

The West Hawai'i Coral Recruitment Project

Recruitment Dynamics of Scleractinian Corals along the Kona Coast of the Big Island of Hawai'i

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Abstract:

Maintenance of adequate levels of coral recruitment is vital to sustain coral reefs. Because early life stages are often more susceptible than adults to environmental stressors, data on settlement and recruitment can help predict potential effects of disturbance from, and resilience to, environmental change. The spatial-temporal variability of scleractinian coral recruitment is currently being investigated along the west coast of Hawai'i.

From April 2004 to present, terra cotta tiles have been placed at nine sites spanning the leeward side of Hawai'i Island. Eight tiles at each of the nine sites have been replaced biannually before and after known seasonal peaks in coral reproduction and recruitment. The tiles are then processed for microscope analysis, and coral recruits are counted and identified to genus. Several spatial and temporal trends are starting to emerge in this ongoing study. The relative contribution of the different families of recruits (Poritidea: 46.9%, Acroporidae 33.9%, Pocilloporidea 12.6%) and recruitment rates (average of all sites: 25 recruits m⁻² year⁻¹) recorded along the Kona Coast are comparably low to other areas around the state of Hawai'i. The two northern most sites, Waiaka'ilio and Puako, have had significantly higher densities of juvenile corals, with much lower densities at all the sites to the south. Approximately 77% of the time the coral recruits preferred to settle out on the bottom outside edge of the tiles compared to the vertical edges (9.78%) and the top (1.20%). This is likely the result of intense competition with filamentous algae, and/or grazing by herbivorous fish and urchins which can occur on the exposed top surface of the tiles. Peak settlement of coral larvae occur 87% of the time during the summer months (approximately April - September) in species with and without planktonic larvae. These distinctive characteristics in recruitment patterns underline the important role of life history strategies in understanding the spatial-temporal patterns of coral populations. The

comparably low coral recruitment rates noted in this study indicate that recovery from natural and/or anthropogenic influences will be slow.

Introduction:

Recovery of coral assemblages is highly dependent on growth of existing colonies and/or settlement and growth of new recruits coming from natal or distant reefs (Pearson, 1981; Sammarco, 1985), therefore a study on coral recruitment processes is critically needed to evaluate the maintenance of Hawaiian reefs. The time-scale of many coral recruitment studies has been too brief to determine long-term trends. Studying single events in isolation can be misleading, and a longer-term approach is necessary for understanding the responses of coral reef assemblages to multiple stressors (Hughes and Connell, 1999). Coral assemblages often show strong spatial-temporal variability at several scales, which are governed by a variety of interacting physical and biological processes that vary in frequency, intensity and spatial scale (Karlson and Hurd, 1993; Hughes and Connell, 1999). Among these processes, recruitment is now widely recognized as being fundamentally important for understanding the spatial patterns, dynamics, and maintenance processes of local adult-coral assemblages (Adjeroud et al., 2007). The West Hawai'i Recruitment Project is a long-term, collaborative investigation by the Hawaii Division of Aquatic Resources and the National Park Service into the coral settlement dynamics off the western coast (leeward side) of the Big Island of Hawai'i. The primary goal of this study is to observe spatial and temporal patterns of recruitment to establish current baseline information for marine resource management. Coral recruitment is now widely recognized as fundamentally important for understanding the dynamics and maintenance processes of adult coral assemblages and reef health. Recruitment is compared across various spatial scales: by region (>10km), by site (>1km), within sites (meters), and on each tile (centimeters), as well as across time (years and 6-month seasonal periods).

Recruitment was sampled using terra cotta tiles, known to be successful in previous studies. Tiles have been found to be one of the best substrates in terms of convenience, ease of searching, non-destructiveness, and recruit attraction (Harriott and Fisk, 1987). Tiles are attached to the substrate using a modified version of Mundy's (2000) design, using individually mounted pins. This method was found to be less obtrusive, and more cost and time efficient. Eight tiles were deployed at each of the nine sites, for a total of 72 tiles replaced every six months. This study is ongoing with eight non-consecutive years of data analyzed and discussed in this report.

Several spatial and temporal trends emerged from the data. Much higher rates of recruitment were observed in the northern sites of Waiaka'ilio and Puako (72 and 56 recruits $\text{m}^{-2} \text{year}^{-1}$, respectively); the northernmost site (Waiaka'ilio Bay) contributing 30.5% of the total recruitment thus far. However, over the study period there was a significant decrease in recruitment at Waiaka'ilio Bay (P-value 0.012) as well as at Miloli'i (P-value 0.019), which is one of the southern sites. *Porites spp.* and *Montipora spp.* were the dominate taxa, at 46.9% and 33.9% respectively. The summer months had notably higher recruitment patterns at 87.6%. This was

expected because peak reproduction of Hawaiian corals occurs during summer months, although reproduction continues year-round for some brooders (Kolinski and Cox, 2003). A large majority of the recruits (77.25%) were observed along or near the underside edge of the tiles. Previous studies on coral recruitment showed that corals tended to successfully recruit to the undersurfaces in shallow water, to vertical surfaces at intermediate depths and to upper surfaces at greater depths (Birkeland, 1981; Adjeroud et al., 2007; Cox and Ward, 2002; Arnold and Steneck, 2011).

Grigg and Maragos (1974) estimated that colonization of lava flows off Hawai'i takes up to 50 years. Given these rates, it is not surprising that few studies are long enough to directly trace successional changes. Therefore, the West Hawai'i Coral Recruitment project, with eight years worth of data to date, is a vital first step to understanding recruitment processes of west Hawai'i reefs. The recruitment process plays a pivotal role in molding the structure and dynamics of many benthic marine communities and also in understanding resiliency of various reefs to anthropogenic and natural stressors. Understanding recruitment patterns and their governing factors is therefore crucial for sound policy-making for coastal zone management and nature conservation (Abelson et al., 2005).

Materials and Methods:

Study area:

This study was conducted at nine sites spanning the west coast of the island of Hawai'i (Figure 1). With three northern sites: (1) Waiaka'ilio Bay, (2) Puako, (3) Ka'upulehu, three central sites: (4) Honokōhau, (5) Keauhou, (6) Ke'ei and three southern sites: (7) Ho'okena, (8) Miloli'i, (9) Manuka (Table 1).

The Hawaiian Islands are the most isolated island chain on earth, being 4,000 km from the closest continental land mass and 1,514 km from the nearest island to the south (Johnston atoll). Hawai'i is the largest of the Hawaiian Islands, with an area of 10,458 km² that is still increasing due to the presence of two active volcanoes.

Our chosen study sites span an area of approximately 130 km of coastline along the leeward (Kona) side of the island from Waiaka'ilio Bay in the north, to Manuka Bay in the South. The Kona coast is completely sheltered from northeast tradewinds-generated seas but is subject to three other classes of wave exposure. Swells generated in the South Pacific and Indian Oceans during the summer (south swells), North Pacific swells generated by winter storms (northwest swells), and local storms and fronts, termed "Kona Storms," which generally cause high winds and waves from the south through the west (Dollar, 1982). Much of the Kona coastline is comprised of a steep vertical profile and narrow reef bench, which causes the zonation pattern to be compressed compared to other Hawaiian offshore areas. As a result, boundaries between the zones are fairly distinct. The physiographic setting consists of a shoreline cliff, nearshore reef bench, sharp shelf break and a steep reef slope (Dollar, 1982). Ocean circulation off the West

Hawai'i coast is often strongly influenced by the presence of energetic mesoscale (50 to 150 km in diameter), cyclonic (counter clockwise) and anticyclonic (clockwise) eddies (Patzert, 1969, Lumpkin, 1998). Although the mechanisms of formation and propagation of these lee eddies are still not fully understood (Calil et al., 2008), a key forcing factor, at least with the cyclonic eddies, appears to be the northeast trade winds passing between the islands of Maui and Hawai'i (Lumpkin, 1998).

Site Design:

Location of the recruitment tiles was chosen randomly within a 50 m x 30 m area centered on existing Division of Aquatic Resources (DAR), West Hawai'i Aquarium Project (WHAP) fish transect sites. DAR established four permanent 25 m long transects per site with stainless steel pins marking the start and end points of each transect. Using these fixed points made for a quick and easy way to help find the tile locations. The tile locations were randomized prior to deployment by establishing random distance and compass bearings from a specified DAR transect pin using a random number generator. Criteria for placement of tiles were to stay within the designated WHAP area; stay within uniform reef habitat, none shallower than 8 m and none deeper than 20 m; and be mounted on dead coral that was sturdy enough to withstand storm swell disturbance. If the randomized spot did not fit all the criteria, than a short survey within a 2 m radius of the original point was made to find a suitable mounting site. The ideal mounting depth was 12 meters, although the chosen mounting locations ranged from 8.2- 17.7 meters deep.

Terra cotta tiles were used, which have shown to provide an acceptable substrate for scleractinian recruitment for a number of studies around the world: Australia (Harriott and Fisk., 1987; Mundy, 2000), French Polynesia (Adjeroud et al., 2007), the Caribbean (Kuffner et al., 2006), the Red Sea (Abelson et al., 2005), and here in Hawai'i (Friedlander & Brown, 2005). We chose a commonly available garden paving tile (Sunshine Pavers: 20.3 x 9.5 x 1.3 cm, 0.045 m² SA/ tile). Eight tiles were placed at each of the nine sites to balance several sampling considerations: increase statistical power by adding to the number of replicate tiles, further randomize their deployment spatially within uniform reef habitat and depth range, and limit the sample processing time. Tiles were attached to the substrate via a modified version of methods described by Mundy (2000). Tiles were drilled through the center to be attached to 5/16" x 6.25" stainless steel threaded rods, pneumatically drilled into the substrate and held fast by E6 EPCON System Epoxy. Construction of the arrays (from bottom to top) is as follows: 5/16" nut, washer, 7" x 7" PVC plate (to create a refuge or "gap" habitat under the tiles), plastic washer (to help with position of the PVC spacer), lock washer, nut, PVC spacer, terra cotta plate, washer, lock washer, and final 5/16" nut. The "gap" was done to inhibit grazing by invertebrates and fish on the underside of the tile where recruitment is most likely to occur at our depth range (Birkeland, 1981; Adjeroud et al., 2007; Cox and Ward, 2002; Arnold and Steneck, 2011). To check for seasonality differences, the tiles were deployed and replaced after 6 months. Old tiles were stored carefully in labeled bags, while being immediately replaced by new tiles. The old tiles were put on ice until they were brought back to the lab to be processed.

Analysis of tiles:

Once the retrieved tiles were back at the lab, they were immediately processed to be analyzed. First, each tile was properly labeled with site code and plate number. The tiles were then soaked in a 10% bleach solution for no less than 24 hours. Rinsed and dried, the tiles were stored in plastic bags and rapped in bubble wrap until microscope examination was possible.

Tiles were analyzed using an Omano OM99T zoom stereo dissecting microscope. Analysis used was following the raster-scanning technique, which consists of scanning the face of the tile twice, once side to side, and once top to bottom. Every surface of each tile was raster-scanned. When a coral recruit was found, it was circled with a fine-tipped Sharpie permanent marker, measured using a centimeter ruler, its general location on the tile noted, an initial taxon assignment made, a general description of the recruit noted, and all data recorded in note form and in a spreadsheet. The coral recruit description included morphology, damage when present, additional location circumstances such as placement within a groove or crevice in the tile surface or recruit placement on top of another sessile invertebrate (e.g. on the shell of a bivalve), and number of polyps when a coral recruit had already developed into a colony. Single polyp recruits that are expanding in to a colony were also indicated as a colony but with only one polyp. When measuring a coral recruit which was already a multi-polyp colony, the greatest basal diameter was measured of the colony, as well as the diameter of the largest or main polyp. Coral recruits were identified by comparison using descriptions and photographs from Dr. Eric Brown of the National Park Service, and with input and verification by Dr. Eric Brown.

Identifying coral recruits has been proven to be difficult because juvenile corals have few useful differentiating taxonomic characteristics (Babcock et al., 2003), therefore the coral polyps were identified to genus according to differences in morphology. Four main taxa were expected (*Porites* spp., *Montipora* spp., *Pocillopora* spp., and *Pavona* spp.) and all recruits were grouped into these taxa. Any that did not fit the known morphologies were put in an unknown category before seeking verification with the experts. Most of the classifications were positively verified.

Region	Site	Site code	Latitude	Longitude
<i>North</i>	Waiaka 'ilio	WA	20°04.4'N	155°51.9'W
	Puako	PU	19°58.2'N	155°50.9'W
	Ka'upulehu	KU	19°50.7'N	155°58.9'W
<i>Central</i>	Honokohau	HO	19°40.3'N	156°03.0'W
	N.Keauhou	KH	19°34.1'N	155°58.2'W
	Ke'ei	KE	19°27.7'N	155°55.6'W
<i>South</i>	Ho'okena	HK	19°22.0'N	155°53.5'W
	Miloli'i	MI	19°10.0'N	155°54.8'W
	Manuka	MU	19°04.6'N	155°54.2'W

Table 1: Coral recruitment sites along the leeward side of the Island of Hawai'i with abbreviated site codes, coordinates, and general location along the Kona coast.

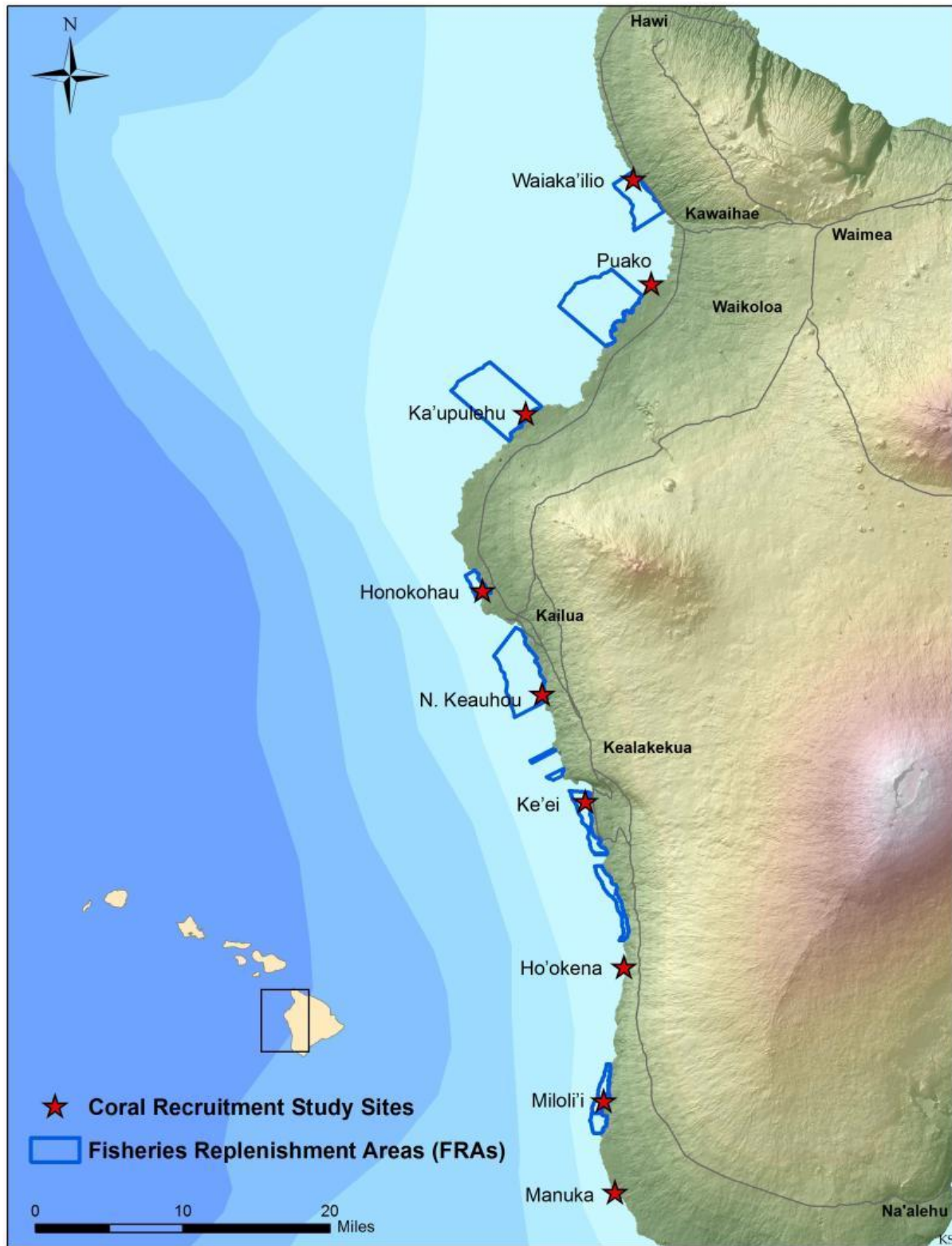


Figure 1: The west coast of the Big island of Hawai'i, with locations of coral recruitment sites both in and out of Fish Replenishment Areas (FRAs).

Results:

This ongoing study used terra cotta tiles (n= 864) to study recruitment rates of scleractinian corals off the west coast of Hawai'i, from April 2004 to March 2012. Recruitment was observed at multiple sites (n=9) using multiple replicate tiles (n=8) per round (1 round = 6 months) in order to discern any spatial or temporal trends (Table 2). In general, the tiles were picked up and deployed every 6 months, but due to sharing of the DAR boat with multiple projects, some were longer or shorter than the 6-month time periods. Also, due to unforeseen circumstances, there was a break in the continuity of the project from October 2006 to September 2007 and January 2010 to August 2011. Over the various time periods the tiles were picked up by DAR and other staff, processed and prepped for microscope analysis. Due to time constraints, and other DAR projects, the tiles were only picked up and replaced twice during these longer time periods. These tiles were processed under the microscope and recorded like the rest, but the data were only used where applicable (e.g. region totals and spp. composition). The observed recruits were counted, identified to genus, sized, and the location of recruits on the tile was noted.

Rounds	Dates	Season	# of months
1	April-Oct. 2004	summer	6
2	Oct.-April 2005	winter	6
3	April-Sept. 2005	summer	5
4	Sept.-April 2006	winter	7
5	April-Oct. 2006	summer	6
6	Sept. 07-April 2008	winter	7
7	April - Nov. 2008	summer	7
8	Nov. - May 2009	winter	6
9	May - Jan 2010	summer	8
10	Jan - Sept 2010	winter/summer	9
11	Sept - Aug 2011	winter/summer	11
12	Aug - March 2012	winter	7

Table 2: Dates, seasons, and number of months the recruitment tiles were in the field.

Spatial trends:

Analyzing the data to the individual tile was not possible because of too many zeros (zero recruits) (mostly winter season tiles). Tile data were then pooled for all eight tiles at each site for each round. Pooling the data this way lacked the replication necessary for a 1-Way Repeated Measures ANOVA. Instead a 1-Way Randomized Complete Block ANOVA, with the rounds as the blocking variable was used. The two northernmost sites Waiaka'ilio Bay and Puako showed a significant difference in abundance compared to two of the central sites of North Keauhou and Ke'ei ($p < 0.04$). Both Waiaka'ilio Bay and Puako combined contributed to over half, 57.89%, of the total recruitment patterns along the coast while North Keauhou and Ke'ei combined only contributed, 5.79% (Figure 2) of the total.

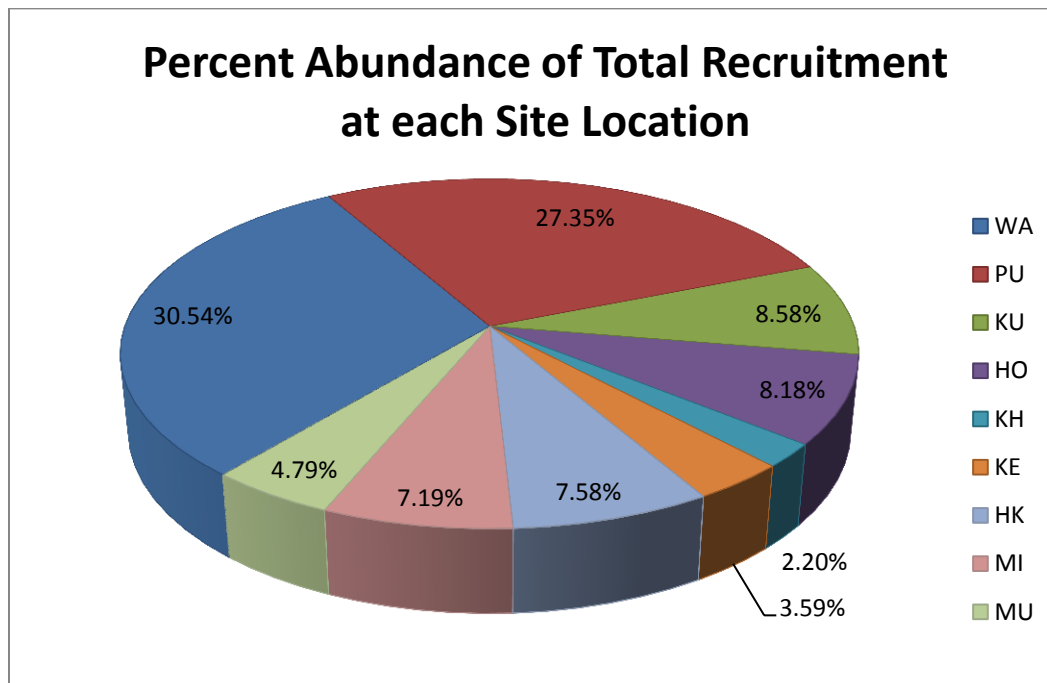


Figure 2: Percent abundances of coral recruits ($n=501$) for all sites in order from the northern most site of Waiaka'ilio Bay (WA) to the southernmost site, Manuka (MU).

Spatial trends at the tile level displayed a dramatic preference (all categories pooled) for corals to settle out on the bottom outside edge of the tile (77.25%), compared to the sides or vertical edges (9.78%), the bottom middle (6.59%), and the bottom center (5.19%, Figure 3). The genera *Pavona* was the only recruit to prefer the bottom center of the tiles and this location was the only place on the tiles *Pavona spp.* were ever discovered. *Porites spp.* recruits were the only genera to settle out on the top surface of the tiles. This pattern settlement location was only observed at one site, Ka'upulehu, and only on rounds nine, ten and eleven.

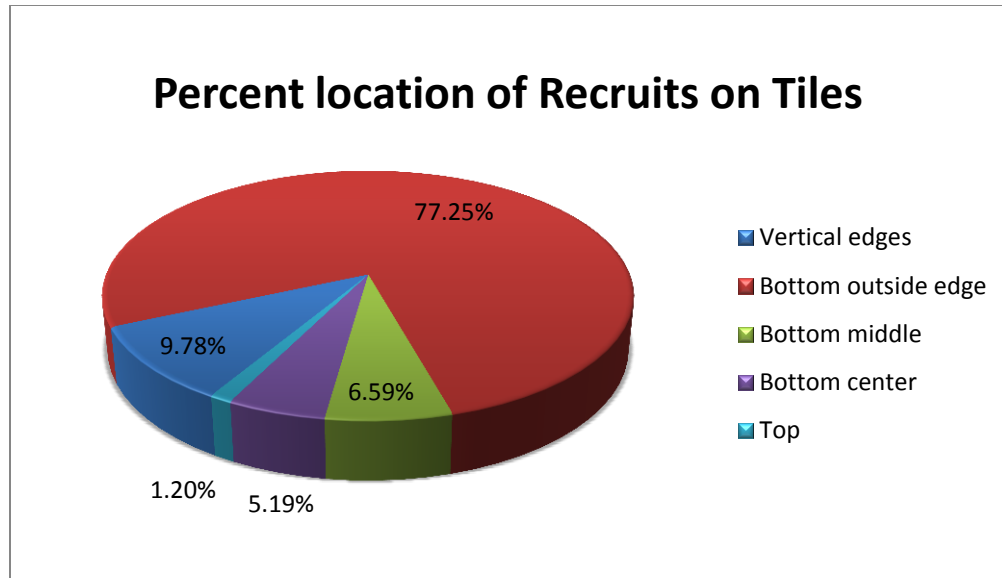


Figure 3: Variation among the relative abundance (%) of recruits (all taxa pooled) for preference of recruitment placement on tile over the entire study period to date.

Taxonomic composition and recruitment rates:

Over the 8-year study period, a total of 501 recruits have been recorded on the 837 tiles analyzed (27 tiles were lost), with a peak of 158 recruits in round 9, to a low of 3 recruits for rounds 2 and 12 (all sites included). Total number of recruits per tile ranged between 0 (many of the winter tiles) and 21 (tile number 8 at Puako, round 9). Recruits were largely dominated by *Porites spp.* (46.9% of the total recorded over the 8 years to date), followed by *Montipora spp.* (33.9%), and *Pocillopora spp.* (12.6%). Recruits of other genera and unidentifiable recruits represented a lower proportion of the total number of recruits (*Pavona spp.* 2.2%, Unidentifiable, 4.4%, Figure 4)

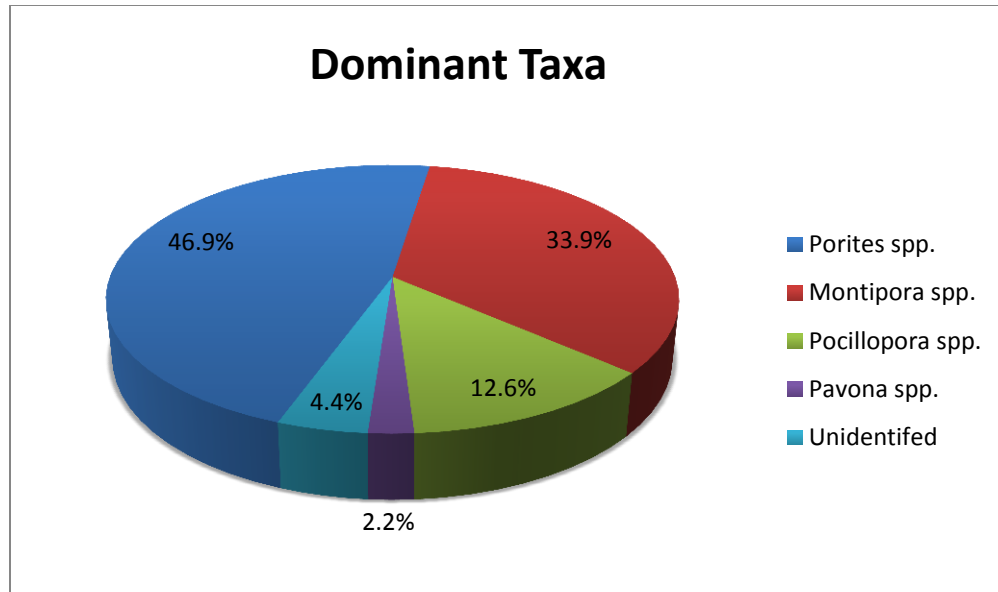


Figure 4: Variation in taxonomic recruitment patterns with the genera's *Porites* spp. and *Montipora* spp. being the majority of coral recruits.

Recruitment rates varied from 72 recruits $\text{m}^{-2} \text{year}^{-1}$ (all rounds pooled) at Waiak'a'ilio Bay, to 4 recruits $\text{m}^{-2} \text{year}^{-1}$ (all rounds pooled) at North Keauhou (Table 3). Recruitment ranges varied at the site level from 0 to 411 recruits $\text{m}^{-2} \text{year}^{-1}$. The zeros were mostly during winter rounds, with the 411 recruits $\text{m}^{-2} \text{year}^{-1}$ observed at Puako during round 9. An average of 25 recruits $\text{m}^{-2} \text{year}^{-1}$ (all sites pooled) was found to be a low recruitment rate compared to other studies from around the world and on the low end for the state of Hawai'i (Table 4). In Hawai'i, the highest recruitment rate was observed in Hanalei Bay, with a an average of 7924 recruits $\text{m}^{-2} \text{year}^{-1}$ (Friedlander and Brown, 2005) to a low of 0 recruits $\text{m}^{-2} \text{year}^{-1}$ found at Kaneohe Bay, Oahu and Waikiki Beach, Oahu (Polacheck, 1978). A later study was done in Kaneohe Bay and found an average of 7.8 recruits $\text{m}^{-2} \text{year}^{-1}$ (Demers, 1996).

	Average Recruits m⁻² year⁻¹	Std Dev.	Range of Recruitment Rates
Waiaka'ilio	72	101.01	0 - 176
Puako	56	115.84	0 - 411
Ka'upulehu	18	15.37	0 - 49
Honokohau	19	22.13	0 - 71
N. Keauhou	4	4.54	0 - 16
Ke'e'i	8	12.57	0 - 41
Ho'okena	16	19.80	0 - 67
Miloli'i	17	22.56	0 - 64
Manuka	10	16.32	0 - 44
Average	25	23.30	

Table 3: Average recruitment rates and standard deviations for all sites, along with the range of recruitment rates found at each site. Bottom is the average rate for the Kona coast. This rate is used when compared to other places within the state of Hawai'i as well as around the world (Table 4).

Temporal Trends:

Analysis of seasonality was used with a 1-Way Randomized Complete Block ANOVA, with the rounds as the blocking variable. There is strong evidence ($P < 0.0001$) of a seasonaleffect over all ten rounds used. Rounds 10 and 11 were left out because of the break in continuity of the project from January 2010 to August 2011. The tiles for rounds 10 and 11 were out in the field for longer than 8 months and spanned too much time into the next season. The summer months (April - September) exhibit much higher recruitment (Figure 4), with recruits settling out 87.63% of the time during summer months. This result was expected because peak reproduction of Hawaiian corals occurs during summer months, although reproduction continues year-round for some brooders (Kolinski and Cox, 2003).

When the 1-Way Randomized Complete Block ANOVA was used to analyze change in coral recruitment over time, there was no evidence of coral recruitment increasing or decreasing over time when looking at the coast as a whole. However, when looking at the sites individually, two sites displayed significant decline in coral recruitment. Data were plotted for the entire study period excluding rounds 10 and 11, and a regression analysis was applied for each of the nine sites. Waiaka'ilio Bay and Miloli'i exhibited a significant decline in recruitment ($R^2=0.27$, $p=0.027$; $R^2=0.18$, $p=0.028$, respectively; Figures 5 & 6). Knowing that seasonality was consequential from the 1-Way Randomized Complete Block ANOVA, data were broken up by season, plotted, and regression analyses were applied. No other sites displayed a significant increase or decrease in coral recruitment except Waiaka'ilio Bay and Miloli'i. The winter-season regression analysis showed no significant change for these two sites (WA: $R^2=0.02$, $p=0.727$; MI: $R^2=0.00$, $p=0.62$; Figures 5 & 6). Nonetheless, the regression analyses of summer months

indicated a significant decline in recruitment at both sites (WA: $R^2=0.68$, $p=0.023$; MI: $R^2=0.49$, $p=0.028$; Figure 5 & 6).

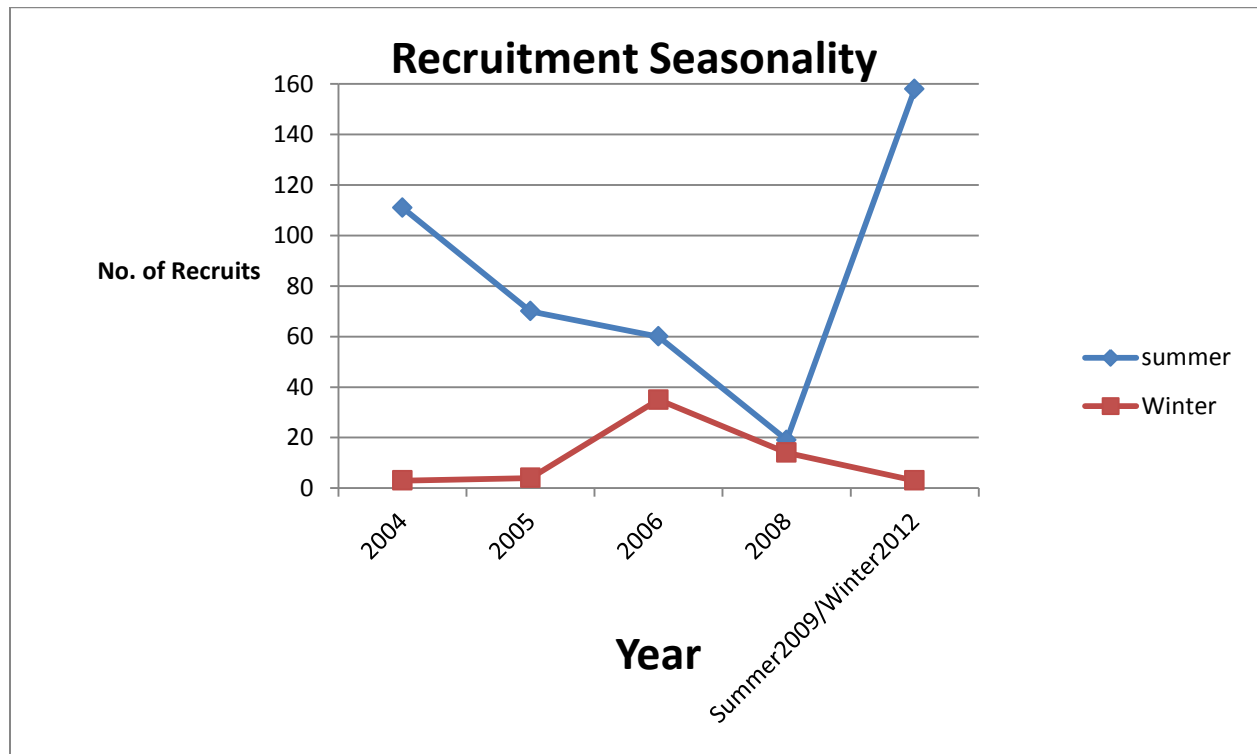


Figure 4: Variation among seasonality differences (summer vs. winter) for all of the rounds that were out for no longer than 8 months. There was a break in continuity of the project between January 2010 and August 2011. During this time period, the tiles were out longer than 8 months and therefore not used in analyzing seasonal differences.

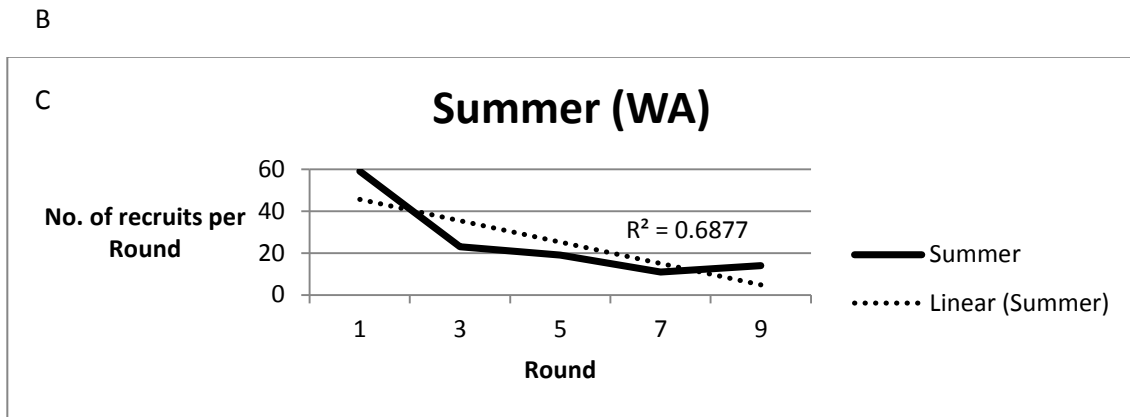
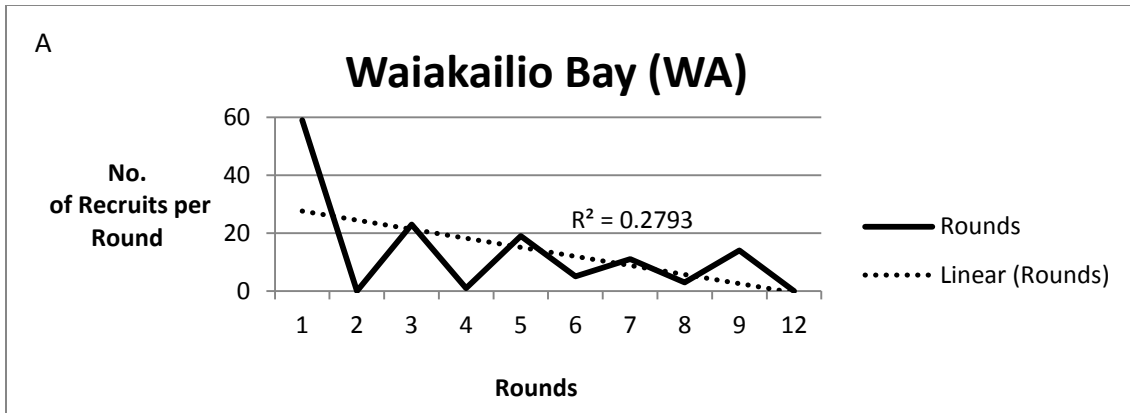


Figure 5: Recruitment patterns for Waiaka'ilio Bay (WA), showing a decline in recruitment from 2004 to 2012, and data separated out to show winter vs. summer patterns. Note the differences in scales due to poor recruitment in winter seasons. Rounds 10 and 11 were left out due to tiles being in the field longer than 8 months.

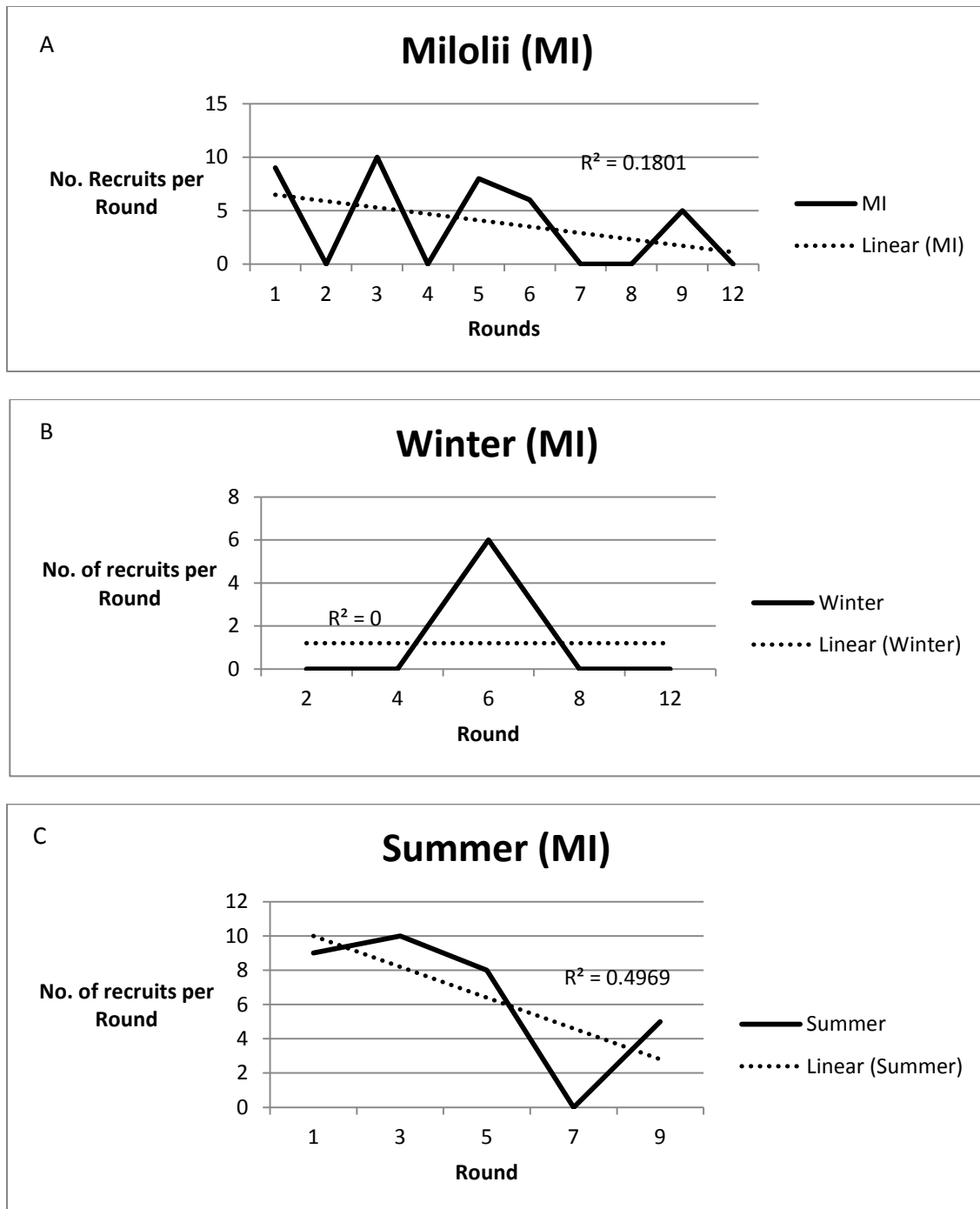


Figure 6: Recruitment patterns for Miloli'i (MI), showing a decline in recruitment from 2004 to 2012. Then separated out to show winter vs. summer patterns. Note the differences in scales due to poor recruitment in winter seasons. Rounds 10 and 11 were left out due to tiles being in the field longer than 8 months.

Discussion:

Coral reefs are highly diverse and dynamic ecosystems. They are very important to tropical coastal communities due to their biological, ecological, cultural, and commercial benefits. They provide millions of dollars per year in terms of employment, income, and tourism revenues (Ahmed et al., 2007). Local reef systems in the main Hawaiian Islands are valued at \$10 billion and estimated to provide \$360 million per year to the state's economy (Ceasar and van Beukering, 2004). Given the high ecological and economical values of reefs it is essential for coastal marine managers to have a solid recruitment baseline in order to better understand local coral reef population dynamics. Any assessment of potential impacts to Hawaiian reef corals must take into consideration local population structure, and timing and location of all life stages of coral reproductive cycles, including recruitment and growth (Kolinski and Cox, 2003). Hughes and Connell (1999) argue that studying single events in isolation can be misleading and that a longer term approach is necessary for understanding the responses of coral reef assemblages to multiple stressors. The West Hawai'i Coral Recruitment Project is an exceptional beginning to a long-term assessment of the recruitment processes of the Kona Coast.

Spatial heterogeneity of recruitment patterns at several scales:

The spatial trends observed between 2004 and 2011 display a strong recruitment pattern in the northern portion of the West Hawai'i coast with two of the northern sites (WA and PU) receiving over half, 57.89% of the coast's total recruitment. The cold-core, cyclonic eddies that are created from currents passing through the Alenuihaha Channel between the islands of Maui and Hawai'i may be a vector supplying this recruitment pattern. These eddies are important agents in bringing nutrient-rich deeper water to the euphotic zone and hence increasing biological activity (Lobel & Robinson, 1986; Seki et al., 2001; Bidigare et al., 2003; Dickey et al., 2008; Kuwahara et al., 2008; Landrey et al., 2008; Mahaffey et al., 2008; Rii et al., 2008). The presence of the cyclonic eddies so close to shore could be a possible reason as to why there are more recruits at the northern sites, with seeding being transported north along the coast from these currents. However, Fox et al. (2012) found these eddies are highly variable in timing and duration with no evidence of any seasonal pattern. Fox et al. (2012) also found no significant correlations between monthly reef fish recruitment and eddy activity as measured by standard deviation or mean monthly sea surface height at the same sites as this study. However, these eddies could have a stronger effect on the planktonic coral larvae than on fish larvae, or the fish may respond to different ecological and/or biological cues for recruitment.

On the smaller spatial scale, the coral recruits tended to prefer the bottom outside edge of the tiles. Other studies around the world and in Hawai'i have found similar patterns (Adjeroud et al., 2007; Cox and Ward, 2002). A study by Birkeland et al. (1981) showed that the greatest amount of successful recruitment was found at intermediate depths (12-20m). As depth increased, there

was a significant tendency for successful recruitment to shift from vertical to horizontal substrata and from lower to upper surfaces. Filamentous algae may grow faster in shallow water creating sediment traps that smother the coral recruits. Partial scouring from suspended sediment is probably worse for corals in shallow water because of greater wave surge. The attenuation of light with increasing depth may have a more pronounced effect on the growth of most species of algae than on the growth of corals. Somewhere between the depths of 12m and 24m the available light may be reduced enough that the growth rate of algae is decreased relative to the rate of coral growth, giving corals a better chance of survival after metamorphosis on upper horizontal surfaces (Birkeland et al., 1981). This may be why only a few recruits were observed on the upper surface.

Taxonomic Trends:

The greatest contribution of the different genera was *Porites spp.*, which was just under half of the total recruits identified. *Porites* is the dominate taxa at all the study sites (Walsh, unpublished data). The chosen sites for this study were nine of the same study sites as DAR's West Hawai'i Aquarium Project (WHAP). These sites were chosen because certain reef fish such as *Z. flavescens* and *C. strigosus*, sought after by tropical fish collectors, prefer to recruit to *Porites compressa* habitats. A study by Dollar (1982) observed twenty-two species of hermatypic corals along the Kona coast; three species accounted for 97% of all coral cover, were *Porites lobata*, *Porites compressa*, and *Pocillopora meandrina*. Differential post-settlement mortality of new recruits tends to drive relative abundances of dominant recruits towards an adult community dominated by the same taxa (Sammarco, 1991). In other words, it is likely the dominate recruit is the same taxa of the dominating adult, and vice-versa.

Recruitment Rates:

The overall recruitment rates found along the west coast of Hawai'i Island were particularly low (average 25 recruits $\text{m}^{-2} \text{year}^{-1}$, Table 4) over the eight years to date. This rate is considerably lower than those found around the world from Australia and the South Pacific to the Caribbean and Israel, using the same recruitment tile methodology. This rate is also low for the state of Hawai'i with a higher rates of 7924 recruits $\text{m}^{-2} \text{year}^{-1}$ (Friedlander and Brown, 2005) in Hanalei Bay, Kauai and 415 recruits $\text{m}^{-2} \text{year}^{-1}$ at Puamana, Maui (Brown, 2004). With much lower rates at 7.8 recruits $\text{m}^{-2} \text{year}^{-1}$ at Kaneohe Bay, Oahu (Demers, 1996), and 0 recruits $\text{m}^{-2} \text{year}^{-1}$ at Waikiki Beach (Polacheck, 1978). Excluding the study of Friedlander and Brown at Hanalei Bay, Hawai'i in general has low overall recruitment compared to other tropical regions (table4). Multiple explanations could account for this difference: 1) Hawai'i's reefs are recruitment limited with the narrow fringing reef ; 2) short term studies are not adequate to capture episodic

recruitment of long-living organisms; 3) recruitment patterns in the main islands may not be representative of the recruitment rates found elsewhere in the Hawaiian archipelago; 4) materials used in previous studies may not have been ideal for recruitment; 5) Recruitment is possibly a function of number of available patches more than the total available area (Birkeland et al., 1981). Whatever the case may be, relatively low coral recruitment rates indicate that that recruits are highly vulnerable to severe or frequent perturbations and that recovery will be slow (Adjeroud et al., 2007).

Average recruitment rates around the world

recruits m⁻² year⁻¹

Taken from Friedlander and Brown (2006) unless noted.

Range of recruitment rates is at the scale of site.

Site, Island	Ocean	Substrate	Average Recruitment	Range of Recruitment Rates	Attachment Method	Latitude	Reference
Hanalei Bay, Kauai, Hawaii	Pacific	Terracotta	7924	403-15386	direct	11 N	Friedlander and Brown (2005)
Great Barrier Reef, Australia	Pacific	Clay	4258	2050-7178	direct	10-23 S	Hughes et al. (1999)
Cape Tribulation, Australia	Pacific	Ceramic	2689	156-7944	—	14 S	Fisk and Harriott (1990)
Fiji	Pacific	Ceramic	734	322-1812	direct	17-18 S	Kojis and Quinn (2001)
Zanzibar, Tanzania	Indian	Terracotta	594	0-3000	—	6 S	Franklin et al. (1998)
Lord Howe Island, Australia	Pacific	Ceramic	538	178-1411	—	31 S	Harriott (1992)
¹ Tanguisson, Guam	Pacific	PVC	530	—	—	13 N	Neudecker (1976)
Great Barrier Reef, Australia	Pacific	Ceramic	489	144-1222	—	15 S	Fisk and Harriott (1990)
Puamana, Maui, Hawaii	Pacific	Terracotta	415	8-1792	direct	21 N	Brown (2004)
Taa, Tanzania	Indian	Terracotta	282	190-374	metal rack	5 S	Nzali et al. (1998)
Discovery Bay, Jamaica	Caribbean	Coral Slab	251	119-341	PVC frame	17 N	Rylaarsdam (1983)
Luminao Beach, Guam	Pacific	PVC	209	0-2433	direct	13 N	Birkeland (1981)
St. Thomas, Virgin Islands	Caribbean	Ceramic	134	89-180	direct	18 N	Kojis and Quinn (2001)
Olowalu, Maui, Hawaii	Pacific	Terracotta	122	95-233	direct	21 N	Brown (2004)
² Heron Reef, Great Barrier Reef	Pacific	Ceramic	112.6	36.3-170	metal rack	23 S	Dunstan and Johnson (1998)
Bermuda	Caribbean	Ceramic	99	4-384	metal rack	29 N	Smith (1992)
Moorea, Tahiti	Pacific	Ceramic	82	38-125	metal rack	17 S	Gleason (1996)
Guana Island, Virgin Islands	Caribbean	Terracotta	59	2-296	metal rack	18 N	Carlson (2001)
Saipan, Northern Marianas	Pacific	Ceramic	49.3	—	direct	15 N	Kojis and Quinn (2001)
Solitary Islands, Australia	Pacific	Ceramic	44	6.0-88	metal rack	30 S	Harriott and Banks (1995)
Honolua Bay, Maui, Hawaii	Pacific	Terracotta	41	7.0-92	direct	21 N	Brown (2004)
² Moorea, Tahiti	Pacific	Terracotta	40.8	27.9-58.6	direct	17 S	Adjeroud (2007)
Kaneohe Bay, Oahu, Hawaii	Pacific	Concrete	36	0-124	resting block	21 N	Fitzhardinge (1993)
² Luminao Beach, Guam	Pacific	PVC	35	19.0-50.9	resting block	13 N	Birkeland et al. (1981)
² Eilat, Israel	Red Sea, Indian	Terracotta	25.3	17.8-32.7	metal rack	29 N	Glassom et al. (2004)
² West Hawaii, Hawaii	Pacific	Terracotta	25	0-411	direct	19-20 N	Martin et al. This study
Northern Mariana Islands	Pacific	Ceramic	24	0-112	direct	14-15 N	Kojis and Quinn (2001)
Tinian, Northern Marianas	Pacific	Ceramic	22.5	—	direct	15 N	Kojis and Quinn (2001)
³ Kaneohe Bay, Oahu, Hawaii	Pacific	Concrete	7.8	0-11.5	resting block	21 N	Demers (1996)
² Bahias de Huatulco, Mexico	Pacific	Terracotta	6.5	0.7-16.1	metal rack	15 N	Lopez-Perez (2007)
St. Croix, Virgin Islands	Caribbean	Coral Slab	6	4.0-18	—	18 N	Rogers et al. (1984)
² Asan Bay, Guam	Pacific	PVC	2	0-4.3	direct	13 N	Minton and Lundgren (2006)
³ Waikiki Beach, Oahu, Hawaii	Pacific	Natural	0.2	.03-.32	perm. quadrats	21 N	Polacheck (1978)
Rota, Spain	Atlantic	Ceramic	0	—	—	36 N	Kojis and Quinn (2001)
³ Kaneohe Bay, Oahu, Hawaii	Pacific	Coral	0	0	resting block	21 N	Polacheck (1978)

¹Only control sites were used for rate calculation.

²Recruitment rate calculated by White (this study)

³Recruitment rate taken from Brown (2004).

*Rate calculated from plates with 12 month deployment

Because of various methods and materials used in past studies, this table only provides a very basic comparison.

Table 4: Average recruitment rates from around the world. Listed from highest to lowest average recruitment rate. Type of recruitment surface and style of attachment methods provided for comparison.

A marked seasonal variability in recruitment patterns was found in west Hawai'i. The seasonality in coral recruitment is strongly related to the spawning patterns of local assemblages,

which is partly controlled by inter-annual and seasonal changes in oceanographic characteristics. Coral larvae recruit year-around, but a vast majority of recruitment takes place during the summer and fall subsequent to spawning of the most abundant species. With strong evidence ($P < 0.0001$) that the summer months are the time when most of the recruitment is occurring, a suggestion can be made to stop the winter rounds, and focus on the summer rounds. With modest to no recruits found on the winter tiles, little to no additional information is produced from these rounds. This change would cut costs and allow for a longer study period, which would provide a longer trend in recruitment processes.

Continuation of recruitment monitoring for corals will further develop our understanding of dispersal and recruitment dynamics on West Hawai'i coral reefs, and will provide essential information for improved management of coral reefs in the Main Hawaiian Islands, and elsewhere. A single survey will provide a snapshot of the status of coral reefs, but a longer term approach is required to understand the processes underlying changes in assemblages (Hughes and Connell, 1999).

At the site level, a significant decline in recruitment was observed at two sites, one in the north at Waiaka'ilio Bay, and one in the south at Miloli'i (Omaka'a). Waiaka'ilio Bay exhibited the highest recruitment patterns along the Kona coast, with 30.54% of the total recruits observed in this study. However, this site expressed an overall decline in adult coral cover from 2003 to 2011 (Kona DAR, unpublished data, Table 5). A Possible reason for this inconsistency could be the cyclonic eddies transporting coral larvae north to Waiaka'ilio Bay, where nearby land development and watershed protection projects are underway. These land-based activities impacts could have contributed to heavy silt run-off over the last decade and stressed the corals in this location enough to cause degradation and decline in adult coral cover, without affecting the recruitment supplied by currents. The positive impact this high recruitment pattern could have is that coral populations appear to rely on sporadic episodes of high recruitment for their maintenance and recovery (i.e., "storage effect"; Warner and Chesson, 1985). Adult population densities are probably the results of 10-year averages of variation in larval production and early juvenile mortality, and present-day populations may reflect successful recruitment that occurred years or decades earlier. For recovery processes, such sporadic recruitment events need to be more frequent than perturbation events if reefs are to be maintained (Adjerdoud et al., 2007). The case is the opposite at Miloli'i. The coral recruitment rate is declining, but the overall adult coral cover increased from 2007 to 2011 (Table 5). This increase could be due to the "storage effect" as well. Potentially, high recruitment rates occurred before this study period started, and are now starting to show in the adult populations. Continued observations of recruitment patterns by the West Hawai'i Recruitment Project are needed to investigate this hypothesis.

Site (N to S)	2003	2007	2011	Δ (2007/2011)	P=	Δ (2003/2011)	P=	
Lapakahi	19.50%	11.37%	11.78%	.41	0.794	-7.69	0.032	Overall Decline, no change from 2007 to 2011
Kamilo	49.50%	38.19%	28.96%	-9.23	0.000	-20.27	0.004	Overall Decline
Waiaka'ilio Bay	54.40%	42.50%	38.78%	-3.72	0.089	-15.13	0.054	Overall Decline, no change from 2007 to 2011
Puakō	49.09%	47.83%	34.21%	-13.63	0.001	-14.88	0.002	Overall Decline mainly between 2007/2011
'Anaeho'omalu	40.58%	31.47%	28.43%	-3.04	0.147	-12.15	0.005	Overall Decline, no change from 2007 to 2011
Keawaiki	29.66%	16.73%	18.68%	1.95	0.220	-10.98	0.031	Overall Decline, no change from 2007 to 2011
Ka'upulehu	40.71%	31.15%	27.05%	-4.09	0.171	-13.66	0.030	Overall Decline, no change from 2007 to 2011
Makalawena	44.88%	47.57%	47.63%	0.06	0.992	2.76	0.489	No Change
Unualoha	N/A	36.82%	36.51%	-0.31	0.873	N/A	N/A	No Change (only measured from 2007/2011)
Wawaloli	37.21%	37.51%	42.26%	4.74	0.061	5.05	0.140	No overall change, increasing from 2007/2011
Wawaloli Beach	37.93%	42.25%	44.45%	2.20	0.479	6.52	0.187	No Change
Honokōhau	43.22%	48.54%	48.32%	-0.22	0.940	5.10	0.437	No Change
Papawai	32.31%	38.31%	41.05%	2.75	0.506	8.84	0.173	No Change
Old Kona Airport	N/A	53.16%	51.19%	-1.97	0.570	N/A	N/A	No Change (only measured from 2007/2011)
S. Oneo Bay	56.09%	61.86%	46.55%	-15.31	0.019	-9.54	0.054	Overall Decline mainly between 2007/2011
N. Keauhou	31.92%	31.28%	28.00%	-3.28	0.134	-3.92	0.165	No Change
Kualanui	52.81%	62.35%	59.78%	-2.57	0.358	6.97	0.124	No Change
Red Hill	30.68%	33.22%	35.26%	2.04	0.470	4.58	0.148	No Change
Keopuka	15.98%	15.59%	14.44%	-1.15	0.600	-1.54	0.559	No Change
Kealakekua Bay	27.10%	28.64%	23.11%	-5.53	0.288	-3.99	0.219	No Change
Ke'e'i	31.20%	28.67%	26.70%	-1.96	0.543	-4.50	0.379	No Change
Kalahiki (Ho'okena)	36.53%	39.62%	38.94%	-0.68	0.720	2.41	0.026	No Change
Ho'okena (Auau)	28.18%	28.44%	29.98%	1.54	0.671	1.80	0.109	No Change
Miloli'i (Omaka'a)	29.76%	27.08%	32.94%	5.86	0.052	3.18	0.414	Increase from 2007/2011
Miloli'i (Manukā)	30.35%	33.17%	33.36%	0.19	0.961	3.01	0.689	No Change

Table 5: Percent coral cover at West Hawai'i sites in 2003, 2007, 2011. Unpublished data from Division of Aquatic Resources (DAR), Kona. Highlighted sites are the nine sites used in this study, sites listed in order from north to south.

Sound natural resource management and conservation must be based on a detailed understanding of reef processes if we are to successfully develop coastal areas in a manner that minimizes impacts to coral reef ecosystems (Kolinski and Cox, 2003). A long-term data set of coral recruitment processes will support dependable and responsible resource management actions for the West Hawai'i reef ecosystem. With thousands of dollars generated for the State of Hawai'i by reef ecosystems such as the Kona coast, it is imperative to continue quality long-term analyses of our reef ecosystems.

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