Comparing coral coverage, growth rates, and growth forms composition on a mineral accretion device during active and inactive periods.

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Abstract

Coral reefs are one of the most diverse and valuable ecosystems in the world. Currently, these reefs are threatened by antropogenic as well as natural causes. On Koh Tao, Thailand, a mineral accretion device was deployed in 2008. This device uses a small electrical current to provide an alkaline environment for reef building organisms. Due to a defect in the electical convertor, the device has not been functional since October 2010. The aim of this study is to compare coral growth rates, growth forms and coverage on the device before and after the defect, using quadrant and photografic data. The results show that there is no significant difference before and after the disfunction. It should be noted that this study used a small data set and for hard conclusions, more research is needed.

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Preface and Acknowledgements

First I would like to thank Chad Scott, for answering all my questions and helping me to write my bachelor thesis, although sometimes, it were busy times. Thanks to Devrim Zahir for the hospitality and moral support. Thanks to the intructors Pau Urgell, Spencer Arnold, Takkinai Rutanapope and Rahul Mehrotra and all the interns for inviting me in the amazing world of marine conservation.
Also, special thanks for Dr. Francesca Sangiorgi for the supervision and giving me the opportunity to do my thesis and internship on Koh Tao and Muaricio.

1. Introduction

Coral reefs are one most diverse ecosystems in the world. They form a habitat for over 9 million species, including 25% of all marine life (Spalding *et al*., 1997). Reefs play a major role in human economies, such as incomes through fisheries, diving tourism, medicine and raw materials (Moberg *et al*., 1999). Reefs also act as natural shore barrier, protecting the coast from erosion.

Coral reefs all over the world are threatened by antropogenic as well as natural causes. Big waves and storms can break apart corals, whereafter the coral fragments are scattered around the reef (Jones *et al*., 1976; Barnes *et al*., 1999;). A storm almost never wipes out an entire reef, but slow growing corals can be overgrown by algae before they can fully recover (UVI, 2001). Massive outbreaks of corallivorous fish and other predetors such as snails and starfish can destroy up to 90% of the corals (Jones & Endean, 1976). Pollution, destructive fishing practices, land based run-off, leaking fuels and mining corals for materials are some examples of threats that are antropogenic (Bryant *et al*., 1998). Together, all of these threats have a disastrous effect on coral physiology and greatly reduce coral resilience (Forrester, 1997). Antropogenic activities, like global warming, eutrophication and ocean acidification, can intensify natural causes, such as algae blooms, and extreme weather and temperatures. High temperatures can cause global bleaching events, and ocean acidification makes it more difficult for corals to accrete minerals, resulting in extreme conditions where their skeleton dissolves (Kleypas *et al*., 1999). Global warming is identified as the the biggest threat to coral reefs (Baker *et al*., 2008; Hoegh-Guldberg *et al*., 1999, 2007; IPCC 2007).

Both active and passive measures are taken in order to protect coral reefs. Passive restoation usually inlcudes protecting a certain area from fishing, diving, and pollution, or other threats and giving the coral reef the time to restore naturally (Terlouw, 2012). Active restoration and rehabilitation techniques are when work or energy is put into the system to replace lost goods or services or encourage faster recovery, for example, artificial reefs and coral nurseries. These measures restore damaged areas much faster than would occur naturally (Epstein *et al*., 2003; Rinkevich 2005). Artificial reefs are made of metal or concrete and provide a good and secure habitat for attached coral fragments, which will overgrow the structure (Terlouw, 2012). Fragments found in the sand can also be attached to a coral nursery, which allows the corals to grow to a certain size, after which they can be transplanted back to the natural reef (Scott, 2011). A mineral accretion device is an artificial reef that uses a small electical current to provide an alkaline environment where corals can accrete minerals more easily, resulting in 3 to 5 times higher growth rates (Goreau, 2003).

This study is based on Koh Tao, a 19km^2 island in the Gulf of Thailand. Koh Tao is surrounded by coral reefs and is popular for its SCUBA diving. The island has many artificial reefs, coral nurseries and, since 2008, a mineral accretion device. Due to an electrical defect in the convertor, the device stoped working in October 2010. The aim of this study is to compare coral growth rates, growth forms, and coverage on the mineral accretion device before and after the defect.

2. Coral reefs and climate change

2.1 Corals and symbiosis

As a member of the class *Anthozoa* of the phylum *Cnidaria*, corals are marine invertebrates that deposit a hard calcium carbonate ($CaCO_3$) skeleton, and therefore are important reef-builders. A coral normally exists of a colony of individual polyps with identical DNA. Most corals have a mutualistic symbiosis with zooxanthellae, a type of algae, in which the coral provides the zooxanthellae with a secure environment and the compounds needed for photosynthesis in exchange for some of the resulting glucose, glycerol and amino acids (Levington, 1995). For photosynthesis the zooxanthellae need light and thus clear water, and therefore corals are mostly found in shallow waters with little suspended material (Barnes, 1987).

2.2 Anthropogenic value of coral reefs

Coral reefs are one of the most productive ecosystems on earth (Grigg *et al.*, 1984). A coral reef provides habitat for thousands of marine species. Countries with healthy coral reefs benefit from a higher tourism rate, which provides millions of jobs in local businesses such as restaurants, hotels, and diving schools. Every year millions of people visit the coral reefs in Florida and these reefs alone are estimated to have a value of 7.6 billion USD (Johns *et al.*, 2001). Even though coral reefs cover less than 1% of the earth's surface, they provide 375 billion USD every year in the form of goods and services (Costanza *et al.*, 1997). Corals themselves are heterotrophioc, but through their symbiosys with zooxanthallae they are functionally autotrophic, and improtant in nutrient and chemical cycling as well as contribute greatly to the base of coral reef trophic strucutre.. Reefs also protect the coast from big waves, erosion, as-well as give shelter to economically valuable areas such as harbors and cities. This is particularly relevant giving the fact that half a billion people live within 100 km from a coral reef and derive direct benefit from it (Bunting *et al.*, 2003). Finally, the natural resources of coral reefs have been utilized in a wide range of medicine (Bruckner, 2002).

2.3 Ocean chemistry

The ocean works as a carbon sink, absorbing carbon dioxide in the form of the gas CO_2 (Sarmiento *et al.*, 1998). In the ocean, the a portion of the dissolved carbon dioxide reacts with water (H_2O) and forms carbonic acid (H_2CO_3). H_2CO_3 is dissasociated in water which can break down into bicarbonate (HCO_3^-) and a proton (H^+) ions. HCO_3^- can further dissociate into carbonate (CO_3^{2-}) and a proton. All these chemical equations can work in reverse, so, for example, CO_3^{2-} can react with a proton to form HCO_3^- (eq. 2.1). The equilibrium of these chemical reactions depends on the pH-level and the global carbon cycle (Terlouw, 2012).

$$H_2O + CO_2 \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- + H^+ \leftrightarrow CO_3^{2-} + 2H^+ \qquad \text{(eq. 2.1)}$$

The four most abundant inorganic forms of carbon in sea water are: CO_2, H_2CO_3, HCO_3^-, and CO_3^{2-}. As the ocean is a carbon sink, increasing atmospheric CO_2 leads to a rise in oceanic dissolved CO_2, thus shifting the equilibrium of the above equation towards the left. Reef building organisms use calcium carbonate ($CaCO_3$) for their skeleton. $CaCO_3$ forms when Ca^{2+} reacts with CO_3^{2-}, so these organisms take a form of dissolved inorganic carbon from the water column and lock it in their skeleton, acting too as a carbon sink (Caldeira *et al.*, 2003).

The pH-scale is a measure of the alkalinity and acidity of an aqueous solution, which is dependent on the amount of H^+ ions. The pH is the negative log of the H^+ concentration (eq. 2.2), so the higher the H^+ concentration, the lower the pH, and the higher the acidity.

$$pH = -\log_{10}[H^+] \qquad \text{(eq. 2.2)}$$

2.4 Climate change

Since the industrial revolution, humans have been burning fossil fuels. The burning of this fuel has resulted in the release of large quantities of CO_2 into the atmosphere. This carbon release has accelerated global warming, bringing with it various other consequences such as the melting of ice caps, alterations to percipitation patterns, sea level rise, and changes to the distibution and abundance of certain organisms (IPCC, 2014; Hughes, 2000). The current concentration of atmospheric CO_2 is higher than that of any point over the past 740,000 years (Petit *et al.* 1999). Over the past 250 years, atmospheric CO_2 concentrations increased by 40%, from 280 ppmv (parts per million volume)(in what year?) to 384 ppmv in 2007 (Solomon *et al.*, 2007). Since 1850 the global average temperature has increased 0.74°C, while the pH of our oceans has decreased 0.1 pH-unit and sea level has risen 17 cm (IPCC 2007).

2.5 Ocean Acidification

Due to the increase of dissolved anthropogenic CO_2 in the ocean, the pH of the ocean has declined, making it more acidic and altering the seawater carbon chemistry (*fig. 2.1*) (Doney *et al.*, 2009). As previously mentioned, the equilibrium of *equation 2.1* (above) changes when more CO_2 is added. How this equilibrium shifts might becounterintuitive, because CO_2 reacts with H_2O to become H_2CO_3 which is an unstable molecule and breaks down into HCO_3^- and a proton. Intuitively one might think that HCO_3^- will break down into CO_3^{2-} and a proton, but this is not the case. The proton formed when H_2CO_3 breaks down will react with CO_3^{2-} to form even more HCO_3^-, limiting the amount of CO_3^{2-} in the oceans (Orr *et al.*, 2005). This additional CO_2 acts like a weak acid, and thus increases the H^+ concentration and decreases CO_3^{2-} concentration in the ocean.

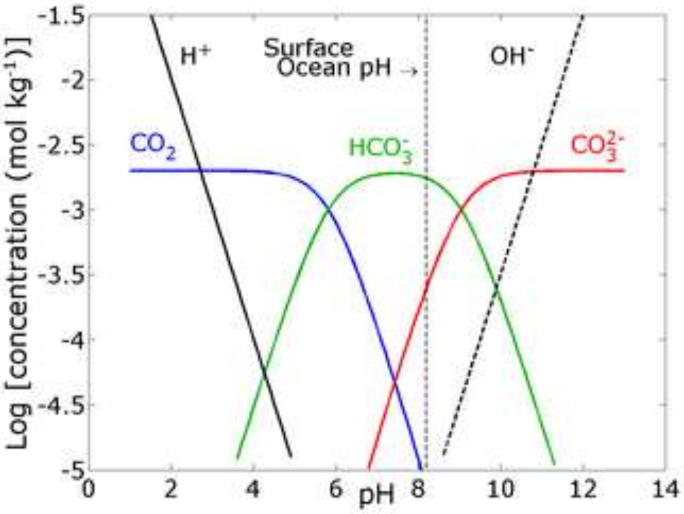


Figure 2.1 Graph which shows how the pH-value influences the concentrations of CO_2, HCO_3^- and CO_3^{2-}.

Ocean acidification limits the quantities of CO_3^{2-} and as such is a threat to reef building organisms (Orr *et al.*, 2005). These organisms use $CaCO_3$ to build their skeleton, which is shown in equation 2.3. Depending on the concentration of Ca^{2+} and CO_3^{2-}, these compounds can precipitate into $CaCO_3$, or $CaCO_3$ can dissolve into Ca^{2+} and CO_3^{2-}: the higher the concentration of Ca^{2+} and CO_3^{2-}, the more likely the compounds will precipitate. Otherwise, the equilibrium will shift in the opposite direction, leading to increased dissolution of $CaCO_3$.

$$\leftarrow \text{Mineral precipitation}$$

$$CaCO_3\,(s) \leftrightarrow [Ca^{2+}] + [CO_3^{2-}] \qquad (\textit{eq. 2.3})$$

$$\rightarrow \text{Mineral dissolution}$$

Equation 2.4 (below) describes the saturation sate of a mineral in seawater, known as Ω. This is a measure of the thermodynamic potential for a mineral to form or dissolve. Ω is measured by dividing the product of the ion concentrations by the product of the ion concentrations when the mineral neither forms nor dissolves. In *equation 2.4*, K_{sp} $([Ca^{2+}][CO_3^{2-}]_{at\ equilibrium})$ is impacted by temperature and pressure (Langdon *et al.*, 2000). When Ω is less than 1, $CaCO_3$ dissolves; when Ω is equal to 1, it neither forms nor dissolves. The physical area where Ω equals 1 can be understood as a line in the ocean, also referred to as the saturation horizon. The addition of CO_2 results in a decline of CO_3^{2-} ions, thus raising the location of the saturation horizon and giving reef building organisms a smaller habitat and increased stress.

$$\Omega = \frac{[Ca^{2+}][CO_3^{2-}]}{[Ca^{2+}][CO_3^{2-}]_{at\ equilibrium}} = \frac{[Ca^{2+}][CO_3^{2-}]}{K_{sp}} \qquad \text{(eq. 2.4)}$$

2.6 Coral bleaching

When corals are stressed by changes in the environment, such as increased temperature or nutrient availability, they release their symbiotic zooxanthellae and turn completely white (pic. 2.1). This is called coral bleaching. When a coral is bleached it is not yet dead, but missing its photosynthetic partnership (Brown *et al*., 1997). As zooxanthellae make up for about 90% of the coral's energy (Marshall *et al*., 2006), when the coral is bleached, it struggles to provide itself enough energy to stay alive. If the stress factors diminish while the coral is still alive, the zooxanthellae can return and the coral can survive. However, extended coral bleaching will eventually kill the coral (Hoegh-Guldberg, 1999). Coral bleaching can occur locally or globally. Since 1979 there have been six mass bleaching events due to global ocean temperature rise (Chumkiew *et al*., 2011), the most serious of which killed 16% of the world's hard corals (NOAA, 1998). Overall, one-third of reef-building corals face elevated extinction risk from climate change and local stress factors (Carpenter *et al*., 2008).

Picture 2.1 Picture of a bleached massive coral of the genus Symphillia with partial algal overgrowth. Picture from noaa.gov.

3. Threats to Koh Tao's coral reefs

Figure 3.1 Map of Thailand, where Koh Tao is marked with the red arrow. Retrieved from monkeetime.com.

Koh Tao is a small island in the Gulf of Thailand covering an area of 19 km^2 (fig. 3.1). The island receives approximately 300,000 visitors per year (Scott, 2009). Most of the population lives on the west side of the island, whereas the east side is relatively unpopulated (Terlouw, 2012). The island's shallow waters contain abundant coral reefs, which are home to a high diversity of coral genera (Hoek *et al*., 1980). Coral Reef tourism comprises a great part of the island's economy, primarily in the form of SCUBA diving and snorkeling. Koh Tao is less developed than the islands nearby, but is becoming rapidly more popular with young tourists for the relatively inexpensive SCUBA diving certificates. Despite its small size, as of July 2015, the island holds nearly 67 dive schools, which offers an impression of the massive amount of tourism. A recent study showed that dive sites on Koh Tao receive about 150 divers per day per site (Hein *et al*., 2015). According to a 2002 study by David Zakai *et al.* on the impacts of recreational diving on coral reefs, the recommended carrying capacity of one dive site in Eilat in the northern Red Sea is between 5,000 – 6,000 guided dives per site per year (Zakai *et al*., 2002). This number would be exceeded in only 40 days on a dive site on Koh Tao.

Although tourism is essential to the economy of the island, such a large influx of people can prove hazardous to the local flora and fauna. One direct impact is coral being damaged by inexperienced divers as they struggle with their buoyancy and hit them with their fins (Thomas *et al*., 2011). In addition, such tourism has lead to increasing quantities of waste water and sewage, which results in increased eutrophication (Terlouw, 2012). A recent study traced anthropogenic nutrient inputs using $\delta^{15}N$ levels in algae on various sites on Koh Tao. This study found that the $\delta^{15}N$ values at sites impacted by sewage disposal was higher than sites with little or no sewage present, suggesting anthropogenic nutrient input from land in the from of untreated sewage (Romeo, 2014). Such eutrophication offers algae a competitive advantage over corals, resulting in algae-dominated ecosystems (Smith, 2003). Further, some species of algae suppress the recruitment of coral larvae (Kuffner *et al*., 2006).

Formerly, Koh Tao was covered in topical rainforest, but due to widespread development the island held only 51% of rainforest coverage in 2005 (Weterings, 2011). This deforestation has led to significant soil erosion which in turn has resulted in increased sedimentation in the water column and on coral, both of which adversely impact the photosynthetic processes of coral colonies.

A recent study showed that reefs which experience a lot of stress tend to be dominated by the weedy coral family Agariciidae (Darling et al., 2013). Other signals for compromised health are grazing scars by corallivorous fish, sponge overgrowth, and pigmentation response. Boat traffic is found to be positively correlated with algal overgrowth, the sedimentation rate and Drupella prevalence (Hein et al., 2015). All these causes lead to stressed corals, which reduces the resilience of the reef and makes it more likely for a bleaching event to occur.

Three types of coral diseases have been recorded on Koh Tao: white syndromes, growth anomalies, and skeletal eroding band disease (Hein *et al*., 2015). These diseases are more likely to infect stressed and weak corals, such as those found on highly used dive sites (Lamb *et al*., 2014). It is also hypothesized that the high densities of fish and invertebrates that come with high coral coverage, in particular the corallivorous crown-of-thorns starfish and *Drupella* snail, are potential vectors of disease transmission (Bruno *et al*., 2007; Antonius *et al*., 1998).

Picture 3.1 Picture of *Drupella* snails hiding under a solitary coral of the family Fungiidae. Photo taken by Chad Scott, 2012.

Since at least the 1990s, there have been plague-like outbreaks of *Drupella* snails foraging on corals, some of which followed major bleaching events (Antonius *et al*., 1998). A recent study about Koh Tao reported that *Drupella* snails have been seen foraging on corals of the family Fungiidae (pic. 3.1), which has never been reported before (Hoeksema *et al*., 2013). These snails are known to be nocturnal foragers, hiding under or at the bottom of the corals during daytime and crawling up to feed at night. On Koh Tao, *Drupella* snails have been reported to be diurnal foragers as well. This shift in diet and foraging activity indicates a plague-like bloom on the reefs of Koh Tao (Hoeksema *et al*., 2013).

In the last 20 years there have been three recorded mass bleaching events on Koh Tao (Terlouw, 2012; C. Scott, personal communication). The first recorded event occurred in 1998 (Yeemin et al 2006), followed by one in 2010 (Chavanich et al 2011) and most recently in 2014 (Scott et al., in prep). The 1998 bleaching event was global in nature, and caused a 16% coral mortality in reefs across the world (Hugh-Goldberg 1999, or Wilkinson 2008). Although many monitored areas recovered after this event, areas with additional stress factors had low recovery rates (Yeemin, 2006). The 2010 bleaching event was the most severe recorded event on Koh Tao thus far and, at the most affected sites, 98% of corals were bleached with a mortality rate of 70%. In 2010, the water temperature had risen from an average of 29°C in March to 31-33°C in April-June (Terlouw, 2012). In 2014, the year of the most recent recorded bleaching event, oceans reached their highest temperature on record (University of Hawaii, 2014). According to local researcher Chad Scott, a high amount of bleaching has already been observed on Koh Tao during 2015.

Koh Tao's coral reefs are under intense pressure from human activitiy and natural causes. The local communtiy group Save Koh Tao and the Scocial Enterprise Organization, New Heaven Reef Conservation Program (NHRCP), both take measures to mitigate or prevent damage done to the coral reefs, as well as to to strengthen resielince and rehabilitate the island's reefs. One method utilized by these organizations is the creation and deployment of artificial reefs(Save Koh Tao, New Heaven, website). These reefs are usually made of metal or concrete to provide a stable environment for corals to thrive, and are monitored for threats such as sedimentation and corallivorous predators. These artificial reefs reduce the pressure of the diving tourism on the natural reefs (Terlouw, 2012) and help the corals rehabilitate more quickly than they could naturally (Epstein *et al.*, 2003). In 2008, Save Koh Tao and NHRCP deployed and monitored multiple artifical reefs called mineral accretion devices around Koh Tao.

4. Mineral accretion devices

4.1 Process

A mineral accretion device is an invention of Prof. Wolf Hilbertz and was patented with the trademark name 'Biorock®' (Patent US005543034). The patent expiredon the 1st of September 2008 due to nonpayment of maintenance fees under 37 CFR 1.362 (USPTO, website). The device works with a low electrical current that runs through an anode and a cathode which, as a result of electrolysis, helps the minerals in the seawater to accumulate at the cathode. Reef building organisms can profit from this because it lowers the pH locally making it easier for minerals to precipitate. Theoretically, the mineral accretion device will work so long as the current flows.

The anode of the mineral accretion device is positively charged and breaks the water down to oxygen gas (O_2) and protons, which lower the pH of the surrounding water (eq. 4.1). On the other hand, the cathode is negatively charged and breaks down H_20 into hydrogen gas (H_2) and hydroxyl ions (OH^-), which in turn raise the pH of the water (eq. 4.2) (Goreau *et al.*, 2005). The net effect of electrolysis on the marine chemistry and CO_2 levels is neutral (Hilbertz, 1992).

Anode: $2\ H_2O(l) \rightarrow O_2(g) + 4\ H^+(aq)$ (eq. 4.1)
Cathode: $2\ H_2O(l) \rightarrow H_2(g) + 2\ OH^-(aq)$ (eq. 4.2)

While the pH of seawater is on average 8.07, the alkaline environment around the cathode can reach a pH level of up to 11. This pH increase ranges only a few centimeters from the cathode (Terlouw, 2012). The pH of the anode, on the other hand, decreases only for a few millimeters, whereafter it is taken up by the natural buffering system of the ocean (Goreau *et al.*, 2005). There is no explanation in this literature of why a difference in the size of the ranges around the cathode and anode might occur.

When functioning properly, the cathode becomes covered in precipitated minerals that are abundant in the ocean, mostly $CaCO_3$ and $Mg(OH)_2$ (magnesium hydroxide) (pic. 4.1). $CaCO_3$ is hard and enduring, while $Mg(OH)_2$ is less usefull for constructing a durable substance. However, the $Mg(OH)_2$ will eventually dissolve in the salty water and be replaced by $CaCO_3$ (Terlouw, 2012). As the percipitated minerals continue to accrete over time on the cathode, it has the ability to self-repair, filling up cracks and damaged areas. On the other hand, due to the localized acidity, minerals will not coat the anode (Goreau *et al.*, 2005).

Picture 4.1 This picture shows the mineral layer on a bar of a working mineral accretion device after two years. Photo by Wolf Hilbertz.

The device provides a favorable habitat for reef building organisms and can support growth rates 3 to 5 times higher than on a natural reef, according to data published by the Biorock Company (Goreau et al., 2003; 2005). The organisms require less energy to build their skeleton, giving the corals more energy for growth, reproduction, and their capacity to resist stress (Romatzki *et al.*, 2014). The cathode can be made out of any conductive material, most commonly steel mesh, and can be made in any shape or size required (Treeck *et al.*, 1997). The anode can be constructed of carbon, lead, aluminium, magnesium, or titanium, as well as more advanced Mixed Metal Oxides (Treeck *et al.,* 1997; Zamani *et al.*, 2010). The electricity used for a mineral accretion device is dependent on the size of the cathode and the speed of growth desired. Higher current densities will result in a different kind of precipitated mineral, shifting towards the weaker $Mg(OH)_2$ in stead of $CaCO_3$. Higher currents are therefore not always favorable. A structure of about 6 to 7 meters in diameter uses around 30 to 50 watts, using approximately the power needed for a dim light bulb (global coral reef alliance, website).

4.2 Koh Tao's mineral accretion device

The cathode of Koh Tao's mineral accretion device consists of four domes, which are approximately 6 meters in diameter and 4 meters tall. It was constructed by more than 100 volunteers of local dive schools and community members, and was deployed on the 5th of October 2008. Each dome is constructed for divers to swim though, as it has an opening on the side and at the top (pic. 4.2). The domes form a square of about 144 m^2 and are located 250 meters from shore, where they have an average depth of 13 meters. One smaller sized dome acts as the control and is not linked to the power source (fig. 4.1). This control has a diameter of 2 meters, a distance of 4 meters from the nearest electrified dome, was deployed at the same time, and has the same substrate type and water depth as the cathodes. The four electrified domes are connected to one another with a metal structure made with wire fence in the shape of multiple waves, which are also conected to the electricity and thus also act as a mineral accretion device (pic. 4.2). The whole device uses a land transformer which converts the 220V/50Hz AC to 60-70V/50Hz AC. The BOLPS unit ('Biorock On Location Power Supply®') is located in the water and supplies the structure with the necessary electricity by converting the power from the land transformer to 8-12 V/10 AMP DC. Since the deployment**,** divers have been continiously transplanting coral fragments onto the structure with small ropes or iron wire**.** The fragments used would otherwise almost certainly die, as they would roll over and be covered in sand and rubble (Goreau *et al*,. 2005). The project is located at Hin Fai, at the North West of the island, and means 'electric rock' in Thai (fig. 4.2). Improvements in fish abundance and coral health have been observed at Hin Fai from the start of the project (Terlouw, 2012).

Picture 4.2 One of the mineral accretion domes covered in corals. The wire fence is visible at the bottom right. Photo by Chad Scott.

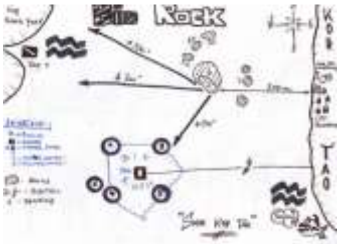


Figure 4.1 Map of the Hin Fai mineral accretion device, drawn by dive master trainers at the New Heaven Dive School.

Figure 4.2 Map of Koh Tao, showing the location of the Hin Fai mineral accretion device. Retrieved from wikitravel.org and modified by Peter van Lunteren.

5. Research

For a better understanding of the coral coverage, growth forms, and growth rates on the Hin Fai mineral accretion device, the NHRCP collected quadrant and phototransect data of the Hin Fai mineral accretion device for almost seven years. Data was gathered from two years while the mineral accretion device was functional, from October 2008 until October 2010, and five years while the device was non-functional, from October 2010 until the present. The aim of this study is to analyse and compare this data in order to gain further insight into the functionality of mineral accredtion devices.

5.1 Methodology

5.1.1 Coral coverage

This investigation included quadrant data from 3rd of March 2009 to the 29th of January 2015 to analyse the

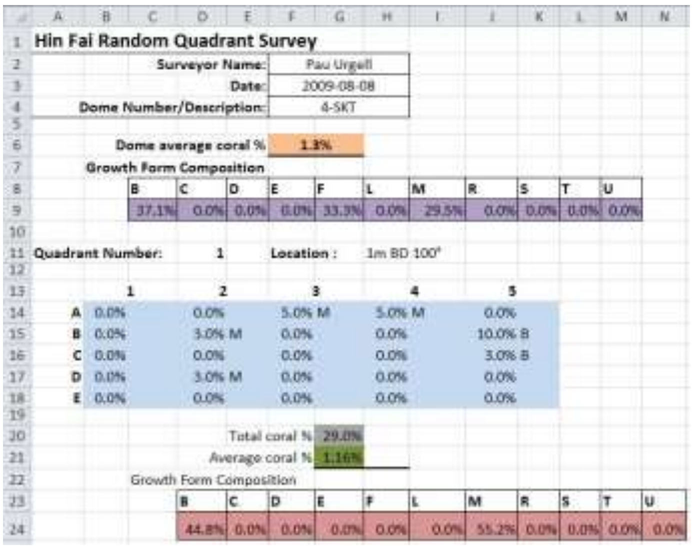
Picture 5.1 Instructor Rahul Mehrotra and a student taking quadrant data on one of the domes. Picture by Chad Scott.

coral growth on the Hin Fai mineral accretion device. A quadrant is a widely used tool to calculate coral coverage and in this case of reef benthos. In this study, the quadrant was one square meter divided in to 25 equal grid sections (pic. 5.1). The quadrant was placed carefully on the marine benthos and the percentage of hard coral coverage and their growth forms was estimated for each seperate grid. Due to their smaller size, the results are more accurate for estimations using the grid sections.

Data collection was atempted to be taken on a regular basis, about once every two months, although this was not always the case, especially between 2011 and 2015. To determine quadrant placement on the mineral accretion device, a haphazard bearing was taken from the boat and the quadrants were placed on the top, middle, and bottom of the chosen dome. This quadrant data was processed in Excel, where an average of all quadrants from that day were calculated. These averages were then processed in a master file to be analysed using Microsoft Excel.

5.1.2 Coral coverage data analysis

For this study, three quadrants were used for each dome, one for the top, the middle, and the bottom. On each grid, data was collected on the growth form and percentage coverage of the hard corals. First, that day's data was entered into an Excel file and place it in a five by five grid (blue section in pic. 5.2, below) and an overall average of coral coverage for this quadrant was taken (green cell in pic. 5.2). In addition, the total coral coverage was determined by the sum of the five by five grid (grey cell in pic. 5.2). At this point, coral coverage for each individual growth form can be calculated by adding up the percentages of a single growth form and dividing it by the total coral coverage percentage. For example, in the quadrant data shown in picture 5.2 below, there is a total of 13% branching corals and a total coral percentage of 29%. 13% divided by 29% is 44.8% (red section in pic. 5.2). Once this data has been input, data from the other two quadrants can be analysed in the same manner and placed in the same Excel file. When the average coral and growth form percentages for all the quadrants are calculated, the coverage averages for the dome can be taken. For the average coral coverage on the entire dome, hard coral data from the three quadrants are averaged (orange cell in pic. 5.2). For the growth form composition of the entire dome, the sum of the percentages of each specific growth form per quadrant is taken and divided by the sum of the combined growth form percentages of the three quadrants (purple section in pic. 5.2). This final calculation is done in order to determine the relative coverage of each coral growth form. When multiple domes were examined in one day, the averages of the total coral coverage and the growth form composition were combined for a daily average. All final results were entered into a final Excel file, which was used to make several graphs and charts.



Hin Fai Random Quadrant Survey

Surveyor Name: Pau Urgell

Date: 2009-08-08

Dome Number/Description: 4-SKT

Dome average coral %: 1.3%

Growth Form Composition

B	C	D	E	F	L	M	R	S	T	U
37.1%	0.0%	0.0%	0.0%	33.3%	0.0%	29.5%	0.0%	0.0%	0.0%	0.0%

Quadrant Number: 1 Location : 1m BD 100°

	1	2	3	4	5
A	0.0%	0.0%	5.0% M	5.0% M	0.0%
B	0.0%	3.0% M	0.0%	0.0%	10.0% B
C	0.0%	0.0%	0.0%	0.0%	3.0% B
D	0.0%	3.0% M	0.0%	0.0%	0.0%
E	0.0%	0.0%	0.0%	0.0%	0.0%

Total coral %: 29.0%

Average coral %: 1.16%

Growth Form Composition

B	C	D	E	F	L	M	R	S	T	U
44.8%	0.0%	0.0%	0.0%	0.0%	0.0%	55.2%	0.0%	0.0%	0.0%	0.0%

Picture 5.2 Screenshot of the excel file used to calculate the results. Colours are added for clarity.

5.1.3 Coral growth Rates

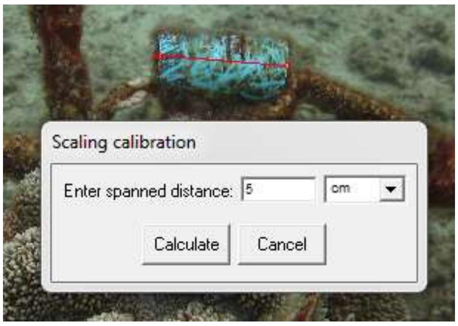
The coral growth analysis included photo-data of tagged corals living on the mineral accretion device for as long as the corals have been attached to the structure (pic. 5.3). Due to the large number of fragments attached to the structure, it is necessary to identify selected corals with a tag.

Picture 5.3 Example of two photos taken of the same coral over a time of 9 months. Made by interns at New Heaven Dive School.

For this study, five corals with larger data sets were selected for analysis. These five corals include two tabular, one corymbose, one branching, and one massive coral. Data was not always taken regularly as sometimes a tag was missed, either at the time the pictures were taken or at the time the pictures were analysed. This resulted in different quantities of data for different tagged corals. Eventually the photos were analysed with the program CPCe V4.0 (Coral Point Count with Excel extensions) and the results were further analyzed in Excel.

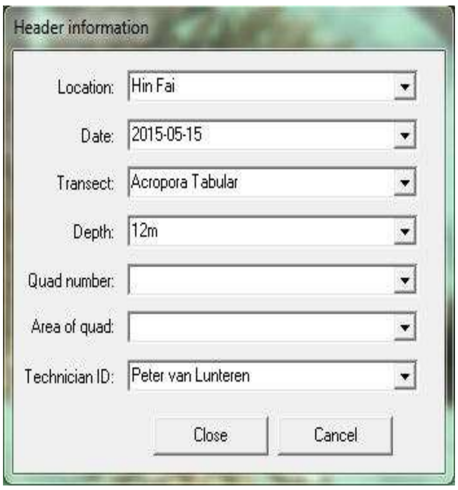
5.1.4 Coral growth data analysis

Prior to picture analysis, it is important to place all the useful pictures in a folder and mention the date of the picture in the name. Once this is done, the pictures can be inported in the CPCe program with the function 'batch linear extension analysis' under 'measurements'. Select all the pictures in this folder and press 'start file processing'.



Picture 5.5 Screenshot of the scaling calibration with CPCe V4.0.

Picture 5.6 Screenshot of the measuring of a tabular coral of the genus Acropora.



Picture 5.7 Screenshot of partly filled in header data.

Because every picture is taken from a slightly different angle or distance, each picture has to be calibrated seperatly. For such calibration, an object with known mesaurements, such as a tag, or a known distance in the metal structure must be visible in every picture. With the 'calibrate picture' function, one can give the measurements for this object by left-clicking on one side of the object and pressing 'enter' if the point is placed correctly, and repeating the process for the opposite side. This is followed by providing the known measurement of the object or distance used for calibration (pic. 5.5). Now the coral can be measured by left clicking on the first point of measurement (point A in pic. 5.6), and right clicking on the final point of measurement (point B in pic. 5.6). The program then automatically calculates the distance between selected points (pic. 5.6). Before proceeding to analyse the subsequent picture by pressing 'next', it is important to supply the necessary header data to the measurement by clicking 'header data', filling in the required information, and pressing 'close' to save the data (pic. 5.7). This information can be exported to Excel for later analysis. Finally, press ‘next’, after which a message appears indicating that the file has been saved, and the process can be repeated. When one is finished analysing the final picture, one can press ‘exit’ and select ‘save data to excel and exit’. When the required Excel format is selected and the workbook is named, the file is saved. Depending on the purpose of the research, different charts and graphs can be made from this file.

5.2 Results

Data obtained in previous studies (Terlouw, 2012; Goreau *et al*., 2003; 2005) show that reef building organisms grow 3 to 5 times faster on a functioning mineral accretion device. Due to a defect in the power transformer, the biorock was not functional after October 2010. This study compares the coral coverage and growth rates of hard corals in general as well as in different growth forms. Table 5.1 offers an explanation of the growth form codes used in the x-axis of the figure 5.1.

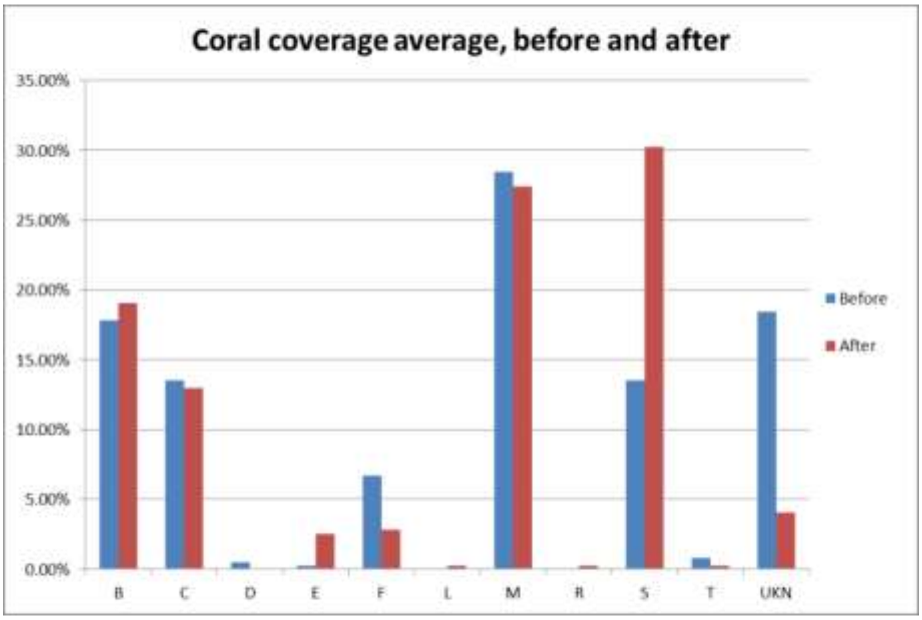


Figure 5.1 Column chart showing the coral coverage per growth form before (blue) and after (red) the defect. The codes for the growth forms are explained in table 5.1.

Code	Growthform
B	Branching
C	Corymbose
D	Digitate
E	Encrusting
F	Foliose
L	Laminar
M	Massive
R	Solitary
S	Submassive
T	Tabulate
UKN	Unknown

Table 5.1 Table explaining the codes used for the growth forms in the graphs and charts.

Figure 5.1 uses the quadrant data for each growth form in order to illustrate the average coral coverage per growth form. Submassive, massive, branching, and corymbose growth forms are those most commonly found on this particular mineral accretion device. A paired t-test found that only encrusting corals and corals with unknown growth forms have a statistically significant difference in coverage before and after the defect ($p_{encrusting}$=0.013, $p_{unknown}$=0.036).

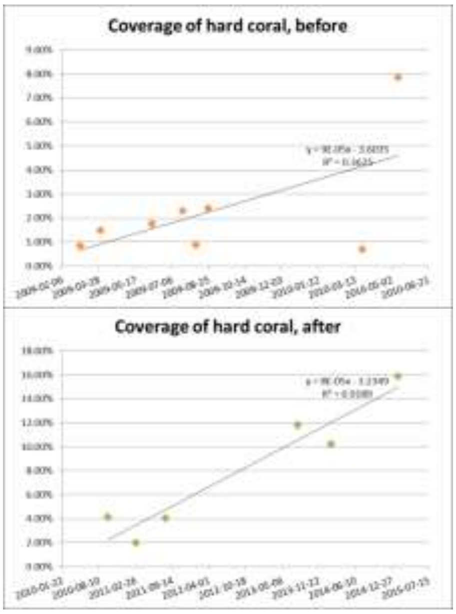


Figure 5.2 This figure shows the percentage of hard coral coverage before and after the defect of the mineral accretion device. Both regression lines and formulas are given as well.

Figure 5.2 visualizes the percentage of hard coral, best fitted regression lines, and formulas before and after the defect. The regression lines have been tested with a linear regression test, where the ANOVA-test showed that the p-value of the regression line before was insignicant (p=0.114, R^2=0.362). The p-value for the regression line after the defect was significant (p=0.003, R^2=0.919). It should be noted that the scaling on the x and y axes is different for both graphs.

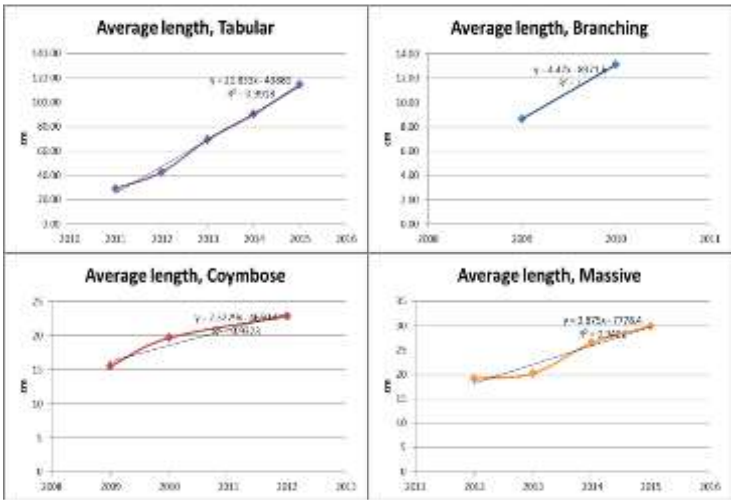


Figure 5.4 This figure shows graphs per growth form, visualizing the actual length in centimeters per calendar year. The regression lines and formulas are displayed. Note that the scaling is different in each chart.

Figure 5.3 shows the average growth rates of tabular, branching, corymbose and massive corals, while figure 5.4 shows the average annual lengths per growth form. Unfortunately, there is data for only one growth form, corymbose, before and after the defect (fig. 5.5). However, as there is only one average for this growth form taken after the defect (and thus no regression line possible), data from this growth form can not be used to compare growth rates.

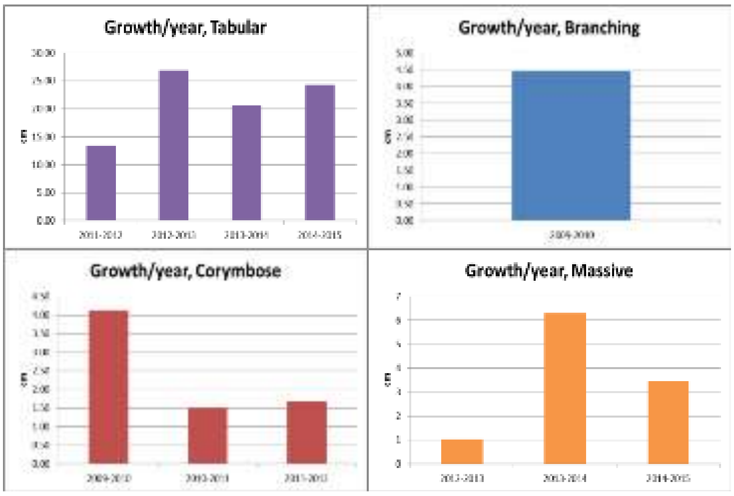


Figure 5.3 This figure shows column charts per growth form, visualizing the growth in centimeters per calendar year. Note that the scaling is different in each chart.

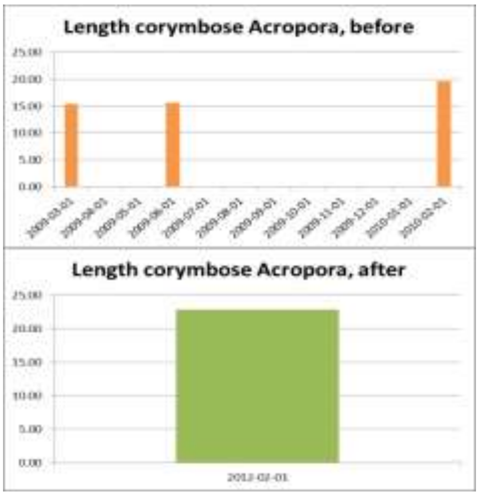


Figure 5.5 Column chart showing the length of corymbose acropora before and after the

5.3 Discussion

Previous research on mineral accretion devices shows that the resilience, growth rate and recruitment of corals increase on functional devices (Yeemin *et al.*, 2006; Goreau *et al.*, 2003; 2005; Terlouw, 2012, Romanski *et al.*, 2014). However, these studies did not research a mineral accretion device that worked for only a few years before falling into dysfunction. The present research found that the coral coverage per growth form before and after the defect did not change significantly, with the exception of encrusting corals. A comparison between the slopes of the regression lines of hard coral coverage could not be done for the regression line of the data gathered before the defect was insufficient, resulting in a p-value higher than 0.05.

The above statistical insignificance is partly due to irregular data collection. The data utilized comes from a research center that teaches students how to collect data. These students remain with the research center for only some weeks or months, resulting in data collected by many different people who may not utilize the same estimation techniques or who may have slighly different understandings of certain growth forms.

In terms of coral growth data analysis, differences in photographic techniques and equipment used by various researchers, such as the use of a fish-eye lens, may have impacted the data collected. In addition, picturtes used for the photo analysis were not always taken from the same angle, making accurate measurements difficult. Further, pictures of larger corals require that the photo be taken from farther away, resulting in relatively smaller tags for use when scaling the image in CPCe and less accurate calibration. Due to the fact that most corals were tagged long after they had been transplanted to the mineral accretion device, there is less data from the first two years of this study. Furthermore, data was not collected uniformely – for example, data on the growth rates of corymbose corals (fig. 5.5) is comprised of four data points, only one of which was collected after the defect, resulting in insufficient information for a statistically significant regression line.

The only growth forms which showed significant increase or decrease in coral coverage after the defect were encrusting corals and those with unknown growth forms. Coral fragments to be attached to the mineral accretion device were selected by researchers randomly and at a constant rate before and after the defect. The fragments found near the mineral accretion device were taken without bias, with the exception of foliose *Pavona*, corymbose *Pocillopora*, and solitary Fungiids. *Pavona* and *Pocillopora* were avoided as they can outcompete other corals with their relatively high growth rates and are not considered endangered on Koh Tao. Solitary corals live unattached on the sea bottom, and are therefore generally not attached to this device or other artificial reefs. Classification as 'unknown coral growth forms' dropped significantly after the defect, however there is no apparent explanation for this occurrence.

The results have shown that encrusting corals cover significantly more surface on an inactive mineral accretion device, rather than on an active mineral accretion device. This might be due to the fact that the mineral accretion layer accumulates on active periods, resulting in overgrowth of encrusting corals.

5.4 Conclusion

This study was conducted to compare the growth forms, growth rates, and coral coverage before and after the electrical defect in the Hin Fai mineral accretion device on Koh Tao. The results show that there was no significant difference between the coral coverage of the various coral growth forms, with the exception of encrusting corals, given the fact that the fragment attachment occured at a constant rate. In this study, there was only one growth form, corymbose, with data from before and after the defect (fig. 5.5). However, the data for this growth form was insufficient to yeild significant results.

The study of Goreau *et al*., 2005 stated that mineral accretion devices should function properly so long as an electrical current flows. The longer the device is working, the thicker the layer of calcium carbonate becomes. Calcium carbonate is not conductive, which could mean that a thicker layer results in a smaller electrical current and thus decreased functionality of the structure over time. This may imply that the most efficient method to manage mineral accretion devices is to let a device build up a certain amount of calcium carbonate, switch it off, and use the current for another mineral accretion device. A structure with a calcium carbonate cover will continue to function and provide the same benefits as an 'ordinary' artificial reef. However, to draw hard conclusions about this, more research is necessary.

The Hin Fai mineral accretion device on Koh Tao is the only one on earth to use a control dome, offering a perfect site for future sudies on the benefit of electrolysis while controling for other variables such as wave action, depth, and water quality. Further, this device is reguarlary maintained and monitered by the research center New Heaven Reef Conservation Program, something that will continue into the future.

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