An Analysis of the Biological and Physical Relationships in the Coral Reefs of Menjangan Island: Effect of declining coral cover on ecological complexity

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Abstract

Reef rugosity, the standard index of coral reef physical complexity, has classically been determined as the ratio between a taught rope and a chain draped onto the substrate of a reef. A new method of measuring reef rugosity, termed Digital Reef Rugosity has recently been pioneered by Phillip Dustan. It is believed, as is true with other biological communities, that increased habitat complexity in a coral population will lead to an increased fish species diversity. The Biosphere Foundation carried out a four month expedition to Bali, Indonesia to access the vitality of Menjangan Island's coral reefs. We found that Balinese coral reefs with greater structural complexity (rugosity) contain more fish most probably due to increased niche diversity. Additionally, reefs with more diverse coral communities also tend to have greater fish species diversity. Thus both physical and biological complexity are significant components of coral reef ecological integrity. However, the correlation between coral and fish biodiversity degrades as a function of decreasing coral cover. Weakening coral and fish diversity relationships with decreasing coral cover may indicate a “tipping point” where the coral reef communitiy begins to collapse.

Introduction

Physical complexity has long been used as an indicator of community health beginning with McArthur's classic work “On Bird Species Diversity” in 1961. A more complex physical structure is known to be associated with increased species diversity of the organisms which live in the community [1]. Much of this is due to the increased variety of habitats which derive from the higher degree of physical complexity and allow for niche specialization. This idea was always accepted to be true for coral reefs, but precise measures of habitat complexity were difficult to capture. We were able to examine this realtionship using rugosity of the reef as a measure of habitat complexity.

Menjangan Island is located in a marine protected area of Bali Barat National Park in Bali, Indonesia. and has been for nearly 35 years [2]. This island is know for it's luxuriant reefs and is rated as a top Indonesian dive stop. The general morphology of the reefs in the area is a very shallow flat reef that drops slightly to a terrace at a depth of approximately 4-6 meters. This transitions to a fore reef with a steep, in some cases vertical wall face at around 6-10 meters [3].

Bali is located in the Coral Triangle which contains about 30% of the world coral reefs in an area of 5.7 million square kilometers, or 1.6% of the worlds oceans [4]. The area contains 75% of roughly 600 known coral species, and over 3,000 fish species making it one of the most diverse biological communities in the world [4]. The Coral Triangle is the protein source of millions of people worldwide. Thus, maintaining healthy reefs in the Coral Triangle is an important conservation goal. Indonesia and the Phillipines contain 77% of the Coral Triangle's reefs and contain about 80% of all threatened reefs [4].

Field studies at Menjangan were completed at 11 different sites: four on the island and seven along the coast (Image 1). The island sites, because of their seclusion, are much better protected and are in brilliant condition. An ocean current running across the northwest corner of the island also helps to provide fish diversity to the area. The sites along the coast show more signs of degradation due to human interactions and proximaty to populated land. The reefs at Menjangan have been subject to damages from blast fishing, coral mining, and the use of cyanide to collect tropical fish. Blast fishing is commonly known as “dynamiting” and various explosives are dropped into the reef to kill the fish. One blast can damage the reef structure within a two mile radius [5]. The crater formed from the dynamite remains in the reef structure even five years post-blast [6] and the rubble resulting from a blast kills adjacent corals. The mainland site Kelor Point is interspersed with areas of rubble that have suffocated the coral life and flattened the reef. The adjacent corals are intact and vibrant, and this site has been termed the “Killing Fields” as the rubbled areas show no signs of recovery [7].

Methods

As described in Dustan et al. Final Report to the Royal Geographic society the methods were as follows:

The field studies were completed in March and April of 2011. For each of the 11 sites, six transects were documented—three in shallow water (2-6m) and three in deep (6- 10m). The transects were laid parallel to the reef zonation, roughly perpendicular across swell directions. The three fifty meter transects were set end-to-end and spaced with about 5 meters in between, covering a 160m span of the reef.

Divers swam along the transects and censused fish and coral populations. The fish were censused in accordance with Wildlife Conservation Society protocol [8]. The abundance and species of the fish were recorded for fish along a 2 meter belt of the transect for small fish (less than 10cm) and along a 5 meter belt for fish longer than 10cm. The general size of the fish was also recorded which was used with general species information to create an approximation of biomass. The divers swam a couples of passes of the reef to allow for the census of both small and large fish.

Substrate cover was done via a point-intercept setup. Every 50cm the corals were noted as alive or dead and their genus and condition wererecorded. Another swimmer examined a 2m belt elaborating on the coral condition recording physical damage, fishing gear, disease, bleaching and crown of thorns starfish.

The fish and coral data were used to calculate diversity using the Shannon Index ($H' = \sum pi\ Logpi$). Two diversity indexes were calculated for fish: $H'_{abundance}$ and $H'_{biomass}$, and H'_{genus} was calcualted for corals.

Rugosity in this study was done pioneering a technique called Digital Reef Rugosity(DRR). DRR is a method which uses a handheld digital gauge that takes fine scale pressure and temperature measurements. The instrument is typically used to track subtle groundwater and and stream level or temperature changes (Onset Computer Company #U21_001-02). It is useful for the purpose of measuring reef rugosity because it allows a swimmer to measure rugosity over much longer transects than with the classic chain and link ratio method and at a much more precise scale than can be achieved with remote sensing. The device operates at depths of 0-30 meters with a resolution of 0.41cm and an accuracy of +/- 1.5cm within it's depth range. The instrument can record up to 42,400 data points at the space of one second apart, with the capacity for nearly six hours of consecutive recording and can be pre-programmed with a recording start time eliminating the need to have a computer at the field site. Some planning is required to ensure adaquate recording space depending on the user's needs, however in this study we were able record an entire half-day session, load the data quickly onto a computer and go back into the field.

The device records pressure continuosly, thus is order to make the individual transects recognizable. the diver quickly raised the instrument above the surface of the substrate 3 times to mark the beginning, middle and end of a transect. Every five meters were marked with a single spike and at the end of the transect the instrument was rested on the bottom for 1-2 minutes.

A measuring tape was pulled taught along the transect so that the swimmer with the pressure gauge could self-monitor his swimming speed. The target speed was 10cm/sec generating 10 samples per meter of transect. It takes some practice to develop the skill needed to swim evenly while tracing the reef as accurately as possible. It was found to be most controlled while swimming opposite the current, which was often diagonal to the transect line.

The DRR data was then "cleaned up" to determine the rugosity index. The raw data from the Onset device is easily exported to Excel for manipulation. A typical data file would include three transects from one site, either shallow or deep. A plot of absolute pressure shows the movement of the diver from the surface of the water down to the transects, the three transects, and the diver's travel back to the surface.

A set of three spikes are visible to mark the beginning, middle and end of a transect as well as a single spike every five meters. From this half-day log of work, the data was separated into the three individual transects. The visual plot of the transects were compared to the field log to help interpret any inconsistencies. All of the spikes were removed and the meter measurements recorded in Excel to be used to verify consistent swimming speed. The finished product was a smooth trace of the reef beginning at meter 0 and ending at meter 50 with all excess points removed. Using this clean data, we were able to take the standard deviation of the absolute pressure as a measure of rugosity. All 66 transects were treated in this way, with Images 2.1, 2.2, and 2.3 illustrating the process.

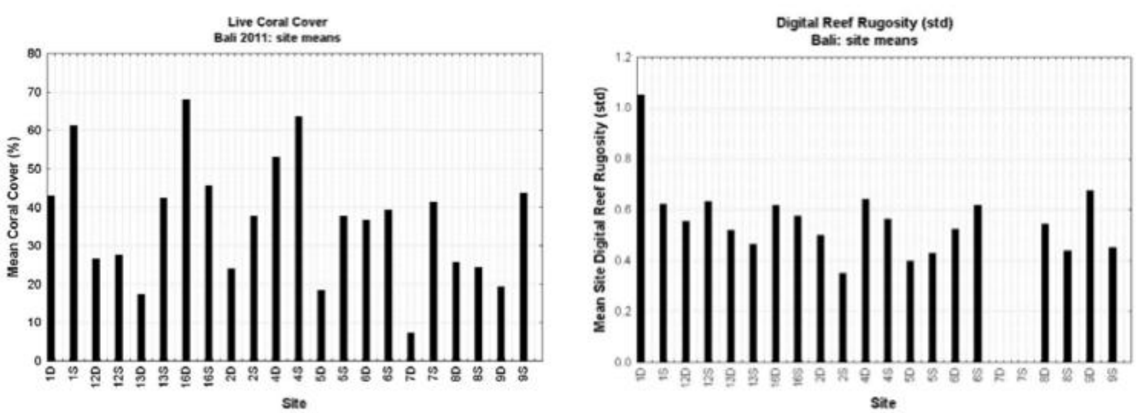
Consecutive differences of absolute pressure were calculated, and this was used as an alternative measure of rugosity. Linear regression analyses were done over the data set in Excel and Statistica. Additionally, a principal component analysis was done in Minitab.

Results

Linear Regression

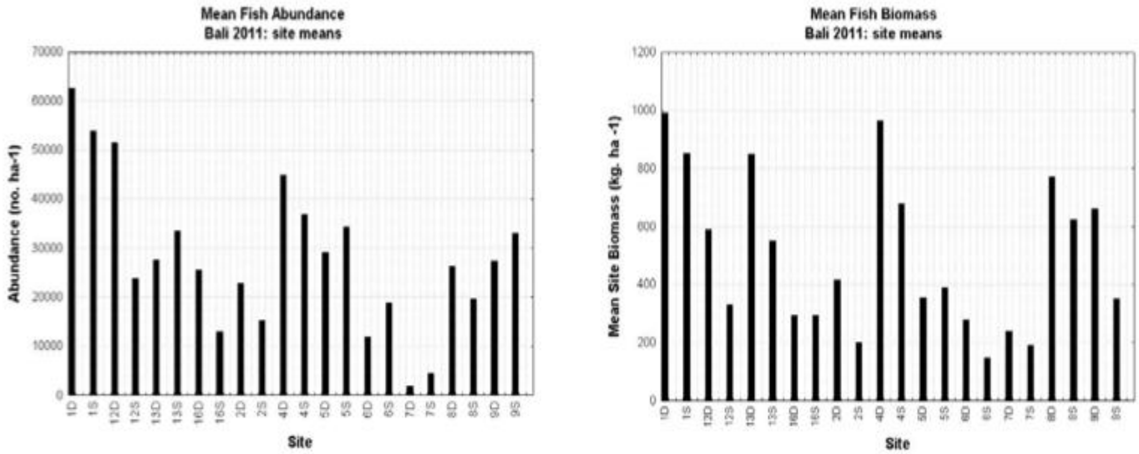
The linear regression results as reported in Dustan et al.'s report to the Royal Geographic Society are as follows:

The different sites varied in terms of ecological vitality. Several sites were in excellent condition with coral cover above 60% and others had less than 10% cover. There were also varying degrees of rugosity among the sites.



Mean live coral cover at eleven study sites off N.W. Bali, Indonesia. Digital rugosity was not measured at Site 7.

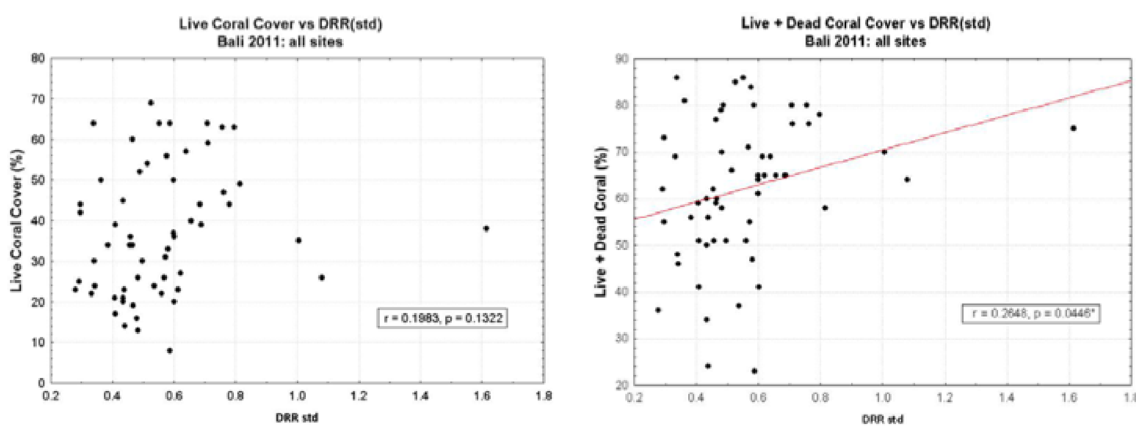
Fish abundance and biomass also varied greatly over the 11 sites.



Mean fish population densities and biomass estimates at eleven study sites off N.W. Bali, Indonesia.

High amounts of variation in these elements indicates that we have an excellent sampling of communities.

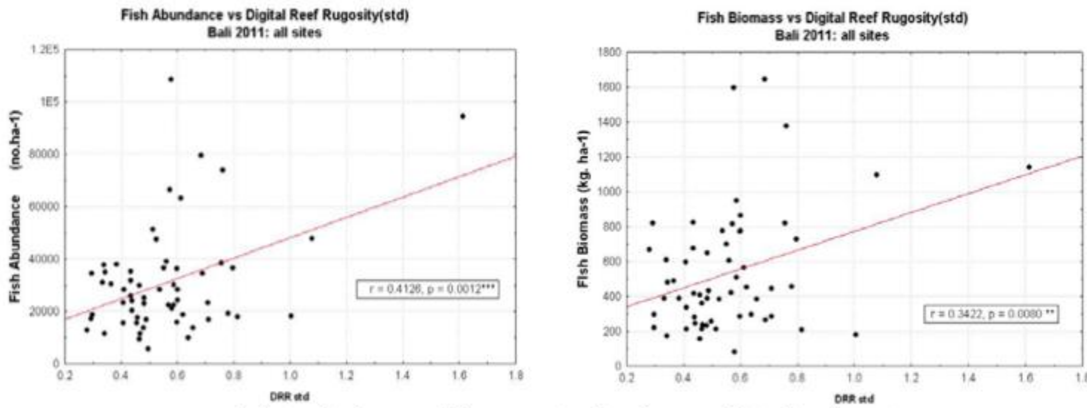
Suprisingly, although coral is the element that creates the structure of the reef, there was not a significant linear relationship between live coral cover and DRR. The correlation did appear however when dead coral was added in. Dead coral, although not providing any biological diversity to the reef is an important physical element of the reef. Degredation does not immediately result in a loss of habitat (Alvarez) as dead coral can exist on a reef for many years before breaking down completely and continues to provide habitat complexity.



Relationship between coral community cover and digital reef rugosity

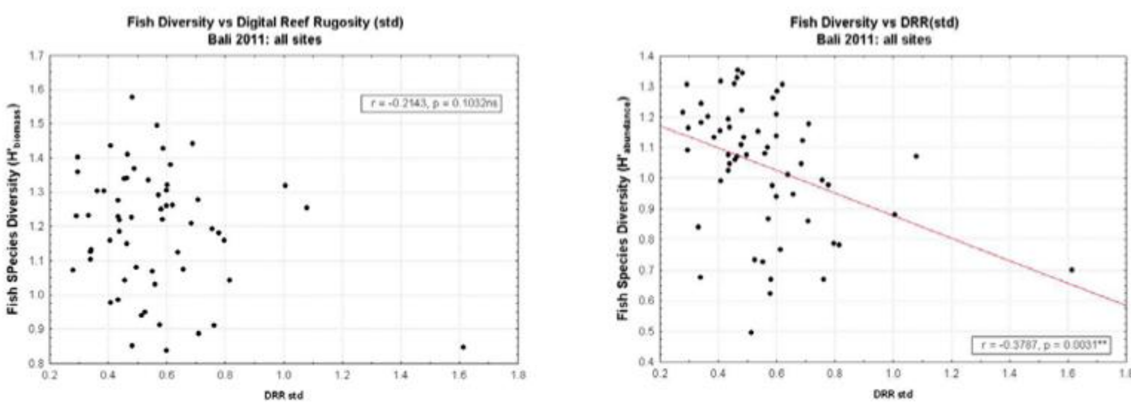
We observed a significant positive relationship between DRR and fish abundance and

DRR and fish biomass. This indicates that more fish live in reefs that are more physically complex.



Relationship between fish community abundance and digital reef rugosity

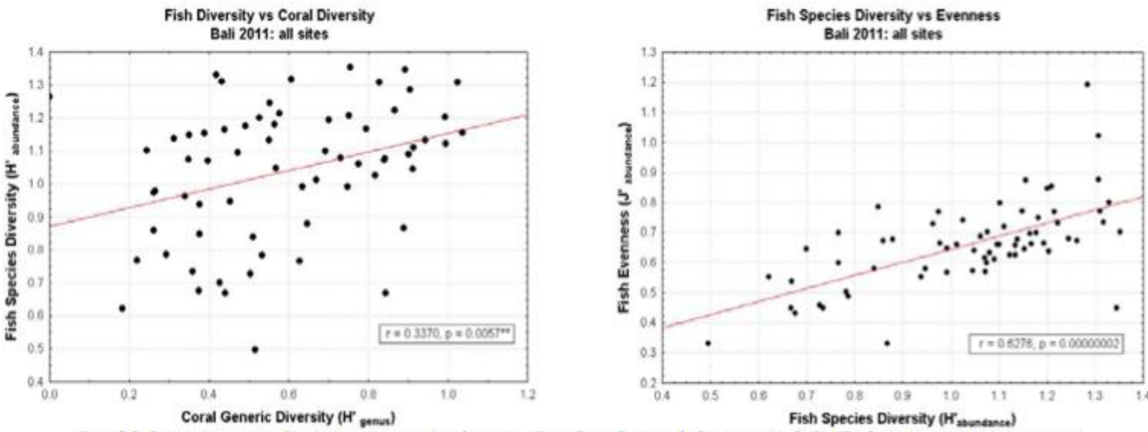
While more fish live in more structually complex reefs, increased rugosity does not increase fish diversity. In fact, there is a significant negative relationship between $H'_{\text{fish abundance}}$ and DRR standard deviation. This is somewhat surprising but strongly indicates that the biological and physical aspects and interdependancies of the reef are separate and are both crucial



Reef fish community diversity based on abundance is not significantly correlated with digital rugosity while fish diversity based on the number of individuals shows a significant correlation with rugosity.

elements of the reef.

The evenness index was calculated using the Shannon and Weaver index for Evenness (J') by taking the ratio of $H'/H'_{maximum}$. The positive relationship between diversity and evenness



Reef fish community diversity is positively correlated with coral diversity while Fish community evenness increases with fish species diversity.

indicates a top-down controlled community.

While there was not a positive relationship between coral structure specifically and fish diversity, fish diversity positively correlates with coral diversity. This is indicative of species-specific interactions which allow for niche packing [2].

A separate paper by Dustan at the same location using similar methodology yielded different results. This study did not find a significant relationship with fish biomass or abundance and DRR, but found a positive relationship between DRR and fish species diversity based on both biomass and abundance (Kendall tau=0.87 and 0.73, $p<.05$)[7].

Consecutive Differences

There was no significant relationship found with DRR_{cdiff} and fish diversity or fish density. This is somewhat surprising as the consecutive differences of pressure between points responds to point-to-point substrate height variation.

Principal Components

A principal component analysis was done using the variables DRR standard deviation, $H'_{coral\ genus}$, $H'_{fish\ abundance}$, $H'_{fish\ biomass}$, total coral, fish biomass, and fish abundance. (Image 3) The first component was the "physical component" with rugosity, total coral, biomass and abundance loading highly. The third component held the biological elements of diversity and total coral. This is reinforcement that both the physical and biological elements play distinct and important roles in the reef environment. However, the first factor explained only 41% of the variance, with the first 5 factors explaining 91% (Image 3).

Ranked Linear Regression

This is a complicated system, where we assume that at one time all of these transects were in pristine condition, but have been damaged in various ways and to various degrees. It is our assumption that we are dealing with 66 transects that were at one point the same essential environment. We also assume that low coral cover indicates a damaged reef. The damages that have affected this reef include blast fishing, coral bleaching due to elevated water temperature, anchor damage and plastic debris. These damages can kill corals which will eventually decay, reducing the coral cover of the reef.

We would imagine an ideal system to have a positive relationship between fish diversity and coral diversity. When the transects were ranked by percent coral cover, the transects with total coral cover above 80 percent had a highly significant positive relationship between the diversity of the coral and the diversity of the fish by abundance. The relationship was then assessed with the transects which had coral cover above 70%, then with those above 60%, and so on until we had regained the full model. With each addition of transects with lower coral cover, the R-squared value decreased (Image 4).

Discussion

The linear models used in the Biosphere Foundation Expedition analysis are lacking. The data does not appear to the eye as a linear relationship, thus log transforms were attempted to produce a better fit. Yet, the data still tended to cluster. While highly significant ($p<.05$) relationships were found using linear regression, it is clear by looking at the graphs that we are not dealing with simply a linear model.

Ranking reefs by percent coral cover is a common classification scheme for reefs. One scheme assigns the classification “excellent” for reefs with coral cover greater than 75%, “good” for coral cover between 50-75%, “fair” for 25-50% and “poor” for reefs with less than 25% coral cover [9]. Bell and Galzin found that fish “discriminate” between reefs of varying coral cover. A large percentage of fish will not frequent areas that have a lot of dead coral [10], making coral cover an important determinant in fish density and diversity.

The R-squared value graphs shows a clear and dramatic drop off in the correlation between coral and fish diversity as the coral cover decreases. As the coral cover reaches 50%, the biological integrety of the reef is severly comprimised. An ecological tipping point is often decribed as a point where a system tips into disequalebrium (Cairns). The tipping point is normally caused by small changes in the environment which have tremendous effects on the biological interactions in that environment. This is certainly the result we have discovered—even a 10% change in coral cover destabilizes this reef community. Fifty percent coral cover may mark a “tipping point” at which we are able to recognize that the biological aspects of the reef are not operating ideally. The system no longer behaves as it does in an undamaged community. At 50% coral cover, there is not only 50% less reef, there is an entirely different reef both physically and biologically. This is an important factor to consider in reef preservation and conservation. If a tipping point can be indentified, there is a functional dialogue with which to discuss sustainability using concrete measures (Marten). A tipping point in the data helps to explain why we did not find the linear relationships we sought after when first analyzing this data set. The system is in different states of disarray and is not at all points in equilibrium. Once a tipping point is reached the damages may be irreversible, therefore understanding that a tipping point exists and having some idea of where it is gives a functional target number for preserving coral reefs as well as revitalizing them.

Acknowledgements

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Appendix

Images

Image 1.1

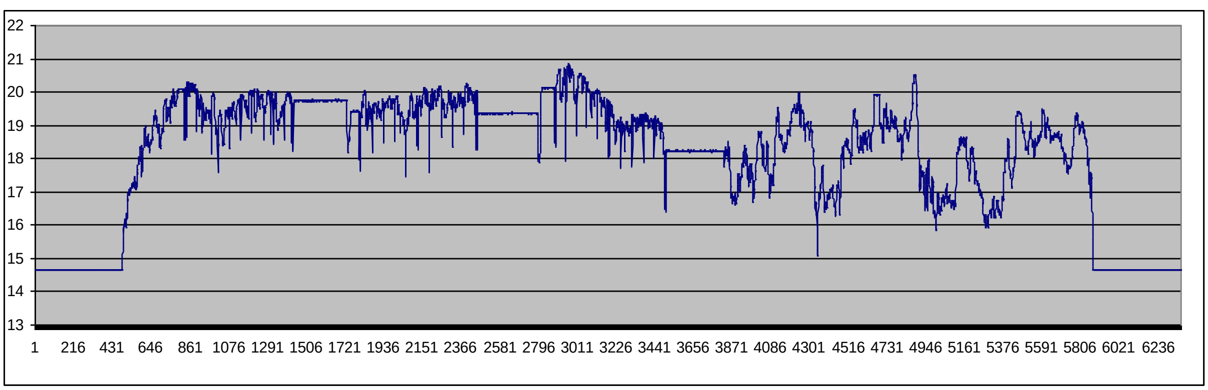
Site Map: The 11 field study sites. 4, 11, 12, 13 are the Menjangan Island sites.

Image 1.2

Site ID	Site Name	Latitude S	Longitude E	Facing direction	Tourism, diving	Exposed/ Sheltered	Reef description
2	Batu Togog	08° 07.127'	114° 35.712'	N	N	E	sand and rubble patches with coral patches and bommies between
4	Garden Eels	08° 07.127'	114° 35.712'	N	T	E	reef slope with high coral cover
5	Teluk Kelor	08°05.809'	114°31.652'	N	N	E	Patchy reef, soft coral, with sand and rubble between
6	Kisik 1	08° 06.720'	114° 36.309'	N	N	E	mix of live and dead coral patches with sand and rubble between
7	Kisik 2	08° 06.767'	114° 36.862'	N	N	E	mostly dead coral rubble and sand
8	Kotal	08° 06.767'	114° 36.862'	E	T	S	Bommies and sand
9	Labuan Lalang	08° 06.767'	114° 36.862'	N	N	S	Lots of sediment, sand, with patches of reef
11	Pos 1	08° 06.767'	114° 36.862'	SW	T	S	close to the edge of the reef as it fell to rubble and sand.
12	Pos 2	08° 06.767'	114° 36.862'	SE	T	S	mixed reef sparse cover of hard coral
13	Pura	08° 06.767'	114° 36.862'	NE	T	E	extensive soft coral and sand
16	Tanjung Gelap	08°08.066'	114°33.540'	NE	T	S	Mostly *Porites* fingers bushes

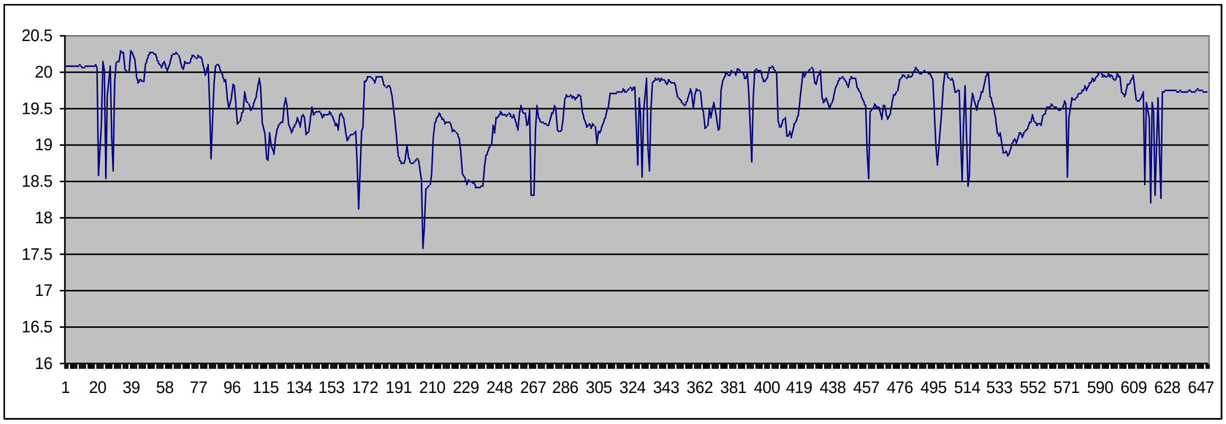
Site location details

Image 2.1



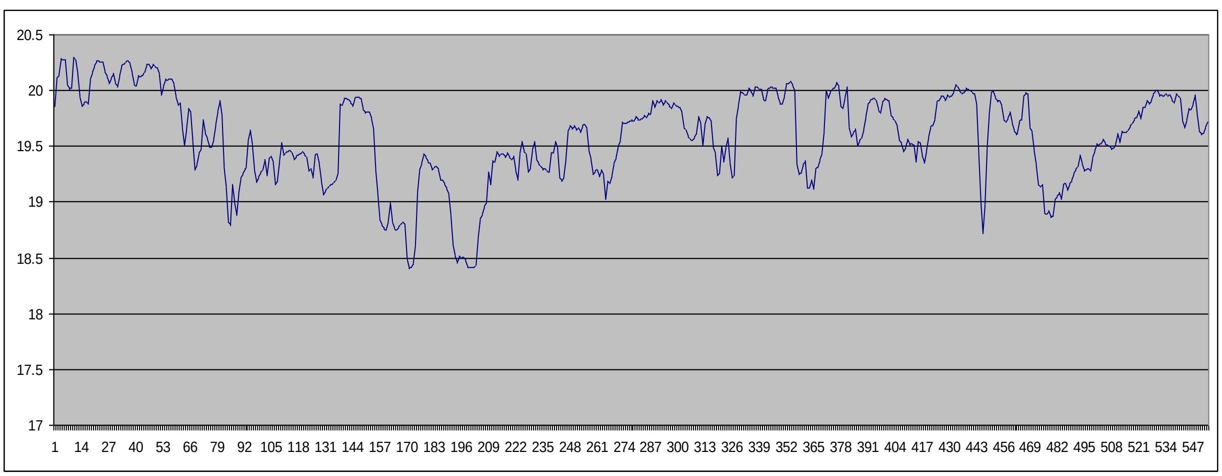
A morning's work: Pressure plot from the shallow site at Site 8-Kotal. The plot begins at the surface, the diver does three transects, separated by the flat areas inbetween and swims back to the surface.

Image 2.2



08Kotal_S1: The plot of the first transect before it is “cleaned up”.

Image 2.3



Finished Transect (invert y-axis for a picture of the reef)

Image 3

Principal Component Analysis: DRRstd, coralHGenus, fishHAbundan, fishHBiomass,

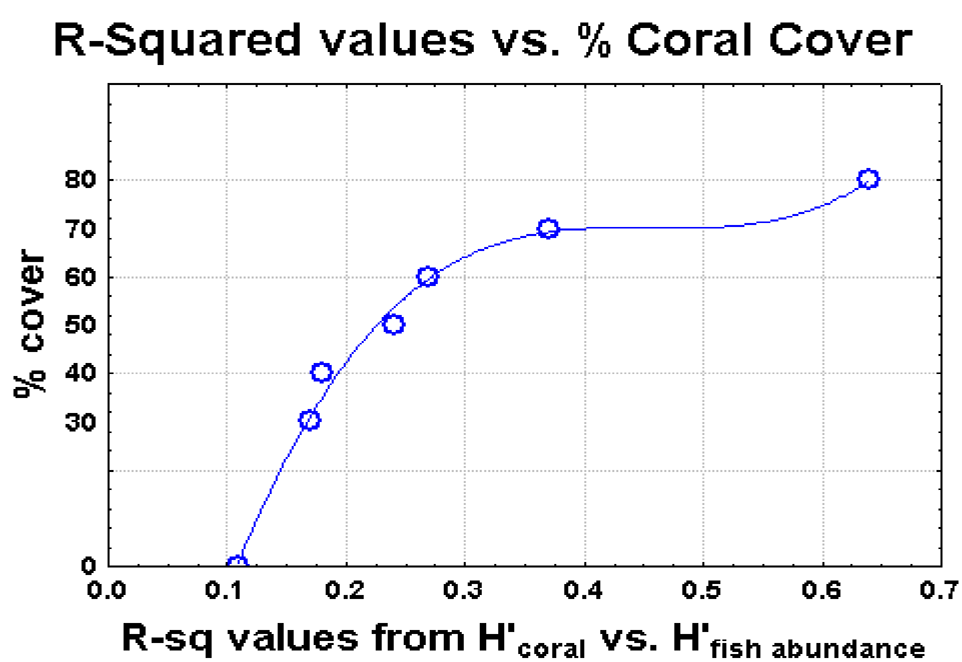
Eigenanalysis of the Correlation Matrix

Eigenvalue	2.8768	1.1784	0.9121	0.7791	0.6479	0.4667	0.1389
Proportion	0.411	0.168	0.130	0.111	0.093	0.067	0.020
Cumulative	0.411	0.579	0.710	0.821	0.913	0.980	1.000

Variable	PC1	PC2	PC3	PC4	PC5	PC6	PC7
DRRstd	0.372	-0.100	0.200	-0.471	-0.764	-0.062	0.037
coralHGenus	-0.230	-0.441	0.636	0.507	-0.219	0.193	-0.072
fishHAbundance	-0.464	-0.335	-0.062	-0.125	-0.045	-0.658	0.467
fishHBiomass	-0.348	-0.286	0.212	-0.699	0.317	0.374	-0.151
totalCoral	0.307	0.304	0.683	-0.119	0.397	-0.416	0.034
Biomass	0.378	-0.606	-0.193	0.025	0.198	-0.343	-0.543
Abundance	0.486	-0.377	-0.042	0.036	0.260	0.308	0.676

PCA Minitab Printout: Results of the Principal Component Anaylsis as output by Minitab

Image 4



Tipping Point?: Plot of R-squares values (when linear regression was done with fish diversity and coral diversity) against percent coral cover--notice the drop off at 50% coral cover