Assessment of intertidal and subtidal impacts of the Alder Creek Landslide

Final Report

Submitted to:

Monterey Bay Sanctuary Foundation

December 27, 2015

Principal Investigators:
Dr. Peter Raimondi
Dr. Mark Carr
Department of Ecology and Evolutionary Biology
University of California, Santa Cruz
Long Marine Lab – 100 Shaffer Road
Santa Cruz, CA 95060

Background

On April 14, 2011 a landslide occurred just south of Alder Creek, blocking Highway 1 at post mile marker 7.75. The Alder Creek Slide Area (ACSA) buried and overtopped Highway 1, which closed the highway in both directions. This created an emergency requiring immediate action by permitting agencies and the California Department of Transportation (Caltrans).

An emergency coastal development permit (CDP 3-11-032-G) was authorized by the California Coastal Commission (CCC) on April 26, 2011. As noted in the permit, this allowed for "…debris removal and landslide stabilization over a 350-linear foot distance at Highway 1 between post miles (PM) 7.7 and 7.8 on the Big Sur coast just south of Alder Creek, as well as debris placement at the Grey Slip retaining wall (PM 6.8), and the Caltrans Willow Creek site (PM 10.4) and the existing permitted landslide material disposal and rehandling site at Treebones (PM 11.0). The operation will also consist of material placement and spreading at the base of the bluff in the vicinity of the slide (avoiding direct ocean disposal as much as possible) to allow for coastal processes to disburse the material in a manner that mimics natural sloughing (all as more specifically described in the Commission's ECDR file)."

As noted in the Authorization Letter from Monterey Bay National Marine Sanctuary (MBNMS) to the CCC and Caltrans (April 26, 2011), "Caltrans estimates that stabilization of the slide will result in additional slide material seaward of the existing toe of the slide currently located on the adjacent beach. It is expected that approximately 25,000 cubic yards of this landslide material will come to reside on the adjacent beach, resulting in a total of approximately 50,000 cubic yards of material seaward of the highway."

The Alder Creek Slide Area (ACSA) includes the slide above the road and a substantial toe that extended through the intertidal and into the subtidal. On April 22, 2011 NOAA's RV FULMAR and MBNMS science divers conducted a subtidal site visit. Divers investigated two areas, one north of the slide through the persistent kelp bed, and a second area directly into the toe of the slide (Figure 1). Based on aerial images of the area in previous years, staff divers expected the bottom to be mostly sandy with interspersed rocks. To the contrary, the bottom was consolidated reef and boulders with an extensive macroalgae subcanopy (i.e. below the water surface) and extensive coverage by turf (i.e. less than 10 cm tall) macroalgae and invertebrates. The dive headed towards the toe of the slide was aborted at a depth of 20 feet due to poor visibility. The sediment plume generated by the slide was visible from aboard the FULMAR and prevented divers from reaching the actual toe of the slide. Divers stopped about 150 m short of the swash zone at the toe of the slide.

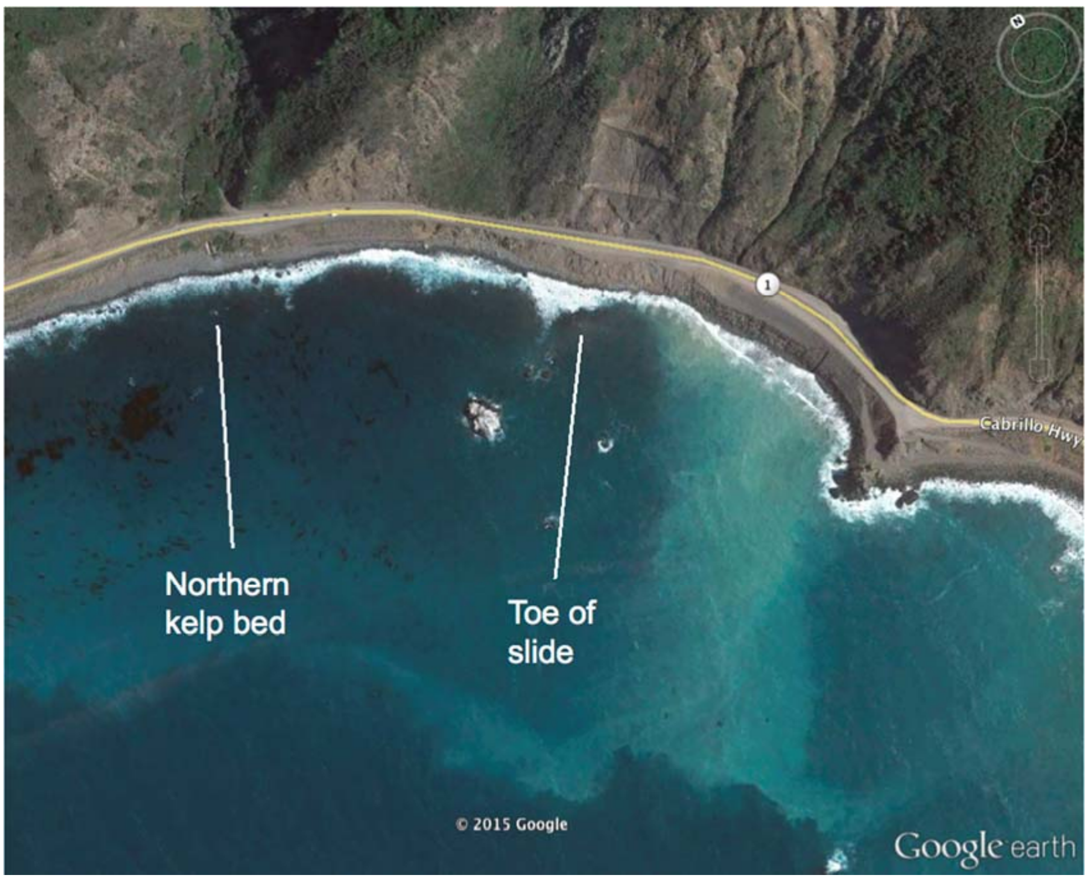


Figure 1. Alder Creek Slide Area at post mile 7.75, Big Sur, CA. White lines indicate the path divers swam, from roughly south to north (deep to shallow) during investigative dives from the NOAA RV FULMAR on April 22, 2011.

It was recognized early on that the state of knowledge regarding the impact of landslide material to the intertidal and adjacent subtidal was wanting. Clearly, areas buried by the landslide suffered immediate and direct impacts. However, it was less clear to scientists what other direct and indirect impacts were the result of the natural slide and additional engineering and disposal work. For example, it was not known how the sediment plume in the nearshore would affect the benthos (i.e. community of macroalgae and animals inhabiting the seafloor), particularly sedentary and sessile species. Scour, turbidity and subsequent sediment settlement—among others—were likely to increase the zone of influence around the toe of the slide, both in the intertidal and subtidal zones.

MBNMS and Caltrans staff worked with local scientists to develop a monitoring plan that would provide insight on these issues. Specifically, a proposal was submitted by the Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO) in consultation with MBNMS and Caltrans staff to assess the pattern of intertidal community composition as a function of distance from the ACSA. General questions include:

1. Does the pattern of intertidal community composition vary as a function of distance from the ACSA?
2. Does this pattern change over time?
3. Are the spatial and temporal patterns (questions 1 and 2) consistent with an impact to the community due to the ACSA?
4. If the answer to question 3 is yes, then what is the expected time to recovery?
5. Does the relative abundance of substrata (rock versus sand) and vertical relief differ between the shallow subtidal rocky reef site offshore of the ACSA relative to sites to the north and south
6. Do species abundances of macroalgae and invertebrates on the shallow subtidal rocky reef just offshore of the ACSA differ from sites to the north and south?
7. Does species composition (identity and relative abundances) of macroalgae and invertebrate assemblages on the shallow subtidal rocky reef just offshore of the ACSA differ from sites to the north and south?
8. Are the differences in the shallow subtidal rocky reef consistent with what might be associated with changes in the physical environment associated with the ACSA (e.g., sediment burial, scouring, turbidity)?
9. Do these patterns (5, 6 and 7) vary among depth zones in the shallow subtidal rocky reef and do they change over time?
10. Does the relationship between giant kelp (*Macrocystis pyrifera*) biomass (derived from Landsat imagery) and distance from the ACSA differ before and after the slide event?

In this report, we summarize the results of our three-year study of ecological impacts in the rocky intertidal and subtidal zones, including our sampling designs, protocols, analyses and interpretations of our analyses.

I. Assessment of the pattern of intertidal community composition as a function of distance from the Alder Creek Slide Area (ACSA)

General Questions

1. Does the pattern of intertidal community composition vary as a function of distance from the ACSA?
2. Does this pattern change over time?
3. Are the spatial and temporal patterns (questions 1 and 2) consistent with an impact to the community resulting from the ACSA?

Background

Intertidal Zonation

Because of the gradient of tidal exposure, intertidal areas have strong species zonation patterns. Often this gradient is divided into three zones: high, medium and low. Our surveys were designed to sample the shoreline so that all three zones will be evaluated. This allowed us to determine if patterns of community composition in each zone varies as a function of distance from the ACSA.

Intertidal Sampling Methods: Design and Protocols

We relied on methods (http://www.eeb.ucsc.edu/pacificrockyintertidal/index.html) used in our Marine Protected Area baseline assessments to characterize the intertidal community composition. These methods were also the basis of our assessments of impact in the Cosco Busan and Dubai Star Oil Spills (Raimondi et al. 2009, 2011).

Zonation

Because of the gradient of tidal exposure, intertidal areas have strong species zonation patterns. Often this gradient is divided into three zones: high, medium and low. Our surveys were designed to sample the areas so that all three zones were evaluated. Transects were parallel to the shore and positioned in each of the three zones (low, mid, high): see additional explanation of methods below.

Sampling Methods

Separate transects were run up- and down-coast from the edges (Figure 2). The length of each transect was 1000 meters and originated at the middle of the ACSA. Photographs, bearings and GPS coordinates were recorded for all transects so that they could be relocated and sampled again in the future. Photo and mobile plots were then sampled along each transect. These plots were set up in two sections on each side of the slide (i.e. north and south): first in a progression initiated at the slide, which yielded a higher number of plots close to the slide and a decreasing density of plots (number per unit distance) with increasing distance, since potential effects of the slide were expected to diminish with distance. This first section included those plots considered 'in', 'close', and 'further.' The second section of plots was the last set of plots, which were arranged closer together to yield a set distance in the north and south to provide a set of "control" plots and were called 'farthest.' For analytical assessments we grouped the plots into these four "corrected treatments" (i.e. in, close, further, and farthest) relative to the ACSA (Figure 2). High resolution photos (using 50 cm by 75 cm quadrat frames to standardize sampling) were used to characterize sessile species. For each photoplot, a set of notes was taken *in situ* that described the species in the plot and their location. These notes were used in subsequent sampling in the lab when the identity of a species was uncertain. The 'photoplots' were either sampled in the field using a gridded quadrat or in the lab each photo was projected on a computer screen and overlaid with a grid of 100 points. The species under each point was entered in a database and used to calculate the percent cover of sessile species within photoplots. Mobile invertebrate species were also identified and counted within identically sized quadrats along each transect. These plots along the transect using a 1 meter offset from the photoplots to avoid disturbing the plots (which may need to be subsequently re-sampled). In the mobile plots rocks were turned over to count crabs and snails, which often are not exposed. Sampling was done in each of three years (12/2012, 12/2013, 1/2015).

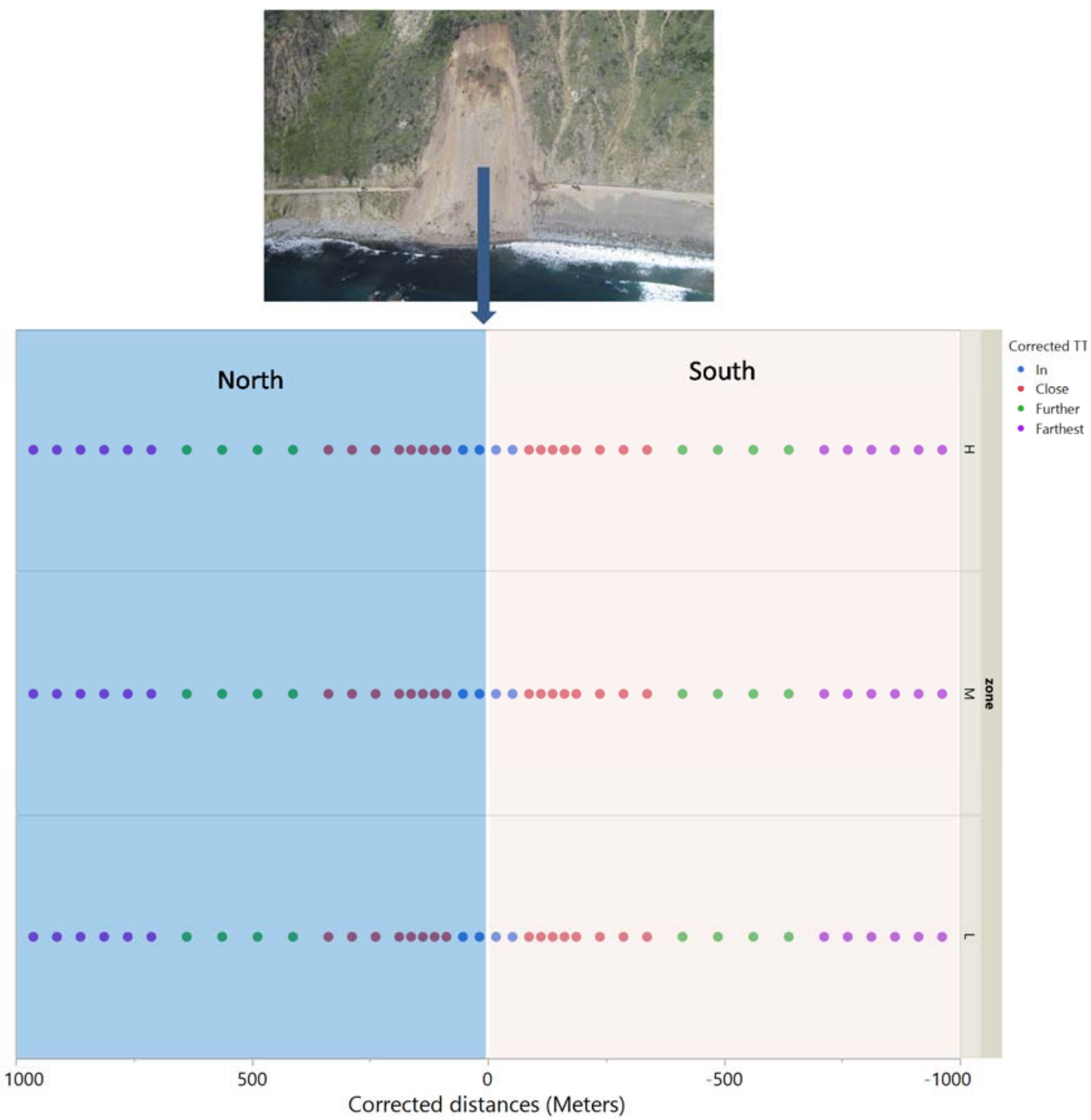


Figure 2. General layout of transects showing lines parallel to shore and extended both up- and down-coast from slide. The three zones (High, Mid and Low) are also shown. Each point indicates a sample plot. Color of point indicates the distance category that was assigned to the point.

Analytical Approach for Intertidal Data

We used a community-based approach to assess the potential for impacts related to the slide. As noted above we were interested in three questions:

1. Does the pattern of intertidal community composition vary as a function of distance from the ACSA?
2. Does this pattern change over time?
3. Are the spatial and temporal patterns (questions 1 and 2) consistent with an impact to the community resulting from the ACSA?

We used multivariate statistical approaches to address question 1 and 2. We relied on resemblance matrices developed using a Bray-Curtis (similarity) calculations (Primer E ver.7 software package). For our first two questions we used a PERMANOVA approach to determine if there was a decrease in similarity between corrected treatments (i.e. between pairs of three distance categories: close, further, or farthest) as the spatial separation from the ACSA increased. The specific model tested was:

Community Similarity = Year+Location+Zone+Corrected Treatment+all interactions

where:

Year = 2012, 2013, 2015
Location = Upcoast (North), Downcoast (South)
Zone = High, Mid, Low
Corrected Treatment = Close, Further, Farthest (note: 'In' was left out of analyses because it was buried by debris but the data can be used to assess changes in the footprint of the slide in the future, once the overburden is washed away)

For question 3 we examined the species contributing to the relationships to determine if differences seen were consistent with an impact. For example, there would be support for an impact if the main species driving the change in community as a function of distance from the slide were all ephemeral species that were much more common close to the slide than far from it. This assumes that ephemeral species can colonize in these areas and that they are taking advantage of modified habitat closest to the ACSA.

Results

Sessile Species

The PERMANOVA values for sessile species are shown in Table 1. Many terms in the model were significant ($P<0.05$). No term including Year was significant, indicating that community patterns did not vary over the three-year time period of this study. The key term was the three-way interaction between Location (north or south), Zone (high, mid or low) and Corrected Treatment (close, further or farthest), which suggested that the sessile community varied as function of distance and direction (i.e. upcoast [north] or downcoast [south]) from the ACSA. These patterns are shown in more detail in Figures 3-6, which are the same similarity diagram showing different highlighted terms. Note the absence of any clear spatial pattern in Figures 3 and 5 and the striking patterns in Figure 4 and 6. In Figure 3, which highlights the north vs. south term, there is a mix of north and south plots in clusters 2-4, and only cluster 1 has all downcoast plots from the 'close' treatment. In Figure 4 clusters 2-4 represent the expected tidal zonation (high, mid and low), but cluster 1 departs from this pattern and by looking at Figure 4 it is clear that the community differed from that expected in the area close to (within 400 meters) and downcoast from the ACSA. Figure 7 shows some of the species (and substrata) that contributed to this result. The key result is that the downcoast area close to the slide is strongly affected by a high percentage of sand, some bare rock, and few organisms (Figure 7, group 1). High sand cover likely influenced turbidity and sand scour and reduced the cover of several species. Figure 7 also shows the very strong zonation pattern for high, mid and low zones (groups 2-4). Figure 8 shows species richness as a function of the groups in Figure 7. Highest richness is found, as expected, in the low zone, followed by mid then high. Group 1, which is the downcoast close area (all zones), had the lowest species richness.

Table 1. PERMANOVA results for intertidal sessile community. Terms significant at P<0.05 are shown in red. The main factors were: Year (2012, 2013 or 2015); Location (upcoast or downcoast of the ACSA); Zone (high, mid, or low); and Corrected Treatment (Corrected TTT; close, further, or farthest - in was excluded).

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms
year	2	8779.1	4389.5	2.7774	0.005	999
location	1	32394	32394	20.497	0.001	997
zone	2	1.83E+05	91642	57.986	0.001	999
Corrected TTT	2	77040	38520	24.373	0.001	999
yearxlocation	2	3138.6	1569.3	0.99295	0.417	999
yearxzone	4	9240.2	2310	1.4617	0.078	998
yearxCorrected TTT	4	5549.2	1387.3	0.8778	0.617	997
locationxzone	2	8033.7	4016.8	2.5416	0.01	999
locationxCorrected TTT	2	77655	38827	24.568	0.001	998
zonexCorrected TTT	4	33383	8345.7	5.2807	0.001	995
yearxlocationxzone	4	4197.8	1049.5	0.66403	0.878	998
yearxlocationxCorrected TTT	4	5481.9	1370.5	0.86715	0.622	998
yearxzonexCorrected TTT	8	10145	1268.1	0.80238	0.817	999
locationxzonexCorrected TTT	4	25630	6407.6	4.0544	0.001	998
yearxlocationxzonexCorrected TTT	8	10593	1324.1	0.83784	0.78	997
Res	270	4.27E+05	1580.4			
Total	323	9.45E+05				

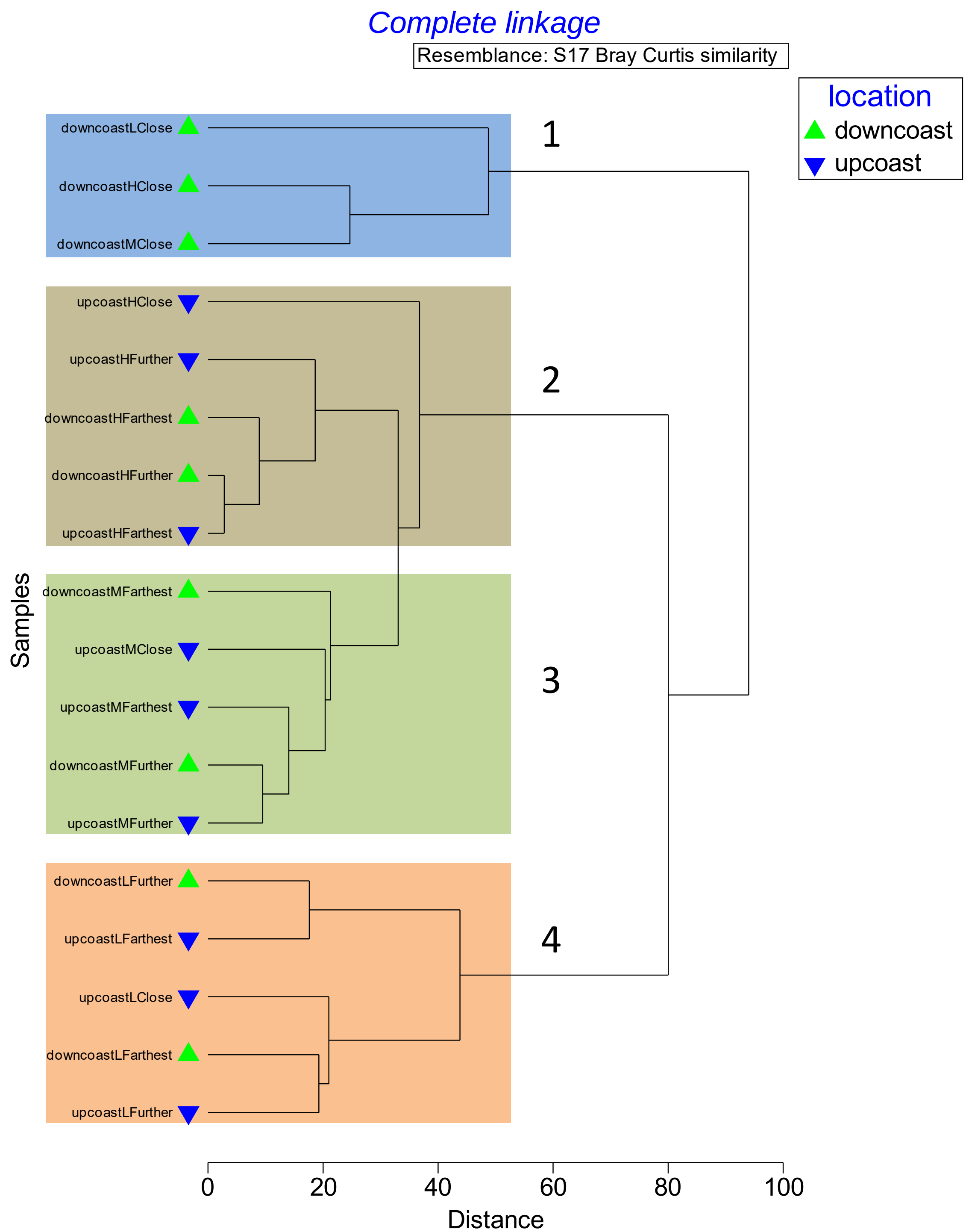


Figure 3. Results for cluster analysis for intertidal sessile species highlighting the Location term. Shown are distinct clusters (1-4) along with symbolic key for Location (i.e. upcoast [north] or downcoast [south]).

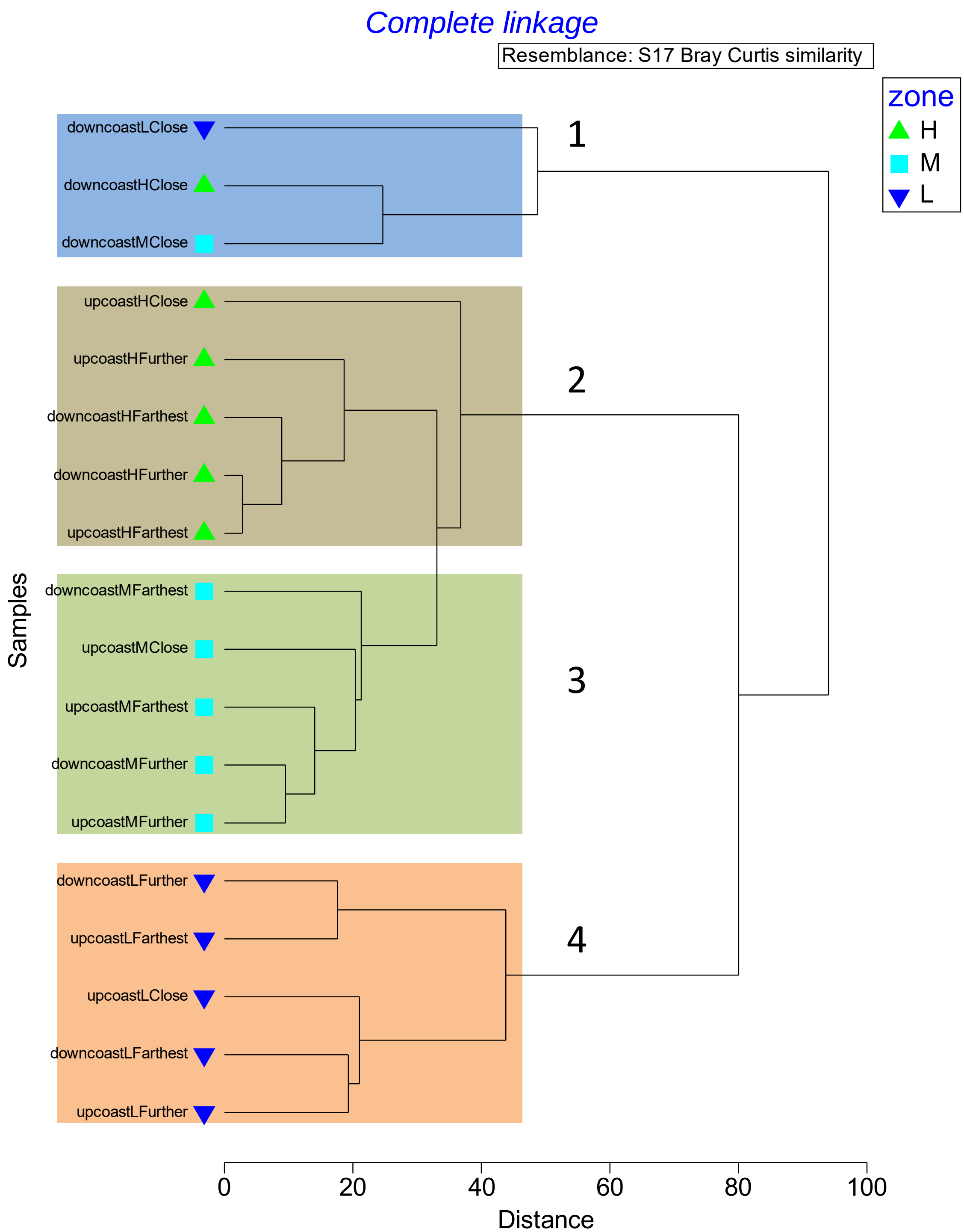


Figure 4. Results for cluster analysis for intertidal sessile species highlighting the Zone term. Shown are distinct clusters (1-4) along with symbolic key for Zone (High, Mid, Low).

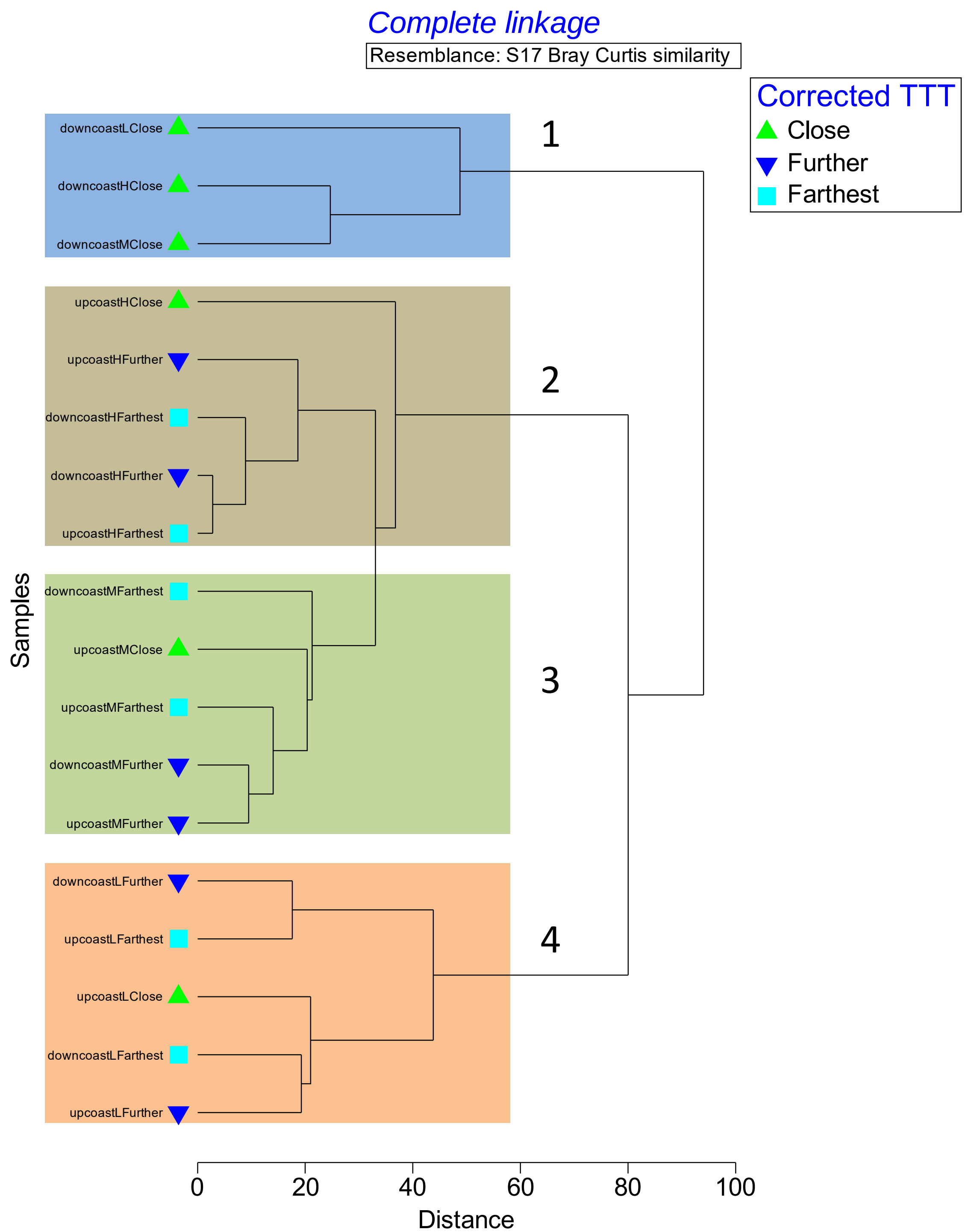


Figure 5. Results for cluster analysis for sessile species highlighting the Distance term (also called corrected treatment [TTT]). Shown are distinct clusters (1-4) along with symbolic key for Corrected Treatment (Corrected TTT not including IN).

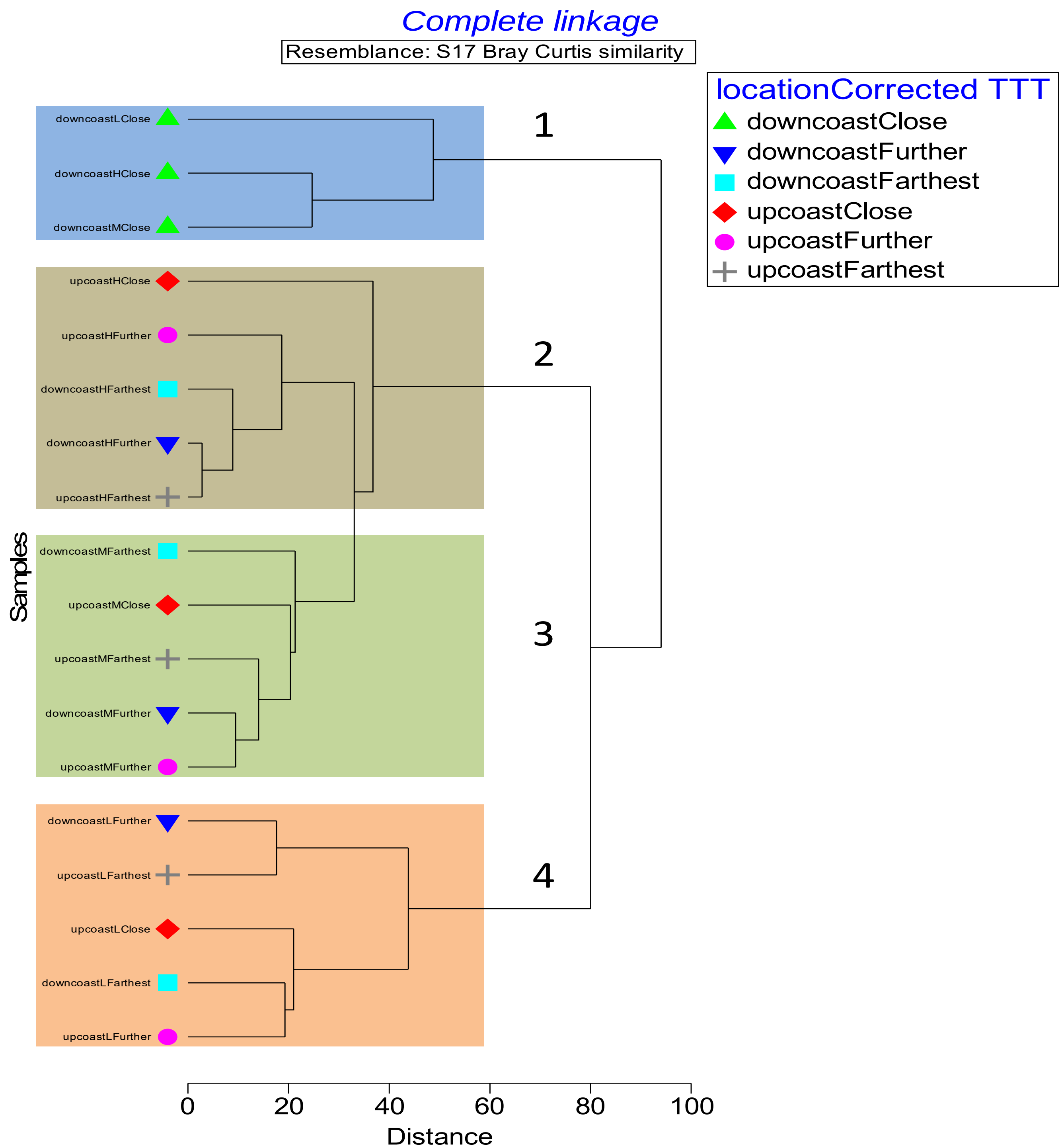


Figure 6. Results for cluster analysis for intertidal sessile species highlighting the Location x Distance interaction term. Shown are distinct clusters (1-4) along with symbolic key for the interaction between Location and Corrected TTT (representing distance from the ACSA).

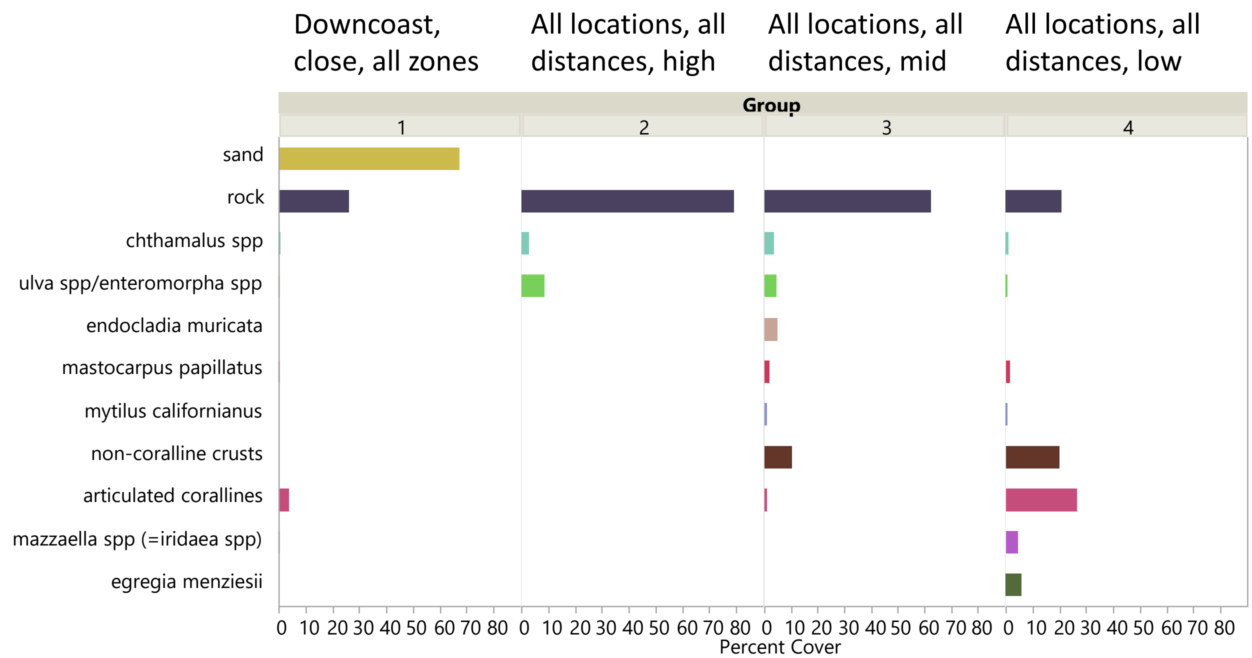


Figure 7. Species or substrate that contributed to differences among groups for intertidal sessile species. Note the change in community for high, mid and low intertidal zone (groups 2-4).

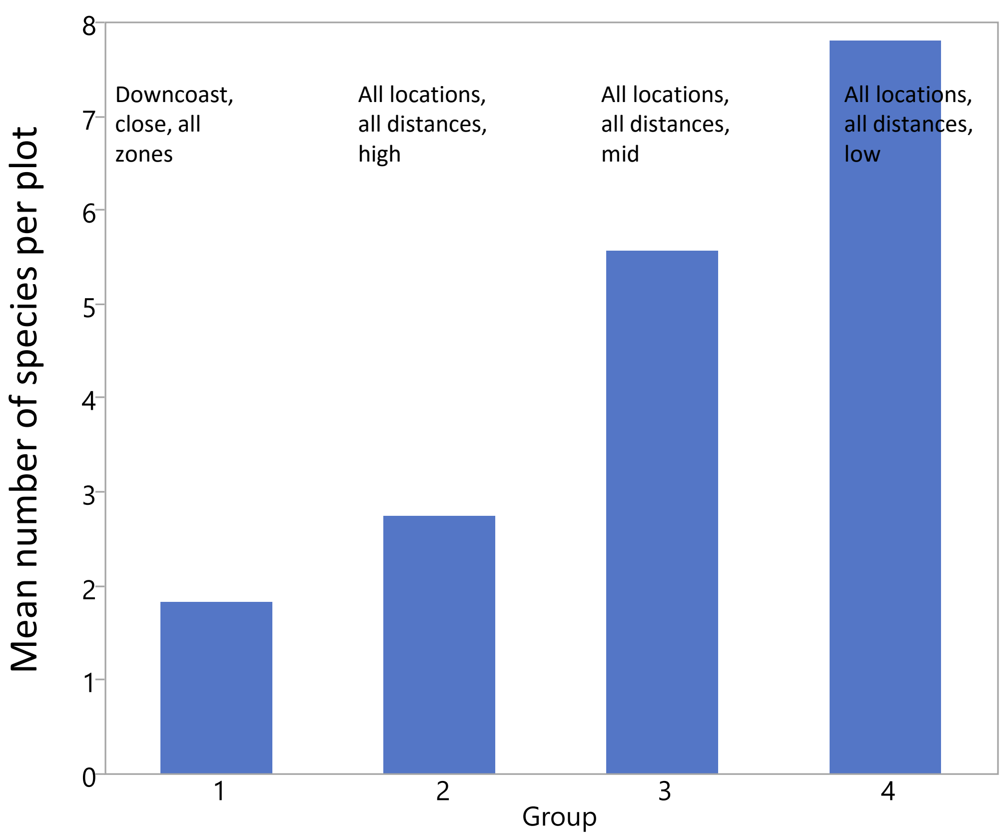


Figure 8. Species richness (intertidal sessile species) for individual groups used in Figure 7.

Mobile Species

The PERMANOVA values for intertidal mobile species are shown in Table 2. Many terms in the model were significant (P<0.05). Some were expected and not informative to the question of community level impact resulting from the slide, such as all terms that included Zone, since distinct zonation patterns were expected for sessile intertidal communities. In contrast to the results for the sessile species, many terms including Year were significant indicating that community patterns varied over the three-year time period of this study. The key term was the four-way interaction between Year, Location, Zone and Corrected Treatment, which suggested that the mobile community varied as function of year, distance and direction from the slide. These patterns are shown in more detail in Figures 9-12, which are the same similarity plots showing different highlighted terms. Other than the pattern of zonation (Figure 11), which was not as striking as for the sessile species, note the absence of any clear spatial or temporal pattern in these figures. This result suggests that while community patterns for mobile species vary in space and time, they do not conform to any pattern that would indicate an effect derived from the ACSA. Figure 13 shows species richness as a function of group. Similar to the intertidal sessile community, mobile species richness was lowest in the high intertidal (group 1).

Table 2. PERMANOVA results for the intertidal mobile community. Terms significant at P<0.05 are shown in red.

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms
year	2	17687	8843.7	4.6939	0.001	997
location	1	16323	16323	8.6634	0.001	998
zone	2	1.13E+05	56405	29.937	0.001	998
Corrected TTT	2	6066.4	3033.2	1.6099	0.054	999
yearxlocation	2	3543.4	1771.7	0.94036	0.545	999
yearxzone	4	22518	5629.5	2.9879	0.001	998
yearxCorrected TTT	4	11659	2914.7	1.547	0.03	997
locationxzone	2	9165.7	4582.9	2.4324	0.001	998
locationxCorrected TTT	2	31205	15603	8.2813	0.001	999
zonexCorrected TTT	4	6355.3	1588.8	0.84329	0.742	997
yearxlocationxzone	4	11919	2979.7	1.5815	0.021	999
yearxlocationxCorrected TTT	4	12637	3159.3	1.6768	0.012	999
yearxzonexCorrected TTT	8	23674	2959.3	1.5707	0.002	999
locationxzonexCorrected TTT	4	16463	4115.7	2.1844	0.001	997
yearxlocationxzonexCorrected TTT	8	27188	3398.5	1.8038	0.001	998
Res	203	3.82E+05	1884.1			
Total	256	7.65E+05				

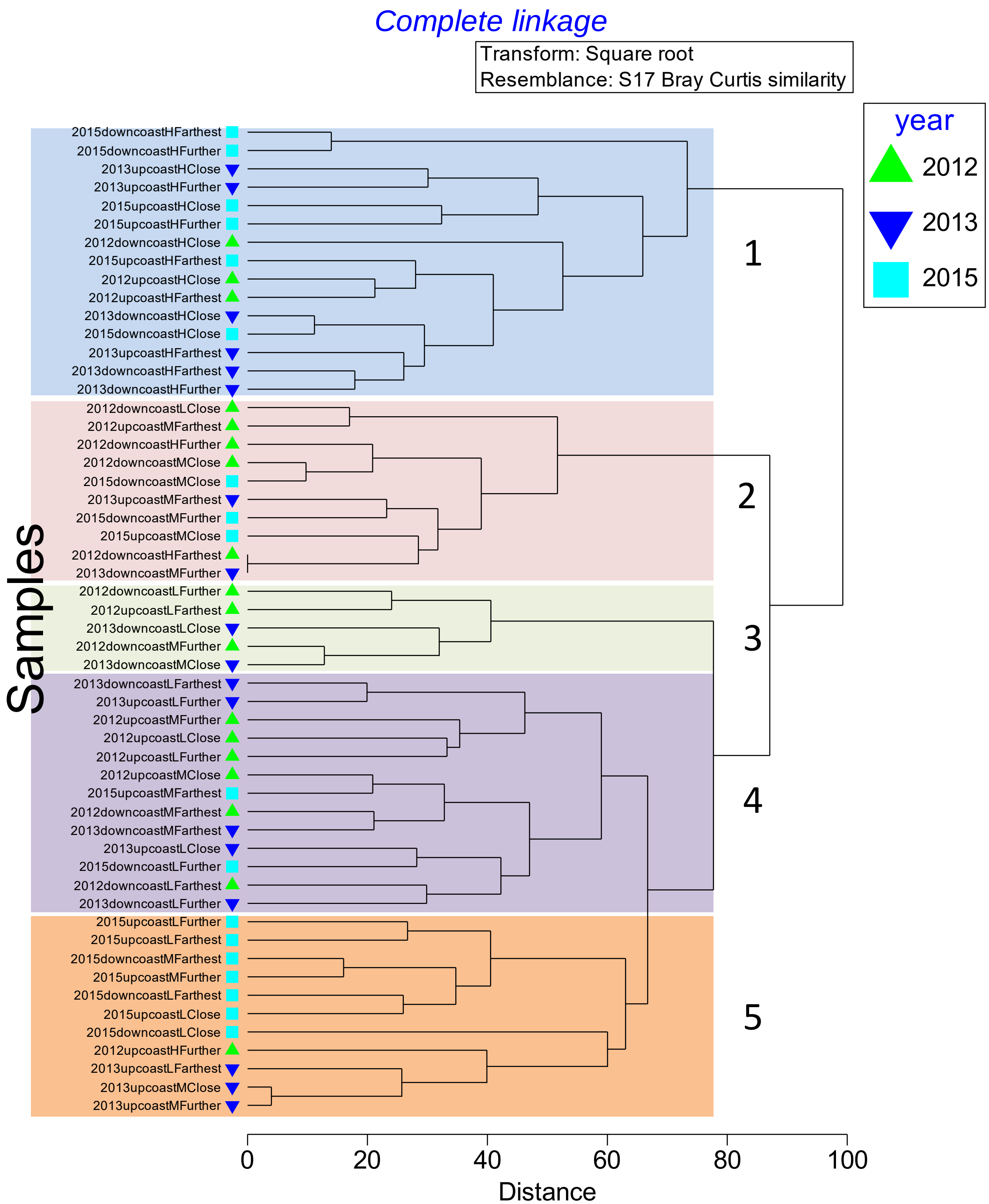


Figure 9. Results for cluster analysis for intertidal mobile species highlighting Year. Shown are distinct clusters (1-5) along with symbolic key for Year.

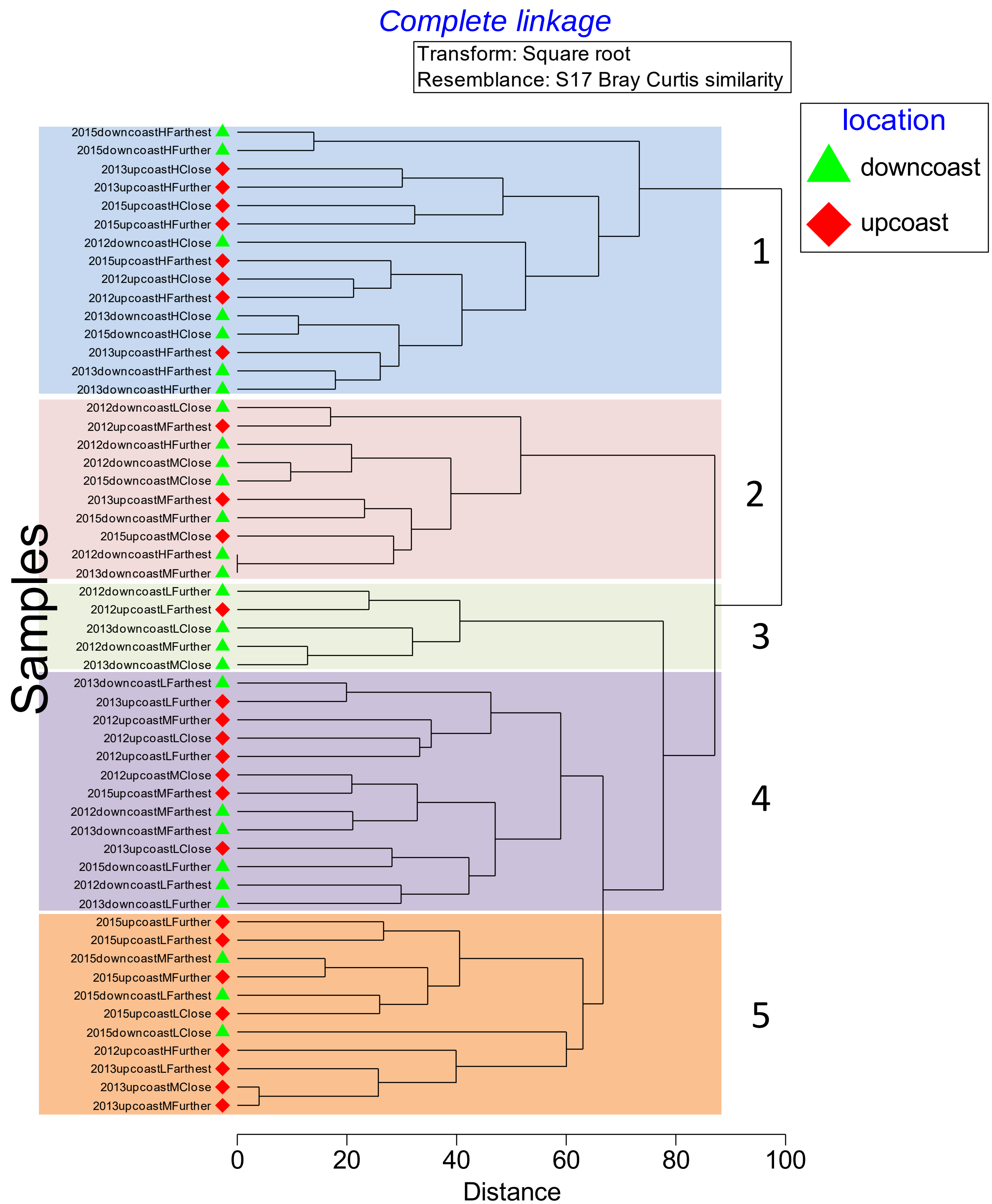


Figure 10. Results for cluster analysis for intertidal mobile species highlighting Location. Shown are distinct clusters (1-5) along with symbolic key for Location.

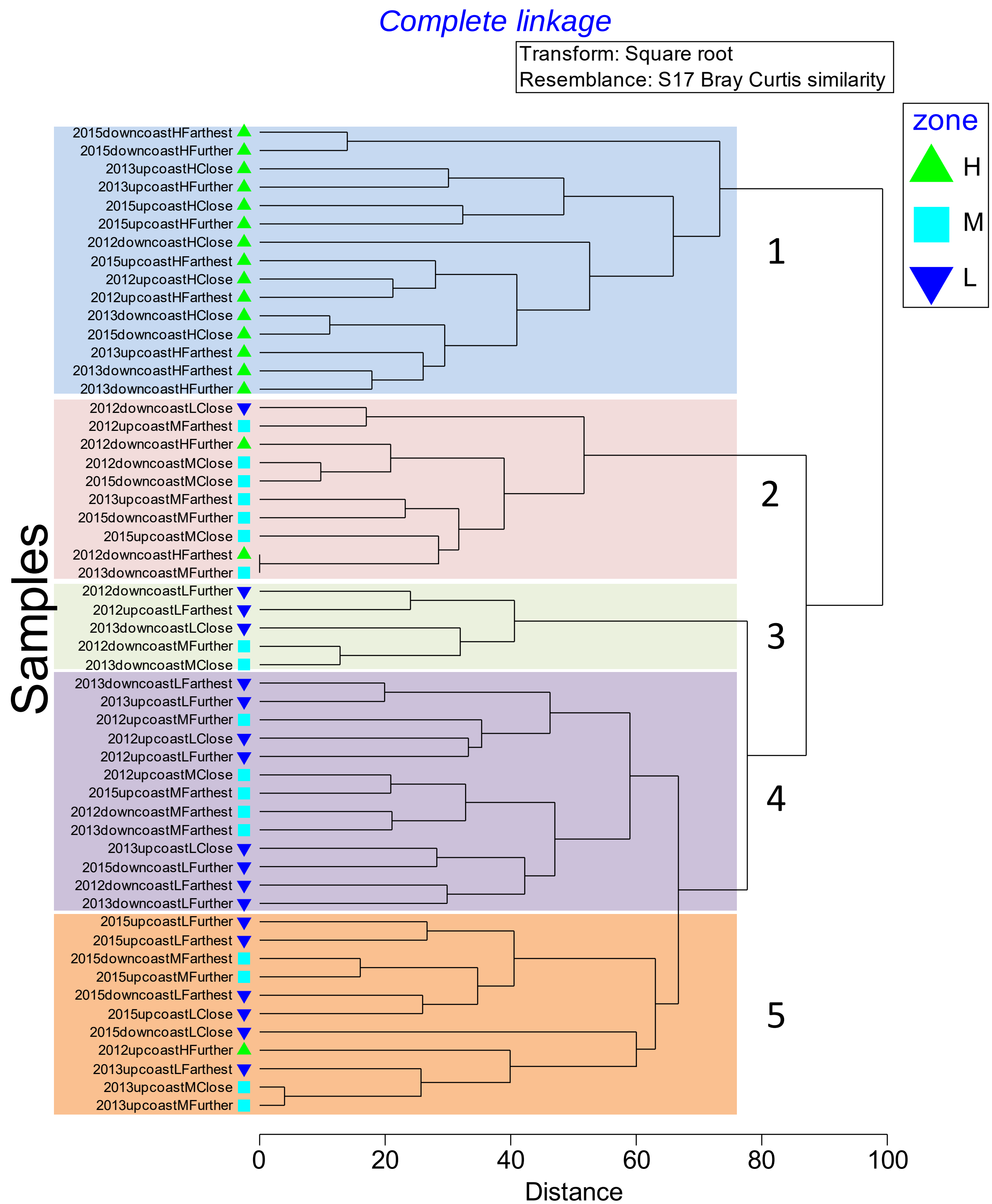


Figure 11. Results for cluster analysis for intertidal mobile species highlighting Zone. Shown are distinct clusters (1-5) along with symbolic key for Zone.

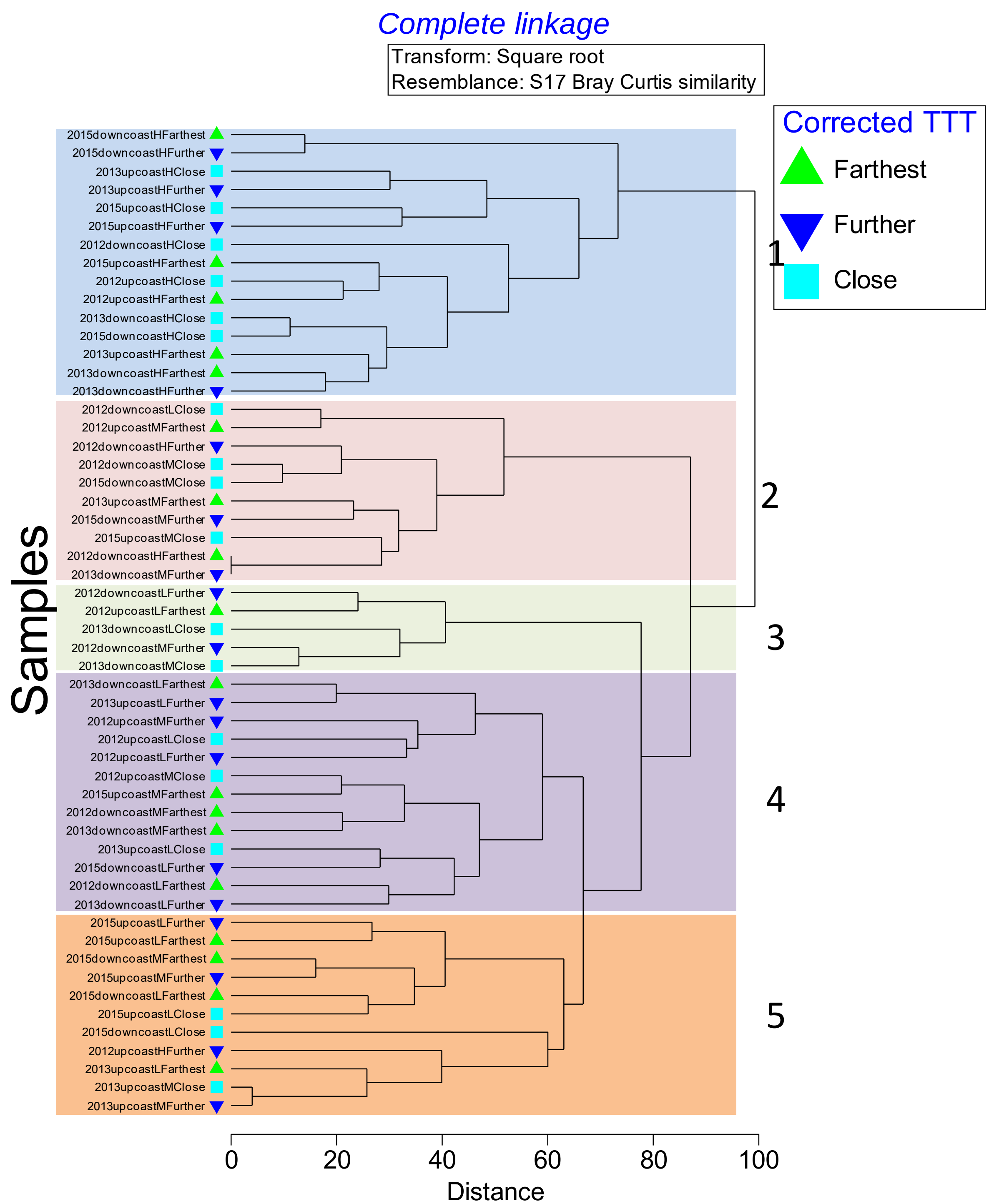


Figure 12. Results for cluster analysis for intertidal mobile species highlighting Corrected Treatment. Shown are distinct clusters (1-5) along with symbolic key for Corrected TTT (not including IN).

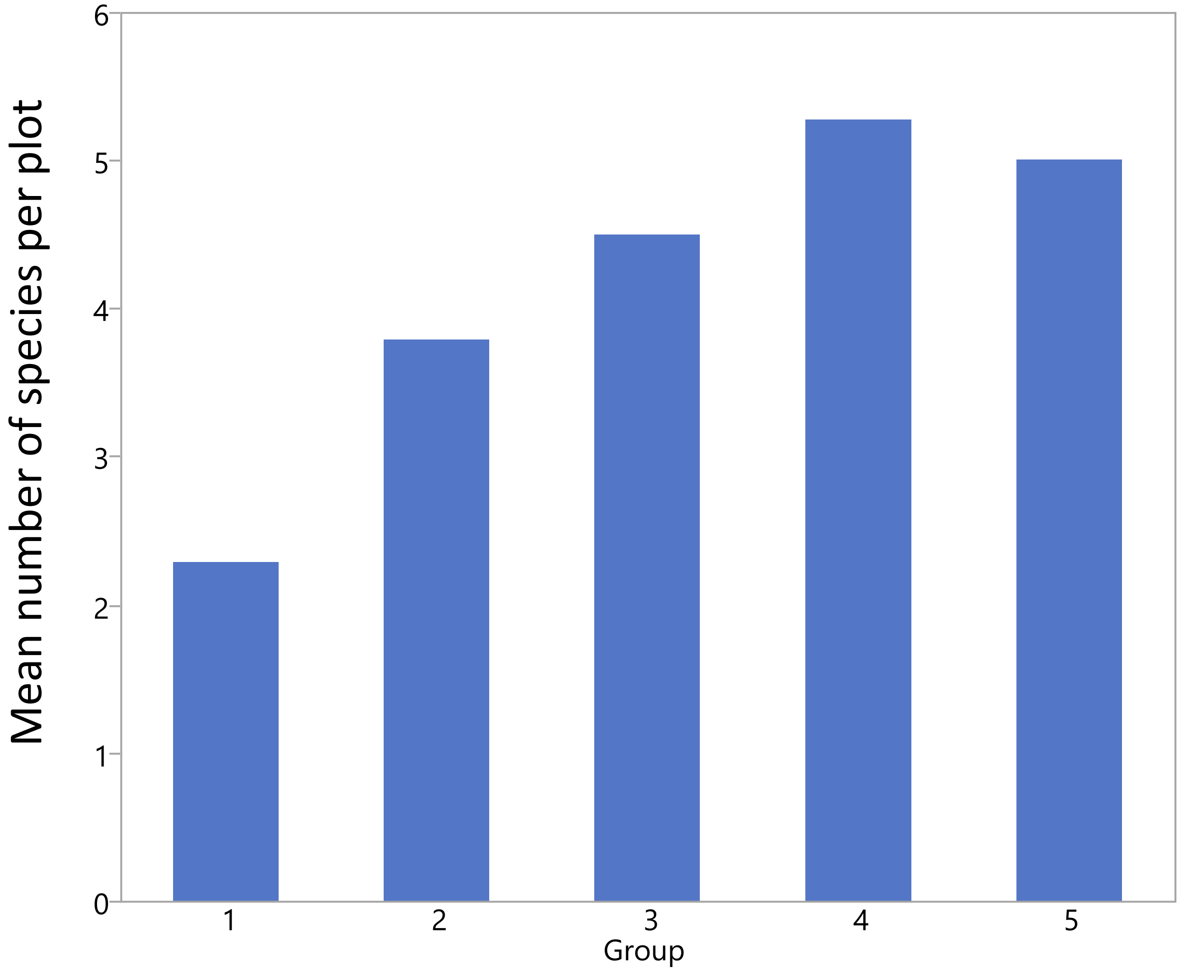


Figure 13. Species richness (intertidal mobile species) for individual groups.

II. Assessment of effects by the ACSA on subtidal kelp forest species and community composition

General Questions

1. Does the relative abundance of substrata (rock versus sand) and vertical relief in the shallow subtidal differ between the site seaward of the ACSA and sites to the north and south of the slide?
2. Do species abundances of macroalgae and invertebrates on the shallow subtidal rocky reef just seaward of the ACSA differ from sites to the north and south?
3. Does species composition (identity and relative abundances) of macroalgae and invertebrate assemblages on the shallow subtidal rocky reef seaward of the ACSA differ from sites to the north and south?
4. Do these patterns (1, 2 and 3) vary among depth zones or change over time?
5. Are the differences consistent with what might be associated with changes in the physical environment associated with the ACSA (e.g., sediment burial, scouring, turbidity)?
6. Does the relationship between giant kelp (*Macrocystis pyrifera*) biomass (derived from Landsat imagery) and distance from the ACSA differ before and after the slide event?

Background

Sediment and sediment-derived turbidity generated by the Alder Creek landslide may impact both geological and biological components of the nearshore subtidal ecosystem. Rock and sediment may have either been delivered to the subtidal environment adjacent to the slide at the time of the slide, or will eventually be washed into the adjacent subtidal environment by subsequent winter storm events. This influx of rock and sediment could alter the geologic nature of the area of impact by altering the relative abundance of exposed hard rocky reef and finer sediment or by changing the grain size of the natural sediment habitat. Such changes in the natural substratum could lead to decreases in algae or sessile (non-mobile) invertebrates. This study was designed to evaluate any such impacts on, and possible rates of recovery of, four components of the subtidal ecosystem directly seaward of the slide: (i) the relative abundance and distribution of exposed rocky reef versus sediment substratum (i.e. extent of reef burial), (ii) the density or percent cover of benthic macroalgae and sessile invertebrates, (iii) the species composition and relative abundance of macroalgae and invertebrate species that constitute the kelp forest community, and (iv) the abundance (biomass) of the giant kelp *Macrocystis pyrifera*.

The Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO) developed comprehensive subtidal monitoring methods to survey kelp forests with trained science divers, and since 1999 these methods have been used to monitor long-term, large-scale changes in kelp forests throughout California. In addition, these same sampling methods were employed in a previous biological sensitivity assessment for shallow subtidal rocky reef habitats along the Big Sur Coast as part of the Coast Highway Management Plan (CHMP; Carr et al. 2006).

Sampling Methods: Design and Protocols

In the absence of quantitative estimates of the relative cover of substrate types (exposed hard rocky reef versus sediment) or species abundances prior to the slide event, it is not possible to determine if this particular slide had any impact on the relative cover of these substrata or species within the ACSA. However, we can characterize the relative abundance of these substrate types and species abundances at the subtidal site directly seaward of the ACSA and sites to the north and south by collecting data soon after the slide occurred and for three consecutive years (2012-2014) to determine how these sites may differ, how these differences change over time, and whether these changes indicate recovery from potential slide impacts. There are multiple scenarios that could explain observed patterns. In the simplest case, all sites are similar to each other and stable over time, which suggests the slide had little impact beyond the actual footprint in the intertidal, and no detectable impact in the subtidal. Or there could be persistent differences among sites, but these do not change over time, which suggests different but pre-existing conditions remain stable and the slide had little or no impact in the subtidal. A third possibility is that there are differences among sites and also change over time but, notably, changes are variable among sites. If the effects of burial, scour and/or turbidity can explain this differential pattern of change, then this suggests the slide did indeed have an impact.

For example, recovery from temporary burial by landslide-derived material could manifest as a consistent trend of increase in the relative cover of exposed rocky reef in excess of what is observed in the adjacent reference sites. The very same analysis applies to the density (number of individuals per unit area) and percent cover of benthic macroalgae and sessile/sedentary invertebrates, where trajectories at the subtidal site seaward of the ACSA and adjacent reference sites are compared to determine if there were differences in annual patterns of variation. The power of these analyses to compare trajectories of these substrate and benthos variables is dependent on the magnitude of the putative impact and the number of years that constitute the time series. These analyses do not assume that these sites are similar, but instead compare their trajectories subsequent to the slide event.

Estimates of cover of the substrate types and the cover and density of the flora and fauna were generated by trained research divers from MBNMS and UC Santa Cruz while sampling benthic transects. To determine any on-offshore extent of slide effects on the substratum and biotic cover, the distribution of survey transects within a study site were stratified from the outer edge of the kelp forests toward shore in four depth zones, with two 30-m long transects per depth zone (Figure 14). In addition to the site at the base of the ACSA, adjacent reference sites were surveyed to the north and south (hereafter referred to as "Alder North" and "Alder South", respectively).

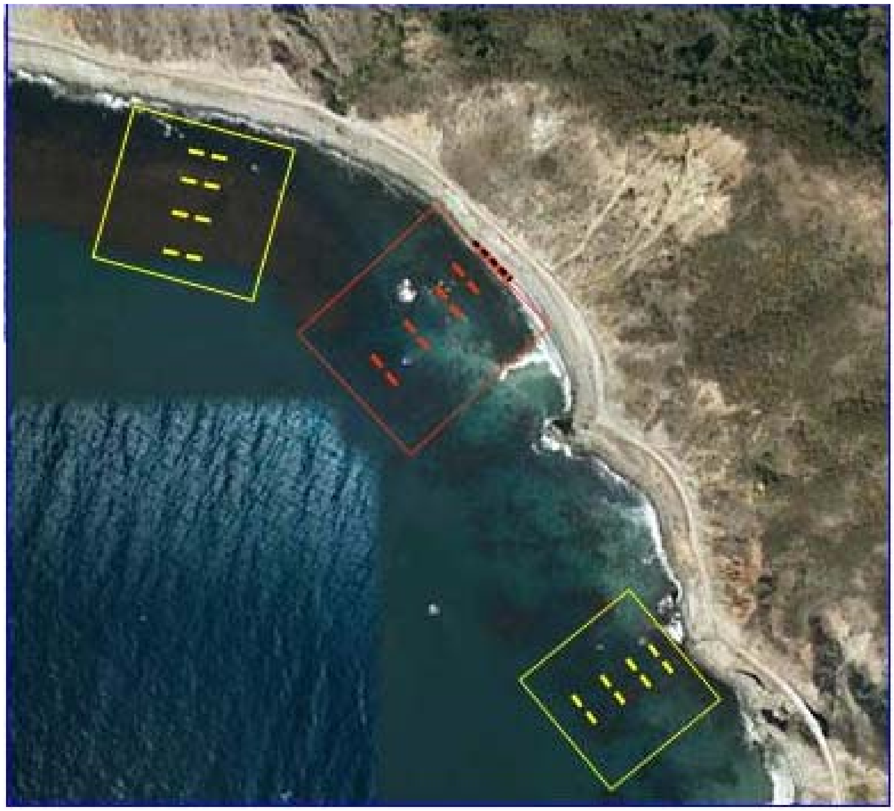


Figure 14. Relative location of replicate benthic transects (dashes) at the Alder Creek slide area (red) and two reference sites (yellow) to the north and south.

Surveys were conducted from NOAA's RV FULMAR, a 20.5 m catamaran operated by the West Coast Region of the Office of National Marine Sanctuaries. This small boat is ideally suited for diving research excursions that require overnight stays along the Big Sur coast. Surveys were conducted in a 2-3 day period during the fall each year: November 13-15, 2012, October 22-24, 2013 and November 18-19, 2014. Divers were deployed to an inflatable and taken to drop sites (based on GPS locations) that were initially determined in 2012.

Within a depth zone, two replicate transects were randomly placed and sampled using two methods: swath sampling and uniform point contact (UPC) sampling. The purpose of the swath sampling is to estimate the density of conspicuous, solitary and mobile invertebrates as well as specific macroalgae. A targeted list of invertebrates and algal species were counted along the entire 30 m x 2 m band transect. A swath diver slowly swims one direction counting invertebrates (see Table 1 for list of species) and then covers the same area counting macroalgae. For the invertebrates, cracks and crevices were searched and understory algae are pushed aside. When counting algae, only *Macrocystis pyrifera* taller than 1 m were recorded. The number of stipes at 1 m above the substrate on each *Macrocystis* were recorded. *Nereocystis luetkeana*, *Pterygophora californica*, *Laminaria setchellii*, *Pleurophycus gardneri*, and *Eisenia arborea* were counted when stipes were taller than 30 cm. Only *Cystoseira osmundacea* greater than 6 cm in diameter were recorded. All individual *Costaria* and *Alaria* were counted regardless of size. No organisms were removed. Any organism with more than half of its body outside the swath was not counted. Transects were divided into three, 10-m long segments to allow sub-sampling of the more numerous species. When sub-sampling, once 30 individuals of a targeted species had been reached, the diver noted the distance covered and would stop counting that particular species for the rest of the 10 m segment. This produces estimates of species density for highly abundant species that would otherwise add significant bottom time.

The second method, UPC, involves a second diver collecting three types of information beneath 30 points at meter intervals along the transect: substrate type, physical relief, and percent cover of space occupying organisms. Substrate type was recorded as one of four categories: sand, cobble (≥10 cm diameter), boulder (10 cm – 1 m diameter) or bedrock (≥1 m diameter). Physical relief was measured by the greatest vertical relief that exists within a rectangle centered on the UPC point and extending perpendicularly 0.5 m to either side and along the tape in either direction 0.25 m, creating a 1 x 0.5 m rectangle. The percent cover of space occupying organisms was estimated by recording what was directly under each point every 1 m along the 30 m transect tape. Trained divers recorded what organism was under each point, although in many cases these were broad taxonomic categories (e.g., sponge, bryozoan, tunicate, branching red alga). The purpose was to capture a two-dimensional, "photo style" representation of the percent cover of organisms that were directly attached to the primary substrate. Therefore, epibionts and mobile organisms were not included. Algae whose blades were under the point but were attached somewhere else on the primary substrate were included with one exception: for blades of all Laminariales, the blade was moved and the organism under it was recorded.

Because of the relatively limited sample size of this study (two transects in each of four depth zones at each site) and the random location of transects from year to year, the data generated by this study contains moderate levels of variability (noise) relative to potential patterns arising from ACSA impacts (signal). This is typical of PISCO's subtidal monitoring surveys in the Big Sur region where we commonly see levels of background inter-annual variability at a given site in the range of 10-15%. We have therefore made an effort to interpret our results conservatively in this regard.

Examples of datasheets, which include the taxa and categories recorded on swath and UPC transects, are in **Appendix 2**.

Do the abundances of substrata (rock versus sand), vertical relief, macroalgae and invertebrates differ between the subtidal site seaward of the ACSA and sites to the north and south of the ACSA?

Do these patterns vary among depth zones and change over time?

Mean percent cover of each substratum type, relief category, select macroalgae (foliose reds and coralline algae) and sessile invertebrate taxonomic groups were generated from the UPC surveys. Mean densities (number of organisms per unit area of reef) of macroalgae and sessile and mobile invertebrates were generated on the swath transect surveys. We used a three-factor analysis of variance (ANOVA) to test for differences in these mean abundances between Sites (north, slide, south), Zones (4 depths) and Years (2012-14) for all eight substratum categories and every species or taxonomic group that was recorded in sufficient numbers to conduct the analysis (total = 76). Interaction terms (e.g., site by year, site by zone by year) in these analyses determine whether changes in abundance among sites or depth zones differ by year (i.e. sites and zones exhibit different temporal trajectories). For each taxonomic or substrate characteristic tested, model selection was carried out using backward stepwise removal whereby non-significant terms were removed. The results presented for each model, therefore, are the terms remaining in each model following model selection and missing values can be assumed to be non-significant. Interpretations of these analyses are based on the explicit assumption of the relative exposure of the three sites to intertidal sediment influx from the ACSA. Because of the prevailing current to the south (see images of plume in Appendix 1), it is assumed that immediate and continued changes caused by the slide would be strongest at the "Slide" site, intermediate at the "South" site, and least at the "North" site. In addition, it is assumed that the changes would be greater in the shallower depth zones than the deeper zones. Given these assumptions, significant ($P < 0.05$) effects of the terms in the analysis can be interpreted as follows:

Site: A significant Site effect (and no significant interaction with Zone or Year) could be attributable to a slide impact under two scenarios. First, the Slide site exhibited reduced cover of hard substrate types (e.g., rock, moderate relief) and rock-associated organisms because they were negatively influenced by changes in the environment caused by the slide (i.e. sedimentation, turbidity, scouring). Second, the Slide site exhibited increased densities of species positively influenced by these changes (e.g., sediment, low relief, sand-associated organisms) relative to the South and North sites. But this assumes these differences did not exist before the event, occurred prior to onset of sampling, and persisted over the three year study.

Zone: A significant Zone effect (and no significant interaction with Site or Year) is unlikely attributable to a slide impact because changes in the shallower depths relative to the deeper depths would have occurred across all three sites prior to and throughout the sampling period. It is difficult to envision a mechanism by which the slide impact would vary with depth equally across all three sites. A significant Zone effect with no Site or Year effect is also contrary to the assumption that the North and South reference sites were not affected by the slide.

Year: A significant Year effect (and no significant interaction with Site or Zone) is unlikely attributable to a slide impact because changes over time would have occurred similarly across all three sites throughout the sampling period. This is contrary to the assumption that the North and South sites were not altered (or altered less) by the slide than the Slide site.

Site by Zone: Significance in this term could be attributable to a slide impact if the Slide site exhibited differences among depth zones that were not detected in the other sites and that were consistent with predicted changes in substrates (e.g., increase in sediment in shallower depths) and species (e.g., reduction of rock-associated species in shallower depths). It assumes that these differences did not exist prior to the event and occurred prior to and persisted over the sampling period.

Site by Year: Significance in this term could be attributable to a slide impact if the Slide site exhibited changes over time in substrate types (e.g., increase or decrease in sediment over time) or species (e.g., increase or decrease of rock-associated species over time) that were not detected at the other sites. A decrease or increase relative to the reference sites could reflect a cumulative impact or recovery, respectively, at the Slide site.

Zone by Year: Significance in this term is unlikely attributable to a slide impact because changes among zones over time would have occurred similarly across all three sites throughout the sampling period. This is contrary to the assumption that the North and South sites were not altered (or altered less) by the slide than the Slide site.

Site by Zone by Year: Significance in this term could be attributable to a slide impact if the Slide site exhibited changes among zones (e.g., a decrease or increase of hard substrate or rock-associated species in time) at the Slide site that were not detected at the other sites. A decrease or increase relative to the reference sites could reflect a cumulative impact or recovery, respectively, at the Slide site.

Does the species composition (identity and relative abundances) of macroalgae and invertebrate assemblages on the shallow subtidal rocky reef seaward of the landslide differ from sites to the north and south?

Do these patterns vary among depth zones or change over time?

The individual taxa analyzed above collectively constitute assemblages of species (or taxonomic groups), each of which constitute the community of algae and invertebrates that inhabit shallow rocky reefs. To determine whether the composition of the subtidal rocky reef assemblages and the composition of substrata differed between Sites, Zones, and Years, we separately compared the composition of the substrata and six particular assemblages of the community: (i) the large macroalgae and invertebrates recorded on swath surveys, (ii) the six species of the stipitate kelps recorded on swath surveys, (iii) the 38 species of mobile invertebrates recorded on swath surveys, (iv) the sessile invertebrates and understory algae combined on UPC surveys, (v) the twelve categories of understory algae recorded on the UPC surveys, and (vi) the 14 categories of sessile invertebrates recorded on the UPC surveys. A permutational multivariate analysis of variance (PERMANOVA) in the statistical package Primer was used to test for differences in the taxonomic composition (identity and relative abundance) between Sites, Zones, and Years and, like the analyses described above, interaction terms were tested to determine whether any differences in the relative abundance of taxa among Sites or Zones changed differently over time (i.e. Sites and Zones exhibit different temporal trajectories). An additional contrast specifically compared the Slide site to the North and South sites, and the interaction between this contrast and Year is tested as well. To visually depict the relative similarity of the assemblages recorded, we used a multidimensional scaling plot. These graphs plot each transect sampled at each site in each Zone and Year as a separate point. The closer points are to one another, the more similar the transects are in terms of assemblage composition.

Does giant kelp (Macrocystis pyrifera) biomass (derived from Landsat imagery) differ before and after the slide event, and how does that pattern differ between the likely impact and control sites?

Our approach to determining whether deposition of material in the intertidal influenced the abundance of giant kelp on seaward subtidal rocky reefs was to compare change in the abundance of giant kelp biomass before and after the slide deposition event at the sites more likely to have been most influenced by the slide versus a site less likely to have been influenced. We first reviewed all of the Google Earth images taken annually at the study region and extracted those that provided visually discernable images of the giant kelp canopy and sediment plume (Appendix 1). These images provide episodic instantaneous visual qualitative assessments (i.e. occasional "snapshots") of change in the distribution and abundance of the kelp canopy and the sediment plume. These images were not used in analyses, but inform the analytical design and interpretation of the more formal analyses described below. Examination of patterns of plume distributions depicted in these images (contrast Appendix 1, A through E), indicate two very important patterns of the sediment plume. First, there is a preexisting and persistent plume of sediment toward the southern portion of the Slide site that extends into the kelp forest to the South site. Secondly, the sediment plume in ACSA is much greater in images taken in September 2011 (D) and April 2015 (E), indicating that the area in the southern portion and to the south of the ACSA is much more likely to have been influenced by the sediment plume associated with the slide event added to the preexisting plume. In contrast, in these aerial images the upcoast kelp forests at the North site are apparently less influenced by the slide event due to clearer water. Therefore, our analysis explicitly compares change in kelp canopy biomass both before and after the slide event, to the north and south of the center of the slide site, and we examine these patterns both near (within 1 km), and further (within 5 km) from the ACSA.

Surface canopy biomass estimated by Landsat satellite imagery was used as the metric of kelp abundance (Cavanaugh et al. 2011, Reed et al. 2011, Raimondi et al. 2015). These images are comprised of 30 m^2 "pixels" and geometrically corrected with ground control points and for atmospheric effects. The percent of each pixel's spectral reflectance signal that was influenced by giant kelp is calculated, and these kelp fractions are transformed into canopy biomass using a relationship generated from comparisons to co-located diver collected measurements of canopy biomass. Estimates of the biomass of giant kelp canopy per pixel are standardized among years by using images collected within a three-month window (June, July and August) when peak canopy cover occurs along the Big Sur coast. We estimated the annual (June, July and August) canopy biomass per pixel within 1 km, 2.5 km and 5 km distances to the south and north of the center point of the ACSA. Estimates for each of these areas included all pixels that included canopy at any time within the period from 2005 to 2014. We calculated the mean kelp biomass of each pixel over seven years before (n=7: 2004-2010) and four years after (n=4: 2011-2014) the slide event and compared the mean biomass per pixel within each area to the north versus south (direction effect), before and after the slide event (time effect), and how any differences between north and south areas changed before and after the event (direction-by-time interaction) with a two-factor analysis of variance (ANOVA). We did this separately for the three distances: 1 km, 2.5 km and 5 km to determine how the magnitude of change varied with increasing distance and area from the ACSA.

In addition, to characterize the historic trends in kelp canopy biomass and how that trend changed before and after the slide event, we plotted the mean canopy biomass per pixel to the north and south within a 1 km radius of the center of the ACSA.

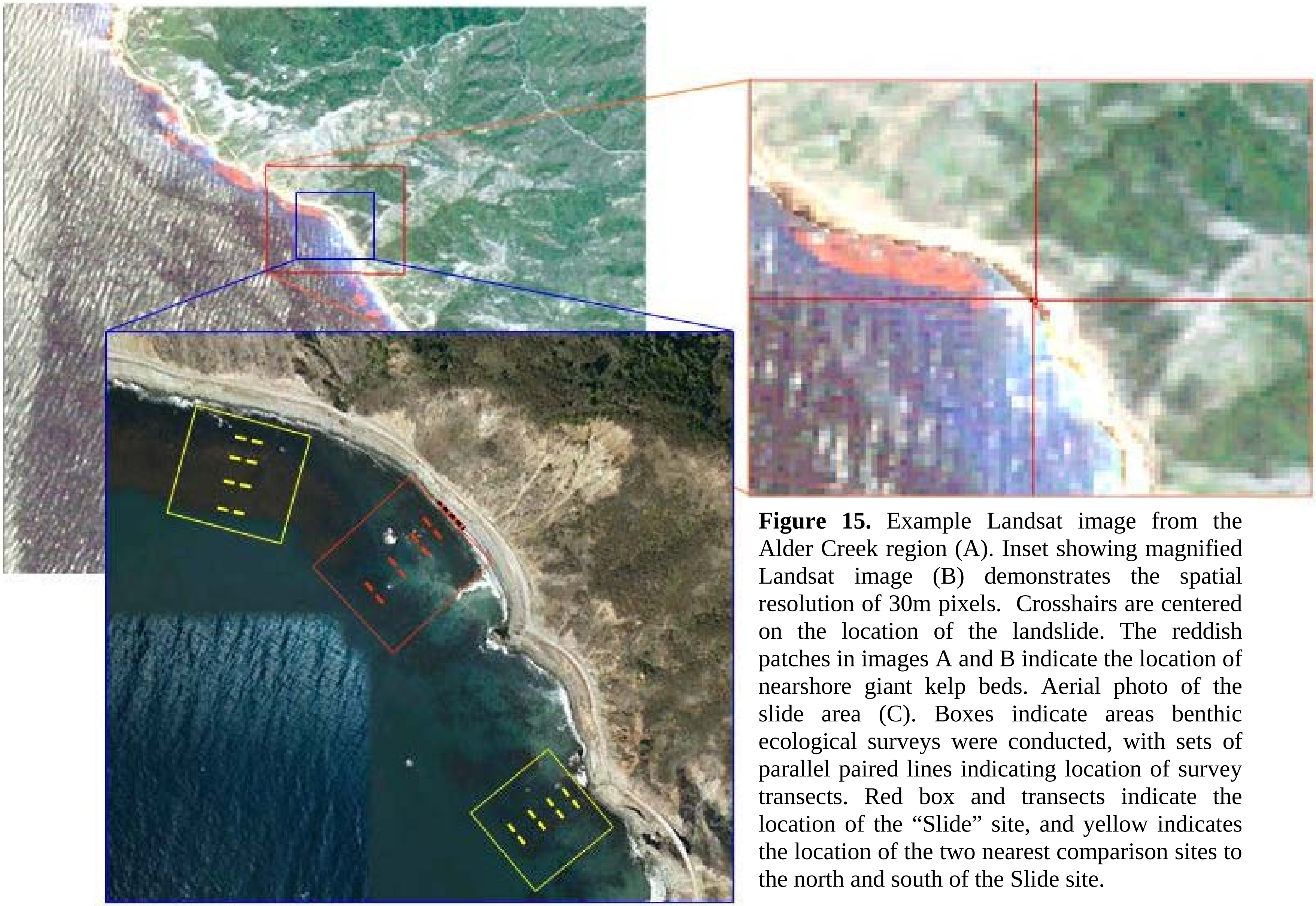


Figure 15. Example Landsat image from the Alder Creek region (A). Inset showing magnified Landsat image (B) demonstrates the spatial resolution of 30m pixels. Crosshairs are centered on the location of the landslide. The reddish patches in images A and B indicate the location of nearshore giant kelp beds. Aerial photo of the slide area (C). Boxes indicate areas benthic ecological surveys were conducted, with sets of parallel paired lines indicating location of survey transects. Red box and transects indicate the location of the "Slide" site, and yellow indicates the location of the two nearest comparison sites to the north and south of the Slide site.

Results

Do the abundances of substrata (rock versus sand), vertical relief, macroalgae and invertebrates differ between the subtidal site seaward of the slide and sites to the north and south of the slide? Do these patterns vary among depth zones or change over time?

Of the eight substrate type and vertical relief variables examined, the only significant terms detected were a site-by-zone interaction for high (>2m) relief and a site-by-zone-by-year interaction for cobble substrate (Table 3). The site-by-zone interaction for high relief is unlikely attributable to a slide effect because such high relief is unlikely to be influenced by sediment deposition (i.e., amount of material required to bury >2m relief would be greater than observed in this event). The site-by-zone-by-year interaction for cobble substrate largely reflects increases in cobble cover in the mid-depth zones over time at the North site and these are unlikely attributable to the slide, assuming the North was not influenced by the slide (i.e. a proper reference site)(Figure 28). The effect also reflects an increase in cobble in the inner zone at the Slide site, which could reflect more deposition material from the intertidal if the material came from there, or a removal (i.e. recovery) of sediment, exposing the natural cobble substrate at that site (Figure 28). Addition of new cobble derived from the slide is unlikely since divers did not observe new cobble *in situ*, which is visually different from pre-existing cobble: old cobble is smoothed and rounded whereas new cobble is sharp-edged and angular (S. Lonhart, personal observation).

Of the 76 species and taxonomic groups examined, 58 significant terms were detected, of which 46 were considered not attributable to the slide (i.e., did not show Site, Year or Zone effects compatible with those described above). Of the twelve remaining species or groups that could be attributable to slide effects, two were macroalgae and five were large invertebrates recorded on swath surveys. Significant terms were also detected for two additional understory algae, two sessile invertebrates, and the percent cover of bare rock on the UPC surveys.

- A site-by-zone-by-year effect was detected for the cover of the barnacle, *Balanus nubilus* (Table 3), reflecting an increase in barnacle cover in the outer-mid zone of the Slide site over time (Figure 16). It is unclear why this increase would have been restricted to that single zone. For example, deposition of new substrate that could be colonized by barnacles would also be expected to have increased in the inner and inner-mid zones, and therefore those terms should show a similar pattern to the outer-mid zone, but they did not.
- A site-by-zone-by-year effect was detected for the macroalga *Cystoseira osmundacea* (Table 3), reflecting an increase in density of this species in the inner zone at the North site relative to the other two sites (Figure 17). As a relatively shade tolerant species, commonly found under kelp forest canopies, it is possible that the temporary reduction of kelp canopy cover at the North site, and in particular in shallow waters where kelp is already reduced, allowed for differential recruitment and/or growth of *Cystoseira* relative to the Slide and South sites, which were consistently more turbid and less hospitable to *Cystoseira* recruitment and growth.
- A site effect was detected for the giant kelp, *Macrocystis pyrifera* (Table 3), reflecting their greater density at the North site as compared to both the Slide and South sites, which were not different from each other (Figure 18).

- A site-by-year effect was detected for the red abalone *Haliotis rufescens* (Table 3), reflecting an increase in 2014 in the inner-mid and outer-mid depth zones of the North site and absence at the Slide and South sites (Figure 19).
- A site effect and year effect was detected for the sunflower star *Pycnopodia helianthoides* (Table 3), reflecting lower density at the Slide site than both the North and South sites and an overall decrease in density at all three sites over time (Figure 20). This species was devastated by sea star wasting syndrome, which caused a range-wide reduction during the mass mortality event of 2013-14.
- A site-by-zone-by-year effect was detected for the anemone *Urticina coriacea* (Table 3), reflecting an increase in the inner and inner-mid zones of the North site relative to the other sites (Figure 21). This species is particularly patchy in shallow waters.
- A site-by-year effect was detected for the anemone *Urticina piscivora* (Table 3), reflecting a greater increase in density at the North site relative to a delayed increase at the Slide site and absence at the South site (Figure 22). This pattern is difficult to interpret (other than typical sampling variation), but unlikely attributable to a slide effect.
- A site-by-year effect was detected for bare rock (Table 3, Figure 23), reflecting an increase in cover in 2014 at 3 of 4 zones of the North site (no change at the outer zone) and no discernable changes among all depth zones at the Slide and South sites. An increase in bare rock at the North site is unlikely attributable to a slide effect.
- A site-by-year effect was detected for branching red algae (Table 3), reflecting a greater decline in cover of this algal category at the Slide site relative to the North and South sites (Figure 24).
- A site-by-year effect was detected for the infaunal ornate tube-worm *Diopatra ornata* (Table 3), reflecting an increase in cover of this species in the outer depth zones at the North site (Figure 25). There was also an increase in cover of this species at the Slide site.
- A site-by-zone effect was detected for erect coralline algae (Table 3), reflecting the greater cover of this group at the two inner depth zones of the North site (Figure 26).
- A site-by-year effect was detected for the reef-building worm *Phragmatopoma californica* (Table 3), reflecting a marked increase in cover of this sand-associated species at both the Slide and South sites but not at the North site (Figure 27). However, this species was relatively abundant at the South site at the onset of surveys in 2012.

Table 3. Summary of ANOVA tables for individual taxa and substrate characteristics. These categories are grouped according to survey method: density from swath transects or UPC percent cover. P-values for terms selected in the final model using backward model selection are presented. For the relevant terms in each model (highest order interactions or single effects found to be significant – red text) P-values are highlighted in orange if the pattern they represent was consistent with effects attributable to impacts of the slide. Values highlighted in blue represent patterns that are not attributable to potential slide effects.

Category	site	zone	site*zone	year	site*year	zone*year	site*zone*year
Swath categories							
Alaria marginata	0.0877	0.0727	0.0497	0.1089	0.0878	0.0728	0.0498
Anthopleura sola	.	.	.	0.2051	<.0001	.	.
Anthopleura xanthogrammica	0.1224	0.0943	0.0424	0.0695	0.1225	0.0944	0.0425
Balanus nubilus	0.1919	0.0298	0.0079	0.0687	0.1916	0.0297	0.0079[1]
Ceratostoma foliatum	.	.	.	0.0495	.	.	.
Crassadoma gigantea	.	.	.	.	.	.	.
Cryptochiton stelleri	.	.	.	.	.	.	.
Cucumaria miniata	.	.	.	0.011	.	.	.
Cystoseira osmundacea	.	.	.	0.1143	0.0614	0.0038	0.0385[2]
Dermasterias imbricata	.	.	.	0.5175	0.0003	0.645	0.0007
Haliotis kamtschatkana	1	0.0346	0.0197	1	1	0.0346	0.0197
Haliotis rufescens	0.0136	.	.	0.0332	0.0135[3]	.	.
Henricia leviuscula	.	.	.	.	.	.	.
Kelletia kelletii	.	.	.	.	.	.	.
Laminaria setchellii	.	.	.	0.8044	.	<.0001	.
Leptasterias hexactis	0.2624	0.168	0.0309	0.0306	0.2621	0.1678	0.0308
Loxorhynchus grandis	0.2619	0.1676	0.0307	0.0306	0.2621	0.1678	0.0308
***Loxorhynchus/Scyra* spp.**	.	.	.	.	.	.	.
***Macrocystis pyrifera* (stipes)**	<.0001[4]	.	.	.	.	.	.

[1] Increased more at Slide Outer-Mid - potential recovery, but unlikely
[2] Increased more at North Inner relative to Slide and South
[3] Increased more at North - stayed absent at Slide and South
[4] More at North than at Slide or South.

Category	site	zone	site*zone	year	site*year	zone*year	site*zone*year
Mediaster aequalis	.	.	.	.	.	.	.
Mimulus foliatus	1	0.0346	0.0197	1	1	0.0346	0.0197
Nereocystis luetkeana	.	.	.	.	.	.	.
Orthasterias koehleri	0.0099	.	.	0.0096	0.01	.	.
Patiria miniata	.	0.0438	.	.	.	.	.
Pisaster brevispinus	.	0.0368	.	0.001	.	0.037	.
Pisaster giganteus	.	0.003	.	<.0001	.	0.0031	.
Pisaster ochraceus	0.0001	.	.	0.0011	0.0001	.	.
Pomaulax gibberosus	.	.	.	.	.	.	.
Pterygophora californica	.	0.0004	.	0.0381	.	.	.
Pugettia producta	0.2619	0.1676	0.0307	0.0306	0.2621	0.1678	0.0308
Pycnopodia helianthoides	0.0298[5]	.	.	0.0046	.	.	.
Solaster dawsoni	.	.	.	.	.	.	.
Strongylocentrotus franciscanus	.	.	.	.	.	.	.
Strongylocentrotus purpuratus	.	.	.	0.0163	.	.	.
Stylaster californicus	0.0879	0.0729	0.0499	0.1089	0.0878	0.0728	0.0498
Styela montereyensis	0.0038	0.0151	.	.	.	.	.
Urticina lofotensis	0.0719	0.1295	0.045	.	.	.	.
Tethya californiana	.	.	.	.	.	.	.
Urticina columbiana	.	.	.	.	.	.	.
Urticina coriacea	0.0002	0.0089	0.0038	0.001	0.0002	0.0089	0.0038[6]
Urticina crassicornis	.	.	.	.	.	.	.
Urticina piscivora	.	.	.	0.2478	0.0116[7]	0.0258	.
***Urticina* spp.**	0.0059	0.2971	0.013	0.0122	0.0059	0.2976	0.013
UPC categories							

[5] Abundance at Slide is lower than North or South, but all three sites declining indicative of coast-wide seastar wasting event.
[6] Increasing at North Inner & Inner-Mid. Stays absent at Slide and South.
[7] Increasing at North relative to South. Slide is intermediate.

Category	site	zone	site*zone	year	site*year	zone*year	site*zone*year
Anemone	.	.	.	.	.	.	.
Barnacle	.	.	.	.	.	.	.
Bare Rock	0.0069	.	.	0.01	0.0069[8]	.	.
Bare Sand	.	.	.	.	.	.	.
Branching red algae	.	.	.	0.0676	0.0099[9]	0.0047	.
Bryozoan	.	.	.	.	.	.	.
Bushy red algae	.	.	.	0.0352	.	.	.
Compound tunicate	.	.	.	.	.	.	.
Corynactis californica	.	.	.	.	.	.	.
Crustose coralline	.	.	.	<.0001	0.0006	0.4721	0.0379
Cup coral	.	.	.	0.2215	0.0003	0.0009	0.0111
Cystoseira osmundacea	.	.	.	0.4365	.	0.02	.
Dead holdfast	0.0485	.	.	.	.	.	.
Desmarestia spp.	0.0228	.	.	0.0868	0.0229[10]	.	.
Dictyotales	0.0877	0.0727	0.0497	0.1089	0.0878	0.0728	0.0498[11]
Diopatra ornata	.	.	.	0.1112	0.0043[12]	0.0003	.
Dodecaceria spp.	.	.	.	.	.	.	.
Egregia menziesii	.	.	.	.	.	.	.
Encrusting red algae	.	.	.	.	.	.	.
Erect coralline algae	<.0001	0.0314	<.0001[13]	0.1084	.	0.0316	.
Hydroid	.	.	.	.	.	.	.
Lacy red algae	.	.	.	0.0461	.	.	.
Laminariales holdfast	.	.	.	.	.	.	.

[8] Increasing at North relative to Slide and South - possible recovery at least impacted site.
[9] Decreasing at Slide relative to North and South.
[10] Decreasing at South, absent at North and Slide.
[11] Decreasing at North, absent at Slide and South.
[12] Increasing at North relative to Slide and South - possible recovery at least impacted site.
[13] Higher at North Inner and Inner-Mid relative to Slide and South.

Category	site	zone	site*zone	year	site*year	zone*year	site*zone*year
Leafy red algae	0.3842	0.7601	0.0158	0.475	0.384	0.7604	0.0158[14]
Phragmatopoma californica	.	.	.	0.1617	0.031[15]	.	.
Scallop	0.0879	0.0729	0.0499	0.1089	0.0878	0.0728	0.0498[16]
Scum	.	.	.	.	.	.	.
Shell hash	.	.	.	.	.	.	.
Solitary tunicate	0.0001	<.0001	<.0001	<.0001	0.0001	<.0001	<.0001[17]
Sponge	.	.	.	.	.	.	.
Tubemat	0.0879	0.0729	0.0499	0.1089	0.0878	0.0728	0.0498
Tubeworm	.	.	.	0.0295	.	.	.
Red algal turf	.	.	.	0.2279	0.0301	0.0182	0.0061
Substrate relief: flat 0-10cm	.	.	.	.	.	.	.
Substrate relief: slight 10cm-1m	.	.	.	.	.	.	.
Substrate relief: moderate 1-2m	.	.	.	.	.	.	.
Substrate relief: high >2m	0.662	0.358	0.0176	.	.	.	.
Substrate type: bedrock	.	.	.	.	.	.	.
Substrate type: boulder	.	.	.	.	.	.	.
Substrate type: cobble	0.2363	0.0366	0.0132	0.0289	0.236	0.0366	0.0131
Substrate type: sand	.	.	.	.	.	.	.
Totals							
Not attributable	2	3	2	8	4	8	19
Attributable	2	0	1	0	6	0	3
Groups							
Kelps	.	0.0035	.	0.353	.	0.0035	.
Large invertebrates	0.2915	0.309	0.0495	.	.	.	.

[14] Decreasing at North Inner, increasing at South Inner.
[15] Increasing at North relative to South - Slide intermediate
[16] Increasing at South Outer - absent elsewhere.
[17] Decreasing at Inner-Mid of Slide and South, absent at North.

Category	site	zone	site*zone	year	site*year	zone*year	site*zone*year
Non-living (upc)	.	.	.	.	.	.	.
Turf algae (upc)	.	<.0001	.	.	.	.	.
Sessile invertebrates (upc)	.	0.0013	.	.	.	.	.

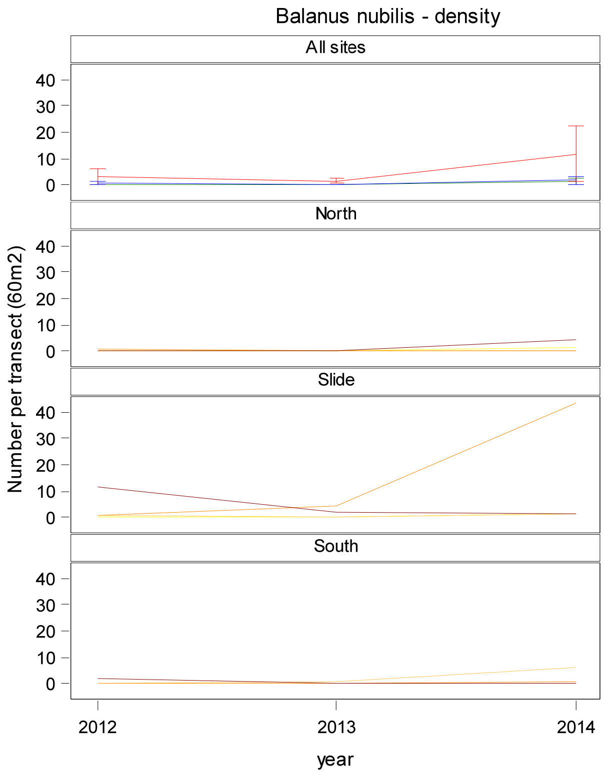
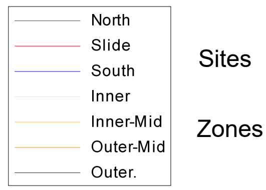


Figure 16. Density of *Balanus nubilis* at the North, Slide, and South sites across years 2012-2014 (error bars depict standard error among depth zones). Graphs below show density at the four depth zones at each of these three sites.



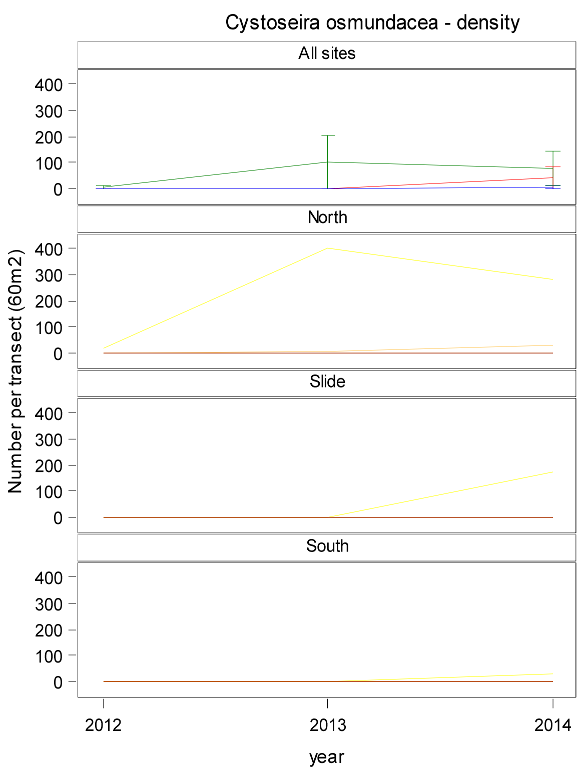


Figure 17. Density of *Cystoseira osmundacea* at the North, Slide, and South sites across years 2012-2014 (error bars depict standard error among depth zones). Graphs below show density at the four depth zones at each of these three sites.

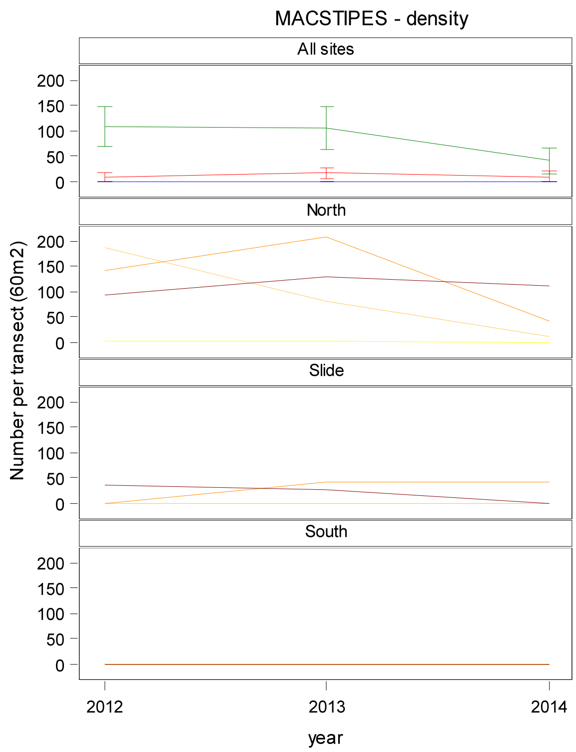


Figure 18. Density of *Macrocystis pyrifera* stipes at the North, Slide, and South sites across years 2012-2014 (error bars depict standard error among depth zones). Graphs below show density at the four depth zones at each of these three sites.

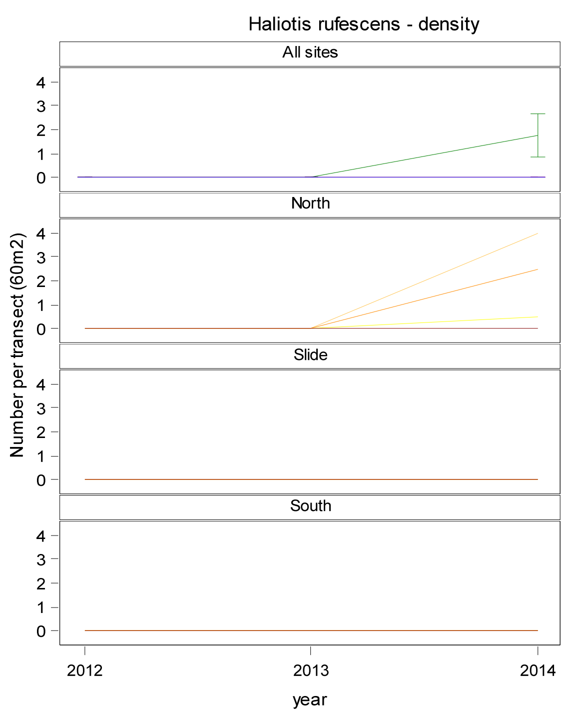


Figure 19. Density of *Haliotis rufescens* at the North, Slide, and South sites across years 2012-2014 (error bars depict standard error among depth zones). Graphs below show density at the four depth zones at each of these three sites.

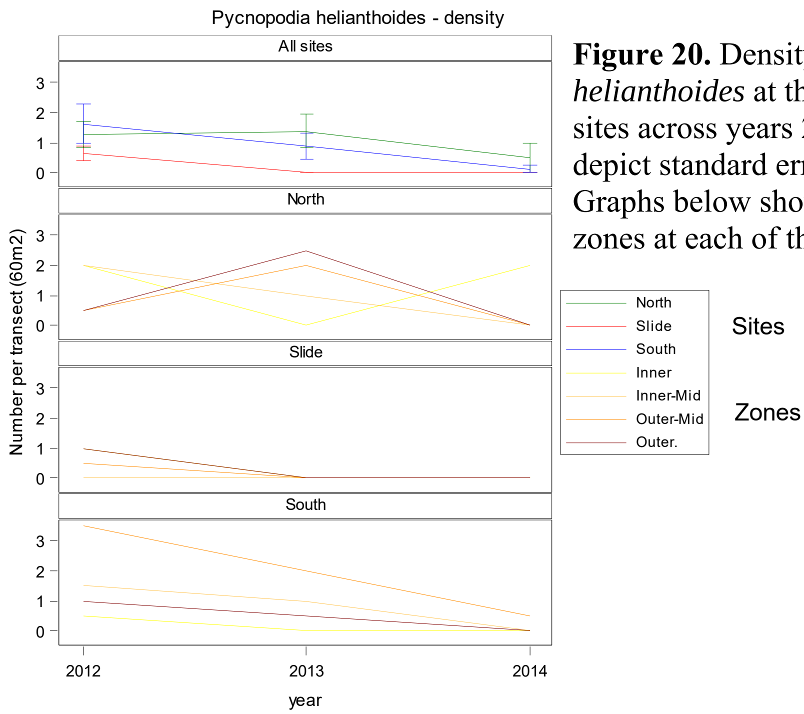


Figure 20. Density of *Pycnopodia helianthoides* at the North, Slide, and South sites across years 2012-2014 (error bars depict standard error among depth zones). Graphs below show density at the four depth zones at each of these three sites.

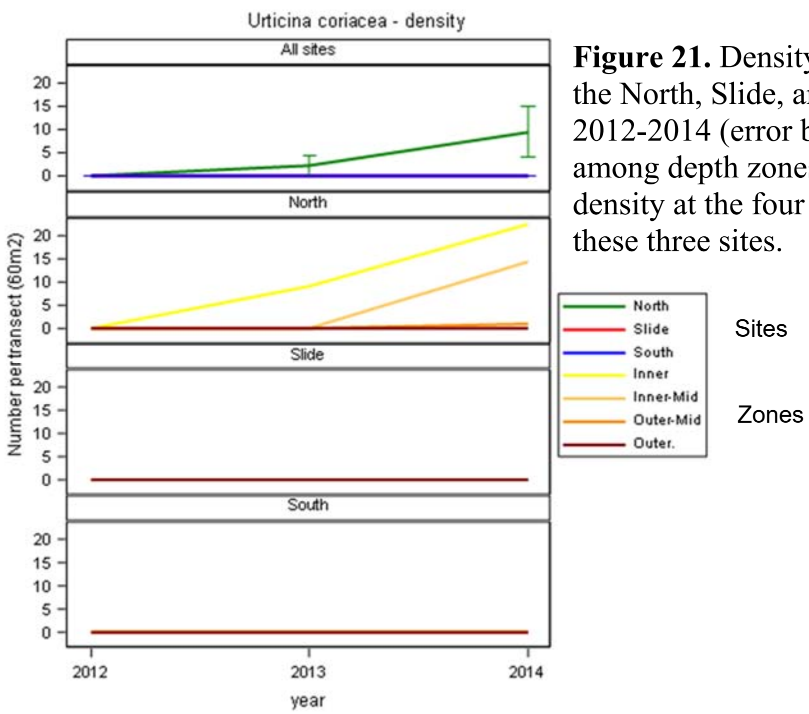


Figure 21. Density of *Urticina coriacea* at the North, Slide, and South sites across years 2012-2014 (error bars depict standard error among depth zones). Graphs below show density at the four depth zones at each of these three sites.

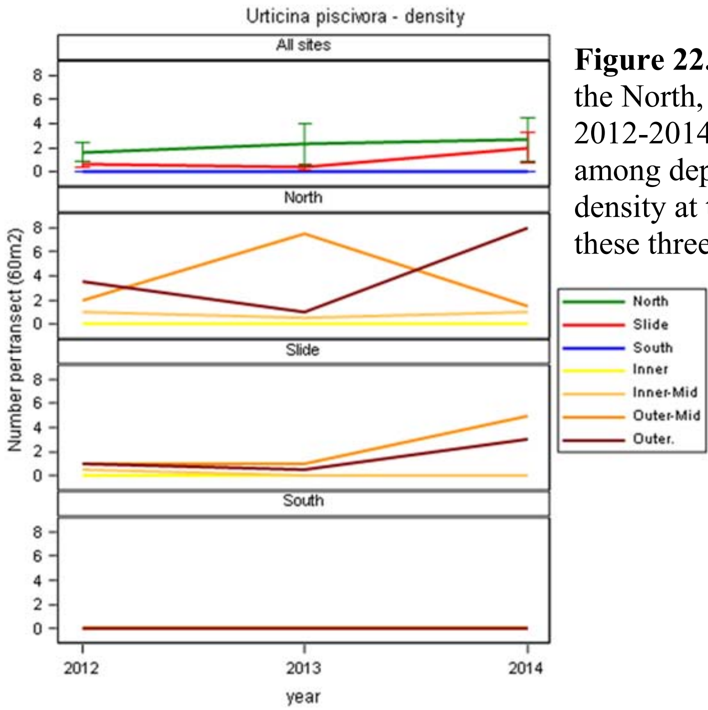


Figure 22. Density of *Urticina piscivora* at the North, Slide, and South sites across years 2012-2014 (error bars depict standard error among depth zones). Graphs below show density at the four depth zones at each of these three sites.

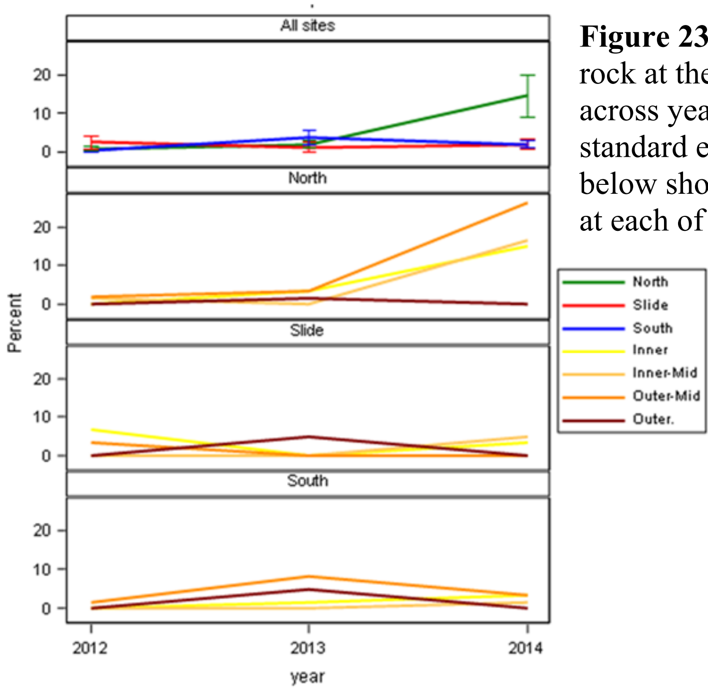


Figure 23. Percent cover of bare exposed rock at the North, Slide, and South sites across years 2012-2014 (error bars depict standard error among depth zones). Graphs below show density at the four depth zones at each of these three sites.

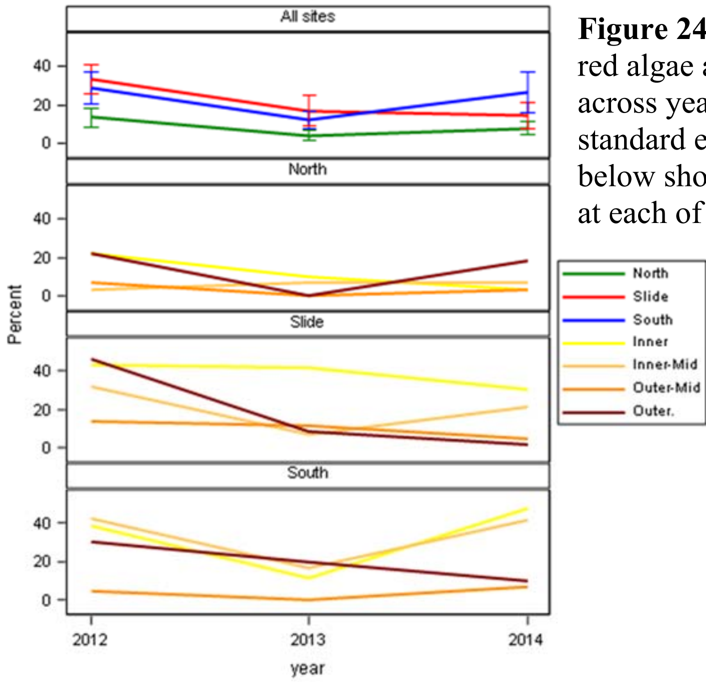


Figure 24. Percent cover of branching fleshy red algae at the North, Slide, and South sites across years 2012-2014 (error bars depict standard error among depth zones). Graphs below show density at the four depth zones at each of these three sites.

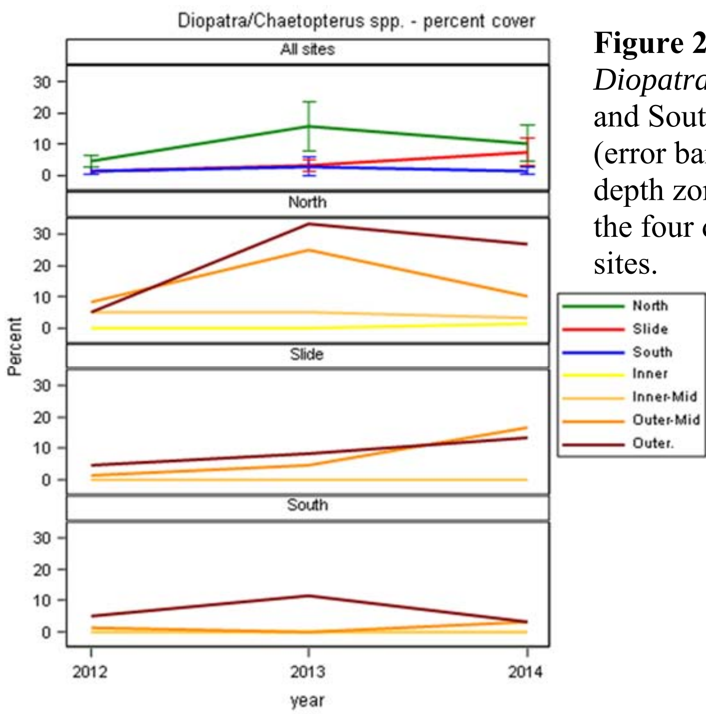


Figure 25. Percent cover of *Diopatra/Chaetopterus* at the North, Slide, and South sites across years 2012-2014 (error bars depict standard error among depth zones). Graphs below show density at the four depth zones at each of these three sites.

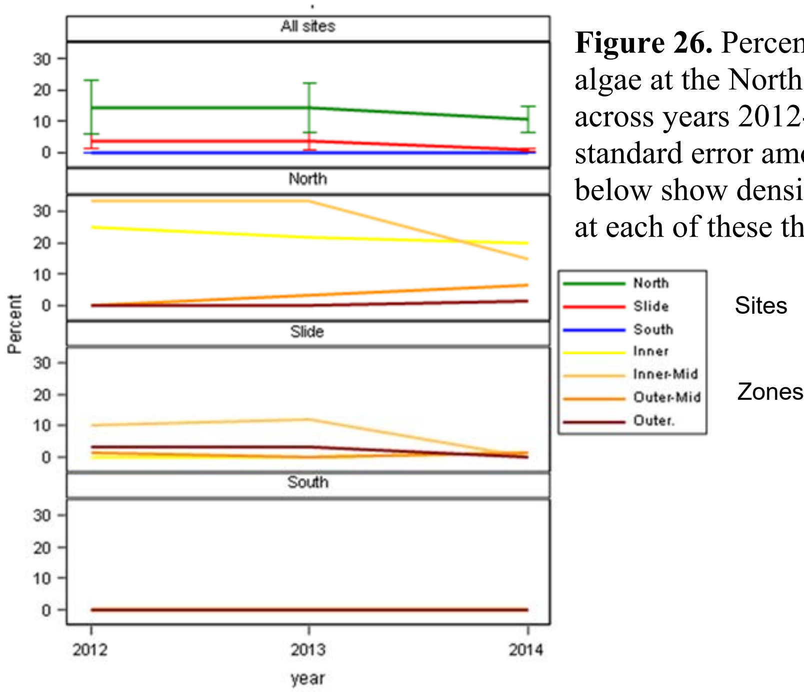


Figure 26. Percent cover of erect coralline algae at the North, Slide, and South sites across years 2012-2014 (error bars depict standard error among depth zones). Graphs below show density at the four depth zones at each of these three sites.

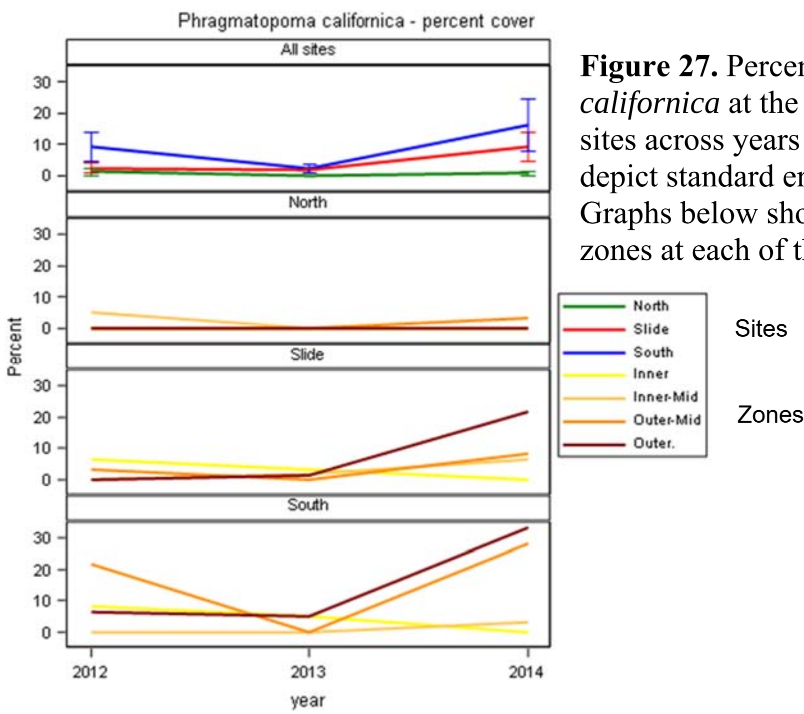


Figure 27. Percent cover of *Phragmatopoma californica* at the North, Slide, and South sites across years 2012-2014 (error bars depict standard error among depth zones). Graphs below show density at the four depth zones at each of these three sites.

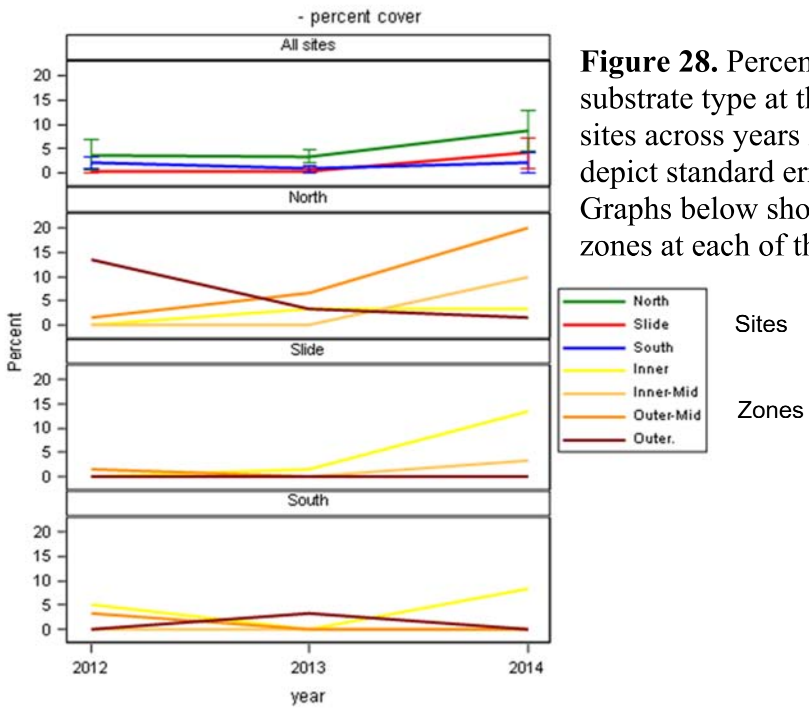


Figure 28. Percent cover of the cobble substrate type at the North, Slide, and South sites across years 2012-2014 (error bars depict standard error among depth zones). Graphs below show density at the four depth zones at each of these three sites.

Are any observed differences consistent with what might be associated with changes in the physical environment associated with the slide (sediment burial, scouring, turbidity)?

Of the two patterns of change detected for the geomorphology of the sites, only one is potentially attributable to an impact of the slide. The site-by-zone-by-year interaction for **cobble** (Table 3) reflects an increase in cobble in the inner zone at the Slide site, which could either reflect new deposition of cobble material from the toe of the slide, or removal of land-slide derived sediment, exposing the pre-existing cobble substrate (Figure 28) that had been buried initially and is now becoming exposed over time. To determine this, the cobble material would have to be evaluated to determine if it was transported into the subtidal zone or if it is pre-slide substrate that was once covered and is beginning to be uncovered. Cobble derived from the slide was fundamentally different, since it had sharp edges from having been recently derived from boulder fragmentation. This type of sharp-edged cobble was evident in the intertidal at the toe of the slide within a few days of the slide occurring (Lonhart, personal observation). The slide did not release material that was smooth-edged and rounded. In contrast, cobble associated with the subtidal is rounded, much like river rock, since it often moves during large swell and surge, which tends to abrade surfaces, smoothing away rough edges and angles.

Of the 58 biological taxa and substrate characteristics that exhibited spatial or temporal patterns, twelve may be attributable to the influx or eventual removal of slide material into the rocky reef habitat seaward of the slide deposition:

- One important pattern that is difficult to evaluate without data at the Slide and South sites prior to the event is the eventual increase in both **red abalone** and the anemone ***Urticina coriacea*** at the North site relative to the others. This may reflect an effect of the slide if abalones and the anemone had been removed at both the Slide and South sites by the slide and individuals at the North site became more detectable in 2014 by either growing into the recorded size range or, in the case of the abalone, moving into more exposed locations. Mean size of abalone (7.6 cm; std. dev. 4.3) at the North site in 2014 was small enough that they would likely not have been observed in previous years. Abalone in size classes <6 cm are generally highly cryptic and well concealed under rocks. Without data from the Slide and South sites prior to the event, we cannot say unequivocally whether these two sites never supported sufficient densities of abalone to be detected on the surveys because of natural sedimentation influx at the site. It is very peculiar, however, that abalone were never detected at these sites, given the likelihood of detecting at least some abalone on surveys elsewhere along the Big Sur coast. The anemone *Urticina coriacea* is typical of shallow, rocky reef habitats along Big Sur. These anemones occupy cracks and crevices, often covered with pebbles and shell debris, and when retracted, can be difficult to detect. The results for this species could be due to sampling artifacts.

- Another important pattern detected in the surveys, which collaborates the Landsat time series, is the higher density of **giant kelp**, *Macrocystis pyrifera,* at the North site than both the Slide and South sites. This could reflect the loss of kelp at the Slide and South sites after the event and before sampling was initiated in 2012. The lower density at the South site might be a preexisting condition, since a turbidity plume extending that direction prior to 2011 was visible in the Google Earth images (Appendix 1). If the slide added to the existing turbidity and increased it, the greater light attenuation would reduce growth rates and could ultimately kill kelp plants. In addition, increased sedimentation can smother giant kelp spores and increase scour, preventing future recruitment of other giant kelp. Based on historic aerial images, the North site typically has a more extensive kelp forest than the Slide and South sites, and based on the apparent circulation patterns in this area, these ACSA turbidity plume might exacerbate pre-existing differences.
- The observed increase of the macroalga ***Cystoseira osmundacea*** in the inner zone at the North site relative to the other two sites would be attributable to an effect by the slide material if a recruitment event was prevented or significantly diminished at the Slide and South sites due to sedimentation and/or increased turbidity. Similar to giant kelp, sedimentation and turbidity have both been shown to prevent the survival and growth of algal spores.
- Densities of the sunflower star, ***Pycnopodia helianthoides,***were initially lower at the Slide site than the North and South sites (Figure 20), and this could reflect a reduction in density of the sea star at the Slide site after the event and before sampling was initiated in 2012. Their decline in density at all three sites across all three years, however, is more consistent with the decline in density associated with the sea star wasting epidemic observed throughout this region. Again, without data from the Slide site prior to the event, we do not know if this site always supported fewer *Pycnopodia* because of the preexisting sedimentation influx at the Slide site.
- Similarly, although the Slide site always supported higher cover of **branching red algae** than the North site, the greater decline at the Slide site relative to the North and South sites might reflect an effect of an influx of slide material (Figure 24). Increased sedimentation, scour and turbidity could all contribute to a decrease in abundance of branching red algae.
- An increase of the infaunal, ornate tube-worm ***Diopatra ornata*** at the North site could be a consequence of sampling error. This species occupies soft sediment habitats, with worms burrowing into the sediment at least 15 cm. Although placement of a transect

targets rocky reef, there is variation of placement among divers and it is possible that this variability led to differences among sites (recall these are not fixed transects). The outer edge of the North site is mostly low boulders, emergent reef, and extensive patches of *Diopatra* (Lonhart, personal observation).

- Another tube worm, ***Phragmatopoma californica,*** associated with sandy habitats increased at the Slide and South sites, and remained largely absent at the North site. Notably, this species was always of greater cover at the South site, and this reflects the greater cover of sand sediment at the South site relative to the other two sites over the three years surveyed after the slide event. *Phragmatopoma* uses sand to build tubes, and a colony creates a short-lived reef of thousands of worms. Suspended sediment is typically more abundant near the reef-sand interface, which is where these worms tend to settle and aggregate.
- The consistently greater cover of **erect coralline algae** at the North site could also reflect a reduction of this group at the other two sites after the event and prior to surveys. Erect coralline algae photosynthesize like other algae and are susceptible to burial by sediment. Whether the North site always supported higher cover of this group relative to the other sites is unclear without data prior to the event. However, this is a very common group and its far lower abundance at the Slide site and absence from the South site is unexpected.

Of the 46 taxa that showed significant effects of site, zone, year or their interactions, we determined that these effects were not attributable to the slide for the following reasons:

- Significant effects of year, zone or their interactions without significant interactions with the site effect do not fit expectations since the pattern does not vary between impact and reference sites. Species and taxa include: *Ceratostoma foliatum, Cucumaria miniata, Laminaria setchellii, Patiria miniata, Pisaster brevispinus, Pisaster giganteus, Pterygophora californica, Strongylocentrotus purpuratus,* bushy red algae, *Cystoseira osmundacea,* lacy red algae, tubeworms).
- Too few observations to be ecologically meaningful (e.g., *Alaria marginata*, *Anthopleura xanthogrammica, Haliotis kamtschatkana, Leptasterias hexactis, Loxorhynchus grandis, Mimulus foliatus, Orthasterias koehleri, Pugettia producta, Stylaster californicus,* scallops, tube mats, red algal turf).
- Increase or decrease at only one of two reference sites, couple with no change at the Slide site (e.g., *Anthopleura sola, Dermasterias imbricata, Pisaster ochraceus, Urticina lofotensis,* leafy red algae).
- Increase or decrease at Slide site, and similar pattern at the North site (e.g., solitary tunicates, cobble substrate).
- Pattern counter to expected effects of slide, such as rock-associated species higher at Slide site (e.g., *Styela montereyensis*) or sand-associated species higher at the North site.

Does the species composition (identity and relative abundances) of macroalgae and invertebrate assemblages on the shallow subtidal rocky reef just seaward of the landslide differ from sites to the north and south?

Do these patterns vary among depth zones and/or change over time?

We detected strong differences between sites, depth zones and years in the combined **mobile invertebrate and stipitate kelp assemblages recorded on swath surveys**, but the patterns between depth zones and among years did not differ among the three sites (Table 4). More importantly, all three sites were different from one another (Table 4; contrast terms). Transects sampled across depth zones and years in the North site and clearly separated (above) from transects sampled from the other two sites (Figure 29). In contrast, transects sampled at the Slide and South sites are more similar (mixed together on the graph) and the Slide transects lie in between the sites to the North and South. Differences between years are less obvious (Figure 29), but consistent differences between depth zones across the three sites are: inner zones to the left of the plot, mid in the middle, and outer zones to the right.

We also detected strong differences between sites, depth zones and years in the **stipitate kelp assemblage** recorded on swath surveys, as well as a site-by-zone-by-year interaction (Table 4). The pattern is very similar to that described for the combined kelp and invertebrate assemblage described above. With the exception of one (South site) transect, transects in all depth zones and years sampled at the North site are distinct from the other two sites (Table 4; contrast terms), with high overlap between the Slide and South sites and the Slide site intermediate of the North and South sites (Figure 30). Again, the depth zones are distinct; inner sites to the lower left section of the plot, but mid and outer depth zones more interspersed (less distinct) in the upper right sector of the plot. The temporal (year) differences are less visually distinct. The site-by-zone-by-year interaction likely reflects changes in *Macrocystis* and *Cystoseira* densities as described in the previous section.

We also detected differences between sites, depth zones and years in the assemblage of **mobile invertebrates** (which includes red abalone and *Pycnopodia*), and these differences between sites did not differ between depth zones or change over time (i.e. no site-by-zone-by-year interaction; Table 4). Moreover, we did detect a consistent difference between the Slide site and the other two sites for this assemblage (Table 4, the contrast term). This may reflect the presence and absence of certain mobile species (e.g., red abalone, *Pycnopodia*) at the North and Slide sites, respectively. Again, the Slide site appears to be intermediate between the North and South sites in the MDS plot (Figure 31).

We detected differences between sites, depth zones and years in the assemblage of **sessile invertebrates and understory algae combined on UPC surveys** (Table 4), and like the swath surveys, the Slide samples lie intermediate of the North and South sites (Figure 32). However, while the North is different from the Slide and South, Slide and South sites are not different (Table 4, contrast terms).

The only difference detected in the **understory algae** assemblage was among the three sites, which was consistent across depth zones and years (i.e. no interaction). However this difference exists only between the North and South sites and the Slide site was not different from the other two sites. (Table 4). This pattern is evident in the MDS plot with samples across zones and years in the North site clustered to the left side, samples from the South site clustered to the right, and the Slide samples in the middle between those two sites (Figure 33).

In contrast, the only differences detected for the assemblage of **sessile invertebrates** recorded on the UPC surveys was among the four depth zones, which was consistent among the three sites and over time (i.e. no interaction; Table 4). This is evident by the greatly interspersed distribution of samples among the three sites and years (Figure 34) and the segregation of the outer, mid and inner depth zones to the left, middle and right sides of the plot, respectively. This pattern was driven primarily by the cover of barnacles and compound tunicates (higher in the middle zones than the inner zone), and *Phragmatopoma* and *Diopatra* (higher in the outer zone).

No overall differences were detected in the composition (relative abundance) of **substrata type and relief** among the three sites, depth zones or years (Table 4). It is interesting however, that all samples from the Slide site tend to be much more similar to (i.e. clustered with) one another (Figure 35), whereas samples from the two reference sites are more different across depth zones and years. This suggests more homogeneous substrata across depths and years at the Slide site relative to the other two sites.

Are any observed differences in assemblages consistent with what might be associated with changes in the physical environment associated with the slide (sediment burial, scouring, turbidity)?

The most pronounced patterns that were detected were the distinct assemblages in the North site relative to the Slide and South sites. This was the case for the stipitate kelps, the conspicuous sessile and mobile invertebrates, and all swath species combined. In addition, the mobile invertebrates contributed to differences in all swath species combined between the Slide and South sites. Whereas similar differences between the North and the other two sites were observed for all sessile invertebrate and understory algae combined, these differences were not detected for these two groups when analyzed separately. The overall differences seen between the North site and the other two sites could reflect the vulnerability of all these assemblages (sessile and mobile invertebrates, kelps and understory algae) to sedimentation, scouring and turbidity associated with an influx of sediment from the intertidal.

Importantly, the community composition at the North site is similar to sites previously surveyed by PISCO in close proximity to the north (Plaskett Creek, 8.8 km and Duck Pond 1.1 km) and south (Salmon Creek, 6.6 km) (Figure 36) during the period 2003-2008. The overlap between the North site and these prior PISCO surveys suggests that the North site represents an appropriate reference site with species abundances typical of kelp forests in the area, and that the Slide and South sides are distinct with atypical community composition. Without a baseline of survey data from before the Alder Creek Slide it is difficult to say whether the community composition at these sites represents a ‘natural’ condition for this area that results from the local geology and topography, or whether the differences seen between the North and the Slide and South sites have arisen since the slide event.

Table 4. Summary of permutational ANOVA (PERMANOVA) of components of the algal and invertebrate assemblage at the slide and control sites. Table values represent permutational P-values (P(perm)) for the main effects of site, year, and zone and their interactions. Additional contrasts compare assemblages between each site with one another. Significant values ($P<0.05$) are highlighted in red text.

	site	zone	year	site*year	site*zone*year	North vs Slide	North vs South	Slide vs South
all species (swath)	0.001	0.001	0.001	0.915	0.403	0.001	0.001	0.025
stipitate kelps (swath)	0.001	0.001	0.039	0.475	0.036	0.001	0.001	0.266
mobile invertebrates (swath)	0.001	0.001	0.001	0.921	0.85	0.001	0.001	0.003
All species (UPC)	0.022	0.008	0.009	0.977	0.941	0.008	0.013	0.594
understory algae (UPC)	0.021	0.134	0.061	0.92	0.985	0.175	0.014	0.149
sessile invertebrates (UPC)	0.176	0.005	0.204	0.941	0.98	0.067	0.074	0.85
substrate type and relief (UPC)	0.197	0.191	0.064	0.87	0.76	0.045	0.338	0.464

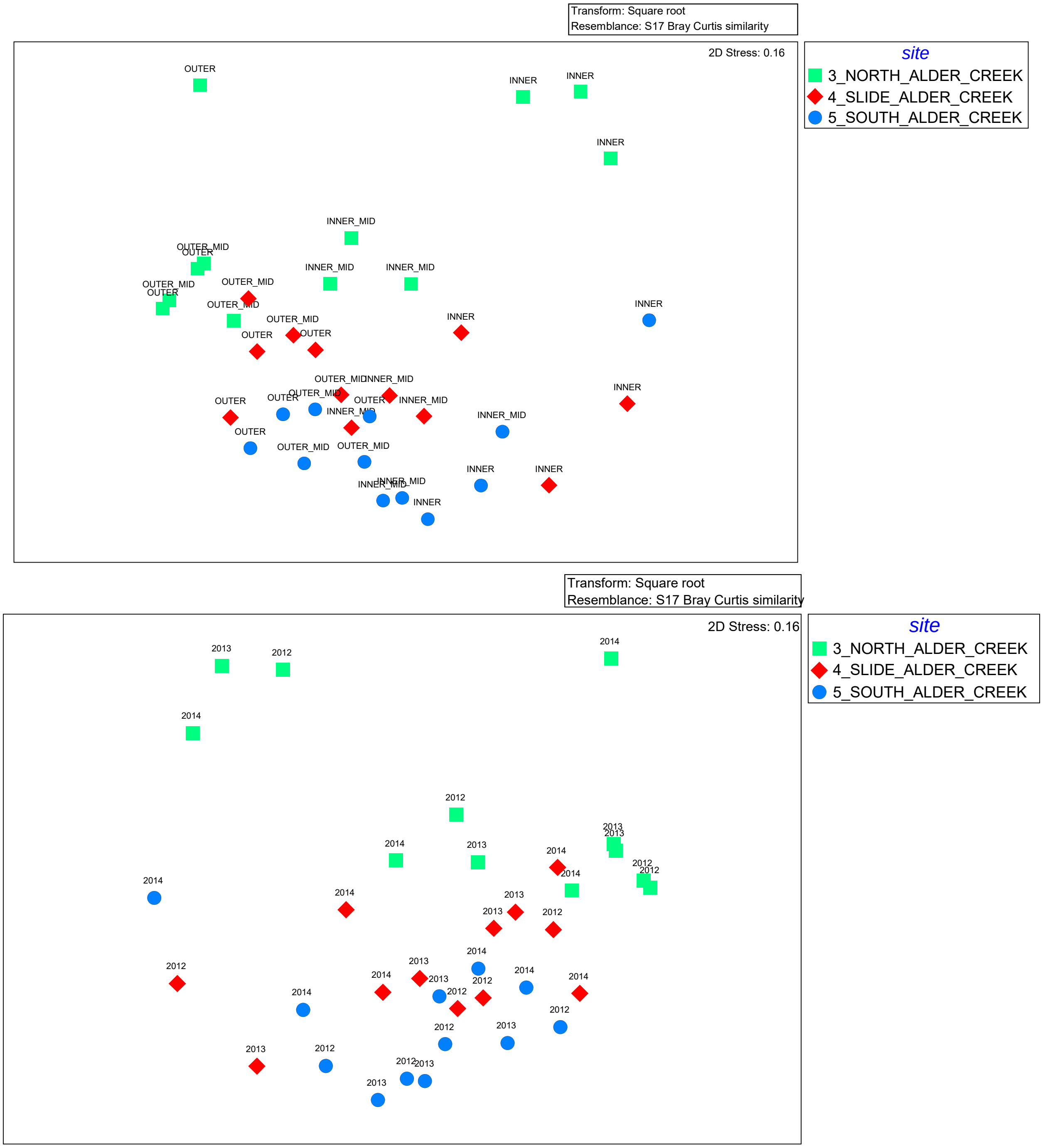


Figure 29. Multidimensional scaling plot of the combined mobile invertebrate and stipitate kelp assemblages (all swath) at the slide and control sites. Samples represent individual depth zones (inner, inner-mid, outer-mid, and outer) surveyed at each site annually 2012-2014. Plot is presented with text labels indicating depth zone (A) and survey year (B) for clarity.

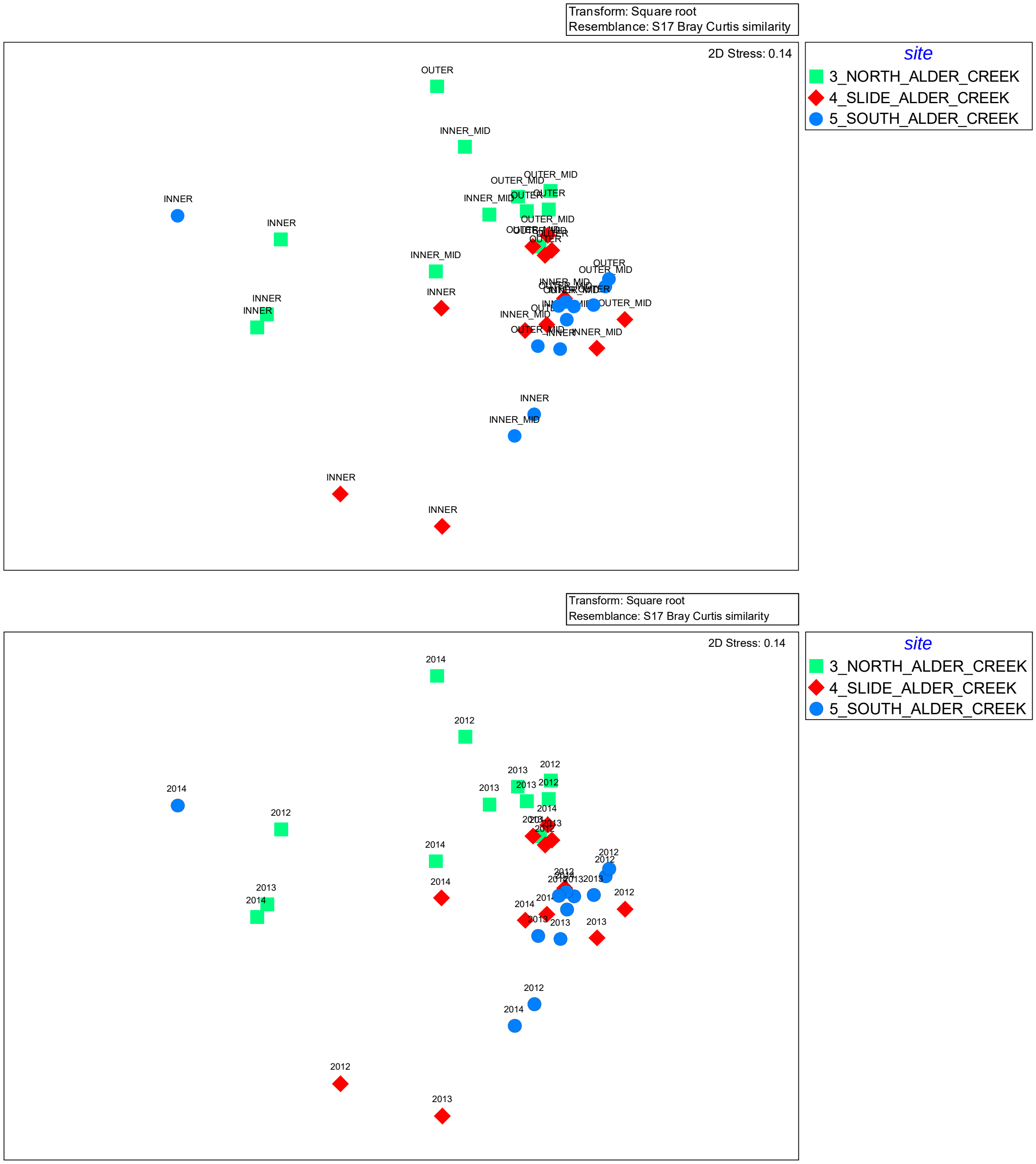


Figure 30. Multidimensional scaling plot of the stipitate kelp assemblage (swath) at the slide and control sites. Samples represent individual depth zones (inner, inner-mid, outer-mid, and outer) surveyed at each site annually 2012-2014. Plot is presented with text labels indicating depth zone (A) and survey year (B) for clarity.

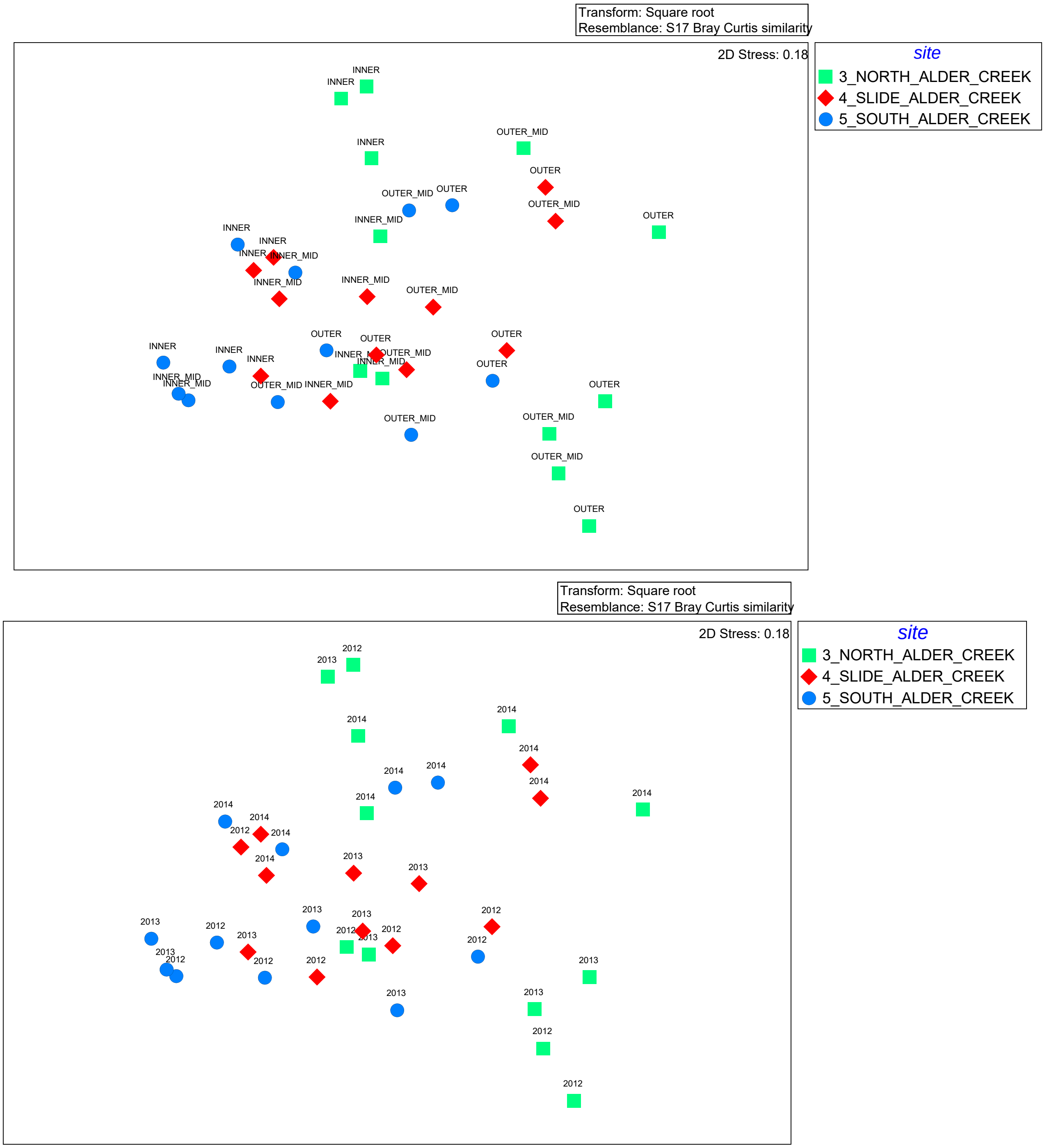


Figure 31. Multidimensional scaling plot of the mobile invertebrate assemblage (swath) at the slide and control sites. Samples represent individual depth zones (inner, inner-mid, outer-mid, and outer) surveyed at each site annually 2012-2014. Plot is presented with text labels indicating depth zone (A) and survey year (B) for clarity.

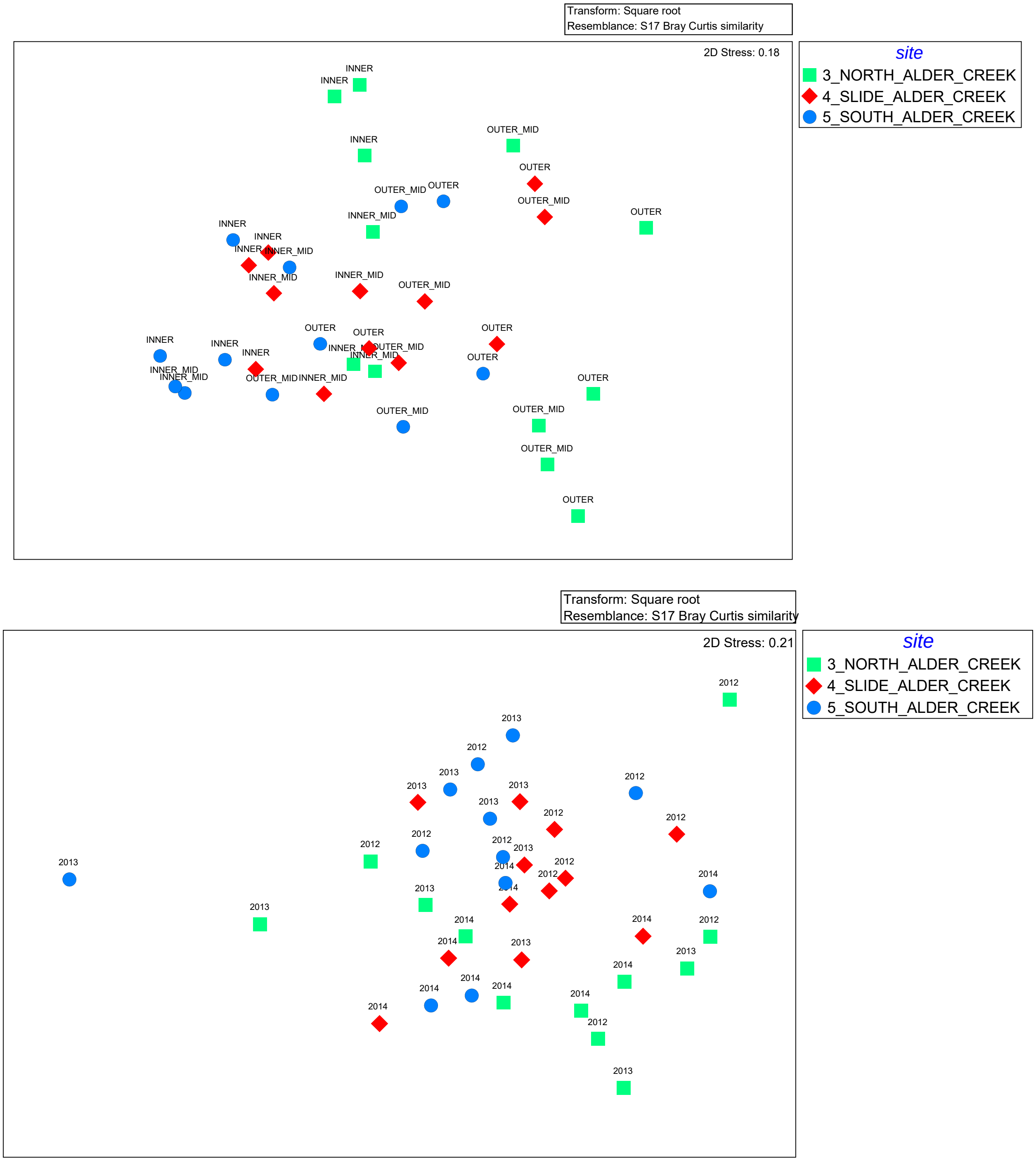
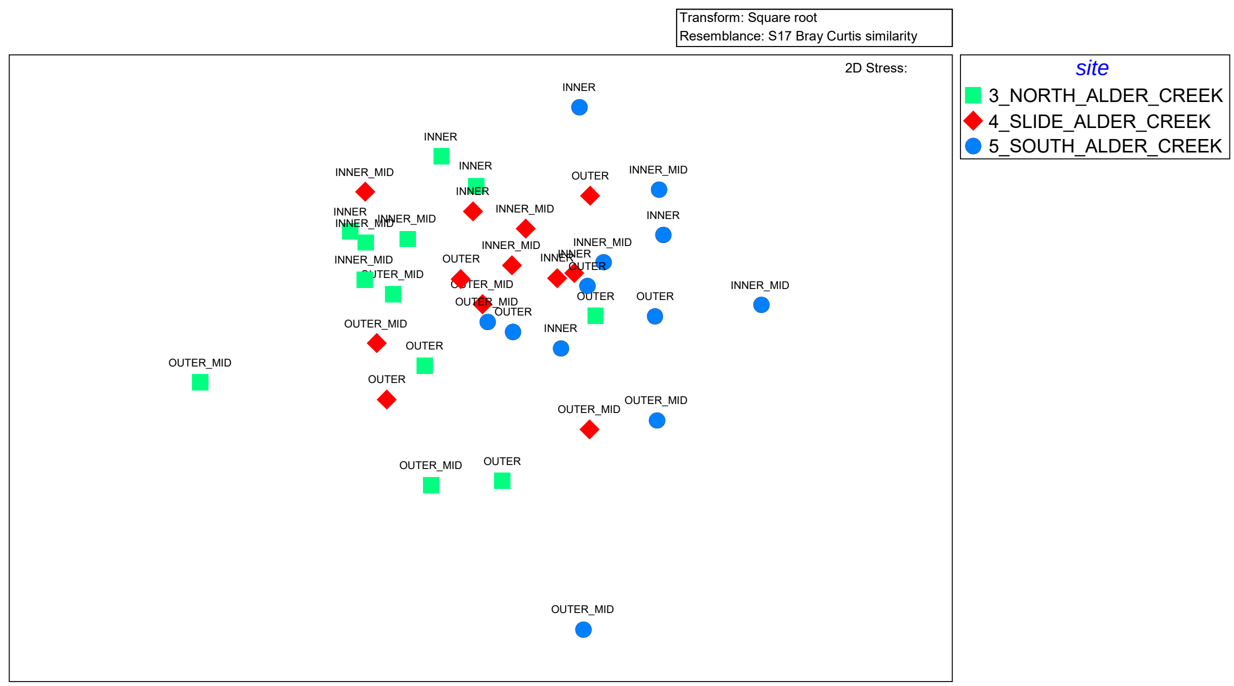


Figure 32. Multidimensional scaling plot of the combined understory algae and sessile invertebrate assemblages (UPC) at the slide and control sites. Samples represent individual depth zones (inner, inner-mid, outer-mid, and outer) surveyed at each site annually 2012-2014. Plot is presented with text labels indicating depth zone (A) and survey year (B) for clarity.



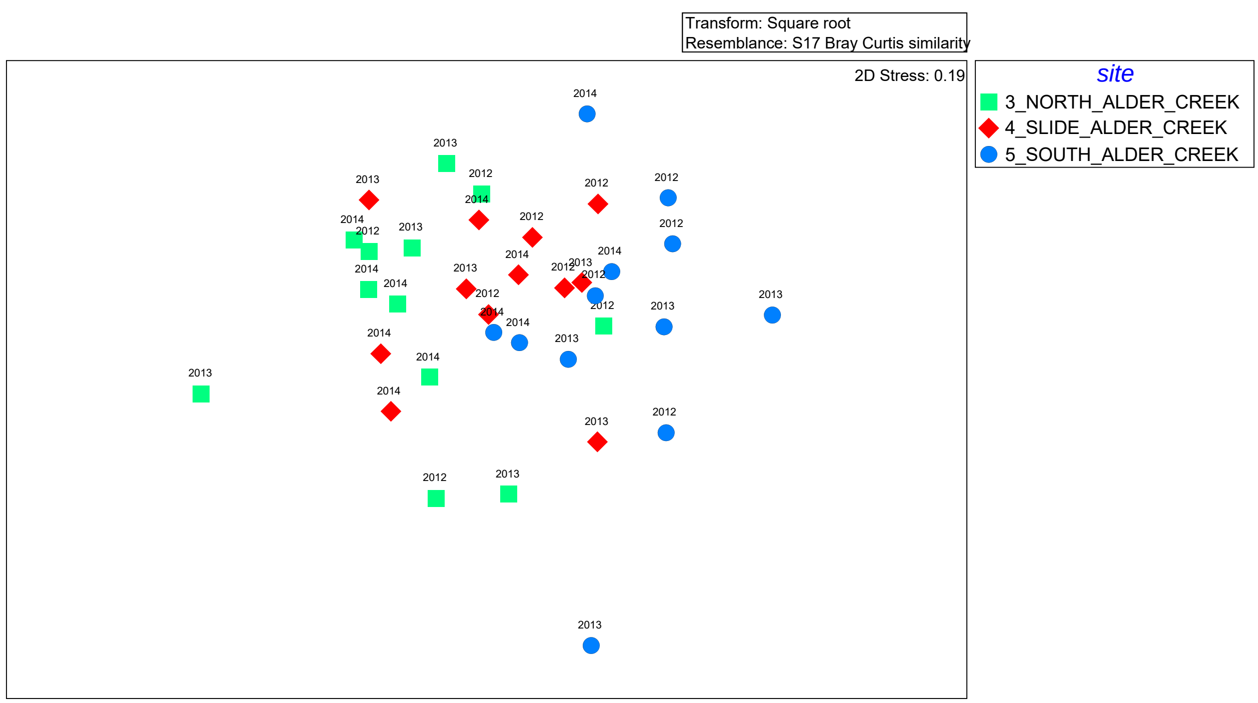
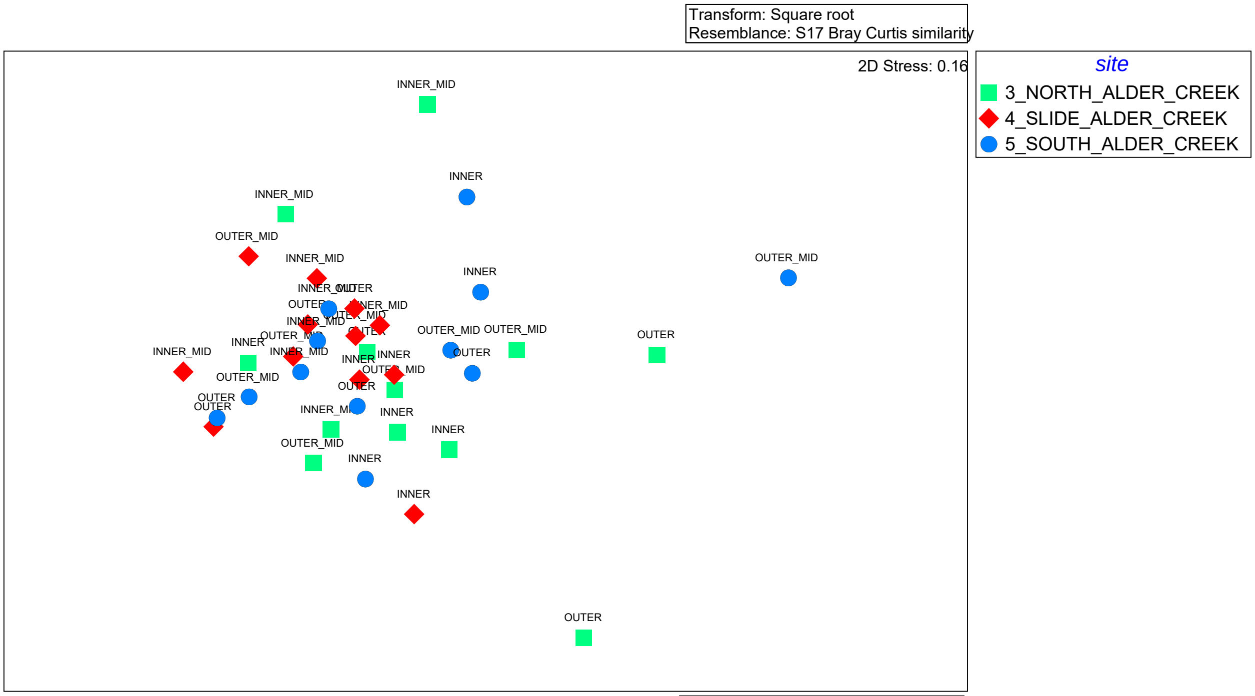


Figure 33. Multidimensional scaling plot of the understory algae assemblage (UPC) at the slide and control sites. Samples represent individual depth zones (inner, inner-mid, outer-mid, and outer) surveyed at each site annually 2012-2014. Plot is presented with text labels indicating depth zone (A) and survey year (B) for clarity.

Figure 34. Multidimensional scaling plot of the sessile invertebrate assemblage (UPC) at the slide and control sites. Samples represent individual depth zones (inner, inner-mid, outer-mid, and outer) surveyed at each site annually 2012-2014. Plot is presented with text labels indicating depth zone (A) and survey year (B) for clarity.



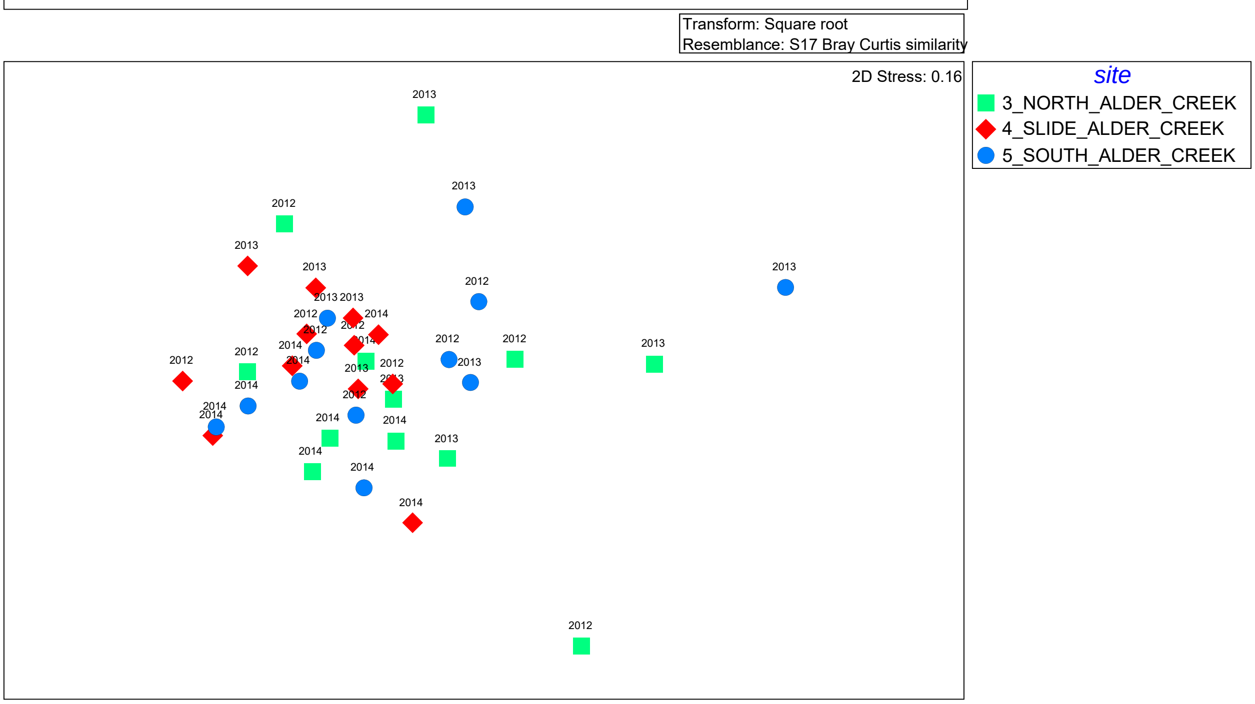
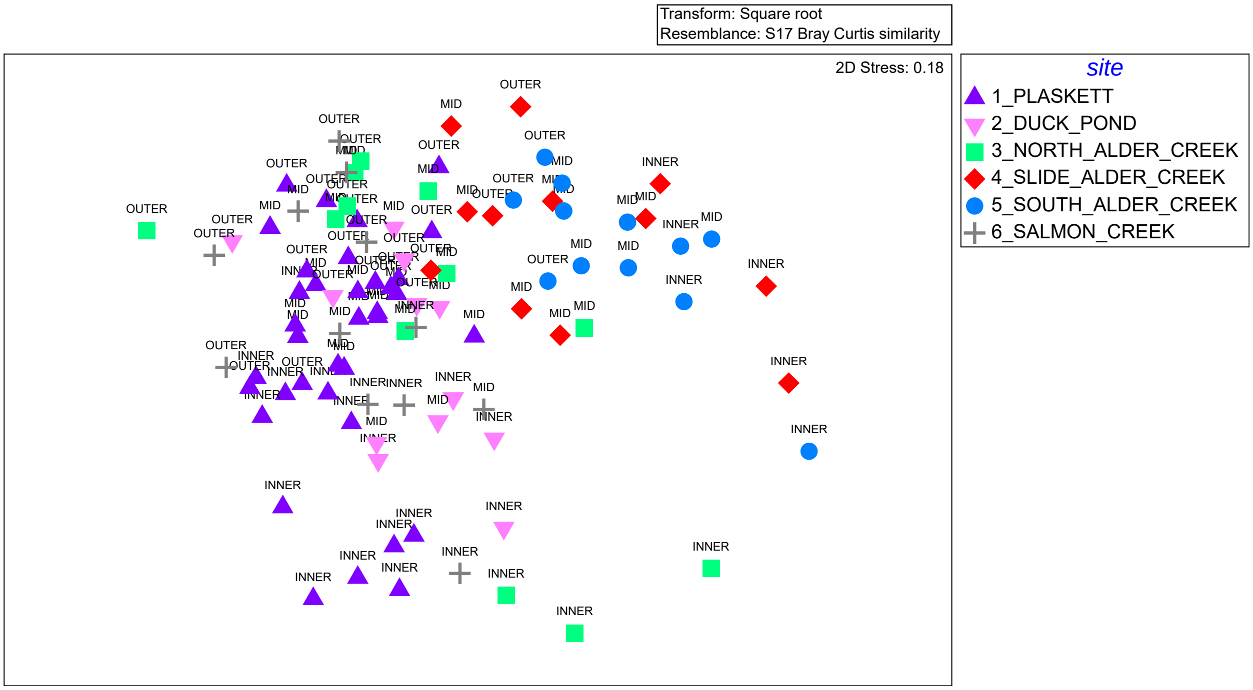


Figure 35. Multidimensional scaling plot of the substrate type and relief variables (UPC) at the slide and control sites. Samples represent individual depth zones (inner, inner-mid, outer-mid, and outer) surveyed at each site annually 2012-2014. Plot is presented with text labels indicating depth zone (A) and survey year (B) for clarity.



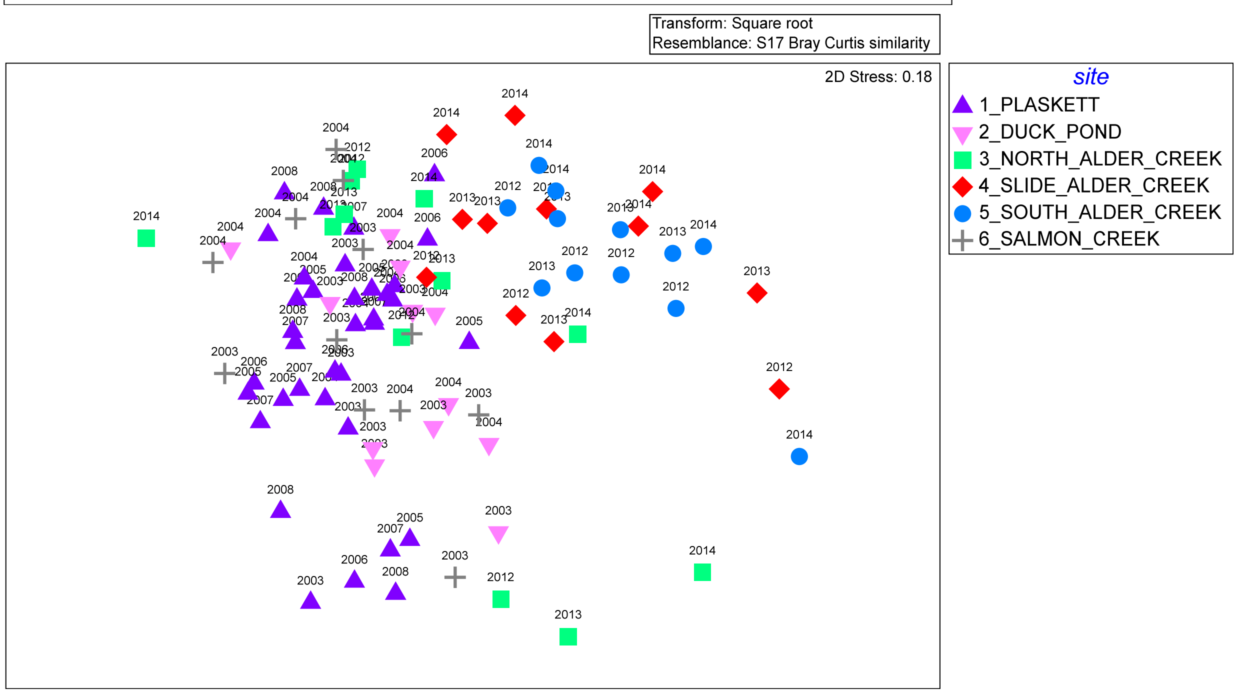


Figure 36. Multidimensional scaling plot of the combined mobile invertebrate and stipitate kelp assemblages (all swath) at previously sampled (2003-2008) PISCO monitoring sites as well as the slide and reference sites from the current study. Samples represent individual depth zones (inner, inner-mid, outer-mid, and outer) surveyed at each site annually 2003-2014. Plot is presented with text labels indicating depth zone (A) and survey year (B) for clarity.

Does giant kelp (Macrocystis pyrifera) biomass (derived from Landsat imagery) differ before and after the slide event, and how does that pattern differ between the likely impact and control sites?

As suggested by the Google earth images, there are clear historic differences in kelp canopy biomass to the north and south of the Slide site, but these differences increase after the slide event (Figures 37 and 38). Subsequent to the slide event, kelp canopy remained low through the study duration within 1 km of the Slide site, whereas canopy increased again to the north (Figure 37). The much higher canopy biomass in the north direction persisted before and after the slide event while canopy biomass declined markedly to the south (direction-by-time interaction: $P<0.0001$) and this pattern was evident at all three spatial scales (1 km, 2.5 km, and 5 km). The proportionate change in canopy biomass was greater with closer proximity to the slide (1 km and 2.5 km), which decreased with increasing area to the south (5 km; Figure 38). This reflects the fact that as this impact radius increases, the relative proportion of 'typical' or un-affected habitat increases, which in turn diminishes the signal of the slide.

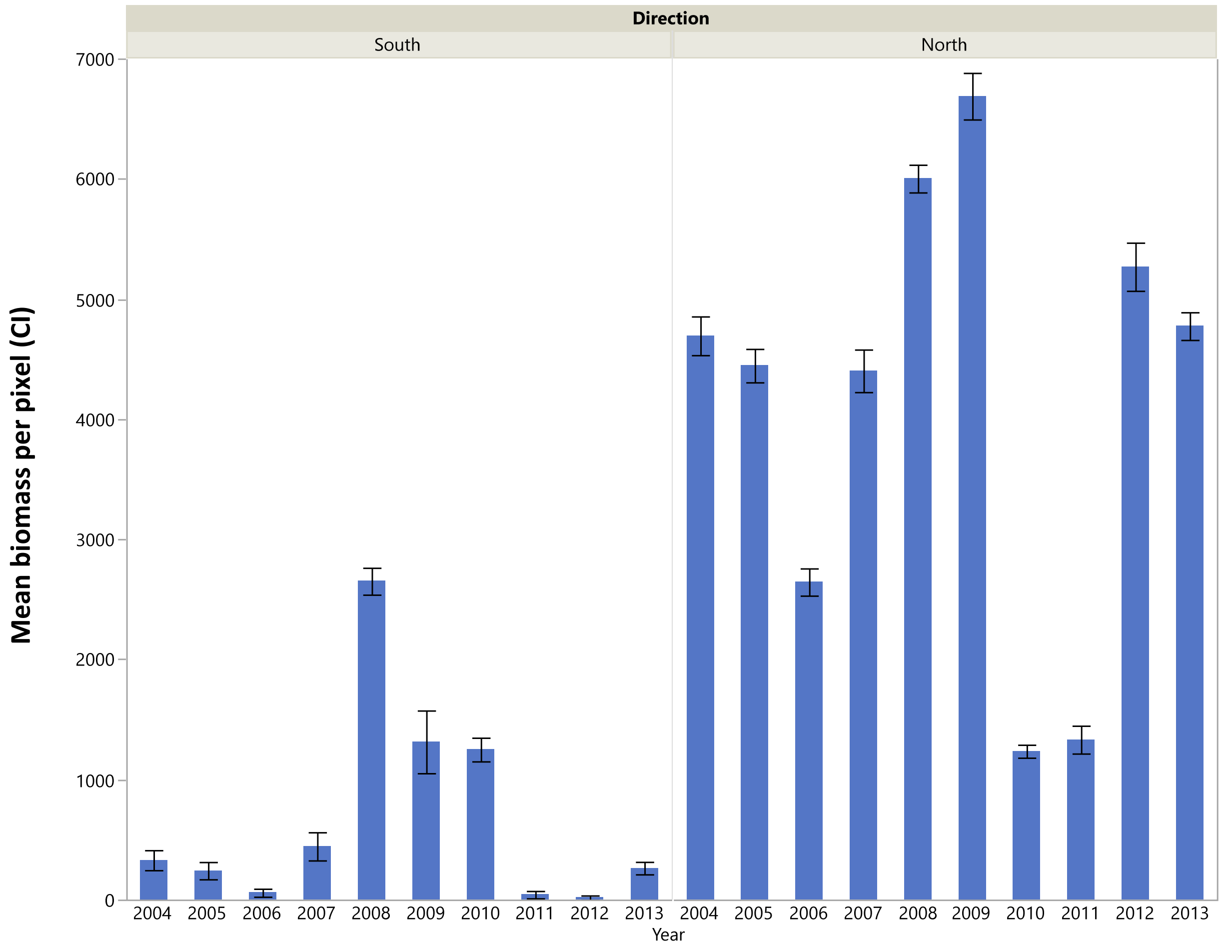


Figure 37. Mean *Macrocystis pyrifera* biomass per pixel by year from Landsat imagery of kelp beds within a 1 km radius from the slide area. Values are grouped by areas south (left) or north (right) of the slide area. Error bars represent standard error.

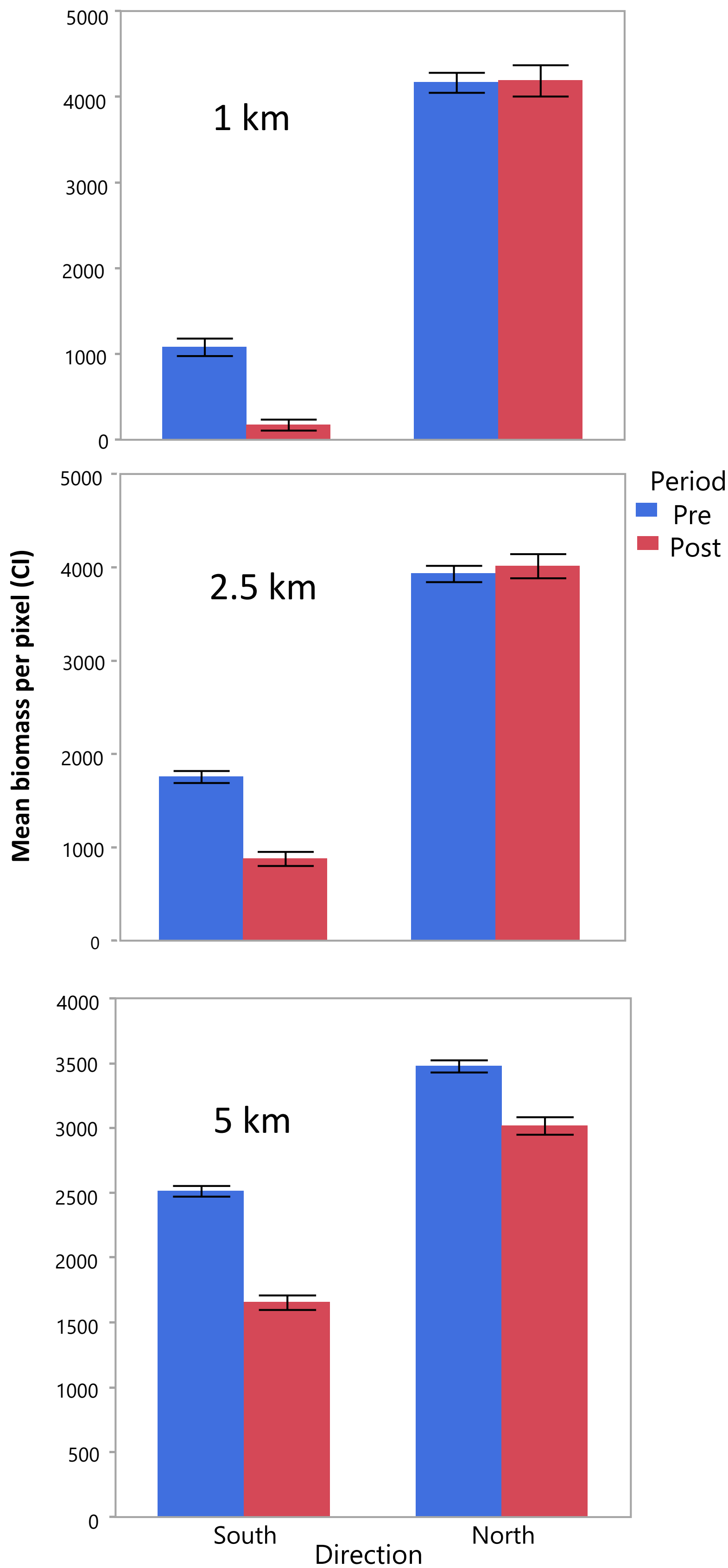


Figure 38. Mean *Macrocystis pyrifera* biomass per pixel from Landsat imagery of kelp beds within increasing radii (1, 2.5, and 5 km) from the slide area. Values are grouped by “pre” (blue, 2004-2010) and “post” (red, 2011-2014) periods and by areas south (left) or north (right) of the slide area. Error bars represent standard error.

Conclusions

Results of the analyses of intertidal surveys suggest that there was and continues to be an impact on the biological community near to the footprint of the slide. The community downcoast and within 400 meters of the slide was very different from all other locations and was characterized by a paucity of species, more bare rock and evidence of sand scour. The other locations sampled showed the expected community patterns: (1) diversity increases from high to low tide zones and (2) community composition becoming more dominated by algae from high to low tide zones. We saw no change on the community patterns over time indicating no improvement in the affected area.

Results of the subtidal surveys and analyses are suggestive of impacts to particular species and assemblages that constitute shallow rocky reef communities of the Big Sur Coast. In particular, kelp density surveyed by divers across all three years of the study was greater at the North site than it was at the Slide or South sites. The Landsat analyses of kelp canopy biomass suggest that these differences coincide with the slide event; north of the slide there was no difference in kelp canopy before and after the slide event, whereas kelp canopy south of the slide declined after the slide event. In addition to these patterns of change in kelp abundance, we detected similar differences among sites for various invertebrates and subcanopy and understory algae. In particular, greater densities of red abalone and *Pycnopodia* likely contributed to the differences in the mobile invertebrate assemblages between the North and other sites. Likewise greater densities of *Cystoseira* and *Macrocystis* contributed to differences in the stipitate kelp assemblages between the North and other sites. However, with the exception of *Macrocystis*, these differences in species and assemblages between the North and other sites may have existed prior to the slide event. In the absence of data prior to the slide event, the observed spatial differences are consistent with the potential impacts of increased sedimentation and turbidity on species in the southern portion of the study area (Slide and South sites). Only for *Macrocystis*, for which we have abundance data before and after the slide event, can the observed patterns be unequivocally attributed to the slide event.

The spatial extent, magnitude and duration of the ACSA impacts to the biological communities in the rocky intertidal and adjacent subtidal zones reflect the combined effects of the footprint, volume and type of material deposited in the intertidal by the slide and the subsequent addition of material by CalTrans. The footprint defines the spatial extent of direct impact to the rocky intertidal by burial of organisms within the ACSA, however, a greater spatial extent of impacts results from wave-mediated dispersal of material along the intertidal and into the adjacent subtidal, causing additional burial, scouring and increased turbidity. This study did not assess how the addition of material on top of the natural slide footprint would affect impacts to the intertidal and nearshore subtidal, so it is difficult to separate the impacts of the slide material from the added material. Nonetheless, it is reasonable to suspect that any addition of material on top of the existing slide will extend the duration of any impacts, and in particular those impacts due to increased burial, scour and turbidity caused by redistribution of suspended sediment.

Literature Cited

Carr, M. H., P. T. Raimondi, S. Lonhart, M. Readdie, K. Kusic, R. Gaddam, H. Livingston, and D. Malone. 2006. Informing decision-making for the coastal highway management plan: a biological sensitivity assessment for intertidal and shallow subtidal habitats on the Big Sur Coast. 186 pages, plus appendices. Report for the Monterey Bay National Marine Sanctuary, available at http://www.mbnms-simon.org/other/gen/about_simon_downloads.php

Cavanaugh, K.C., D. A. Siegel, D.C. Reed, and P. E. Dennison. 2011. Environmental controls of giant kelp biomass in the Santa Barbara Channel, California. *Marine Ecology Progress Series* 429: 1-17.

Raimondi P, M Miner, D Orr, C Bell, M George, S Worden, M Redfield, R Gaddam, L Anderson, D Lohse. 2009. Determination of the extent and type of injury to rocky intertidal algae and animals one year after the initial spill (Cosco Busan): a report prepared for OSPR (California Fish and Game). 62 pages

Raimondi P, M Miner, D Orr, C Bell, M George, S Worden, M Redfield, R Gaddam, L Anderson, D Lohse. 2011. Determination of the extent and type of injury to rocky intertidal algae and animals during and after the initial spill (Dubai Star): a report prepared for California Department of Fish and Game Office of Spill Prevention and Response (DFG-OSPR). 22 pages

Reed, D.C., A. Rassweiler, M.H. Carr, K.C., Cavanaugh, D.P. Malone and D.A. Siegel. 2011. Wave disturbance overwhelms top-down and bottom-up control of primary production in California kelp forests. Ecology 92:2108–2116.