat area for food or refuge services. Thus, at the San Rafael site, we chose a size deemed large enough to meet our science goals but small enough to still be a reasonable pilot project to install and permit.

An experimental approach was important to the project team, as we wished to understand the successes and shortcomings of the restoration project in a rigorous way. However, we settled on only one replicate of each treatment type at the San Rafael site because of space limitation on the San Rafael shoreline parcel owned by The Nature Conservancy. Also, current regulatory policies limit the amount of fill (including oyster shell) that can be placed in the estuary; thus, our project team worked thoughtfully to limit the overall size of the installation to meet permit requirements, while carefully experimenting with methods and techniques to construct the largest reefs in San Francisco Bay to date. The goal of this pilot project was to learn what materials, designs, and approaches work best, ideally leading to additional pilot projects at more sites and also larger-scale projects of this type in the future. From the standpoint of statistical analysis, having only one plot per treatment type means that replicate samples within a plot are not true replicates, as they are not interspersed with other treatment types across the space of the San Rafael property. The risk in interpreting data with only the four large plots spread across the site is that there could be other differences across that space that are not related to the treatments (e.g., sedimentation), thus confounding interpretation of differences by treatment. Still, with care in interpretation, we can say quite a bit about how the treatments evolved habitat and physical functioning characteristics over time and relative to each other. For the smaller-scale comparison of oyster substrates, we were able to achieve true replication at both the San Rafael and Hayward sites, making a rigorous comparison of treatments possible statistically for a number of measures.

We intended to repeat the same design in multiple locations around the Bay so that we could determine how environmental context influenced our results; however, we found it difficult to identify locations that met our site selection criteria (e.g., bathymetry, relative ease of access, appropriate depths for eelgrass and oysters, willing landowners, etc.) and thus began with just one larger-scale project. At Hayward, many of our site selection criteria were met; however, we felt we did not have enough information about the site to be confident that we could establish both oysters and eelgrass and were unwilling to scale up to a larger project until that was achieved.

The project team recently assessed seven candidate sites in SF Bay for a next-phase living shorelines project, to actively enhance native foundation species: eelgrass and Olympia oysters as in the current project, as well as several other habitat types. This assessment resulted in selection of Giant Marsh at Point Pinole for the next living shorelines project. Our integrated approach involves restoring these habitats as a linked gradient from the terrestrial border through the marsh to shallow subtidal oyster reefs and eelgrass beds, to increase habitat connectivity and structure and promote both restoration goals and physical goals such as wave attenuation.

Objective 2: Compare the effectiveness of different restoration treatments in establishing these habitat-forming species

We have used five approaches to address the effectiveness of different restoration treatments in establishing native oysters and eelgrass. **First,** our project explicitly aimed to test whether restoring oysters and eelgrass together versus each organism alone would improve outcomes for either species. This test entailed evaluating eelgrass growth patterns (densities, heights, etc.) when eelgrass is grown alone versus in proximity to oyster shell reef, and similarly by assessing oyster growth patterns (densities and sizes) when oyster shell reef is restored alone versus in proximity to eelgrass. Later in the project, we also addressed the potential benefits of oyster reefs in protecting eelgrass plantings on the shore side of the reefs. **Second**, we tested five types of oyster settlement substrates to determine which would perform the best. In the ideal, a substrate would promote native oyster recruitment, growth, and survival, while discouraging the growth of nonnative species; would not be prone to sinking into soft sediment substrates; and would not cause significant scour, or accumulate large amounts of sediment. Obviously, restoration substrates also need to maintain their structural integrity over time or until biogenic species can add or maintain physical structure independently. **Third,** we tested transplants versus seeding of eelgrass at the San Rafael site. **Fourth**, we tested whether the donor (the natural bed collected from) mattered to the outcomes achieved for eelgrass establishment and development of functional attributes of the restored eelgrass. **Fifth**, we assessed whether the position on oyster elements or the placement of whole oyster settlement substrates at different elevations would influence the effectiveness of native oyster success.

For the first approach, several lines of evidence suggest that there is a benefit to restoring native oysters and eelgrass together. Although trapping has caught a limited number of individuals, a few species of fish were found among oyster reefs at San Rafael only when eelgrass was also present. In addition, suction sampling of epibenthic invertebrates showed that the eelgrass in the combined eelgrass + oyster treatment at San Rafael supported additional species found in the oyster-only plots as well as those found in the eelgrass-only plot. On the other hand, we did not find benefits of oyster reef presence to eelgrass growth characteristics (and in fact eelgrass performed better over time when planted alone than in our combined plots with the checkerboard design), nor have we seen oyster abundance or size increase in the presence of eelgrass (but we have not documented any negative effects of eelgrass on oysters). However, with replanting of eelgrass in spring 2016, we found evidence that oyster reefs are beneficial to eelgrass planted along the shoreward side of reefs, with much greater densities establishing there than on the bayward side or where eelgrass was planted alone. In order to adequately test for effects of dual restoration, we need additional sites where oysters and eelgrass are restored both together and separately, although we suggest greater spacing between oyster reefs and eelgrass in future projects. We also recommend further testing of the potential benefits of oyster reefs on eelgrass plantings on the shoreward side.

For our second approach, we found that oysters performed equally well across the various types of baycrete structures at San Rafael, with one exception—there were fewer oysters on layer cakes. This may be because oysters performed better for several years on vertical versus horizontal surfaces, and layer cake surface area is primarily horizontal. Initially, shell bag mounds outperformed all baycrete structures in terms of number of oysters on a per-element basis, but this difference did not persist as overall numbers of oysters declined with time. Two element types appear to have less structural integrity than the others: layer cakes and small reef ball stacks, both of began to shift or break down. Very little sediment accumulated on the surfaces of baycrete elements (never more than 4 mm). The shell bags at the top of the mounds accumulate variable amounts of sediment and within a bag some shells, particularly those that are deeply cupped, can fill with mud, but other, flatter shells are relatively clean. We have not formally analyzed the cover of non-native species, but the sponges, tunicates, and large arborescent bryozoans found particularly at lower tidal elevations on the elements were not present inside the shell bags, although they did grow sparsely on the outsides of the bags at the top of the mounds and more heavily on the lower portions.

At Hayward, oysters recruited initially to shell bags only, but later were most abundant on the oyster blocks. This may be because the oyster block elements at Hayward have more vertical surface area at higher tidal elevations than the other structures, which appears to discourage oyster drills. However, very low numbers at present currently suggest caution in emphasizing the value of any one settlement substrate at this site.

For our third approach, we were only able to use buoy-deployed seeding at the San Rafael site and flowering shoots only from the Point San Pablo donor site, as flowering shoots were not available at the time of our late summer project start for the other three populations used as donors for transplant material. At San Rafael, we did not detect seedling recruitment in the spring of 2013 after buoy-deployed seeding, and we did not repeat seeding after we conducted the second transplant that April; we would not have had flowering shoots available until summer and did not want to risk damaging transplants by adding the seed buoys into the plots afterward. Thus, in comparing the two methods of eelgrass establishment, we conclude that transplanting whole shoots was the more effective technique overall, in terms of both availability of propagules and success of establishment. However, we still recommend seeding when possible because sexual reproduction can increase the genetic diversity of restored stock and may therefore increase the resiliency of eelgrass to perturbations at restoration sites over time.

In our fourth approach, the Point Molate donor bed showed a trend of greater transplant success at San Rafael, with higher overall densities than the Point San Pablo donor. Point Molate eelgrass may be better suited to the sediment conditions found at San Rafael, as both sites have a higher proportion of fine sediments than at Point San Pablo (Boyer and Wyllie-Echeverria 2010). Although we found no difference in growth characteristics between the two donors used at the Hayward site in the limited time we had to assess the eelgrass, the trend of differential success among donors at San Rafael, and similar evidence from previous projects (e.g., Lewis and Boyer 2014), lends support to our hypothesis that donor choice can matter to restoration success.

In our fifth and final approach to assessing restoration techniques, we found tidal height, surface orientation, and direction to influence oyster density at the San Rafael site, although these effects decreased over time. Across all element types at San Rafael for the first several sampling periods, more oysters were present at the lower and mid-level elevations than at the high elevation. Additionally, more oysters were present on the north side than on the south side and on vertical versus horizontal faces. While longer immersion times could explain greater abundance at lower tidal elevations, the north–south and surface orientation differences suggest that heat or desiccation stress was a factor in determining initial oyster abundance at San Rafael. Oyster abundances at the mid- and low tidal elevations began to decline in spring 2014, however, and densities at all tidal elevations became similar. This decrease was concurrent with an observed increase in fouling species, particularly bryozoans, sponges, and algae at these lower tidal elevations, which may compete with oyster spat for settlement space or overgrow adult oysters, and with a decrease in recruitment to the site over time, as indicated by our recruitment plates. At Hayward, while oysters recruited initially to shell bags and then to the interior surfaces of the large oyster balls, two structure types that would be expected to be the best in mitigating heat and desiccation stress, more oysters were found on the higher elevations of oyster blocks and large reef balls. As mentioned above, this can likely be attributed to predation by the Atlantic oyster drill *U. cinerea*, which is more abundant at the lower elevations. Results from this work and elsewhere (e.g., Trimble et al. 2009) indicate that oysters generally settle in higher numbers and grow faster at lower tidal elevations. At Hayward, this nonnative predator may thus restrict oysters to a non-optimal tidal elevation.

Objective 3: Determine the extent to which restoration treatments enhance habitat for invertebrates, fish, and birds, relative to areas lacking structure and pre-treatment conditions

We have accumulated evidence that providing the physical structure of our project design attracted a number of mobile invertebrate species that benefit from such structure. At both San Rafael and Hayward, wading bird presence increased after the placement of reef structures. At San Rafael, overall avian species richness and diversity increased in the treatment area relative to the control area. Black oystercatchers and Forster's terns were found to utilize the reefs for foraging and roosting. Additional monitoring is necessary to determine how the strengths of these relationships will develop over time. Acoustic detections indicate that several fish species of concern came near the project site at San Rafael, but shallow depths may have limited use of the treatment area proper.

Objective 4*: *Determine if the type of treatment (e.g., oyster reefs, eelgrass plantings, or combinations of oyster reefs and eelgrass) influences habitat values differently

We can conclude from the San Rafael experiment that certain species are benefited more by one substrate than the other. Black oystercatchers and wading birds increased in the presence of the oyster reef structures. Black surfperch and bay pipefish were shown to have a greater association with eelgrass habitat than with oyster-only or control plots, and epibenthic invertebrate assemblages are differentiated between the eelgrass and oyster reef habitats. Eelgrass presence increased the occurrence of certain fish species among oyster reef structures (bay pipefish, shiner surfperch, and saddleback gunnel), thus restoring the two habitats in proximity to each other can increase the number of species present.

Objective 5: Begin to evaluate potential for subtidal restoration to enhance functioning of nearby intertidal mudflat, creek, and marsh habitats (e.g., by providing food resources to species that move among habitats)

As we do not have marsh or creek habitat in proximity to the San Rafael site, we are not able to determine the degree to which our added structures influence functioning or provide subsidies to these habitats. We are able to say that increasing physical structure enhances functions relative to mudflats, at least for species that benefit from the refuge and food resources that are provided by our project. An increase in wading birds and in black oystercatchers through the addition of our project is a good indication that certain guilds of birds are benefiting. Further, the overall number of infaunal invertebrate taxa was higher in treatment compared to control areas, suggesting a potential for increased foraging opportunities for benthic foraging birds and fish.

Objective 6: Evaluate potential for living subtidal features to reduce water flow velocities, attenuate waves, and increase sedimentation, and assess whether different restoration treatments influence physical processes differently

We observed less and shorter-term subsidence of the reefs in soft sediment than we expected. Our data showed only a 0.11 m subsidence into the sediments over the first several months, thus even in the very soft sediments of the San Rafael site sinking of reef structures is not a great concern. Sediment accumulated around the oyster shell bags during the early part of the project, and in periods like this, the reefs are unlikely to support oyster survival at the lower elevations. This sediment accumulation led us to include only the upper portions of the reefs in our estimates of oyster abundance and also suggests that future projects should consider this issue when predicting habitat availability on the reefs. Since, with the exception of the layer cakes and small reef ball stacks, the different element types appear to have performed similarly in terms of stability, the choice for the construction of future reefs should be made based on their performance in oyster habitat terms, which may point to the use of shell bags, reef balls, or perhaps oyster blocks (based on the Hayward results). Future deployments should allow for the loss of available space for oysters owing to subsidence and sedimentation. Larger elements, if used in the future, will tend to subside more.

Our reefs achieved a reduction in wave energy (30%) more so than the broad mudflat alone at MTL; however, we are cautious in our interpretation of this result considering we measured only a limited combination of waves and water levels. Ideally, we would have similar reefs located in multiple locations with different slopes and wave regimes to permit further assessment of such structures in attenuating wave energy along San Francisco Bay shorelines.

Objective 7: Determine if position in the bay, and the specific environmental context at that location, influences foundational species establishment, habitat provision, and physical processes conferred by restoration treatments

Although we currently have just two project sites to compare, and only the small substrate comparison at the Hayward site, there are a number of conclusions we can draw about the effects of environmental context. For example, eelgrass persistence and spread was far superior at San Rafael, perhaps due to much less exposure on the low tides in this deeper site or due to the Eastern mud snails at Hayward (not present at San Rafael) weighing down the plants or blocking light to the leaves with their egg masses. In addition, oyster shell bags easily outperformed other substrates in oyster recruitment early in the project at San Rafael, but at Hayward, oyster blocks appeared to be the best. A shell bag element offers more surface area than any of the baycrete elements and likely provides greater protection from heat or desiccation stress due to more shading and water retention and perhaps the somewhat lower tidal elevation relative to the baycrete structures. However, at Hayward, where predation pressure is strong and greater at lower elevations, taller structures with more exposed surfaces outperformed shell bags. Thus, it appears that selection of optimal substrate needs to be guided by an understanding of the key stressors for eelgrass and oysters at each site. Having additional sites at which to deploy test substrates and measure potential stressors would be useful to further refine site-specific design criteria.

Objective 8: Where possible, compare the ability to establish restoration treatments, habitat functions, and physical changes along mudflats/wetlands versus armored shores

At this point, our project does not include a comparison of a soft shoreline versus hardened shoreline environment. A future project at Hayward could accomplish this by comparing areas north (riprap) and south (marsh) of Mount Eden Creek. A new project at Giant Marsh at Point Pinole will allow active restoration of foundational marsh plant species in an integrated design with eelgrass and oyster reefs, as described earlier; however, this site does not also include armored shoreline that can be used in comparison.

6 Recommendations and Lessons Learned, Applicability to Future Similar Pilot Living Shorelines Projects

6.1 Project Development, Fundraising, and Assembling Teams

- Incorporate San Francisco Bay Subtidal Habitat Goals (2010) science and restoration recommendations into designs, as well as Baylands Goals Science Update (2015), SF Estuary Adaptation Atlas (2018), and other regional planning documents. Follow the recommended phased stepwise approach for native oyster and eelgrass restoration, starting with site monitoring and small scale treatments before scaling up, unless available data collected by others can inform design, or there are other key reasons to jump forward.
- Allow extra time for assembling an interdisciplinary team of ecologists, biologists and engineers; allow more time and budget for integration between disciplines. Take time at the beginning to define terms, goals, site selection criteria, design criteria, and key synergies and challenges between planning approaches for biological and physical outcomes.
- Pilot nature of project- capital D in Demonstration- requires willingness to share project information and process, data and outcomes, successes and lessons learned. This can be a conflict for contractors or consultants who have proprietary methods that they prefer not to share, and requires comfort level with approaching and implementing the project with full transparency on project details. We have benefited from an enthusiastic team who is excited to be part of and share this demonstration project widely.
- Identify local, state, and federal funding sources that are a good match with the project type, scale, and outcomes. Leverage grant applications, it can often be beneficial to write several and submit at thesame time- saves effort in preparing proposals and allows for a comprehensive project description with all match. Plan and include as many project phases in one proposal as possible- often it's common to get an initialseed grant for conceptual design phase, but try to avoid writing multiple grant proposals for each phase. Include permitting, implementation, monitoring, and maintenance as part of the project. Even if this means anticipated future phases by funder and not directly funded all upfront.
- Plan for

6.2 Site Selection

- We started from a list of sites recommended in the SF Bay Subtidal Goals recommendations and additional opportunities that had been identified; and put three sites through an initial screening process that included multiple key feasibility factors to consider.

6.3 Design and Pre-Construction Monitoring

- Develop specific and agreed upon project goals, objectives, and design criteria early in the process. Modify as needed while the design process progresses, but note that substantial changes to approach mid-design can cause design steps to be repeated, project delays, and additional costs.
- Implement pre-construction existing conditions assessment/monitoring, for one year or more prior to design, during appropriate seasons for species of focus. Make sure there is enough site-based data or modeling on physical and biological conditions that are critical to design- including site bathymetry/elevations, wave energy, wind energy, special status species presence, etc.
- Get early input on conceptual designs- from biological and physical technical experts not on the design team, regulators, contractors, landowners, adjacent landowners, community members, nearby residents, and current and potential funders.

Oyster and Eelgrass Design:

- Continue further testing of successful oyster reef approaches- Pacific oyster shell bag mounds, large reef balls, oyster blocks.
- Discontinue use of stacked small reef balls and layer cake designs- do not hold up well physically.
- Construct oyster reefs/hard structure treatments prior to installation of eelgrass
- Optimal oyster reef construction – April-October besttiming for oyster recruitment in San Francisco Bay.
- Optimal eelgrass installation timing- April-June to time with best growing season. Avoid late timing- limited light later in season- can result in eelgrass not establishing well.Design and implement eelgrass experimental plantings both inshore and offshore of oyster reefs
    a. Inshore most protected from oyster reefs
    b. Offshore may add value to subtidal mudflat protection
- The presence or absence of eelgrass does not seem to impact the success of oyster recruitment and performance, as this study found no differences in oyster recruitment and performance in the oyster-only vs. oyster and eelgrass combination plots.
- There are biological benefits to restoring native oysters and eelgrass together. This project found a few species of fish were found among oyster reefs at San Rafael only when eelgrass was also present. Invertebrate sampling also showed that the eelgrass in the combined eelgrass + oyster treatment at San Rafael supported additional species to those found in the oyster-only plots as well as those found in the eelgrass-only plot.
- Reduced habitat availability on lower portions of the reef elements was due to sediment accretion, not due to structures sinking after placement.
- Plan for sedimentation in oyster element design. Best oyster substrate is at upper and mid elevations of reef elements- don't use half shell at base, use more available materials like baycrete.
- Consider adding shell bags to top of reef balls- combination element to best use materials at specific elevations.
- Enhance native crab habitat at lower elevations of elements- can act as biological cleaners to remove detritus and organic debris, and algae, from reefs.
- When placed too close together, the reef elements had detrimental impacts on the survival of eelgrass plantings, however reef elements seemed to provide protective benefits to eelgrass planted on the shoreward side of the reefs. Allow enough space (up to 25 meters) between oyster and eelgrass treatments, to allow space for eelgrass expansion, and limit abrasion of eelgrass from hard structures.
- Avoid areas with non-native oyster drills, or locate oyster treatments higher in the tidal frame.
- Develop new source of clean Pacific half shell- create pilot oyster shell recycling program with local growers and restaurants.

Fish considerations in Design:

- Tagged fish preferred deeper treatments, design specific elevational treatments per fish guilds

6.2 Fabrication and Construction

- Selection of optimal construction materials must be guided by an understanding of the key stressors for oysters at bag elements offer more surface area than any of the baycrete elements and are effective at higher elevations, taller structures with more exposed surfaces outperformed shell bags when located in lower elevation areas with strong predation pressure.
- Selection of optimal construction materials must also be informed by input from the regulatory agencies and what types/amount of fill they will allow. Early consultation is critical to discuss the specifics about the materials and methods to see what is permittable.
- Fabrication of oyster reef elements (including shell bags using clean Pacific oyster half shell, and various baycrete or concrete reef ball type forms, and other elements) is an innovative new activity that is in the research and development stages in San Francisco Bay and on the west coast. It takes extra time and requires higher costs until methods become standardized and contractors gain experience and training. Allow extra time and budget for planning and assembling teams that are willing to collaborate on these pilot projects, which requires extra effort, strong communication with interdisciplinary partners, willingness to test and fail and modify designs, and willingness to provide documentation of methods, successes, and also lessons learned.
- Tap into the national expertise that has been developed on the east and gulf coasts, and engage experienced east and gulf coast and other consultants who can help to modify designs that are appropriate for the west coast. For this project, it worked well to have a consultant come out from Reef Innovations in Sarasota, FL who worked alongside local contractor Dixon Marine Services who provided materials, yard space, and labor.
- Pilot nature of project- capital D in Demonstration- similar as in design guidance, it's worth noting again that it requires willingness on the part of fabricators and contractors to share project information and process, data and outcomes, successes and lessons learned. This can be a conflict for contractors or consultants who have proprietary methods that they prefer not to share, and requires comfort level with approaching and implementing the project with full transparency on project details. Add info here on discussions with concrete fabrication companies, econcrete, etc.
- Fill Type and
- Fabrication materials must be carefully planned and considered. For this project, we used two methods: clean Pacific half shell placed into mounds, and reef structures made from a mix of concrete and native bay materials, The clean Pacific half shell was purchased from Drakes Bay Oyster Company, which has closed and is the last local source of shell as they had a shucking/canning facility to sell the meats and the shell was a waste product that could be reused for reefs. The shell must be stored, ideally outside in areas of good sunlight, and the shell piles should be regularly turned so that the material on the bottom rotates to top and also receives air and sunlight to cure. The shell needs to be clean of any disease or invasive species that could negatively impact ecosystems when the shell is placed into aquatic waters. Zabin and Cohen 2010 shell curing protocols were approved by the regulatory agencies and used for this project.
- Baycrete development:
- The location and air temperatures can affect the curing time for shell, and for baycrete- warmer locations will allow shell and elements to cure faster, versus cooler, foggier locations. The 75 baycrete elements were

- Construction- funding considerations with selection process- not well suited for standard public bid/lowest cost approach at this research and development stage.

- Construction management- relationships between project owner, contractor, project team- with such interdisciplinary and specific roles. Requires extra effort and willingness by all partners to spend more time on communications and with more entities.

6.3 Monitoring Methods and Frequency

- Mismatch of method, frequency- can result in unusable data or data with minimal value.
- Coordinated field events- conflicts between teams- bird monitoring conflicts with other teams monitoring on site, or with preferences on access timing/frequency/amount of people on site by landowner.
- Wave monitoring- adcp then model.
- Sediment monitoring- sediment plates
- Construction monitoring- clarity on purpose and methods for pre and post bathymetry

6.4 Governance and Permitting

- Allow 6-12 months for permitting, allow a minimum of 3-4 months after final permits received to incorporate requirements and select contractor to mobilize

- Substantial information is requested by the agencies in the permit applications, but then it can often become too much material for regulatory staff to review which can cause delays and also cause confusion on the project components.

- Challenging for regulatory staff to interpret content on species, techniques, methods for less common applications (subtidal habitats, etc.) historically. Hard to recognize/value connections to regional recs such as Subtidal Goals if staff are not familiar with these documents.

- Inconsistency within and between agency staff on understanding/analysis of subtidal habitats/restoration methods; benefits; and impacts. Example: SWRCB- length of permit/timing of consultation for San Rafael vs for Giant Marsh.

- Need for improved/shared understanding of regional recs like Subtidal Goals, Baylands Goals, TMRP, CCMP, etc. Understandably a lot to review, but important for staff to be familiar with documents and history of prior multi-agency planning.

- Discuss Subtidal Goals science, management, and restoration goals; and phased restoration approaches for oyster and eelgrass.

1. Recommend regulatory review/improvements to allow more thoughtful testing of beneficial bay fill to improve habitat.
2. Recommend regulatory review/improvements to support science-based experimentation in the face of data gaps. Test at small scale to learn more about best techniques, timing, approaches for future larger scale projects.

Recommend exploration of need for regional programmatic permits to facilitate small scale pilot restoration and make requirements clearer and more consistent for applicants.

Outreach and Information Sharing- include summary of 60+ presentations and 30+ media and online articles, conferences, webinars, etc.
General Audience/ SF Bay Area
Technical

Priority Topic Areas for Deepened Information Sharing:

- **Multi-habitat projects- proximity conflicts to address in design:** construction of eelgrass beds and oyster reefs adjacent to tidal wetlands, upland ecotones, etc. Major global, national, local recommendations to conduct multi-habitat approaches, for connectivity and function, and for increased climate adaptation/green infrastructure that is more robust and able to adapt to climate changes. Regulatory restrictions can prevent these activities from being in close proximity, but there are several good outcomes from the permitting of the Giant Marsh Living Shorelines Project that can be considered for similar future multi-habitat project consultations.

  Goals of linking habitats, reasons for close proximity for wave attenuation, habitat connectivity, species connectivity (foraging, nesting, roosting, etc.)

  Seasonal species conflicts: optimal species construction can be during adjacent habitat species nesting, breeding, etc. Plan for best timing to address species considerations, plan methods and equipment and duration to minimize disturbance, conduct biological surveys during unavoidable access, adhere to strong conservation measures that limit impacts. Share conservation measures for LSP Giant.

  Solutions for Giant Marsh:

  <u>Rail/subtidal proximity- restrictions if rails within 500'-</u>

  a. needed to conduct rail call count monitoring prior to construction- EBRPD- confusion on which protocol and final confirmed was "contractor protocol"- 4 call count rounds, playback on last 2 if birds not heard on first 2. Mitigation level monitoring- but results in additional impacts from 4^{th} round. Prefer to use the North American Protocol or Site-Specific Protocol- USFWS uses term X. Need consistency for monitoring protocols.
  b. On site, required to have a biological monitor- approved by agency staff, not "FWS service approved" which is a technical definition that only applies to limited personnel in SF Bay.

c. If rails present, follow X protocol and document, but can still continue to work.

Seasonal window for oyster recruitment/windows for birds, salmon, etc.

a. Best timing for oyster construction- April-October- later period potentially better but need to continue testing. April-May allowed at Giant with conservation measures. For projects that also have eelgrass component- oyster reefs must be installed first, but eelgrass needs to be planted in seasonal window April-June. Have seen poor results with July-August eelgrass plantings- too late in the season. Construction is often short in duration for many projects- Giant Marsh oyster construction occurred 4/11-5/3 during specific tide dates within that period (ie not occurring daily for months on end). Examples: modifications- If ospreys found, can relocate. If salmon or other special status species observed, can stop work. Turbidity monitoring is conducted to confirm no long term turbidity increases occurring during construction, plan for stopping if this occurs.

1. **Pilot level projects, first of their kind projects**- moving forward with careful testing in context with existing lack of data on these project types.

2. **Fill placement/materials (baycrete, reef balls, shell bag structures, etc.)**
    1. More information sharing-
        1. Shell suitability, availability, curing
        2. PVC mesh bag use and performance- higher success in less wave energy/slope
            1. Performed very well at San Rafael and Hayward since 2012.
            2. Portion of Red Rocks site had issues- due to fabrication method and also due to slope/wave energy.
        3. Shell bag mound height and design
            1. Physical goals
            2. Elevational benefits/zones for oysters
            3. Benefits to other species- substantial data from San Rafael- more than 10 taxa, 100 species- need to increase understanding of benefits as it relates to each agencies' mandates.
            4. Shell availability- extremely limited until shell recycling program initiated. Need to use other materials in place of shell until then.
            5. Baycrete- fill material type- incorporating natural mined bay sand, fossilized olympia shell. Benign impacts of marine grade concrete- appropriate material for piling replacement and structures in subtidal, also for restoration if well planned and monitored.

3. **Habitat conversion- placing oyster elements within eelgrass or soft sediment substrates.**
    1. Soft substrate most common habitat in bay- 90% of bay bottom is mud. Goals recs encourage expansion of historic habitats that have been lost due to urbanization (SF Bay is 1/3 of original size due to fill) and have received less active restoration intervention- eelgrass, oysters, rocky intertidal, seaweeds, coarse grain beaches, etc.
    2. Oyster and eelgrass habitats co-exist at many locations in the bay- not necessary to prioritize one over the other, better to design pilot projects that assess interactions/synergies/conflicts. Example: oyster recruitment onto bamboo stakes and anchors for eelgrass test plots. San Rafael- from our data, rec to include both habitats in same design bc increase of biodiversity- each support different fish assemblages, etc. But not so close that there is limitation of eelgrass spread, or damage to leaves from abrasion. Most designs do not include 100% footprint covered by oyster reef element fill- elements sited within subset of total area with space between for habitat and flow or water/propagules- can test while also allowing eelgrass patches in between, avoidance of high density eelgrass, etc.
4. **Seasonal windows and construction timing**- especially in hard to access shallow subtidal areas- balancing targeted windows for species of project focus with avoidance of impacts to listed bay species; discuss constraints of construction equipment available locally.

6.4 Changing Conditions
Extreme rainfall and drought

- Marine species and habitats can be ephemeral in estuarine environments, and spatial extent and persistence of species such as native oysters and native eelgrass can show wide fluctuations both within and between years. This has been recently observed during heavy winter flood events in San Francisco Bay (winters 2006-07, 2010-11, 2016-17). Such events can create low salinity conditions (less than 10 ppt) for weeks or months, with resulting die-off of many marine species, including oyster and eelgrass beds observed during heavy flood years, but often with rebound of the affected species within one recruitment season. This is because sources of propagules (oyster spat, eelgrass plants, etc.) do not necessarily get generated at the same site as the future location of the healthy adult populations and not all sites are equally impacted by flood events. This speaks to the need to better understand connectivity among populations at different sites within San Francisco Bay and to protect source site populations as well as adult habitat populations. It is important to continue to assess both short and long term survivability of these habitats in the context of variable water quality and other potential stressors. It is also important to continue assessing the short-term and long-term habitat benefits and ecosystem services generated by these ephemeral habitat types, as the value of even short-term benefits (such as reproductive substrate for plants, oysters, invertebrates, and fish; juvenile Dungeness crab rearing on the reefs; increased wave attenuation) may make the overall long-term restoration worth it -- even if regular maintenance (e.g., replanting eelgrass) and additional resources and funding may be needed over time.

- Key stressors for oysters vary with location within San Francisco Bay and may also shift over the life of a restoration project. Low recruitment and predation appear to be the main factors controlling oyster populations at Hayward; variable recruitment, space competition, and low salinity events may be more important at San Rafael.
- Existing invertebrate communities at reef instillation sites have a critical impact on oyster restoration success. This includes the presence of sessile invertebrates, particularly sponges and large bushy bryozoans, the presence of non-native oyster drills, and barnacles, as all of these species negatively impacted oyster recruitment and success.
- Projects may require maintenance (ie eelgrass replantings after freshwater loss, etc.)
- Projects may see loss during temporary extreme weather events- lag time for passive recruitment to occur again- (ie oysters can die off, passive oyster recruitment can reinitiate after a lag time, as early as 6 months as seen at San Rafael).
- Extreme weather events may result in need for phased repeat actions in same season (multiple planting events of eelgrass to avoid full loss associated with one low tide heat wave event)
- Extreme weather events result in the need for more locations of oyster and eelgrass test projects- certain sites may act as salinity refuges and provide nursery propagules to sites that were impacted by events.

Maintenance and Monitoring

3. Consider actively adding native species to site that aren't passively colonizing- native isopod, native sea hare.
4. Fish monitoring methods are limited in feasibility- trapping, seining- hard to get seine fully around structures. Test use of new technology- ARIS sonar cameras, etc.

7 Future Project Recommendations

So far, we are able to draw the following conclusions toward future designs:

- Key stressors for oysters vary with location within San Francisco Bay and may also shift over the life of a restoration project. It is unlikely that there is a single best design that can be used across estuaries or even within the Bay. Low recruitment and predation appear to be the main factors controlling oyster populations at Hayward; variable recruitment, space competition, and low salinity events may be more important at San Rafael. Ideally stressors would be identified prior to future site selection and would help provide information on project design.
- This project and several others suggest that eelgrass should be restored early in the growing season; we did not have success in establishing eelgrass at either site in late July and early August 2012. Our second planting in April and early May 2013 was much more successful at both sites, as was an additional planting effort at San Rafael in May 2016.
- Shell bags outperformed baycrete elements in terms of oyster densities, at least early on in the project at San Rafael. Two baycrete designs (large reef balls and oyster blocks) performed well in terms of oyster densities, structural integrity, low sediment accumulation, and low scour and subsidence rates. Our other main measure of oyster performance, oyster size, was unaffected by substrate type. We can eliminate two of the baycrete element designs: layer cakes and small reef

ball stacks. Neither stands up well structurally over time, and layer cakes had fewer oysters compared with other configurations.

- Where possible, pre site-selection surveys and experimental deployments should evaluate longer-term survival as well as recruitment of oysters over several tidal elevations. This might help us identify the "sweet spot" for oysters, which provides the best balance between the biotic and abiotic stresses associated with different tidal elevations. However, it is also important to note that such "sweet spots" are also likely to vary between locations within the bay.
- Additional protection from oyster predators and cover of fouling species might be gained by encouraging larger mobile predators (such as cancrid crabs) and mesograzers to settle on restoration substrates. Future designs might include developing substrate types and configurations that attract large crabs and fish.
- We tentatively suggest that restoration projects incorporating both oyster reef and eelgrass together should be considered; although neither species benefited from the other in the original patchwork configuration, evidence that differences in the two habitats encourage a greater number of invertebrate and fish species suggests that their co-location will maximize habitat value. Different configurations for integrating oysters and eelgrass, including spacing them farther apart, might reduce the negative impacts on eelgrass noted in this project. Further, the finding that oyster reefs provide protection for eelgrass planted on the shoreward side is promising and warrants further testing.
- Oyster reef designs should consider the fact that the lower portions of elements are likely to experience sediment burial at times. Future designs could be elevated on materials (such as oyster blocks made of baycrete) that are less difficult to source than bags of Pacific oyster shell, which will be less available in the future.
- Our data underscore the need for long term monitoring for evaluating project success, as these new communities develop and change over time.
- Oyster and eelgrass populations are dynamic: year-to-year variation in recruitment will affect oyster restoration projects dependent on natural recruitment (as opposed to seeding). Planted eelgrass in this project failed twice at each site; and oyster mortality at this location is likely to be impacted by low salinities during years of heavy rainfall. Success metrics for restoration need to take these highly variable factors into account.
- Wave energy reduction measured in our San Rafael project is encouraging, but we recommend additional sites be used for similar projects and measurements in order to determine optimal designs and the need for site-specific differences in reef configuration.

Site-Specific Recommendations:
San Rafael:

- Conduct a longer term monitoring snapshot at least once sometime years 8-10 (2020-22). Confirm that oyster reef elements are physically remaining in place, and provide data regarding presence of oysters, eelgrass, and epibenthic invertebrate and plant cover on the reefs.
- Retrieve at least one full shell bag mound and one reef ball element, to bring in to shore to assess full coverage of oysters and other species within the reef structure interior surfaces.
- Explore the potential to expand the project and build out over a broader footprint to continue testing reef approaches and gathering data on benefits. Assess feasibility with adjacent private subtidal landowners, and with regulatory staff. Explore potential for partnership with Marin Audubon Society to expand onto their adjacent property and others.
- Encourage placement of a water quality sonde by local municipalities to monitor dissolved oxygen, chlorophyll, temperature, salinity, and potential contaminants including PAH's from auto and marine repair shops in the adjacent area including the San Rafael Canal.

- Encourage additional partners and projects to engage in developing living shorelines efforts with oyster reefs and eelgrass, and consider potential existing beach and tidal wetland projects where a low intertidal/ shallow subtidal nearshore component could be integrated into the design. Potential examples include the Tiscornia Marsh Restoration Project, potential City of San Rafael climate adaptation and shoreline restoration projects, building off of Resilient By Design concepts which promoted expansion of this project at the San Rafael shoreline area.

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Table 1. List of epibenthic invertebrates found by site (SR = San Rafael, KB = Keller Beach, PM = Point Molate, and H = Hayward) and sampling method (su = suction, sh = shoot collection, and t = trapping). Abbreviations used in Figure 9.

Taxon	**Abbreviation**	**Site**	**Survey**
Annelids			
Oligochaete	OLIsp	SR, KB, PM, H	su, sh
Polychaete	POLsp	SR, KB, PM, H	su, sh
Crustaceans			
Crabs			
Cancer maenas	CANMAE	SR, H	t
Cancer productus	CANPRO	SR	t
Hemigrapsus oregonensis	HEMORE	SR, H	t
Megalopae	Megal	SR, KB, PM	sh
Metacarcinus magister	METMAG	SR, H	t
Pugettia productus	PUGPRO	SR	t
Romaleon antennarium	ROMANT	SR	t
Amphipods			
Ampelisca sp.	AMPsp	SR	su, sh
Ampithoe valida	AMPVAL	SR, KB, PM, H	su, sh
Caprella californica	CAPCAL	SR	sh
Caprella sp. (incl. juveniles)	CAPsp	SR, KB, PM, H	su, sh
Corophidae (incl. *Monocorophium* sp.)	CORsp	SR, KB, PM, H	su, sh
Gammarus sp.	GAMsp	SR, PM, H	su, sh
Grandidierella japonica	GRAJAP	SR, KB, PM, H	su, sh
Jassa sp.	JASsp	SR, KB	su, sh
Paradexamine sp.	PARsp	SR, KB, PM, H	su, sh
Isopods			
Isopod	ISOsp	SR, PM, H	su, sh
Pentidotea resecata	PENRES	KB, PM	sh
Shrimp			
Cumacean	CUMsp	SR, H	su, sh
Shrimp (incl. *Crangon franciscorum* and *Palaemon macrodactylus*)	Shrimp	SR	t
Other crustaceans			
Cirripedia	CIRsp	SR, H	su, sh
Copepod	COPsp	SR, KB, PM, H	su, sh
Ostracod	OSTsp	SR, H	su, sh
Bivalves			
Gemma gemma	GEMGEM	SR, H	su
Potamocorbula amurensis	POTAMU	SR, H	su
Siliqua patula	SILPAT	H	su
Gastropods			
Ilyanassa obsoleta	ILYOBS	H	t
Patella sp.	PATsp	SR	sh
Phyllaplysia taylori	PHYTAY	SR, PM	sh
Urosalpinx cinerea	UROCIN	H	su
Snail (round)	Snail 1	SR, KB, PM, H	su, sh
Snail (cork)	Snail 2	SR, H	su, sh

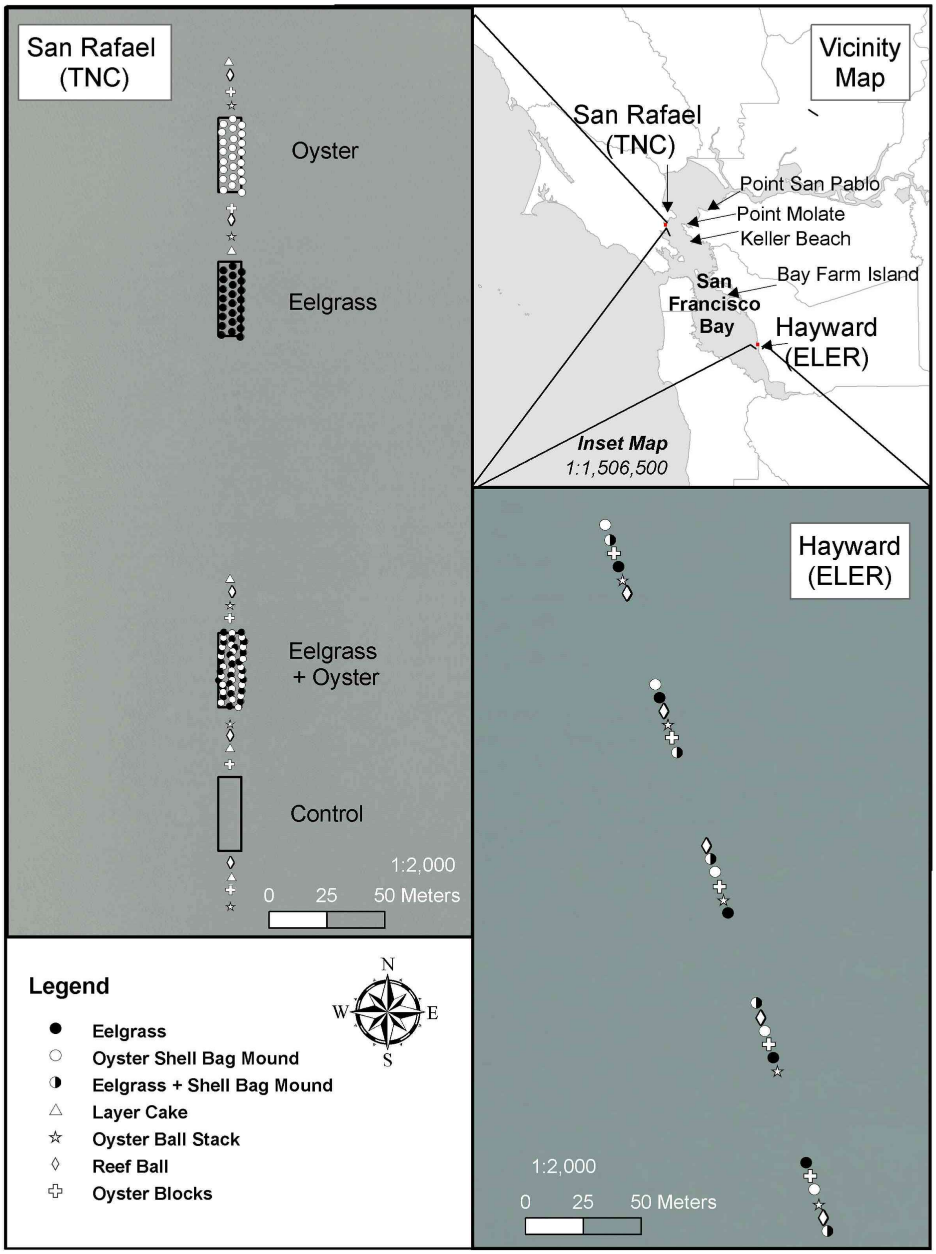


Figure 1. Maps showing the location and configuration of (left) the larger-scale and small-scale experiment designs at San Rafael (property of The Nature Conservancy [TNC]) and (right) the small-scale design at Hayward (offshore of Eden Landing Ecological Reserve [ELER]). Space was left at the center of the San Rafael project for preexisting test plots of eelgrass. Eelgrass transplants were collected from Point San Pablo and Point Molate for the San Rafael site and from Bay Farm Island and offshore of ELER for the Hayward site (top right map). Point Molate and Keller Beach eelgrass beds were used as reference sites for epibenthic invertebrate community development at San Rafael.

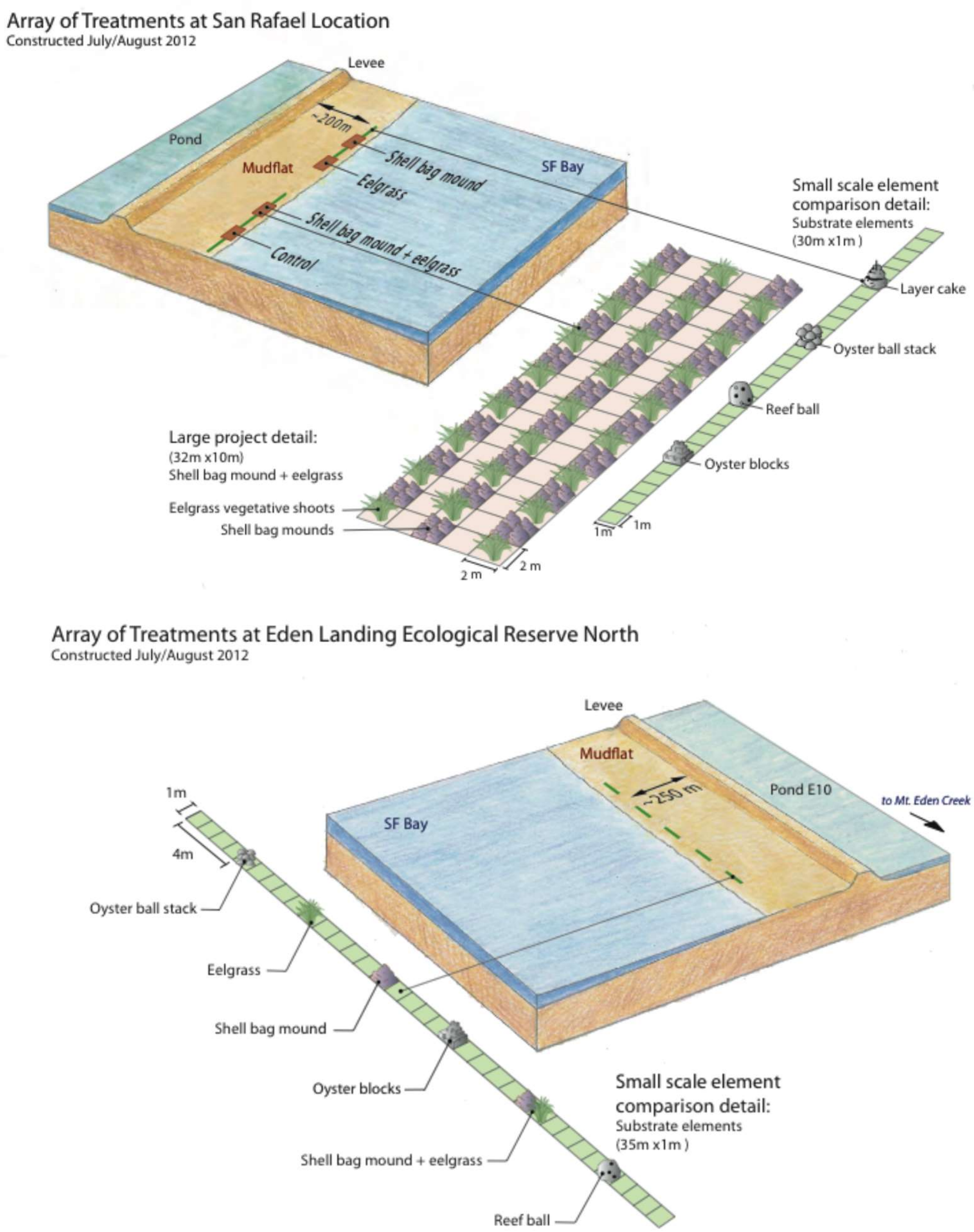


Figure 2. Schematic of the Living Shorelines: Nearshore Linkages project. Top: the larger-scale project design, as placed at the San Rafael site, with the four types of baycrete elements (the small-scale substrate design) in rows between the four large plots. Bottom: the small-scale substrate design as planned for the Hayward site; note that ultimately the layer cake was not used at Hayward due to concerns about structural integrity with higher wave action. Shell bag mounds were placed as single elements for comparison to baycrete at the Hayward site, and small eelgrass plots, alone and adjacent to oyster elements, were included. (Drawings courtesy Environmental Science Associates.)

Figure 3. Top: Photos of treatments used in the project. Bottom: Eelgrass planting using bamboo stake technique, including, on the right, a schematic of planting design within an eelgrass unit at San Rafael and Hayward. Two donors were used to plant each site, as indicated by shading in the schematic. For San Rafael, the donor in the center alternated in each patch.

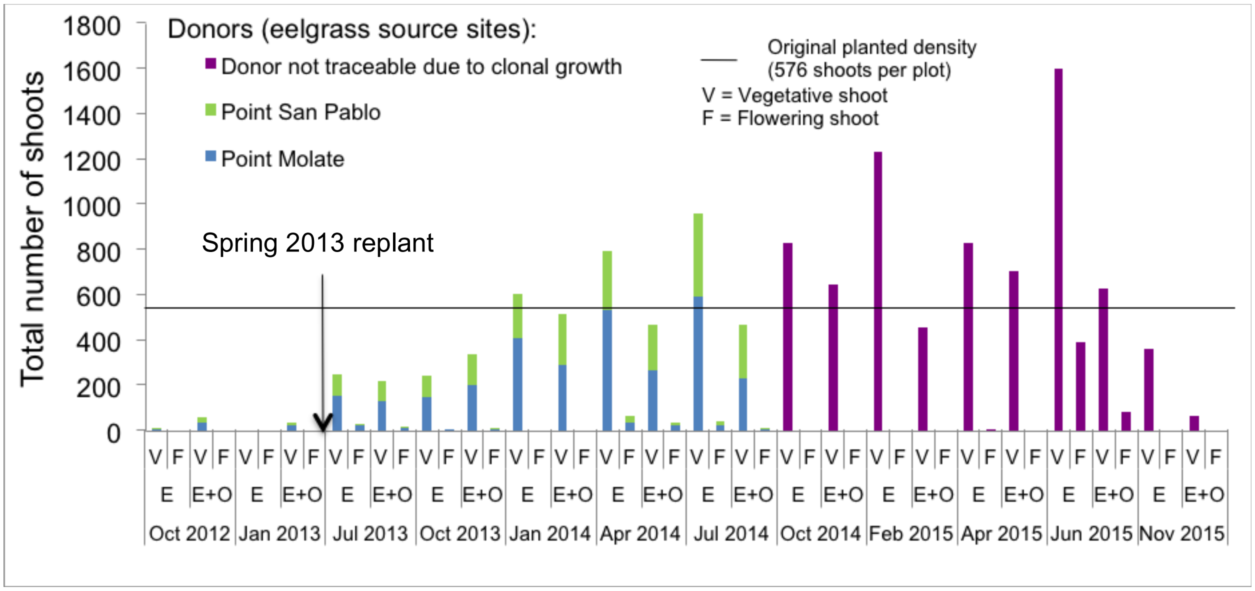
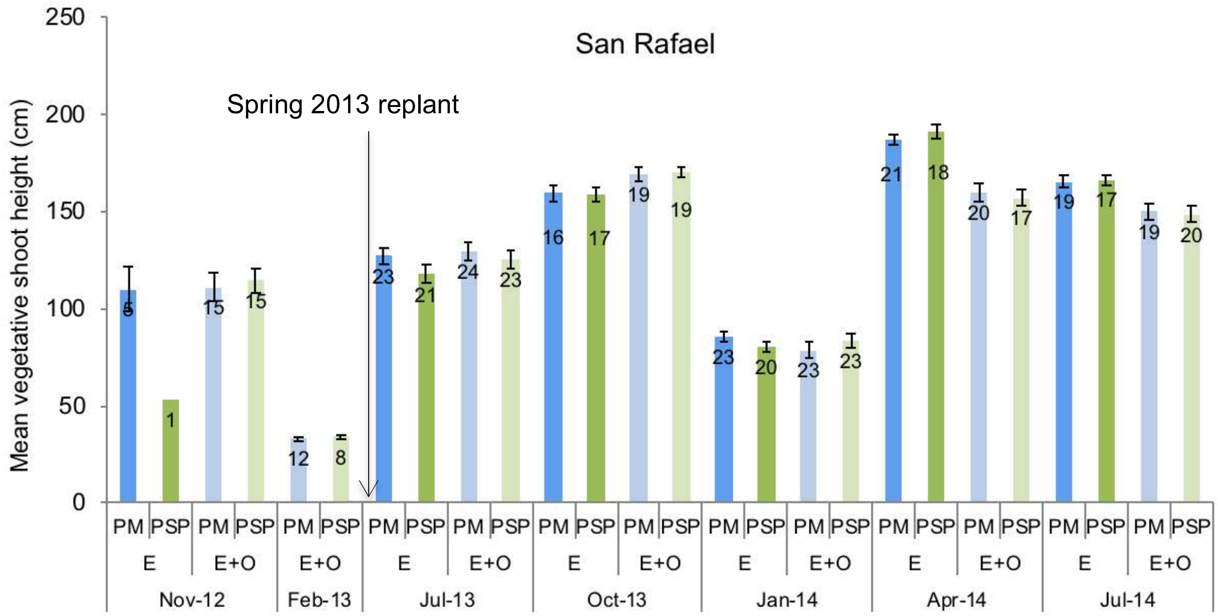


Figure 4. Total number of vegetative eelgrass shoots present, per donor and treatment plot at the San Rafael site, quarterly through summer 2015. E = eelgrass plot, E+O = eelgrass and oyster plot. Plants originating from the Point Molate and Point San Pablo donors could only be distinguished through July 2014 and counts were pooled thereafter.

a)



b)

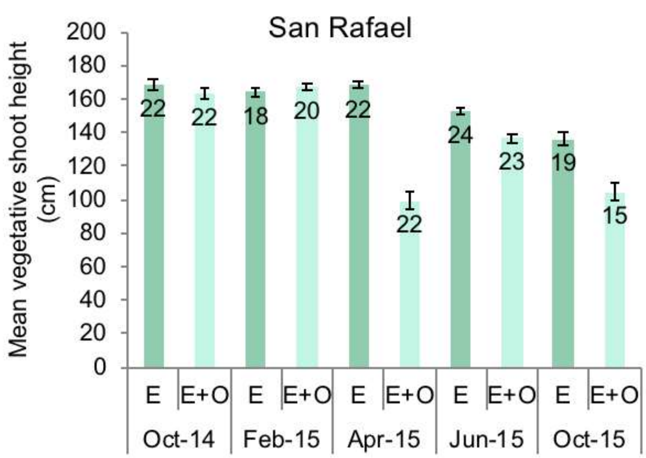
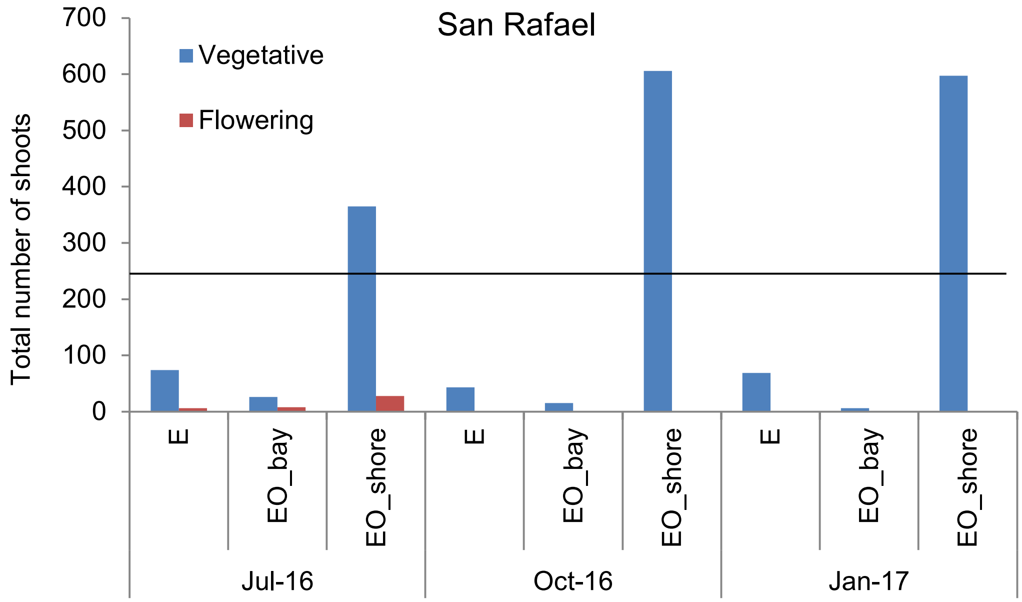


Figure 5. Mean height of the tallest vegetative eelgrass shoot in each unit (n = 24; ±95% CI), by treatment and donor as in Fig. 4, at the San Rafael site for each quarterly monitoring effort through a) summer 2014 and b) continuing through fall 2015 when the donors could no longer be tracked.

a)



b)

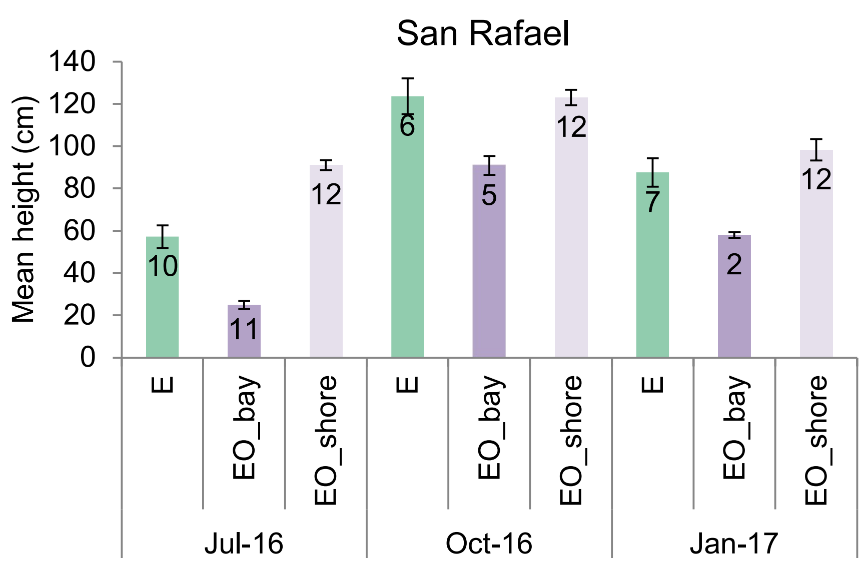


Figure 6. a) Total number of vegetative and flowering eelgrass shoots present per treatment plot at the San Rafael site, recorded quarterly after the April 2016 replant. E = eelgrass only plot, E+O_bay = eelgrass plot on bay side of oyster units in the previous oyster + eelgrass plot, E+O_shore = eelgrass on shore side of the same units. Line indicates the initial planted density (= 240 shoots) within each plot. b) mean height of tallest shoots in each treatment for the same plots and dates.

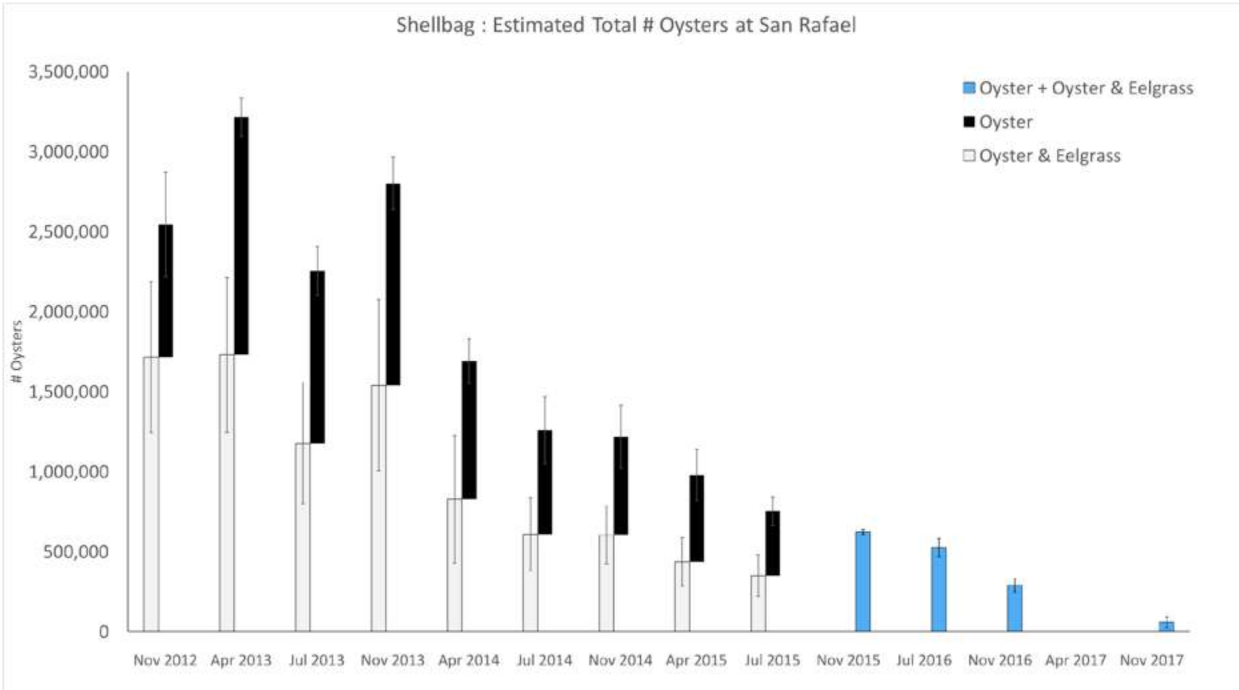


Figure 7. Estimated total number of native oysters on shell bag mounds at the San Rafael site over time in the oyster-only plot and oyster + eelgrass plot. To be conservative, only the upper portion of the mounds is included here. Means (±95% CI) were calculated from five replicate shell bags removed from the mounds for oyster counts on each date, which were then scaled up to estimate oyster numbers at the plot level.

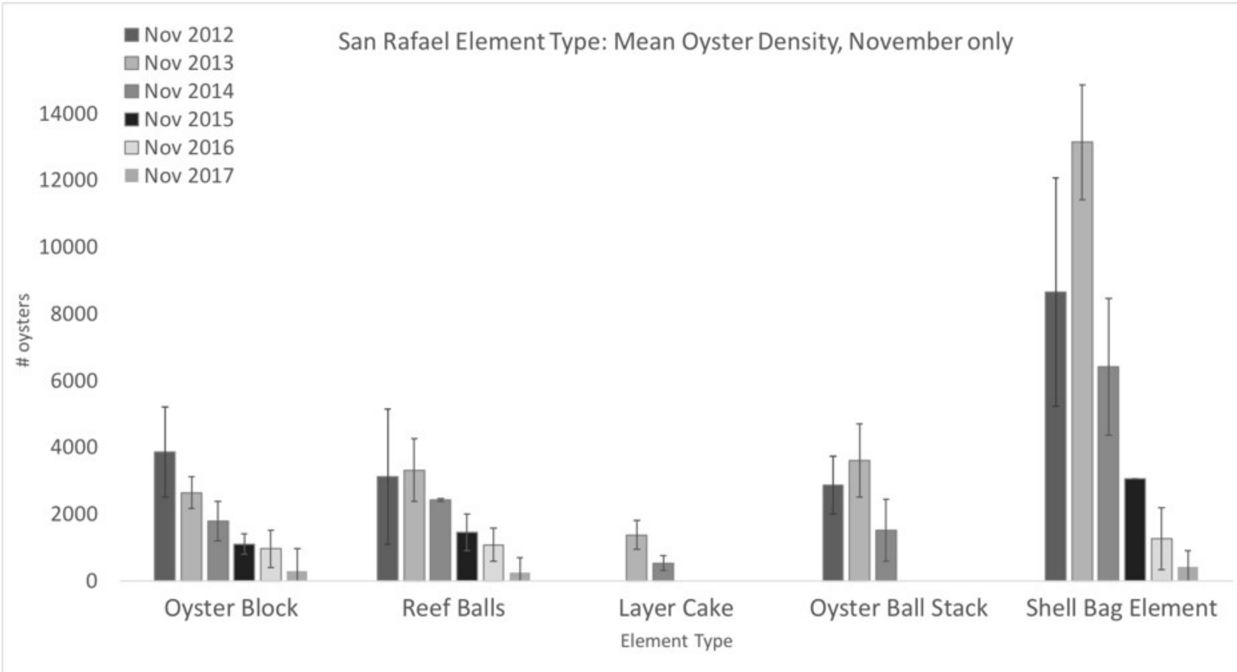


Figure 8. Estimated native oyster abundance per baycrete or shell bag element, November time points, at the San Rafael site (TNC). Means (±95% CI) were generated by scaling up from 10 small replicate shell bags (five each from oyster-only and oyster–eelgrass treatment plots) or from six 100-cm^2 quadrats placed on each of five replicate baycrete elements at the San Rafael site. Given their relatively poor performance (see text), layer cakes and oyster ball stacks were not monitored in 2016.

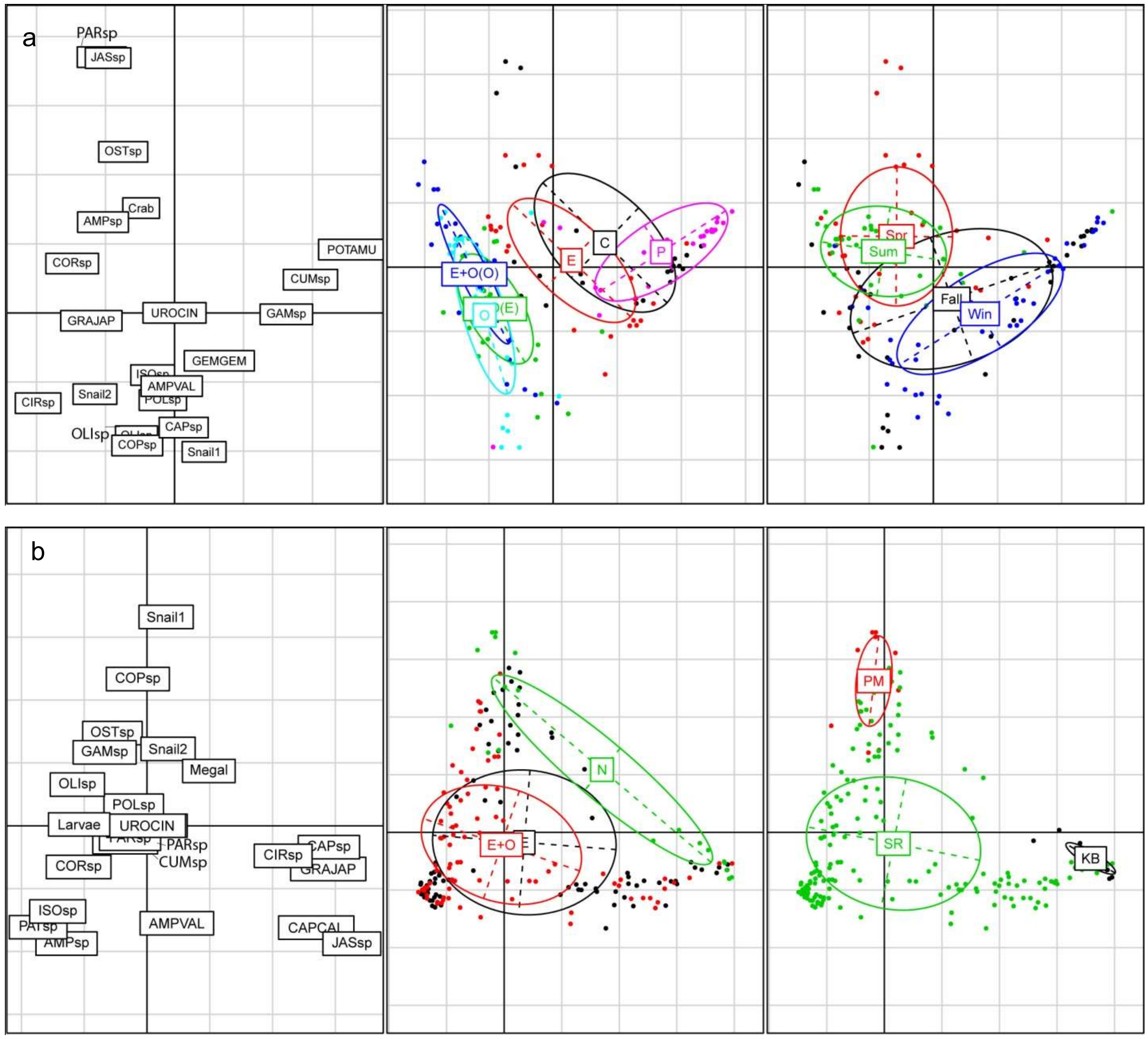
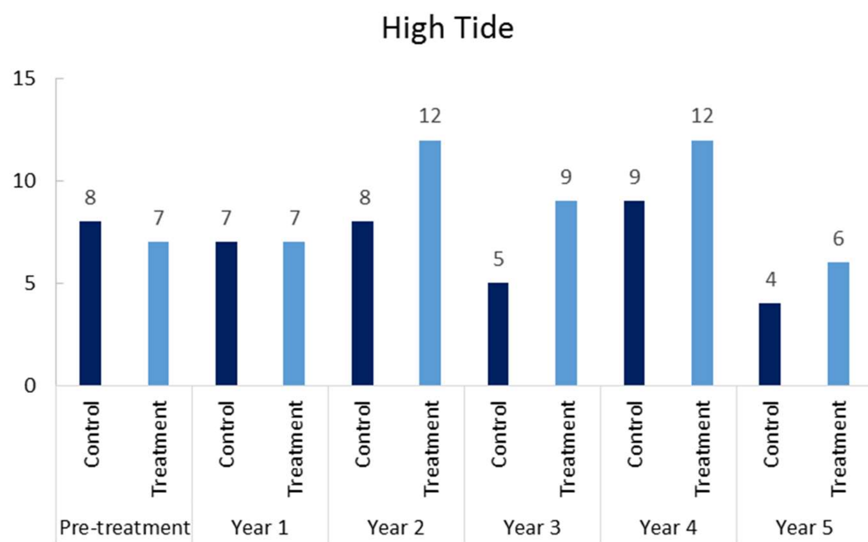


Figure 9. Correspondence analysis of epiphytic invertebrates: (a) San Rafael suction sampling patterns by taxa, treatment, and season, fall 2013 through summer 2014 (Year 2 of the project), in comparison to pretreatment (P) samples. C = control, E = eelgrass, O = oyster, E+O(E) = eelgrass from E+O plot, and E+O(O) = oyster from E+O plot. (b) Eelgrass shoot collection patterns in spring 2014 comparing assemblages at the San Rafael (SR) plots from the E or E+O plots to that of two natural (N) beds at Keller Beach (KB) and Point Molate (PM). Two species, *Phyllaplysia taylori* (Taylor's sea hare) and *Pentidotea resecata* (an isopod), were absent or rare at San Rafael and were removed from b as their presence obscured differences produced by other parts of the assemblage. Taxa abbreviations as in Table 1.

Species Richness in Zone B



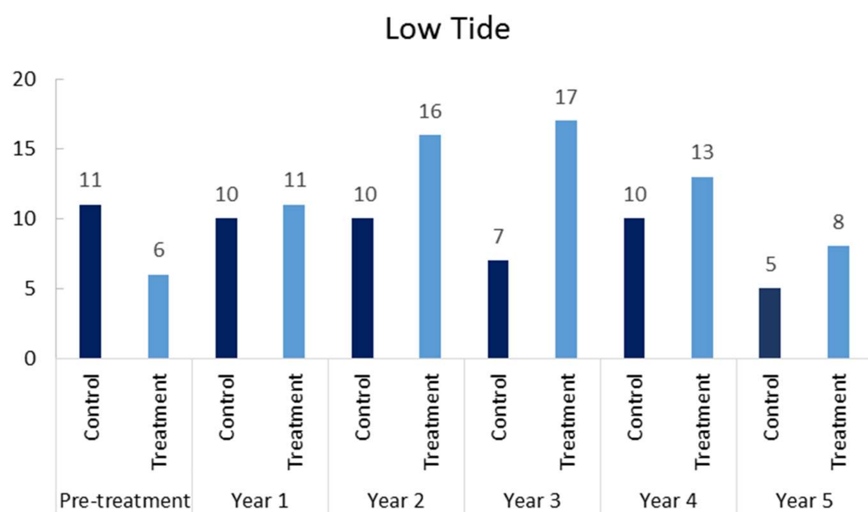


Figure 10. Cumulative species richness of all birds in the treatment and control areas of Zone B over the 5 years of monitoring.

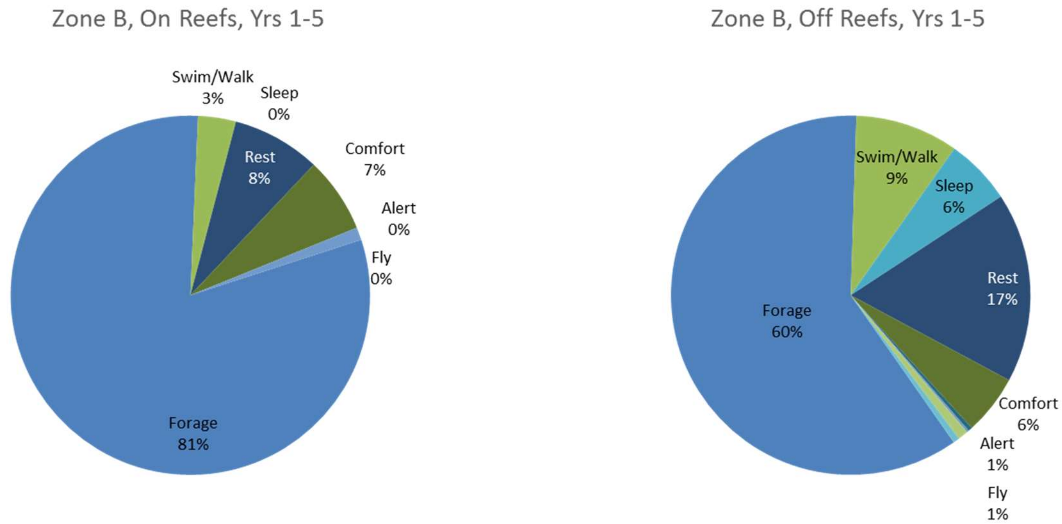


Figure 11. Bird behavior in Zone B of the treatment area, on and off of the oyster reef treatments during treatment years (1-5). Data shown is from 2 surveys per season per year with the exception of summer in Year 3, which includes one survey.

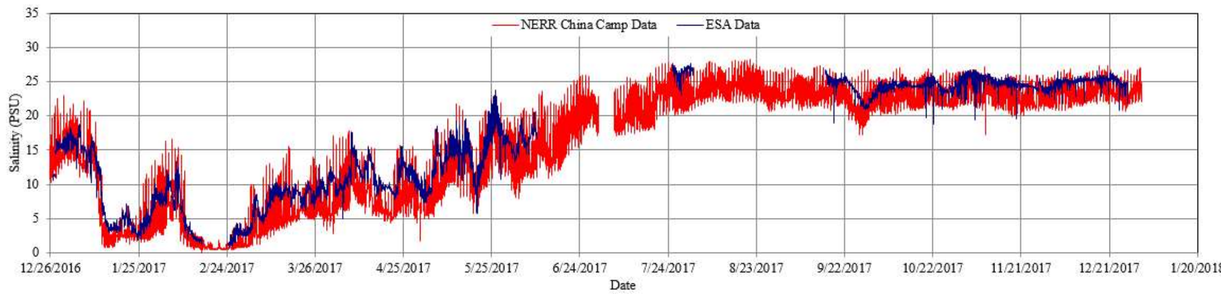


Figure 12. Salinity (PSU) collected from the water quality data sonde deployed at the San Rafael project site (ESA data) and at China Camp State Park (NERR China Camp Data), showing the effects of the record storms of early 2017.

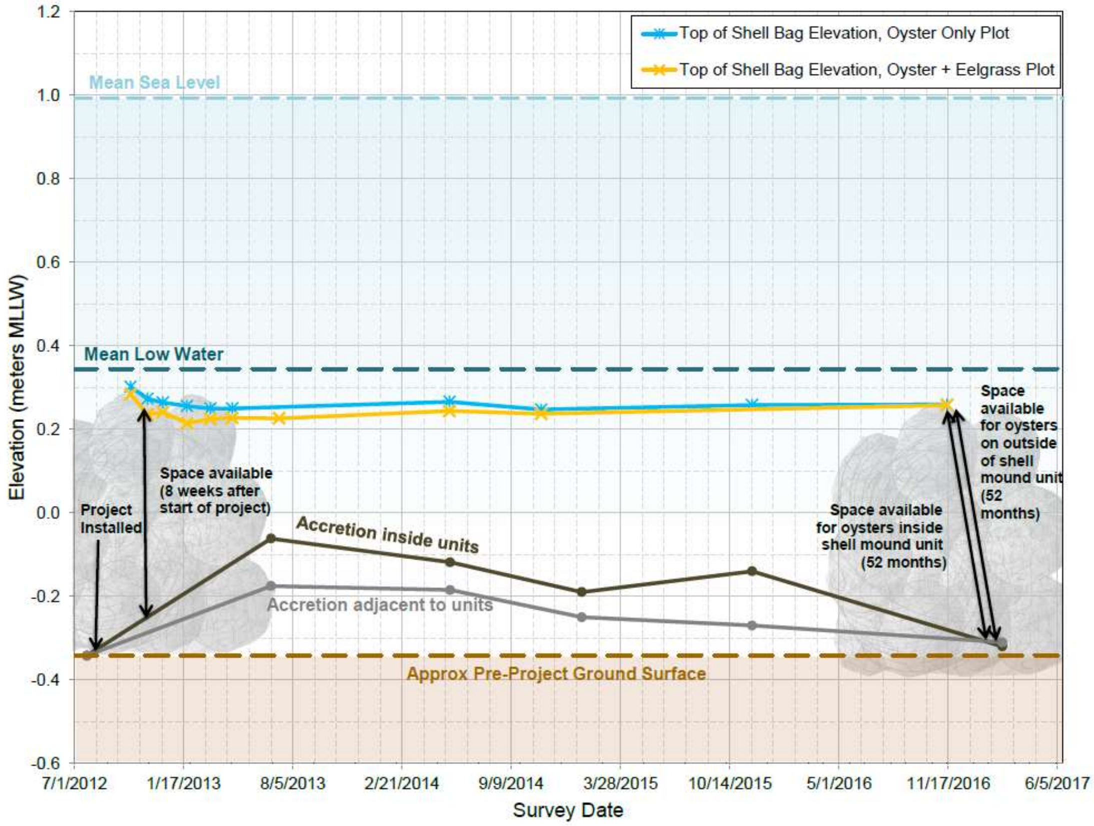


Figure 13. Sedimentation and oyster space for shell bags at the San Rafael site over time.

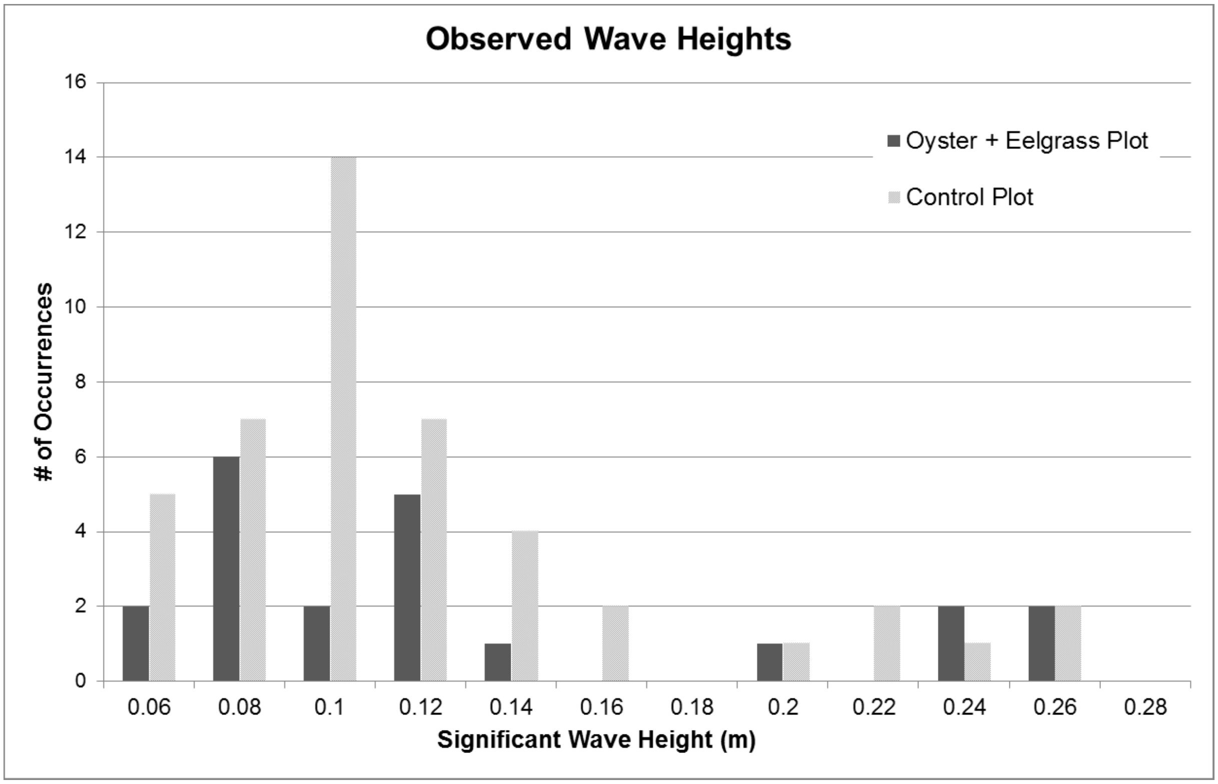


Figure 14. Wave heights measured on the shore side of the oyster + eelgrass and control plots at the San Rafael site, February 26, 2013, to April 15, 2013. There were a total of 45 significant waves measured in-shore of the control plot and 21 significant waves measured in-shore of the oyster + eelgrass plot for the sampling duration, indicating that the latter limits significant wave occurrences.