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- late development of hypothesis
- weak hypothesis
- last second survey

Long term response of coral community in leeward Hawaii to Iron addition

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Abstract

Iron limits phytoplankton growth in the open ocean and may be a driving force behind the global carbon sequestration cycle. Additionally, benthic cyanobacteria species show a tendency to increase in abundance in the presence of iron. A Hawaiian reef survey conducted at Mahukona determined the effects of benthic iron debris on the coral reef community. Algal abundance decreased with proximity to a large iron anchor chain. Conversely, coral abundance and diversity exhibited a significant increase nearer iron debris. Considerations include possible explanations for this counterintuitive trend such as herbivory and settlement substrate availability. Sea urchin abundance measurements with distance from the anchor showed an interesting pattern, and one possible explanation for the obtained distribution is explored. Synthesis of herbivory, predation, substrate, and iron introduction provide a new perspective of the ecological dynamics of disturbed coral reefs

why underlined?

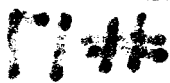
Introduction

The fossil record indicates a rocky relationship between coral and algae focusing on settlement substrate competition and dating back at least to the early Cenozoic (Wood 1998). Recent studies on the Great Barrier Reef documented coral mortality in the absence of herbivory as a result of macroalgal overgrowth (Jompa and McCook 2002). Under laboratory and field conditions, cyanobacteria growth rate increases with the introduction of nitrate (Jeanfils et al. 1993), phosphate (Shapiro 1970; Ahlgreen 1988), cobalt (Saito et al. 2002), and iron (Wilhelm and Trick 1995).

In addition to increasing nutrient assimilation rates, cyanobacteria are able to accumulate reserves of phosphate for extended growth once suspended concentrations have dropped to low levels (Gerloff and Skoog, 1954; Stewart and Alexander 1971). In low iron conditions, cyanobacteria utilize siderophores to increase uptake and sustain growth (Wilhelm and Trick 1994; Wilhelm et al. 1998). These factors, along with inhibitory substance production, enable cyanobacteria to outcompete green algae for average coral reefs (Lam and Warwick 1979). Since many species of algae and coral require hard substrata, cyanobacteria may alter patterns of coral growth and survivability in environments conducive to algal growth.

The significance of the planktonic cyanobacteria growth response to iron continues to be a topic of considerable speculation. Researchers herald growth rate increases with the introduction of iron as the most significant marine mechanism for the removal of atmospheric CO₂ (Longhurst 1991; Martin 1990) and, alternatively, as inconsequential compared to global productivity figures (Fuhrman and Capone 1991; Peng and Broecker 1991; Wells 1994). Iron addition studies span the oceans, but few studies have focused on coastal habitats. Perhaps prematurely placated, prior researchers devoted little effort to studying non-Aeolian iron introduction (Duce and Tindale 1991) and the solubility of crustal iron (Kuma et al. 1992). In light of the documented dominance displayed by cyanobacteria species, a study of a disturbed coral reef habitat seems timely.

Additionally, cyanobacteria are a valuable commodity in a fledgling biotechnology industry (Patterson 1995) and show potential as pharmaceutical sources (Borowitzka 1995).



Yagashita proposed a model for energy creation using cyanobacteria-powered fuel cells (1996). Simulated wastewater treated with high nitrate levels returned to acceptable drinking water levels (0.71mM) after cyanobacteria growth (Hu et al. 2000). Both planktonic and benthic cyanobacteria have been considered as candidates for wastewater treatment (Hoffman 1998). Recent evidence suggests a practical use for benthic cyanobacteria as indicators of coastal iron debris (Siciliano 2002). The historic uses of tropical islands have contributed to agglomerations of debris on coral reefs. Reynolds (1984) wrote that algae physiology and growth depend on abiotic factors, the effect, if any, of this specific abiotic disturbance has not been adequately documented in Hawaiian coral reef environments. This study aimed to contribute to a growing body of knowledge about the interaction between iron, coral, and algae on a Hawaiian reef.

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Materials and Methods

Mahukona, Hawai'i makes an ideal ^{site} sight for the examination of benthic iron impact. As a shipping and railroad center since 1881, marine debris accumulation from sunken ships and storm damaged anchors rest throughout the gradual reef slope. The 0.25m wide experimental anchor chain extends from 20m to 150m offshore over water depths of 10 ft to 50 ft.

Surveys were performed and samples collected on March 24 and April 4, 2003. Drogues deployed on March 24 indicated a Southerly current. Previous dives during various seasons support this current trend. Divers using SCUBA deployed 5m transects at depths ranging from 10 ft (30m from shore) to 30 ft (150m from shore) at 5m intervals. The first transect followed the anchor chain and downcurrent transects at distances of 1m and 5m paralld the chain. Standard AAUS benthic survey techniques were used to ascertain species distributions. Each transect saw bottom composition determined using 0.25 m² quadrats placed at 1m intervals along the line. Three commonly occurring species of sea urchin (*Echinometra mathaei* de Blainville, *Tripneustes gratilla* Linnaeus, and *Heterocentrotus mamillatus*) were counted along each transect. All individuals within 0.25m of either side of the transect line were recorded. Collection of 5 algal samples per 5m transect assisted in genus level identification of observed species and elucidated the presence of macroalgal species growing in the sample area but falling outside quadrats. Samples were transported to the University of Hawaii at Hilo campus for identification.

Results

Divers recognized 7 coral species (Table 1.1) and 21 genera of algae (Table 1.2) resulted from laboratory identification. Of the coral species present, one species, *Porites Lobata* occurred much more frequently than any of the other six species (78% of coral at 0m, 80% at 1m, and 84% at 5m). Obseovations of *Porites evermanni*, *Pocillopora meandrina*, *Pocillopora damicornis*, *Pavona varians*, *Montipora capitata*, and *Montipora patula* complete the recorded coral species at Mahukona that grow in association with the anchor chain. *P. lobata*, *P. evermanni*, *M. capitata*, and *P. meandrina* colonies show some abundance at all distances, while the other species exhibit more restricted distributions. *P. varians* showed up along the anchor chain and the 5m transect, but was absent along the intermediate transect line. *M. patula* appeared only at the two downcurrent distances but was absent along the chain. *P. damicornis*, the least commonly observed coral, persisted at the farthest transect from the iron source. Explanations for *P. damicornis* scarcity could result from its usual association with near shore wave affected

habitats. It was only present at the shallowest depth. No other corals showed a depth biased distribution and the relative abundance of *P. damicornis* precludes any consideration of depth with regard to total coral abundance.

Algal samples were only identified to Genus level in order to facilitate comparisons between algal composition and coral composition figures (Table 1.2). No 1m transect identifications took place to enhance the focus of iron on algal diversity at the source and 5m away. No prominent macroalgal growths were observed using visual transect methods, and rocks, monofilament line, and turf scrapings accounted for the resulting genera. The 29 genera of algae identified at 0m represented 44% of the total algae identified when compared to the 37 species from the 5m transect. For the purpose of this study significant algal genera constitute those groups that occurred 5 or more times at a given distance from the iron source providing a likelihood that they occur at every depth studied. *Lyngbya*, *Polysiphonia*, and *Jania* conform to this definition. *Lyngbya*, the cyanobacteria species cited in the Northwestern Hawaiian Islands remote sensing experiment (Siciliano 2002) was the predominantly occurring genus along the anchor chain, accounting for 17% of all algae collected and identified along the 0m transect. *Lyngbya* was entirely absent at 5m indicating an association with the Iron source. The dominant algal genus at 5m was *Polysiphonia* accounting for 24% of all identified algae at 5m. Three times more *Polysiphonia* occurred at 5m than along the anchor chain, where it constituted 10% of identified samples. No clearly dominant genus of algae exhibited a similar effect to the clear dominance at all distances *P. lobata* showed for coral species. *Jania* showed a nearly inverse distribution to *Lyngbya* with 5 occurrences at 5 m representing 13% of all samples at this distance. One identification of *Jania* at 0m represents 3% of algal identifications along the anchor chain.

Abundance data were used for diversity depictions in Figures 1.3 and 1.5. The Shannon-Wiener Index of species diversity is commonly used in to quantify quadrat surveys (McDermid 2002). The abundance of all 7 coral species combined with the recorded algal abundances underwent a 20% decline from the Iron source to a distance of 1m (Table 1.3). This drop was carried over to the 5m transect linearly and diversity values at 1m and 5m were quite similar. When only the 7 coral species were considered, a 22% decline occurred from the anchor chain to the 1m transect. This trend continued with a 16% decrease from 1m to 5m.

To consider algal diversity, information gleaned from genus identifications was analyzed. No data is available for the 1m transect, but algal diversity exhibited an 8% drop from the anchor chain to the 5m transect. Further identification to species level would make this trend clearer, but would also negate the assumed definition of significant algal genera in this study. What is clear is that algae exhibited decreased diversity in both abundance measurements and collection identification.

Graphically, total diversity (Fig. 1.3) exhibits a minimum 1m from the anchor chain, but shows a consistent decrease from its maximum at 0m. A similar trend in coral diversity (Fig. 1.5) reveals a minimum along the 5m transect, this time with a consistent decrease from 0m to 5m. Figure 1.4 shows the declining trend in algal diversity from samples collected on the anchor to those collected along the 5m transect.

Sea urchin species *Tripneustes gratilla* (Fig. 1.1) and *Echinometra mathaei* (Fig. 1.2) were present at all depths along all transects and were the dominant echinoderm species observed. *T. gratilla* dropped 6% from the Iron source to the 1m transects then rose again to return to its maximum of 20 individuals/m² by the 5m transect. A more pronounced trend for the more abundant *E. mathaei* occurred with a 41% decline in the first meter. Unlike *T. gratilla*, *E. mathaei* achieved its maximum abundance of 115 individuals/m² 5m from the Iron source.

Relative to *T. gratilla*, *E. mathaei* was dominant on the reef and was 82% more likely to occur than the other echinoderm species. *H. mamillatus* exhibited extremely patchy distribution and was not considered in the urchin analysis.

Figure 1.6 depicts the negative correlation between coral and algal abundance with distance from the Iron source. The abundances show a clear inverse relationship. Figures 1.7 and 1.8 demonstrate this inverse trend in terms of the actual abundance values relative to the anchor chain. In Figure 1.7, total coral abundance drops 55% from 0m to 1m then another 14% from 1m to 5m. Clearly the more pronounced trend is the severe drop right next to the anchor chain, but the continued decrease in values shows the overall decline of coral as proximity to Iron decreases. Alternatively, algal abundance increases 39% from 0m to 1m before dropping 16% from 1m to 5m.

Due to the strong dominance of *P. lobata* and turf algae over other coral and algal forms, these two groups were considered separately in Figure 1.8. *P. lobata* again shows a decline from 0m to 1m, this time 58%. *P. lobata* then shows a 5% decrease from 1m to 5m. Turf species, on the other hand, increase 40% from 0m to 1m and 16% from 1m to 5m. Occasional and scarce coral species affected the trend in coral abundance, but the inclusion of crustose coralline algae during visual surveys had little impact on algal abundance.

Substrate considerations show a large increase in the availability of basalt from 0m to 1m (Fig. 1.9) and a more gradual increase from 1m to 5m. Sand abundance increases more gradually from 0m to 1m (Fig. 1.9) and more severely from 1m to 5m. Plotting sand abundance vs. basalt abundance reveals a curvilinear relationship showing little that shows the dominance of basalt over sand from 0m to 1m and sand over basalt from 1m to 5m (Fig. 1.10). All substrate data were obtained from visual percent cover surveys and were originally recorded along with coral and algal data.

Discussion

Statistical analysis of the results of the study proved trends hinted at in graphs and tables. Distance from iron source had a significant effect on both total coral ($p=0.000$) and *P. lobata* ($p=0.001$) as well as turf ($p=0.013$) and total algae ($p=0.009$).

While *Lyngbya*, a cyanobacteria clearly relied upon the anchor chain for growth, *Polysiphonia* and *Jania*, Rhodophyta, were more likely to be found at the farthest transect from the Iron source.

Relatively scarce coral species affected the more pronounced decline of total coral relative to *P. lobata* representing a 42% discrepancy in declination values between the 1m and 5m transects.

No significant effect on total coral abundance ($p=0.280$) or *P. lobata* abundance with depth ($p=0.690$) exists, but turf ($p=0.009$) and total algae ($p=0.002$) vary significantly with depth in addition to variation with distance from Iron source.

Based on statistical trends, coral growth is probably retarded with distance from the anchor chain as a result of the abiotic impact of the chain itself. Though algal growth significantly increases with distance from the chain, it also decreases significantly with depth – an indication of multiple factors at work.

Declining diversity of total species from the anchor chain to 1m coupled with a less severe decline from 1m to 5m indicate an effect of the anchor chain of species diversity (Table 1.3). The continuing declination of coral species diversity is both an indication of spatial

variability in the effects of Iron on coral growth and settlement and a sign that algae constitute a stabilizing factor in the diversity data.

Strong correlation between total coral and algal abundance ($p=0.000$, $y = -0.69x + 80.224$) prove a significant inverse relationship. Predictably, dominant coral and algal species analysis demonstrate an opposite trend toward total abundance. Coral species diversity exhibits a decline as distance downcurrent from an iron source increases. Factors other than depth determined the abundance of corals on the sample transects. Depth could not be eliminated as a significant impact on algal abundance.

No significant effect of echinoderm presence on coral or algal abundance could be determined.

Substrate availability and type (Fig. 1.9) shows an increasing trend in abundance of hard settlement substrate necessary for algal and coral growth. No significant effect of sand abundance on coral ($p=0.107$) or algal ($p=0.072$) abundance arose as would be expected if substrate availability did not limit coral or algal growth. Both of these figures are close enough to the significance level for consideration in the conclusions section, however.

Conclusions

To address the potential of hyperspectral data applicability toward location and identification of sunken vessels and marine debris, it would appear that this is not a feasible suggestion at Mahukona. Cyanobacteria were among the least commonly collected algal species and the occurrence of *Lyngbya* along the anchor chain, though greater than the occurrence of other species, represents such small abundance that its recognition from space would be difficult. One may as well use *P. lobata* growth as an indication of sunken vessels in West Hawai'i.

More interesting are the spatial distribution patterns of the two major species of urchins. Both seem to follow an identical trend with bimodal abundance maxima at 0m and 5m and minima along the 1m transect. Additional transects at each meter may normalize this distribution enough for more accurate ANOVA execution. While this study does not validate laboratory studies that have shown an increase in cyanobacteria growth in the presence of iron, it differs from those studies in that the iron impact at Mahukona has had over fifty years to equilibrate with regard to the complex coral reef community upon which it rests. Rather than detrimentally impacting that community as might be expected from rapid stimulation of cyanobacteria, it is becoming assimilated into the reef itself as a focus point for both coral growth and algal diversity.

Why do the trends exist, if not for the presence of iron? ^{confusing sentence} Herbivory and predation may play a more significant role in the community than nutrient input. Several species of herbivorous and echinovorous fishes are common in the area that surrounds the anchor chain. One meter from the chain, where echinoderm grazing is minimal, algal growth increases 30%. The fact that this benthic herbivore trend is reversed 5m away necessitates an additional assessment. *T. gratilla* will feed on sand in the presence of abundant algae, and *E. mathaei* more commonly eats crustose than turf algal forms when both are present (Ogden et al. 1989). It is likely that the impact of these two species on *Lyngbya* abundance is not very great based on dietary preferences. No observed benefit of shelter was noted as habitats far from the chain contained numbers of urchins as high as or higher than those farther away. Perhaps invertebrates graze near the chain where coral growth is stimulated, while fish and invertebrates graze at a distance where algal growth is sustained. A simple caging experiment combined with fish count analysis could verify or vilify this hypothesis.

When considering the effect of substrate composition on coral or algal distributions, it is important to remember that this factor was not targeted in the study. Although this was not the focus of the study, statistical tests revealed no effect of substrate availability on coral abundance. Intuitively, if increasing sand abundance were a factor of decreased coral growth, a more pronounced drop from 1m to 5m should occur for this corresponds to sand abundance dominance over basalt (Figs. 1.9 and 1.10). Such a drop is neither shown in Figures 1.7 and 1.8 nor indicated in the data. Both coral and algal diversity trends are inconsistent with any effect of limited substrate and show no correlation or effect as a result of increasing sand or basalt abundance.

Depth does seem to influence algal abundance, but whether this is a function of wave interference with coral settlement and growth, light level, grazing, or some other factor could not be determined. The effect of distance from iron source showed more statistical significance than depth, an indication that it is the primary driving factor behind algal distribution, but depth effects remain nevertheless. It is noted that a large wave event occurred one month before this study with large breakers inundating a concrete platform seven feet above the water surface at low tide, an indication that waves of sufficient size to disturb the bottom at the shallowest transects may have impacted the coral community. No dead or broken corals were observed however to confirm the significance of this wave event.

In light of all available data, it is reasonable to state that this study determined two effects of iron on the reef in the long term: enhancement of coral colony growth and survivability in close proximity to an iron source; and facilitation of algal growth at distances downcurrent from a stationary source of iron. No other verifiable factor accounts for the trends observed. Next, it would be interesting to perform similar studies at areas that have experienced recent iron impacts such as the new mooring installed at Pawai Bay to determine how equilibration of additional dissolved iron impacts disturbed communities in the short run. Equally beneficial would be a competitive study in which coral species were displaced to monitor algal settlement and growth, they algal species were moved to see if coral distributions alteration ensued.

Acknowledgements

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Thank you for reading.

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	0m	1m	5m
<i>Porites lobata</i>	18.675	8.130	7.740
<i>Porites evermanni</i>	2.625	0.750	0.525
<i>Pocillapora meandrina</i>	1.875	0.450	0.300
<i>Montipora capitata</i>	0.675	1.500	0.675
<i>Pavona varians</i>	0.019	0.000	0.004
<i>Montipora patula</i>	0.000	0.019	0.023
<i>Pocillapora damicornis</i>	0.000	0.000	0.002

Table 1.1 Coral cover in m² at three distances from anchor

	0m	1m	5m
Total	0.4989	0.4083	0.412
Coral	0.3281	0.2569	0.2155
Algae	1.1394		1.0442

Table 1.3 Shannon Weiner Diversity Indices

Genus	0m	5m	Genus	0m	5m
<i>Lyngbya</i>		5	<i>Sphacilaria</i>	2	3
<i>Centroceras</i>		1	<i>Oscillatoria</i>	1	0
<i>Ceramium</i>		3	<i>Jania</i>	1	5
<i>Claudophoropsis</i>		4	<i>Crovania</i>	1	0
<i>Asparagopsis</i>		1	<i>Vanvoorstia</i>	1	0
<i>Dictyota</i>		1	<i>Hinksia</i>	0	2
<i>Antithamnion</i>		1	<i>Laurencia</i>	0	2
<i>Polysiphonia</i>		3	<i>Champia</i>	0	1
<i>Claudophora</i>		1	<i>Padina</i>	0	1
<i>Heterosiphonia</i>		1	<i>Hypnea</i>	1	1
<i>Balliella</i>		1			

Table 1.2 Algal occurrence on samples collected along anchor chain and 5m removed

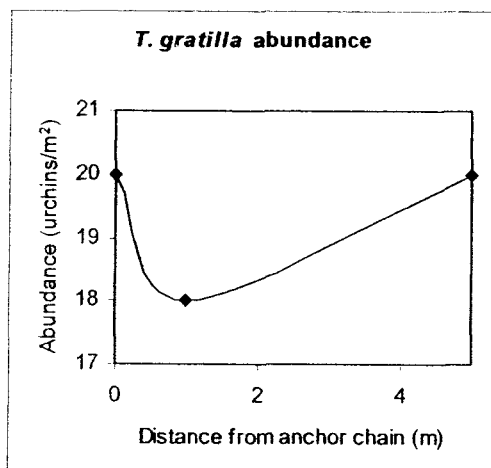


Fig. 1.1 Abundance of *Tripneustes gratilla*

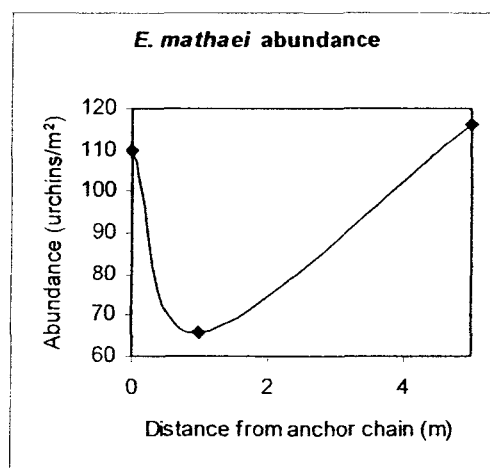


Fig. 1.2 Abundance of *Echinometra mathaei*

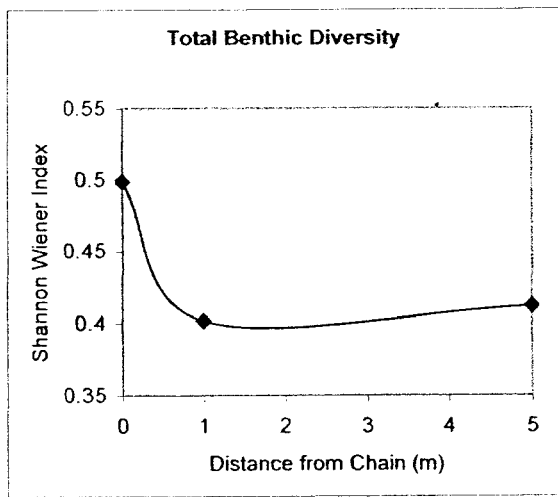


Fig. 1.3 Total species diversity

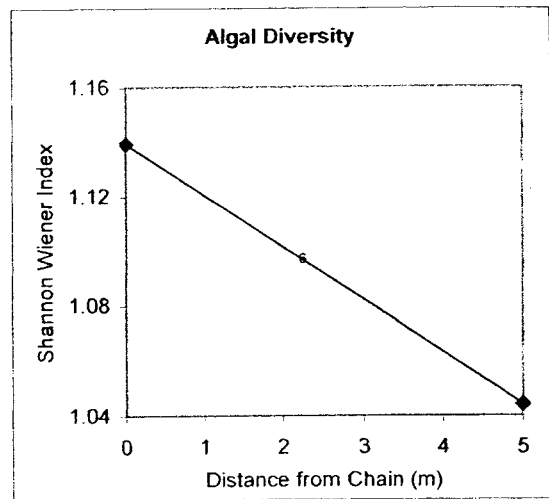


Fig. 1.4 Algal species diversity

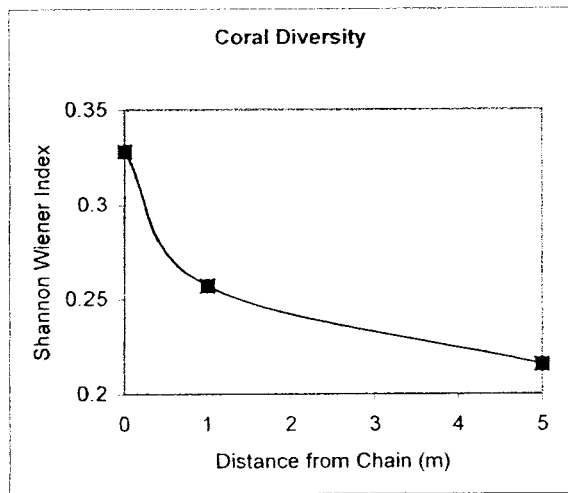


Fig. 1.5 Coral Diversity

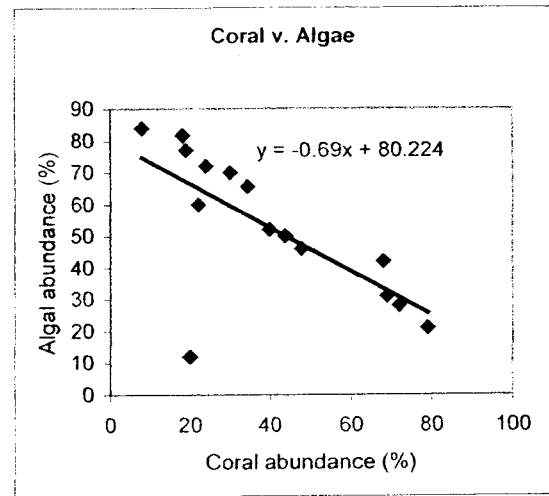


Fig. 1.6 Relationship between Coral and Algae

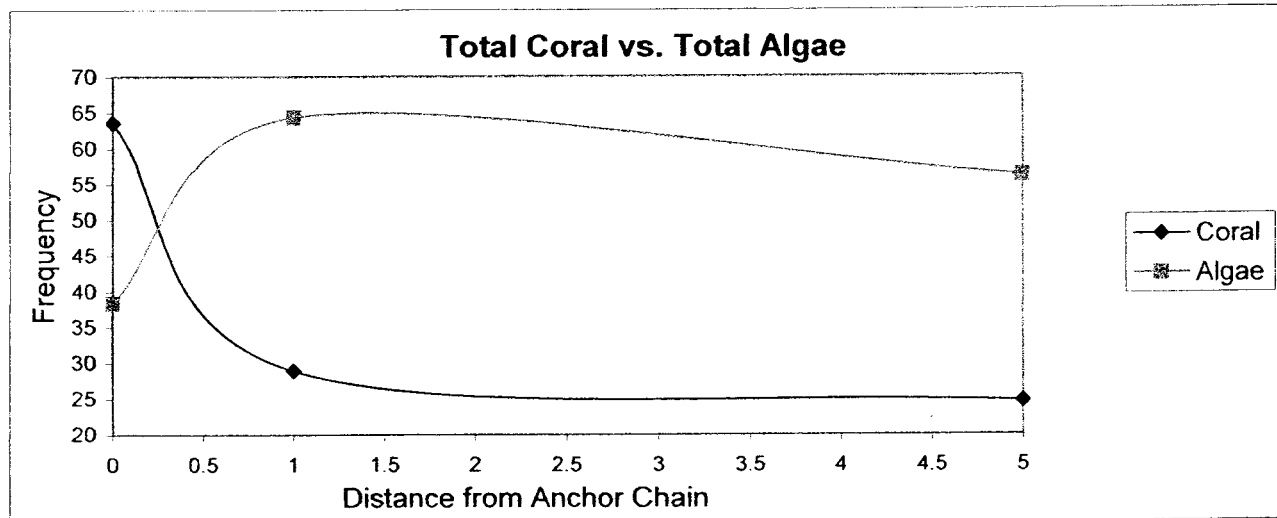


Fig. 1.7 Total abundance data for all species of coral and all types of algae present

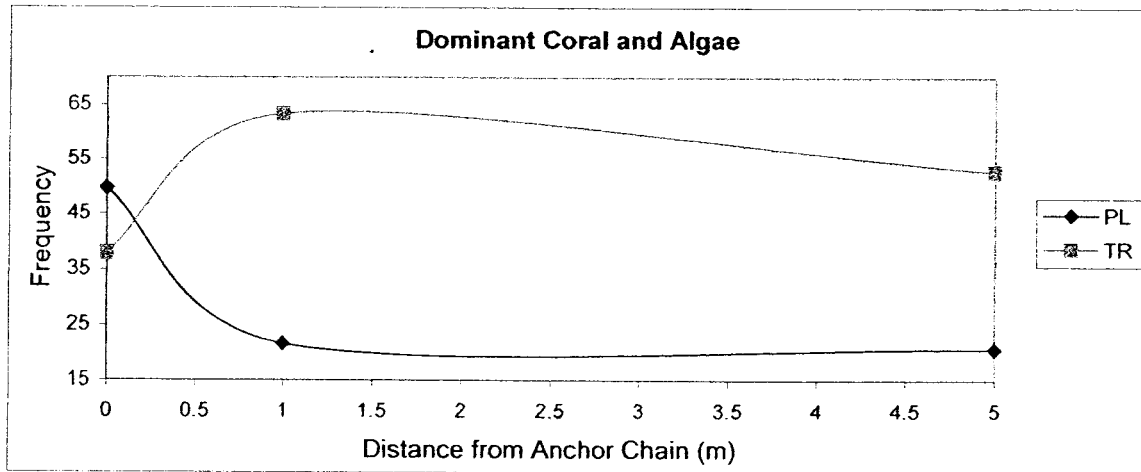


Fig. 1.8 *P. lobata* and Turf algae abundance

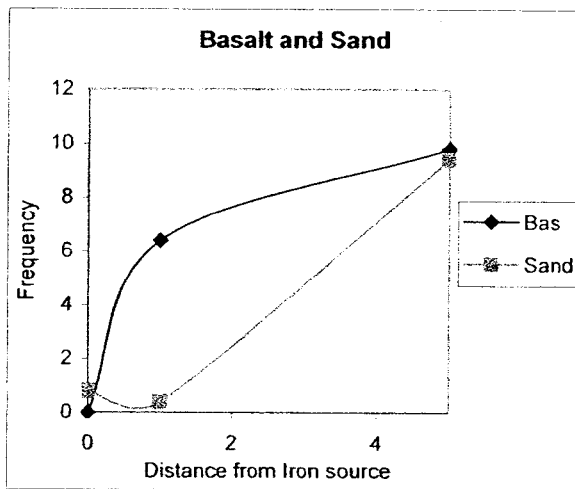


Fig. 1.9 Substrate Abundance

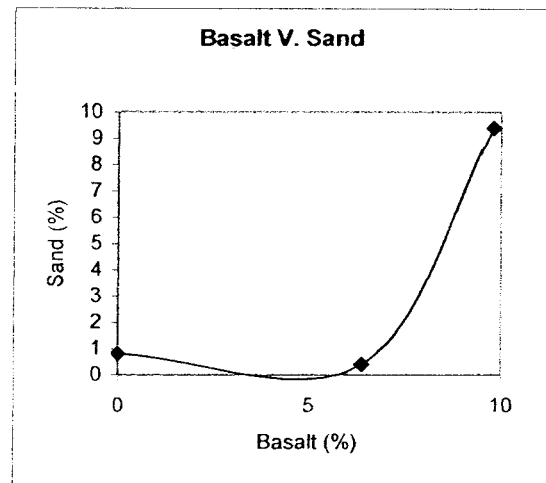


Fig. 2.0 Substrate Character