Creating Comprehensive Protected Areas: The Ecology of the Pūpūkea Tide Pools and Their Value to the Pūpūkea Marine Life Conservation District

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Abstract

The aims of this project were to assess the biological community and environmental variables in the Pūpūkea tide pools on the North Shore of O‘ahu, Hawai‘i. These data were compared to a historical baseline and relevant literature to better understand the ecological role of the Pūpūkea tide pools within the Pūpūkea Marine Life Conservation District (MLCD). Depth and tide were significant factors effecting fish abundance in the Pūpūkea tide pools. The fish community was dominated by large schools of *Kuhlia spp.* (āholehole), and the tide pool fauna differed significantly between day and night. Depth data were used to improve the bathymetric resolution of existing maps of the study area, and bottom composition results suggested the important role of macroalgae in the tide pools. Results indicated that the Pūpūkea tide pools are habitat for several nearshore fish species, has maintained and possibly increased biological diversity since the 1970’s, and is unique from the surrounding MLCD and nearby intertidal areas on O‘ahu.

Introduction

The marine environment of Hawai‘i is unique, with a wide diversity of habitats and a high percentage of endemic species. Compared to other tropical islands in the Pacific, Hawai‘i has low fish diversity; 580 species of shallow reef fish versus thousands in other Pacific areas (State of Hawai‘i 2005). However, because of its isolation, the islands have an unusually high amount endemism; 25-30% of Hawai‘i’s marine species are not found anywhere else in the world (Kay 1994).

The coastal zone of Hawai‘i is known for maintaining a higher diversity of fish when compared to offshore areas, because coastal habitats offer multiple ecological niches and food resources (Castellanos-Galindo & Giraldo 2008). One of these unique coastal habitats, intertidal rocky shores, sustain large numbers of fishes and invertebrates (Lewis 1964, Paine and Levin 1981, Denny 1988, Little & Kitching 1996) and tide pools are also considered among the coastal habitats with the greatest functional diversity of potential prey items for fishes (Norton and Cook 1999).

Tide pools can play several roles for their inhabitants, including acting as nursery habitat, breeding areas, refuges for intertidal and subtidal invertebrates, and parts of home ranges for some species (Moring 1986, Underwood & Chapman 1996, Rosa et al. 1997, Chargulaf 2011). Tide pools are important not only for the fauna they support, but also because resident and transient fishes may act as important links of energy between intertidal and adjacent subtidal habitats (Castellanos-Galindo & Giraldo 2008). The relationship between humans and intertidal habitat is also unique in that intertidal areas may be more exposed to overexploitation and habitat degradation due to accessibility, proximity to pollution and human trampling (Cunha et al. 2008).

This study aims to describe the ecological role of an intertidal zone on the North Shore of O‘ahu, located in the protected Pūpūkea Marine Life Conservation District (MLCD). Preliminary studies of Hawai‘i's intertidal communities described a diversity of fishes and porous limestone pools that were full of life (Gosline 1965, Abbott 1999). Hawai‘i's tide pool fauna and habitats vary greatly, as is consistent with other intertidal areas worldwide (Cunha 2008, Cox et al. 2011). Intertidal fish assemblages are known to vary in composition across latitudes, continents, regions, and within individual locations (Gibson & Yoshiyama 1999). Several factors affect the structure of tide pool fish communities in Hawai‘i, including unique microtides (variation of less than 1m), wave regimes, geologic composition, temperature, water level, substrate, and vertical gradients in temperature, air exposure, wave action, salinity, and land relative isolation (Cox et al. 2011). Compared to other sites across the Pacific, Hawai‘i's tide pools are low in species richness but high in endemism, much like their deeper reef counterparts (Cox et al. 2011). Tide pools in Hawai‘i can serve as nursery habitat; some fishes observed in small tide pools grew faster than individuals of the same species in open water (Iglesias 2012).

The no-take, recreation area known as Pūpūkea MLCD was established in 1983 in response to community concerns about overfishing, coastal development, and tourism, with the intent to regulate recreational use while still attracting visitors to the site. The site was chosen for protection after an evaluation, conducted by University of Hawai‘i Sea Grant scientists, which assessed biological characteristics, including coral cover and fish diversity (Kimmerer & Durbin 1975). The protected area at Pūpūkea was the third MLCD in a series created in the State of

Hawaiʻi. It is estimated that over 1 million people visit the Pūpūkea MLCD every year (MPW 2012).

In 2003, the boundaries of the Pūpūkea MLCD were expanded, and overall habitat quality and ecosystem health has since improved (Friedlander et al. 2010). The MLCD now comprised a more representative sample of depths and habitats, including a large boulder field. The expansion has resulted in a 14% increase in fish abundance since 2004, as well as an increase in the presence of apex predators (Friedlander et al. 2007, 2010). There was also an increase in fish biomass, species richness and density inside the MLCD boundary when compared to neighboring fished areas, especially for fish of interest to recreational fishermen (Stamoulis 2012). However, the boundaries amendment neglected to include the intertidal area within the Pūpūkea MLCD boundaries. The first and only quantitative survey of this area identified valuable marine resources there, including 37 fish species, a diversity of invertebrates, and a unique salinity regime (Kimmerer & Durbin 1975).

In 2008, an executive order by the Governor of Hawaiʻi transferred responsibility for the tide pools at Pūpūkea from the City and County of Honolulu to the authority of the State Department of Land and Natural Resources (DLNR) (State of Hawaiʻi 2009). The pools were removed from the boundaries of City's Pūpūkea Beach Park with the mandate to "restore the premises to a condition satisfactory and acceptable to the DLNR." This placed the Pūpūkea tide pools within the boundaries of the Pūpūkea MLCD after 44 years. However, administrative rules that would express the law to the public and allow DLNR to enforce the law within the MLCD have not yet been drafted. The community effort to press DLNR to draft administrative rules for the tide pools is presently stalled. Because the tide pools currently have ambiguous legal protection, a scientific assessment of their value is all the more important.

The primary objective of this study was to create an updated ecological baseline of the habitat, environmental variables, and biological communities represented in the Pūpūkea tide pools. These data were compared to data from the surrounding Pūpūkea MLCD and clarifies the role played by the intertidal zone. This study created an ecological baseline of the tide pools and compared this to the the original 1975 baseline, established by W. Kimmerer and W. Durbin Jr. from the University of Hawaiʻi Sea Grant program. Finally, these data were compared to information about tide pools on Oʻahu and throughout the state of Hawaiʻi. The findings of this study may help inform future management decisions and the development of administrative rules for the protection and enjoyment of the tide pools at Pūpūkea.

Methods

Survey Site

The study site is located in the ahupua’a of Pūpūkea, a community on the North Shore of the island of Oʻahu (Figure 1). During the time of the study, Pūpūkea had a relatively low population and little commercial development when compared to other areas of the island. Despite, or perhaps because of, its rural appearance, Pūpūkea is a very popular and frequently visited place. The marine life in the Pūpūkea MLCD also attracts a substantial number of visitors. The coastal area around the tide pools, including Sharks Cove, retains many valuable, recreational resources including a unique system of caves and volcanic structures popular to SCUBA divers and snorkelers. Before the near complete ban on fishing in 2001, most areas within the Pūpūkea MLCD were also heavily used for subsistence and recreational fishing from shore.

The tide pools at Pūpūkea are also known as "Old Quarry," because they are a human-made feature. In 1929, C.W. Windstedt blasted the once exposed reef flat to build a mountain overpass (MPW 2012). The shallow tide pool habitat is more protected from wave action than other surrounding areas, making it popular year-round for snorkeling and wading for both visitors and residents.

Objectives:

Objective 1: Measurement of Biological Variables

In this study, I surveyed fish and invertebrate abundance, species richness, and diversity in the Pūpūkea tide pools and conducted a spatial analysis to identify hotspots.

Abundance and species richness (S) of fish and macro-invertebrates were quantified using 10m X 2m belt-transect surveys. The tide pools were divided into three depth classifications, and one transect survey was conducted in each section per visit to the study site (Figure 2). Locations within each section were chosen haphazardly, based on accessibility and water level (Appendix I). Surveys were completed July 2, 2012 and August 25, 2012 and between the hours of 9:00-19:00 at varying tidal heights and phases of the lunar cycle. This study involved a community-based approach, and 60 surveys were conducted by volunteers from MPW, as well as Mililani High School's Advanced Placement Environmental Science class during the sampling period. Volunteers received a 30-minute introduction to fish and invertebrate species and general field protocol prior to sampling. Provisions were made to help accuracy in the field including providing photos of commonly found species and personal supervision and assistance during all data collection events.

During each visual survey, volunteers quantified fish and invertebrate species using the belt transect. Images of the abundant species were provided on the datasheet for ease of identification (Appendix II). For coral species, volunteers indicated presence or absence of the species within the 1m belt transect. All observed fauna were identified to the species level. Volunteers used a digital camera to photograph species they could not identify in the field. Parrotfish (family *Scaridae;* uhu), hawkfish (*Cirrhitidae;* po'opa'a), and unicornfish (genus *Naso*; kala) were identified to family or genus, respectively. A GPS location was obtained at the starting point of each transect survey using a Garmin GPS unit.

Spatial analyses were conducted using ArcMap 10.0. Interpolated layers of fish and invertebrate abundance and species richness were generated using the Geostatistical Analyst tool. Bartlett, Kruskal-Wallis, Wilcox, and Chi-squared tests were run using R Statistics software to compare the average fish abundance and species richness values between the three depth strata, tide (low, high, or rising/falling), month (June or July), and time of day (morning, afternoon, or night).

Objective 2: Measurement of Environmental Variables

In this study, I documented temperature, salinity, depth, and bottom composition in the tide pools and conducted spatial analyses to identify hotspots, correlations, and relationships to biological information.

To measure temperature variations in the tide pool between June and August 2012, I used a temperature logger deployed within a spatial sampling grid. Three HOBO Pendant® temperature loggers were deployed within the shallow, middle, and deep depth strata (Appendix

III). These pendants were fixed to the bottom, and they measured the ambient temperature every five minutes for 45 days, from June 3 to August 16, 2012.

I also conducted a sampling grid regime, collecting snapshot measurements of both temperature and salinity on August 29, 2012. For the sampling grid, 25 random locations were chosen across all three depth strata (Appendix IV). Temperature grid measurements were obtained by placing a thermometer on the bottom for 60 seconds at the sample site. Water samples were collected from the thermometer site and measured for salinity content with a refractometer.

Depth was measured at the starting point of each fish and invertebrate transect manually with the transect tape. A total of 60 measurements were taken throughout the sampling period. An interpolated depth layer was created with the Geostatistical Analyst tool in ArcMap 10.0. Remote sensing depth data was acquired from the State of Hawaii GIS program and used for comparison with the manually collected data.

I used a digital reclassification method, as well as a line intercept method (Bauer 1943, White 1965, Schmid 1965), to analyze the bottom composition of the Pūpūkea tide pools. For the digital reclassification, a high-resolution image from Google Earth was imported and rectified in ArcMap 10.0. The image was then digitized into habitat categories using the Iso Cluster Unsupervised Classification tool that automatically assigns categories to the colors the program reads from the aerial image. The line intercept method was employed on 17 random selected transects throughout the sampling period. Bottom substrate was recorded every two meters for the length of the transect.

To correlate the environmental conditions of the tide pools to the observed biological variation, the Band Collection Statistics tool in ArcMap 10.0 was used. This tool statistically compared the interpolated layers that were created for the temperature, salinity, depth, fish abundance, invertebrate abundance, and total faunal abundance data. The tool created a correlation matrix from the interpolated layers with correlation values from +1 to -1, representing positive or negative relationships of the biological factors. A value of zero indicates independence of the factors.

Objective 3: Comparison of Findings

I compared biological and environmental information collected in 2012 to 1975 baseline established by Kimmerer & Durbin, to similar data collected in and around the surrounding Pūpūkea MLCD, and to research conducted at other tide pool sites around Oʻahu.

To understand if and how the ecology of the Pūpūkea tide pools has changed since the last ecological baseline was measured, I compared my observations to those described in Kimmerer & Durbin (1975). Fish and coral species composition, species dominance, and the general site description were compared.

Data were also compared between the tide pool and surrounding waters of the Pūpūkea MLCD. Data on fish presence and abundance were obtained from seven 80m transects originally collected by community volunteers for MPW's biological monitoring efforts. These data were gathered between July 7 and August 25, 2012 from the Shark's Cove area of the Pūpūkea MLCD (21.651188°, -158.062659°). The mean number of fishes per transect and the mean number of species per transect in Shark's Cove and the Pūpūkea tide pools were compared statistically using a Wilcox test.

Biological and environmental data were also compared with data from tide pools in other areas of O'ahu. Fish species composition and abundance seen in Cox et al. (2011) and Iglesias (2012) were evaluated. Variables from Iglesias (2012) were compared using a Chi-squared test. Depth, temperature, and salinity measurements obtained from tide pools across O'ahu in Cox et al. (2011) were also compared to values observed in the Pūpūkea tide pools during summer 2012.

Results

Biological Variables

A total of 1820 individual fishes from 21 families and 42 different species were documented in the Pūpūkea tide pools (Table 1). The three most abundant fish species were *Kuhlia spp.* (Family: Kuhliidae; Hawai'ian common name:) (41.8% of individuals), *Acanthurus triostegus (*Acanthuridae; manini) (26.5%), and *Meomyxus leuciscus* (Mugilidae; uouoa) (14.2%). The majority of fish observed (85.7%) were herbivorous, and 23.8% of the species identified are of interest to recreational fishermen.

The visual belt transect surveys also revealed a total of 2940 macroinvertebrates representing 26 species. The sea urchin *Echinometra mathaei* ('ina kea) was the dominant species, accounting for 97.5% of the macroinvertebrate observations. *Holothuria whitmaei* (loli) and *Echinothrix diadema* (wana) were also identified in the surveys (0.47% and 0.30% of observations, respectively).

Pocillopora damicornis (ako'ako'a) was the most commonly documented stony coral, accounting for 27% of observations (Figure 3). *Porites lobata (*pohaku puna) and *Montipora sp.* were also commonly observed (23% of observations each), followed by *Porties evermanni*, which was the third most frequently encountered coral (20% of coral observations). *Pavona varians* (3%), *Pocillopora meandrina* (2%), and *Porites compressa* (2%) were less frequently observed in the belt transects.

Fish abundance in the Pūpūkea tide pool was generally higher in the nearshore zone (Figure 4a), while fish species richness was higher toward the oceanside "back" of the pool (Figure 4b). Macroinvertebrate abundance was observed to be the highest toward the back of the pool as well (Figure 4c). The highest number of coral species was also observed toward the back of the pool, similar to the invertebrate distribution (Figure 4d). When the total faunal abundance (fish and invertebrates) was calculated for each transect, a more even distribution was observed, with higher values around the nearshore and deeper strata in the tide pool (Figure 4e).

Depth strata and tide level significantly influenced fish abundance (Figure 5). Fish abundance data were not normally distributed, despite a log transformation (Bartlett's test p>0.5), and non-parametric statistics were therefore used. Mean fish abundance was highest in the nearshore zone (Kruskal-Wallis, mean= 52.2, sd= 74.5, p<0.04), and more fish were documented during a rising or falling tide, as opposed to the peak high or low tide (Kruskal-Wallis, mean= 56.8 fish per transect sd= 78.2, p< 0.01). On average, slightly more fish were observed per transect in June (mean=31.5 fish t^{-2}, sd= 54.1) than in July (Wilcox Test, mean=22.1, sd=27.1, *p*>.05), although these results were not significant. More fish were also observed, on average, in the afternoon (12:00 – 15:00) versus the morning (9:00 – 12:00) or evening (15:00 – 19:00) surveys (Kruskal-Wallis, mean= 25.8, sd= 23.9, *p*>.05). There was a significant difference in species composition observed among the three most abundant species observed in diurnal and nocturnal invertebrate populations in the tide pool (Chi-square test *p*<.001). The two, most dominant nocturnal species were *Aplysia dactylomela* (kualakai) and *Polyplectana kefersteini* (weli).

Environmental Variables

Only one of the three temperature loggers remained in its location after the 45-day deployment. Temperature logger #1, located in the southern-most area of the pool in 0.5m of water, survived the deployment. The average temperature was 26.5 (± 0.9) °C (79.7°F). The lowest temperature recorded was 26.1°C (75.5°F), and the highest was 28.8°C (83.8°F). There was a general increase in temperature throughout the deployment and a diurnal change in temperature from day to night readings (Figure 6).

Temperature readings were also recorded using a spatial sampling grid. The coldest temperatures were recorded on the extreme south and north ends of the tide pool, while warmer temperatures were concentrated in the center and nearshore areas (Figure 7a). The average temperature in the entire Pūpūkea tide pool using the grid method was 25.1 (± 1.4) °C (77.3°F). The maximum temperature recorded with this method was 27.8°C (82°F) on 8/29/2012, and the minimum was 24.4°C (76.9°F). Salinity concentration was highest in the north-western area of the tide pool and lowest in the southern area (Figure 7b). Average salinity in the tide pool was 29.7 (± 2.9) g/L. The highest salinity value observed was 35 g/L and the lowest was 24 g/L.

A depth layer was created using 60 depth measurements acquired at the beginning of each visual survey. These measurements were interpolated to create a bathymetric layer of the Pūpūkea tide pool (Figure 8a). The maximum depth recorded in the tide pool was 2.9 m, and the shallowest survey area was 0.3 m. The average depth in the Pūpūkea tide pool, based on these measurements, was 1.0 m (± 0.5m). An interpolated map was also produced from the depth measurements from the Hawaiʻi State GIS Program for comparison to these data (Figure 8b).

Using the Isocluster Unsupervised Reclassification method in ArcMap, three benthic habitat categories were identified: "rock", "sand", and "crevices", which were shadows caused by the angle of the aerial image (Figure 9). The line-intercept method revealed four distinct bottom types: "rock," "sand," "algae/rock," and "algae," "Algae/rock," was defined as a mixture of bare rock and turf algae and "algae" was defined as a homogeneous layer of thick, turf algae. Using the line-intercept method, "rock" was the predominant benthic type identified in the analysis (42.4%), followed by "sand" (36.4%), and "algae" (16.5%). In the Isocluster method, "sand" was the dominant characteristic in the habitat classification after "rock" (61.4% and 22.1% respectively; Figure 10).

Fish and invertebrate abundance were significantly correlated to depth (r = -1.1, r =0.6 respectively, p<0.05). Total faunal abundance was significantly, negatively correlated to depth (r = -1.0) and salinity (r = -0.8). The least correlated variables were found to be fish abundance and temperature (r = .01, p>0.05). Finally, there was no significant relationship between lunar illumination and average fish abundance (Linear Regression, p>0.05).

Site Comparisons

The data collected in this study were compared to data collected by MPW volunteers in the neighboring deeper Shark's Cove area, which is also part of the Pūpūkea MLCD. Although fish abundance from the Shark's Cove was slightly higher than the tide pool, these data were not statistically significant (Wilcox Test, $p > 0.2$). Also, there were more species observed per transect in Shark's cove than the tide pools, but this difference was not statistically significant (Wilcox Test, $p > 0.08$; Figure 11). Species composition also differed in the Shark's cove transects. The three most dominant species in Shark's cove were (in order of abundance) *Acanthurus nigrofuscus* (maiko), *Acanthurus triostegus* (manini), and *Kyphosus Hawai'iensis* (nenue).

Biological and environmental information from the Pūpūkea tide pool was compared to the Kimmer & Durbin 1975 baseline. There was a 14% increase (37 – 42 species) in fish species observed from 1975 to 2012 (Table 2). Kimmer & Durbin (1975) also described a more extreme salinity range from 21 – 36 g/L than that observed in this study (24 – 35 g/L). Dominant corals observed in the deeper water outside the Pūpūkea tide pools in the 1975 baseline are similar to those documented in this study (i.e. *Porites lobata* and *Montipora spp.*).

Results were also compared to the composition of other tide pools around the island of O'ahu, as described in Cox et al. (2011) and Iglesias (2012). The Pūpūkea tide pools had a shallower average depth and a lower average salinity than the pools measured by Cox et al. (2011). The mean temperature identified in both studies was close to 25℃. There were fewer total species documented in Cox et al. (2010; 19 species from 10 families versus 42 species from 21 families in the Pūpūkea tide pools). Species composition also differed. The three most common species documented in Cox et al. (2010) were *Bathygobius cocosensis* ('o'opu 'ohune) , *Istiblennius zebra* (pao‘o), and *Abudefduf sordidus* (mamo), compared to *Kuhlia spp.* (āholehole), *Acanthurus triostegus* (manini), and *Meomyxus leuciscus* (uouoa) in this study.

Iglesias (2012) also documented tide pool fish assemblages around O‘ahu and documented 15 total species, which is 35% lower than the 42 species found in the Pūpūkea tide pool. *Kuhlia spp.* (āholehole) contributed to a smaller proportion of the fish populations studied by Iglesias (2012) vs. Pūpūkea (22% versus 41.8%, respectively), while *Abudefduf sordidus* (mamo) and *Abudefduf abdominalis* (mamo) both contributed to a larger proportion (33% and 7% respectively). Additionally, *Meomyxus leuciscus* (uouoa) was not observed in the pools measured in Iglesias (2012), while it comprised 14.10% of the fish observed in Pūpūkea. *Acanthurus triostegus* (manini) had a similar relative abundance in the two studies, comprising 26.5% of the total fish observed in Pūpūkea and 22% of the fish in Iglesias (2012; Figure 12).

Discussion

This study demonstrated that the Pūpūkea tide pools are habitat for several nearshore fish species, has at least maintained, if not increased biological diversity since the 1970s, and is unique from the surrounding MLCD as well as other tide pools studied in Hawai‘i in biology as well as environment.

The high fish abundance seen in the nearshore areas was predominately because of large (100 – 200 individuals) schools of āholehole (*Kuhlia spp*.), a tightly schooling species that frequently dominated fish abundance when present. This species demonstrated a common theme of high variation seen in the fish abundance average calculations; caused by the schooling nature of commonly observed species. Āholehole are known for their ability to survive in challenging environments, including extreme fluctuations in salinity, oxygen, and temperature (Takata 1953) and are common in Hawai‘ian freshwater streams, rocky shores, tide pools, and sandy beaches (Tester & Takata 1953, Gosline 1965). *Kuhlia sandvicensis* is endemic to Hawai‘i and has long been an important fish for food and cultural practices (Titcomb 1972). The manini (*Acanthurus triostegus*), the second most commonly observed species, is known to be the most abundant surgeonfish in Hawai‘i and is considered very important for commercial and recreational fisheries (Meyer 2003).

. Depth stratification and tide cycle were significant factors influencing fish abundance in the Pūpūkea tide pools. This is consistent with the available literature that describes how deeper pools provide habitat to stentopic species (Gibson and Yoshiyama 1999). Because the tide pool at Pūpūkea is fully connected to the adjacent Shark’s Cove area, as well to open ocean through wave action, it is likely other factors, including availability of macroalgae and refuge for fishes to hide from predators could also influence fish abundance and distribution. Previous studies have shown that morphometry, availability of resources, degree of isolation from the sea, structural complexity, and connectivity can all affect pool fish assemblages (Mahon & Mahon 1994, Davis 2000, Castellanos-Galindo et al. 2005, Rojas & Ojeda 2010).

There are few examples of how tide pool fish or invertebrate assemblages differ between day and night. Weaver (1969) investigated tropical tide pools in the eastern Pacific but did not find a significant difference in nocturnal fish composition. The significant difference in invertebrate assemblage between day and night surveys indicates nocturnal species may be often overlooked in tide pool assessments, especially in areas where chemical or removal methods cannot be applied like in Pūpūkea because of size and connectivity to surrounding areas. However, it is possible that the visual nocturnal surveys in this study overlooked cryptic individuals that were more difficult to observe at night and this may have accounted for the apparent changes in fish assemblage.

An investigation of the ambient environmental conditions in the Pūpūkea tide pools revealed several notable findings. The highest temperature recorded in the tide pool during the study was 28.8 °C. It has been well established in the literature that carbon fixation in corals becomes substantially compromised in temperatures over 28 °C (Jokiel & Coles 1990). This may explain why coral colonies were predominantly concentrated in deeper water, furthest from shore in the tide pool. It is also important to note that the average temperature, 26.5 °C, is well within "ambient" conditions described by Jokiel and Coles (1990). Thus, there was no evidence that corals in the Pūpūkea tide pools were under conditions of unusual thermal stress. The average salinity in the Pūpūkea tide pools (29.7 g/L) suggests there could be substantial freshwater inputs into the area, as observed by Kimmerer and Durbin (1975) and is commonly acknowledged among native Hawaiʻian practitioners (Yagodich, J., personal communication, June 2012). Evaporation of sea water and rising salinity is usually a limiting factor for tide pool biota (Klugh 1924); however, this does not seem to be an issue at Pūpūkea, as seen in the lack of relationship between salinity and fish abundance values.

The interpolated depth layer created during the transect survey portion of the study greatly improved the bathymetric resolution available for the Pūpūkea tide pool. These manual readings revealed a small section of deeper water that supported the highest invertebrate abundance and fish species richness. This is also where most of the corals were documented, and qualitative observations indicated high macroalgal cover.

Two methods were employed to create a bottom composition layer, the manual line-intercept method and the GIS-based Isocluster Unsupervised method. Although the Isocluster Unsupervised method appeared to produce a higher spatial resolution of bottom composition, the 11 categories of habitat that this tool produced could be synthesized into three, basic categories: rock, sand, and shadows created in the aerial image. Therefore, this method was unable to capture macroalgal cover, which is a potentially influential biotic factor. "Algae" constituted 16.47% of the line-intercept readings and may play an important role as food and refuge for tide pool fauna.

Species richness values were higher in the deeper Shark's Cove area than in the tide pool, whereas fish abundance values were similar in both areas. Shark's Cove is a much more heterogeneous habitat with access to deep water, allowing for a larger variety of species to enter. The fact that fish abundance was similar is surprising considering how the habitats differ. However, it seems that large, homogenous schools of *Meomyxus leuciscus* (uouoa) and *Kuhlia xenura* (āholehole) most likely accounted for this similarity. This study suggests that Shark's Cove, which is has a different assemblage of fish species than the tide pool area of the MLCD.

It is difficult to ascertain from these data whether there was truly a 14% increase in the number of fish species in the tide pool from 1975 to 2012, or whether this can be explained by the difference in methodology. In the 1975 UH Sea Grant study, the Shark's Cove area of the MLCD was the research focus. Although the tide pools were mentioned, transect surveys were not performed, and the species data were derived from a brief visual census. It is also encouraging that similar dominant coral species were mentioned in both this and the 1975 study. Coral composition in the Pūpūkea MLCD is shaped mainly by the extreme physical conditions that occur in the area during the winter months (CRAMP 2012). Many species, those that commonly have mounding or branching shapes, are found as encrusting forms in the Pūpūkea area (CRAMP 2012). This phenomenon was also observed in this study, and coral diversity and distribution was congruent with available data from the surrounding MLCD (CRAMP 2012, Friedlander 2010).

When data from the Pūpūkea tide pool were compared to information known about tide pools around O'ahu, there were significant differences in depth, salinity values, and fish assemblages. This is most likely due to environmental differences between the large, open tide pool at Pūpūkea and the other smaller, more isolated pools in other areas. This environmental difference emerged as a unique trait of the Pūpūkea tide pool in this study. It is difficult to compare the biota and ecology of the Pūpūkea tide pool with others because it is such a unique habitat. Although some physical characteristics, such as temperature, were consistent with other pools on the island, ecological characteristics, including total species observed, were higher at Pūpūkea, which can potentially be attributed to the volume of the pool and its accessibility to open ocean or its adjacency to a protected area.

Conclusions

Several biological and environmental traits described in this study could be used to quantify the value of the Pūpūkea tide pool. Over 40 fish species, representing nearshore and reef environments, seek refuge in the tide pool. It is a vastly large area compared to other tide pools around O'ahu, with an uncharacteristic salinity regime, regulated by freshwater seeps unique to the area. It was observed to be biologically unique from the surrounding deeper water area and other similar intertidal areas on the island adding variation and biological complexity to the already existing MLCD.

Many species of cultural and recreational interest were observed outside of the fish surveys in small numbers, including *Caranx melampygus* (papio), *Polydactylus sexfilis* (moi), the endemic *Conger marginatus* (puhi uha), *Parribacus antarcticus* (ula-pehu), and *Callistoctopus ornatus* (he‘e puloa). Therefore, there is some evidence that this area, like many tide pools, is a sheltered habitat for larval, juvenile, and recruit stage fishes that are found in nearshore and reef habitats. The large schools of the āholehole observed distinguished this area from other tide pools on O‘ahu and the world because of the fish's endemism. This finding also raises concern for the area and its biological resources. On July 18, 2012, during this study, a man was arrested for laying fishing net in the Shark's Cove area of the MLCD, presumably to catch this species (Star Advertiser 2012). Evidence of fishing was observed in the tide pools during this study and if these activities occur in the tide pool, or if the āholehole schools move between the two areas, this could endanger these MLCD resources (Appendix V).

Although the tide pool exhibited lower fish abundance and species richness than the adjacent Shark's Cove, another unique trait of this area is its accessibility. During the study period, children were observed on a daily basis swimming, snorkeling, and at times catching small invertebrates and fish in the Pūpūkea tide pool. The children's activities do not seem to be a threat to the marine resources in the tide pool but perhaps can become a great asset. In addition to being used by children for casual play, the tide pool has become an outdoor classroom for the children of MPW's recently started Ka Papa Kai youth marine science program. This program fully immerses local children in the biological principles relevant to their marine community, while also allowing the tide pools to serve as a gateway for youth to personally view and interact with their environment. This was also true for the high school students that aided in data collection during the fish survey portion of this study. With relatively shallow water and a plethora of easily visible biota, the Pūpūkea tide pool is a valuable marine amphitheater to those interested in local ecology, environmental issues, and scientific research.

If the Pūpūkea tide pools were to be fully protected by the MLCD through administrative rules in addition to the executive order, it would add to the comprehensiveness and uniqueness of this protected area. The tide pools offer biological value, distinct environmental conditions, and the accessibility for educational experiences and improved stewardship of local, marine environments. The goal of the MLCD system is to protect valuable nearshore fisheries, while providing systematic access to prized recreational areas in Hawai‘i. From what was observed during this study, the Pūpūkea tide pools is an area warranting further legal protection and its unambiguous inclusion in the no-take zone would promote the mission of the Pūpūkea MLCD to conserve and replenish the marine resources of Hawai‘i's nearshore environment.

Tables

Table 1. Fish species list, shaded cells indicate species of interest to recreational fishermen (Chung, L., personal communication, November 2012)

Family	Scientific Name	Common Name	Hawai‘ian Name (University of Hawai‘i 2012)
Acanthuridae	*Acanthurus triostegus*	Convict Tang	manini
	Acanthurus nigrofuscus	Brown Surgeonfish	mā'i'i'i
	Acanthurus dussumieri	Eyestripe Surgeonfish	palani
	Acanthurus blochii	Ring tail Surgeonfish	pualu
	spp.	Unicornfish	kala
Pomacentridae	*Abudefduf vaigiensis*	Indo-pacfic sergeant	mamo
	Plectroglyphidodon johnstonianus	Blue-eye damselfish	
	Abudefduf sordidus	Blackspot Sergeant	kūpīpī
	Abudefduf abdominalis	Hawai‘ian sergeant	mamo
	Plectroglyphidodon sindonis	Rock damselfish	
	Plectroglyphidodon	Bright eye	

	imparipennis	Damselfish	
Labridae	*Thalassoma duperrey*	Saddle wrasse	hīnālea lauwili
	Anampses cuvier	Pearl Wrasse	ʻōpule
	Stethojulis balteata	Belted wrasse	ʻōmaka
	Thalassoma trilobatum	Christmas wrasse	awela
	Coris flavovittata	Yellowtail coris	hilu
	Coris venusta	Elegent coris	
	Cymolutes lecluse	Hawaiʻian knifefish	laenihi
Kuhliidae	*Kuhlia xenura*	Hawaiʻian flagtail	āholehole
Mugilidae	*Meomyxus leuciscus*	Sharpnose mullet	uouoa
Chaetodontidae	*Chaetodon auriga*	Threadfin butterflyfish	kīkākapu
	Chaetodon lunula	Racoon butterflyfish	kīkākapu
Kyphosidae	*Kyphosus hawaiensis*	Hawaiʻian Chub	nenue
Ostraciidae	*Ostracion meleagris*	Spotted boxfish	moa
Belnniidae	*Entomacrodus marmoratus*	Marbled blenny	pao’o
	Istiblennius zebra	Zebra Rockskipper blenny	pao’o
Scaridae	*spp.*	Parrotfish	uhu
Mullidae	*Mulloidichthys vanicolensis*	Yellowfin goatfish	weke 'ula
	Parupeneus multifasciatus	Many bar goatfish	moano
	Melloidicthys flavolineatus	Yellowstripe goatfish	oama
Lutjanidae	*Lutjanus fulvus*	Blacktail snapper	toʻau
Carangidae	*Caranx melampygus*	Bluefin Trevally	omilu (papio)
Tetraodontidae	*Canthigaster amboinensis*	Ambon Toby	
Scorpaenidae	*Dendrochirus barberi*	Hawaiʻian Green Lionfish	nohu
Cirrhitidae	*spp.*	Hawkfish	piliko'a
Synodontidae	*Synodus dermatogenys*	Clearfin Lizardfish	'ulae
Zanclidae	*Zanclus cornutus*	Moorish Idol	Kihikihi

Serranidae	*Cephalopholis argus*	Peacock grouper	roi
Balistidae	*Rhinecanthus rectangulus*	Reef triggerfish	humuhumunukunukuapua'a
Muraenidae	*Gymnothorax eurostus*	Stout moray	puhi
Muraenidae	*Echidna nebulosa*	Snowflake moray	puhi kāpā

Table 2. Comparison of data from the Pūpūkea tide pool to recent literature.

Source	**Location**	**Depth (m)**	**Temperature (℃)**	**Salinity (g/L)**	**Total Fish Species Observed**
Rosinski (2012)	Pūpūkea Tide Pool	1.0	25.2	29.7	42
Kimmerer & Durbin (1975)	Pūpūkea Tide Pool	n/a	n/a	21 - 36	37
Cox et al. (2011)	Oʻahu	3.1	25.3	36.2	19
Iglesias (2012)	Oʻahu	n/a	n/a	n/a	15

Figures

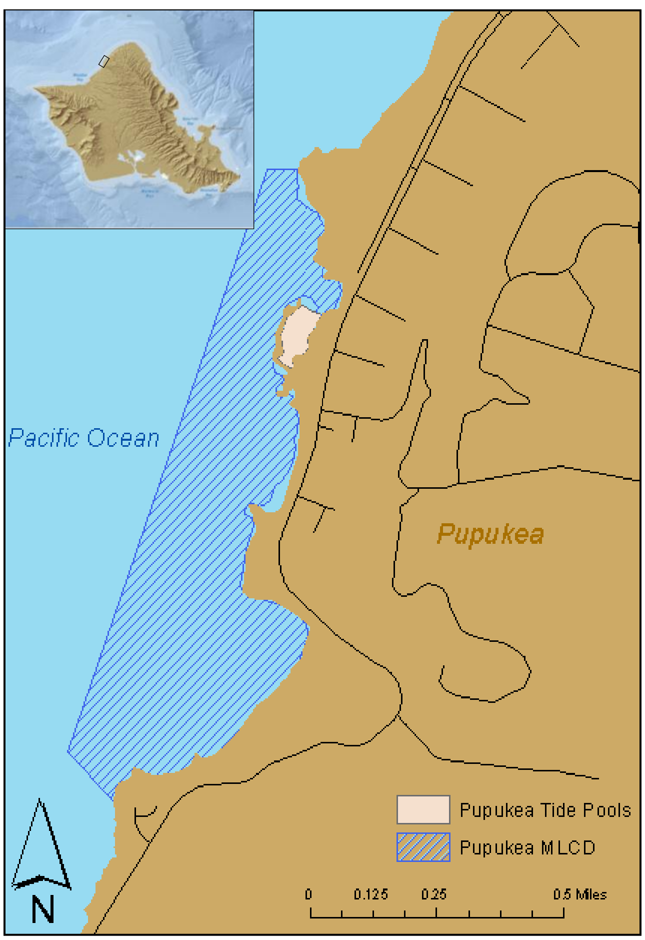

Pacific Ocean
Pupukea
Pupukea Tide Pools
Pupukea MLCD
0
0.125
0.25
0.5 Miles
N

Figure 1. Map of O‘ahu, Hawai‘i (insert), indicating the location of Pūpūkea, the Pūpūkea Marine Life Conservation District (MLCD), and the Pūpūkea Tide Pools

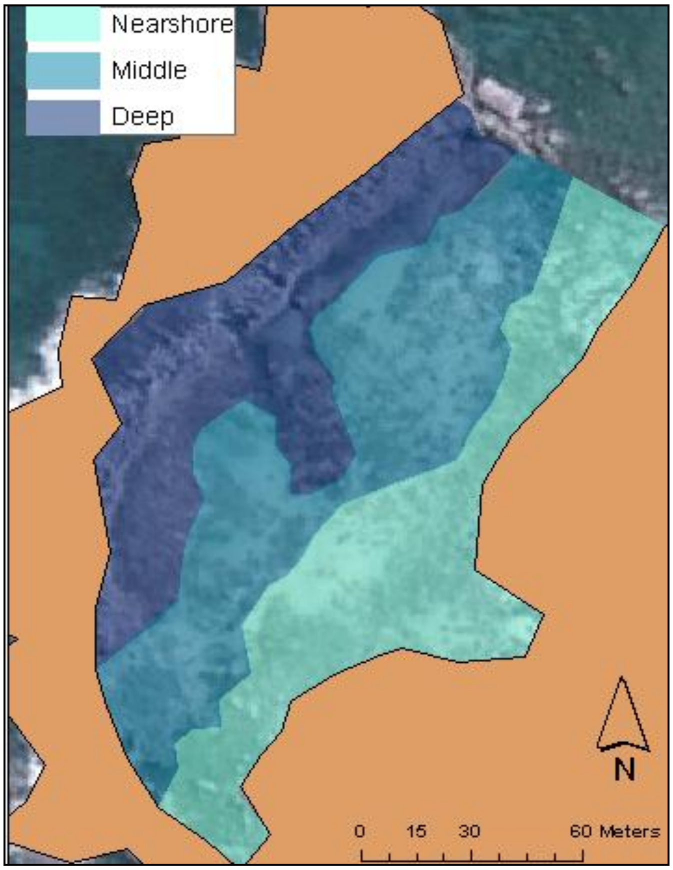


Figure 2. Depth classifications used for Pūpūkea tide pool transect locations (mean depth nearshore = 0.73 m, middle = 0.85 m, deep = 1.19 m)

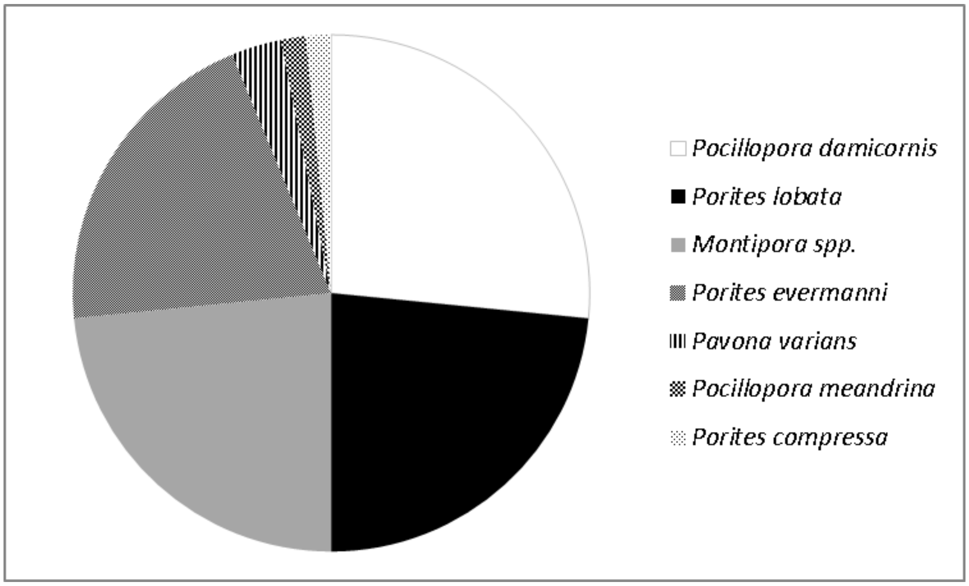


Figure 3. Frequencies of Pūpūkea tide pool coral species (percentage of observations)

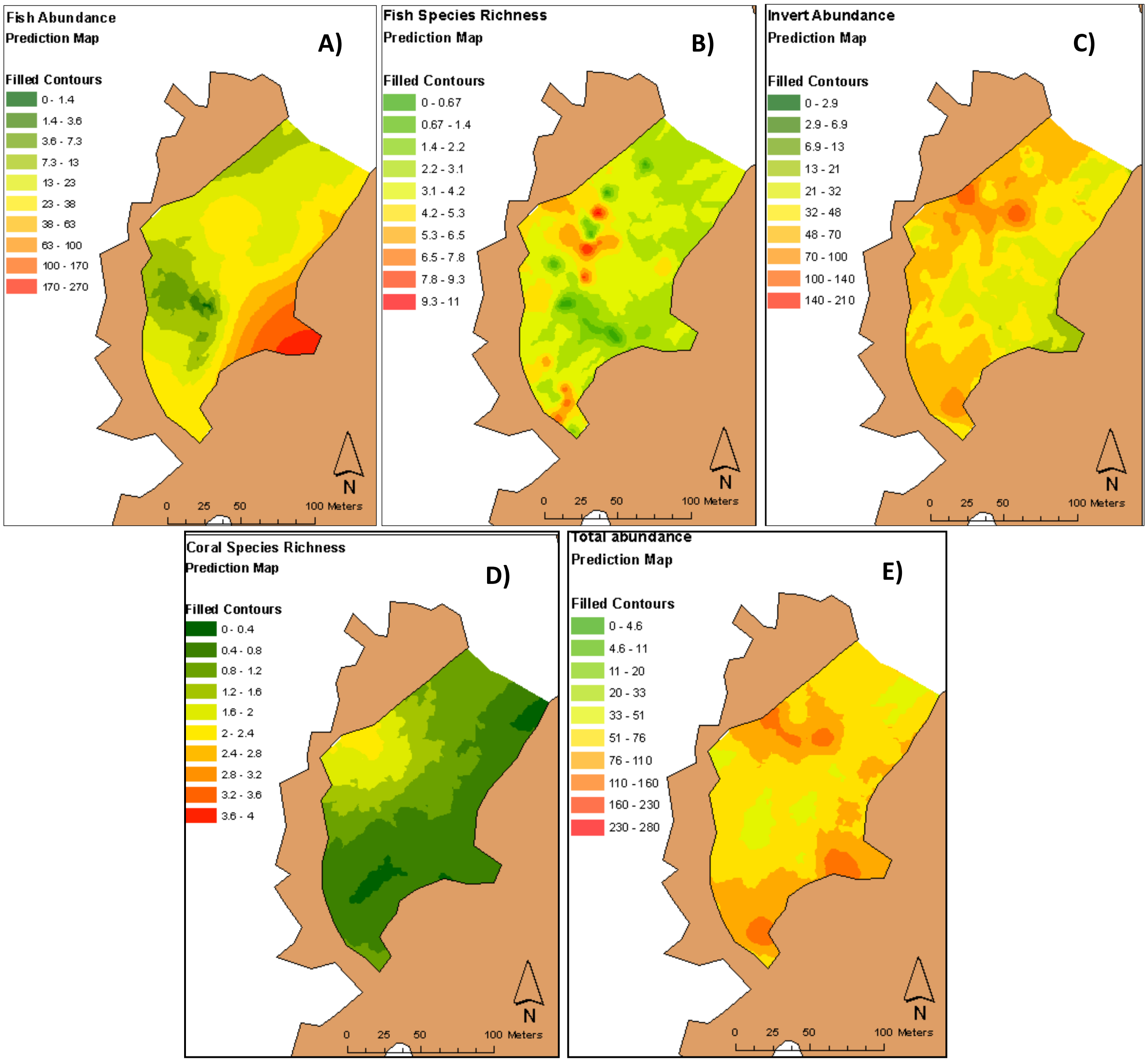


Figure 4. a) Interpolated GIS map of fish abundance per transect b) fish species richness per transect c) Invertebrate abundance per transect d) Coral species richness per transect e) Total faunal (fish and invertebrate) abundance per transect.

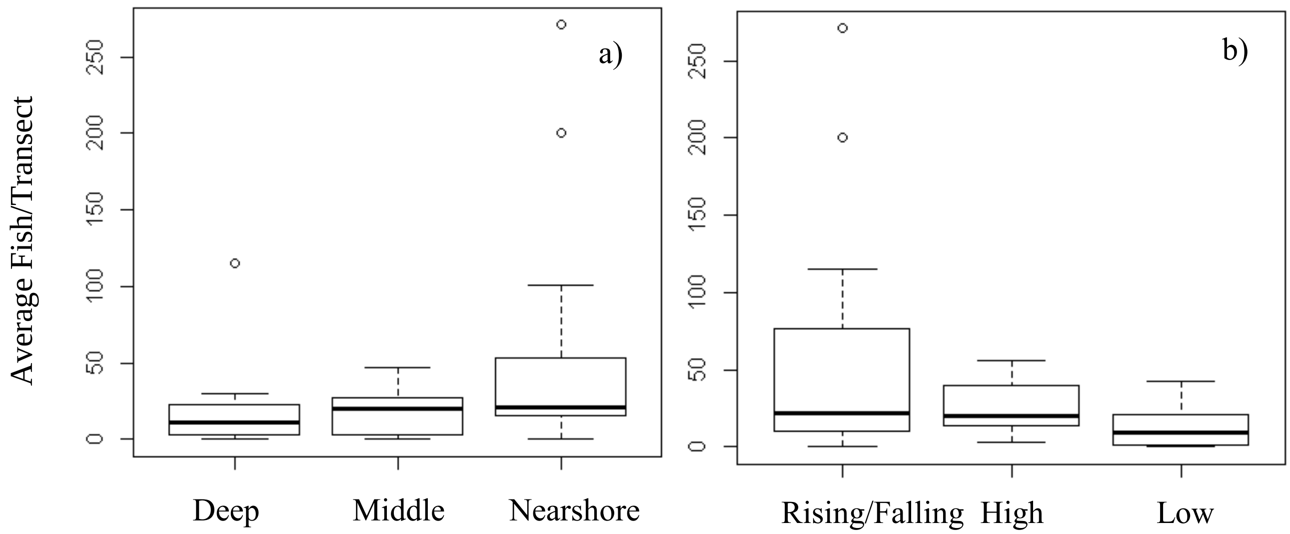


Figure 5. Pūpūkea Tide Pools Significant differences in fish abundance based on a) depth stratification ($p<0.04$) and b) tidal cycle ($p<0.01$)

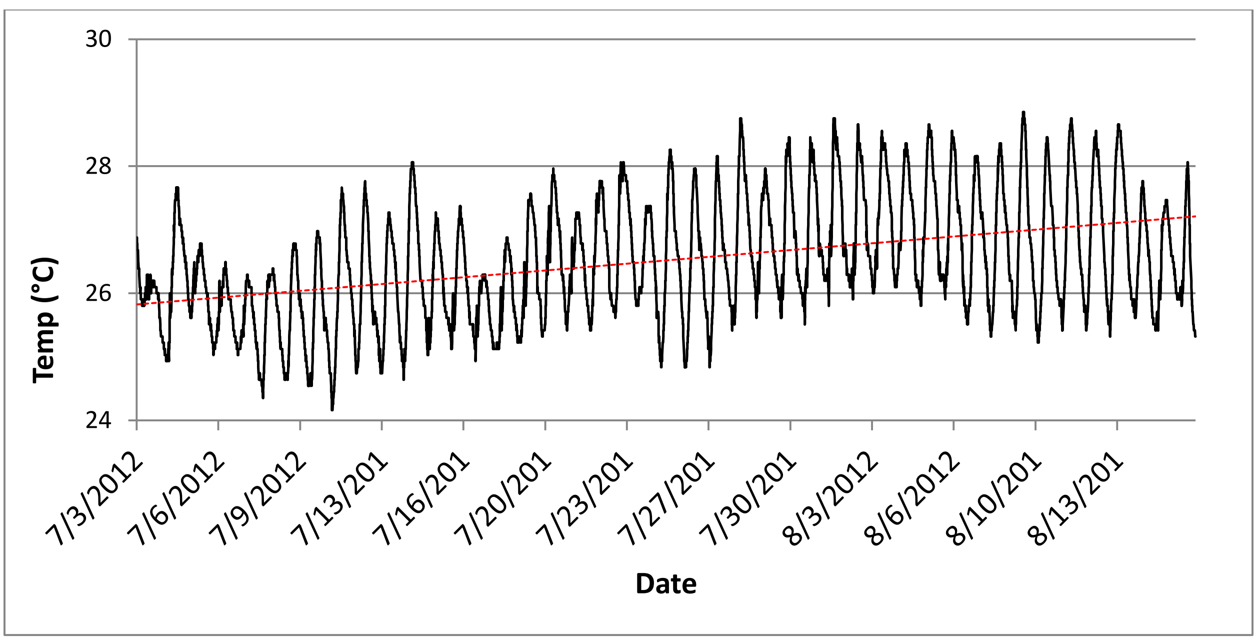


Figure 6. Temperature (°C) plot for logger #1, deployed in the southernmost area of the Pūpūkea tide pool from 7/3/2012 to 8/16/2012 (21° 38.953, 158° 03.816)

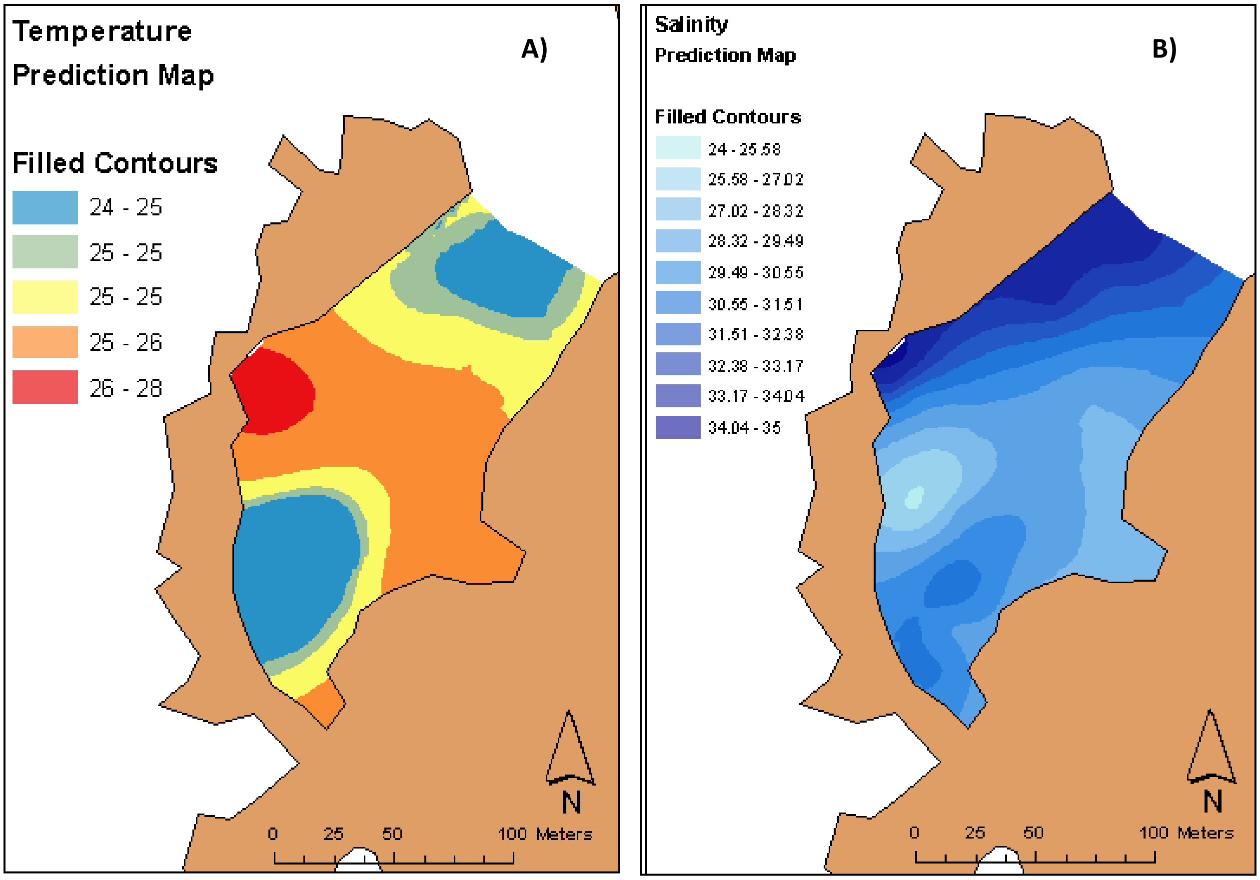


Figure 7. a) Temperature (° C) and b) Salinity (g/L) interpolated layers from sampling grid measurements

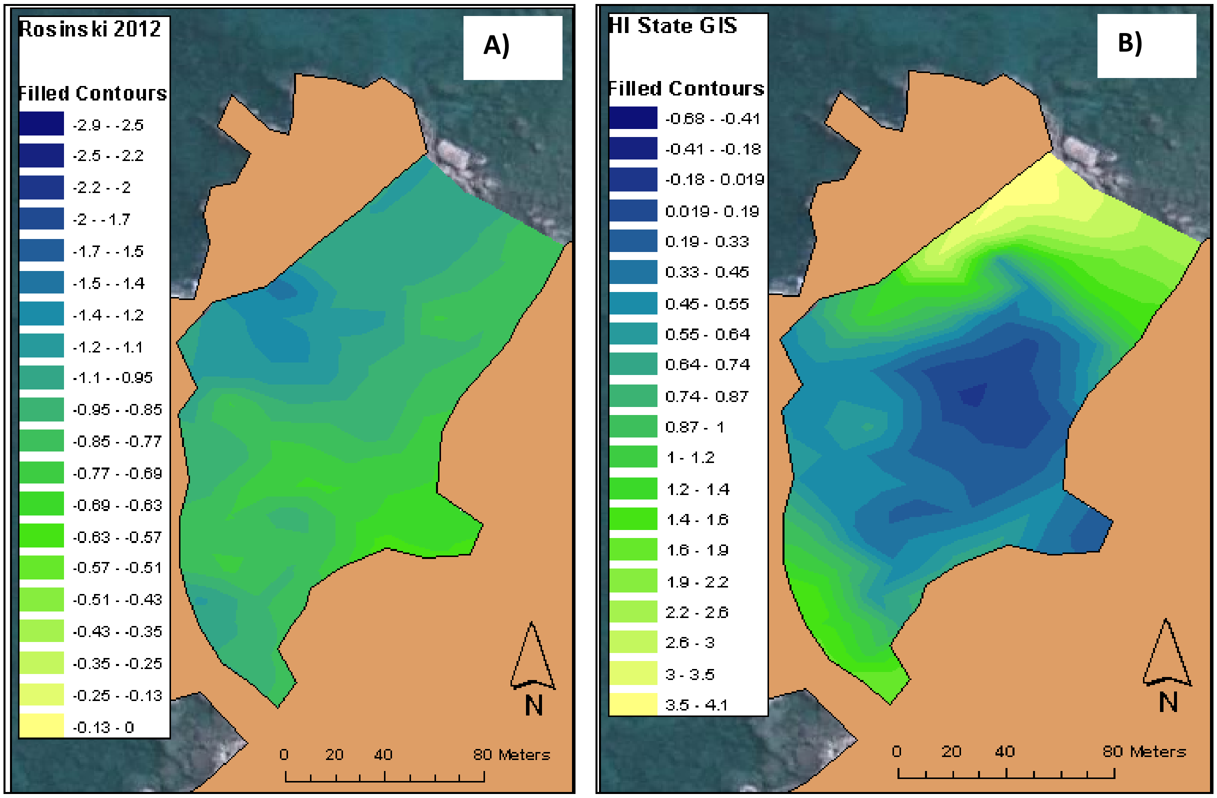


Figure 8. Bathymetric interpolated layer created from a) manually collected depth measurements and b) Hawai‘i State GIS Program (depths in meters)

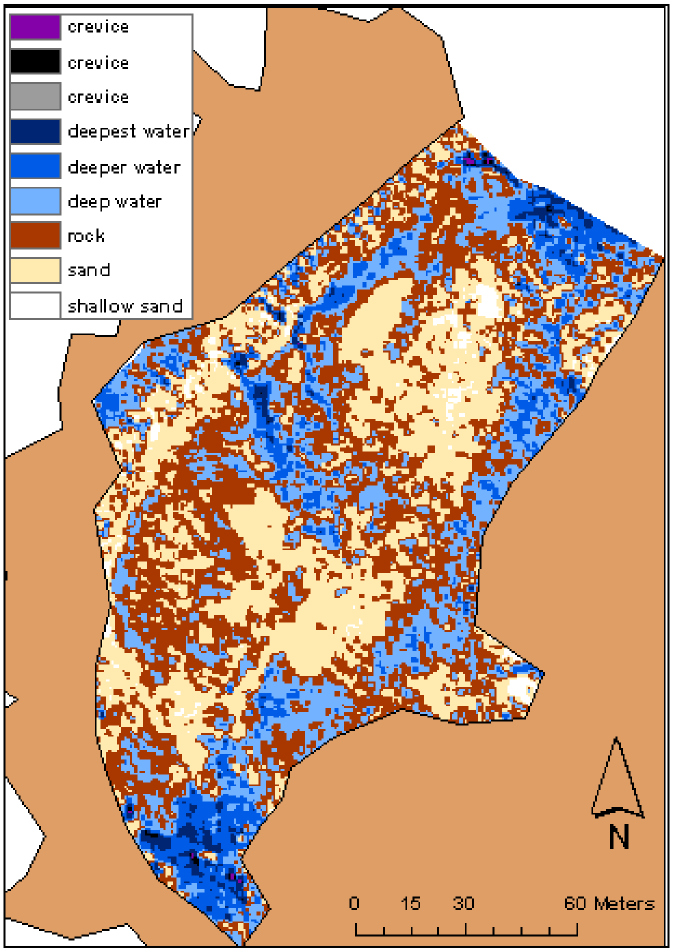


Figure 9. Map of Isocluster Unsupervised Classification of Pūpūkea tide pool using nine categories.

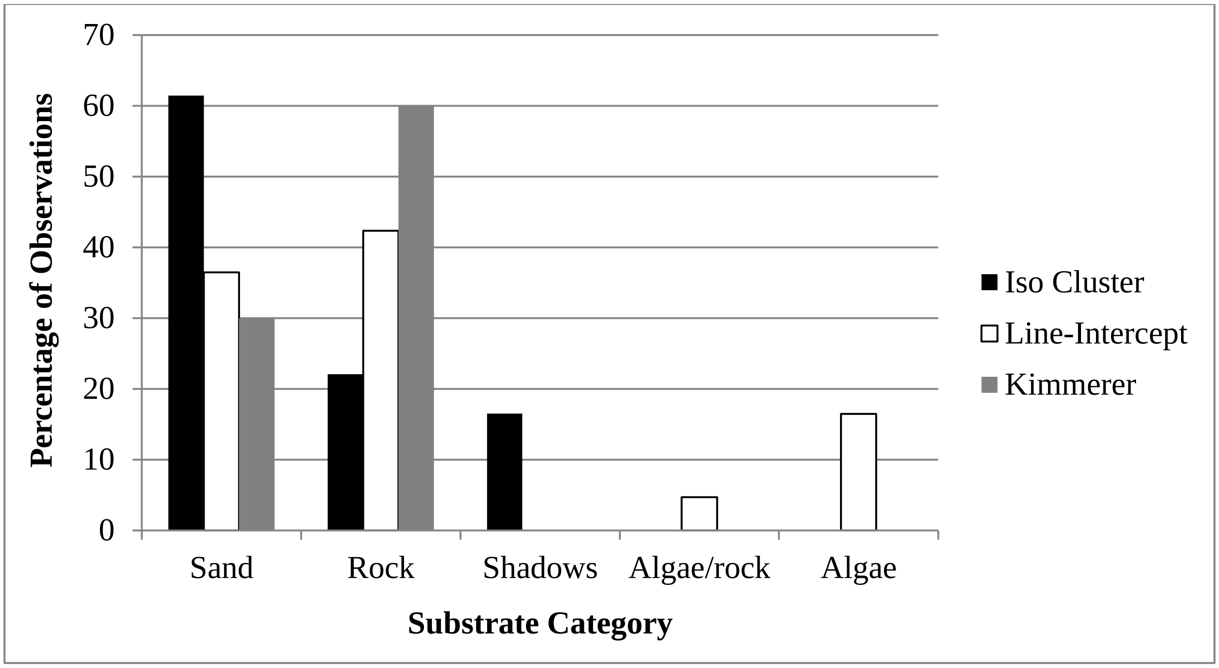


Figure 10. Tide pool habitat composition, include the relative proportion of sand, rock, shadows, algae/rock, and algae, using the Iso-cluster Unsupervised Classification method and the Line-Intercept method

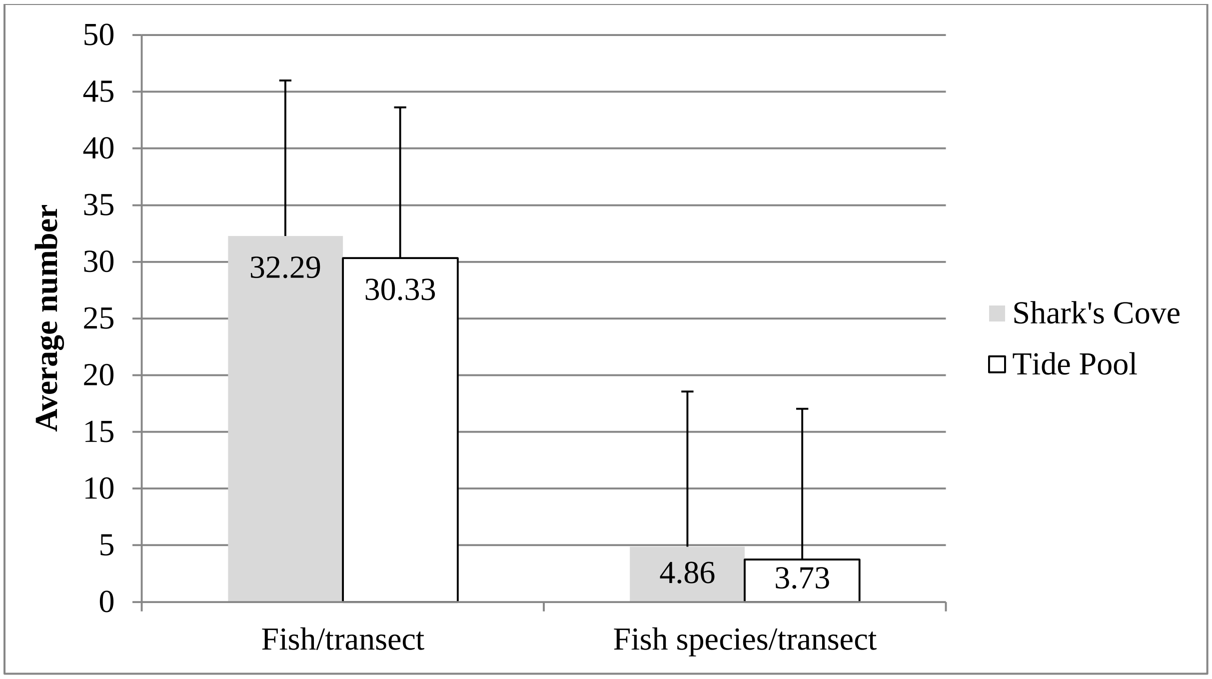


Figure 11. Mean (±20.5) fish abundance and mean (±0.9) species richness per transect in Shark’s Cove and the Pūpūkea tide pool

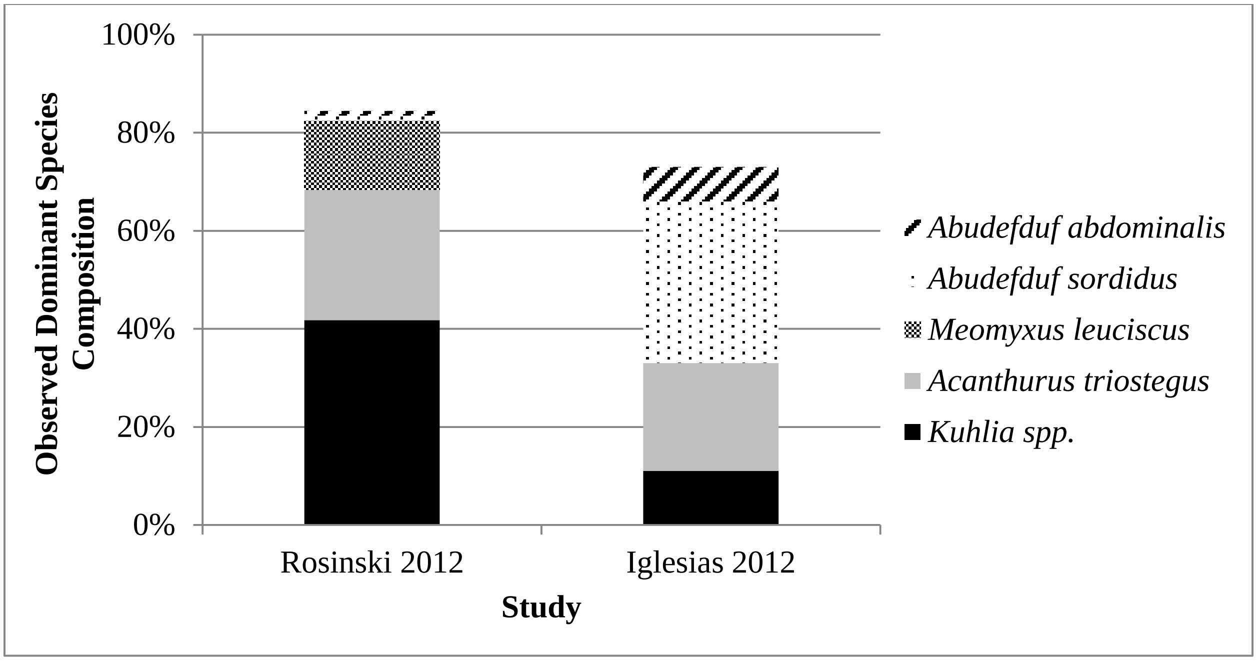
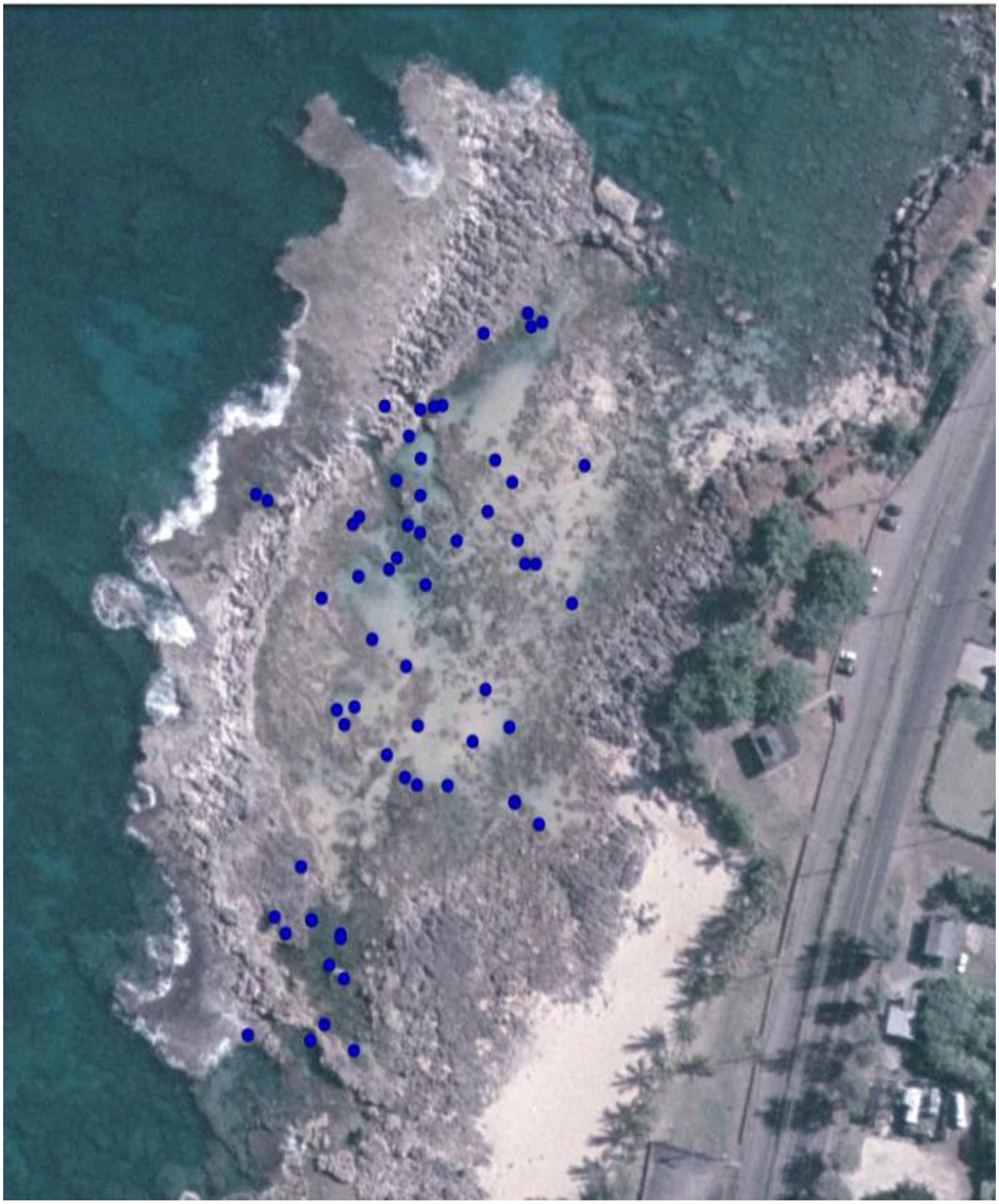


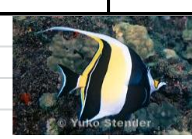
Figure 12. The observation frequency of dominant fish species in assemblages assessed in Iglesias 2012 and the Pūpūkea tide pool data (Rosinski 2012).

Appendix



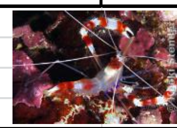
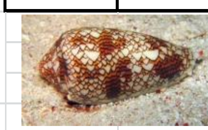
Appendix I. Transect locations in the Pūpūkea tide pool used for the acquisition of biological data

Name:			Transect #		/			
Date:			Tide:			Moon Phase:		
Time:		/	Starting Depth:		/	Wave Height:		

	Mamo - Hawaiian Sergeant		Manini - Convict Tang		Uoua - Sharnose Mullet (any Species)
	Mamo - IndoPacific Sergeant		Aholehole - Flagtail		Nenue - Chub (any Spcies)
	Malu - Sidespot Goatfish		Weke 'ula - Yellowfin Goatfish		Alo'ilo'I - Damselfish
	Blue-eye Damselfish		Palani - Eyestripe Surgeonfish		Humuhumunukunukuapua'a - Reef Trigger
	hīnālea 'akilolo - Yellowtail Coris		hīnālea lauwili - Saddle Wrasse		Opule - Pearl Wrasse
	Kala - Bluespine Unicorn		Kikakapu - Raccoon Butterfly fish		Uhu - Parrotfish (any species)
	Roi - Peacock Grouper		Po'opa'a - Hawkfish		Kihikihi - Moorish Idol
	Moa - Spotted Boxfish		Puhi Kapa - Snowflake Moray		Puhi - Stout Moray

Notes:	Photo Credit: Keoki Stender, if sheet is LOST please scan to: Rosinski.anne@gmail.com

Name:		**Transect #**	/		
Date:		**Tide:**		**Moon Phase:**	
Time:	/	**Starting Depth:**	/	**Wave Height:**	

	Ina Kea - Rock Boring Urchin		Wana - blue-black urchin		Slate Pencil Urchin
	White Spot Sea Cucumber		Loli - Plump Sea Cucumber		Loli okuhi kuhi - teated cucumber
	Brittle Star		Fisher's Star		Banded Coral Shrimp
	A'ama - Rock Crab		Seven Eleven Crab		Slipper Lobster
	Spaghetti Worm		He'e Mauli - Day Octopus		Opihi - Limpet (Any Species)
	Pipipi - Black Nerite		Cowry (Any Species)		Cone Snail (Any Species)
	✓		✓		✓
Lace Coral		Cauliflower Coral		Lobe Coral	
	✓		✓		✓
Mound Coral		Finger Coral		Rice Coral	

Notes: Photo Credit: Keoki Stender, if sheet is LOST please scan to: Rosinski.anne@gmail.com

Appendix II. Datasheets provided to volunteers for biological data collection

Appendix III. Location of temperature loggers in the Pūpūkea tide pool

Appendix IV. Temperature and salinity collection locations used for the sampling grid in the Pūpūkea tide pool

Appendix V. Summary of anthropogenic effects in the Pūpūkea tide pool

The mean number of people observed in the tide pool during the transect survey time of the study was 9.73 (maximum = 45, minimum = 0). Five incidences of fishing activity evidence were observed over 54 days. These were typically hand line tied to a rock with a large piece of bait in the water. Verbal communication with fishermen alludes to possible fishing for *Conger* *marginatus* (Puhi uha). Two observations of fish feeding were also observed. Approximately five large groups of children were seen in the tide pool during the study collecting macroinvertebrates, typically with a school or summer camp group.

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