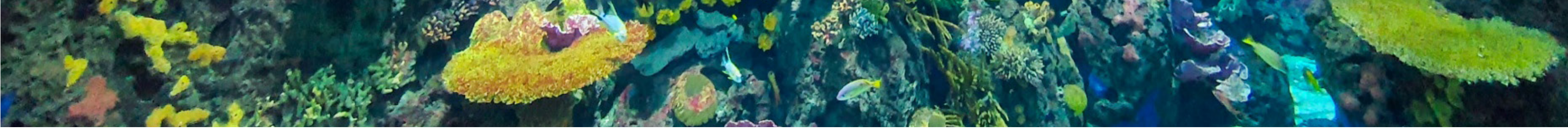

Factors That Limit Establishment of Stony Corals

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ABSTRACT

Corals occupy less than 1% of the surface area of world oceans but provide a home for 25% of all marine fish species. This study analyzed individual coral heads, specifically the genus *Pocillopora* (tentative identification: *Pocillopora elegans*), and their establishments in Cuajiniquil using 3 locations in the Guanacaste province of Costa Rica to understand why coral reefs are not establishing at some sites. These sites occur at Bajo Rojo, Bahía Thomas West, and Isla David. The size of establishing coral heads, the surrounding water temperature where each coral head occurred, the urchin cover in a 30 cm radius of each coral head, the bleaching of each individual coral head, the substrate the coral was establishing on, the approximate angle of the substrate, the depth of the coral, and the surge of the water at each site were recorded. The potential factors that affect coral establishment of *Pocillopora* in Guanacaste, Costa Rica along the coast of Cuajiniquil were investigated: urchin populations may compete with corals for substrate, strong surges may displace larvae, and a range in coral health measured by bleaching may affect coral establishments observed at Isla David and Bajo Rojo. *Pocillopora* spp. are, however, establishing in larger numbers at Bahía Thomas which may be due to the weak surge, the smaller quantities of urchins, and the good health of individual establishing corals.

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INTRODUCTION

Coral reefs are the most biologically diverse of shallow water marine ecosystems, yet they are being degraded worldwide by human activities and climate change (Roberts, 2002). Central American coasts are currently exposed to more pollution, both natural and anthropogenic, than ever before. This has had a devastating effect on most reefs and corals in the tropics. Coral reefs have been deemed the marine equivalent of tropical forests in both diversity and productivity, yet management and conservation of corals are not given the attention they deserve (Guzman, 1991).

Stony corals of the world's oceans are divided into two groups: the reef-building, or hermatypic corals and the non-reef building, or ahermatypic corals. Hermatypic corals are responsible for reef existence. Their success depends on the presence of microscopic algae known as zooxanthellae (Hickman, 2008). Corals have a symbiotic relationship with the colorful zooxanthellae that live in their tissues. When the symbiotic relationship becomes stressed due to increased ocean temperatures or pollution, the algae are expelled from the tissues of the coral. Without the algae, the coral loses its major source of food, turns white or very pale, and is more susceptible to disease (US Department of Commerce, 2010).

During the last few decades, however, severe bleaching events, like major storms and rising global water temperatures, have killed the zooxanthellae of many corals that rely on the microscopic plants for survival. These bleaching events can occur when corals are stressed by changes in conditions such as temperature, light, or nutrients, causing them to expel the symbiotic algae (zooxanthellae) living in their tissues. This leads the coral to turn completely white and is called coral bleaching. Furthermore, continuous degradation of coral reef habitats is increasing in the eastern Pacific as intense natural disturbance and frequent human impact, like boating and fishing practices, devastate corals and reefs of Costa Rica. Surviving individuals for some *Pocillopora* spp. are extremely small and reef recovery by sexual and asexual means has been significantly reduced (Guzmán, 1991). Corals can reproduce asexually when the tips of the branches are broken off. The fragments are distributed by ocean currents and can form a new colony at new locations. Corals can reproduce sexually through spawning by releasing buoyant sperm and eggs into the water column. These sperm and eggs are able to fertilize in the water (Gomez and Pawlak, 2018).

Recovery of coral reefs in the eastern Pacific is linked to several important biological processes including coral reproduction, availability and location of parent coral populations, dispersal mechanisms, extent of coral predation, and the amount of reef framework destruction. This study attempts to answer the following questions: Why are corals, specifically *Pocillopora* spp., not establishing in large numbers at some sites in Cuajiniquil? Where are *Pocillopora* corals establishing prominently in Cuajiniquil? In the study, several hypotheses concerning these questions are found in the table below (Table 1). Two-way ANOVA in JMP was used to compare variables at three sites.

1. *Pocillopora* coral in poor health do not grow large enough to create reefs and bleached *Pocillopora* coral may affect reproductive events. Shallow depths and warm water may also be indications of poor coral health.
2. Sea urchins are so populous in the area that they may be overtaking viable spaces and crevices for establishing corals.
3. The surge at some sites may be too strong at some sites for reefs to form.
4. *Pocillopora* corals are not establishing at some sites because larvae are not arriving.

Table 1. The potential factors that may affect coral establishment.

MATERIALS AND METHODS

The observations included in this study took place from 10 May 2019 to 16 May 2019. A total of 30 hours in the water in six days were spent observing and measuring over 100 individual corals for the three sites. Establishing *Pocillopora* spp. coral heads between 0-20 cm in size were examined. "Establishing heads" were defined as individual *Pocillopora* not connected to any part of another *Pocillopora* reef or coral. Coral coverage is different than the number of coral heads in each transect. Coverage takes into account coral abundance and reef cover if it is available in a transect at a site. The amount of coral coverage is measured by square meters of coral over a 30 m x 2 m transect. The fraction is then converted into a percentage used in the results for Figure 3 and accounts for hypothesis 1. Urchin cover is defined as the number of visible urchins counted over a 30 m x 2 m transect and accounts for hypothesis 2. Urchins may have been hidden or miscounted. Therefore, the number of urchins per transect is an approximation.

Three locations were surveyed in Guanacaste, Costa Rica along the coast of the Santa Elena Peninsula and Cuajiniquil. These sites included Bajo Rojo, Bahía Thomas West, and Isla David. At Bajo Rojo, the leeward exposed side of sedimentary rock was used for transects 1 through 4. This side contained substrate of mainly rocks affected by bio-erosion. On the windward side of the sedimentary rock was one large 40-meter ridge, angled at about 45 degrees that had no corals visible. Both sides of the site had strong surges and the sediment was almost completely underwater. At Isla David there were mostly sedimentary and bio-erosion rocks, while at Bahía Thomas West the substrate was mostly sand with few bio-erosion rocks.

At each site, individual coral heads between 0-20 cm in size were found and a weighted tape-measure transect was placed 30 m from the first coral head found (unless coral heads were not found for a transect—then the transect was placed randomly). Along the 30 m transect, the number of sea urchins and coral heads approximately 1 meter on each side of the transect were counted to analyze hypotheses 2 and 4. The size of each coral head was measured, and the surrounding water temperature was noted (based on body temperature change) to account for factors in hypothesis 1. Temperature was categorized on a scale of 1 (coldest) to 5 (hottest) which was converted into temperature names (1= cold, 2 = cool, 3 = warm-cool, 4 = warm, 5 = direct sunlight). Qualitative data was used to establish this scale. The urchin cover in a 30 cm radius of the given coral head was recorded and that coral head was assigned a bleach rating on a scale of 1-3 (1 = healthy, no bleaching, 2 = some bleaching but zooxanthellae present, 3 = complete bleaching) to account for factors in hypotheses 1 and 2.

The distance to the next coral head, the distance of the coral head to the shore, and the depth of the coral were all recorded. The substrate the coral was on was noted to account for hypothesis 4. The surge angle

Figure 1. Surge angle tool. *A weighted string on a PVC pipe with a protractor was used to measure the surge angle. The highest angle a surge reached was 90 degrees.*

Site	# transects	Avg. # coral heads/ transect	Standard deviation
BR	4	3	1.83
ID	4	1.75	1.5
BT	4	21	9.56

Table 2. Comparison of average number of coral heads per transect for each of the 3 study sites. *4 transects were used at each site. This table is helpful for comparing coral occurrence at Bajo Rojo, Isla David, and Bahía Thomas. Bahía Thomas had the most coral heads on average per transect with the largest standard deviation.*

of the water at each site was noted to account for hypothesis 3. The angle was measured by a weighted string on a PVC pipe used with a protractor to measure the surge angle (the angle at which the surge pulled out the dangled string) (Fig. 1). This measurement served as a proxy for surge strength. Lower angles correlate to weaker surges and higher angles correlate to stronger surges. The highest angle a surge reached was 90 degrees. The entire procedure was repeated for 4 transects at each of the 3 sites.

RESULTS

Bleach rating vs. size of individual coral head

At Bahía Thomas, individual establishing corals ranging in size from 4 cm to 20 cm mostly had a bleach rating of 1 and a few had a bleach rating of 2. None were completely bleached with a bleach rating of 3. At Isla David, an observable visual trend occurred; as size of individual corals increased, bleach rating decreased. The smallest recorded coral at Isla David had a bleach rating of 3 while the largest recorded coral at Isla David had a bleach rating of 1. Corals at Isla David with bleach ratings of 2 occurred at sizes between the smallest and largest corals of Isla David. Finally, at Bajo Rojo, individual establishing corals ranged in size and bleach without following a continuous pattern. The relationship between size and bleaching depends on the site ($F = 10.9$, d.f. = 3, 58, $p < 0.0001$) (Fig. 2) (Table 2).

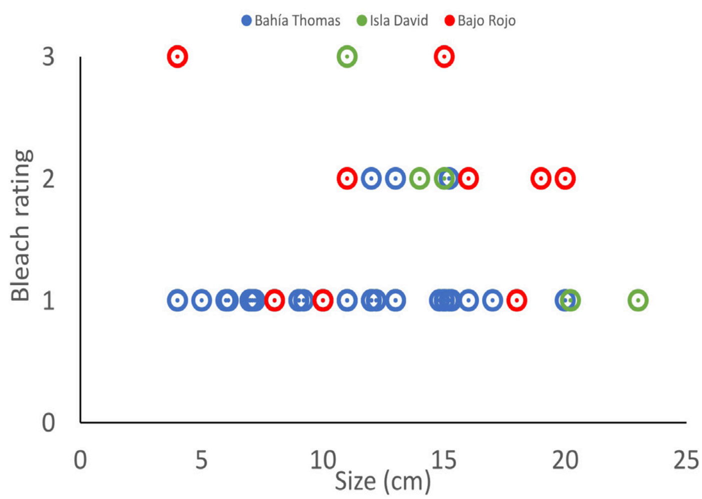

Figure 2. Bleach rating vs. size of coral head. *The relationship between bleaching and coral head size varied by site. At Isla David, larger corals faced distinctly less bleaching than smaller corals, compared to Bajo Rojo which had a random distribution and to Bahía Thomas where bleaching was minimal and appeared unrelated to size.*

Percent of coral coverage per transect vs. counted number of urchins per transect

The most coral coverage occurred when less than 100 urchins per transect were present. Bahía Thomas sustained coral coverage at a higher percent cover of urchins than the other two sites. At Bahía Thomas, average overall coral coverage was 44.7% and occurred in areas with no more than 350 urchins present in each transect (Fig. 3).

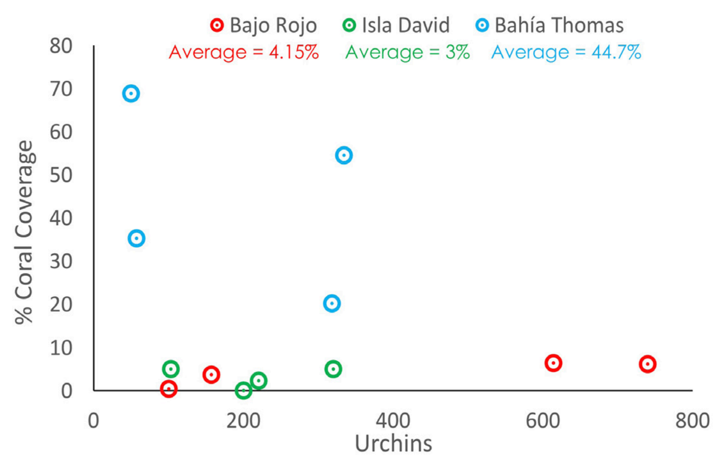

Figure 3. Percent of coral coverage per transect vs. counted number of urchins per transect. *At Isla David, average overall coral coverage was 3% and occurred in areas of 100-350 urchins. At Bajo Rojo, average overall coral coverage was 4.15% and occurred in areas of 100-200 urchins and 600-800 urchins. The relationship between urchins and coral coverage also depends on site ($F = 8.6$, d.f. = 3, 8, $p = 0.007$) (Fig. 3).*

Total number of coral heads vs. surge angle in degrees per transect

More corals were establishing in areas with weak surges. The highest number of individual establishing coral heads occurred at Bahía Thomas which had the weakest surge angle of 20 degrees or less. Isla David had surge angles between 35 and 65 degrees, but less than 5 heads occurred per transect. Finally, at Bajo Rojo, the surge was the strongest with an angle between 80 and 90 degrees, and 5 or less heads per transect. At 20 degrees and below, the highest amounts of coral heads were found. Above 35 degrees, less than 5 coral heads

Effect	*F-ratio*	*d.f.*	*P*
Size of individual coral head vs. depth	2.27	3, 58	0.0899
Bleach rating vs. depth	13.66	3, 58	<.0001*
Bleach rating vs. angle of substrate	13.97	3, 58	<.0001*
Bleach rating vs. temperature	17.42	3, 57	<.0001*
Size of individual coral head vs. urchin cover surrounding individual coral head	2.00	3, 58	0.1233
Bleach rating vs. urchin cover surrounding individual coral head	11.48	3, 58	<.0001*
Size of individual coral head vs. angle of substrate	1.55	3, 58	0.2111

Table 4. Two-way analysis of variance for all 3 study sites, depth, bleach rating, size, temperature, angle of substrate, and number of urchins in 30 cm radius of individual coral. *Significant tests are marked with an asterisk . Size of individual coral head is in centimeters and depth of coral is in meters. Angle of substrate is in degrees and is measured on the horizontal upward from the ocean floor.*

per transect were found. The relationship between surge angle and number of establishing coral heads depends on site (F= 11.67, d.f. = 3, 8, p = 0.0027) (Fig. 4). The p-value represents the relationship between surge factor and the number of coral heads, since at each site, different amounts of coral heads occurred with different surge strengths.

Bleach rating vs. urchin cover surrounding individual coral head

At Bahía Thomas, most corals had a bleach rating of 1 and were surrounded by 0 to 25 urchins. Three corals at the site with a bleach rating of 2 had 0 surrounding urchins. No corals at this site had a bleach rating of 3. At Isla David, individual corals with a bleach rating of 1 had 10 to 15 urchins present. Individual establishing corals with a bleach rating of 2 had only 1 urchin present. With 20 surrounding urchins, the establishing coral had a bleach rating of 3. At Bajo Rojo, for all individual coral heads, all bleach ratings occurred with less than 10 surrounding urchins. The relationship between bleach rating and surrounding urchins depended on the site and resulted in a significant interaction (Table 4).

Total coral heads for each specific substrate at each of the 3 study sites

Finally, the study looked at establishing corals and the substrates they occurred on at each site. At Bahía Thomas, most establishing cor-

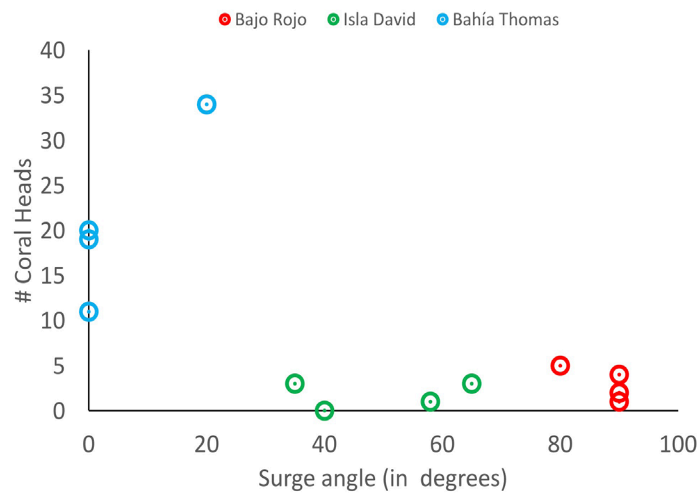

Figure 4. Total number of coral heads vs. surge angle in degrees per transect. *Some individual coral heads were larger than 20 cm in size. It was important to include them in the total number of coral heads per transect to see how well corals were doing overall in different surge strengths. However, those that were much larger than 20 cm in size were not counted as "establishing corals" and thus were not included in most other results of the study.*

Table 5. Total number of coral heads for each specific substrate at each of the 3 study sites. *Substrates are ordered from top down by roughest/most uneven to smoothest/most even surfaces. Some individual coral heads were larger than 20 cm in size. It was important to include them in the total number of coral heads per transect to see how well corals were doing overall on different substrates. However, those that were much larger than 20 cm in size were not counted as "establishing corals" and thus were not included in most other results of the study.*

	Site		
Substrate	**BR**	**BT**	**ID**
uneven rock, crevice	3	1	1
bio-erosion rock	8	0	3
multiple rocks	0	13	0
flat rock	0	4	1
on coral	0	1	0
sand and rock	0	8	0
sand and pebbles	0	1	0
sand	0	16	0

Figure 6. A side-by-side view of establishing corals with different bleach ratings. The coral farthest left is rated a 1 because it is healthy with no bleaching. The middle coral is rated a 2 because there is some bleaching. However, zooxanthellae are present. The coral farthest right is rated a 3 because it is completely bleached and almost all of its zooxanthellae are gone.

al heads occurred on sand. Bahía Thomas had more coral heads on multiple rocks, flat rock, sand and rock, and sand than at the other two study sites. At Bahía Thomas, individual coral heads were found on all substrates except for bio-erosion rocks. At Isla David, the few establishing coral heads of the site occurred mostly on bio-erosion rocks. However, Isla David had fewer coral heads occur (compared to the other two sites) on bio-erosion rocks, flat rocks, and uneven rock crevices. Individual coral heads at Isla David were only found on bio-erosion rocks, flat rocks, and uneven rock crevices. At Bajo Rojo, most establishing coral heads occurred on bio-erosion rocks. More coral heads occurred on uneven rock crevices and bio-erosion rocks at Bajo Rojo compared with the other two sites. At Bajo Rojo, establishing corals did not occur on any other substrate other than uneven rock crevices and bio-erosion rocks (Table 5).

DISCUSSION

To examine why *Pocillopora* corals are not establishing in large amounts at some sites and to understand where *Pocillopora* corals are establishing prominently in Cuajiniquil, the potential hypotheses were compared to the results. In the study, establishing coral heads are defined as individual *Pocillopora* not connected to any part of another *Pocillopora* coral or reef between 0 and 20 cm in size.

The first hypothesis was that *Pocillopora* coral in poor health do not grow large enough to support reef growth. Although three-quarters of all stony corals sexually reproduce by releasing thousands of eggs and sperm into the water (Veron, 2000), bleached *Pocillopora* coral may prevent some asexual reproductive events. In asexual reproduction, new clonal polyps bud off from parent polyps to expand or begin new colonies (Sumich, 1996). This occurs only when the parent polyp reaches a certain size and divides. This process continues throughout the animal's life (Barnes and Hughes, 1999). Results from Isla David show that as bleaching increases, size decreases. These results support the hypothesis, showing that smaller corals that are unhealthy, described by high bleach ratings, may lead to less success since asexual reproductive events occur when the parent polyp reaches a certain size before dividing. However, the other two study sites do not show a pattern that supports this hypothesis.

The second hypothesis is that vast quantities of sea urchins may be overtaking available spaces and crevices. Sea urchins settle equally well in the presence of rock surfaces encrusted with coralline algae, rock surfaces away from urchins, and rock surfaces forming an urchin pocket (Cameron, 1980). At both Isla David and Bajo Rojo, large numbers of urchins may be overtaking crevices and rocky substrates that are not available at Bahía Thomas. This may reduce the ability of corals to cover more than 10% of each transect at these two sites. Since urchins are grazers and scrapers, they typically do not favor sandy substrates. For this reason, it is possible that Bahía Thomas had the most coral coverage of all 3 sites with some of the lowest numbers of sea urchins due to the sandy substrate most corals of the site were establishing on. These data support the hypothesis due to the overwhelming success of the coral reef and the individual establishing coral heads, as well as the lower numbers of urchins in each transect at Bahía Thomas. Although the relationship between urchins and coral coverage statistically depends on site, there is strong evidence to support that large numbers of urchins affect coral establishments by residing in spots on rocky substrates that stony coral propagules could settle on, specifically at Isla David and Bajo Rojo.

Although surge may bring some food particles to these corals (other than their main food source of zooxanthellae), the surges and currents throughout Costa Rica and Central America are currently exposing corals to a larger range of metal pollution than ever before as a result of the increasing environmental contamination from sewage discharges, oil spills, agricultural chemicals and fertilizers, and topsoil erosion (Guzmán and Jiménez, 1992). Not only do strong surges bring pollutants from land to sea, they also seem to play a significant role in the ability of individual corals to settle. The third hypothesis is that the surge at some sites may be too strong, compared to the surge of other sites, for some establishing corals to settle. The data is consistent with this hypothesis, as the largest amount of individual establishing corals occurred in weak surges with angles of 20 degrees or less. Based on the data, there may be a maximum capacity of surge strength that establishing corals can withstand without difficulty; at surges 35 degrees and higher, at both Isla David and Bajo Rojo, no more than 5 coral heads were found per transect. This supports the hypothesis that surge strength may have an impact on establishing corals. Rough surges may break coral larvae loose, pull these larvae far from a viable site, or even unsettle establishing corals that are not entirely secure due to their small size or young age. Surge may thus affect coral numbers at some sites if propagules from parent corals are disrupted by strong surges since these propagules may take anywhere from 2 hours to 103 days to settle (Richmond, 1987).

The fourth hypothesis discussed is that larvae are not arriving to some sites. This is supported only by one side of Bajo Rojo. For the ridge of the windward side of Bajo Rojo, it is hypothesized that coral growth may not be occurring due the possibility that larvae are not arriving to that specific side. On the windward side of the sedimentary rock is an expansive 100 m by 40 m ridge, angled at about 45 degrees, where no coral growth was observed. Coral growth may not be occurring on the windward ridge because the surge is too strong, and the windward side is not protected from rough waves or direct sunlight. The steep ridge may be missing biofilm, a key inducer of coral settlement that sends out chemical signals to floating coral larvae to settle (SECORE Foundation, 2015). If biofilm is present, then perhaps larvae are not arriving to the windward side of Bajo Rojo due to currents and wave action. These factors may be preventing new coral larvae from settling or even arriving on the windward side of Bajo Rojo. The site's leeward exposed side is sedimentary rock and was used for transects 1-4.

Pocillopora corals may not be establishing in large numbers at some sites in Cuajiniquil due to the strong surges that may displace larvae, the large number of urchins that may take over viable substrates and eat newly settled corals, and the range in health that could influence reproductive success of establishing corals experienced at Isla David and Bajo Rojo. Establishing *Pocillopora* are, nonetheless, occurring in large quantities at Bahía Thomas potentially due to the weak surge, the smaller numbers of urchins, the overall good health of individual establishing corals, and the abundant sandy substrate. Furthermore, at Bahía Thomas, some corals establishing on sand may be unsettled by forceful storms, marine-animal encounters, or boat anchors, allowing these corals to be moved into a favorable temperature zone. The corals in these favorable and potentially temperate water zones can resettle, thrive, and be naturally selected for if they are reproductively fit. These successful corals can then begin the growth of a coral reef.

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