San Francisco Bay Living Shorelines Project: Assessment of oyster performance on constructed reefs and adjacent shorelines.

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Report through July 2014

Methods

Performance of restoration project by site and across elements

Assessing oyster restoration success and associated community

To evaluate the overall success of the San Francisco Bay Living Shorelines Project restoration project, and to compare across treatment types (oyster-only vs. oyster-eelgrass) and element types, we monitored oyster performance and sessile and small mobile communities on the restoration substrates three times a year, in April, July and November, beginning in November 2012. The project set up is described online and in the summary report, which can be found at sfbaylivingshorelines.org. This appendix covers results through July 2014, but monitoring is ongoing.

We used non-destructive methods to sample the substrates, collecting five replicate samples from each substrate type at each location. To sample shell bags, we retrieved from the sites monitoring bags that are 1/3 the size of the bags used to construct the shell-bag elements, and these were brought to the lab for processing. We opened each bag within 24 hours of collection, removed all shells and placed them into a bin. We rinsed the shells to collect and measure sediment in the bag, collected mesograzers (between 500 microns and 1 mm) and larger mobile organisms. On a randomly selected subsample of shells we counted and measured oysters. On a set of marked shells we measured growth and mortality of individual oysters. The shells were then returned to the bags and stored in a bay water system (for a maximum of 7 days) and redeployed at the next low tide.

To monitor "baycrete" elements we used 10 cm^2 quadrats placed at three tidal heights to estimate oyster abundance, sizes, cover of oysters and other organisms, and sediment accumulation on vertical and horizontal faces and on the north and south sides of the elements. The interiors of some of the elements were difficult (or impossible) to measure accurately; we made these measurements less frequently.

We assessed oyster fecundity on the restoration substrate (TNC/San Rafael site only) by collecting oysters larger than 20 mm from the surfaces of the shell bag elements during their potential brooding period (April to November). From the oyster-only and the oyster-eelgrass treatments, each month 15 to 30 individual oysters were opened with an oyster knife and reproductive status was recorded along with shell size.

To estimate the total number of oysters at our sites at each time point we used the counts of oysters from the sample shell bags to roughly estimate a total number of oysters on the shell bag elements. The shell bags are the major restoration surface at San Rafael, and measurement error for the whole restoration project far exceeds the numbers of oysters on the test elements. At Eden

Landing, the elements are much greater contributor to the total population. Based on current estimates, the elements have two times as many oysters on them as do the shell bags there.

To estimate the number of oysters on shell bags, the mean number of oysters per shell from our samples was multiplied by the mean number of shells per sample bag to generate an estimate of live oysters in the whole sample bag. This number was next multiplied by three to estimate the number of oysters per large shell bag (since sample bags contain ~1/3 as many shells as the large bags). Because sediment has built up on the lower layers of the shell-bag mounds, we assumed for the sake of these calculations that there were oysters only on the top layer of six shell bags, and multiplied our estimate of oysters per large bag by six to get a per-element estimate. At TNC/San Rafael we then multiplied this number by 96 to get a per-plot estimate; at Eden Landing, we multiplied by 5 for the total number of shell-bag elements at the site. Estimates from the oyster-eelgrass and oyster-only plots were generated separately and added for the site level estimate for the shell bags alone.

To estimate the number of oysters per "baycrete" element, we first calculated the dominant surface area of each element type: estimating the vertical surface area as rectangles for the oyster blocks, the vertical surface area as cylinders for the reef balls, and the horizontal surface area as circles for layer cakes. Measurements of element dimensions were made at the high, mid- and low elevations on the elements and the surface area calculated separately for each elevation. The mean number of oysters from the quadrats was then used to calculate the number of oysters per unit area for each elevation. These were added to get element totals.

Comparison of treatment type and element type

We used the data generated from the monitoring activities described above to compare oyster performance in the oyster-only vs. oyster-eelgrass combination treatments at San Rafael. Because we do not have replication at this site, we cannot use statistical methods to detect differences, so our comparisons of oyster number, cover of oysters and other species, and oyster size, growth, fecundity and survival were made informally.

At each site, we have five replicates of each of our test elements. In addition to comparing the element types to one another, we compared oyster performance and sessile community composition and abundance across three tidal elevations, north and south facing substrates and vertical and horizontal substrates. These data will inform future design considerations.

Shoreline population monitoring

To measure the potential impact of the restoration projects on existing oyster populations and vice versa, we collected data on intertidal populations at the sites three times a year (quarterly for 2012), except for fecundity measures, which were made monthly during brooding season at San Rafael only, Eden Landing not having a large enough population to support this type of survey. Measurements were made in ten quadrats placed at random locations along a permanent 30-m transect in the oyster zone at each site. We used 10 cm^2 quadrats to estimate percent cover of oysters and other sessile organisms and 25 cm^2 quadrats for counts of oysters and oyster drills and to characterize substrate. We also measured 10 oysters (if found) in each of the larger quadrats. To obtain an unbiased sample, we measured the first 10 oysters encountered starting in the upper left corner of the quadrat and moving to the right and then down. Measurements of existing populations began before the construction of the restoration project and were made inshore of the restoration substrates as well as in a control plot with no project offshore at each location.

To measure recruitment at the treatment and control sites, we deployed two PVC frames with three 10 x 10 cm ceramic tiles, rough face down, parallel to the elements at each site, in both treatment and control plots, at the same tidal height as the lowest portion of the elements (Fig. 1). The tiles were removed and replaced three times a year, coincident with the restoration monitoring (but quarterly in 2012). Beginning in summer 2013, we also placed recruitment tiles along the shoreline at San Rafael. The tiles are brought to the laboratory, where they were viewed under a microscope. Newly settled oysters were counted and measured, and percent cover of other sessile organisms on the tiles was recorded.

Measurement of physical factors

We used PVC poles set into the substrate to measure sediment accumulation/erosion in treatment and control plots (N=3) along the same transects used for the shoreline population measurements above. The height of the poles was measured to the nearest 0.5 cm three times a year. We measured temperature at the site level using loggers placed near the elements, set to record every hour. In July 2013, we set out additional loggers to measure small-scale differences in temperature at the element level, placing these at three tidal heights on north and south faces and on interior and exterior surfaces at both sites (Fig. 2).

Oyster drill predation

Assessment of predation by the Atlantic oyster drill

To assess the degree to which the Atlantic oyster drill *Urosalpinx cinerea* is impacting the native oyster population at Eden Landing, and whether these impacts are influenced by tidal height and by oyster size, we established an experiment (hereafter oyster refuge experiment) in June 2014. These data may be useful in selecting future restoration sites and in considering design for future projects. Along a 50 m transect on the seaward side of and parallel to the elements, we deployed 30 10 cm^2 ceramic tiles that were seeded with oysters (via natural recruitment within San Francisco Bay during the previous year). Each tile was randomly assigned one of two tidal heights: + 37 cm above MLLW or + 7 cm above MLLW, corresponding to the low and high elevations of the baycrete elements at the site. At each of these tidal elevations, tiles were also set up in one of three surface orientations: vertical north facing, horizontal facing up and horizontal facing down (Fig. 3). Tiles were assigned to one of five experimental blocks, each block consisting of 6 tiles in each possible elevation and surface orientation treatment combination (ex. +37 cm MLLW north vertical facing). The blocks were spaced 5 m apart; within the blocks, tiles were spaced 1 meter apart. Tiles were secured in place with a 1/2 inch PVC stake in the shape of an L. The vertical portion of the PVC stake was submerged 40 cm into the sediment and tiles were attached to the horizontal portion of the PVC stake via a nylon hex bolt and nylon wingnut. Plastic turf was glued to the back of each tile to deter drills and other organisms from establishing, thus isolating the experiment to the front of the tile with the seeded oysters. Tiles have been mapped to track oysters individually over time. We monitored tiles monthly for oyster survival and drill densities. On a quarterly basis tiles were brought to the lab for a 24-hour period to measure oyster sizes, assess cover of sessile organisms and to photograph.

Oyster drill management

In June 2014 we deployed an experiment to determine colonization rates of hard substrates by oyster drills and to determine whether the numbers of drills could be reduced by hand removals (hereafter removal experiment). A 105-m transect was centered and placed 50 meters shoreward of and parallel to the elements. Along this transect 15 8-cm^3 cinderblocks were placed every 7 meters to allow a 2 meter treatment zone around the blocks and 5 meter spacing between treatments. Each block was secured in place with a heavy duty 60 cm cable tie inserted through the cinderblock opening and around two 76 cm long pieces of 0.6 cm ribbed rebar, which were placed at each south facing corner and submerged in the sediment by 40 cm. Cinderblock orientation was set to create a north vertical, horizontal up and horizontal down surface. One of three experimental treatments were randomly assigned to each block: hand removal of all drills on the blocks and surrounding two-meter treatment zone 1. monthly 2. quarterly or 3. not at all (=control). Because there may be some interactions between oyster drills and *Ilyanassa obsoleta* (Eastern mud snail), we are counting both species (but removing only the drills) across the various surface types, north vertical, horizontal up, horizontal down, exterior, interior, mud flat on a monthly basis.

Data analysis

Data were analyzed with ANOVAs and T-tests as appropriate after ensuring that data meet appropriate assumptions. More complex community-level data will be analyzed using nonparametric multivariate approaches such as MDS plots and ANOSIM.

Results

Performance of restoration project by site and across elements

Assessing oyster restoration success

The estimated number of oysters at the San Rafael site on the shell bags alone has fluctuated from between from a high of 3 million in April 2013 to ~1.5 million (+/-300,000) in April 2014, our most recent data point (Fig. 4). Oyster recruits were not seen at Eden Landing until April 2013 (Fig. 5). The oyster population there was largest in July 2013, with more than 22,000 oysters total across the 10 shell bag mound elements. At this time point, there were ~3x as many oysters per shell at San Rafael than at Eden Landing; but the overall population was two orders of magnitude higher due to the far greater number of shell bag mounds at TNC. The population at Eden Landing decreased by an order of magnitude by the next time point (November 2013) and again by another order of magnitude by April 2014, with most the most recent population estimate at 720 individuals on shell bags, and twice that across elements for a total of approximately 2200 oysters. The major loss of oysters in shell bags at Eden Landing was due to oysters having settled almost exclusively on barnacles, which subsequently died and fell off, taking the oysters with them (Fig. 6). Predation by non-native oyster drills (*Urosalpinx cinerea)* also resulted in a large loss of oysters at Eden Landing (Fig. 7).

Size frequency histograms for each time point at San Rafael indicate a general trend of decreasing numbers of oysters in the smallest size classes and an increasing number into larger size classes over the first three time points (Fig. 8). This is the expected trend as a recruitment cohort gets older. Smaller size classes appear again in November 2013, after the second recruitment season, although the number of new recruits is not as high as it was in the first year of the project. At Eden Landing, size frequency histograms show a relatively large recruitment event in July 2013 (Fig. 9); there are many fewer oysters in these smaller size classes at later time points, but also little transition into larger size classes, indicating high juvenile mortality as indicated above.

Comparison of treatment type and element type

Treatment type: counts and sizes

Initially, at San Rafael, oyster numbers were highest in shell bags in the oyster and eelgrass combination plot than in the oyster-only plot (Fig. 10). In November 2012, we estimated that the oyster population in the oyster-only plot was about half that in the oyster-eelgrass plot, but this difference disappeared by April 2013 and the two plot types have been roughly equivalent since then. Since the eelgrass was nearly gone by the end of 2012, this trend was more likely explained by environmental differences at the site.

At TNC in November 2012, there was also a trend toward slightly larger oysters in the oyster-eelgrass treatment, but this trend disappeared by the second time point. At Eden Landing, the opposite trend is seen across all time points (Fig. 11), but this may be simply the result of a small sample size, as the eelgrass has failed to establish there. Overall, oysters are larger on average at TNC than at Eden Landing (two-way ANOVA: significant effect of project location on oyster sizes, $F=17.406$; $P<0.0005$). This could be due to delayed recruitment at Eden, which would result in younger and thus smaller oysters overall, or low survival of oysters, or both.

Element type and patterns at the element level

Overall, comparing across elements, shell bags have performed the best per unit in terms of numbers of oysters (Fig. 12). With the exception of the layer cakes, the baycrete elements have all performed about the same in terms of oyster recruitment.

As a general trend at TNC, there were fewer oysters on the elements at the highest elevations (Fig. 13 a,b). This trend was most pronounced during the first three time periods, and although differences between elevations became smaller over time, they are still statistically significantly (two-way ANOVA, $F=209.841$, $P<0.005$). There were also more oysters on the north sides of the elements than on the south sides across element types and tidal elevations (Fig. 13a,b). These differences were statistically significant (two-way ANOVA, effect of surface orientation $F=15.448$, $P<0.005$; this effect was the same across all element types (effect of element type, $F=0.814$, $P=0.487$).

While the differences in the number of oysters on the lower portions of the elements could be attributed to the greater amount of time these surfaces are available to larvae, heat stress may also play a role in oyster distribution on the element surfaces. This hypothesis is supported by the observation of more oysters on the north faces than on south faces and on vertical as opposed to horizontal surfaces There were also significantly more oysters on vertical vs. horizontal faces across elements and tidal heights (paired T-test, $T = 10.13$, $P < 0.0005$.)

Surprisingly, at Eden Landing there were *fewer* oysters on the elements at the lowest elevations and more oysters on the high elevations (Fig. 14; two-way ANOVA: significant effect of elevation on oyster densities, $F=11.444$, $P<0.0005$). Based on our observations, this pattern appears to have developed over time. Initially, the only element type on which oysters were found was the shell bags, when new recruits were first seen in April 2013. These element types are likely cooler than the baycrete elements -- they provide lots of shade and retain moisture – and they are lower in tidal elevation than the mid and upper portions of the elements. Oysters next appeared in the interiors of the large reef balls, although in such low numbers they were not captured our quadrats. But after November 2013, there were very few live oysters remaining on the shell bags or in the interiors of the large reef balls. Instead, oysters persisted on the other elements, and in greater numbers at higher elevations, the opposite of the observed pattern at TNC. Although less clear than at TNC, there also was a trend of higher numbers of oysters on the north vs. south sides of elements across all tidal heights. Thus it appears that factors other than heat stress are key drivers of oyster patterns at Eden Landing (see Oyster Drill Predation section below).

While oyster density does appear to vary with tidal elevation and surface orientation at both locations, oyster sizes did not appear to be affected by these factors at either site (Figs. 15a,b and 16a,b). It is possible that lower densities on these surfaces allow for greater growth.

Associated community

In addition to oysters, numbers of other species across a wide range of phyla have settled on or are using the restoration substrates. As a general trend, species have continued to accumulate over time (Fig. 17). At both sites, more organisms are found in the shell bags, although this is undoubtedly largely due to our method of taking whole sample bags into the lab, which captures small mobile species inside the bags that would not appear in our quadrats. As of our last time point, the shell bags at San Rafael had the greatest species richness, followed by those at Eden Landing, the Eden Landing elements and the San Rafael elements. Organisms found on or in the shell bags include both native species and non-natives, among them Dungeness crabs, gobies, shrimp, and mating aggregations (and eggs) of the nudibranch *Doris montereyensis* and the sea hare *Aplysia californica* (Table 1).

Table 1. Taxa from restoration substrates.

Taxa	Phylum	Shell Bags										Elements									
		November 2012		April 2013		July 2013		November 2012		April 2013		November 2012		April 2013		July 2013		November 2012		April 2013	
barnacle	Arthropoda	EL	TNC	EL	TNC	EL	TNC	EL	TNC	EL	TNC	EL	TNC	EL	TNC	EL	TNC	EL	TNC	EL	TNC
isopod	Arthropoda	EL		EL		EL		EL	TNC	EL	TNC							EL		EL	TNC
amphipod	Arthropoda							EL	TNC	EL	TNC									EL	
sea spider	Arthropoda					EL		EL		EL								EL		EL	
bryozoan (encrusting)	Bryozoa	EL	TNC	EL	TNC	EL	TNC	EL	TNC	EL	TNC	EL	TNC		TNC	EL	TNC	EL	TNC	EL	TNC
bryozoan (upright)	Bryozoa	EL	TNC	EL	TNC	EL	TNC	EL	TNC	EL	TNC	EL	TNC		TNC		TNC	EL	TNC	EL	TNC
solitary tunicate	Chordata	EL	TNC			EL	TNC	EL	TNC	EL	TNC		TNC								
clonal tunicate	Chordata		TNC				TNC		TNC		TNC		TNC					EL	TNC	EL	TNC
anemone	Cnidaria	EL				EL	TNC	EL	TNC	EL	TNC	EL						EL	TNC	EL	TNC
hydroid	Cnidaria	EL	TNC			EL		EL	TNC	EL	TNC	EL	TNC		TNC	EL	TNC	EL	TNC	EL	TNC
Atlantic oyster drill (*Urosalpinx cinerea*)	Mollusca	EL		EL		EL		EL		EL		EL		EL		EL		EL		EL	
eastern mudsnail *(Ilyanassa obsoleta)*	Mollusca					EL		EL		EL		EL		EL		EL		EL		EL	
Mytilus	Mollusca		TNC		TNC				TNC		TNC										
native oyster (*Ostrea lurida*)	Mollusca	EL	TNC	EL	TNC	EL	TNC	EL	TNC	EL	TNC	EL	TNC		TNC	EL	TNC	EL	TNC	EL	TNC
slipper snail	Mollusca		TNC		TNC	EL		EL	TNC	EL	TNC							EL	TNC	EL	TNC
polychaete	Polychaeta	EL				EL		EL	TNC	EL	TNC								TNC		TNC
scale worm	Polychaeta	EL				EL		EL	TNC	EL	TNC										
tube worm	Polychaeta		TNC	EL	TNC	EL	TNC	EL	TNC	EL	TNC		TNC		TNC		TNC	EL	TNC	EL	TNC
sponge	Porifera		TNC		TNC		TNC		TNC		TNC		TNC		TNC		TNC		TNC	EL	TNC
algae (red macro)	Rhodophyta	EL							TNC		TNC		TNC		TNC				TNC	EL	TNC
algae (green macro)	Chlorophyta	EL							TNC		TNC	EL	TNC		TNC		TNC		TNC	EL	TNC
mud crab (*Hemigrapsus oregonensis*)	Arthropoda	EL	TNC	EL	TNC	EL	TNC	EL	TNC	EL	TNC										
bay shrimp (*Crangon franciscorum*)	Arthropoda	EL		EL		EL	TNC	EL	TNC	EL	TNC										
chameleon goby (*Tridentiger trigonocephal*	Chordata	EL		EL		EL		EL		EL		Not Assessed		Not Assessed		Not Assessed		Not Assessed		Not Assessed	
blackeyed goby (*Rhinogobiops nicholsii*)	Chordata	EL		EL																	
bay goby (*Lepidogobius lepidus*)	Chordata	EL		EL		EL															
yellow nudibranch (*Doris montereyensis*)	Molluska				TNC						TNC				TNC						TNC

Shoreline population monitoring

Oyster density and population size

The density of oysters along the shoreline at San Rafael at both treatment and control plots has varied over time, averaging about 400 oysters per m^2 (Fig. 18). With the exception of a peak in both plots in fall 2012 and a in peak at the treatment plot in summer 2014, oyster abundance has been relatively stable at both plots over the course of our project. No measurement was made in the fall of 2013 due to staffing shortages.

Eden Landing had significantly fewer oysters, with few to zero oysters found along our study transects for many time points (Fig. 19). Oyster numbers increased for both treatment and control plots in fall 2012 and continued to increase at the treatment plots, but not the control plot in winter 2013. In spring 2014 more oysters were found than in the previous spring, with slightly more in the treatment plot, but fall 2014 numbers were lower than in fall 2012.

Nine other sites in San Francisco Bay were surveyed from spring 2012 through fall 2013 using the same methods as our project as part of the NERR Science Collaborative Project. Compared with those sites, the San Rafael site was third highest in terms of oyster density, while Eden Landing was the lowest (Fig. 20, from Wasson et al. 2014, Appendix 2, their Figure 2). The density of oysters along the San Rafael shoreline is most comparable to that of highest elevations of the elements, and an order of magnitude lower than that on the mid and low portions of the elements (see Figs 15a,b). This suggests that the restoration substrates outperform the shoreline populations on rip-rap, likely because they extend lower into the intertidal zone.

Our oyster density estimates, combined with measurements of hard substrate at the appropriate tidal height were used to make an order of magnitude estimate of the total population at each site over the study period. At San Rafael, approximately 73% of the ~650 m shoreline is gravel, cobble or rock (rip rap) at 0 tide. We estimated the population there to be in the tens of thousands. Our restoration project thus easily increased the site's population by two orders of magnitude. At Eden Landing, at zero tide, approximately 84% of the shore along ~400 m long stretch of rip-rap is hard substrate. We estimated the population there to be in the 100s of individuals. Thus, we have increased the population by an order of magnitude by the provision of the test elements.

Recruitment

Recruitment to the tiles was greater at San Rafael than at Eden Landing across all time points (Fig. 21). In each year, some recruitment was measured in the summer (tiles in place from May-July), followed by greater recruitment in the fall (tiles in place from July-Nov). There was more recruitment in 2012 than in 2013 at San Rafael, but more in 2013 at Eden Landing. These patterns are consistent with the appearance of small size class oysters on our restoration substrates both in terms of timing and magnitude. This suggests that the lower numbers of small oysters seen on restoration substrates at San Rafael in 2013 was due to lower recruitment at the site rather than competition for space.

Oyster sizes, size class frequency distribution

At TNC, oysters were present in all size classes (binned by 10 mm increments from 0 -10 up to 41-50 mm, Figs. 22a,b). Across all time points at both treatment and control plots, most oysters were in the middle three size classes. New recruits (oysters in the smallest size class) showed up at slightly different times in the control plot compared with the treatment plot. For example, these smallest oysters were present in the control plot in spring and summer 2013 in the control plot, but not in the treatment plot, but new recruits were present in the treatment plot but not in the control plot at both fall time points. Both sites showed a loss of the largest oysters at our most recent time point, fall 2014.

Eden Landing contrasts with San Rafael (TNC) in that all oysters are found in the three smallest size classes. Across all time points, the smallest oysters represent 50 to 80% of total oysters, while oysters in the 21-30 mm size class represent ~10% of all oysters found (Figs. 23a,b)

Fecundity

Fecundity data have been analyzed for the period June 2012 August 2013. To increase sample size, shoreline data (treatment and control plots) were combined to compare with and reef data (oysters and oyster-eelgrass combination plots combined). Future analyses of the more recent data, where more oysters were sampled at each time point, will allow us to compare among all four treatments.

Over this first time span, the percent of brooding oysters both on the shore and on the reef was highly variable (Fig. 24). Reef oysters in general were slightly more fecund than shore oysters over sampling periods in which they overlap, except for July 2013. Longer-term data analysis may confirm this as a general trend.

Percent cover of oysters and other sessile organisms

These analyses are not yet complete.

Oyster drills

Oyster drill numbers along the shore at Eden Landing have fluctuated over time, but are typically at less than 150 individuals/m^2. Across three summer quarters and two spring quarters, there is no apparent change in drill density (Fig. 25). There are no clear trends in terms of any differences in our treatment and control plots and we are missing data points for several fall and winter quarters. Longer term data analysis will help to discern likely seasonal trends.

Measurement of physical factors

Sedimentation and durability of elements

There has been very little sediment accumulation on the elements at either site and no measureable differences by element type. Typically, during quarterly monitoring events, we measure 0-2 mm of sediment on vertical surfaces, and 2 mm on horizontal surfaces. Within our sample bags, sediment volume ranges widely, 20 ml to 85 ml with no defined difference between oyster and oyster eelgrass plots. However, it is hard to know how well these rates compare to bags that are not periodically removed and rinsed. Longer-term sample bags will be sampled in 2017 (5 years after deployment). Clearly, there is significant sediment build up in the shell bag mounds, as evidenced by photographs. At the present, only the top layer of shell bags is above the sediment.

The oyster blocks and large reef balls appear to be very robust. To date we have observed no structural problems. However, both small reef balls and layer cakes are showing signs of decay with material breaking off at edges and reef ball structures collapsing due to ropes that hold them together decaying in water environment (Fig. 26).

Sediment deposition/erosion

At the site level (as measured by the sediment poles) sediment fluctuated quarterly and patterns of erosion and accretion were different between sites (Fig. 27). On the whole, the TNC site tended to be more erosional than EL, although both sites lost sediment between winter and spring quarters in 2013 (poles measured in Jan and April). At TNC sedimentation in the treatment and control plots generally followed the same seasonal pattern, but the treatment plot tended to be more erosional than the control plot (Fig. 28). This could be due to position along the shore rather than due to the effect of the restoration project. At Eden Landing, treatment and control plots tracked each other less well, and there was no consistent trend of difference between them (Fig. 29).

Temperature

These data have not yet been analyzed.

Oyster drill predation (Eden Landing)

Oyster drill abundance and zonation

Oyster drills first began appearing on our test elements in small numbers at Eden Landing in November 2012. They are not present at San Rafael. Numbers of drills at Eden Landing increased to a peak in July 2013, decreased in November that year, and were on the rise again as of April 2014 (Fig. 30). These seasonal patterns are expected as drills hatch from eggs and become more active during the warm summer months.

Oyster drills are more abundant at lower tidal elevations on the test elements. They are also found on the mudflat, but typically aggregate around hard substrate, including driftwood and other objects beached by the tide. This suggests an inability to tolerate exposure during the low tides, and was the basis for an experiment we carried out to determine whether oysters might have a refuge from oyster drill predation at higher tidal elevations. If this is the case, it could inform future the configuration of future restoration projects in areas with high drill densities. This experiment also allowed us to better quantify the effect of drill predation on oyster survival.

Assessment of predation by the Atlantic oyster drill

Oyster drills recruited rapidly to the experimental surfaces. Within 30 days of the deployment of our experiment, 5-10 drills were found on tiles at the lower elevation and oysters had suffered 50% or greater mortality with telltale drill holes indicating predation. At the lower elevation there were fewer drills on the upward facing horizontally oriented tiles, and slightly lower oyster mortality (two-way ANOVA : elevation of the tiles has a significant effect on drill densities $F=66.538$ $P<0.0005$, and on oyster mortality $F=24.317$ $P<0.0005$; surface orientation of the tiles had a significant effect on drill densities $F=3.991$ $P=0.025$, but did not have an effect on oyster mortality $F=0.680$ $P=0.511$). Very few drills were found on the higher elevation tiles, and no oysters died due to predation. This pattern was still holding 2 months after the start of the experiment in August 2014 (Fig. 31). There were no differences in oyster survival by size, indicating that at least over of the range of sizes we tested, there is no size refuge from predation (Fig. 32).

Figure 1. Recruitment tiles on a PVC frame.

Figure 2. Temperature loggers deployed at three tidal elevations.

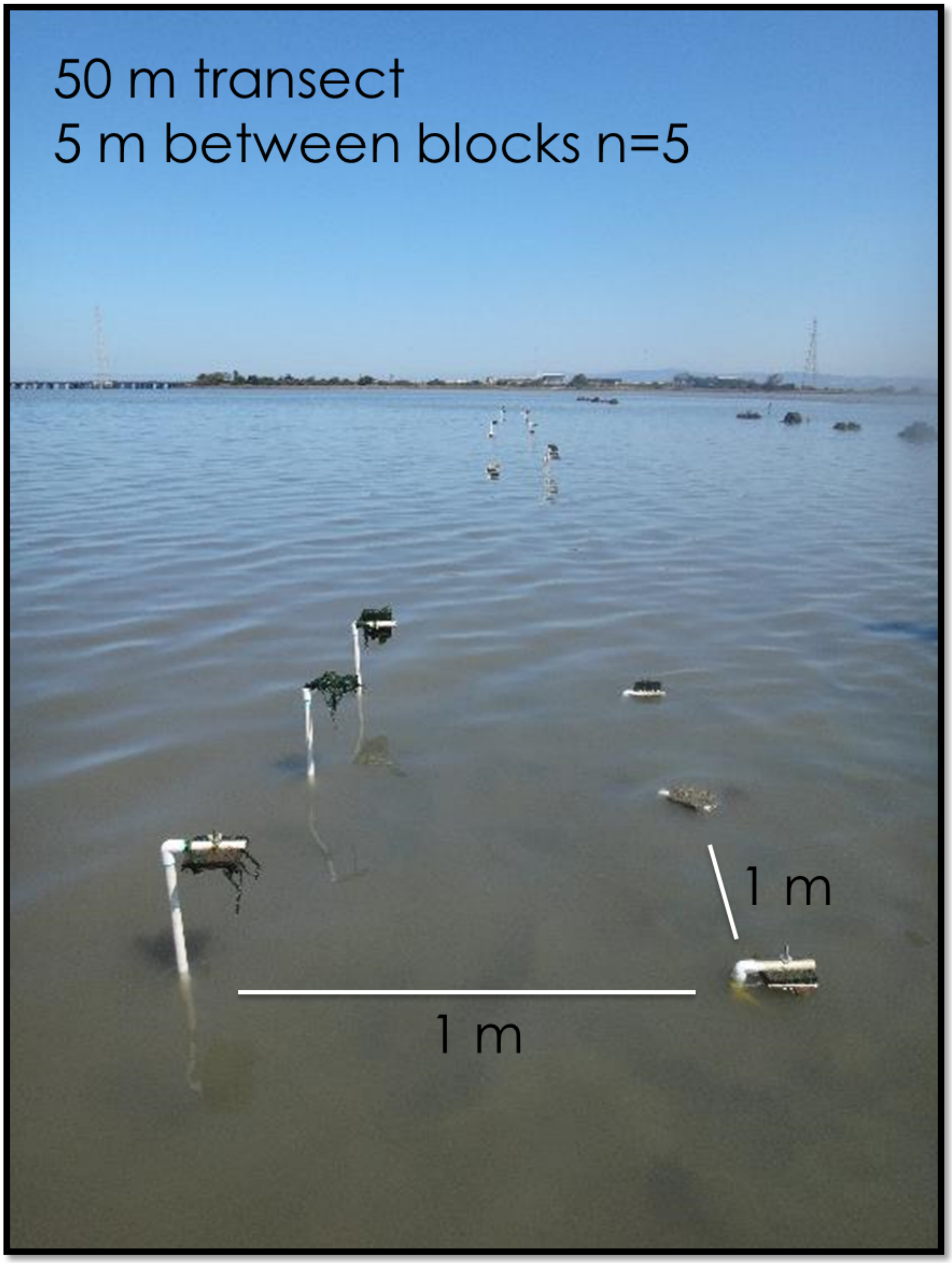


Figure 3. Set up for oyster drill predation experiment.

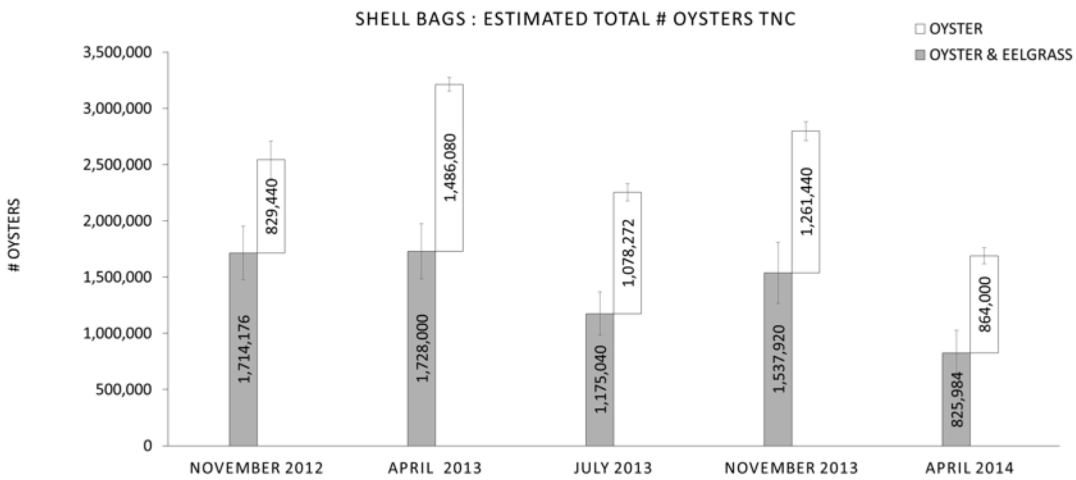


Figure 4. Estimated number of oysters at TNC site on shell bags across monitoring time points through April 2014. Gray bars indicate oysters in the oyster and eelgrass plot; white bars indicate the number in the oyster-only plot. The height of the stacked bars provides an estimate of the total population at the site, as the test elements represent a small number of oysters overall.

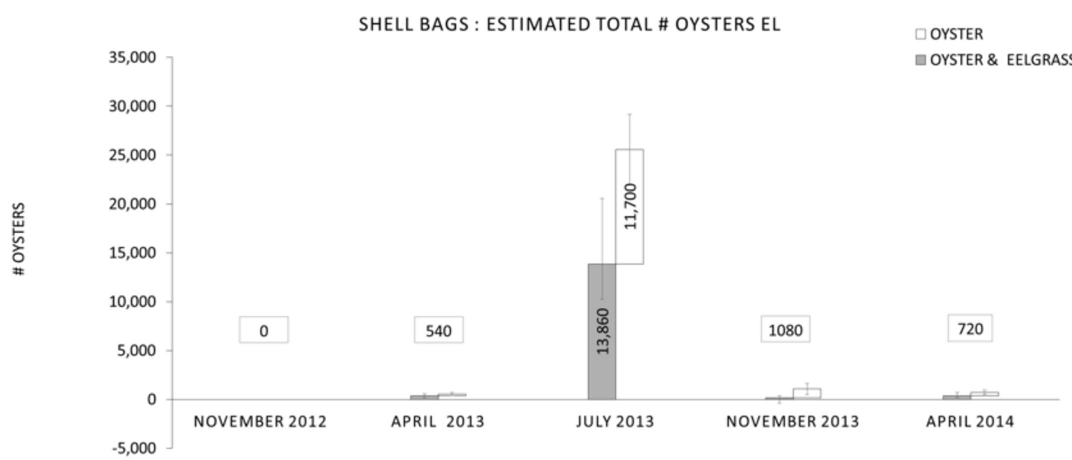


Figure 5. Estimated number of oysters at the Eden Landing site on shell bags across monitoring time points through April 2014. Gray bars indicate the number of oysters in the oyster and eelgrass treatments (N=5); white bars indicate the number in the oyster-only treatments (N=5).

Figure 6. Juvenile oysters settled on top of barnacles.

Figure 7. Atlantic oyster drills preying on small oysters at Eden Landing.

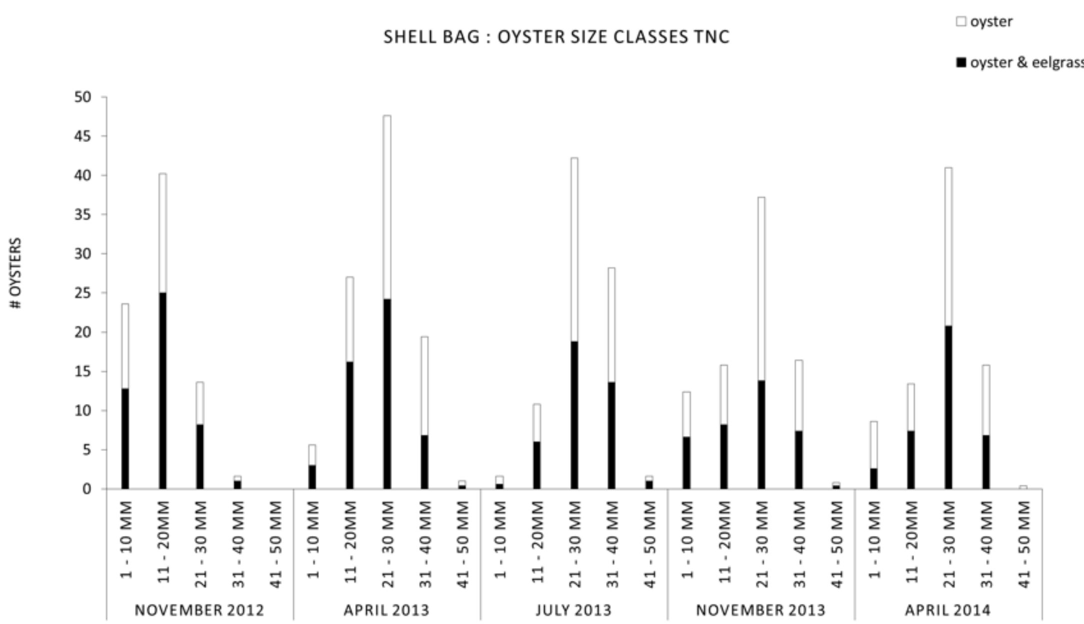


Figure 8. Size class frequency histograms for oysters on the shell bags at TNC, increments of 10 mm. Black bars = oyster and eelgrass treatments; white bars = oyster only.

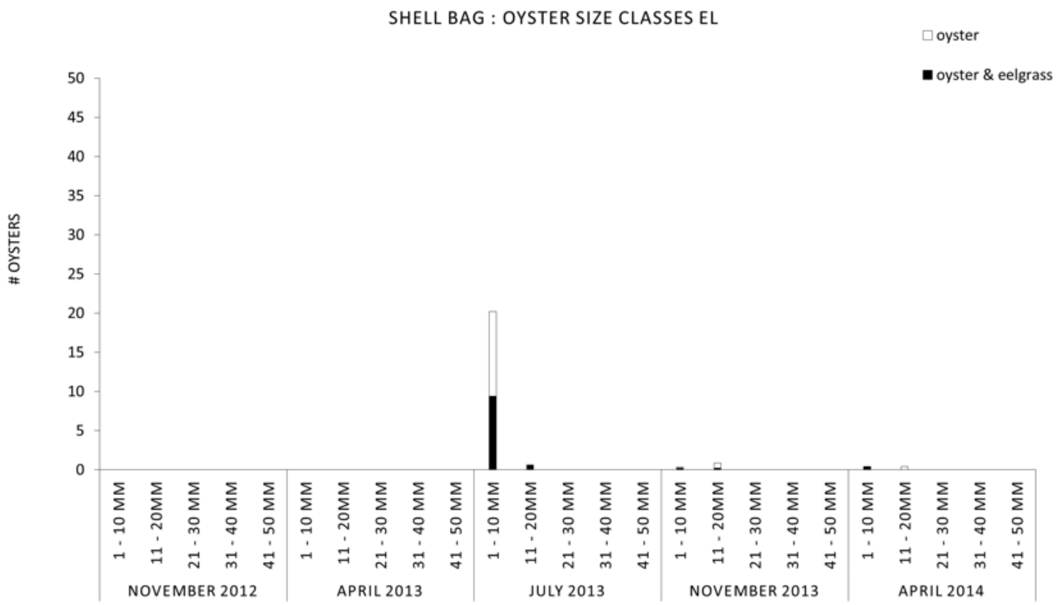


Figure 9. Size class frequency histograms for oysters on the shell bags at Eden Landing, increments of 10 mm. Black bars = oyster and eelgrass treatments; white bars = oyster only

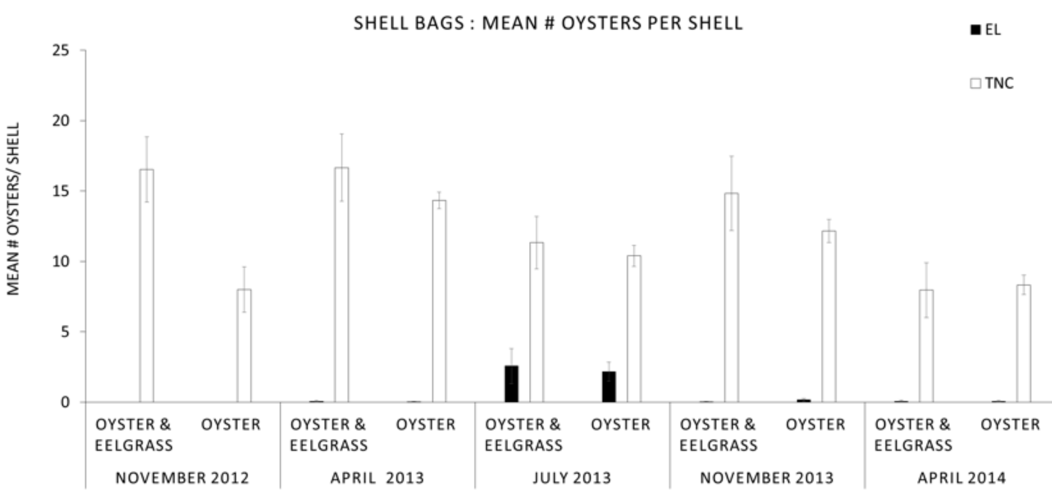


Figure 10. Mean number of oysters per shell at both project locations and across the oyster and eelgrass and oyster-only treatments. Black bars = Eden Landing; white bars = TNC. Bars indicate standard error.

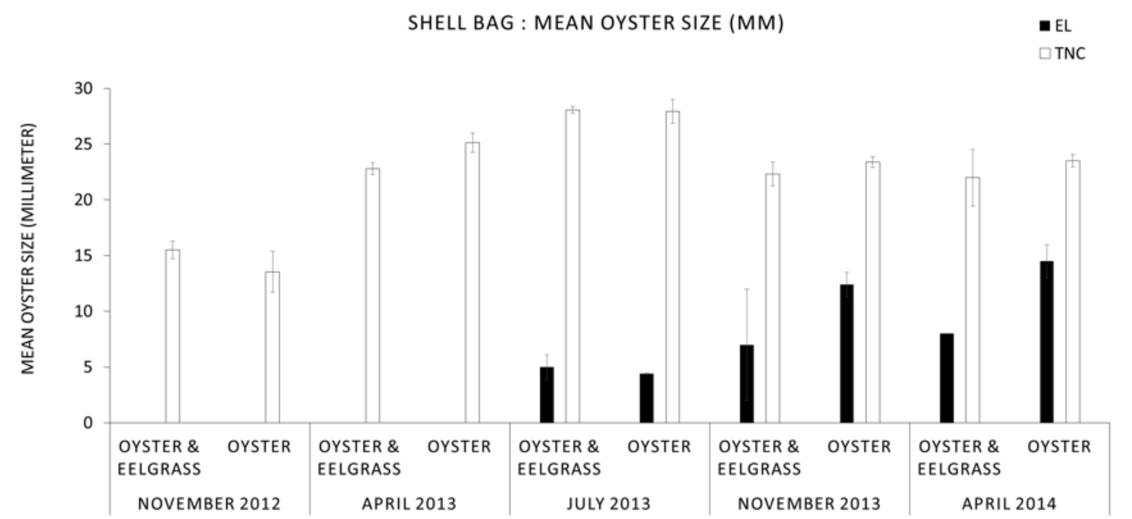


Figure 11. Mean size of oysters in the shell bags at both project locations and across oyster and eelgrass and oyster-only treatments. Black bars = Eden Landing; white bars = TNC. Bars indicate standard error.

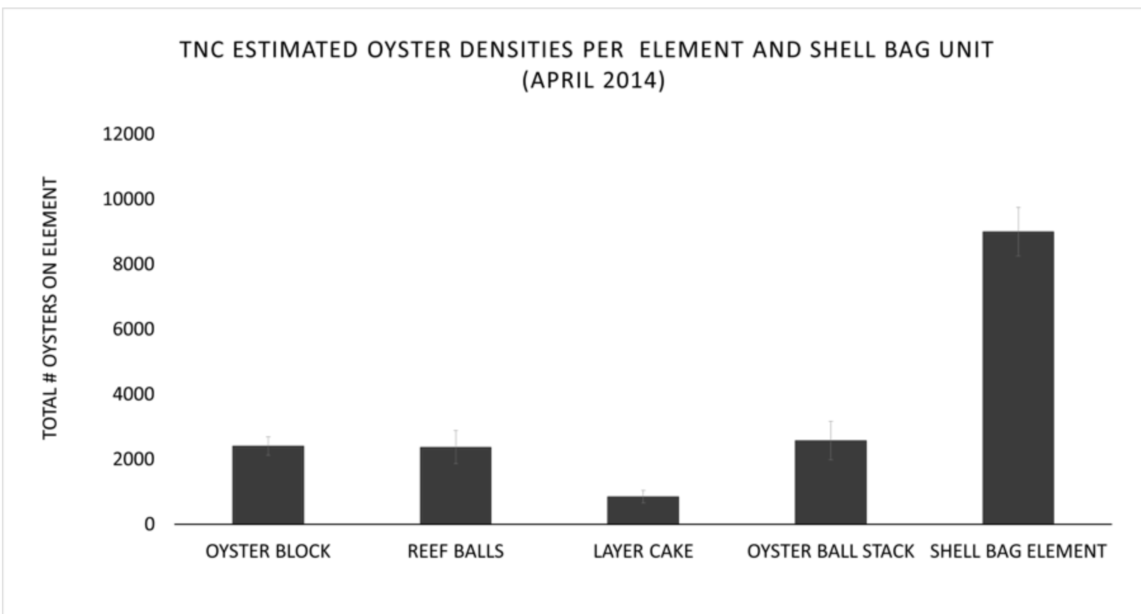
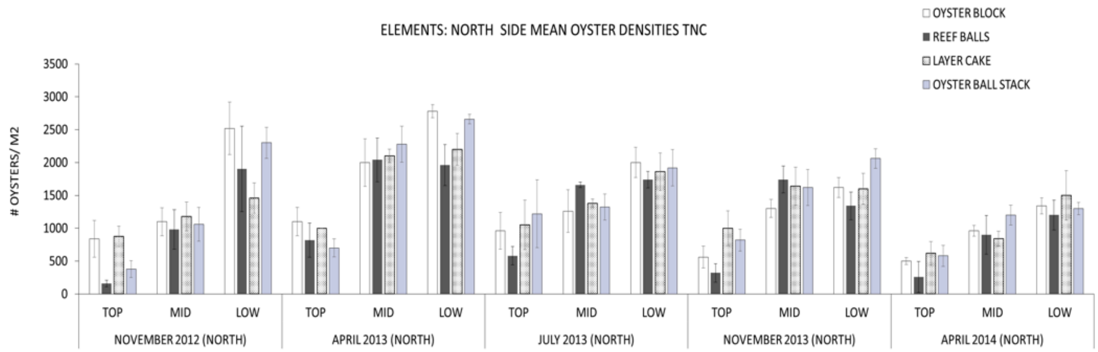


Figure 12. A comparison of the average number of oysters across the element types. Bars indicate standard error.



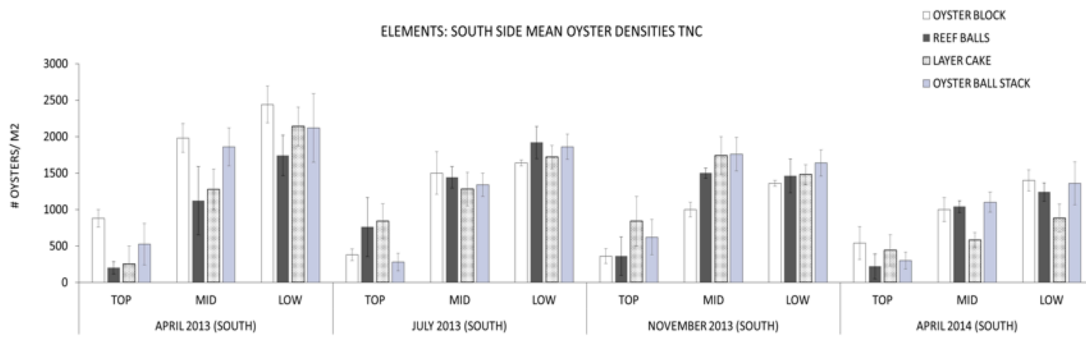


Figure 13 a (top). The number of oysters standardized to per m^2 by tidal elevation across four element types and time points for north facing sides of the elements only at TNC. Bars are standard error.

Figure 13 b. (bottom) The number of oysters standardized to per m^2 by tidal elevation across four element types and time points for south facing sides of the elements only at TNC. Bars are standard error.

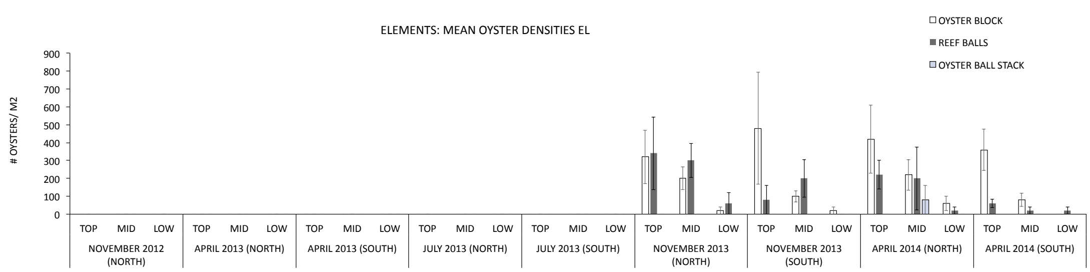
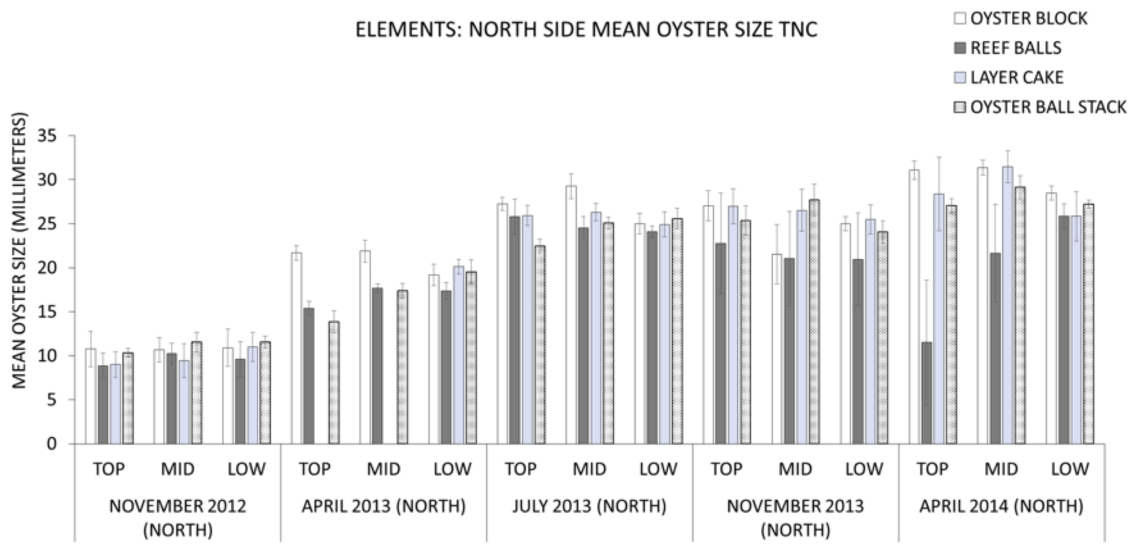


Figure 14. The number of oysters standardized to per m^2 at Eden Landing across three tidal elevations and three element types and on the north and south sides of the elements. Oysters were not present in our samples of the elements until November 2013. Bars are standard error.



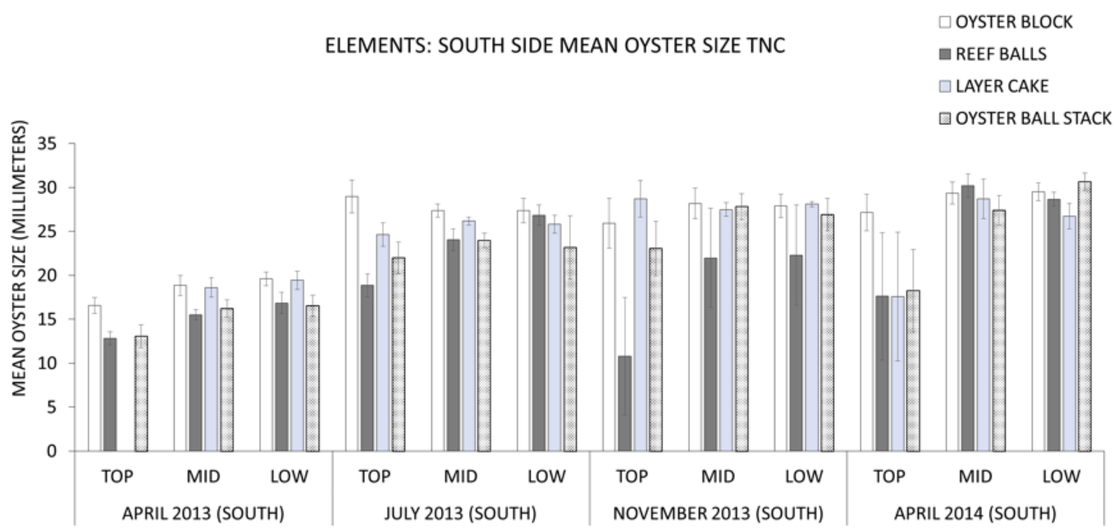


Figure 15a (top). Mean size of oysters at TNC across four element types and three tidal elevations, north side; 15b (bottom) south side. Bars are standard error.

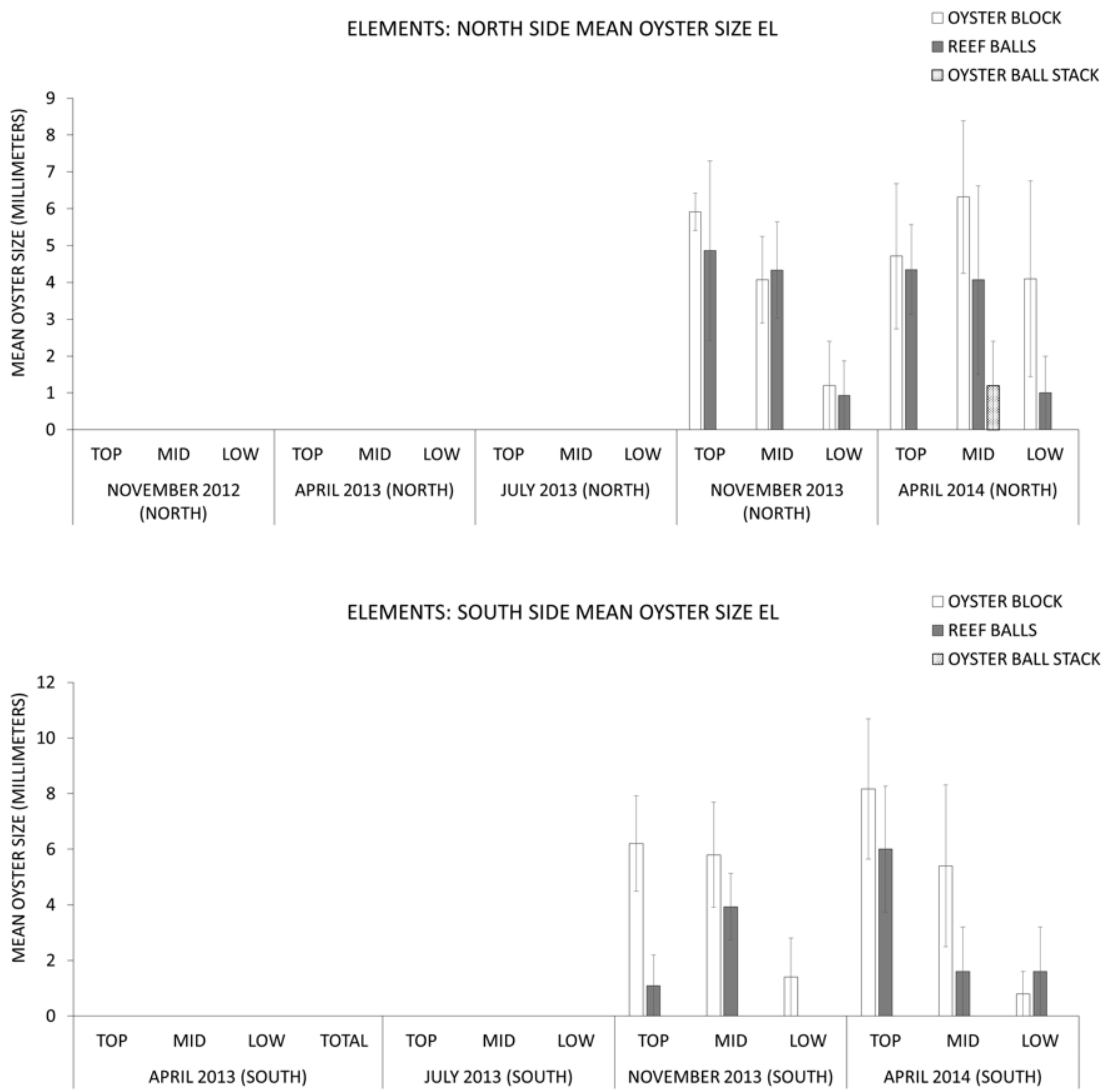


Figure 16a. (top) Mean size of oysters at Eden Landing across three element types, three tidal elevations north side; 16 b. (bottom) south side. Bars are standard error.

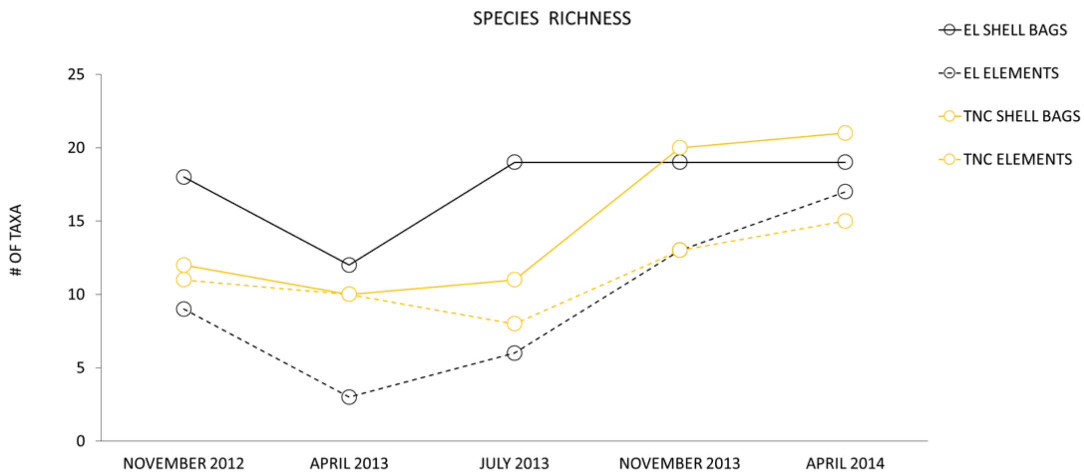


Figure 17. Species richness accumulation at the restoration sites over time.

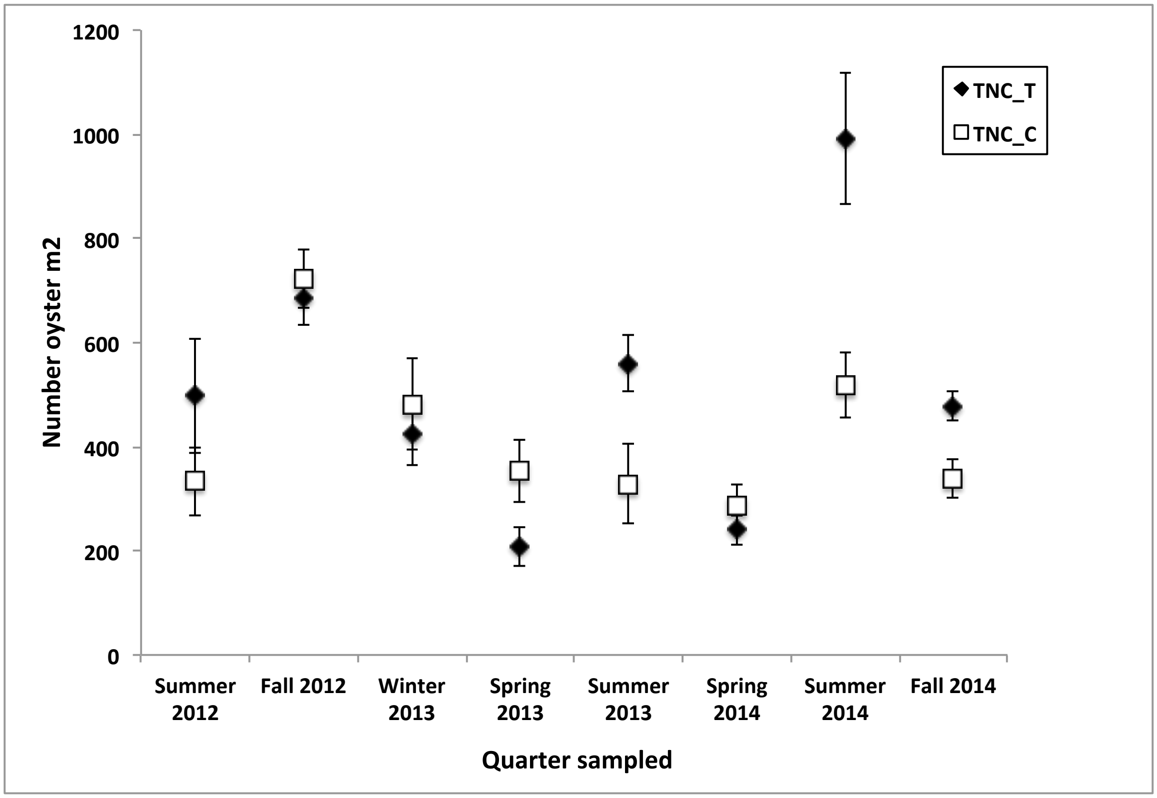


Figure 18. Number of oysters per m2 along the shoreline at the San Rafael treatment and control sites. Bars are standard error.

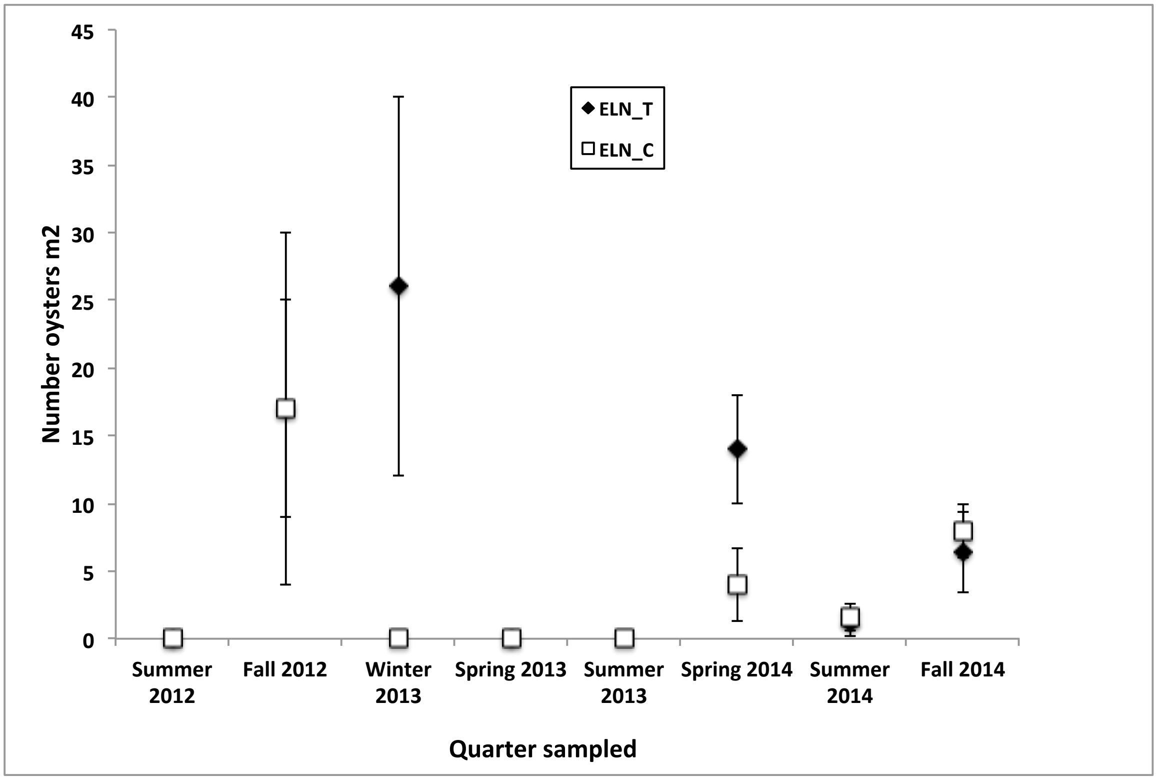


Figure 19. Number of oysters per m2 along the shoreline at the Eden Landing treatment and control sites. Note the difference in Y axis compared with the figure for San Rafael. Bars are standard error.

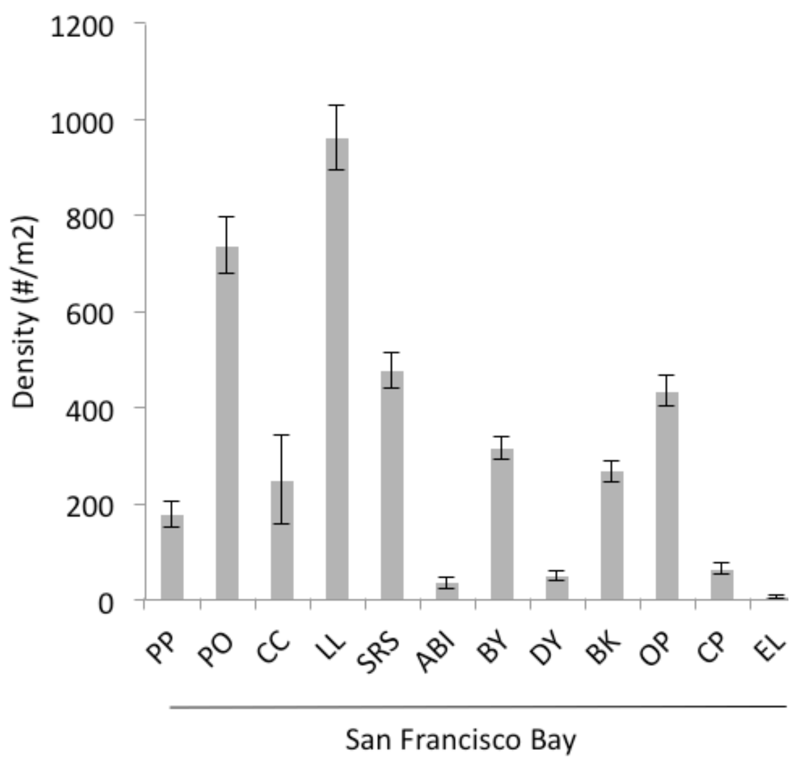


Figure 20: Density (number per square meter) of oysters at 21 study sites averaged over the monitoring period from Spring 2012 – Fall 2013 as part of a NERR Science Collaborative project (adapted from Wasson et al. 2014). PP = Pt. Pinole; PO = Pt. Orient; CC = China Camp; LL = Loch Lomond Marina; SRS = San Rafael Shoreline (this project); ABI = Arambaru Island; BY = Brickyard Cove (Strawberry); DY = Dunphy Park; BK = Berkeley; OP = Oyster Point; CP = Coyote Point; EL = Eden Landing (this project).

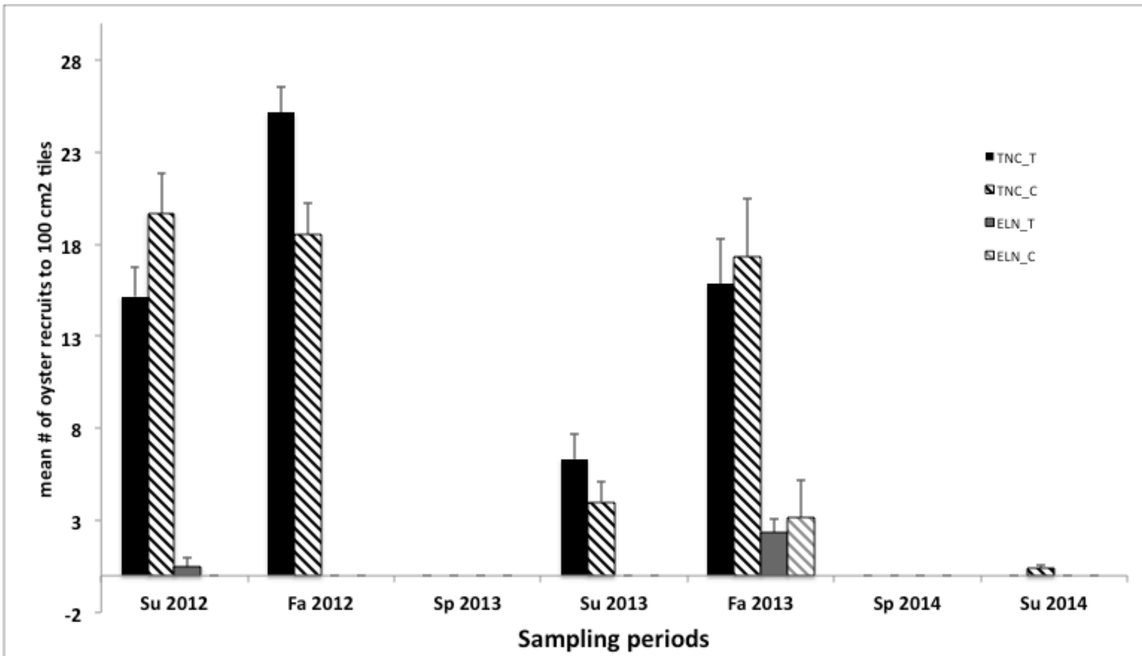
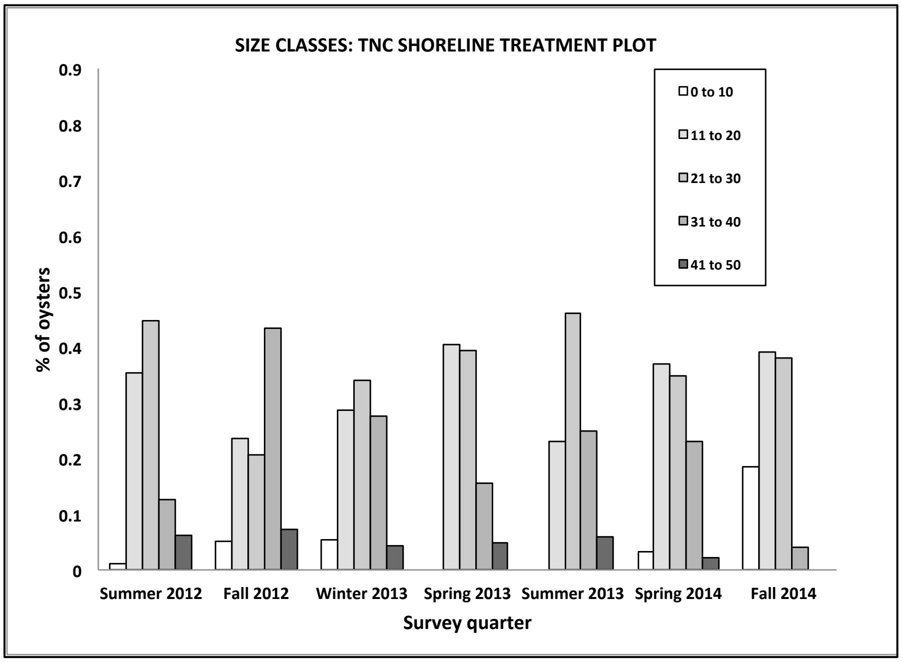


Figure 21. Recruitment to 10 x 10 cm tiles at the restoration sites and the control sites. Bars are standard error.



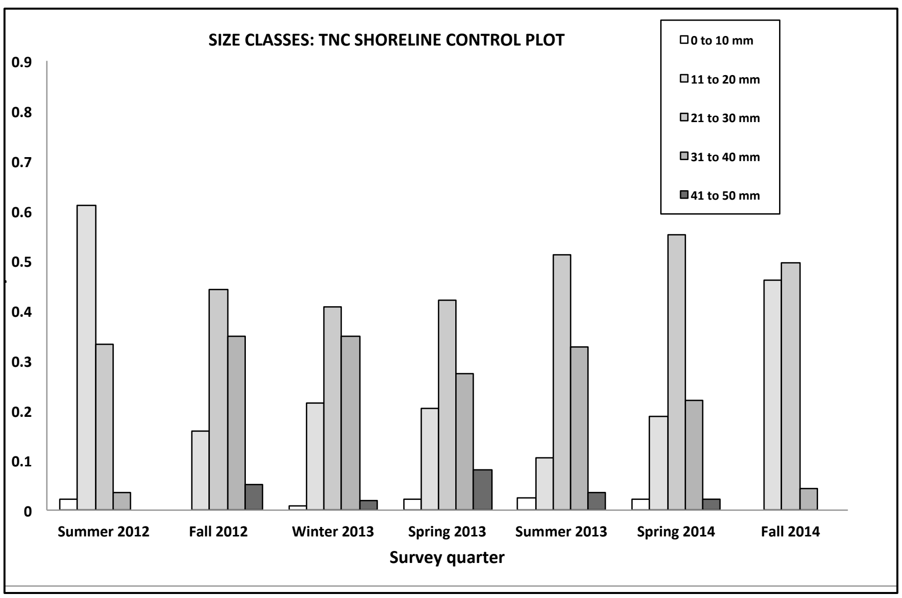
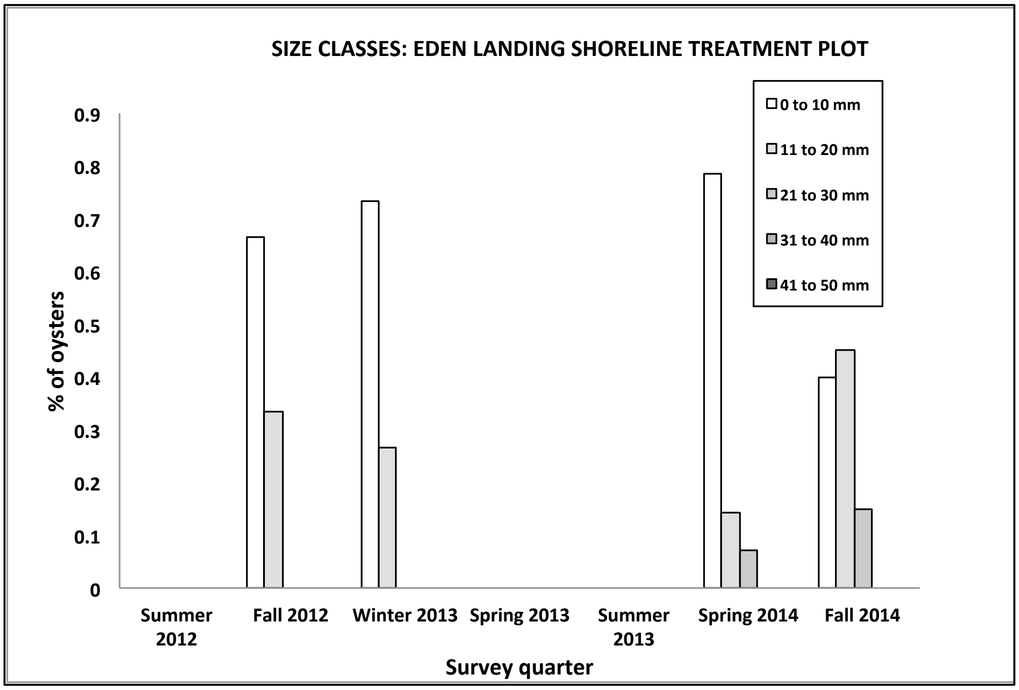


Figure 22a (Top) Size frequency distribution of oysters by size class at the TNC treatment plot, and 22b (bottom) and in control plos.



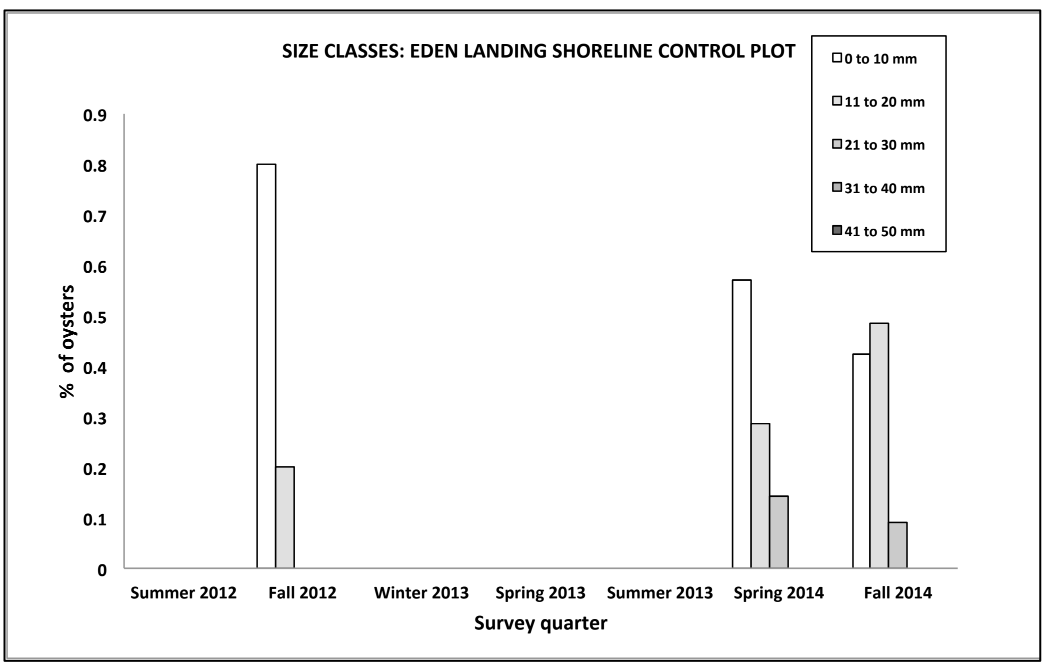


Figure 23a. (Top) Size frequency distribution of oysters by size class at the Eden Landing treatment plot and, Figure 23b, control plot.

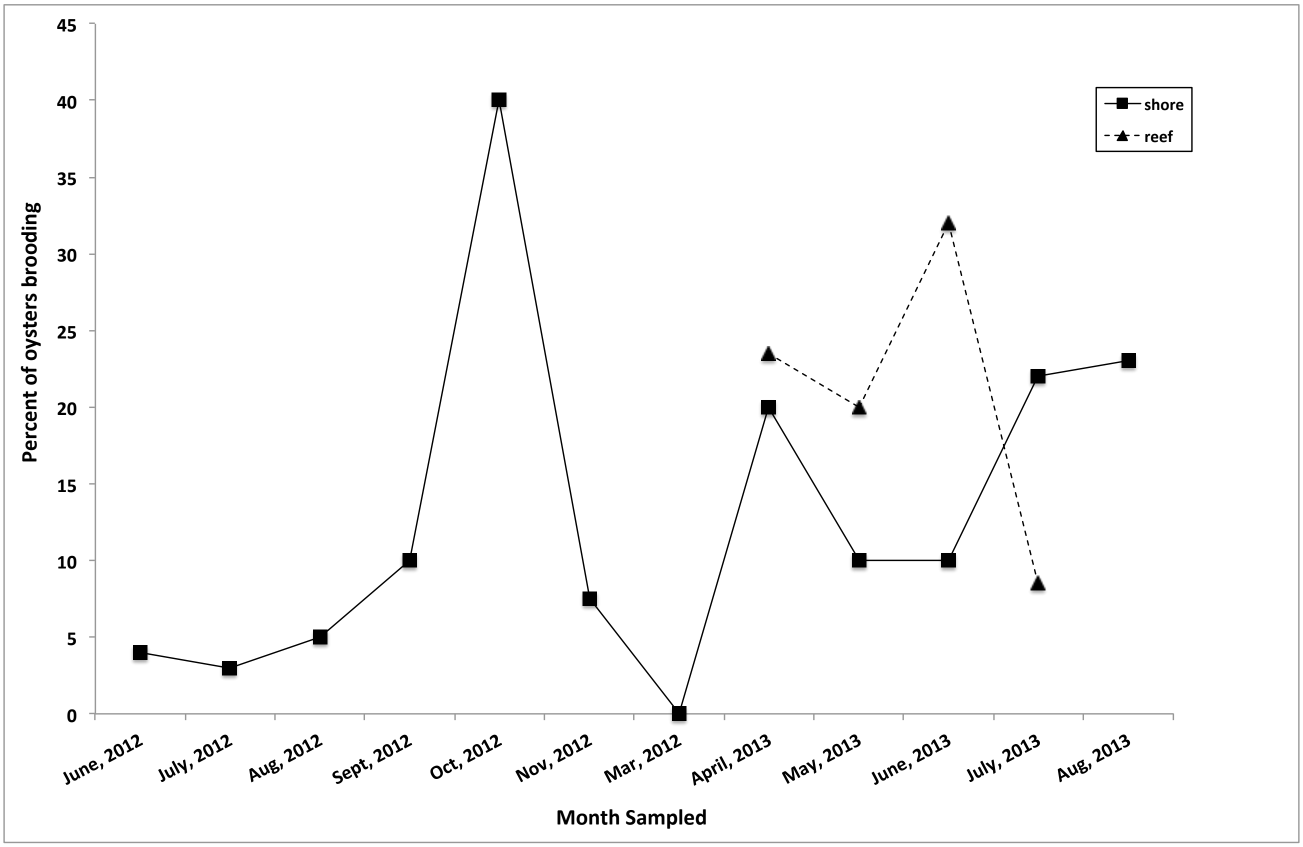


Figure 24. Percent of oysters brooding for shoreline (squares) and constructed reef (triangles) at the TNC site. The reef was constructed in July 2012; reef oysters were not sampled until 2013.

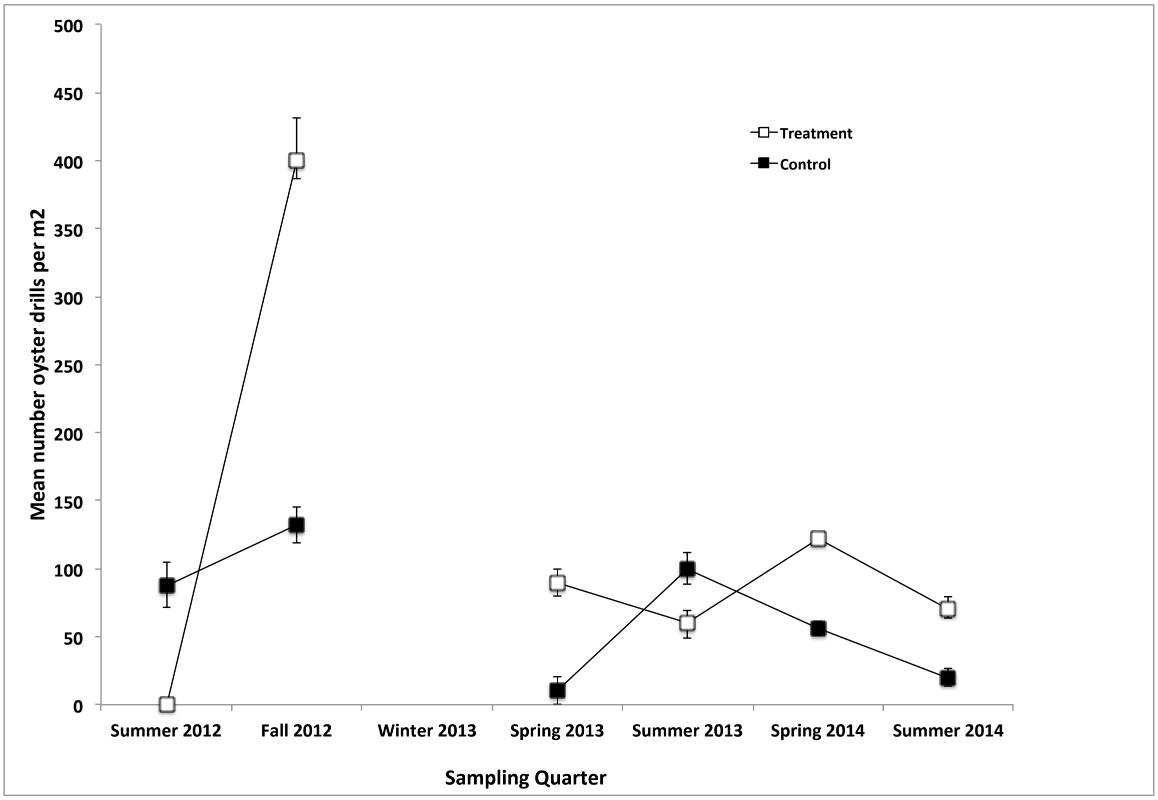


Figure 25. The number of drills in sampling quadrats from our shoreline surveys at Eden Landing. Data were not collected in winter 2013, fall 2013, or winter 2014. Bars are standard error.


Figure 26. Small reef ball stack at TNC site is collapsing.

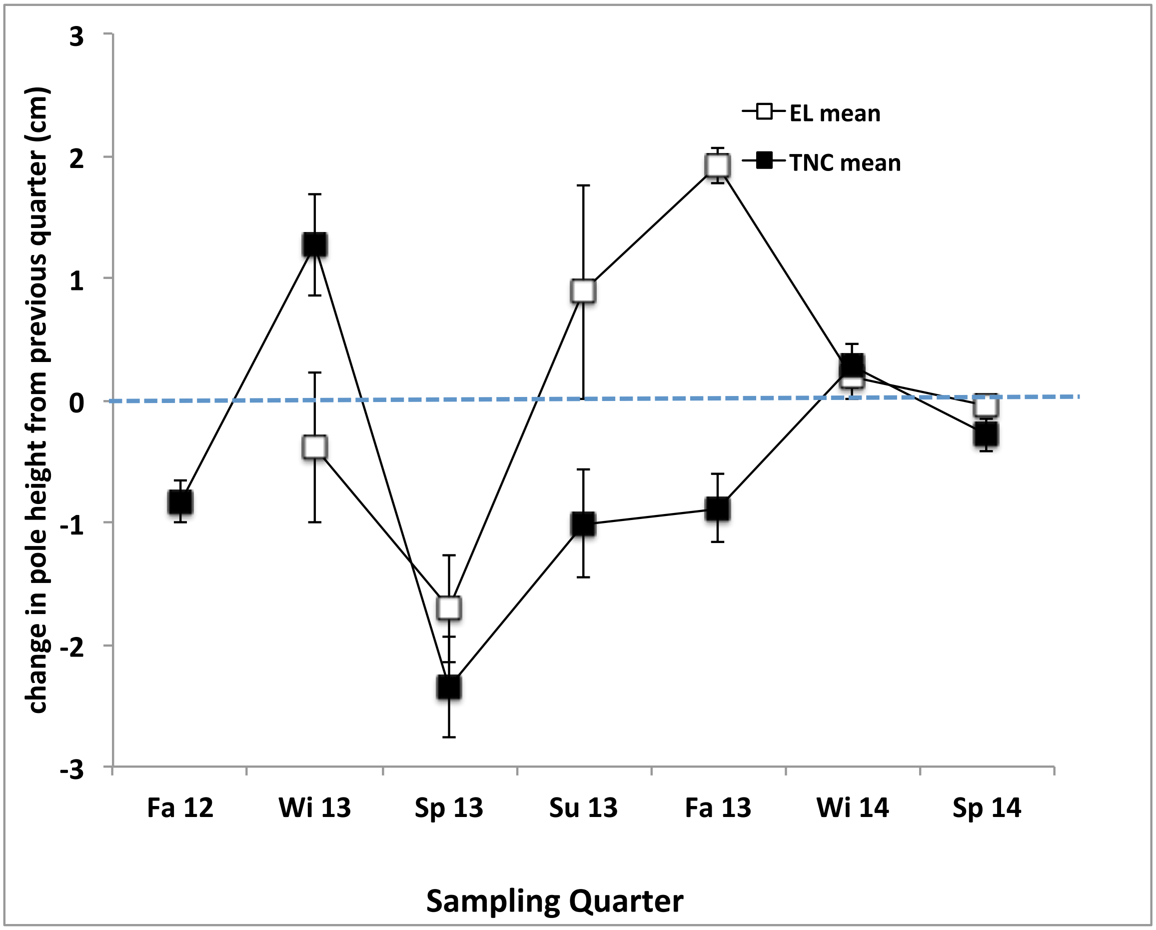


Figure 27. Mean change in height of sediment poles between quarters. White boxes are Eden Landing; black boxes TNC. Values below 0 (blue line) indicate erosion; values above 0 indicate accretion. Bars are standard error.

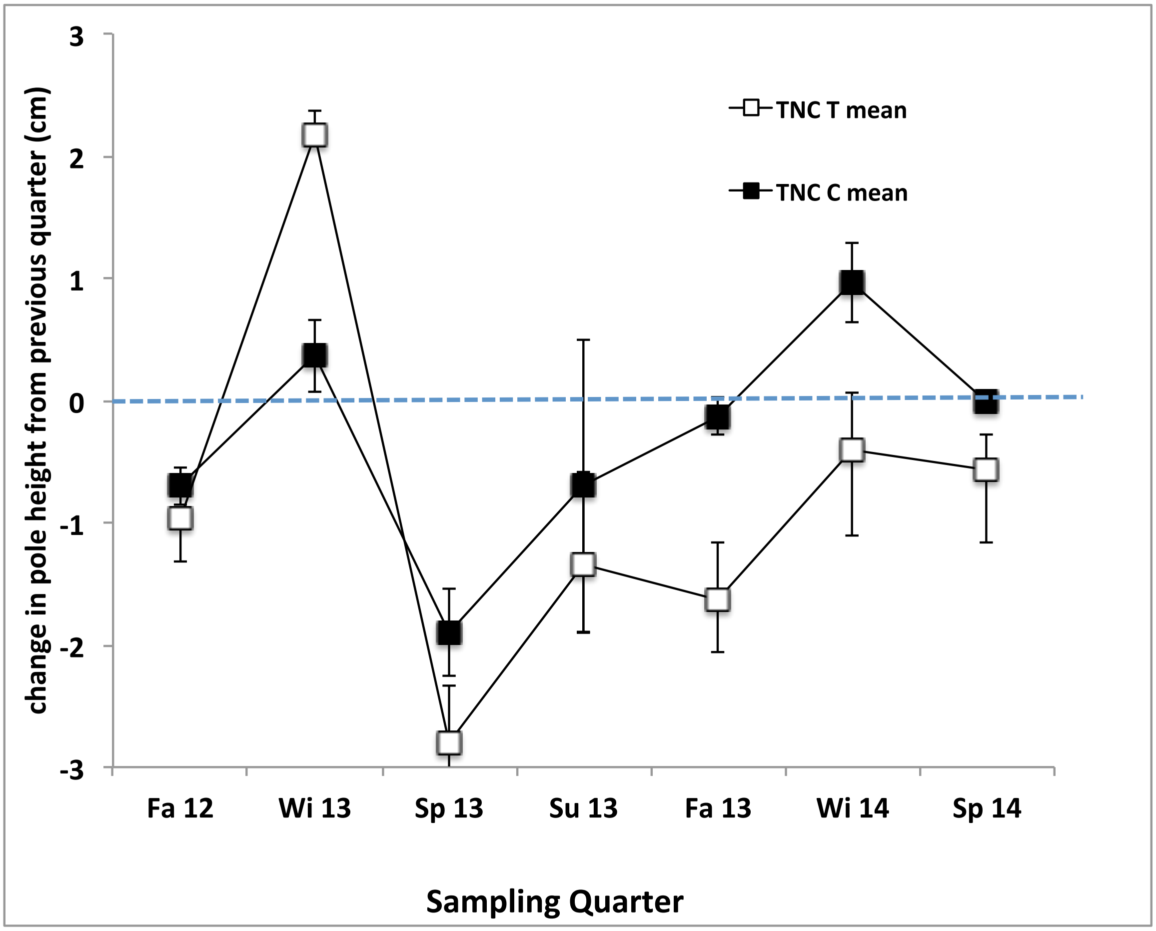


Figure 28. Mean change in height of sediment poles between quarters at TNC. White boxes are poles in the treatment plot; black boxes are poles in the control plot. Values below 0 (blue line) indicate erosion; values above 0 indicate accretion. Bars are standard error.

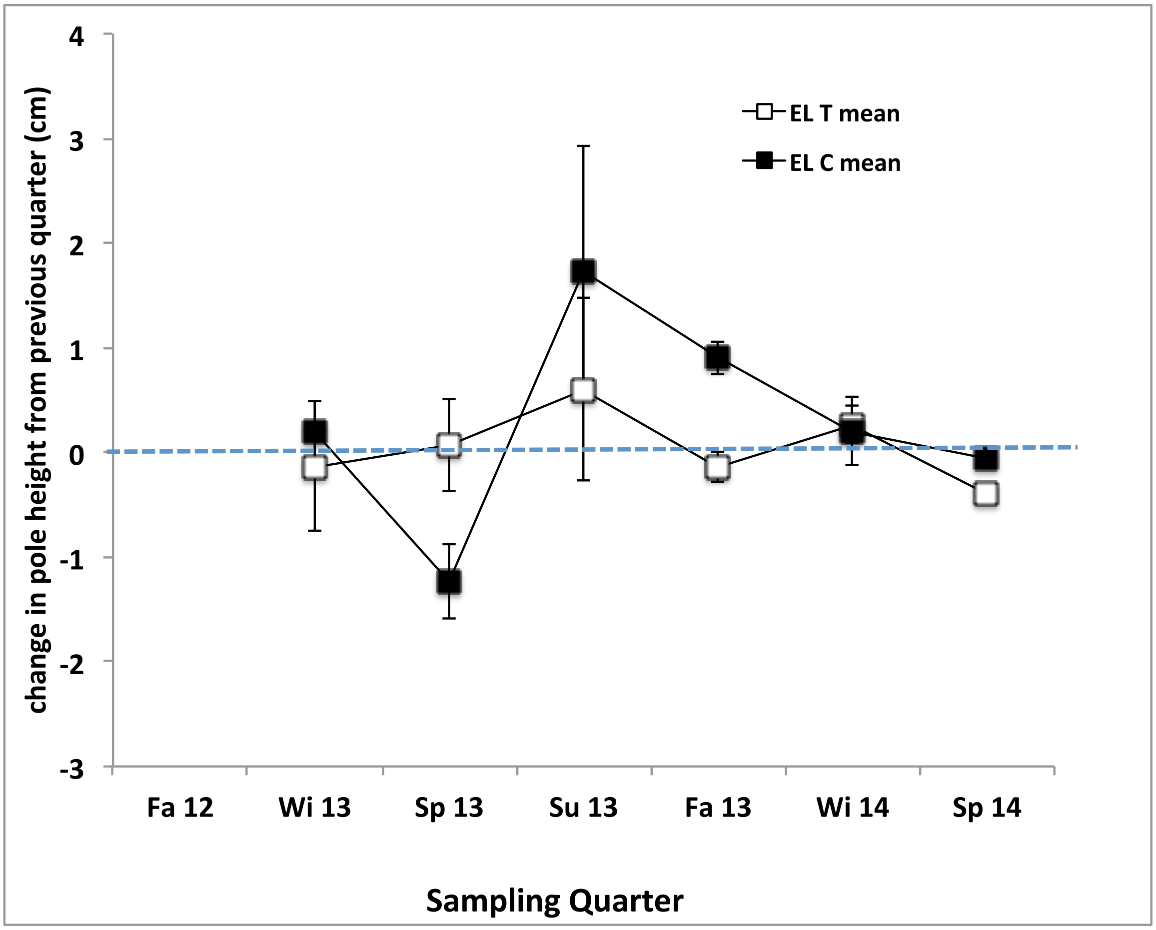


Figure 29. Mean change in height of sediment poles between quarters at EL. White boxes are poles in the treatment plot; black boxes are poles in the control plot. Values below 0 (blue line) indicate erosion; values above 0 indicate accretion. Bars are standard error.

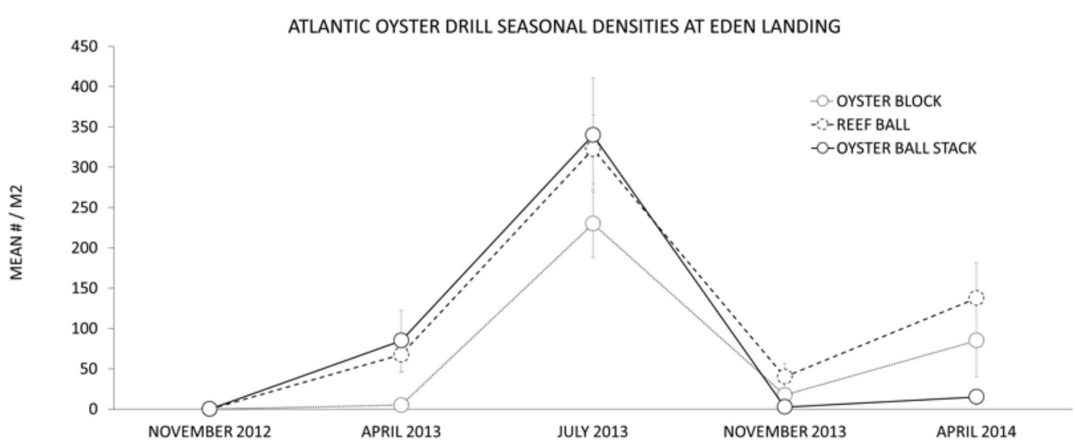


Figure 30. The number of drills in sampling quadrats on our test elements at Eden Landing.

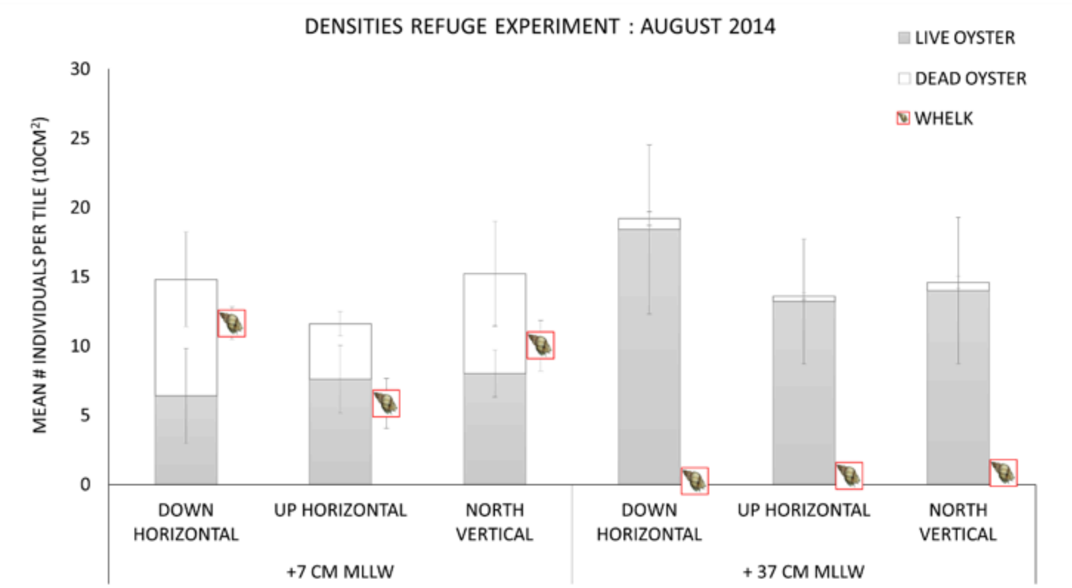


Figure 31. The number of live and dead oysters and oyster drills at two tidal heights and across three surface orientations, two months after the start of the experiment.

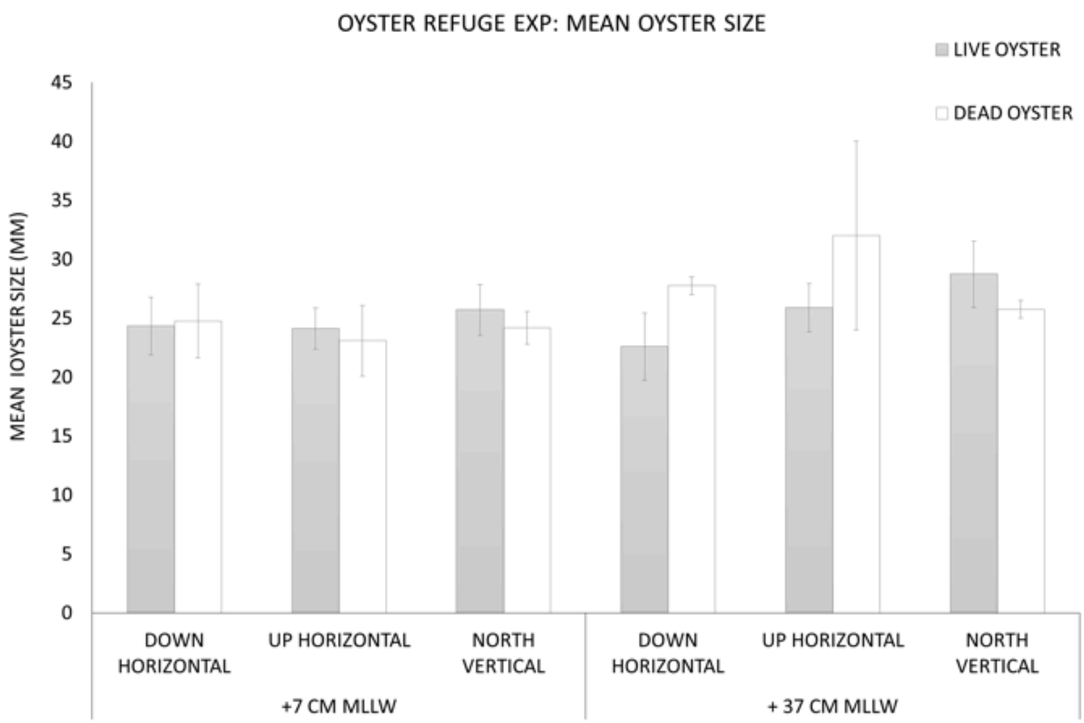


Figure 32. Mean size of both live and dead oysters on the experimental surfaces.