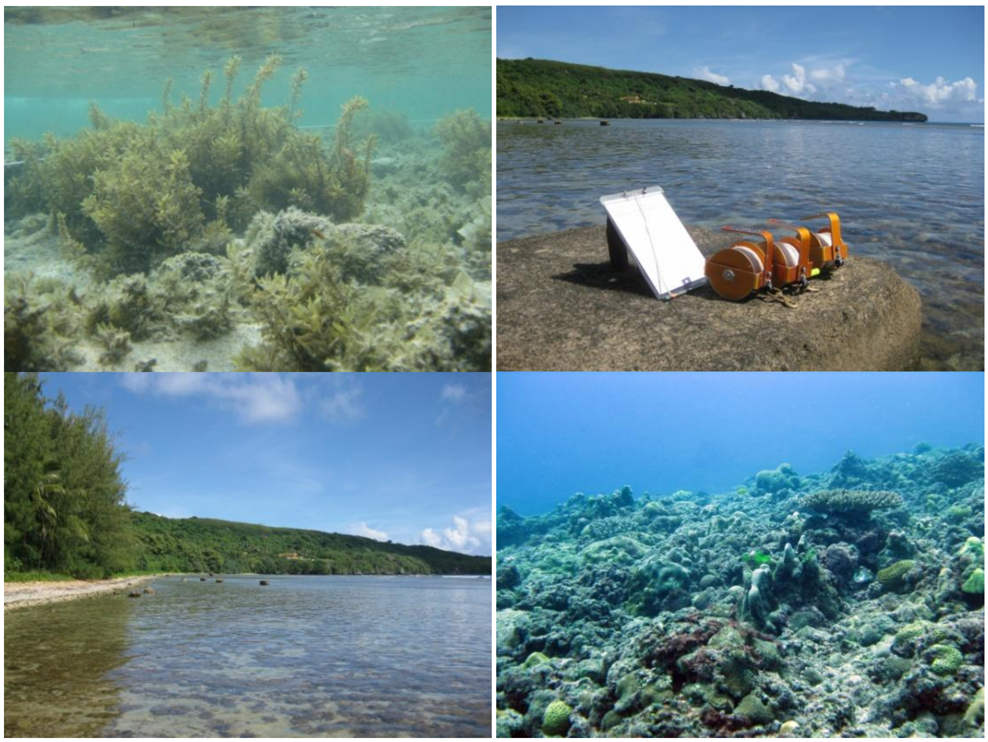
Laolao Bay Road and Coastal Management Improvement Project: Ecological and Water Quality Assessment

Phase I Report: Pre-construction condition report, including an integrated assessment of ecological change since 1991



A Report Prepared by the Pacific Marine Resources Institute for the CNMI Division of Environmental Quality

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Executive Summary:

Due to an extremely favorable natural environmental setting, Laolao Bay is one of Saipan's most desirable coastal areas, with some coral reefs valued at over 10 million dollars per square kilometer based upon a recent economic study. However, in recent times Laolao's environmental integrity has been declining, leading CNMI's natural resource management agencies to prioritize improved management for the bay. Armed with management plans and strategies, the CNMI Division of Environmental Quality applied for and received funding from the American Recovery and Reinvestment Act (ARRA) to conduct the Laolao Bay "*Road and Coastal Management Improvement*" project. Briefly, the project includes road construction and drainage improvement in the western portion of the bay that will decrease land-based pollution being washed into the bay during storm events. The project also includes multi-year, re-vegetation efforts that aim to replant barren savannah uplands with native trees and shrubs. In association with these activities, ecological and water quality monitoring are being conducted by the Pacific Marine Resources Institute (PMRI), in collaboration with CNMI's marine monitoring program (comprised of member from Division of Environmental Quality (DEQ) and Coastal Resources Management (CRM) offices) to evaluate the current ecological and environmental conditions, and their expected improvement due to project activities.

The current monitoring design was based upon historical surveys conducted in 1991 that provide a robust set of baseline data to place modern ecological assemblages into context. A total of six stations were re-established throughout Laolao, with transect-based data collected in two key habitats: 1) the outer reef flat, and 2) the reef slope at a 3–5m depth. In addition, one new station was established further south of existing sites in order to evaluate the watershed drainage associated with the San Vicente access road, a major component of construction activities. Benthic, coral population, fish, and macroinvertebrate data were collected using standardized protocols. In addition, water quality profiling activities were conducted.

Reef flat assemblages. Reef flat benthic substrates were dominated by macroalgae. The most abundant were the seasonal brown algae, *Sargassum polycystum*, and several persistent red algae, *Laurencia* and *Palisada*. While red algal were prolific throughout Laolao, the relative abundances of individual species varied between sites, and even between transects within a site. Comparative analyses between 1991 and present indicate significant increases of macroalgae, mainly comprised of persistent red algae, but also in seasonal *Sargassum* growth. The largest increases in macroalgae were found at sites adjacent to road improvement activities suggesting that improved water quality expected from construction efforts should eventually have a direct, positive influence upon these assemblages. Multivariate algal richness data support these findings; highlighting the greatest influences of controllable land-based pollution is evident in western Laolao. Macroinvertebrates on the reef flats consisted mainly of three species of sea cucumbers: *Holothuria atra*, *Holothuria leucospilota*, and *Actinopyga echinites*. *H. atra* were most abundant, reaching densities of over 50 individuals per 100 m^2 at some sites. There were no clear relationships between sea cucumber densities and algal assemblages, nor were there any ubiquitous changes since 1991.

Water quality profiles. Water quality profiles conducted in the shallow waters outside the reef margin showed differential trends in freshwater discharge across the bay. During a full moon period when monthly tidal exchange was maximal, the easternmost section of the bay had relatively low salinity levels. It appears this natural gradient in salinity is an artifact of greater connectivity with the island aquifer, as freshwater seepage through the reef matrix is the proposed mechanisms of delivery during large, negative tide events associated with full and new moon periods. In contrast, the opposite trends were seen during a period of consistent rainfall and limited tidal exchange to promote connectivity with the aquifer. During this time period, surface discharge was highest in the western portion of the bay, where the largest volcanic watersheds exist.

Reef slope assemblages. Benthic surveys reported lower coral coverage in the eastern portion of Laolao, where turf algae dominated the substrate. These findings are consistent with water quality profiling data, whereby lower coral and higher turf algal abundance are associated with suspect groundwater influence. Beyond coverage, the composition of coral assemblage was also significantly different between the two regions. Where groundwater influence was noted, coral assemblages were mainly comprised of smaller *Porites*, *Leptoria*, *Favia*, and *Galaxea* colonies, genera that provide for reduced three-dimensionality compared with other sites where *Montipora*, *Porites*, and several branching corals were more common. Overall, a universal increase in coral population density has become evident across the entire bay, as colony sizes have significantly diminished. The nature of these trends, defined in the main report, suggested high partial mortality of large colonies over the years, and findings are consistent with studies reporting increasing pollution and/or decreasing herbivory as probable causes. Notably, two stations had coral assemblages contrary to the main findings, where colony sizes and assemblage evenness remained more similar through time, and are discussed.

Reef slope fish assemblages were dominated by small-bodied acanthurids (i.e., herbivorous surgeonfishes) with a near absence of piscivore and benthivore consumers observed. Mean food-fish biomass observed during each stationary point count was less than 2 kg. One site showed contrasting trends, similarly noted above as where coral and benthic assemblages had the least amount of negative change through time. Overall, the low abundance and diversity of food-fish assemblages are characteristic of high fishing pressure and reduced ecological functional redundancy. In support, there have been significant declines in food fish abundances and diversity since 1991, whereby functionally diverse assemblages have been replaced mainly by small acanthurids that grow and reach reproductive maturity over much shorter time periods.

Macroinvertebrate assemblages on the nearshore reef slopes were expectedly dominated by grazing *Echinometra* and *Echinothrix* sea urchins. *Echinometra* urchins were found in high densities (~40 per $100m^2$) at all sites but one, where compromised reef condition was noted through time. The larger, black-spined *Echinothrix* urchins have been slowly increasing through time, however current densities are less than 10 individuals per 100 m^2, well below *Echinometra* abundances. In light of the contemporary doctrine this study does not suggest compromised grazing rates of urchins exist across for 5m reef slope assemblages, considered across the entire bay.

Algal assemblages on the reef slope had greater within-site variability as compared with the reef flat, suggesting they may be less desirable indicators of changing water quality through time, and are better indicators of other environmental regimes. However, future water quality trends being collected during phase II of the project will provide a better context for reef slope algal assemblages.

Conclusions. This study provides quantitative, measurable data that describe the current condition of Laolao bay's coral reef assemblages and change over time in a spatially-robust manner. While these data provide sound guidance for setting ecological targets for ongoing conservation planning activities, their main purpose are to provide a baseline upon which (positive) change can be detected due to ARRA-project activities. The footprint of construction activities is centered upon the western portion of Laolao Bay, where access road and drainage crossing improvements are ongoing. While ecological assemblages are formed through the time-integrated responses of individual species to driving environmental regimes, the time required for detectable responses may be longer than the project timeline allows for. The reef flat algal assemblages represent the fastest growing ecological indicators of project success. While reductions in persistent red algal biomass are expected as water quality improves, the associated ecological response may require several years before becoming evident. Water quality data will be the first and immediate measure of project success. Water quality monitoring is currently ongoing and will be the major focus of the second phase of collaborative monitoring.

Introduction:

Throughout the past decade, the Commonwealth of the Northern Mariana Islands (CNMI) long-term marine monitoring program has documented declining, compromised, coral reef condition throughout Laolao Bay (http://www.cnmicoralreef.net/monitoring.htm, Houk and van Woesik 2010). These trends have corroborated public opinion and insight from CNMI's resource management agencies (CNMI CRI 2009). Negative changes include a lack of coral growth and overall ecosystem recovery in the years following high populations of *Acanthaster planci* (coral predator starfish), while sites elsewhere continue to show positive recovery trends. Laolao's compromised coral assemblages have previously been attributed to increasing land-based pollution discharging into Laolao during storm events (Houk and van Woesik 2010), and corroborated with decreased herbivory as a result of unsustainable fishing practices. It is well known that together, poor water quality and reduced herbivory provide an advantage for macroalgae to outcompete corals for space on the reefs, and through time, result in less architecture to support desirable, biologically diverse assemblages (Smith et al. 2001; Lapointe et al. 2004; Burkepile and Hay 2006; Mork et al. 2009). The negative trends that have emerged from Laolao bay over the past 10 years formed a backbone for generating management plans and strategies to mitigate against further negative change (CNMI CRI 2009).

Building upon management plans and strategies, the CNMI Division of Environmental Quality (DEQ) applied for and received funding from the American Recovery and Reinvestment Act (ARRA) to conduct the Laolao Bay "*Road and Coastal Management Improvement*" project. Other documents describe the project in greater detail, but briefly, the project includes road construction and drainage improvement to decrease the sediment load being washed into the bay during storm events. The project also includes re-vegetation activities to replant portions of the denuded watershed with native trees and shrubs to reduce soil erosion and provide habitat for a healthy forest fauna.

In association with the ARRA project, ecological and water quality monitoring are being conducted by the Pacific Marine Resources Institute (PMRI), Division of Environmental Quality (DEQ), and Coastal Resources Management Office (CRM) to evaluate current ecological and environmental conditions, and their expected improvement due to project activities. Here, we summarize findings from initial ecological surveys and water quality monitoring activities. We utilize an extensive dataset developed in 1991 as part of the Laolao Bay golf course construction (Cheenis Pacific Company 1992) to evaluate the magnitude of negative change in Laolao Bay over the past two decades. Historical data regarding fish, coral, macroinvertebrate, and algal assemblages, as well as water quality, provide a rarely available context upon which modern ecological assemblages are characterized. Combining historic and modern datasets, this study provides unique insight into reef condition at high spatial resolution, appropriate to assess patterns and changes for individual sub-watersheds.

Laolao bay marine environment

Modern reef assemblages in Laolao Bay are influenced by environmental regimes that naturally occur, and must be introduced prior to assessing condition, or change over time. The environmental differences that are expected to be most influential to coral reef assemblages throughout the bay are related to watershed geology. Karst limestone bedrock exists in the easternmost portion of the bay, while progressing westward, volcanic soils and bedrock become evident (Cloud 1959). As a consequence, significantly greater connectivity with the freshwater aquifer in the eastern side of the bay is expected due to the presence of karst bedrock. Elsewhere, the thick soils and volcanic basement are expected to reduce percolation, and facilitate the transfer of greater surface water discharge during storm events. Differences in the nature of freshwater delivery to the nearshore marine environment have consequences for coral reef assemblages, which grow in response to environmental conditions through time. Such differences in watershed geology have previously been shown to dictate the modern coral assemblages that exist throughout the CNMI (Houk and Starmer 2010, Houk and van Woesik 2010). Thus, when evaluating resource condition and change over time we first stratify our statistical designs when appropriate.

The degree of wave exposure also changes throughout the bay. Reefs in the easternmost part of the bay are more protected from northeast, tradewind-generated waves that are common throughout the year. Moving westward, wave exposure gradually increases. Wave energy has previously been shown to structure coral reef assemblages in the CNMI, based upon long-term marine monitoring surveys conducted at 8 – 10 m depth (Houk and van Woesik 2010). However, the influences of wave energy diminish with depth. Generally, shallower depths are associated with more vigorous coral growth due to increased light availability, increased flushing from wave energy, and greater metabolic rates of corals subjected to these conditions (Birkeland 1997; Yentsch et al. 2002). These conditions are expected to reduce the magnitude and potentially alter the nature of negative changes from local stressors (De'ath and Fabricius 2010). For example, negative changes over time are expected to be more substantial at greater depths (Fabricius 2005); a notion supported by CNMI’s long-term monitoring data (8 – 10 m) that highlight reduced, and nearly halted recovery in the western part of Laolao since the mid-2000’s, when high predator starfish abundances were evident. Continued collection of long-term monitoring program data will augment the present study, and a formal analysis is planned for the upcoming fiscal year. Here, we focus efforts on describing the current condition of Laolao Bay coral reef ecosystems; thereby providing a robust ecological baseline to detect change over time with respect to the Laolao ARRA construction activities.

Study Design and Data Collection Methods:

Sampling designs were based upon historical surveys conducted in 1991. A total of six stations were established throughout Laolao as part of an ecological assessment for the construction of Laolao Bay Golf Course (Figure 1). Here, we revisited all stations throughout the bay, collecting data from two key habitats where robust datasets were available: 1) the outer reef flat, and 2) the reef slope at a 3–5 m depth. In addition, one new station was established further south of existing sites in order to evaluate the watershed drainage associated with the San Vicente access road, a major component of construction activities (Station D1, Figure 1). Only reef slope assemblages were examined from the latter station as no reef flat habitat exists. Finally, in both instances surveys were conducted during October, in the midst of the rainy season, to best account for as much of the inherent variation in seasonal algae growth as possible.

Benthic substrates

In 1991 benthic substrate abundances were estimated along each transect by haphazardly tossing five, 1 x 1 m quadrats at ten-meter intervals. Benthic substrates were recorded under each of 16 intersecting cross-lines within the quadrat, using the highest taxonomic resolution possible, typically at the genus or species level. Turf and crustose coralline algae were separated, while rubble and sand were combined into a single category. These methods yielded a total of 80 data points per transect, and three transect to generate statistical estimates at the station level. Current effort used the same number of transects, and transect placement, but increased the level of replication to improve statistical confidence. Fifty, 0.5 x 0.5 m quadrats were placed at 1 m intervals. On the shallow reef flats, substrate was recorded under each of 6 intersecting cross-lines within the quadrat using the highest taxonomic resolution possible, typically at the generic level. On the reef slopes a digital photograph was taken at each 1m interval, and the benthos under each of five random points were assigned a pre-defined category using the freely available computer software, Coral Point Count (Kohler and Gill 2006). These methods yielded a total of 250 (reef slope) or 300 (reef flat) data points per transect, and three transect to generate sound statistical estimates at the station level (Houk and van Woesik 2006). The benthic categories chosen for analysis were corals (to genus level), turf algae (less than 2 cm), macroalgae (greater than 2cm, to genus level if abundant), fleshy coralline algae known to overgrow coral (*Peyssonnelia, Pneophyllum*) (Keats et al. 1997; Antonius 1999, 2001), crustose coralline algae, sand, and other invertebrates (genus level if abundant). Means, standard deviations, and standard errors were calculated based on the three 50m replicates, with n = 300 individual points per transect, n = 900 data points per site for the reef flat, and n = 250 points per transect, n= 750 data points per site for the reef slope.

Corals

For both survey periods coral population data were collected in a similar manner. In each instance, replicate 1 x 1 m quadrats were tossed at equal intervals along the three, 50 m transect lines. In 1991, fifteen replicate quadrats were sampled while the present surveys used ten following an initial inspection of the data showing sufficient statistical power to meet survey demands, as well as species saturation considerations. Within each quadrat all corals were identified to the species level, the maximum diameter and the diameter perpendicular to the maximum were recorded. From these measurements, surface area was calculated considering colonies were circular in nature.

Macroalgae

Algal occurrence and richness data were collected by haphazardly tossing 18, 1 x 1 m quadrats along the three 50 m transect lines at ~8 m intervals. Within each quadrat presence/absence data were collected for all algal species that were visually distinguishable. In the event that species names were uncertain, collections were made and/or unique field names were recorded. Beyond replicated, quadrat-based presence/absence data, these methods also provided for frequencies of occurrence by pooling data from the individual quadrats to the site level.

Macroinvertebrates

For both survey periods macroinvertebrate abundances were collected using identical methods. All conspicuous macroinvertebrates that were observed along 50 x 2 m belt transects were identified to the species level and recorded. Statistical estimates were calculated based upon the three replicate transects surveyed for each station.

Fish data

For both survey periods fish population data were collected in a similar manner. Twelve stationary-point-counts (SPC's) were conducted at equal intervals along the transect lines at each station (Bohnsack 1986). During each SPC the observer recorded the name and size of all food-fish within a 5 m circular diameter at varying taxonomic resolution based upon functional similarity (i.e., large-bodied acanthurids, large-bodied scarids, *Naso unicornis*, *N. lituratus*, small-bodied acanthurids, etc.). Large-bodied fish were defined as species that have a mean reproductive size > 25 cm, while small-bodied were defined below 25 cm. Statistical estimates were calculated based upon twelve replicate SPC's at each station. In 1991 no size estimates were recorded, so historical comparisons are based upon population densities, while the contemporary baseline includes biomass estimates as well. Size at maturity estimates and length-to-biomass coefficients were collected from fishbase (www.fishbase.org).

Water quality data

For the present study, water quality data reporting is limited to profiling activities. Phase II of the study will provide an assessment of stormwater and reef flat water sampling data once they become available. Profile data were collected using a YSI 6600 EDS instrument. In order to generate spatial datasets, an auxiliary bilge pump system was fastened to a small boat to generate a continuous flow of nearshore marine waters (~1ft. in depth) through the YSI sensor casing system. The boat was driven slowly along the reef line following a pre-defined track that was confirmed with GPS locational data collected at 10 second intervals. The YSI instrument was set to collect salinity, conductivity, turbidity, chlorophyll-a, and temperature data at similar 10 second intervals, while moving slowly across the bay. The two events presented here were intentionally collected during varying lunar phases and periods of rainfall to understand natural characteristics of freshwater delivery to the bay. One set of data was collected during a dry period (i.e., no substantial rain 7 – 10 days prior to the survey), associated with a full moon (i.e., monthly maximum tidal exchange and highest expected connectivity with groundwater). The second dataset was collected during a period of high rainfall, with limited tidal exchange (i.e., half-moon).

Data analyses

Historical data from the 1991 ecological assessment of Laolao bay were only available in printed format, as appendices to the submitted report. Combined efforts from PMRI, DEQ, and CRM transcribed these baseline data into electronic formats, needed for processing and analysis. However, in some instances data summaries in lieu of raw data themselves were presented. This artifact introduced some limitations for our ability to conduct statistical examinations of change over time. Described below, the analyses conducted represent the best use of all existing information.

For example, raw data pertaining to historical coral-colony size distributions were not available. In lieu, this study utilized the site-and-species-level data summaries to generate randomized, truncated, log-normal distributions to estimate historical colony size data (Preston 1980). For each site the known means, standard deviations, and number of colonies observed served as inputs to estimate historical size frequency data using the freely available software R (R Core Development Team 2008). We performed 1000 iterations of this process and a representative of the most frequent distribution (i.e., the covergent distribution) was selected for use. In order to test the accuracy of this assumption, the same process was conducted for the 2010 colony size datasets, and pairwise Kolmogorov-Smirnov (KS) tests revealed no significant differences between the generated distributions and the raw data. To compare coral colony size distribution between 1991 and 2010 similar KS tests were conducted between colony-size distributions at each site between years.

Coral colony data were also assessed in multivariate space, using site-level summary statistics. Bray-Curtis similarity distances were calculated between each pair of sites, for both timeframes, and resultant relationships were visualized in multi-dimensional scaling (MDS plots, Anderson et al. 2008). Tests of significance were conducted to examine the change in coral assemblages through time, and across Laolao bay due to gradients in water quality. If multivariate data had similar data dispersion among the a priori groups being investigated (i.e., time frame and geographical separation due to salinity differences, measured by a PERMDISP test, Anderson et al. 2008), parametric multivariate testing was conducted (PERMANOVA tests). If dispersion was significantly different, non-parametric tests were used to examine separation (ANOSIM tests).

No historical data provided replicate measures of algal richness or frequency of occurrence, thus, detailed insight regarding algal assemblages are based upon the present findings. Algal diversity data were assessed in multivariate space, using site-level summaries from quadrat surveys. Initially, presence/absence simple matching similarities were calculated between each pair of sites, and these measures of multivariate differences were visualized in MDS plots (Anderson et al. 2008). Subsequently, tests of significance were conducted to determine if algal assemblages differed across the bay. Described above, statistical testing included initial tests to determine multivariate normality (PERMDISP). If the within-site variance significantly differed, data were transformed into rank-based numbers, and ANOSIM tests were conducted for pairwise examination. Else, PERMANOVA pairwise testing was conducted.

Fish population density data were similarly examined in multivariate space to determine the extent and nature of temporal trends. Bray-Curtis similarity distances were calculated between every pair of SPC's, for both timeframes, and resultant relationships were visualized using MDS plots. Tests of significance were conducted to examine the change in fish assemblages through time, and across Laolao bay due to gradients in water quality, as described above.

For remaining datasets standardized pairwise tests were conducted between timeframes while first grouping data across all sites within Laolao Bay, and subsequently by examining change at each individual site. In all instances of pairwise comparisons, initial homogeneity of variance tests were conducted to ensure that dependent variables met assumptions of normality, and data transformations were conducted as necessary to validate assumptions. If data were not normal, non-parametric testing was conducted to examine for differences.

Results and Discussion:

Reef flat assemblages

Benthic data collected from the reef flat habitat showed three dominant categories covered ~90% of the substrate; brown, red, and turf algae (Figure 2). Brown algal growth was comprised mainly of *Sargassum polycystum*, a seasonal algae common to reef flats of the Marianas (Tsuda 2003). Other notable contributions of *Padina tenuis* were also evident in a spatially inconsistent manner (Figure 3). Red algal growth was comprised mainly of *Laurencia* spp. and *Palisada* sp., more persistently growing algae, known to proliferate where poor water quality and reduced herbivory exist (Burkepile and Hay 2009; Houk and Camacho 2010). While red algae were prolific throughout Laolao, the relative abundance of individual species varied between sites, and even between transects within a site. The cause(s) of species-and-genus-level spatial variance remain unknown, but are thought to be linked with reef flat topography, proximity to intermittent stream discharge, and proximity to channels that flush reef flat waters.

Comparative analyses between 1991 and present indicate significant increases of macroalgae on Laolao reef flats ($P<0.05$, pairwise t-test for all sites grouped). Largest increases were found for persistent red algae, described above, however increases in seasonal *Sargassum* growth were also evident (Figure 4). The largest increases in macroalgae were found at sites adjacent to road improvement activities (sites C1 – C9), suggesting that improved water quality expected from construction efforts should eventually have a direct, positive influence upon these assemblages.

Across Laolao reef flats, the most persistent algae found within 50% of all quadrat surveys included *Gelidiella acerosa*, *Jania capillacea*, *Palisada perforata*, and *Sargassum polycystum*. Comparatively, the algal assemblage at site B1 was unique (R-Statistic > 0.45 for all but one pairwise comparisons, $P<0.05$, ANOSIM, Figure 5), where assemblages comprised relatively high abundances of small gelids (i.e., red turf algae), *Boodlea* (i.e., filamentous green algae), and less *Laurencia* and *Palisada* (SIMPER, species that accounted for the top 30% of differences). Continuously forcing environmental regimes, such as submarine groundwater discharge found to be highest in this section of Laolao, are thought to contribute to the persistence of unique algal assemblages in easternmost Laolao. In general, the degree to which species abundance patterns between replicate measures are different, or within-site heterogeneity, can be a useful indicator of environmental influence (Houk and van Woesik 2010). This study found the lowest heterogeneity at sites B1, B4, and C7, where influences from continuous groundwater or a lack of channels promoting water exchange on the reef flats, respectively, were evident ($P<0.05$, PERMDISP, pairwise comparison between lowest and highest heterogeneity sites, Figure 6). Elsewhere, where large-scale, continuous environmental drivers are absent, coverage, species richness and overall heterogeneity were higher, and thought to be better indicators of land-based pollution. In support richness and heterogeneity were highest at site C4, where watershed size is largest and land-based pollution thought to be greatest based upon watershed size (Figure 6).

These findings agree that in the absence of a restrictive, natural environmental setting, the noted measures of algal assemblages increase with increasing pollution and/or reduced herbivory (Boyer et al. 2004; Fabricius et al. 2005). Therefore, the present findings facilitate a hypothesis that land-based pollution may have greatest affinities with assemblages at C4. Finally, it is noteworthy that the common and persistent red algae, *Palisada perforate*, was dominant at all sites except B1, occurring within 72-94% of the quadrats at each site.

Macroinvertebrates on the reef flats consisted mainly of three species of sea cucumbers: *Holothuria atra*, *Holothuria leucospilota*, and *Actinopyga echinites*. *H. atra* were most abundant, reaching densities of over 50 individuals per 100 m^2 at some sites (Figure 7). There were no clear relationships between sea cucumber densities and algal assemblages, nor were there any substantial changes since 1991 (Figure 8). The sole exception is for site B1-3 where a major decline in *H. leucospilota* abundances became evident. Given these findings, there are no expectations for change in sea cucumber abundances in relation to the present mitigation activities.

Water Quality Profiling

Initial water quality profiling activities clearly define inherent differences in ambient conditions across Laolao bay. Profiling activities conducted during full moon periods with no rainfall found comparatively lower salinity levels in the eastern portion of the bay where karst bedrock exists in the watershed (Figure 9a). Thus, it appears the natural gradient in salinity is an artifact of greater connectivity with the island aquifer, as freshwater seepage through the reef matrix is the proposed mechanisms of delivery during large, negative tide events associated with full and new moon periods (Corbett et al. 1999; Umezawa et al. 2002; Houk et al. 2005; Houk and Starmer 2010). In contrast, the opposite trends were seen during periods of consistent rainfall and limited tidal exchange to promote connectivity with the aquifer (Figure 9b). Surface discharge was highest in the western portion of the bay, where the largest volcanic watersheds exist.

Reef slope assemblages

Benthic surveys reported lower coral coverage in the groundwater influenced, eastern portion of Laolao, where turf algae dominated the substrate (pairwise t-test for coral and turf algae abundances at site B19-24 compared with others, $P<0.05$ in both instances, Figure 10 and 11). These spatial delineations are consistent with the water quality profiling data (Figure 8a), and thus a probable consequence of groundwater influence. In support, numerous studies have found reduced coral and increased algae in association with enhanced groundwater influence (Umezawa et al. 2002; Lapointe et al. 2004; Houk et al. 2010), and highlight reduced coral growth rates and increased post-settlement mortality as the mechanisms leading to these changes (van Woesik 2002; Houk and van Woesik 2010). Beyond coverage, the composition of coral assemblage was significantly different between the two regions, and through time as well (PERMANOVA, F-Statistic >3.5, $P<0.05$, for both comparisons, Figure 11). Additionally, there was a significant interactive effect (F-Statistic = 4.29, $P<0.01$, Figure 11) highlighting that greater changes occurred through time in the eastern part of the bay, where coral assemblages were mainly comprised of smaller *Porites*, *Leptoria*, *Favia*, and *Galaxea* colonies. These genera create reduced architecture in the reef matrix, or three-dimensionality, compared with other stations. Elsewhere, encrusting *Montipora*, massive *Porites*, corymbose *Acropora, Pocillopora*, and *Stylophora*, and an increased richness of corals were found in greater abundance. Comparisons with historical benthic substrate data show non-significant changes in coral coverage when grouping all stations together, however site B25-27 showed an anomalous increase in coral coverage since 1991 (Figure 11), discussed below.

Comparisons through time revealed a universal increase in population density at all stations, especially in the western portion of the bay ($P<0.05$, grouped and pairwise t-tests, Figure 13). Encrusting *Montipora*, massive *Porites*, *Leptastrea*, and *Favia* corals have all shown significant increases in population density, and were drivers of these trends (Figures 13 and 14). Cumulatively, these changes suggest that although there were localized areas of refuge where coral population structure showed minimal change (B25-27 and C25-27, Figure 13), throughout the bay the mean colony size has decreased, along with a shifting composition. Cumulatively, the current condition of benthic and coral assemblages are consistent with published reports describing ecological states under the influence of high sediment loads, enhanced nutrients, and decreased herbivory (Rogers 1990; Fabricius 2005; Dikou and van Woesik 2006; Houk et al. 2010).

Dominant macroalgae that were found in more than half of all survey quadrats on the reef slopes included *Amansia glomerata*, *Amphiroa fragilissima*, and *Dictyota friabilis*. Pairwise examinations of site-level differences across the bay were mainly non-significant, especially in comparison to the reef flat algal assemblages that showed the opposite trends. The only exception was a significant pairwise difference between the algal assemblages at sites B19 and D1 (R-Statistic >0.45, $P<0.05$, ANOSIM, Figure 15). Site B19 is associated with high groundwater influence, noted above as a driver of numerous ecological trends reported. Lastly, a unique algal assemblage appeared to exist at site D1 compared to other, driven mainly by high abundances of gelids (i.e., turf red algae), *Dictyota friabilis*, *Dictyosphaeria versluysii*, *Amphiroa fragilissima*, and *Jania decussatodichotoma* (Figure 15).

Although most pairwise comparisons of algal presence/absence trends revealed non-significant differences, pooling the data to examine frequencies of occurrence highlighted two distinct site groupings. B19, C19, and C22 all had steeper slopes associated with their cumulative dominance curves (Figure 16), suggesting that greater similarities existed between each replicate quadrat as compared with others sites ($P>0.05$ for pairwise comparisons between these three sites, while $P<0.05$ for the majority of pairwise comparisons with others, PERMDISP, Figure 16). In contrast, macroalgal assemblages were most evenly distributed at D1, C25, and B22. No hypothesized explanations are offered for difference in macroalgal heterogeneity, however, future water quality data may provide insight. In summary, when pooling data at the site level to determine frequencies of occurrence, low macroalgal heterogeneity at B19, C19, and C22 was reported. However, when examining algal presence/absence, the composition was more uniform across the bay.

Reef slope fish assemblages were dominated by small-bodied acanthurids (i.e., herbivorous surgeonfishes) with a near absence of piscivore and benthivore consumers observed (Figure 17). Mean food-fish biomass per SPC was less than 2 kg. One site showed differences from these generalized trends, B25-27, noted above as where coral and benthic assemblages have had non-significant change through time. Elsewhere, the low abundance and diversity of food-fish assemblages are characteristic of high fishing pressure and reduced ecological function (Jennings et al. 1995; Bellwood et al. 2003; Elmqvist et al. 2003). In support, there have been significant declines in food fish abundances and diversity since 1991 (Figures 18 and 19), whereby functionally diverse assemblages have been replaced mainly by small acanthurids. While low herbivory levels are corroborated with declining reef 'health' alone, the added influence of land-based pollution may represent a synergistic combination. Existing studies show that both stressors are indeed drivers of negative change, but their synergistic interaction may be strongest (Littler et al. 2006; Sotka and Hay 2009; Houk et al. 2010). The extent, nature, and consequences of reduced fish stocks in Laolao are the subjects of continued investigation, and are being approached in conjunction with enhanced watershed and water quality data.

Macroinvertebrate assemblages on the nearshore reef slopes were expectedly dominated by grazing *Echinometra* and *Echinothrix* sea urchins (Figure 20). *Echinometra* urchins were found in high densities (~40 per $100m^2$) at all sites except C19-21, where relatively strong, negative changes in reef status were noted. In support, historical data show a major reduction in *Echinometra* at C19-21, from over 100 individuals per 100 m^2 to approximately 10 (Figures 21 and 22). The larger, black-spined *Echinothrix* urchins have increased through time (mean of 0.8 compared to 3.2 per 100 m^2, Mann-Whitney U-test, $P<0.05$), however current densities are less than 10 individuals per 100 m^2, well below *Echinometra* abundances. Urchins obviously have key functional roles on Laolao's reefs, documented as keystone species elsewhere (Edmunds and Carpenter 2001; Mork et al. 2009), and despite the localized decline at C19-21, this study does not suggest compromised grazing rates of urchins exist for 5 m reef slope assemblages. However, reef fish also have key functional roles of grazing algae, and their low abundance and functional diversity was noted above. Other trends in macroinvertebrate abundances include an increase in sea cucumber densities in the calmer, eastern side of Laolao, where northeast tradewind generated waves have less influence, and sandy bottoms are more prevalent. Here, the increase in sea cucumber density has been accompanied by a shift in dominance from *Holothuria edulis* to *Stichopus chloronotus* (Figures 20 and 22). No contemporary scientific evidence exists to corroborate if compositional shifts in sea cucumbers reflect changing reef integrity, however the increase in abundance of sea cucumbers (grouped) suggests more detritus material now exists compared to 1991, supporting enhanced nutrient and sediment delivery.

Conclusions and Future Activities:

Summary of findings

Since the inception of CNMI's coral reef initiative (CRI) program in 2000, numerous local scientists and resource managers have been anecdotally suggesting that Laolao's coral reef environment shows negative signs of human influence. However, this study is the first to provide scientific evidence and quantitative, measurable data that describe the current condition and mechanisms of ecological change. Through this study we have generated a second, robust snapshot in time to describe the ecological assemblages in Laolao, and change since 1991. While these data provide sound guidance for setting ecological targets for ongoing conservation planning activities, their main purpose was to provide a baseline upon which (positive) change can be detected pending the completion of construction and revegetation activities.

The collective results highlight that negative changes to Laolao's coral reef assemblages and fisheries have become evident over the past 20 years, and compromised ecological states currently exist. Both land-based pollution and unsustainable fishing are corroborated through comparisons with published literature from the CNMI and elsewhere, yet, continued water quality and watershed data collection will facilitate a more formal analysis. Both compromised ecological status and negative change through time were spatially dependent within the bay. Two stations, B25-27 and C25-27 showed less change through time with respect to their coral and benthic assemblages, and were regarded as having a relatively high reef condition. A review of satellite imagery shows these stations to have less hydrodynamic connectivity with reef flat waters, and thus a perceived reduction in the delivery of watershed drainage runoff. This is visually noted by a lack of channels cut into the reef matrix that facilitate the flushing of inshore waters. Thus, it appears that localized oceanographic conditions may facilitate improved water quality, in turn favoring coral recruitment, growth, and species richness. Further comparisons between these sites revealed that reef condition was better at B25-27 compared to C25-27 (Figures 10-13), in accordance with fish assemblage patterns that showed higher abundances of numerous large-bodied herbivorous fish (PERMDISP test, Pseudo F-Statistic = 7.43, $P<0.05$).

While herbivory or land-based pollution alone are plausible drivers of compromised assemblages in Laolao, the greatest negative changes were evident where reduced herbivory **and** hypothesized lower water quality existed. Published evidence linking reduced herbivory and water quality to compromised ecological states support these findings (Littler et al. 2006; Sotka and Hay 2009; Houk et al. 2010). Clearly it is imperative to examine how much of the statistical variance in benthic and coral assemblages can be explained by water quality, herbivory, or an interaction of the two, in order to prioritize the numerous management targets. Current efforts remain ongoing to improve our understanding of watershed and water quality patterns, and will serve to address these pertinent questions.

Phase II of this project will continue to collect water quality data from runoff waters during storm events, and on the reef flats where runoff discharges. Sampling activities are ongoing and will provide a quantitative context to improve our eventual understanding of change. For the purposes of this project, further investigations are focused upon documenting (positive) change in water quality and nearshore assemblages as a result of restoration activities, within the timeframe of the ARRA project. A collaborative effort between CNMI's monitoring program and PMRI aims to further address the cause(s) of ecological change with respect to herbivory and water quality, over longer time periods, and build statistical models to summarize findings and predict future scenarios.

Project-specific considerations

The footprint of construction activities is centered upon the western portion of Laolao Bay, where access road and drainage crossing improvements are ongoing. Construction activities include the paving and improved drainage of LaoLao Bay Drive, the road entering Laolao from San Vicente, and the re-construction of numerous stream crossings to reduce the transport of sediments to the ocean from these key locations. While ecological assemblages are formed through the time-integrated responses of individual species to driving environmental regimes, the time required for detectable responses may be longer than the project timeline allows for (Connell et al. 1997; Nyström et al. 2000; Brown et al. 2002; Mumby et al. 2005), especially on the coral-dominated reef slopes. The fastest growing benthic assemblages that are expected to improve in integrity from construction activities are the algal assemblages on the reef flats (Schaffelke et al. 2005; Houk and Camacho 2010). While reductions in persistent red algal biomass are expected given improved water quality, the ecological response may require several years before becoming evident, or may proceed slower than expected without a concomitant increase in herbivorous fish biomass.

While future, positive ecological trends over the next 1-2 years are expected, it is suggested that water quality data will be the first and immediate measure of project success. Water quality monitoring consists of stormwater sampling during rain events at 10 locations associated with construction activities, as well as nearshore reef flat marine water sampling on monthly intervals regardless of rainfall (Figure 1). The parameters being investigated are temperature, pH, salinity, total suspended sediments, turbidity, and basic nutrient constituents (nitrates, nitrites, phosphates, total N and P). Phase II of our reporting will be focused upon a formal analysis of these data, and their integration with all ecological surveys.

Finally, it is noted that re-vegetation efforts associated with this project are centered upon a large, semi-barren savannah in the eastern portion of Laolao. Obvious improvements in vegetation cover are becoming evident, and eventually, through following annual re-vegetation plans, are expected to improve the quality of runoff waters. However, the major driver of tainted water quality discharge into the eastern bay is Gabgab road, the unpaved access road to Laolao from Kagman. Given the current situation, we do not expect immediate changes in the nearshore waters of the eastern bay. Additional insight into planting success is available through other project-related reporting and collectively, the eastern portion of Laolao is the topic of continued management planning.

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Figures:

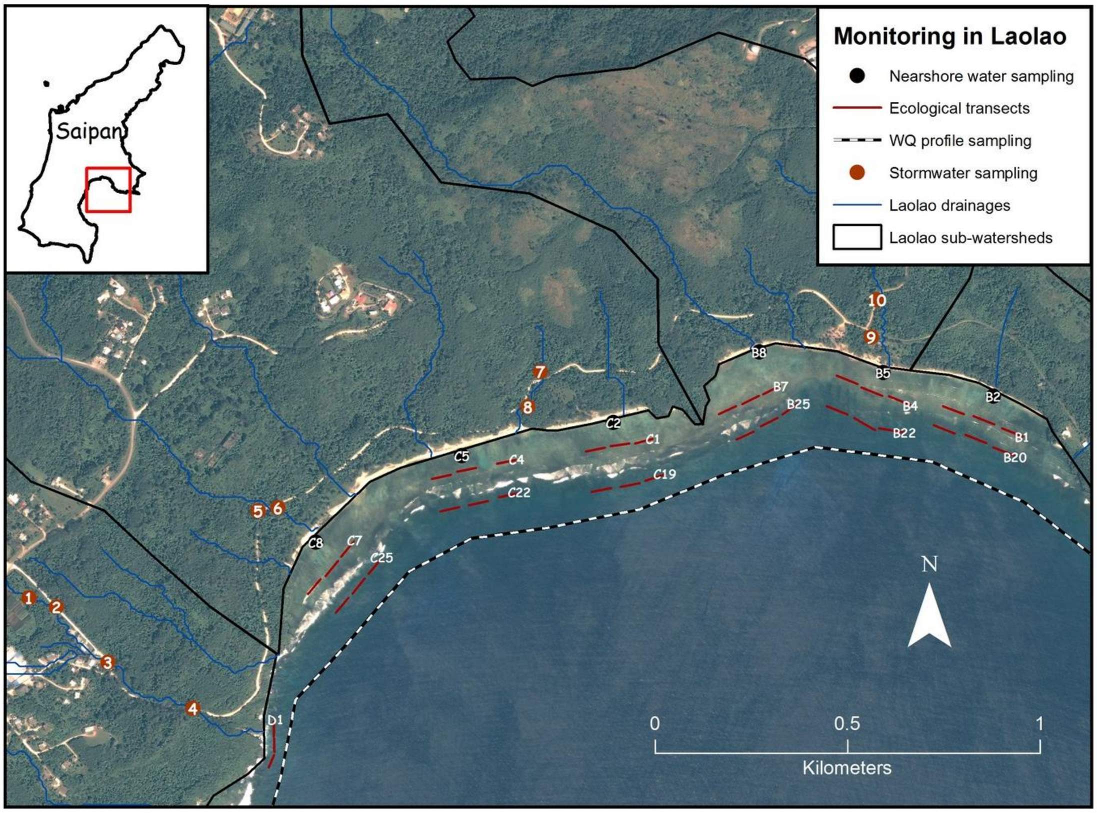


Figure 1. A satellite image of Laolao bay showing major watershed delineations, intermittent streams, water quality sampling locations, and ecological transects surveyed.

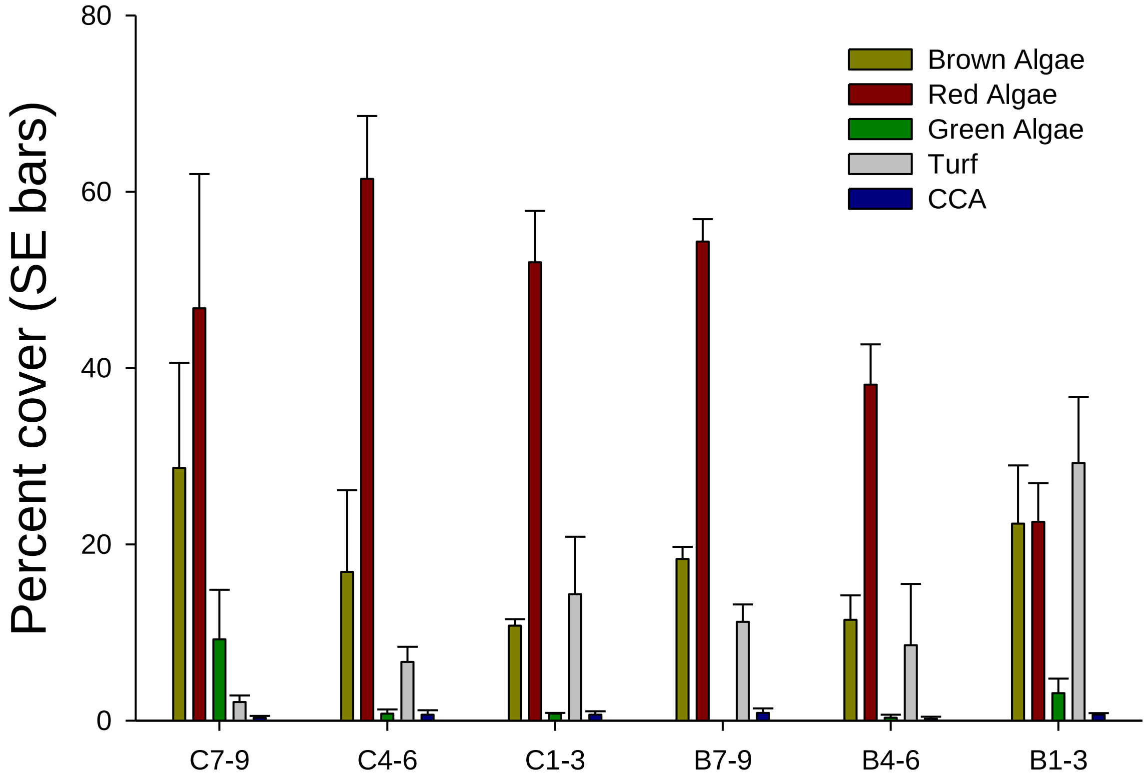


Figure 2. Benthic substrate abundances on Laolao reef flats. Algae are grouped by phylum and/or functionality.

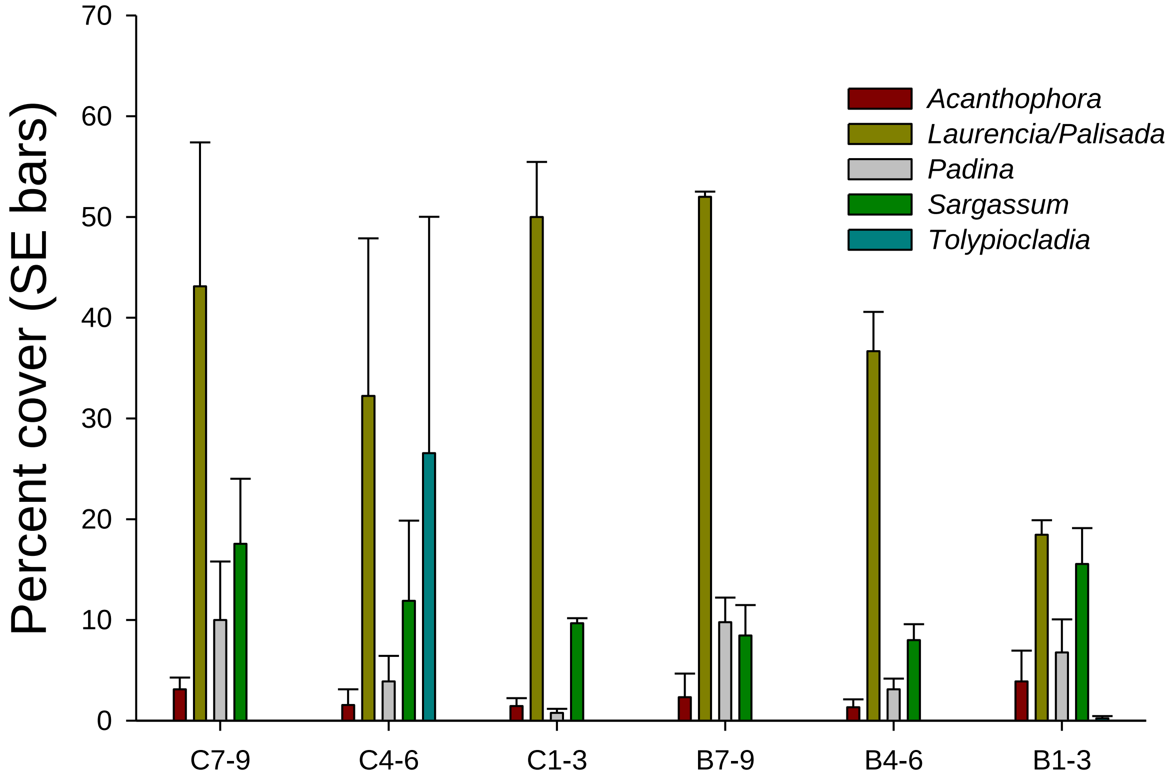


Figure 3. Macroalgal composition on Laolao reef flats. Algae are grouped by genus, with only dominant taxa shown.

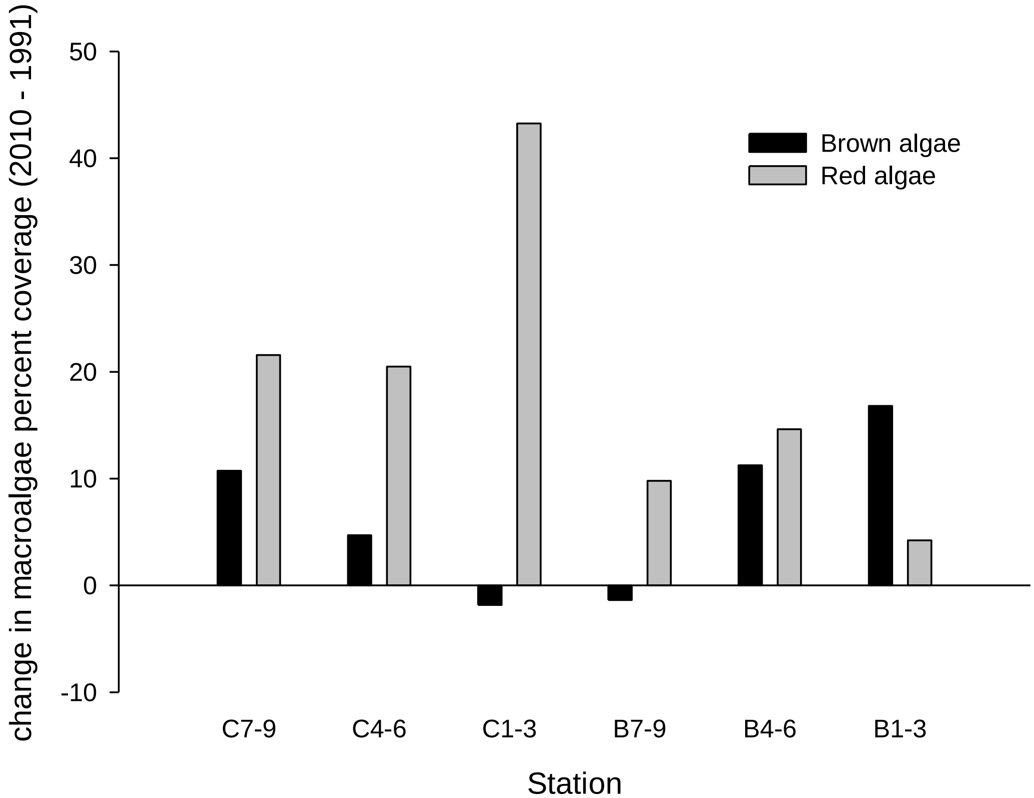


Figure 4. Change in two dominant algal phyla since 1991. Significant increases in red algae, as well as all macroalgae grouped together, were found across Laolao (P<0.05, pairwise t-test between years for all transects across Laolao combined).

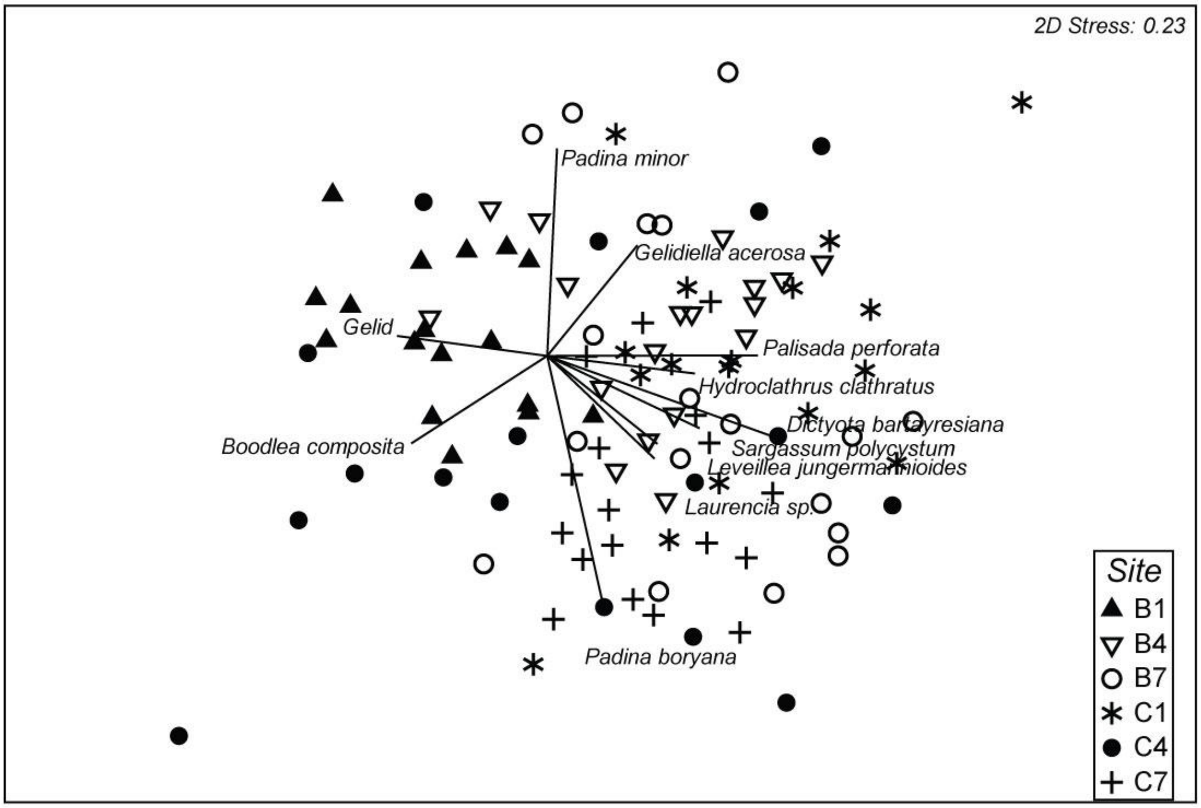


Figure 5. Multi-dimensional scaling plot highlighting relationships between reef flat algal assemblages. Each data symbol represents a replicate, presence/absence, quadrat survey (*see methods*). Comparatively, the algal assemblage at site B1 was unique (R-Statistic > 0.45 for all but one pairwise comparisons, P<0.05, ANOSIM), due mainly to high abundances of small gelids (i.e., red turf algae), *Boodlea* (i.e., filamentous green algae), and less occurrences of *Laurencia* and *Palisada*. Vectors display corals that were significant drivers of these trends (spearman correlation coefficients >0.5).

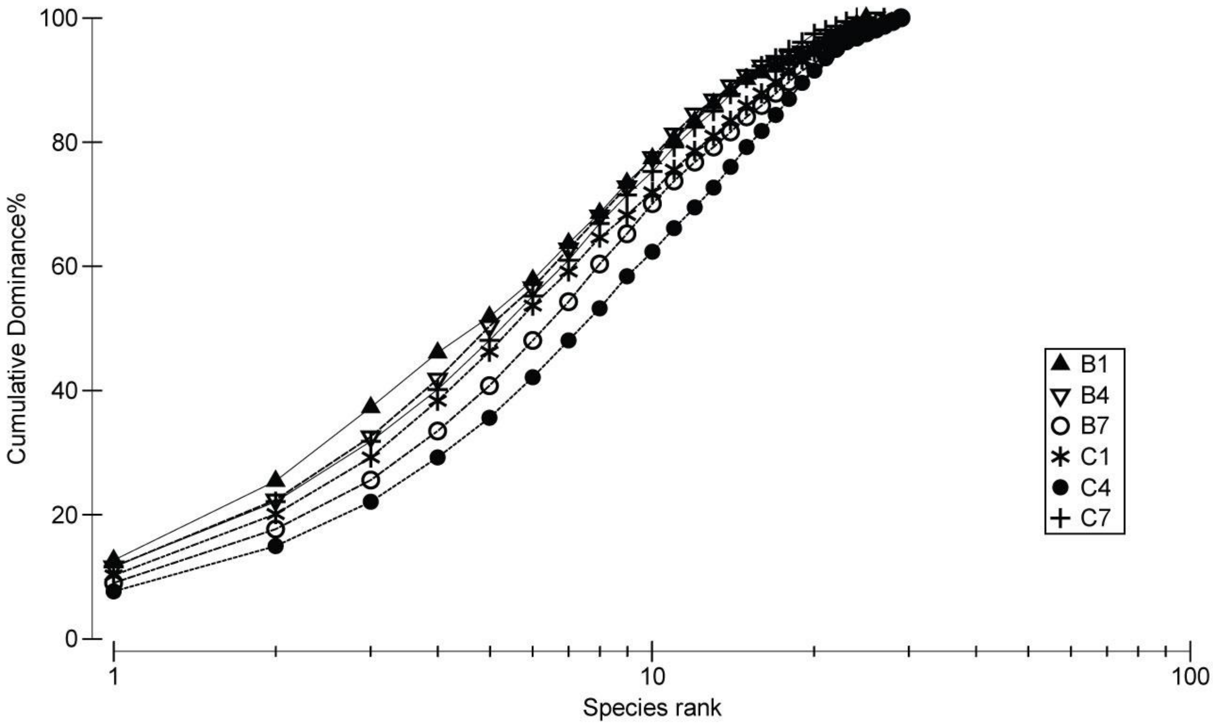


Figure 6. Cumulative dominance plots for reef flat algal assemblages based upon replicated, presence/absence, quadrat surveys (*see methods*). The species saturation curves on the bottom (C4 and B7) indicate that macroalgal assemblages were not dominated by one, or a few, species. Rather, these assemblages had many species that contributed to the overall macroalgal occurrences, relative to other sites, and thus, a greater heterogeneity between replicate quadrats ($P<0.05$, PERMDISP, pairwise comparisons between sites associated with the top and bottom curves). The opposite patterns are associated with curves on the top; whereby the degree of similarity between replicate quadrats was highest.

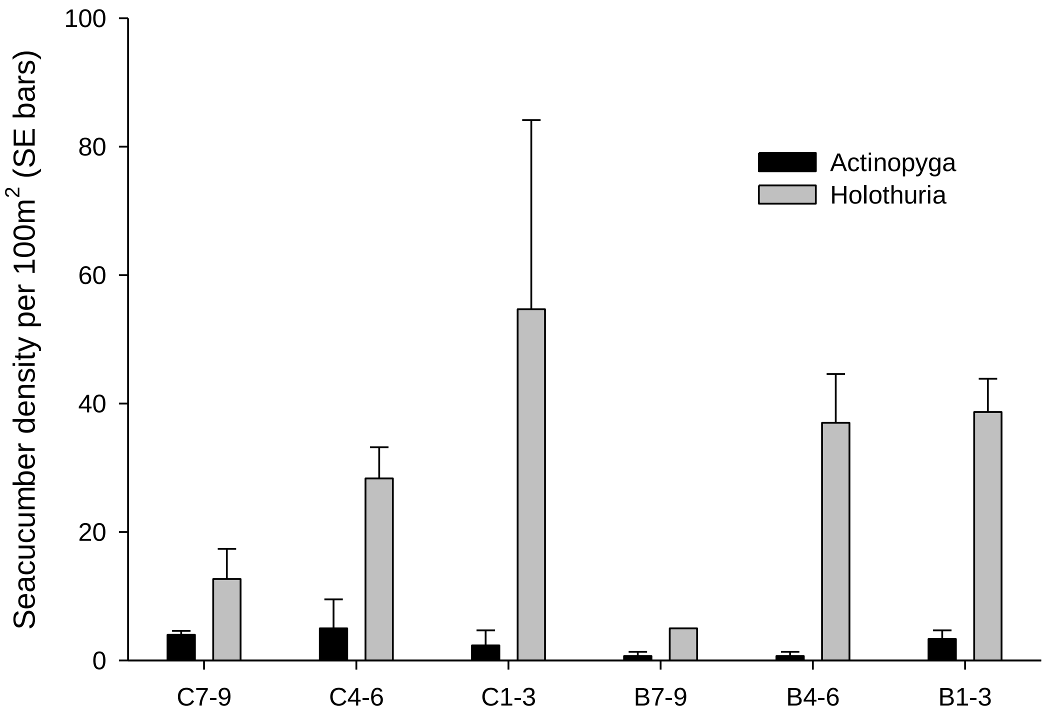


Figure 7. Mean sea cucumber densities on Laolao reef flats. Only two dominant genera, *Actinopyga* and *Holothuria* are shown as all others were rarely encountered.

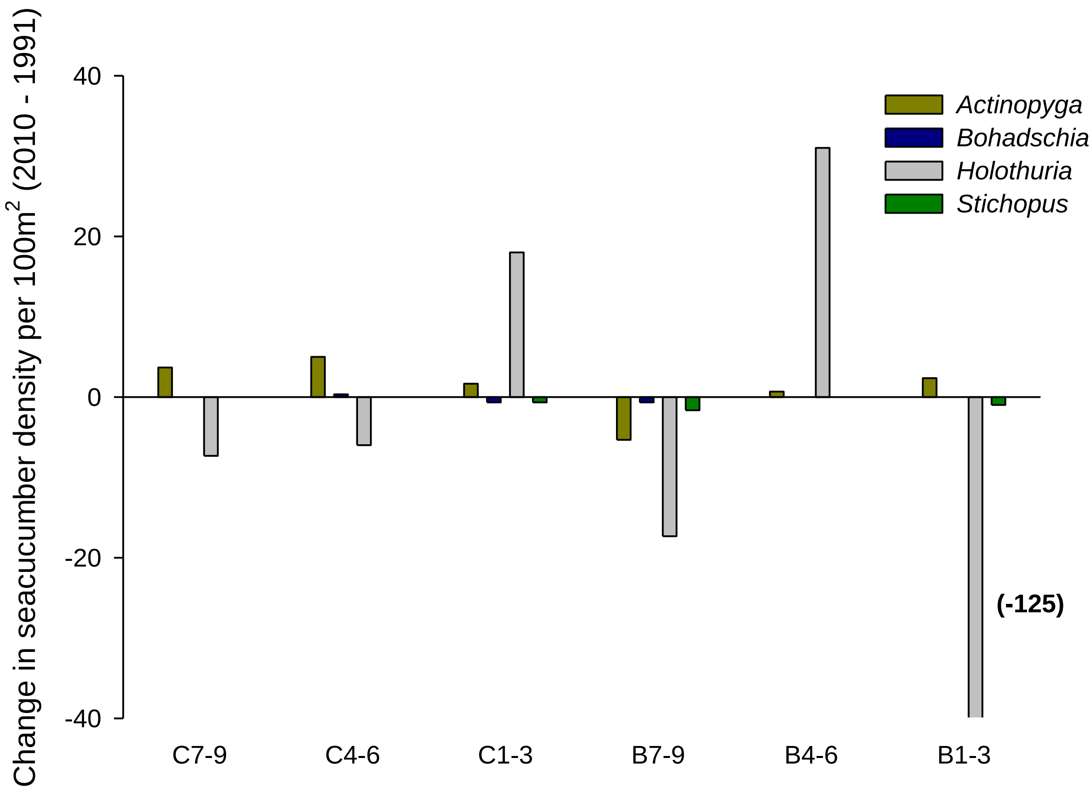
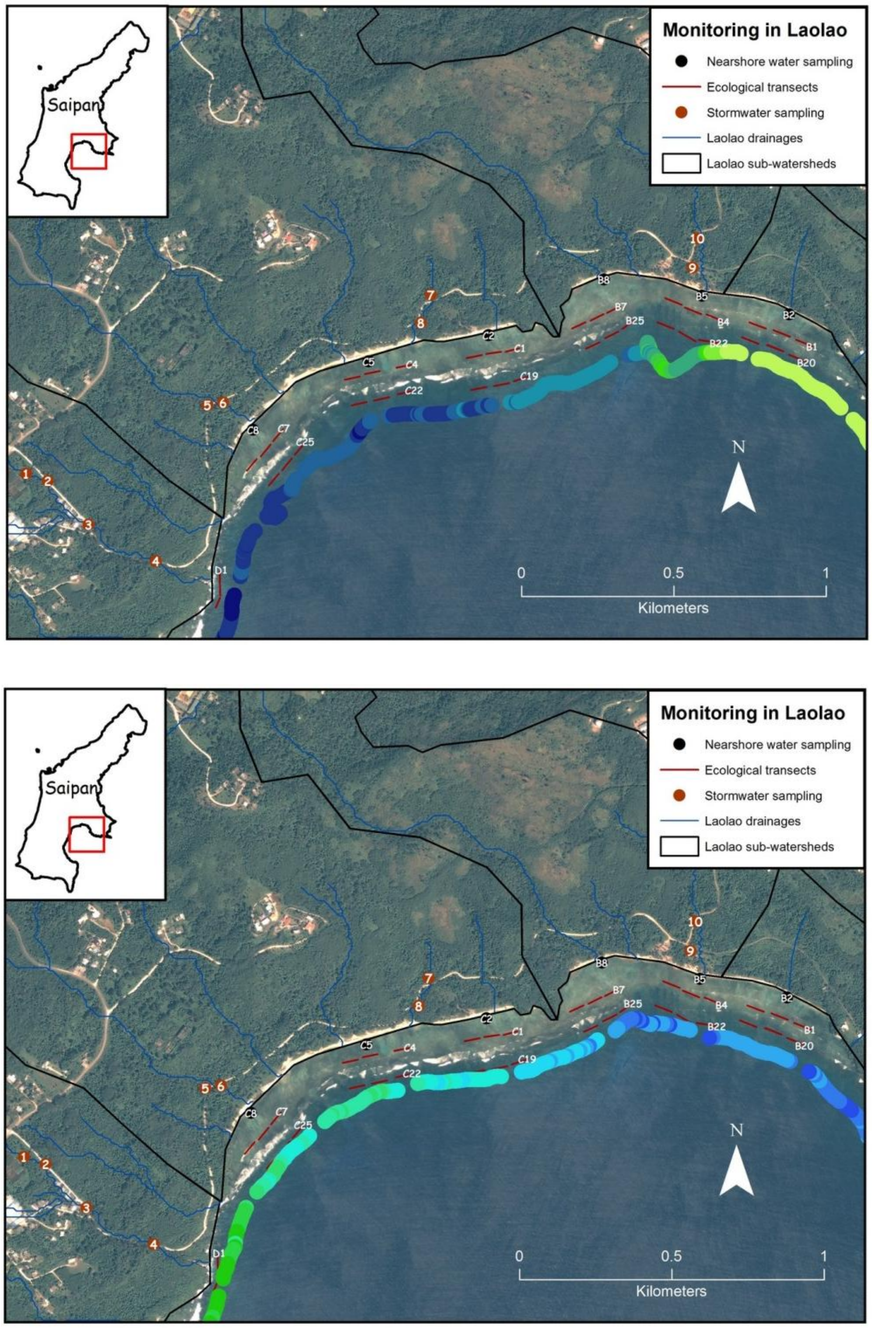


Figure 8. Change in sea cucumber density on Laolao bay reef flats since 1991. The only significant changes noted were at station B1-3, where *Holothuria* densities (mainly *H. leucospilota*) showed a strong but spatially inconsistent decline (Mann-Whitney U-test, $P<0.05$, between years). Non significant differences are reported elsewhere.



a)

b)

Figure 9a-b. Satellite image of Laolao bay with water quality and ecological monitoring stations shown, as well as the initial results of water quality profiling to understand natural characteristics of Laolao discharge patterns. Salinity profile shows a greater influence of freshwater (i.e., lower salinity) in the eastern portion of the bay (Fig. 8a), a probable consequence of limestone bedrock in the watershed promoting enhanced connectivity with the aquifer during full moon, maximal tidal exchange periods. During minimal tidal exchange periods and high rainfall, the opposite pattern was found (Fig. 8b), as freshwater delivery was more proportional to watershed size where volcanic bedrock and soils exist.

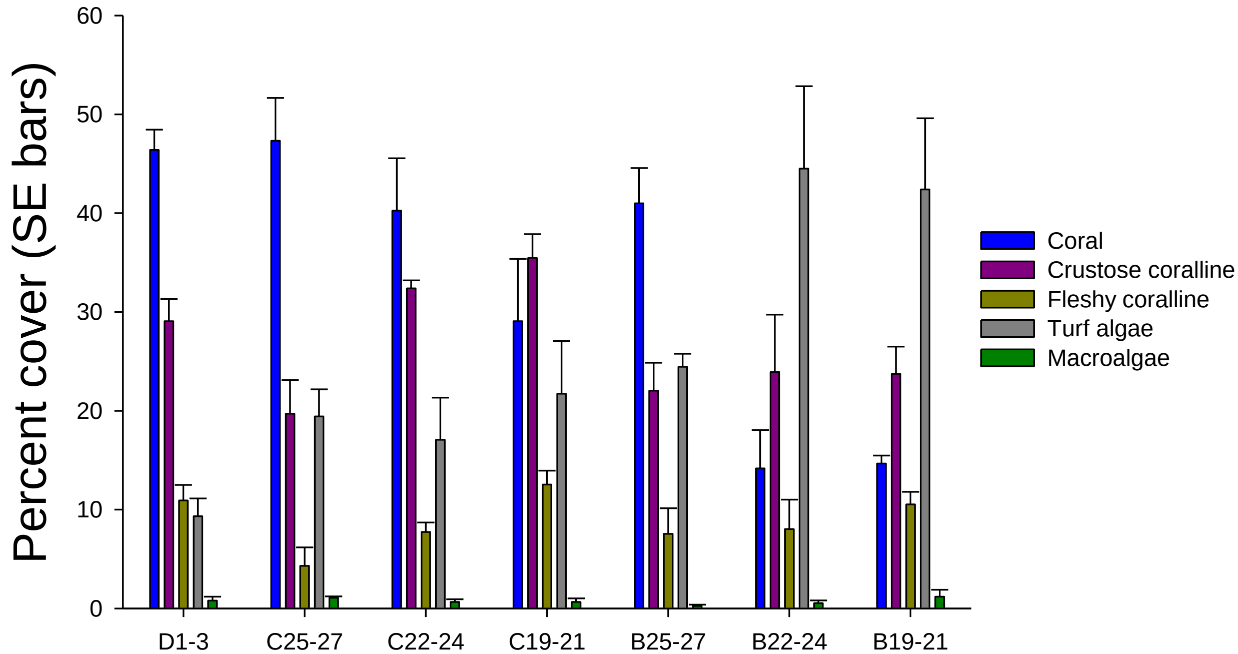


Figure 10. Percent cover of dominate benthic substrates on Laolao reef slopes. Clear difference can be seen between survey stations associated with enhanced groundwater connectivity (B19-21 and B22-24) compare with others. These conditions are less favorable for coral growth and more favorable for turf algae persistence.

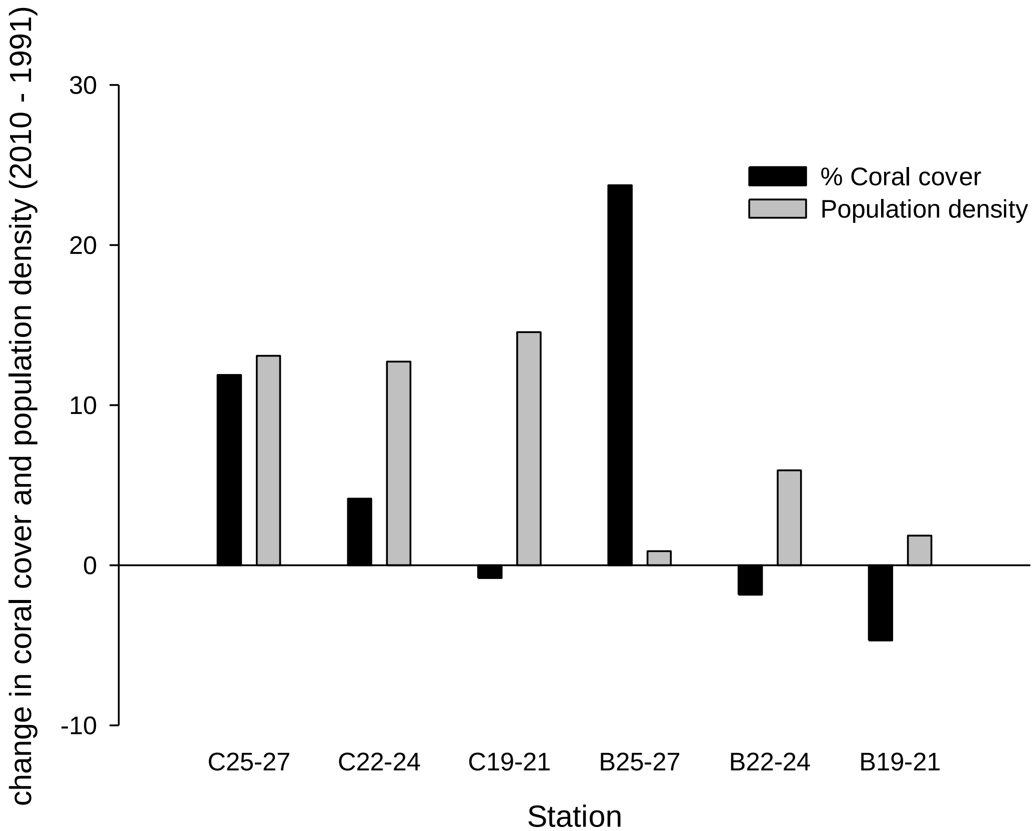


Figure 11. Change in percent coral cover and colony density per m^2 since 1991. Significant increases in population density are noted throughout Laolao ($P<0.05$, pairwise t-test), however changes in coral coverage were spatially inconsistent. Similar to other ecological data collected on the reef slope, inherent difference can be seen between sites associated with enhanced groundwater delivery (B19-21 and B22-24) and others.

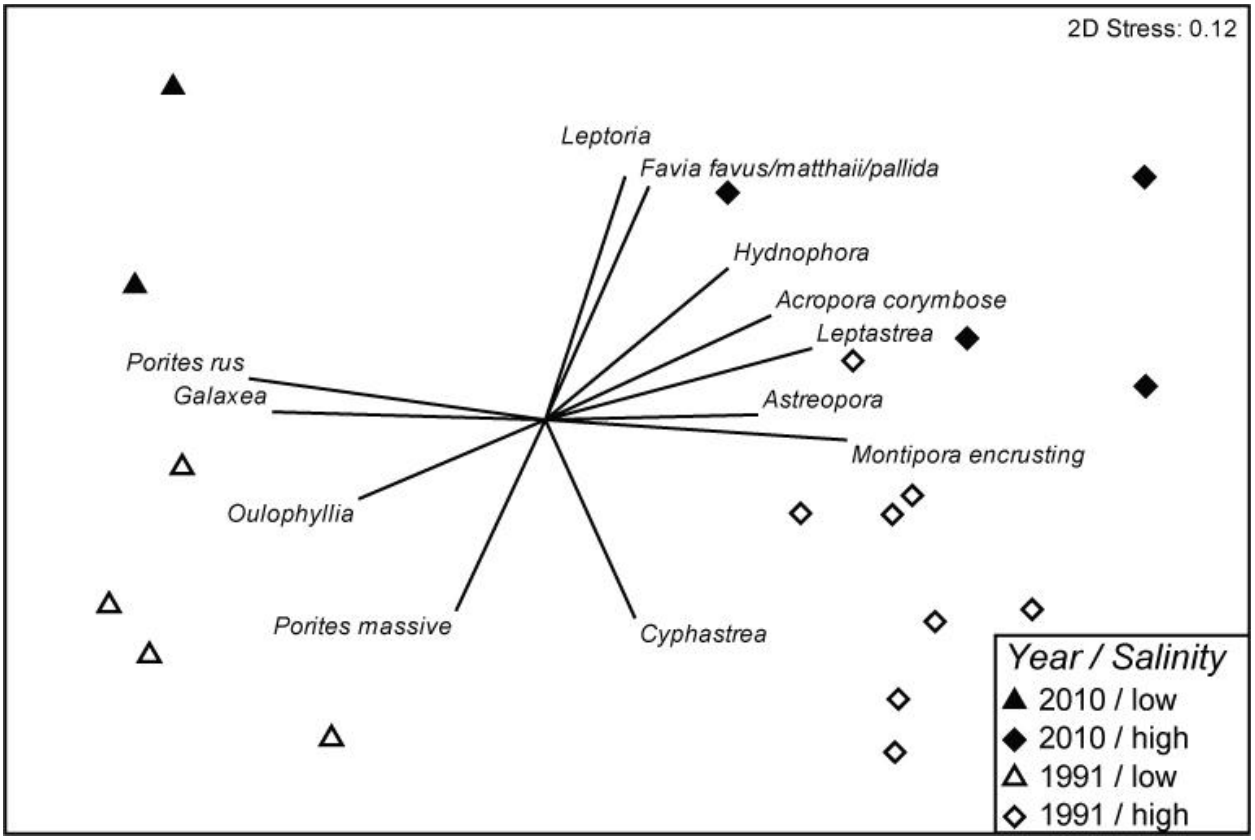


Figure 12. Multi-dimensional scaling plot highlighting the relationship between Laolao coral assemblages. Significant differences were found between coral assemblages based upon groundwater influence (low vs. high) and year (2010 vs. 1991) (PERMANOVA, F-Statistic >3.5, P<0.05, for both comparisons). Additionally, there was a significant interactive effect (F-Statistic = 4.29, P<0.01) highlighting that greater changes occurred through time where high groundwater influence was evident. Vectors display corals that were significant drivers of these trends (spearman correlation coefficients >0.5).

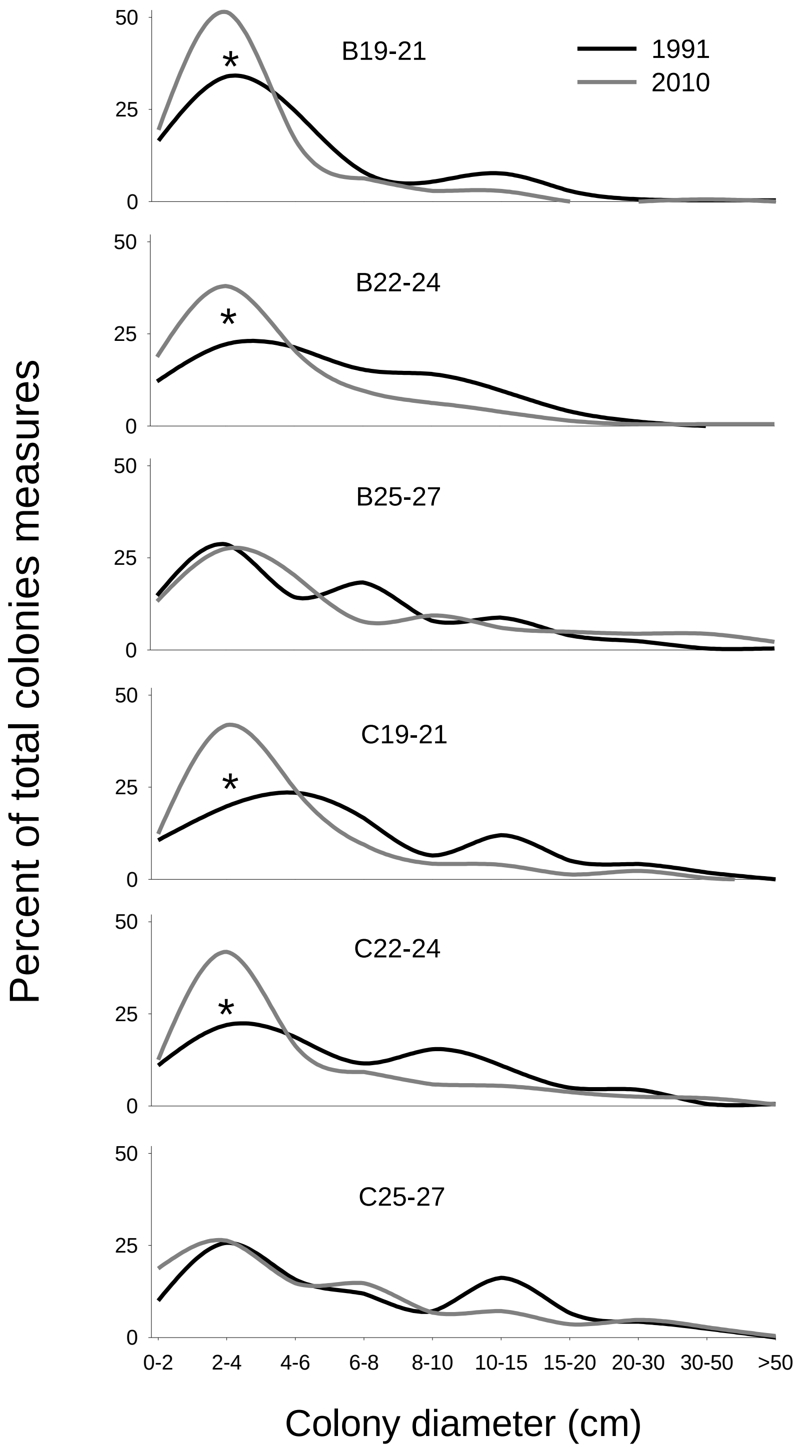


Figure 13. Trends in coral population demography since 1991. Each graph shows comparative colony-size distributions. At four survey stations denoted with an (*) pairwise Kolmogorov-Smirnov tests showed a significant reduction in mean colony size, and a larger proportion of juvenile corals, through time.

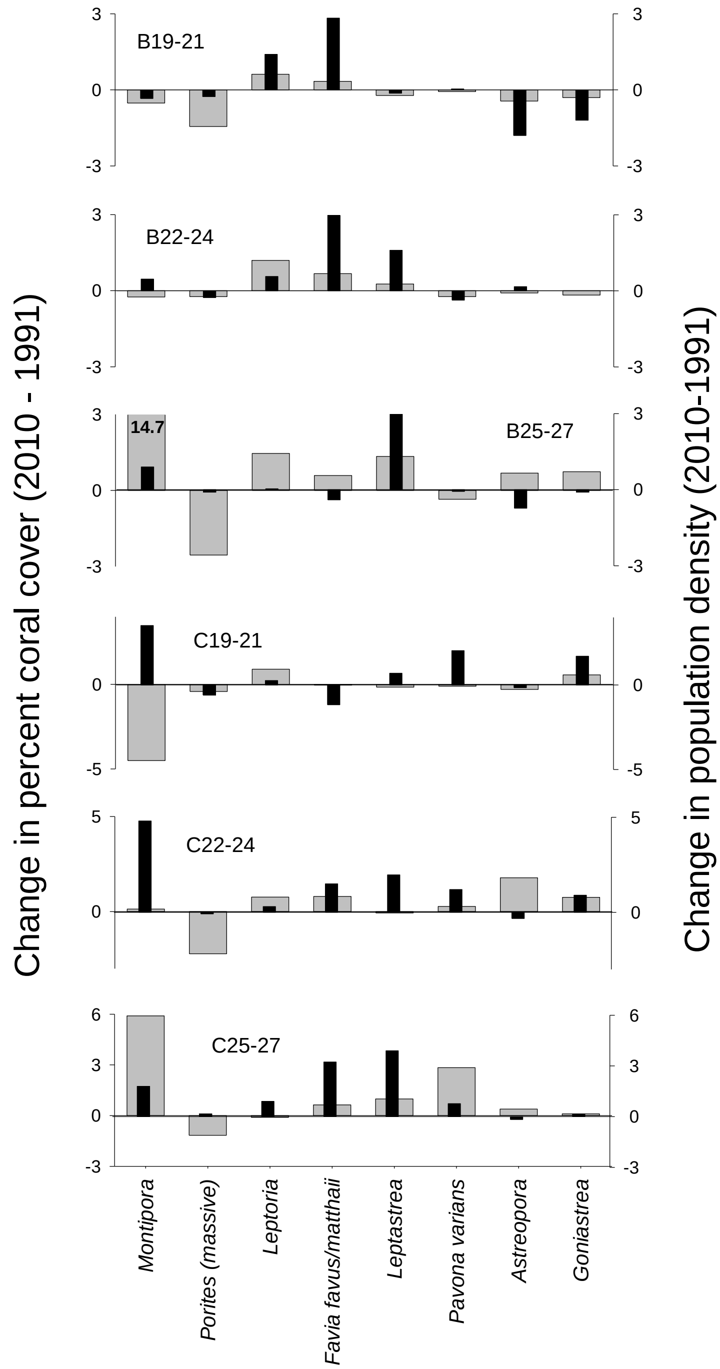


Figure 14. Trends in dominant coral abundances since 1991. Each graph shows the change in percent cover (grey bars, left axis) and population density (black bars, right axis) at individual survey stations. The shift from large-to-small colony dominance (Figure 13) is attributed mainly to the removal (or partial mortality) of large *Montipora* corals, and replacement with numerous small colonies of Montipora, *Favia favus* and *F. matthaii*, *Leptastrea*, and *Pavona varians*.

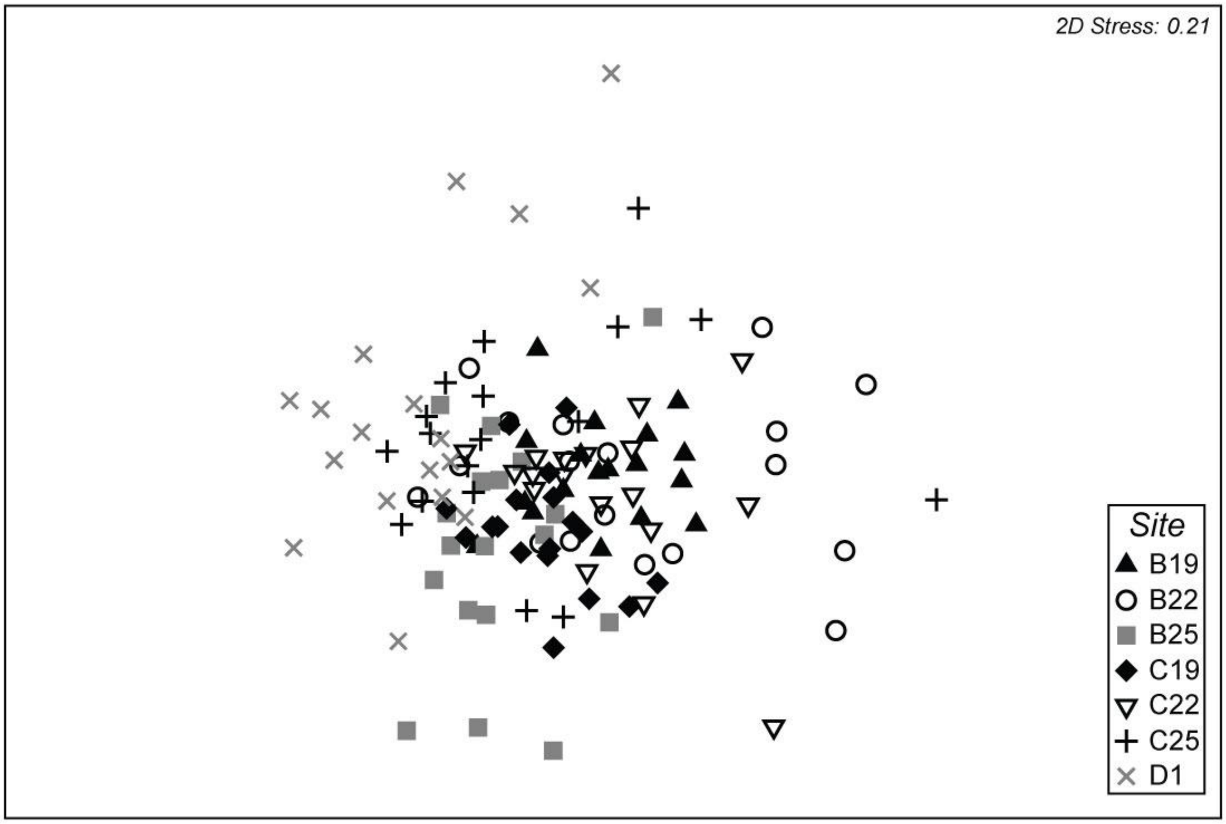


Figure 15. Multi-dimensional scaling plot highlighting relationships between Laolao reef slope algal assemblages. Each data symbol represents a replicate, presence/absence, quadrat survey (*see methods*). Comparatively, the algal assemblages at sites B1 and D1 were statistically distinguished (R-Statistic > 0.45, $P<0.05$, ANOSIM). However, no other pairwise differences were noted, as overall algal occurrences were similar throughout most of the bay on the reef slopes.

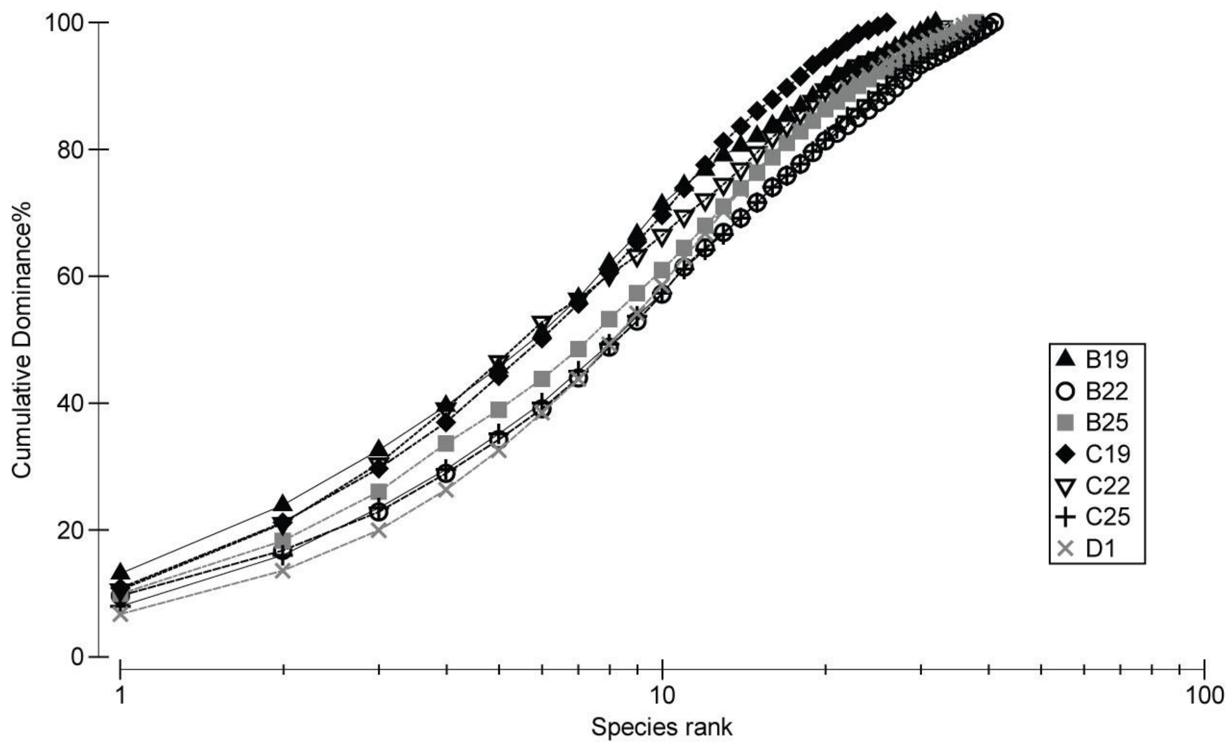


Figure 16. Cumulative dominance plots for reef slope algal assemblages based upon replicated, presence/absence, quadrat surveys (*see methods*). The species saturation curves on the bottom (D1, C25, and B22) indicate that macroalgal assemblages were not dominated by one, or a few, species. Rather, these assemblages had many species that contributed to the overall macroalgal occurrences, relative to other sites, and thus, a greater heterogeneity between replicate quadrats ($P<0.05$, PERMDISP, pairwise comparisons between sites associated with the top and bottom curves). The opposite patterns are associated with curves on the top (B19, C19, and C22); whereby the degree of similarity between replicate quadrats was highest.

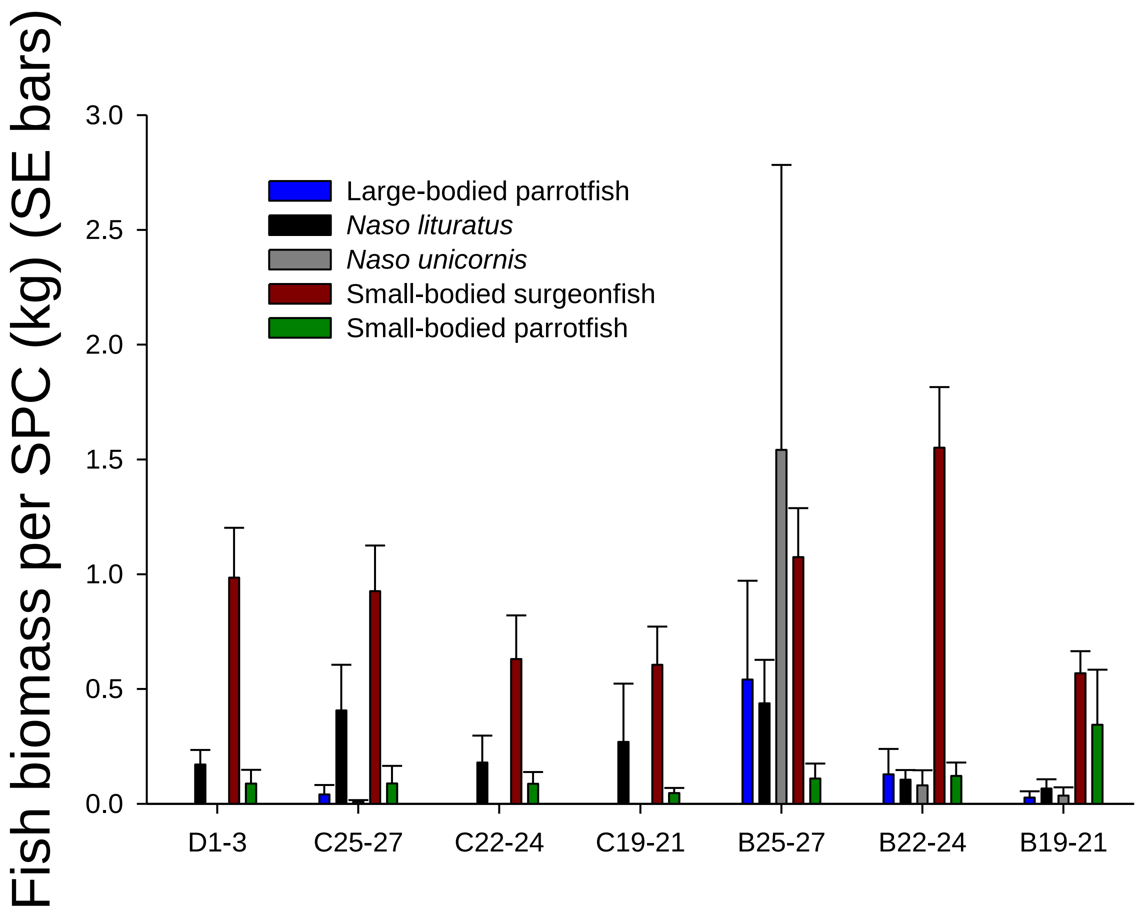


Figure 17. Mean fish biomass per stationary point count survey (SPC) on Laolao reef slopes. Dominant fish, or functionally-similar fish groupings, are shown.

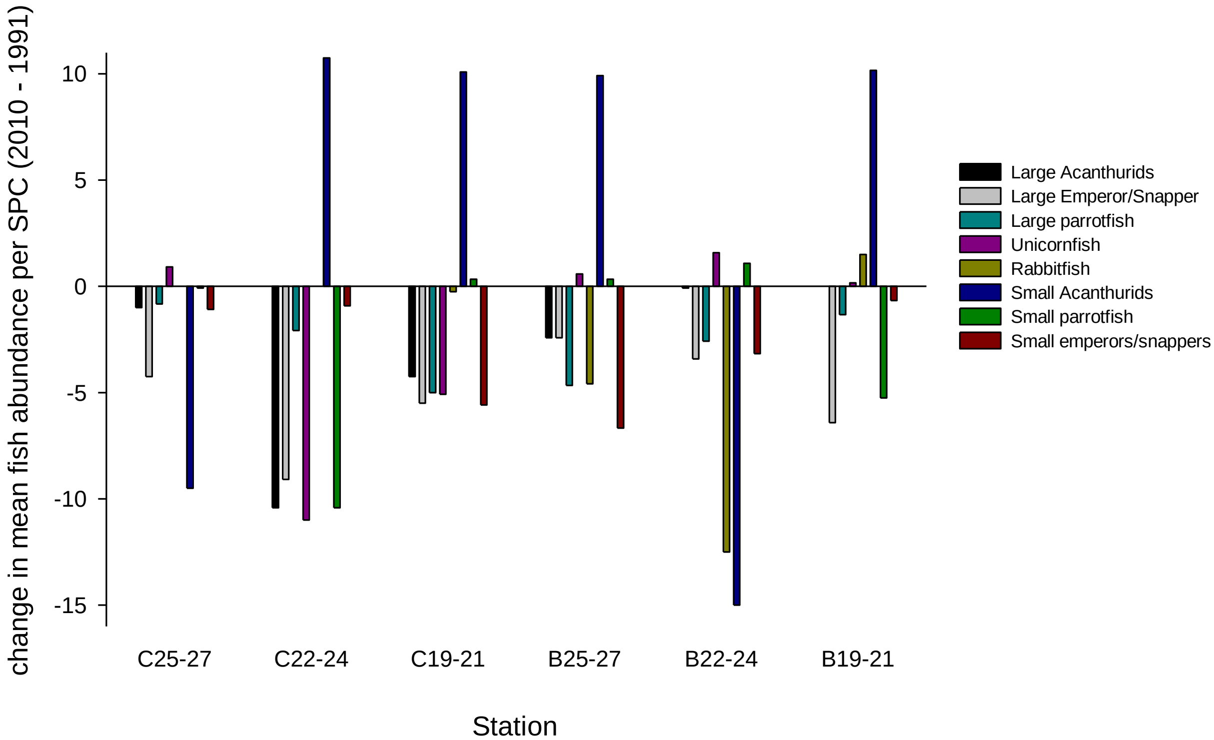


Figure 18. Change in the population density of dominant fish in Laolao since 1991. A significant reduction in fish density, evenness, and functional group abundances was evident (Figure 19), whereby 2010 fish assemblages mainly comprised high densities of small acanthurids.

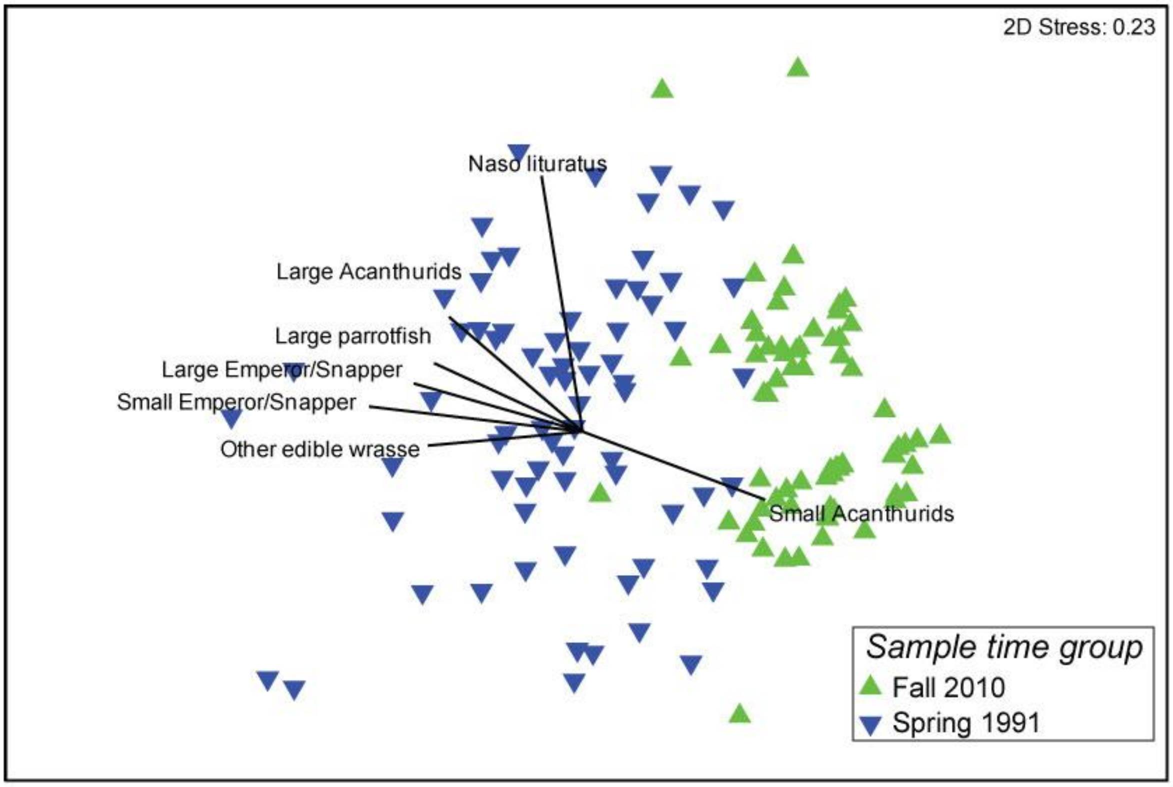


Figure 19. Multi-dimensional scaling plot summarizing findings for Laolao fish assemblages. More diverse and abundant fish assemblages in 1991 have been replaced by high densities of small acanthurids. Significant declines in fish density, evenness, and functional groups were evident since 1991 (ANOSIM R-Statistic = 0.62, P<0.01). Vectors display fish groups that were significant drivers of these trends (spearman correlation coefficients >0.5).

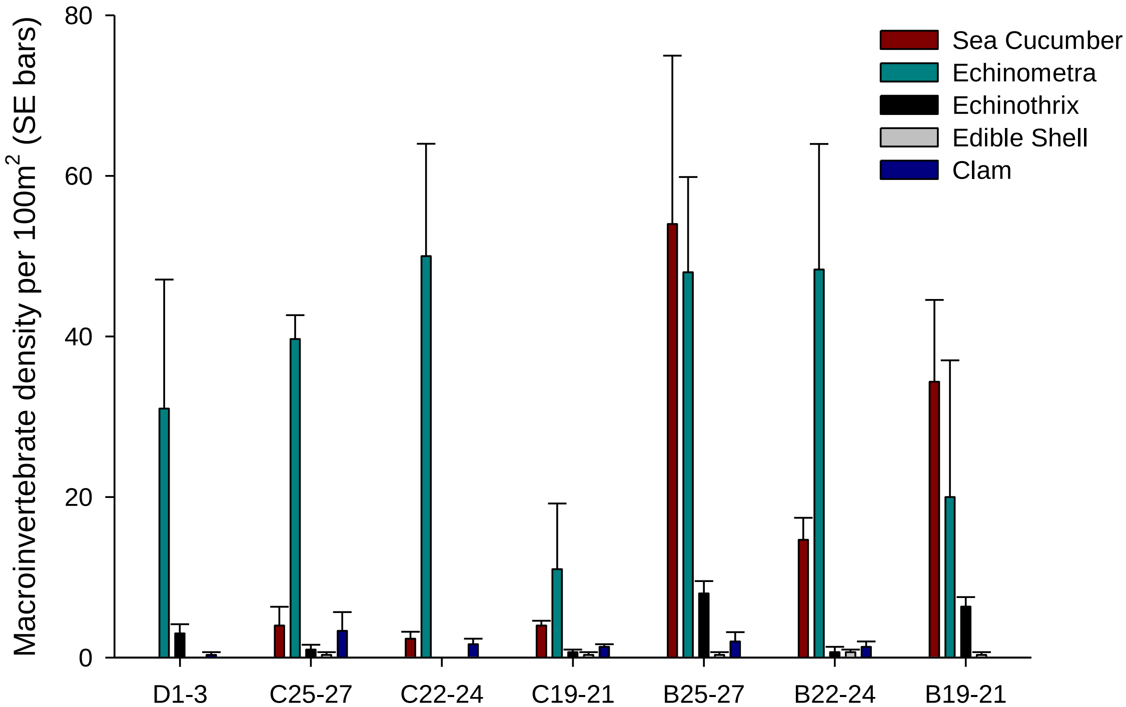


Figure 20. Mean macroinvertebrate density on Laolao reef slopes. Dominant genera or functional groups of macroinvertebrates are show based upon abundance. High standard error bars suggest substantial inter-site variation in many instances (*see results*).

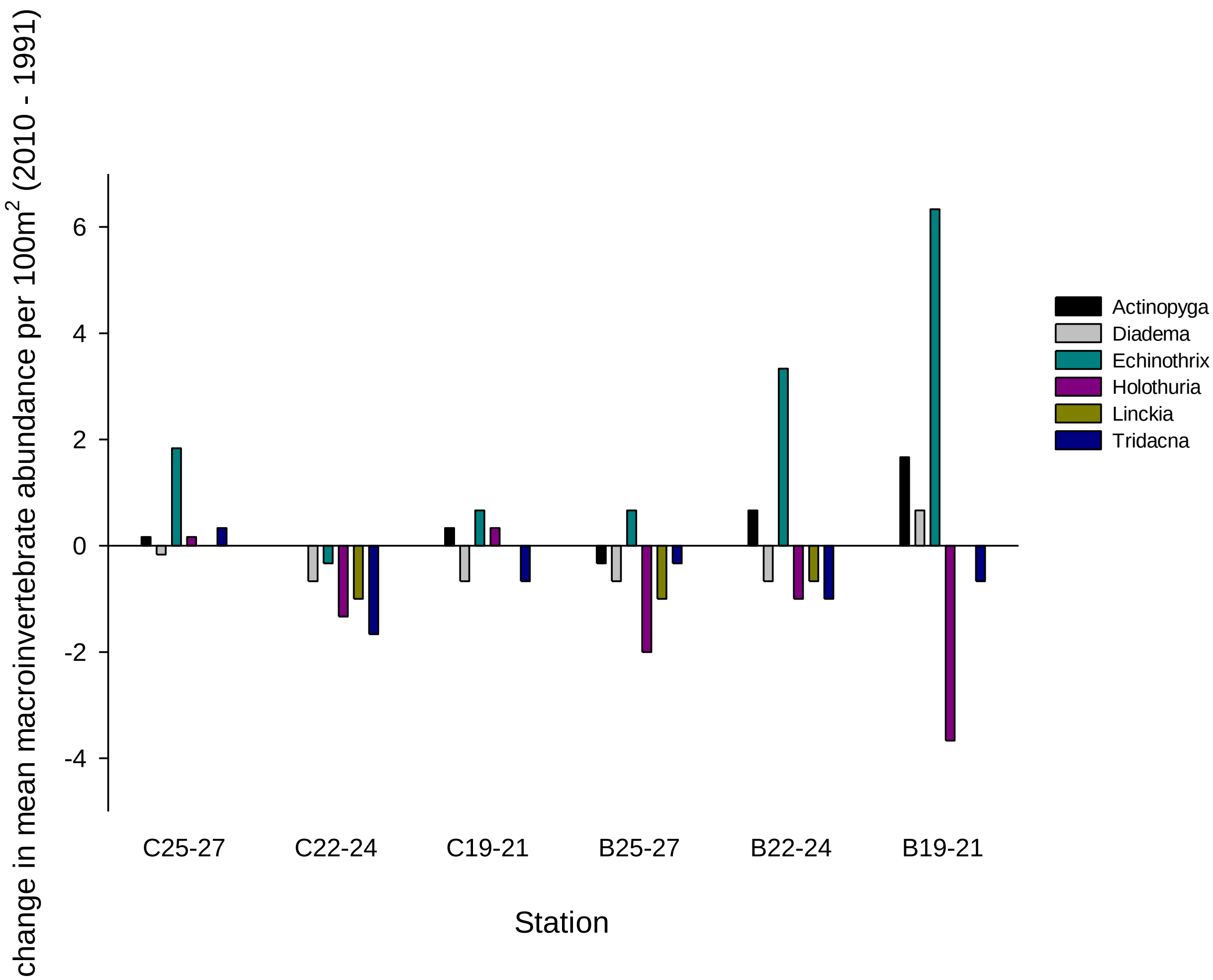


Figure 21. Change in macroinvertebrate density on Laolao reef slopes bay since 1991. Due in part to high variability (Figure 20), no consistent change is reported since 1991 for the majority of macroinvertebrates, in contrast to the coral, benthic, and fish data.

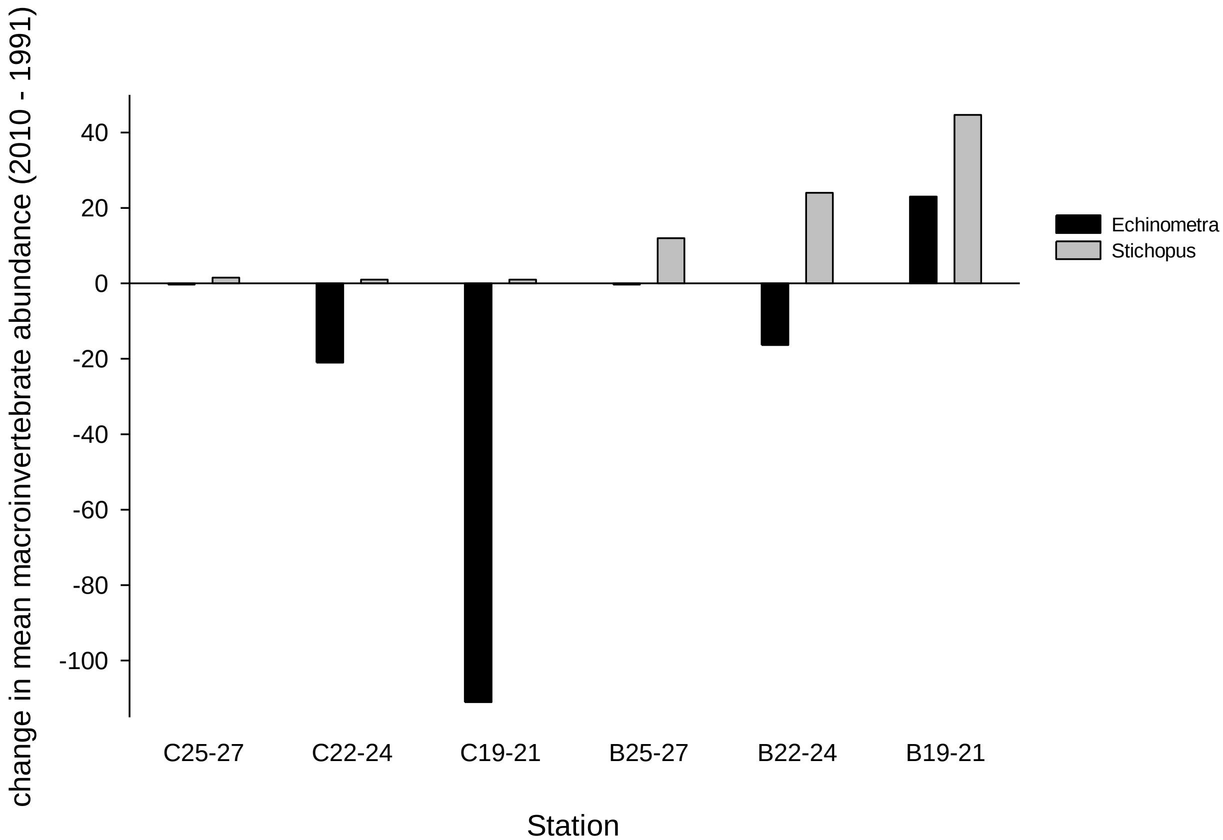


Figure 22. Change in *Echinometra mathaei* (grazing urchin) and *Stichopus chloronotus* (sea cucumber) density on Laolao reef slopes since 1991. Significant declines in urchins were found at C19-21 (Mann-Whitney U-test, $P<0.05$ between years), while significant increases in sea cucumber abundances were evident at B19-21 and B22-24, where enhance groundwater influence was noted.