San Francisco Bay Living Shorelines: Nearshore Linkages Project
Summary of Key Findings Two Years Post-installation
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1. Introduction

Brief Project Summary

The San Francisco Bay Living Shorelines: Near-shore Linkages Project is a multi-objective habitat restoration pilot project managed by the State Coastal Conservancy, in collaboration with biological and physical scientists with San Francisco State University, University of California, Davis, USGS Western Ecological Research Center, and consultants at ESA. Additional partners include landowners The Nature Conservancy and the California Department of Fish and Wildlife, and construction support was provided by the California Wildlife Foundation, Reef Innovations, Drakes Bay Oyster Company, and Dixon Marine Services. The project was fully permitted in July 2012, and constructed over a three week window in July-August 2012. The 2014 monitoring report is the third annual monitoring report for the project, as part of a five year monitoring program through 2017.

General Concept

In general, "living shorelines" projects utilize a suite of bank stabilization and habitat restoration techniques to manage the shoreline, and maintain coastal processes while protecting, restoring, or creating natural habitat for fish and aquatic plants and wildlife. The term "living shorelines" was coined because these techniques provide living space and support for estuarine and coastal organisms, which is accomplished via the strategic placement of native vegetation and natural materials. The approach has been implemented primarily on the East and Gulf Coasts, where such techniques enhance habitat values and increase connectivity of wetlands and deeper intertidal and subtidal lands, while providing a measure of shoreline protection.

In response to the significant detrimental environmental impacts caused by traditional erosion control structures such as bulkheads and revetments along estuarine and riparian shorelines, many environmental groups and state and federal resource agencies support the use of living shorelines to achieve both biological habitat and physical protection objectives. There are some key differences in how living shorelines projects are designed, implemented, and monitored around the country. A 2012 survey of living shorelines projects in Gulf and East Coast estuaries reveals that a growing number of projects classified as a "living shoreline" are relying more on massive hard stabilization with less emphasis on natural stabilization or the development of a significant habitat component, as was the early intent of living shorelines projects (Pilkey et al 2012) and which is the intent of this project.

The SF Bay Living Shorelines Project includes an experimental design that not only provides shoreline protection, but also seeks to integrate biological and physical goals. Living Shorelines can include any habitat type, and this first pilot project focuses on oyster and eelgrass beds. The Coastal Conservancy envisions future additional projects that include additional types of habitat types in the design- including tidal wetlands, mudflats, beaches, algal beds, etc. Since this approach has not been refined for, and tested in, San Francisco Bay, this experimental pilot project seeks to test and demonstrate the success of these treatments, and share new information with other entities in the Bay and encourage continued further testing of living shoreline concepts at additional sites.

Potential Climate Change Adaptation Approach

In developing the California (State Resources Agency) Climate Change Adaptation Strategy, state agencies recommended the use of Living Shorelines as a potential adaptation method to reduce the need for engineered hard shoreline protection and to provide habitat functions and values. The State Coastal Conservancy Climate Change Policy also recommends implementation of Living Shorelines due to their ability to reduce erosion and trap sediment, allowing for both buffering of tidal wetlands and migration of habitats – towards a goal of increasing estuarine habitat resiliency to sea level rise and other drivers of change.

Global Decrease in Seagrasses and Native Oysters

Worldwide declines of seagrasses, in large part related to anthropogenic activities that alter water quality or clarity, have resulted in much interest in restoration techniques to reverse this trend. Seagrasses are foundation species that, by providing physical structure, support diverse communities of invertebrates, fishes, waterfowl and marine mammals, as well as providing attachment locations for algae and encrusting invertebrates. Restoring seagrass beds means restoring vital habitat, the loss of which can promote a cascading downward spiral of nearshore productivity. The only seagrass in the soft sediments of San Francisco Bay, eelgrass provides valued ecological services (Spratt 1981; Kitting and Wyllie-Echeverria 1992; Kitting 1993; Hanson 1998), yet eelgrass beds cover <4,000 acres, or approximately 1% of submerged land in the bay (Merkel and Associates 2003, 2009). Whereas Zimmerman et al (1991) found submarine light levels in the late 1980's to be relatively low and consequently limiting for eelgrass growth and vegetative reproduction, current biophysical modeling efforts indicate that nearly 30,000 acres of bottom area may now be suitable habitat (Merkel and Associates 2004). In fact, recent surveys suggest an expansion of the bay-wide population in the last 14 years into new areas that may have recently become habitable (Wyllie-Echeverria and Rutten 1989, Merkel and Associates 2003, 2009).

Historically, native Olympia oysters *Ostrea lurida* were an abundant and ecologically important part of the fauna in West Coast estuaries and an important fishery (Barnett 1963, Baker 1995). Unfortunately, the popularity of the fishery that began in the 1850s and other habitat impacts resulted in the complete collapse of native oyster populations along the west coast of the U.S. during the late 19th and early 20th centuries (Barnett 1963, Baker 1995). Not only was the fishery lost, but so were the key ecosystem services provided by native oysters. Studies of oysters in estuaries in the eastern U.S. have shown that native oyster reefs (*Crassostrea virginica*) act as a "foundation species" by creating a refuge from predators and physical stress as well as a food source resulting in increased local diversity of fishes and invertebrates. In the largely unstructured, soft-sediment habitats of West Coast estuaries, aggregations of native oysters were likely to have provided similar functions and have been shown to increase invertebrate species richness (Kimbro and Grosholz 2006).

Implementing San Francisco Bay Subtidal Habitat Goals Recommendations

This project helps to implement key recommendations in the 2010 San Francisco Bay Subtidal Habitat Goals Recommendations, and builds upon pilot subtidal restoration projects that have been successfully implemented in San Francisco Bay since 2004. Small-scale eelgrass restoration projects led by Katharyn Boyer (San Francisco State University, Romberg Tiburon Center) have resulted in extensive monitoring and genetics data collected at seven eelgrass beds in the bay, and the restoration of eelgrass at two sites. Native oyster monitoring and restoration projects implemented by Robert Abbott and Rena Obernolte (ENVIRON Corporation), Chela Zabin and Edwin Grosholz (UC Davis), Marilyn Latta (Coastal Conservancy- projects implemented while working for Save The Bay), and others, have resulted in population data for more than 80 intertidal sites, data on substrate surface preferences, and successful restoration at pilot sites. The funding and management of these projects has been overseen by the NOAA Restoration Center, State Coastal Conservancy/Ocean Protection Council, and other agencies; and have also had funding support and involvement from The Nature Conservancy, The National Fish and Wildlife Foundation, Restore America's Estuaries, California Sea Grant College Program and other foundation and community groups.

The 2010 San Francisco Bay Subtidal Habitat Goals Report was led by the California Coastal Conservancy/Ocean Protection Council, Bay Conservation and Development Commission, NOAA Fisheries and Restoration Center, and the San Francisco Estuary Partnership. More than 75 entities contributed to the development of the 2010 report, including science advisor Wim Kimmerer from San Francisco State University and a broad group of consultants, scientists, resource managers, and restoration practitioners working in and around San Francisco Bay. The report's 50-year plan is non-regulatory and presents a 50-year vision for how to move forward with science-based subtidal research, protection, and restoration of submerged habitats in San Francisco Bay, through an adaptive, phased project approach to learn more about subtidal ecosystem services, functions, and interactions between habitat types. The report (see www.sfbaysubtidal.org) recommended that the next generation of projects consider the possibility of integrating multiple habitat types to improve linkages among habitats and promote potential synergistic effects of different habitat features on each other as well as associated fauna. Such habitat features, if scaled up slightly beyond previous projects would have the potential to positively influence physical processes (such as sediment erosion and accretion) that influence shoreline configuration. The forthcoming climate change update to the Baylands Ecosystem Habitat Goals Report (2015, in prep.) also recommends multi-habitat, multi-objective approaches and living shorelines in order to increase resiliency of SF Bay tidal wetlands and associated habitats to climate changes such as sea level rise.

Living Shorelines in San Francisco Bay

While not a new concept, Living Shorelines projects are new to San Francisco Bay, where pilot restoration work on eelgrass and oyster reefs has recently led to recommendations for additional experimental testing of techniques and gradual scaling up to larger projects. The Project builds upon successful methods and planning to date, and takes into account knowledge of constraints, timing, and design issues informed by previous efforts and recommended regional initiatives and goals. The Coastal Conservancy has assembled an interdisciplinary team to build on previous restoration lessons and move toward integrating multiple habitats in the "San Francisco Bay Living Shorelines: Near-shore Linkages Project". The project further tests subtidal restoration techniques, restores critical eelgrass and oyster habitat, tests the individual and interactive effects of restoration techniques on habitat values, and tests alternatives to hard/structural stabilization in a multi-objective project. Due to limited historical information on distribution and abundance of native oysters and eelgrass, we use the term "restoration" in the sense of enhancing valuable functions and services promoted by these types of features in SF Bay and elsewhere, rather than in the strict sense of replacing previously known distributions or extent.

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 pre-treatment 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, e.g., by providing food resources to species that move among habitats.
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.
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

Project Locations

The two locations for the project (Fig. 1) are the San Rafael Shoreline (large and small study; site owned by The Nature Conservancy) and the Eden Landing Ecological Reserve in Hayward (small study only; site owner is California Department of Fish and Wildlife).

Design features

The project includes a large-scale and a small-scale study:

***Larger scale experiment** to test both biological and physical effects*.

This experiment includes four 32 x 10 m treatment plots situated parallel to the shore, approximately 200 m from shore. This design allows comparisons of the effects of one type of native oyster substrate (Pacific shell bag mounds), eelgrass, and both together, in comparison to a control of the same size (Fig. 2). This 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., invertebrate, bird and fish utilization, water quality interactions of oysters and eelgrass). In 2012, this experimental design was implemented at the San Rafael site.

The Pacific shell bag mound treatment plot, described in detail below, has a footprint of 1 meter x 1 meter per element. These were laid out in sets of 4 elements to make larger units of 4 m^2 (Fig. 2, 3). To minimize scour, the design included spaces of the same size (4 m^2) between these oyster reef units. There are 3 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 x 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 at San Rafael, and Eden Landing (small patches offshore) and Bay Farm Island at the Hayward site. At the San Rafael site, seeding (with Point San Pablo flowering shoots) using a buoy-deployed seeding technique was also used, with a seed bag anchored by a pvc pipe at the center of each unit, but did not result in seedlings and is not discussed further here.

The combined oyster and eelgrass plot was based 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 was also included. All four plot types were arranged randomly in the four possible positions, with 30 m between each plot. Adjacent to the overall treatment area, a Project Control area of equal size to the four plots is monitored throughout the project time period for certain measures (e.g., bird use of completely unstructured habitat relative to the whole treatment area containing structure).

"Substrate element" experiment *to examine small-scale biological effects*.
This experiment consists of replicate elements of different substrate (surface) types, intended to compare native oyster recruitment, growth and survival to inform future restoration projects. This experiment is replicated at the San Rafael and the Hayward sites. At the San Rafael site, it is situated in the 30-m spaces between and on either side of the line of larger scale plots described above (Fig. 1-3. At San Rafael, the elements include reef balls, oyster ball stacks, oyster blocks[1], and a layer cake design all made of "baycrete", a cement mixture composed of a high proportion of materials derived from the Bay including sand and shell (Fig. 3). At San Rafael, these substrate types were replicated 5 times, for a total of 20 elements. These elements were placed in groups (blocks) of four, with each of the four substrate types represented in each block.

A similar substrate element experiment was installed at Hayward in August 2012. It also included 1-m^2 substrate elements replicated in five blocks and aligned parallel with the shoreline at ~200 m from shore. However, at Hayward, there were five treatments (substrate types): reef balls, oyster ball stacks, oyster blocks, Pacific oyster shell bag mounds alone, and the latter placed along with an adjacent eelgrass plantings. The layer cakes were not included at this site due to concerns about structural integrity under high wave action, and the oyster shell mounds

[1] Also referred to as reef "castles."

were added since there was not a large-scale project testing their effectiveness at this site as at San Rafael.

Brief Permitting Review

The Coastal Conservancy and consultants at AECOM (formerly URS) prepared all documentation for regulatory permits and approvals required for the project. Additional consultants on the project provided support for coordination with regulatory agencies and assisted in application for permits.

The Coastal Conservancy coordinated early with the permit agencies, including review of draft design and an interagency meeting in Fall 2011 to discuss design modifications, regulatory permit mechanisms, project questions, and input regarding benefits and impacts to specific species. Permitting discussions focused in particular on the methods and resulting benefits and impacts to bay species, seasonal windows for the work, and issues regarding the placement of clean Pacific oyster shell as beneficial fill to create the habitat reefs.

Permit applications were submitted in February 2012, and numerous follow-up meetings and correspondence occurred on particular aspects of each agencies requirements. Final permits were secured in July 2012 prior to construction.

Permit applications and approvals include:

- **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:** 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, and to confirm CEQA compliance.
- **License Agreement with landowner The Nature Conservancy** for the San Rafael site.
- **Letter of Permission with landowner California Department of Fish and Wildlife** for permission to access the Eden Landing Ecological Reserve site.
- **Letter of Permission and support from City of San Rafael**

3. Key Findings, 2 Years Post-Installation (through summer 2014)

San Rafael (TNC) Site

Eelgrass

After replanting eelgrass in April 2013 (as the original late-summer planting in 2012 did not succeed), plants at the larger scale project at San Rafael performed well, reaching 50% of planted densities by July 2013 and 124% by July 2014 (Fig. 4). Plant heights were comparable to those in natural beds (tallest shoots 150-190 cm in spring and summer 2014; Fig. 5). A trend appears to be developing of lower overall densities and heights in the eelgrass + oyster plot compared to the eelgrass-only plot, possibly due to abrasion of plants against the oyster shells. Plants originating from Point Molate tended to produce higher densities than those from Point San Pablo, perhaps due to better matching of site conditions between the Point Molate and San Rafael sites (finer sediments than Point San Pablo). The two donors have become difficult to distinguish due to overlapping clonal growth and we will discontinue tracking them separately on future sampling dates. Stable isotopic signatures of eelgrass appeared different with oyster reef present in an early comparison; a detailed collection of tissues to evaluate isotopic signatures that can indicate food web relationships was conducted in summer 2014 in collaboration with the project's oyster team at UC Davis, and analysis is underway.

Oysters

Native oysters quickly recruited to the reef structures (by the first fall), with over 2 million present in the first year (Fig. 6); to be conservative, the counts included only the top portions of the oyster shell mounds, as the lower portions have accumulated sediment and may not support living oysters. While estimates of the total population show some fluctuations over time, numbers have remained in the millions of oysters. We estimate that the reefs have increased the numbers of oysters in this region of the bay by 2 orders of magnitude. Oysters also recruited in high numbers to the small "baycrete" structures, with the exception of the layer cake configuration, which did not perform as well; overall, baycrete structures did not support as many oysters as the shell bag elements (Fig. 7). The stacked oyster balls are also not holding up as well as the reef balls and oyster blocks. Measures of the baycrete structures in small quadrats (10 cm^2) showed that more oysters were present at lower and mid-level elevations than at the high elevation, on the north side than the south side (Fig. 8), and on vertical than horizontal faces.

Epibenthic invertebrate response

Trapping with minnow and oval traps indicated an early response of species reliant on physical structure, including bay shrimp and Dungeness crab. Additional species that are attracted to physical structure have been trapped in plots with oyster reef and/or eelgrass present (e.g., red rock crabs and red crabs). Suction sampling of epibenthic invertebrates indicated that community composition was distinct in the structured habitats relative to the controls and pre-construction conditions, and eelgrass + oyster invertebrate communities were intermediate between those in the eelgrass-only and oyster-only plots (Fig. 9). Similarly, freshwater dips of eelgrass shoots to assess epifauna communities showed differences where oyster reef is present along with eelgrass. Epifauna assemblages on eelgrass at the San Rafael site have not converged with those at natural comparison sites Point Molate and Keller Beach (the closest two natural beds, just across the bay), with two native species known to remove epiphytes (Lewis and Boyer 2014) notably absent (the isopod *Idotea resecata* and the sea hare *Phyllaplysia taylori*) at the restored site (Fig. 9).

Fish response
Trapping of fish showed much overlap in species composition among the treatments; however, a pattern has emerged of black surfperch and bay pipefish having a greater association with eelgrass habitat. 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 (bay pipefish, shiner surfperch, and saddleback gunnel). Acoustic monitoring to detect tagged fish showed that individuals of several species visited the site, including two white sturgeon, a green sturgeon (threatened species), a leopard shark, a steelhead smolt, and a striped bass. Positional analysis currently underway will help to determine the degree to which the fish were lingering at the site and whether they exhibited preferences among the treatments. Comparisons of visitation at our San Rafael project site with that at the Marin Rod and Gun Club (a site with restored oyster reefs and eelgrass) and Point Molate (on the pier and in the nearby eelgrass bed), should help to put our data in context relative to abundance and composition of acoustically tagged fish within the region.

Bird and infaunal invertebrate response
To evaluate bird and infaunal invertebrate responses, the treatment area at San Rafael was subdivided into zones (Fig. 10) encompassing 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. Densities of Black Oystercatcher increased at treatment plots in comparison to pre- installation and control densities, and Forster's terns and wading birds began using the treatment plots post-installation (Fig. 11). The site was used primarily for foraging at low tide (e.g. Fig. 12), and non-foraging (resting, preening, etc.) behaviors at high tide. Avian diversity and species richness were greater at the San Rafael site than at the Hayward site for nearly all years and tide heights in both control and treatment areas (Table 1). Preliminary analyses suggest that the treatments at San Rafael have positively influenced benthic invertebrate density, richness and biomass. Our results suggest that some avian and invertebrate species are responding to oyster and eelgrass habitat restoration; however, continued monitoring as these habitats will be important for understanding species responses to living shoreline restoration methodologies.

Physical Effects
Sedimentation has occurred adjacent to both the reefs and shell mound units, with the greatest accumulation occurring inside the latter. Using hydrographic survey methods to measure the mudflat surface around the reefs at San Rafael in May 2012 and then again in June 2014 showed sedimentation of roughly 0.07 m in the lee of the treatment plots and erosion of roughly 0.09 m to the north of the plots (Fig. 13). The north-south difference may be related to the proximity of San Rafael Creek to the north. The east-west difference may be related to the treatment elements but the same pattern can be seen in relation to the control plot, which should not have an impact. From the two surveys it appears that the treatment plots have a small impact on the overall pattern of erosion and sedimentation in the area. This is the result of only one repeat survey and

it would be necessary to undertake another survey in the future to see if the pattern of erosion and accretion was an ongoing trend. Roughly 0.04 m of sedimentation occurred around the oyster reefs each since year since construction with slightly less accumulation where eelgrass had been planted (Fig. 14). The reefs subsided about 10 cm over 5 months but did not continue to sink after that (Fig. 15). The combination of shell bag settling, sediment accumulation around the reefs and subsidence means that the space available for oysters on the individual elements decreased over time (Fig. 16). Wave heights show different patterns between the lee of the oyster-eelgrass plot and the control plot. Wave heights ranged 0.06- 0.26 m for both although the waves behind the oyster-eelgrass plot tended to be smaller (Fig. 17). The reefs dissipate approximately 30% more wave energy than the mudflat does alone at mean tide level (MTL), but the broad mudflat itself extracts substantial amounts of wave energy.

Water Quality
We have not detected substantial treatment effects on water quality measures that can be specifically attributed to the treatment plots, and it may be that even our relatively large treatment plots do not influence characteristics of flowing water in a detectable way. Onset HOBO temperature/conductivity loggers provided continuous data for temperature that should be useful for exploring seasonal patterns in response variables for multiple groups within the project team; however, defective conductivity sensors (recalled by the manufacturer) did not provide reliable salinity data.

Hayward (ELER) Site

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 ten small plots. Eelgrass was always shorter at Hayward (~80 cm; Fig. 18) than San Rafael, perhaps due to shallower site conditions at the former. Plants at this site had high densities of the Atlantic mud snail, *Ilyanassa obseleta* (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.

Oysters
Oyster recruitment at Hayward did not occur until Spring 2013 and at a much lower rate than at San Rafael. However, we estimate ~2000 oysters on our test elements there; even this relatively modest effort increased the population of native oysters at that site by one order of magnitude. Oyster blocks and higher tidal elevations currently appear to be the best at supporting oyster recruitment at this site, in contrast to the oyster shell bags performing best at San Rafael.

Epibenthic invertebrate response
Trapping results at Hayward showed that shore crab abundances increased within the treatment area relative to controls and pre-project conditions. Atlantic mud snails (*Ilyanassa obsoleta*) were by far the most common invertebrates in traps, with hundreds found per trap in some seasons but no difference with reef/eelgrass structure. Suction sampling of epibenthic

invertebrates indicates that the oyster shell reefs developed a distinct community relative to the eelgrass (when still present), control area and baseline conditions (Fig. 19).

Fish response
Only trapping was conducted to assess fish use of this site, in the treatment area versus control (unmanipulated) area. Besides leopard sharks, which were commonly caught in both control and treatment areas, only 1-3 individuals of other species were caught (barred surfperch, Pacific staghorn sculpin, topsmelt, jacksmelt, sand dab, sevengill shark) 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).

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 (Fig. 10). While avian diversity and richness were higher at San Rafael (Table 1), 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 significantly post-installation in the treatment area at Hayward. As at San Rafael, the Hayward site 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-treatment 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.

Physical effects
Subsidence of the individual elements at Hayward was similar to San Rafael and was not found to differ by substrate type.

Water Quality
The Hayward project site was frequently warmer and more saline than the San Rafael site, although dissolved oxygen, chlorophyll-a, and light attenuation were generally similar. The small scale of this project does not permit comparison of water quality on a per treatment basis.

4. Progress in 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 concept design carried out in San Francisco Bay and may be the first on the US 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 due to space limitation on the TNC parcel and our need to limit the overall size of the installation as we learned to construct the largest reefs in San Francisco Bay to date and gained permitting approval. 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 TNC 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, thus confounding interpretation of differences by treatment. Still, with care in interpretation, we can say quite a bit about how the treatments evolve 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.

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., with shorelines roughly parallel to waves, relative ease of access, appropriate depths for eelgrass and oysters, willing landowners, etc.) and thus began with just one larger-scale project in this first phase of the work. 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.

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 vs. each organism alone would improve outcomes for either species. This test entails 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, sizes) when oyster shell reef is restored alone versus in proximity to eelgrass. **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 non-native 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. **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, community similarity analysis showed that the oyster reef + eelgrass plots at San Rafael are intermediate in epibenthic invertebrate assemblages between the oyster only and eelgrass only plots. On the other hand, we have not found benefits of oyster reef presence to eelgrass growth characteristics (and in fact eelgrass spread is likely to be limited by the surrounding oyster reefs in our checkerboard design), nor have we seen oyster abundance or size increase in the presence of eelgrass. At Hayward, eelgrass was present for a limited time, so we are unable to assess this effect there. We have not finished analyzing stable isotope data yet, but these may provide a useful indication of how nutrition to eelgrass or oysters differs with the other species present, and more broadly if other aspects of the food web are enhanced in either habitat with the presence of the other species and associated species in that habitat. In order to adequately test for effects of dual restoration, we need additional sites where oysters and eelgrass are restored both together and separately.

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 was because oysters generally did better on vertical vs. 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. 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 and/or break down.
At Hayward, oysters recruited initially to shell bags only, but currently longer-term survival appears to be best on the oyster blocks, with the other baycrete structures doing less well (layer cakes were not included at this site due to the expectation that they would not hold up under high wave action).

For our third approach, we were only able to use buoy deployed seeding at the San Rafael site and only with flowering shoots from the Point San Pablo donor, 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 following 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 afterwards. Thus, in comparing the two methods of eelgrass establishment, we conclude that transplanting whole shoots was the more effective technique overall, both in terms of availability of propagules and success of establishment. However, we still recommend seeding when possible due to the fact that 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 type of sediment conditions found at San

Rafael, as both have a higher amount of clay present 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 (Boyer et al. 2008; 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. Across all element types at San Rafael, more oysters were present at the lower and mid-level elevations than at the high elevation. More oysters were present on the north side than the south side and on vertical vs. horizontal faces. While longer immersion times could explain greater abundance on at lower tidal elevations, the north-south and surface orientation differences strongly suggest that heat and/or desiccation stress is a factor in determining oyster abundance at San Rafael. At Hayward, while oysters recruited initially to shell bags and then to the interior surfaces of the large oyster balls, two structure types that ought to be the best in mitigating heat and desiccation stress, more oysters are currently found on the higher elevations of castle blocks and large reef balls. This is likely due to predation by the Atlantic oyster drill *Urosalpinx cinerea,* which is more abundant at the lower elevations. Further experimental work at this site indicates greater drill abundance and greater mortality of oysters due to predation by drills at lower vs. higher elevations.

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. Preliminary data suggest that several fish species of concern lingered at the project site at San Rafael, although additional analysis is necessary to evaluate these patterns. At both San Rafael and Hayward, wading bird presence increased after the placement of reef structures, and at San Rafael, black oystercatchers are utilizing the reefs for foraging. Additional monitoring over several more years is necessary to determine the how the strengths of these relationships develop over time.

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 benefitted more so by one substrate than the other. Black oystercatchers and wading birds increased in the presence of the reef structures. Black surfperch and bay pipefish were shown to have a greater association with eelgrass habitat, and epibenthic invertebrates assemblages are beginning to differentiate 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 close proximity to the San Rafael site, we are not able to determine the degree to which our added structures influence functioning or subsidies from our project 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.

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 around the reefs, but a small impact on accretion across the area of the project; additional measurements are needed over time to assess this trend. We expected greater subsidence of the reefs and over a longer period of time; our data showing only a 10 cm subsidence into the sediments ending after 5 months suggest that even in the very soft sediments of the San Rafael site, sinking of our reef structures is not a great concern. Sediment accumulating around the oyster shell bags is unlikely to support oyster survival at the lower elevations, leading us to include only the upper portions of the reefs in our estimates of oyster abundance and size, and also suggesting that future projects should consider this issue when predicting habitat availability on the reefs. Since the different element types appear to perform 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, or perhaps oyster blocks based on the Hayward esults. Future deployments should allow for the loss of available space for oysters due 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 accomplished at mean tide level; however, we are cautious in our interpretation of this result considering we had limited measurements. Ideally, we would have similar reefs located in multiple locations with different slopes and wave environments 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 has been far superior at San Rafael, perhaps due to much less exposure on the low tides, or due to the Atlantic 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 terms of oyster recruitment at San Rafael, but at Hayward, oyster blocks currently appear to be the best. A shell bag element offers more surface area than any of the baycrete elements and greater protection from heat and/or desiccation stress due to more shading and water retention and the generally lower tidal elevation relative to the baycrete structures; this is the most likely explanation for their high performance at San Rafael. However, at Hayward, where predation pressure is strong and greater at lower elevations, taller structures with more exposed surfaces have ultimately 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 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. We hope to identify additional areas where such a comparison could be made in future phases of the work.

5. Future Design Criteria

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

-This project and several others (Boyer, unpublished data) 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 led to successful establishment at both sites (although the Hayward site ultimately failed to support eelgrass by fall/winter 2013).

-We can eliminate two of the baycrete element designs: layer cakes and small reef ball stacks. Neither stand up well over time, and layer cakes have fewer oysters compared with other configurations.

-Key stressors for oysters vary with location within San Francisco Bay. Shell bags potentially offer protection from heat and desiccation stress and provide a lot of complex surface area for oysters and other organisms to attach to and live in, but surfaces that are at higher tidal elevations and more stressful in terms of exposure may provide oysters with some measure of protection from marine predators and non-native fouling species.

-Additional protection from oyster predators and cover of fouling species might be gained by encouraging larger mobile predators (such as crabs) and mesograzers to settle on restoration substrates. Future designs might include developing substrate types and/or 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 appears to be benefiting from the other

so far, the preliminary evidence that differences in the two habitats lead to distinct invertebrate and fish communities suggests that their co-location will maximize habitat value.
-Oyster reef designs should consider the fact that the lower portion of substrates will experience burial. Future designs could be elevated on materials that are less difficult to source than bags of oyster shells, which will be less available in the future.
-Wave energy reduction measured in our San Rafael project is encouraging, but we recommend many additional sites should be used for similar projects and measurements in order to determine optimal design and the need for site-specific differences in reef configuration. Size and configuration of substrate arrays as well as distance from shore are likely to have important effects on both physical and habitat features.

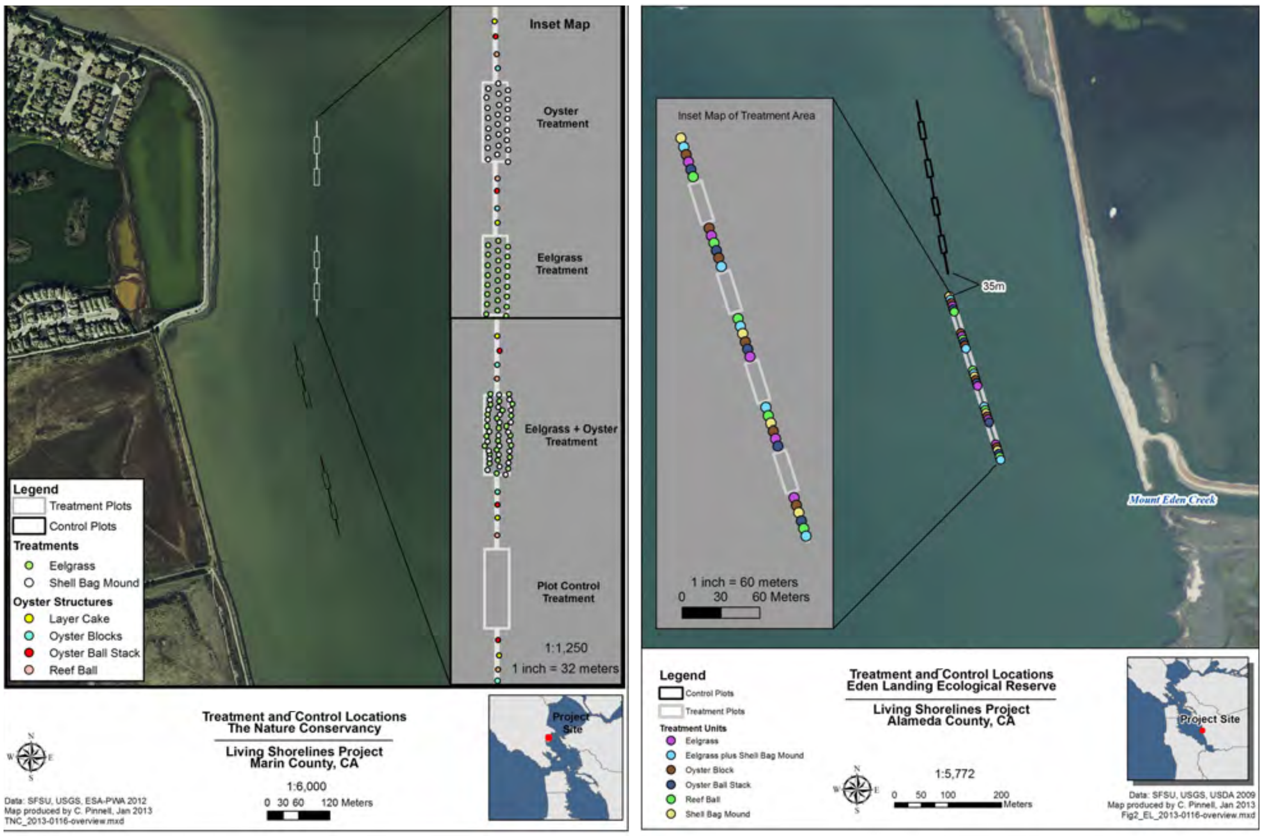


Figure 1. Maps showing the location and configuration of (left) the larger-scale project at San Rafael (property of The Nature Conservancy) and (right) the smaller pilot project at Hayward (offshore of Eden Landing Ecological Reserve).

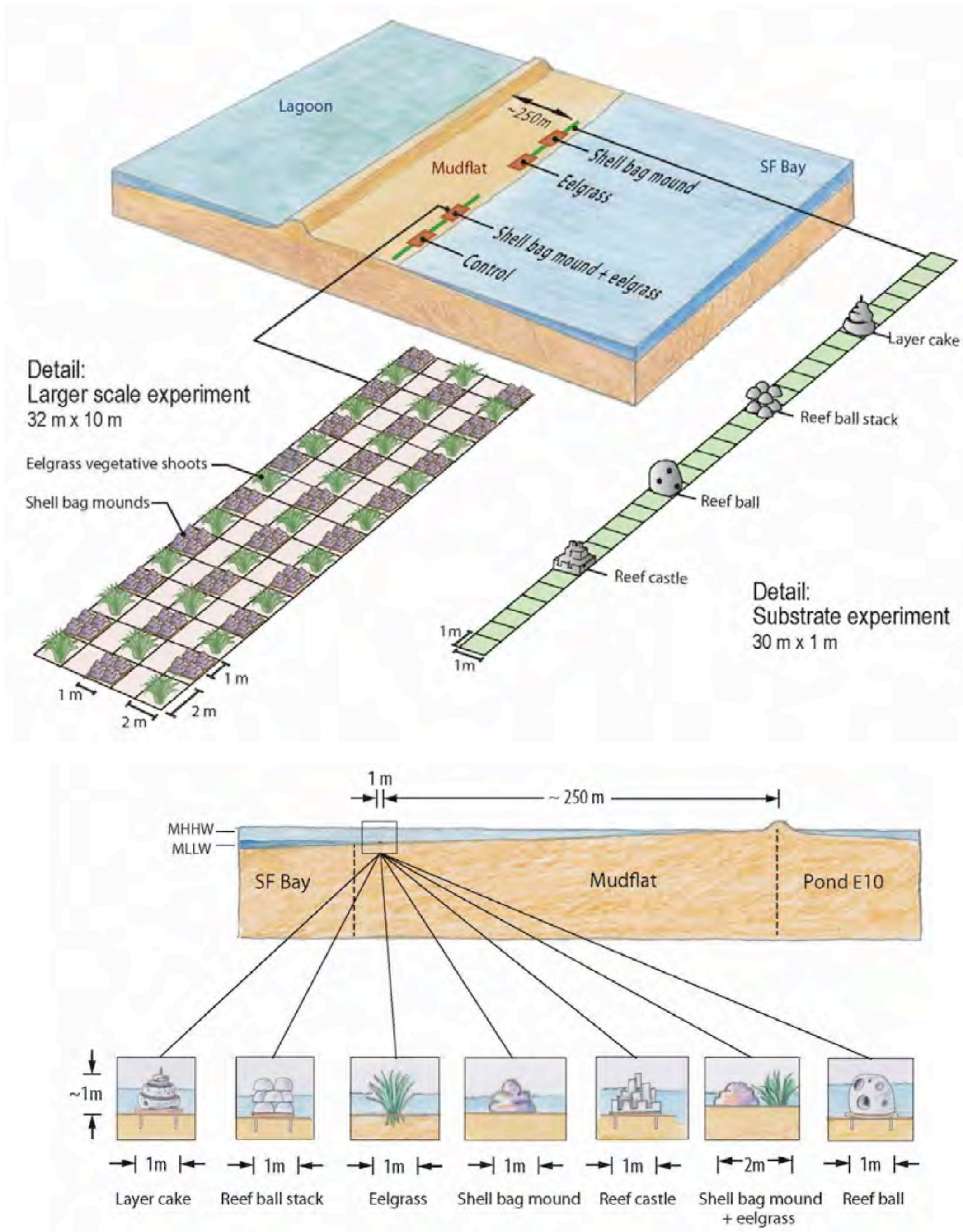


Figure 2. Schematic of the Living Shorelines: Nearshore Linkages project. Top: the larger-scale project design, as placed at the San Rafael site, with the four types of baycrete elements in rows between the four large plots. Bottom: the smaller-scale test elements placed at the Hayward site; note that ultimately the layer cake design was not used at Hayward due to concerns about structural integrity under high 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.

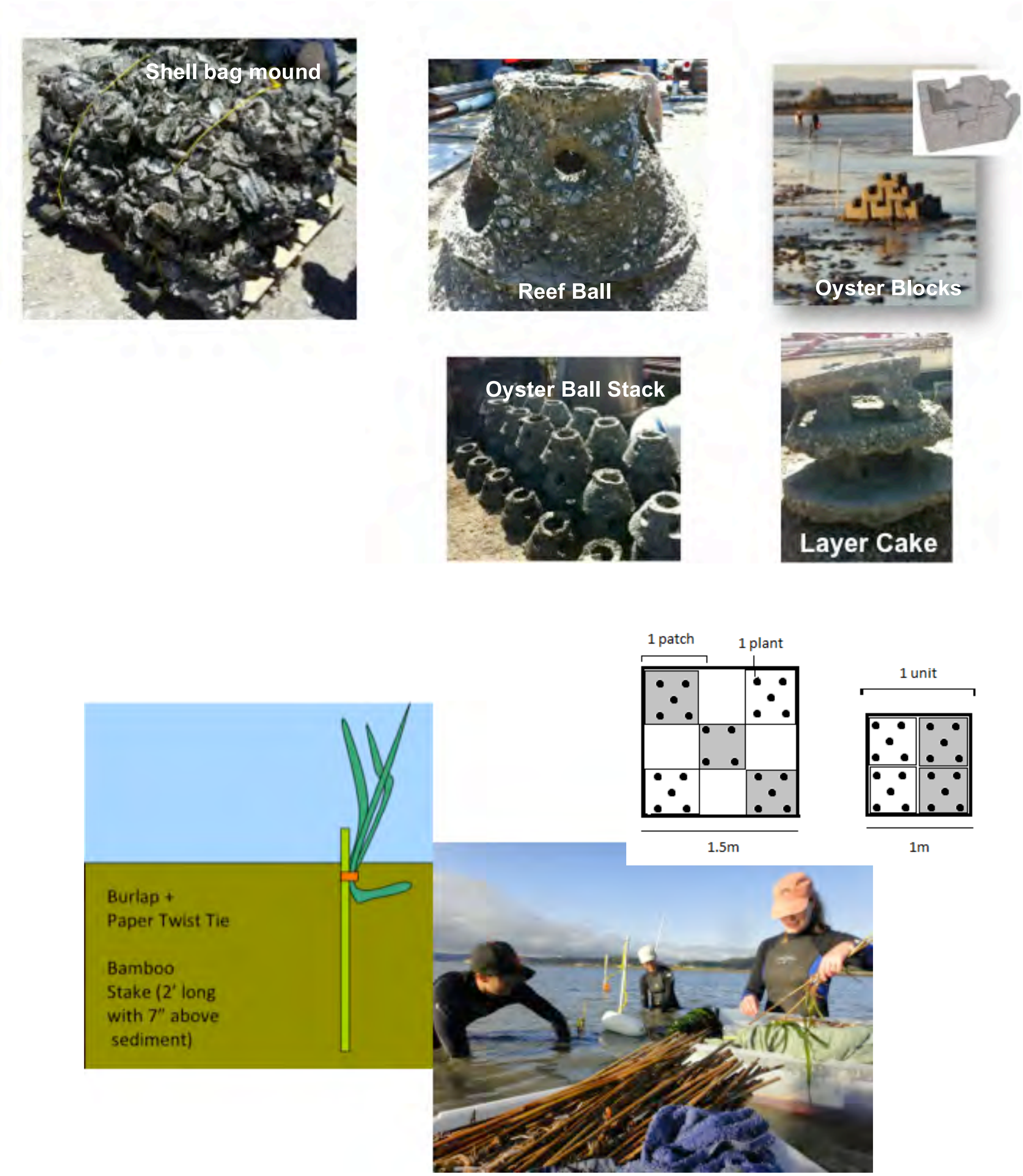


Figure 3. Top: Photos of oyster substrates used in the project (all photos M. Latta). Bottom: Eelgrass planting using bamboo stake technique (diagram and photo S. Kiriakopols). Inset, schematic of planting design within an eelgrass unit is shown for San Rafael (left) and Hayward (right). Two donors were used to plant each site, as indicated by shading in the schematic.

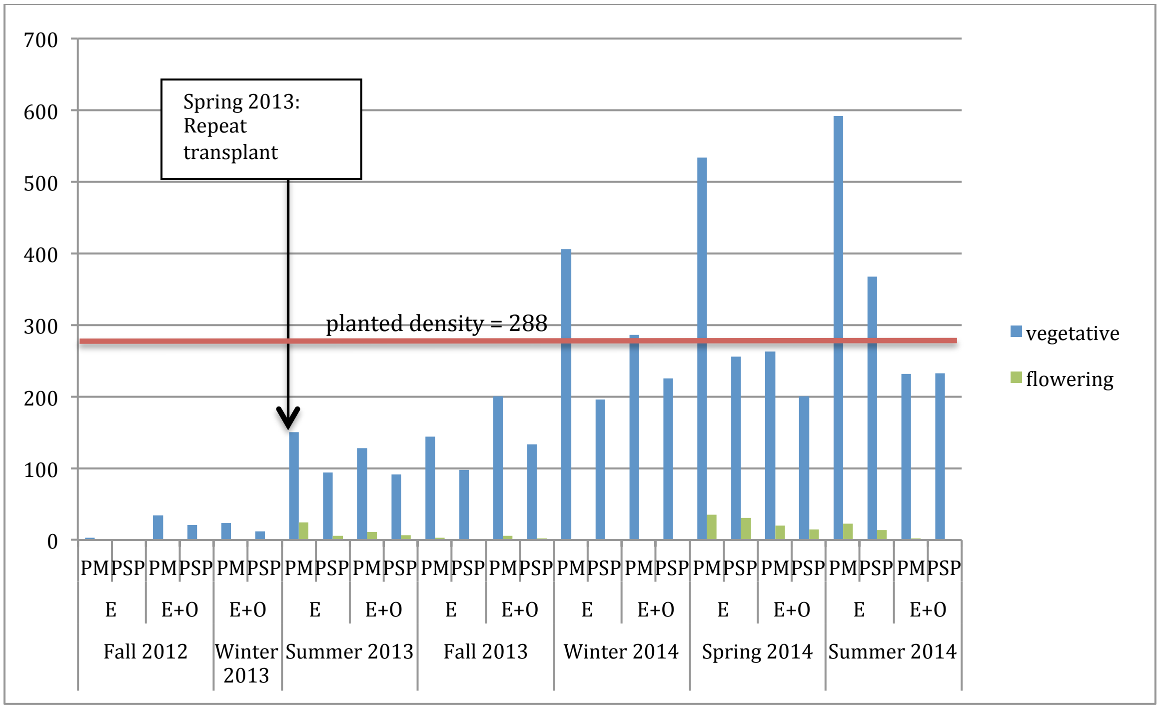


Figure 4. Total number of vegetative and flowering eelgrass shoots present, per donor and treatment plot at the San Rafael site, quarterly through summer 2014. E = eelgrass plot, E+O = eelgrass and oyster plot, PM = plants from the Point Molate donor site and PSP = plants from the Point San Pablo donor site.

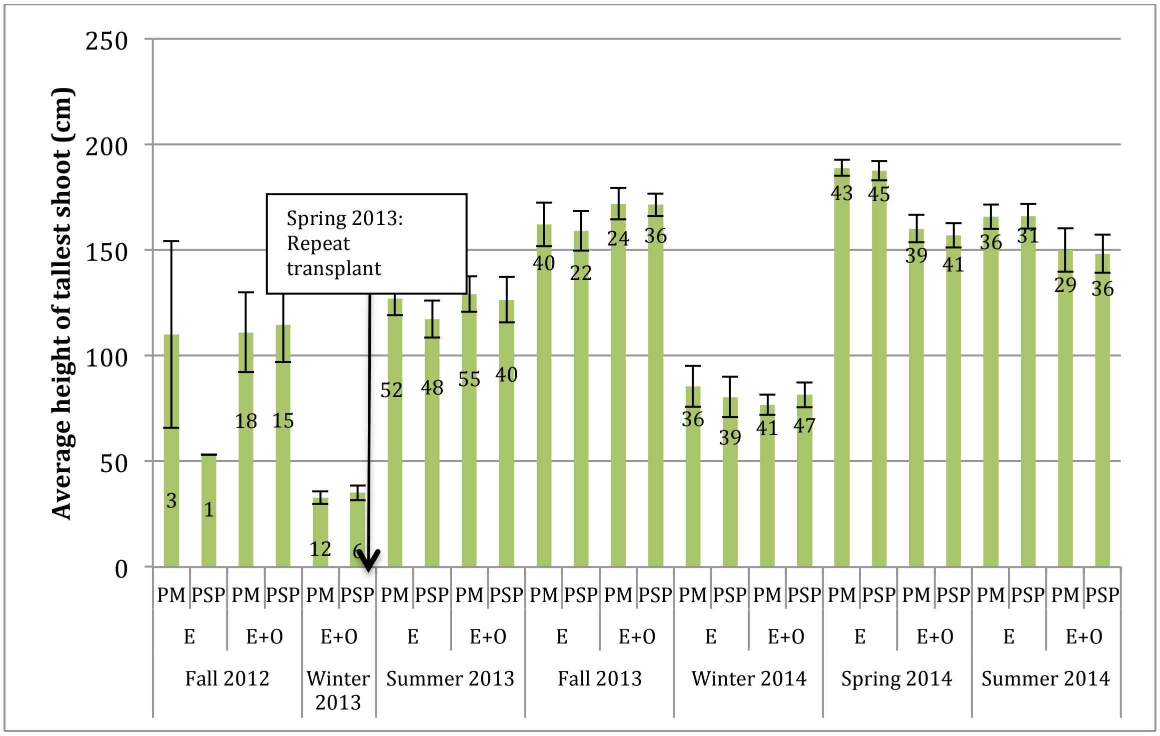


Figure 5. Average height of the tallest eelgrass shoot in each patch, by donor and treatment plots at the San Rafael site in each quarterly monitoring effort. E = eelgrass only plot, E+O = eelgrass and oyster substrate plot, PM = plants from the Point Molate donor site and PSP = plants from the Point San Pablo donor site. Numbers on columns indicate the sample size. Error bars = 95% confidence intervals.

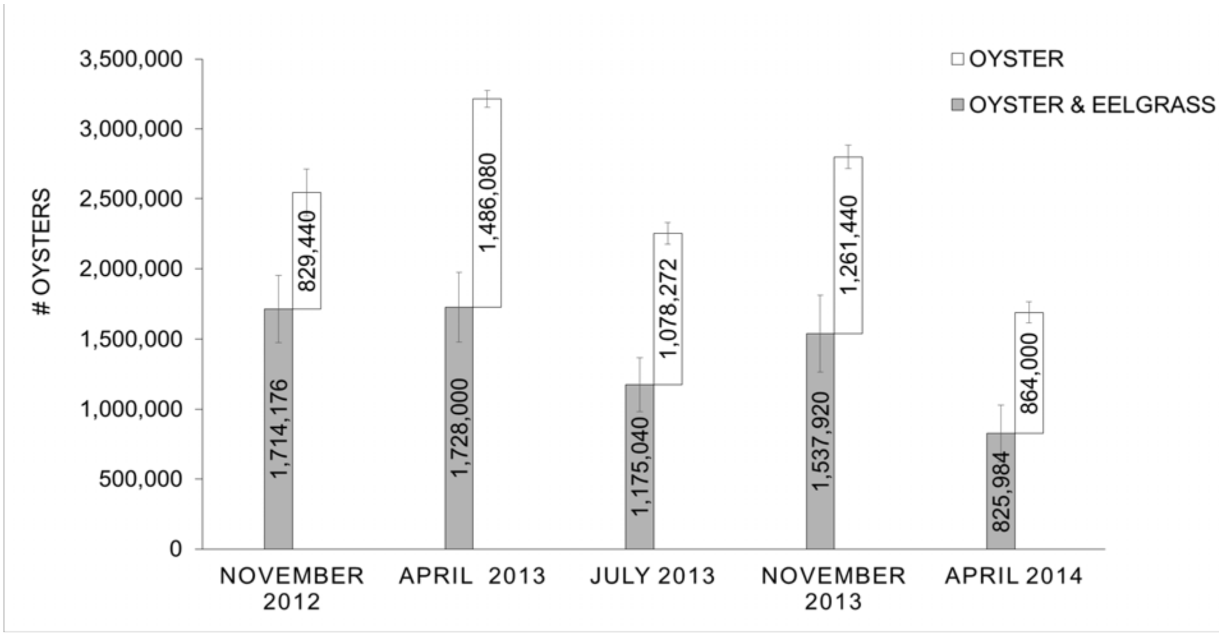


Figure 6. Estimated total number of native oysters on shell bag mounds at the San Rafael site over time. Total equals the number present on the oyster-only plots and in the oyster + eelgrass plots (numbers given separately on bars). To be conservative, only the upper portion of the mounds is included here. Error bars = 95% confidence intervals.

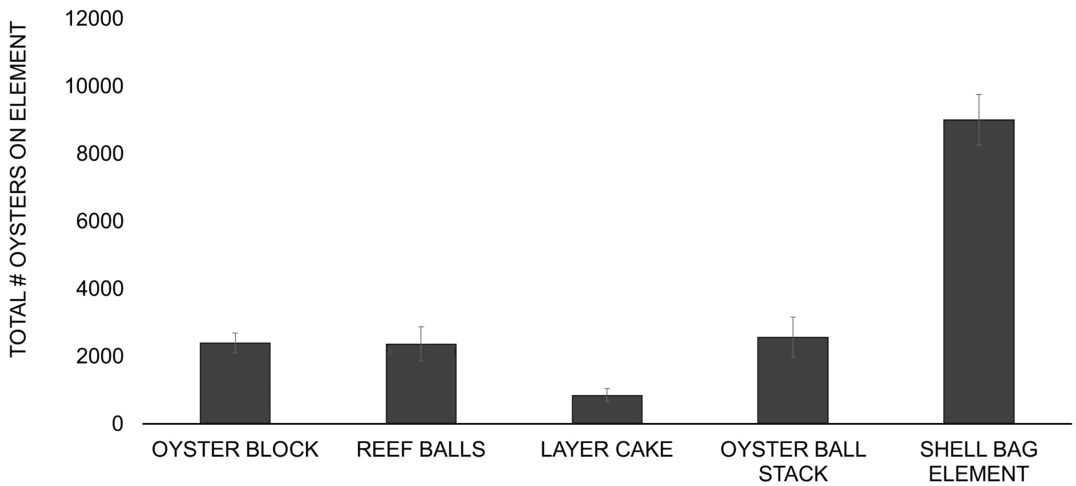


Figure 7. Estimated native oyster abundance per baycrete or shell bag element, April 2014. Error bars = 95% confidence intervals.

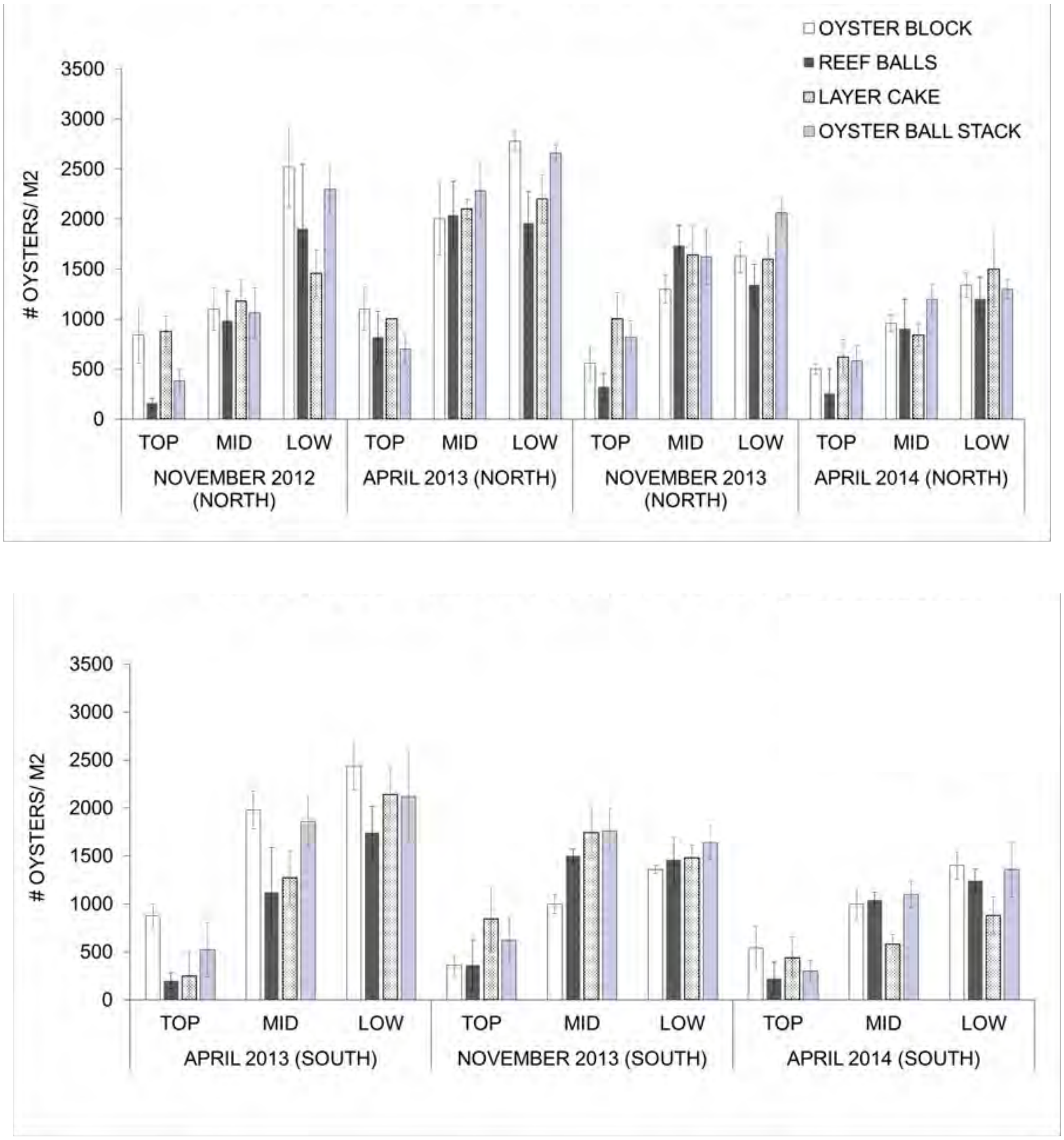


Figure 8. Mean native oyster density on the baycrete elements through time on the north (top panel) and south (bottom panel) sides, San Rafael. Error bars = 95% confidence intervals.

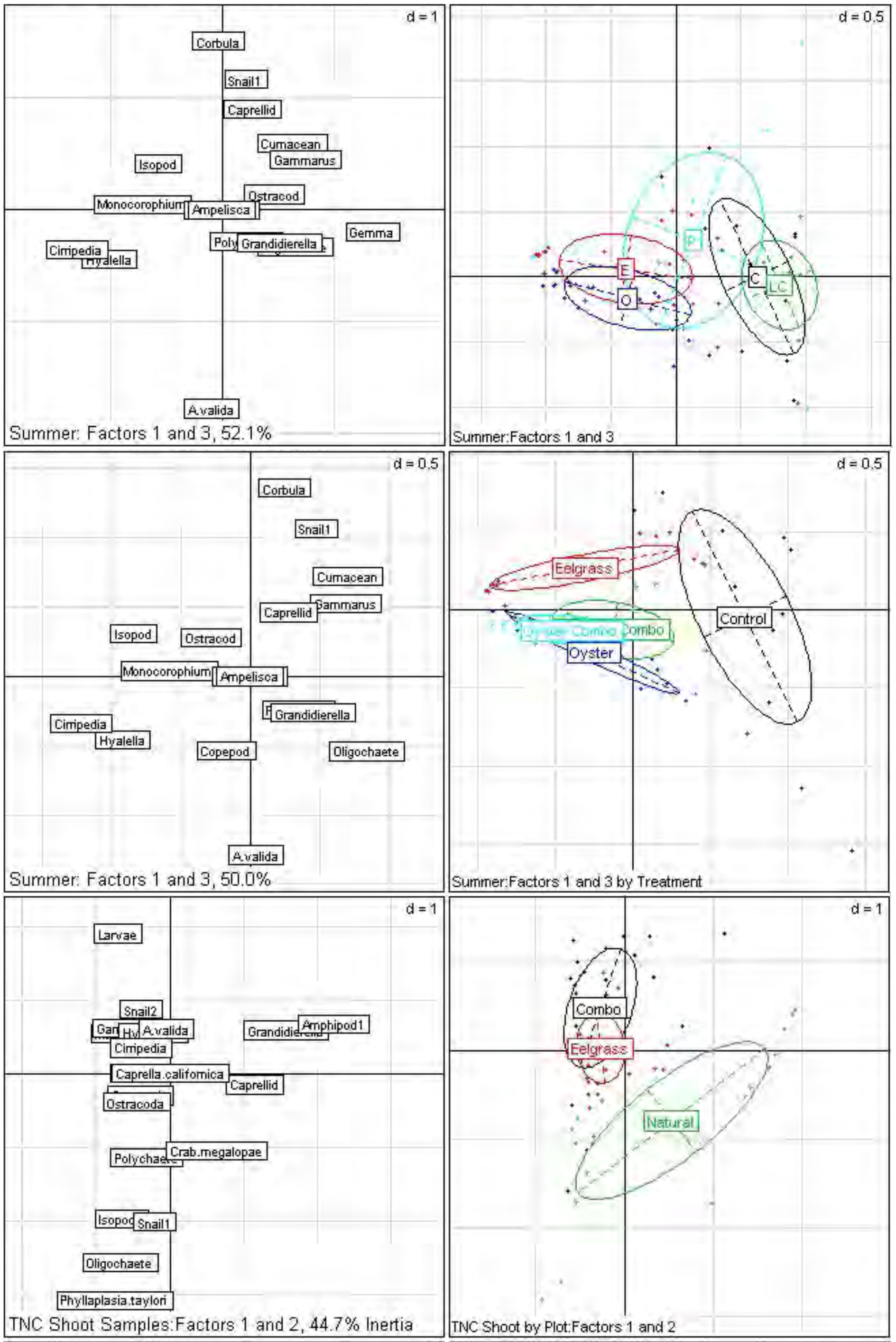


Figure 9. Top: Correspondence analysis of San Rafael suction samples for epibenthic invertebrates. As of summer 2013, the large control (west of the treatment plots, LC) and project control (within the treatment array, C) had a different invertebrate assemblage compared to the oyster and eelgrass samples, with the pre-installation invertebrate community (P) in 2011 intermediate. Middle: By summer 2013, the oyster plot and eelgrass plot had diverged in invertebrate assemblages, with samples in either habitat within the combined treatment plot ("combo") intermediate between them, and the project control plot distinct from all structured habitats. Bottom: Shoot collections in spring 2014 showed invertebrate assemblages within the San Rafael plots were quite different from those in the natural beds at Keller Beach and Point Molate.

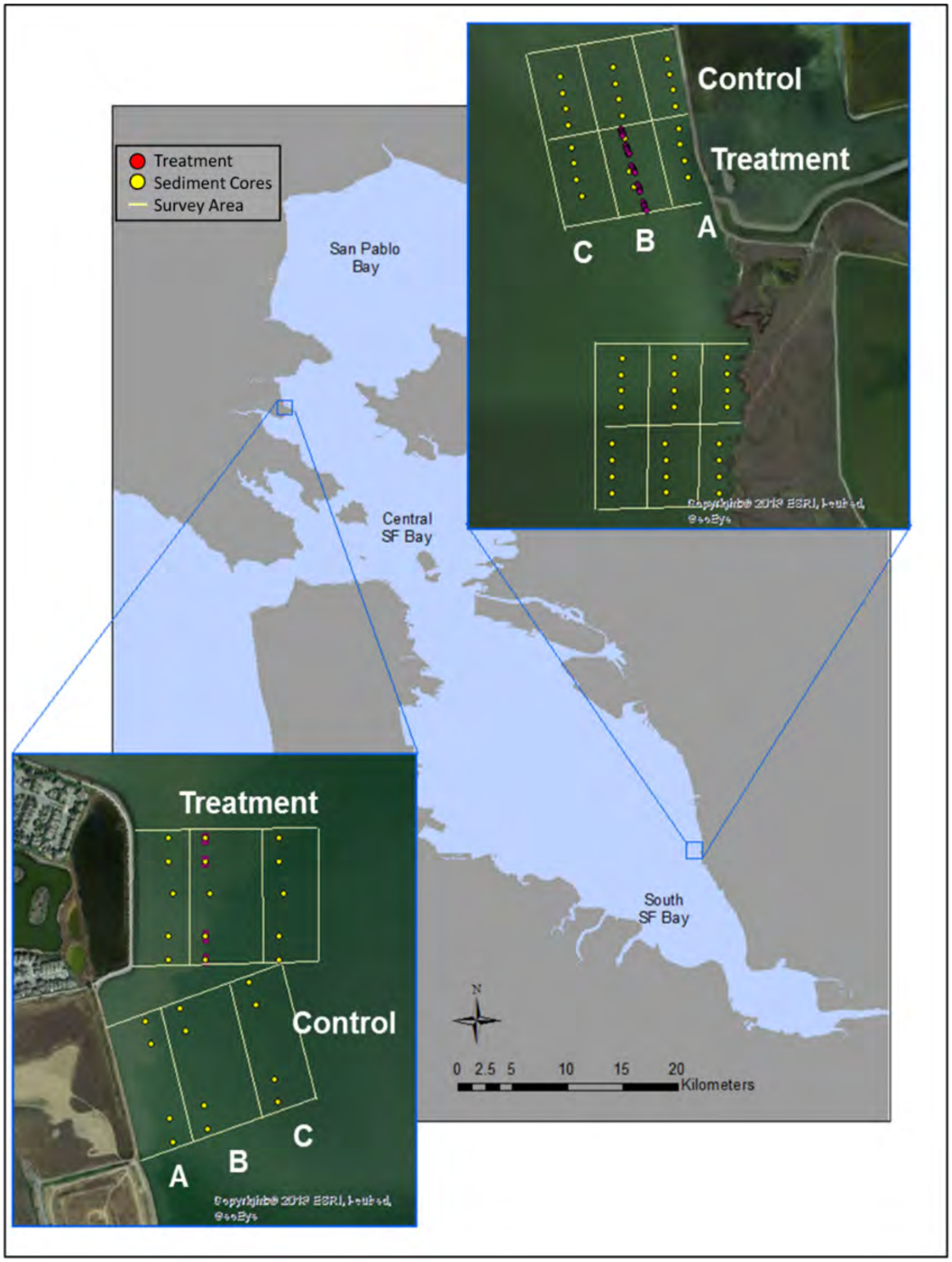


Figure 10. The San Rafael (Nature Conservancy) site in Central San Francisco Bay and Hayward (Eden Landing) site in South San Francisco Bay, with treatment and control plots broken into three survey zones; inshore (A), central (B), and offshore (C), with sediment coring locations (yellow circles), and treatment locations (red circles).

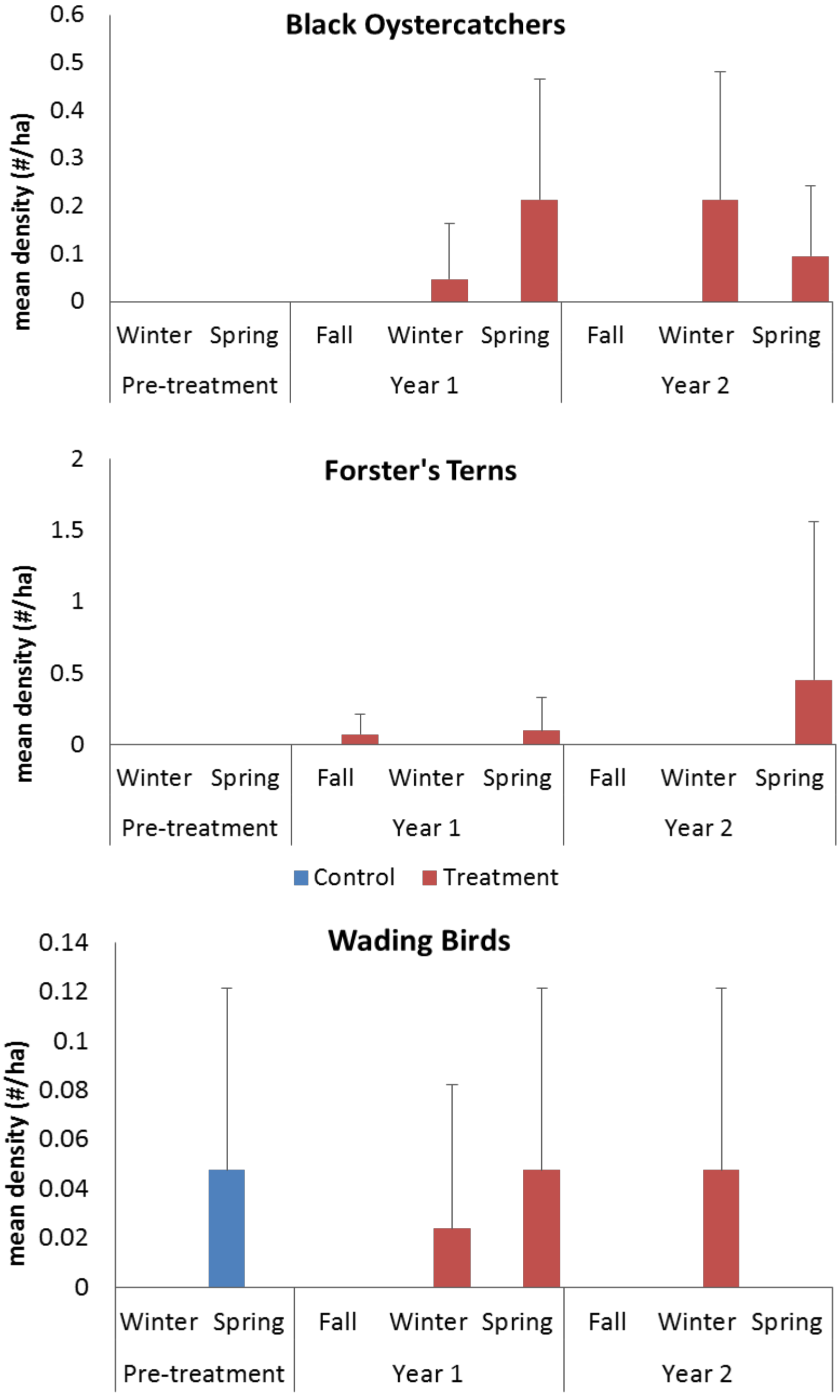


Figure 11. Top and Middle: Mean seasonal density (±SD) of black oystercatchers and Forster's terns in zone B at low tide at San Rafael among pre-treatment and post-treatment years. Bottom: Mean density of wading birds in zone B of the control (blue) and treatment (red) areas during low tide at San Rafael among pre-treatment and post-treatment years. No surveys were conducted during fall of the pre-treatment year. Note: y-axis differs between graphs.

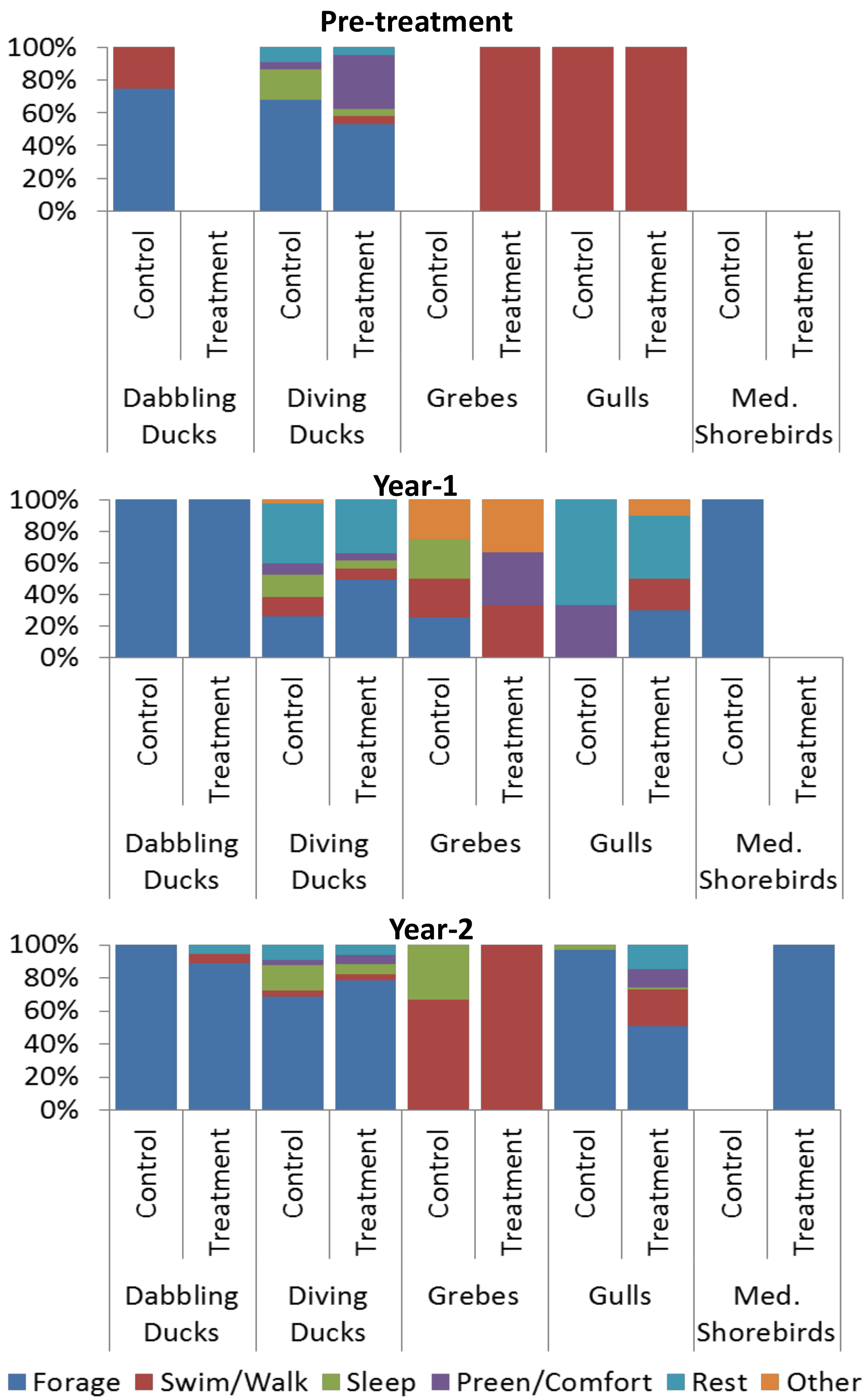


Figure 12. Avian behavior by guild from scan surveys at San Rafael in zone B of both the treatment and control areas during low tide during pre-treatment (top), year-1 (center) and year-2 (bottom).

Table 1. Shannon Diversity Index and species richness of the San Rafael and Hayward sites at low (LT) and high tide (HT) in control and treatment areas for all zones in all years. For Hayward, diversity was calculated only from zone B when the tide line was in zone B.

	San Rafael				Hayward			
	LT		HT		LT		HT	
Diversity	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment
Pre-treatment	2.14	1.68	1.10	1.96	1.47	1.38	1.55	1.07
Year 1	2.29	2.22	1.33	1.70	1.89	1.74	1.37	1.19
Year 2	2.19	2.41	1.33	1.78	1.71	1.31	0.81	0.40
Richness								
Pre-treatment	22	17	15	19	13	14	13	12
Year 1	25	28	14	20	22	26	12	15
Year 2	26	32	15	17	19	25	10	13

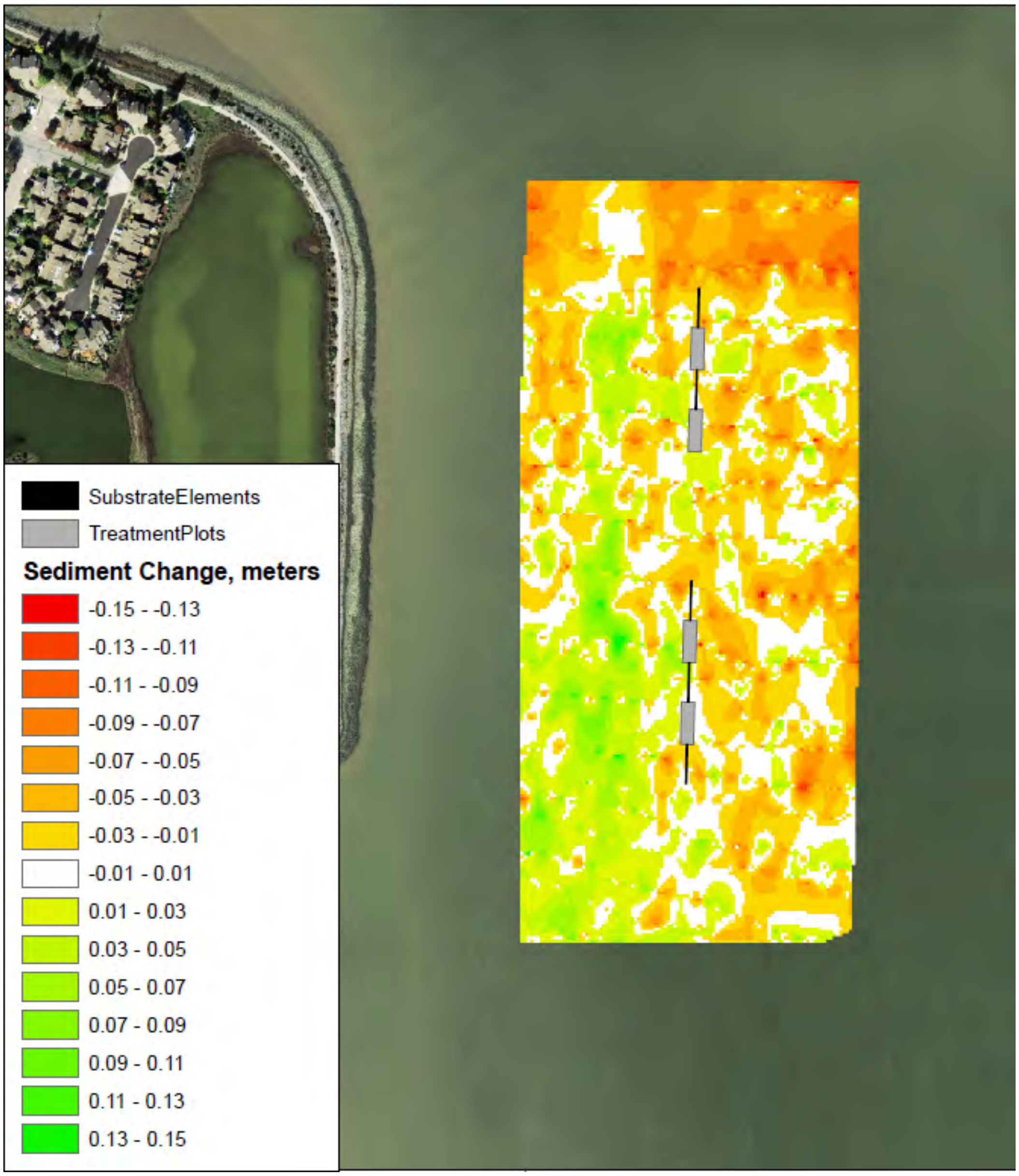
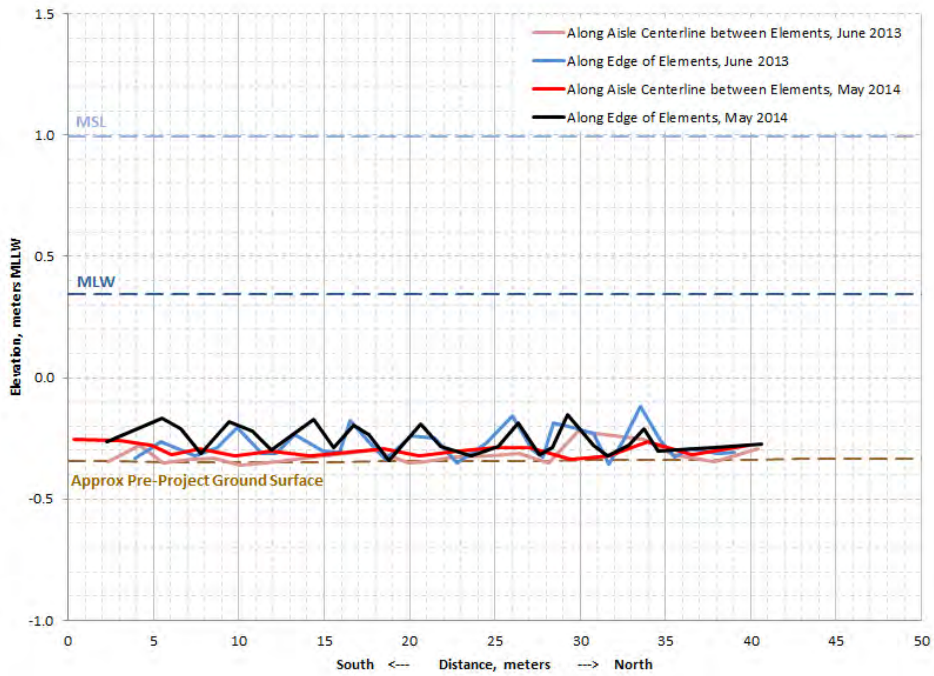


Figure 13. The San Rafael project site showing change in elevation between May 2012 and June 2014. (green is accretion, orange and red is erosion)



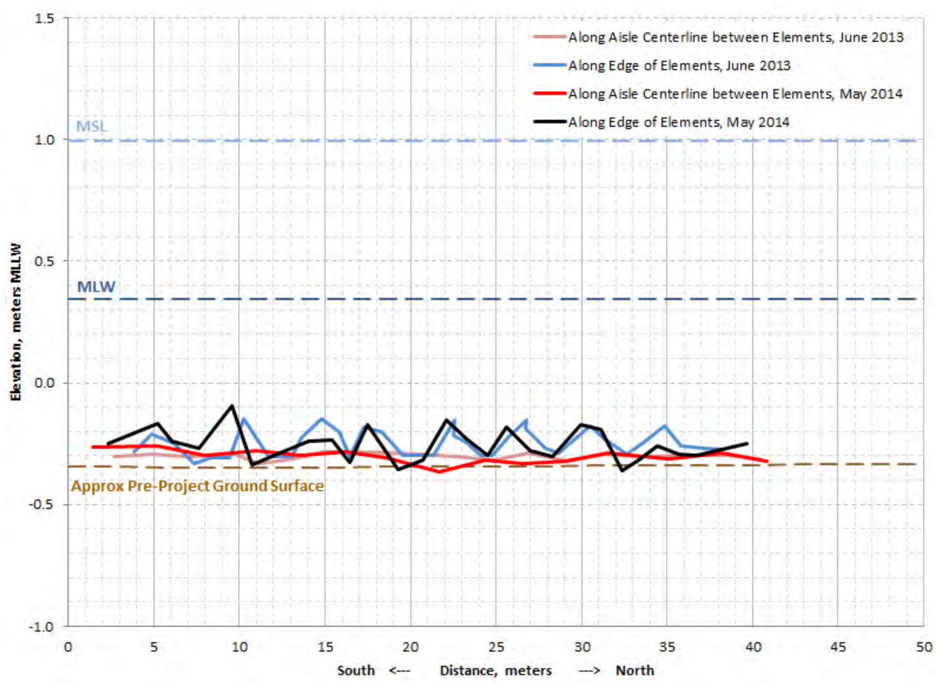


Figure 14. Top: Oyster-eelgrass interior sediment profiles. Bottom: Oyster-only interior sediment profile.

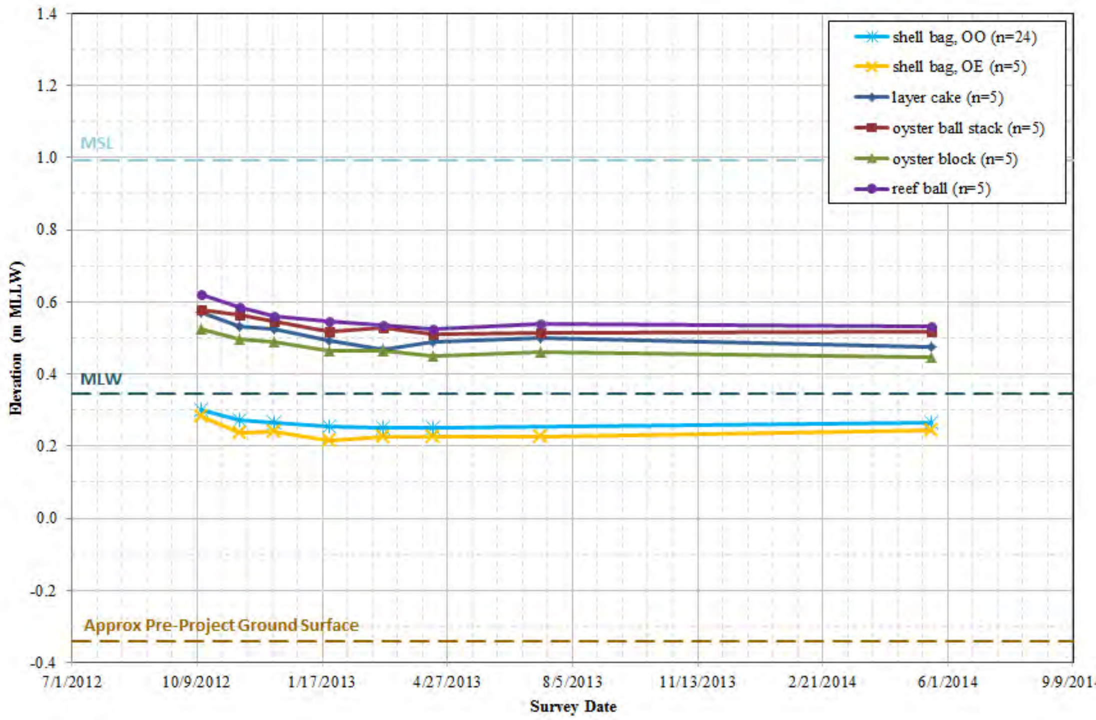


Figure 15. Element elevations over time at TNC. Note: the shell bag mounds were constructed lower than the other four types of elements by approximately 0.25m

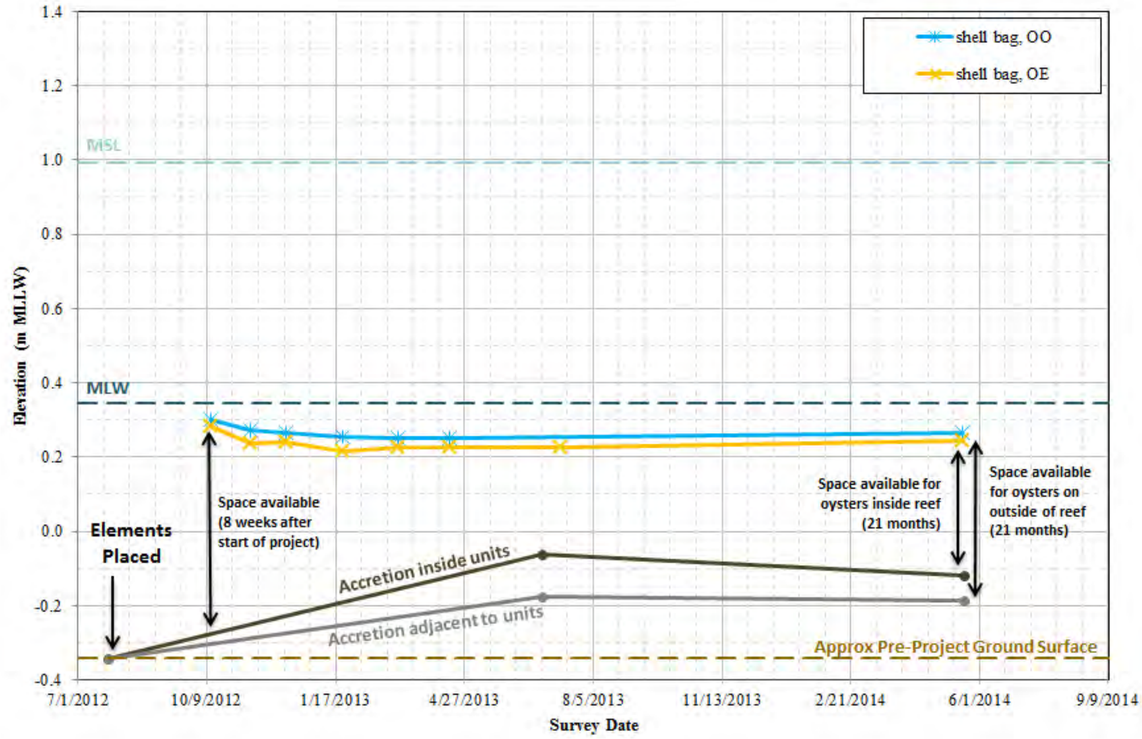


Figure 16. Sedimentation and oyster space for shell bags at TNC.

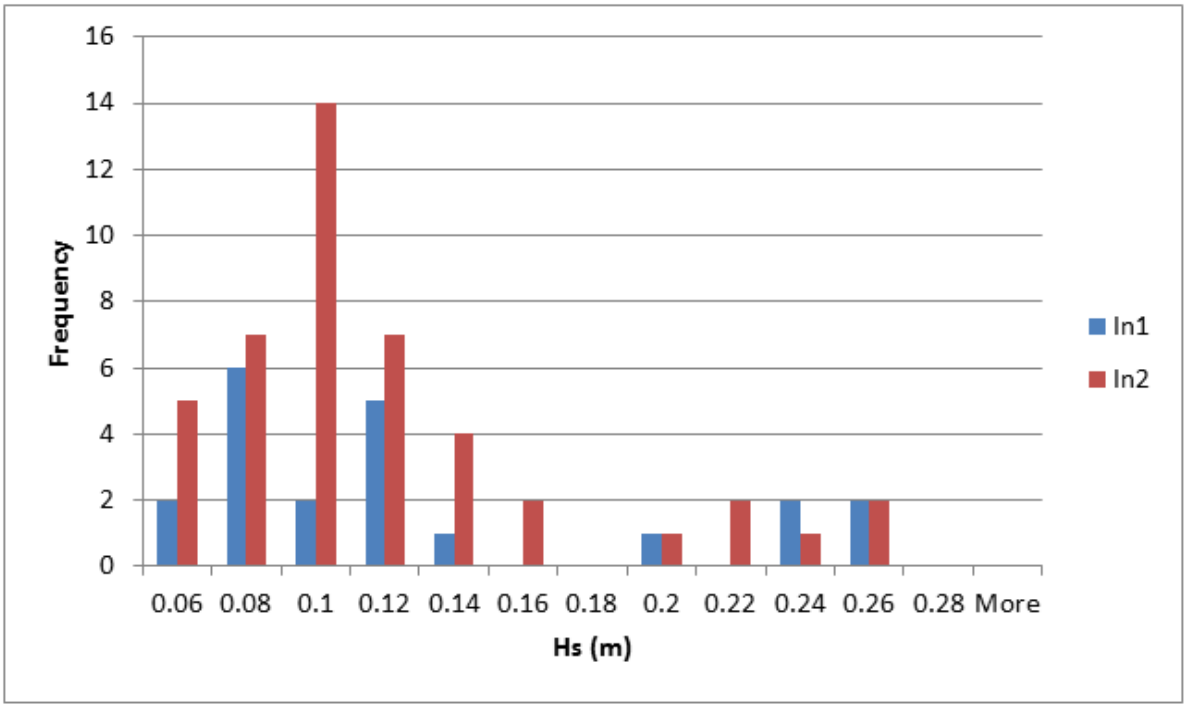


Figure 17. Wave height measured at San Rafael, 02/26/13 to 04/15/13. “In1” is located on the shore side of the Oyster-Eelgrass reef, and “In2” is located on the shore side of the control plot.

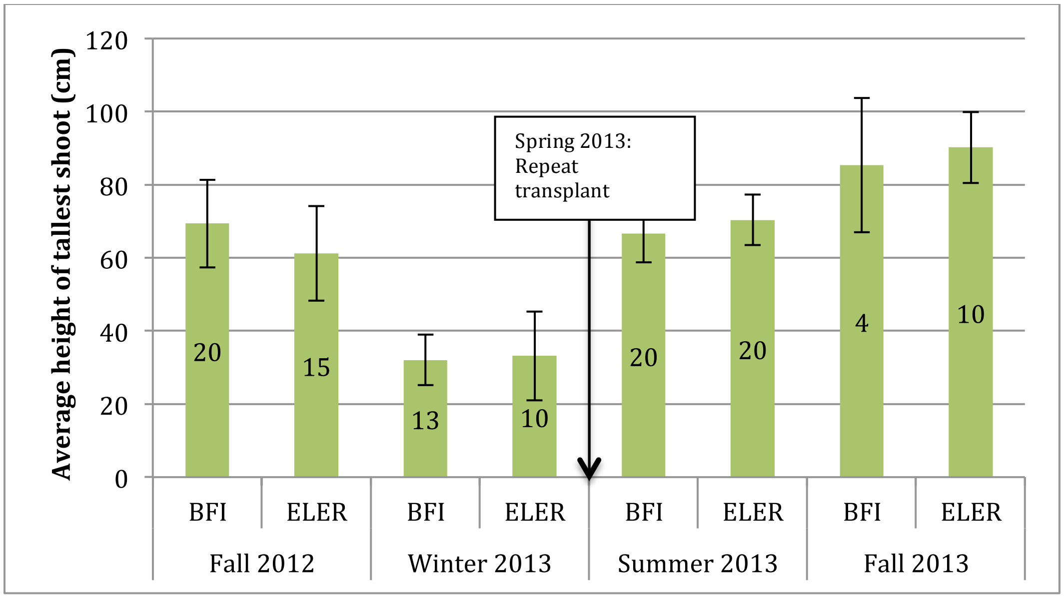


Figure 18. Average height of the tallest eelgrass shoot in each patch, by donor at Hayward. BFI = plants from the Bay Farm Island donor site and ELER = plants from the Eden Landing Ecological Reserve site in fall 2012, winter 2013 and summer 2013. Plants were largely gone by winter of 2014. Numbers in columns indicate the sample size. Error bars = 95% confidence interval.

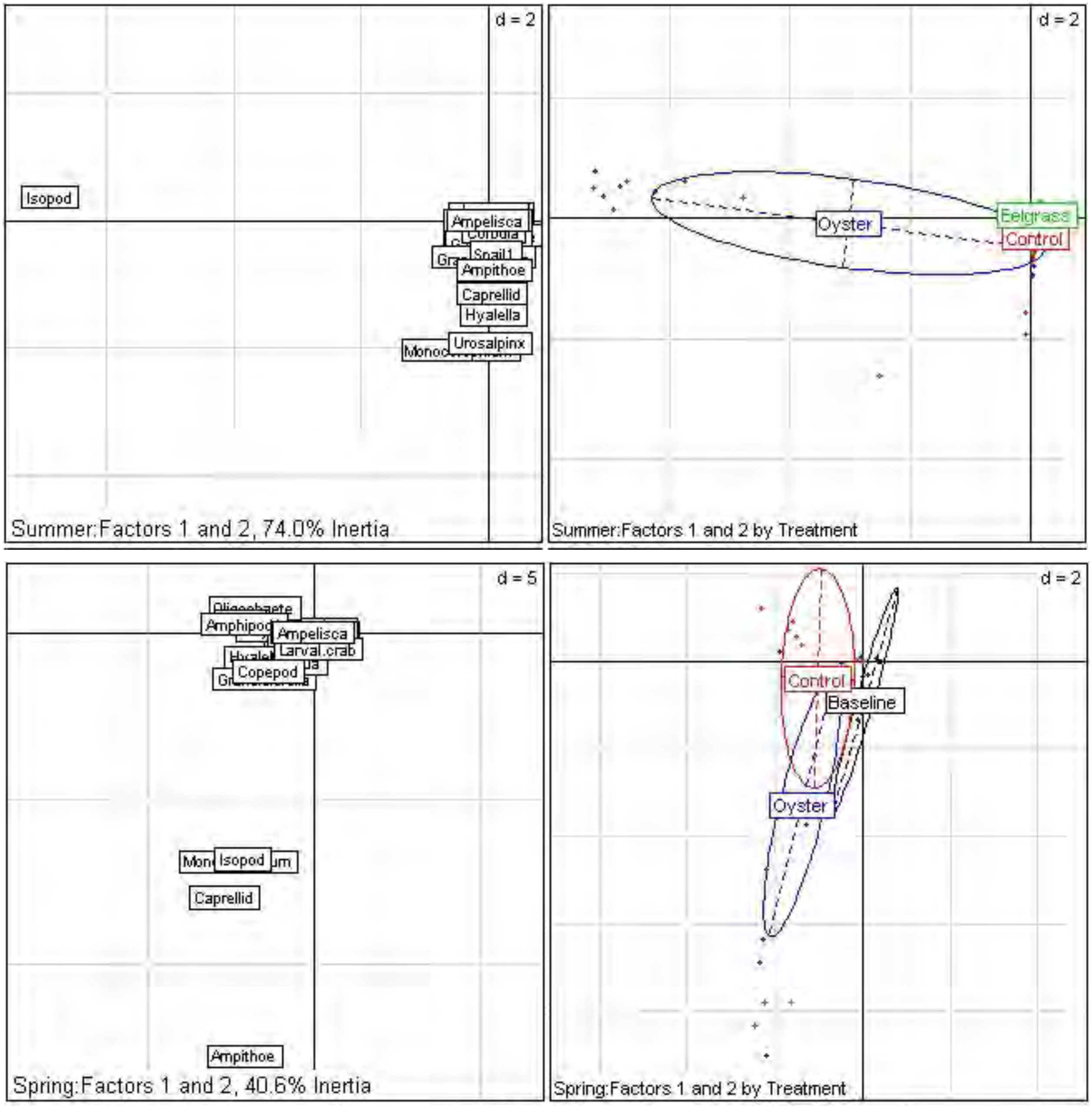


Figure 19. Correspondence analysis of Hayward Eden suction samples. Top: Summer 2013 samples showed development of distinct invertebrate assemblages largely driven by isopods on the oyster reefs. Bottom: In Spring 2014, eelgrass was no longer present; oyster reefs showed a distinct assemblage relative to control and baseline conditions.

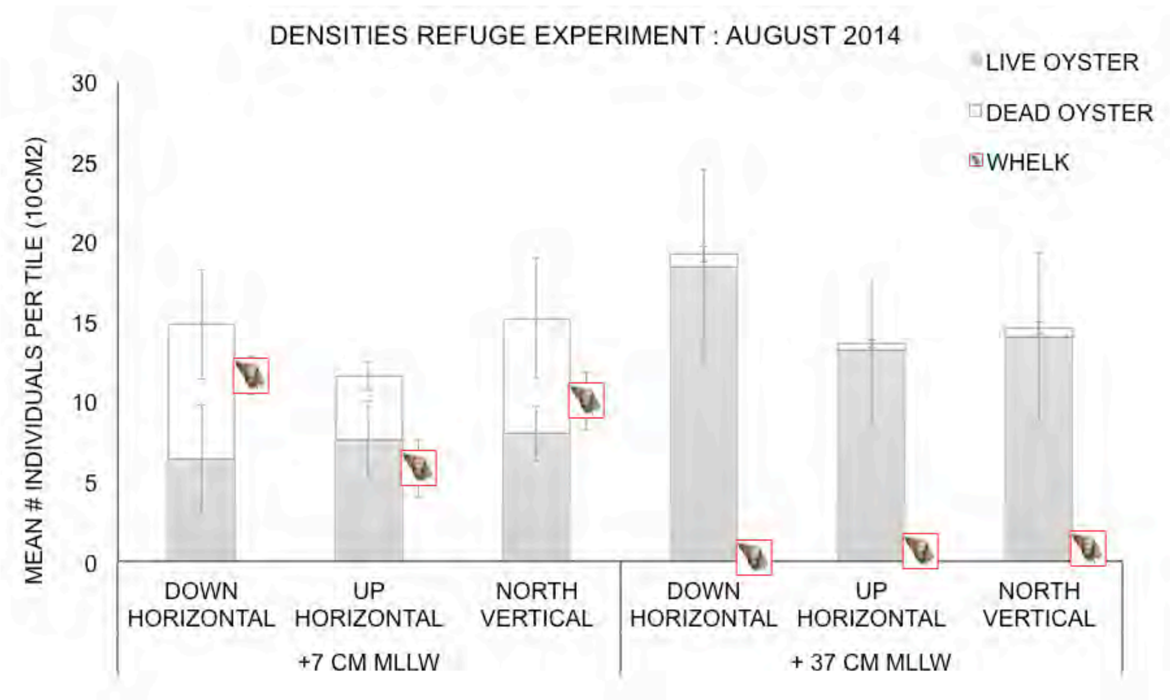


Figure 20. The number of Atlantic oyster drills and live and dead oysters on tiles placed at two elevations and oriented in various directions, Hayward, August 2014.