San Francisco Bay Living Shorelines: Nearshore Linkages Project
Summary of Key Findings Four Years Post-installation
2016 Annual Monitoring Report Summary

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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 Summary Report for 2016, we review our objectives and project design, and evaluate outcomes four years after installation, concluding with an assessment of early 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 ha 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); 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 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 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.

Monitoring of oysters in San Francisco 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 further tests restoration techniques, restores critical eelgrass and oyster habitat, examines the individual and interactive effects of restoration techniques on habitat values, and tests 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 is 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 late 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 Pacific oyster 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 on 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, in which no eelgrass or oyster substrates were 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 sand and 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 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 late 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, Four Years after Installation (through 2016)

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. Counts reached 50% of planted numbers on average by summer 2013 and 124% by summer 2014 (Fig. 4). By summer 2015, more than 200% of planted shoot numbers occurred in the eelgrass-only plot and just over 100% in the eelgrass + oyster plot. 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. Vegetative shoot density was higher in the eelgrass-only plot starting in spring 2014 and continuing through fall 2015. Maximum plant heights typically reached 160 cm or more during spring–fall, 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 shells, limited space for spread within the matrix of the mixed habitat plot, or somewhat higher epiphytic algal loads on leaves (data not shown). During the period when the two donor sites could still be tracked (through summer 2014), plants originating from Point Molate produced significantly higher numbers of shoots than those from Point San Pablo (Kruskal-Wallis, $p < 0.0001$), 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), which was also reflected in shoot heights, although to a lesser degree (Fig. 5). This decline may have been related to a large algal bloom that formed thick mats throughout the site 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 the winter 2016 monitoring period (February 2016), the eelgrass within our project area was completely gone. In addition, the original test plots installed in the center of the TNC property in 2007 also disappeared, after nine years of presence.

In May 2016, we replanted eelgrass at 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. 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 (Fig. 6a). This trend became more pronounced by October 2016, with 43, 15 and 606 vegetative shoots in the E, E+O bay-side and E+O shore-side plots, respectively (Fig. 6a). Eelgrass may experience reduced flows inshore of the oyster reefs, which may be beneficial to the plants directly (protection from higher wave action) or indirectly (e.g., by affecting herbivory or other processes that feed back to eelgrass density). Height of the tallest shoots was also greater in the shore-side plots when first measured in July 2016 but the difference was less apparent by October (Fig. 6b); thus, density seems to have been the stronger response to the planting location.

4.1.2 Olympia Oysters

Olympia oysters quickly recruited to the shell mound structures (by the first fall 2012), 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, with the current population (as of December 2016) estimated at ~288,000 (Fig. 7). This may be at least in part the result of low recruitment to the site (as determined by recruitment tiles placed along the shoreline), which has declined since 2013, along with some expected mortality. This most recent population estimate still represents an order of magnitude increase in the numbers of oysters at this location. No differences in oyster numbers or sizes were obvious between the oyster-only and eelgrass + oyster treatment.

Oysters also recruited readily to the small “baycrete” structures. Measures of these structures in small quadrats (100 cm^2) early in the project indicated that twice as many 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) and on vertical than on horizontal faces; north sides of the elements also typically had 50% more oysters than did south sides. These differences have 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 at lower tidal elevations.

We have found no 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 have performed best overall in terms of structural integrity and oyster densities among the baycrete structures.
For most of the project, baycrete structures did not support as many oysters as the shell-bag elements. However, for reasons not known to us, oyster densities on shell bags have 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 (Fig. 8). 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.

4.1.3 Epibenthic Invertebrate Response

Epibenthic invertebrates were assessed quarterly using baited minnow and oval traps, suction sampling, and shoot collection (for detailed methods, see Pinnell 2016). 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*), seen in higher abundance in all treatment plots compared to pretreatment (Kruskal-Wallis $\chi^2 = 24.85$, df = 4, $p < 0.0001$), and Pacific rock crab (*Romaleon antennarium*), which was significantly more abundant in the oyster plots than pre-treatment levels (Kruskal-Wallis $\chi^2 = 26.51$, df = 4, $p < 0.0001$). Additional species known to be attracted to physical structure have been trapped in plots with oyster reef or eelgrass present, including native red rock crabs (*Cancer productus*) and northern kelp crabs (*Pugettia producta*), as well as a few nonnative green crabs (*Carcinus maenas*). 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) showed that community composition was distinct in the plots with oyster reefs present, relative to the control plot and preconstruction conditions (PERMANOVA [Bray Curtis], $p < 0.001$), with the eelgrass-only assemblage in between (Fig. 9; Table 1). 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 have not converged with 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) continue to be absent (the isopod *Pentidotea resecata*) or extremely rare (the sea hare *Phyllaplysia taylori*) at the restored site.

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 bay pipefish (*Syngnathus leptorhynchus*) having a greater association with eelgrass habitat emerged as well as the bay goby (*Lepidogobius lepidus*) with the oyster reefs. 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 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. 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 after installation (data not shown). Bird species richness and diversity have been greater in the treatment than control area for each successive year since the second year post-installation. During low tide, diving duck densities in the treatment area have become increasingly greater than in the control area over time (Fig. 10). 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. Two focal species, bufflehead and ruddy ducks were found to have shorter dive lengths in the reefs areas than in the control areas suggesting more efficient foraging. Infaunal invertebrate density and biomass have been highly variable in both the treatment and control areas. Polychaetes dominate the benthic invertebrate ash-free dry weight in the treatment area, and amphipods and polychates are the most numerous taxa. The number of phyla, classes, orders, and families are all greater in the treatment than control areas.

4.1.6 Physical Effects

Hydrographic surveys of the mudflat surface within 100 m of the reefs at San Rafael in May 2012 and again in June 2014 and 2016 indicate that the treatment plots have little measurable impact on the overall pattern of erosion and sedimentation in the project area. The surveys show a trend of erosion bayward of the plots and sediment deposition shoreward of the plots, but no discernable difference between the control and treatment areas. Initially, sedimentation occurred adjacent to the shell mound units and, to a greater extent, inside the shell mound elements comprising the shell mound units. However, after an initial pulse of sedimentation adjacent to the shell mound units (average of 0.17 m in the first year), sedimentation rates slowed, and in some areas, a net loss of sediment has been observed since construction. The shell bag mounds subsided approximately 6 cm in the first 5 months, followed by largely stable conditions (Fig. 12). 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. 12). When monitoring began in November 2012, the tops of the shell bags were approximately 0.64 m above the mud surface, but with subsidence and sedimentation in the first year, only 60-70% of the surface area was available to oysters. However, subsequently, as element subsidence slowed and previously-accumulated sediment eroded, as much as 90% of the shell mound surface area is once again available for oyster recruitment.

The shell mound units and baycrete structures have subsided an average of 0.11 m, with the baycrete structures having subsided nearly 4x more than the oyster shell bag mounds (0.15m and 0.04m, respectively), perhaps owing to the greater weight of the structures.

Wave heights showed different patterns in the lee (shoreward) of the oyster–eelgrass plot and the control plot, with fewer waves in the lee of the oyster–eelgrass plot. Waves measured over a 2-month period in February to April 2013 ranged in height from 0.06 m (the minimum analyzed) to 0.26 m for both plots. However, there were far fewer waves above 0.06 m shoreward of the oyster–eelgrass plot compared to the control (21 and 45, respectively) (Fig. 13). According to wave modeling conducted for the project, for waves immediately offshore of the plots, the oyster–eelgrass plot dissipates approximately 30% more wave energy than the control at mean tide level (MTL) over the width of the plot. However, the extent of wave attenuation over the plot is small compared to the large attenuation between the Bay and shore over the broad mudflat. The small relative size of this effect was anticipated in the project performance expectations and reflects this pilot scale and configuration.

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 the former. 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 was 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 since fall 2015, there have been 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 have established a baseline of avian and infaunal invertebrate characteristics that will be very useful if larger-scale restoration projects go forward in the future.

4.2.6 Physical Effects

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 in 2015 and 2016. 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 is 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 San Francisco 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 tidal marsh plants. The seven sites include: additional area adjacent to our current site on the San Rafael shoreline in the City of San Rafael, Giant Marsh within Point Pinole Regional Shoreline in the City of Richmond, Elsie Roemer Marsh in the City of Alameda, Eden Landing Ecological Reserve in the City of Hayward, Ravenswood Slough in the City of Menlo Park, Coyote Point in the City of San Mateo, and Oyster Point in the City of Brisbane. This assessment resulting 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 has 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. At Hayward, eelgrass was present for a limited time; thus, we are unable to assess interactions there. We are also collected stable isotope samples from the common producer and consumer species at the San Rafael site, and these should allow us to disentangle trophic links within and among those different treatments, to assess the level of connectivity with adjacent habitats (bare mudflat, marsh) and to identify the main sources of organic matter fueling the food webs and supporting target restoration species' growth. 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 far 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. Shell bag mounds outperformed all baycrete structures in terms of number of oysters on a per-element basis, although this effect 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 which are beginning 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 are not present inside the shell bags, although they do 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 initially showed a trend of greater transplant success at San Rafael, with higher overall densities than the Point San Pablo donor. This trend continued and became magnified over time, especially in the eelgrass-only plot. We suggest that Point Molate eelgrass may be better adapted 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 have strong effects on 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 are now similar. This decrease is 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 reef balls, two structure types that would be expected to be the best in mitigating heat and desiccation stress, more oysters are currently 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 mobile invertebrates that benefit from such structure. At both San Rafael and Hayward, wading bird presence increased after the placement of reef structures. At San Rafael, black oystercatchers and Forster's terns are utilizing the reefs for foraging and roosting, and overall avian species diversity and richness is higher in treatment zones compared to controls. Additional monitoring is necessary to determine how the strengths of these relationships 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

Preliminarily, 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), suggesting that restoring the two habitats in proximity to each other can increase the richness 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

Our measurements of physical processes have shown accumulation of sediment adjacent to the reefs, but only a small impact on accretion across the whole area of the project; additional measurements are needed over time to assess this trend. We observed less and shorter-term subsidence of the reefs in soft sediment than we expected. Our data showing only a 10-cm subsidence into the sediments, which ended after 5 months, suggest that 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 that can be made at the Hayward site, there are a number of preliminary 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 Future Design Criteria

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

- This project and several others from the Boyer Lab 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.
- 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 San FranciscoBay. 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.
- 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.

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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 8.

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

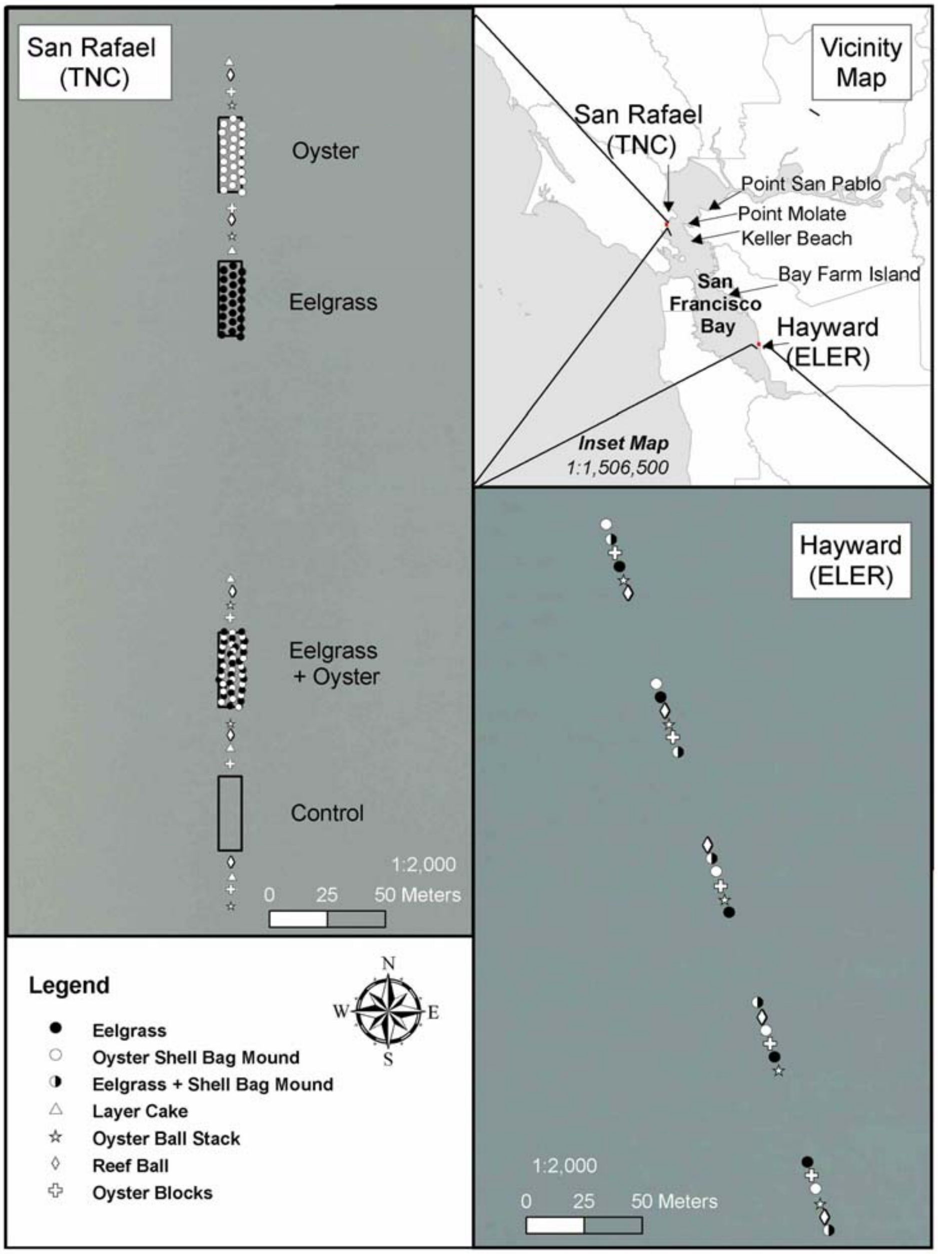


Figure 1. Maps showing the location and configuration of (left) the larger-scale and small-scale experiment designs at San Rafael (property of The Nature Conservancy [TNC]) and (right) the small-scale design at Hayward (offshore of Eden Landing Ecological Reserve [ELER]). Space was left at the center 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.

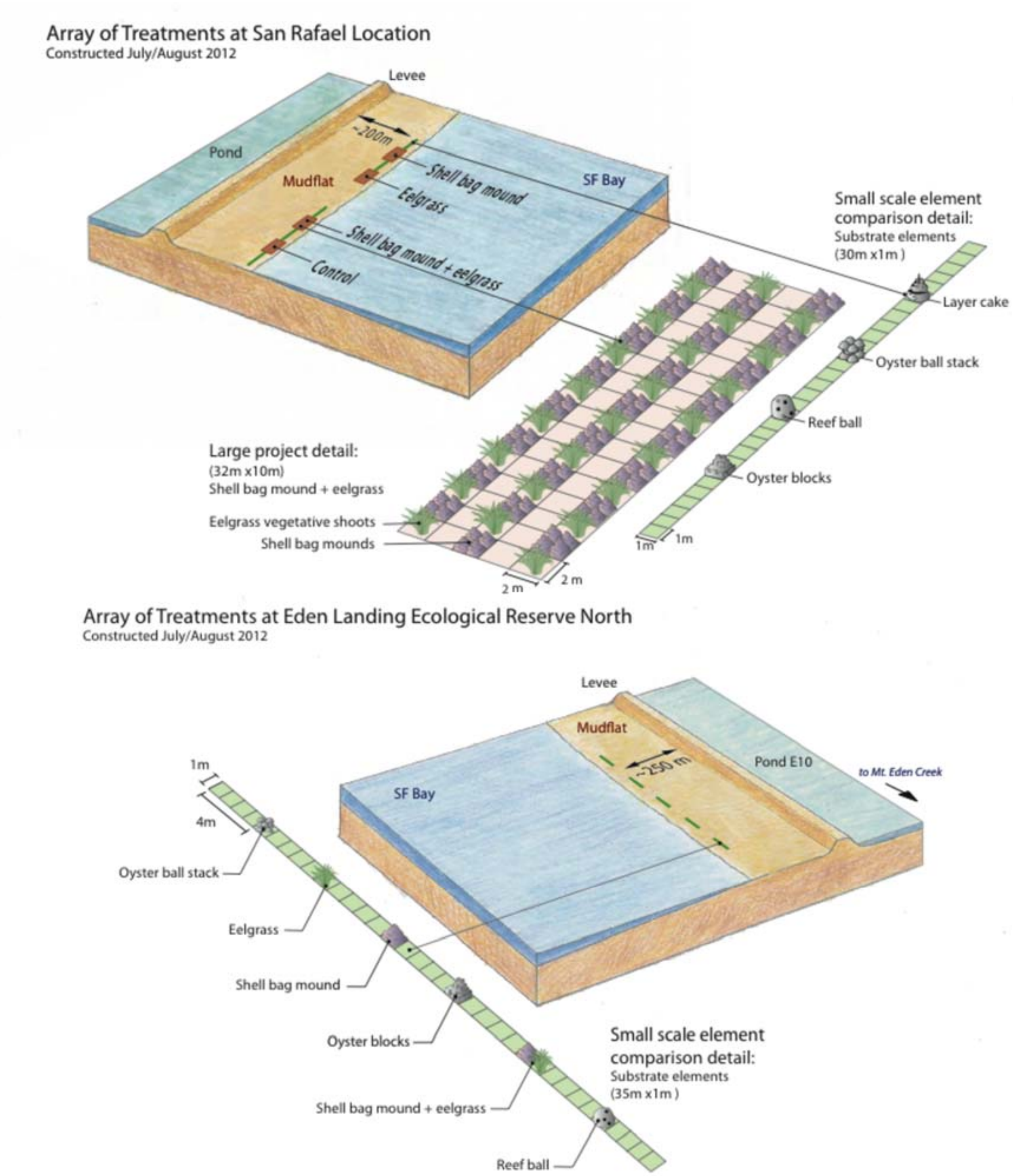


Figure 2. Schematic of the Living Shorelines: Nearshore Linkages project. Top: the larger-scale project design, as placed at the San Rafael site, with the four types of baycrete elements (the small-scale substrate design) in rows between the four large plots. Bottom: the small-scale substrate design 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.

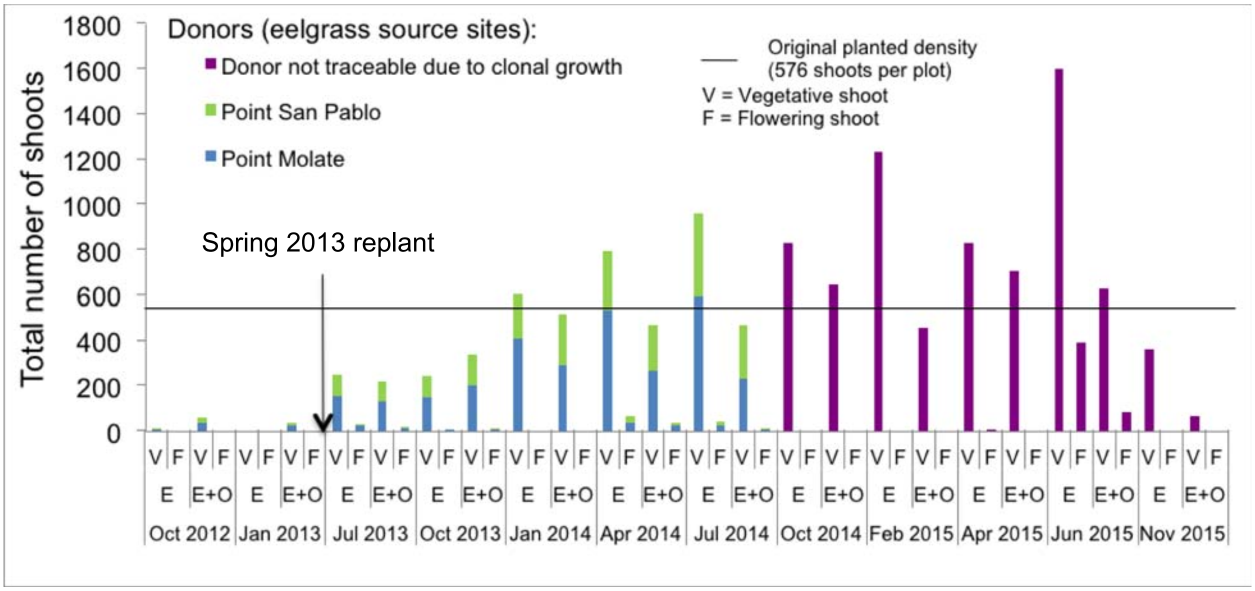


Figure 4. Total number of vegetative eelgrass shoots present, per donor and treatment plot at the San Rafael site, quarterly through summer 2015. E = eelgrass plot, E+O = eelgrass and oyster plot. Plants originating from the Point Molate and Point San Pablo donor sites could only be distinguished through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

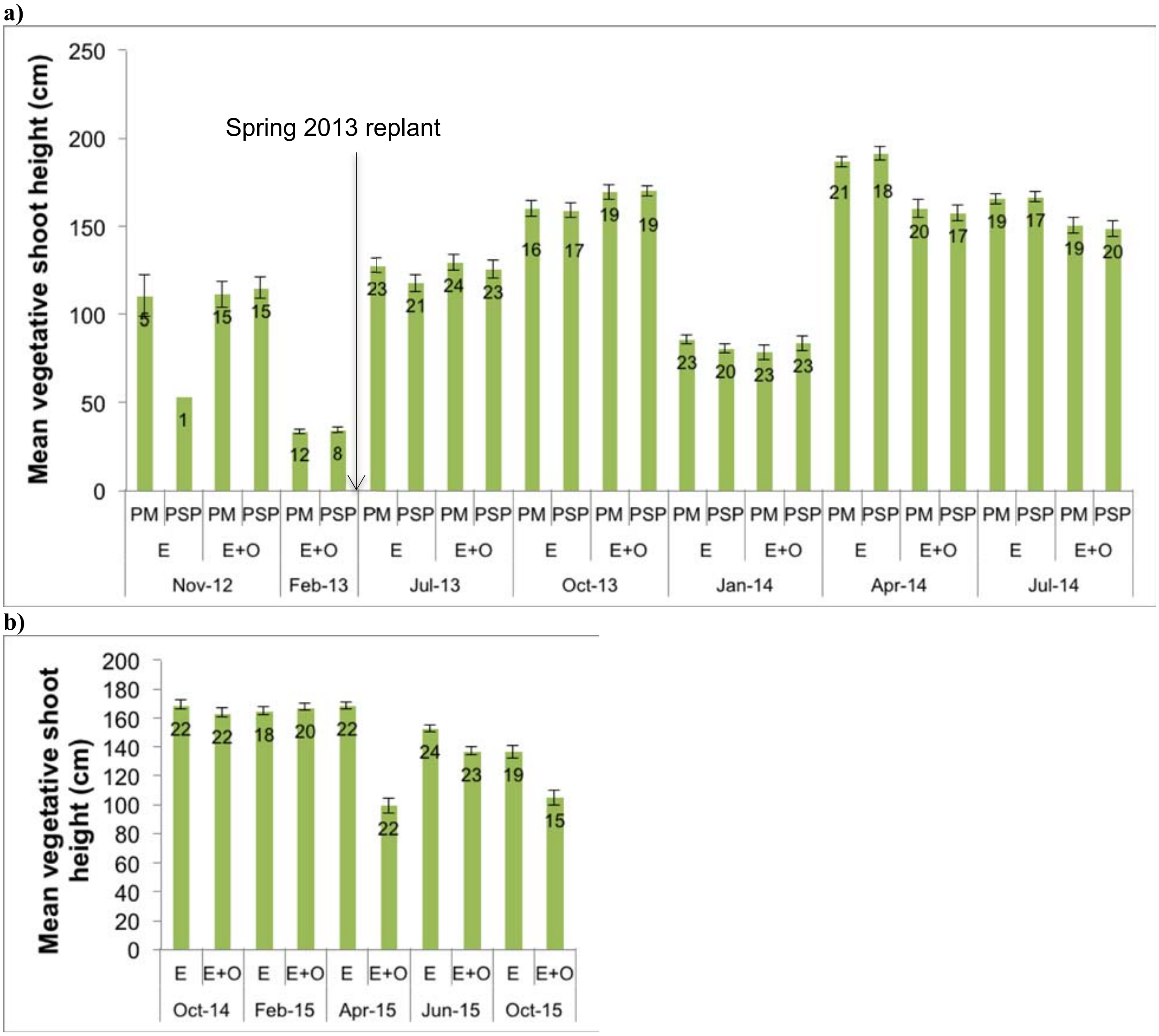
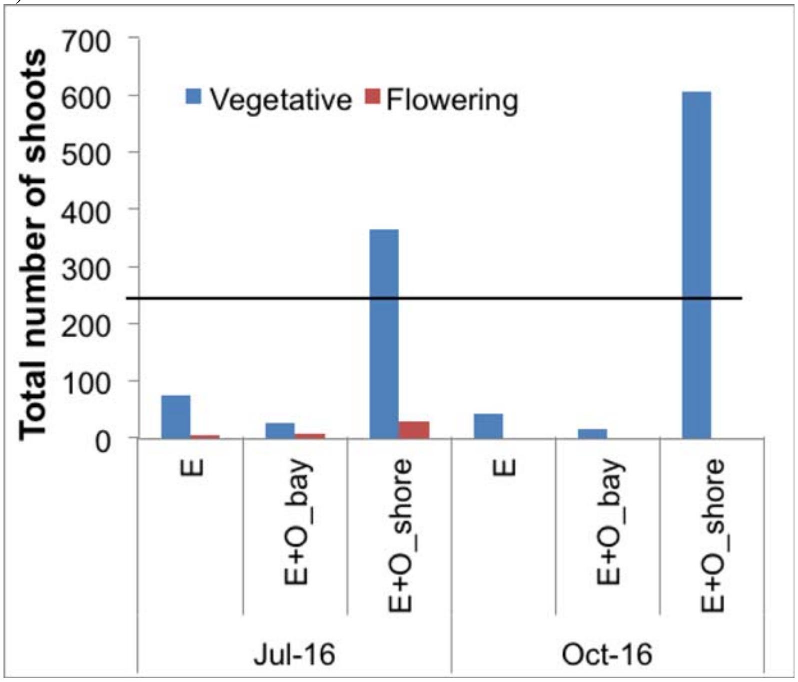


Figure 5. Mean height of the tallest vegetative eelgrass shoot in each unit (*n* = 24; ±95% CI), by treatment at the San Rafael site for each quarterly monitoring effort through a) summer 2014 and b) continuing through fall 2015 when the donors could no longer be tracked. E = eelgrass plot, E+O = eelgrass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

a)



b)

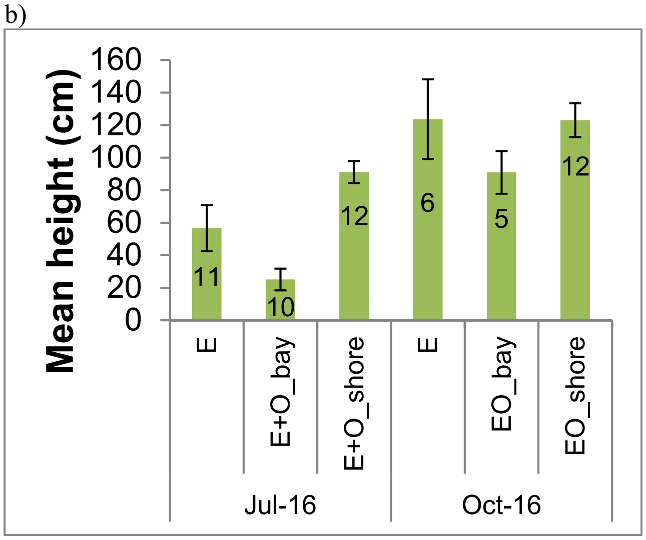


Figure 6. a) Total number of vegetative and flowering eelgrass shoots present per treatment plot at the San Rafael site, recorded quarterly after the May 2016 replant. E = eelgrass only plot, E+O_bay = eelgrass plot on bay side of oyster units in the previous oyster + eelgrass plot, E+O_shore = eelgrass 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.

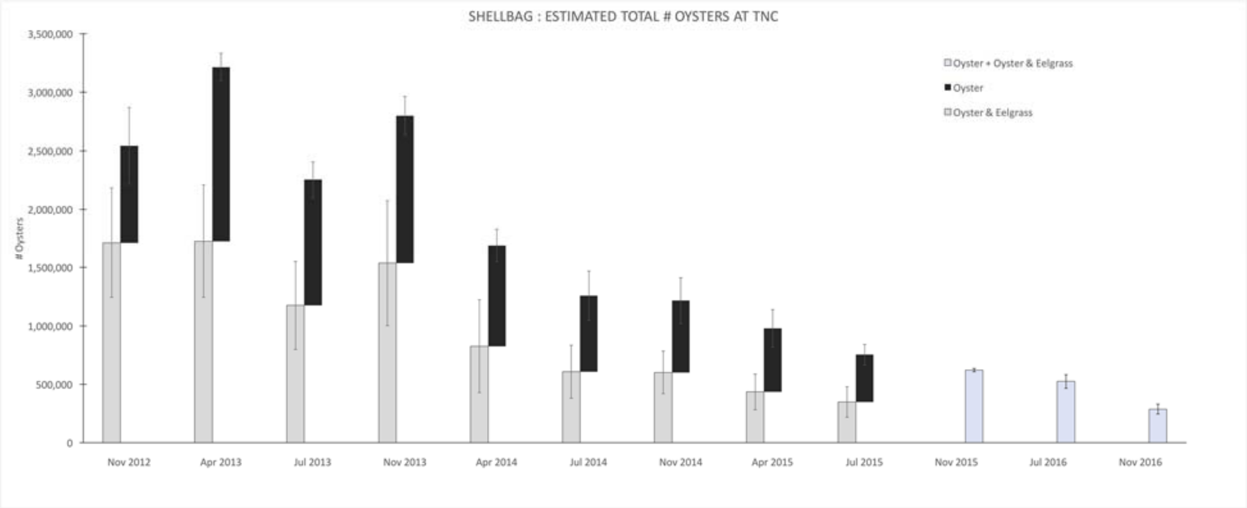


Figure 7. Estimated total number of native oysters on shell bag mounds at the San Rafael site over time in the oyster-only plot and oyster + eelgrass plot. To be conservative, only the upper portion of the mounds is included here. Means (±95% CI) were calculated from five replicate shell bags removed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

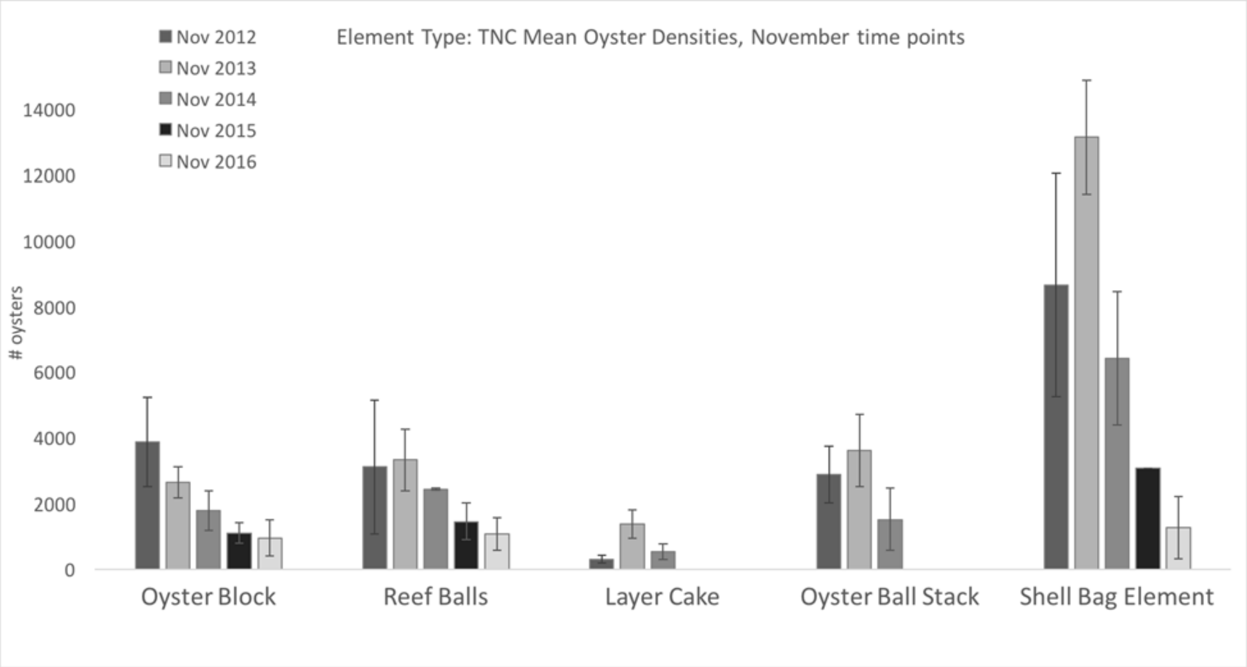


Figure 8. Estimated native oyster abundance per baycrete or shell bag element, November time points, at the San Rafael site (TNC). Means (±95% CI) were generated by scaling up from 10 small replicate shell bags (five each from oyster-only and oyster–eelgrass treatment plots) or from six 100-cm^2 quadrats 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.

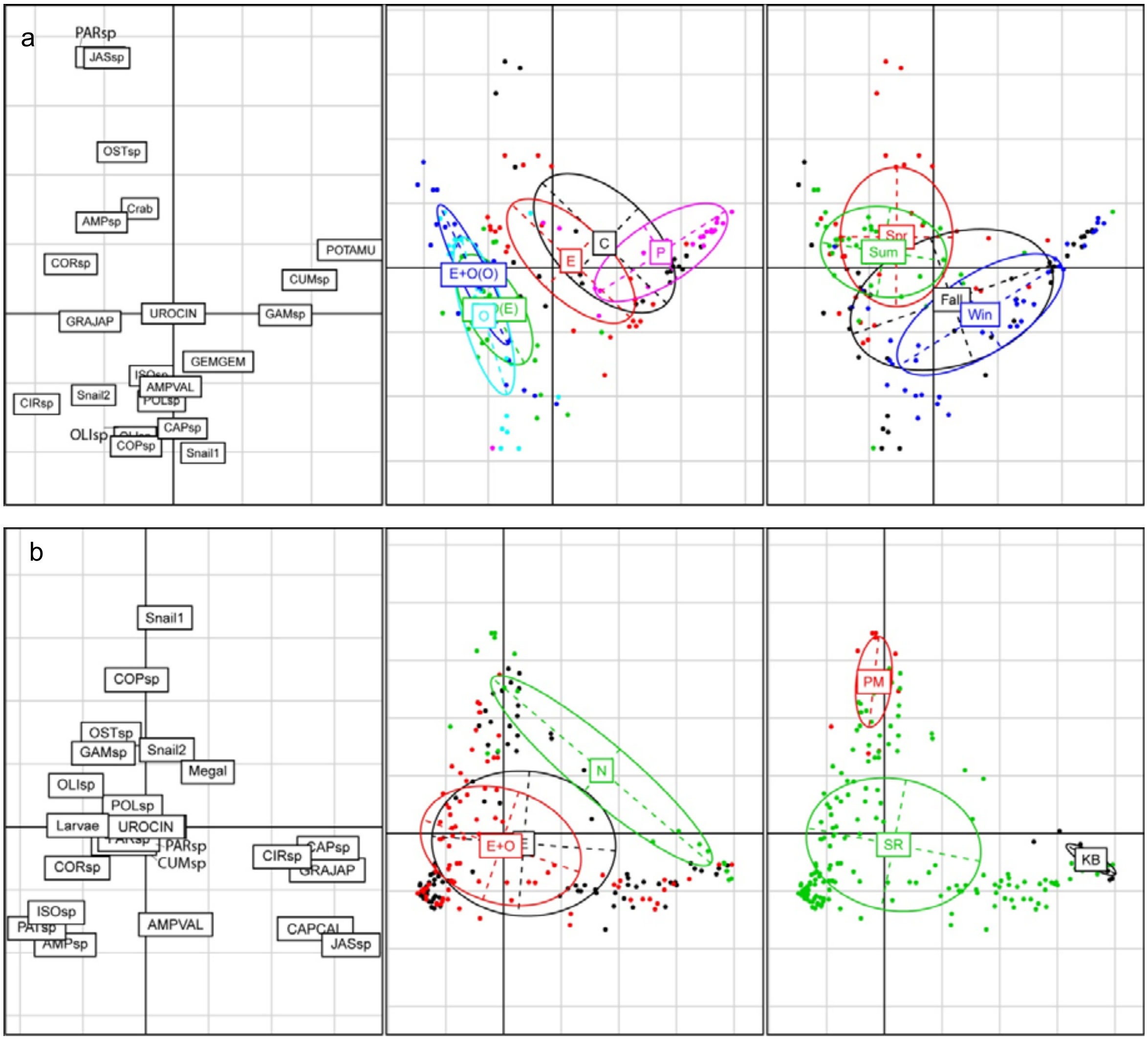


Figure 9. Correspondence analysis of epiphytic invertebrates: (a) San Rafael suction sampling patterns by taxa, treatment, and season, fall 2013 through summer 2014 (Year 2 of the project), in comparison to pretreatment (P) samples. C = control, E = eelgrass, O = oyster, E+O(E) = eelgrass from E+O plot, 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 owing to their presence obscuring differences produced by other parts of the assemblage. Taxa abbreviations as in Table 1.

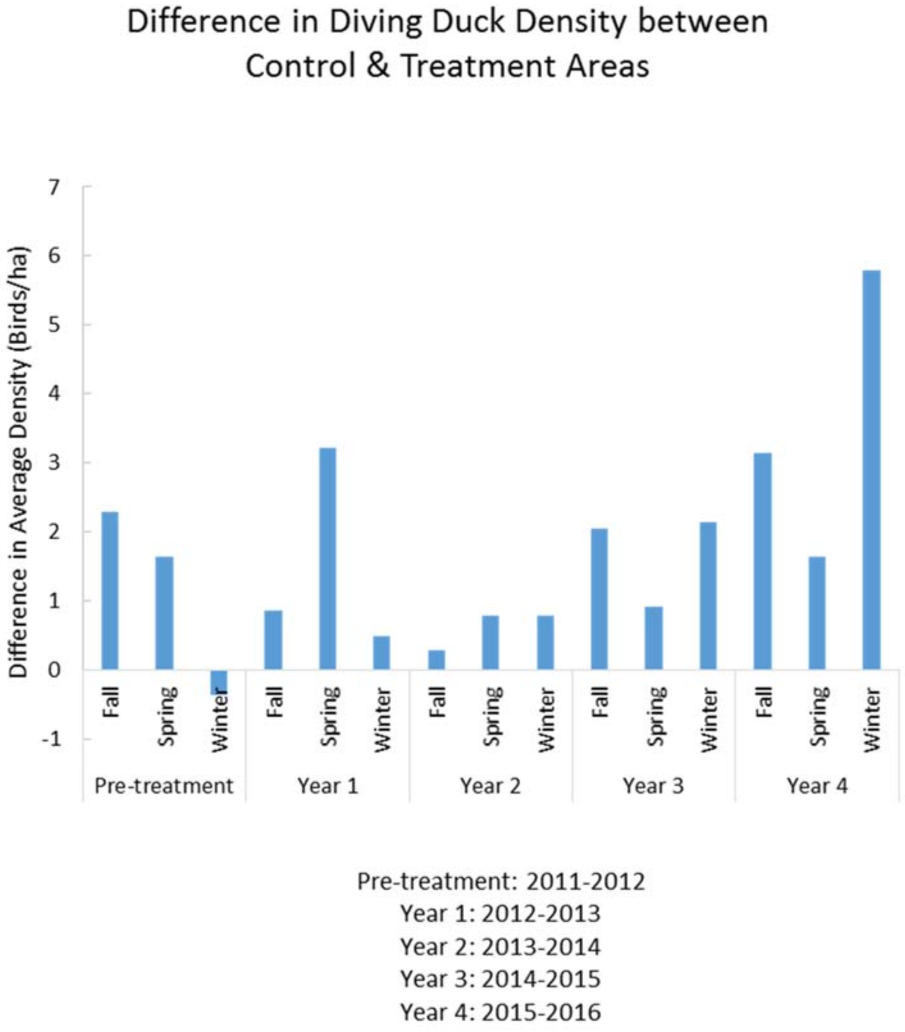


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Figure 10. Mean diving duck density in Zone B of the Control Area subtracted from mean diving duck density in Zone B of the Treatment Area during Low Tide at the San Rafael site.

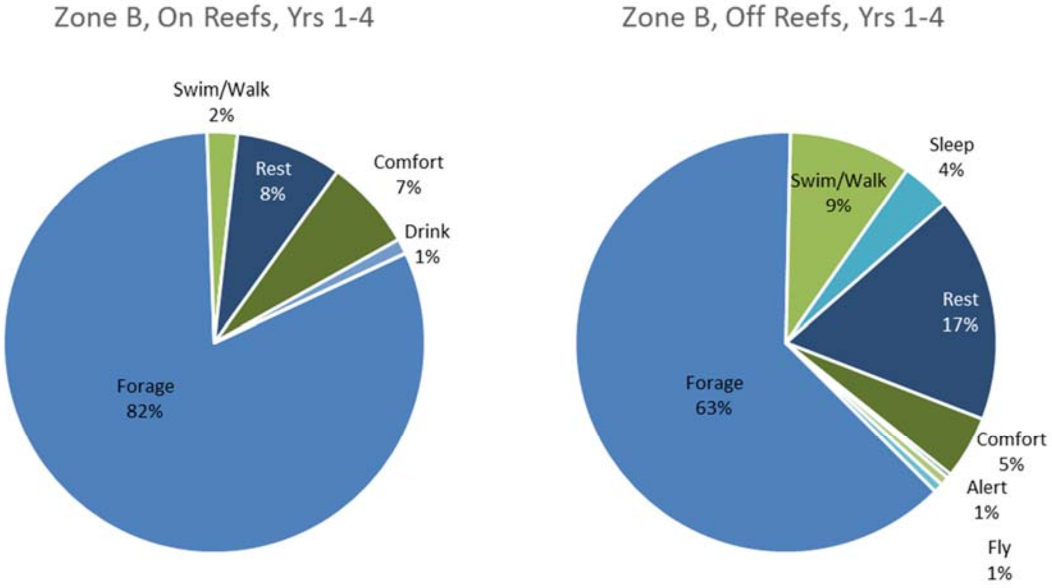

Figure 11. Bird behavior in Zone B of the treatment area, on and off of the oyster reef treatments during treatment years (1-4). Data shown is from 2 surveys per season per year with the exception of summer in Year 3, which includes one survey.

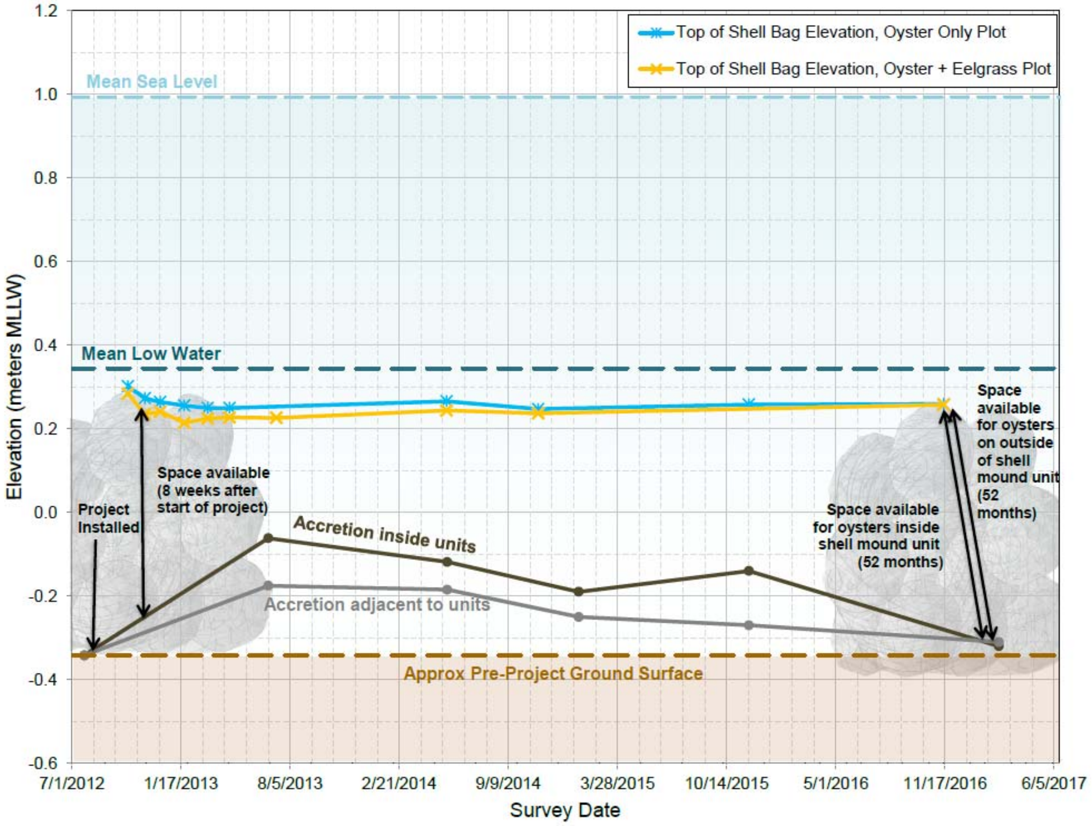

Figure 12. Sedimentation and oyster space for shell bags at the San Rafael site over time.

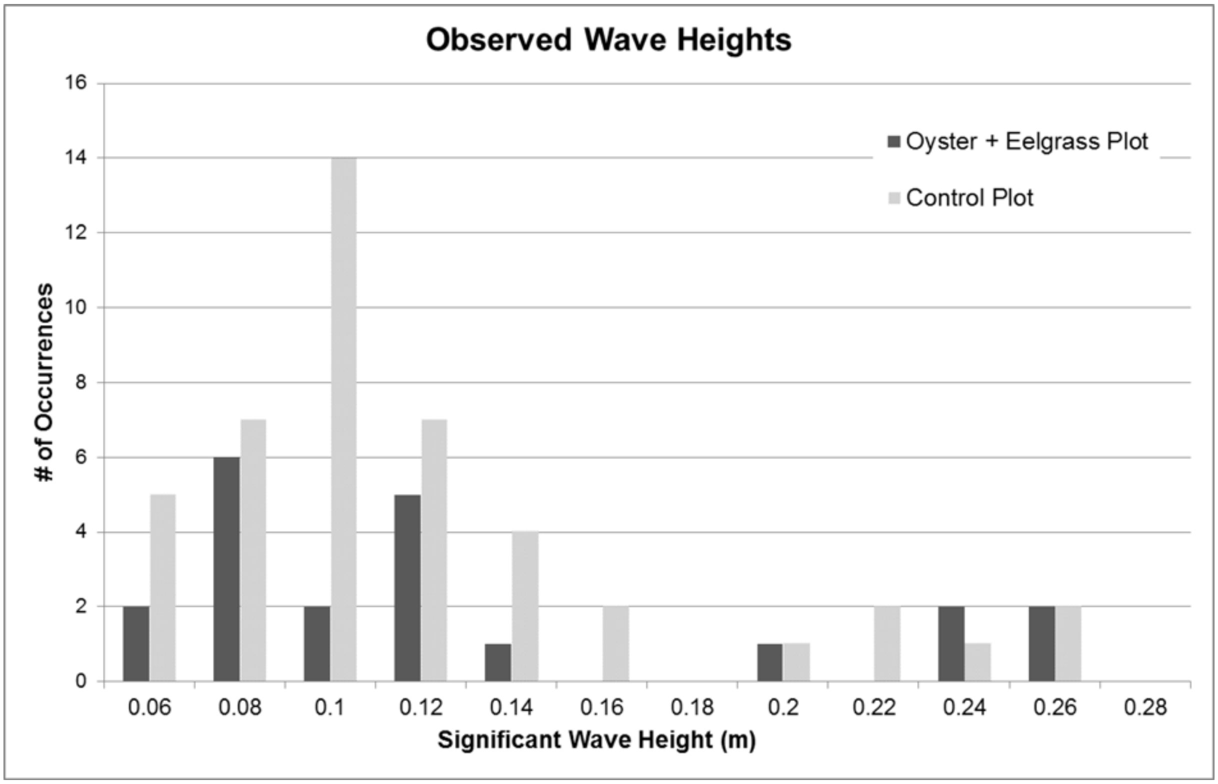

Figure 13. Wave heights measured on the shore side of the oyster + eelgrass and control plots at the San Rafael site, February 26, 2013, to April 15, 2013. There were a total of 45 significant waves measured in-shore of the control plot and 21 significant waves measured in-shore of the oyster + eelgrass plot for the sampling duration, indicating that the latter limits significant wave occurrences.