Artificial Coral Reefs as a Method of Coral Reef Fish Conservation

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Biodiversity is an important factor in all healthy ecosystems. Coral reef ecosystems support an incredibly diverse community of fish species. As coral reefs are in decline due to a combination of factors such as climate change and over fishing, the species which are being supported by the reef are at risk. In particular, coral reef fish communities have been shown to be in decline. Coral reef fish biodiversity is important for the health and sustainability of the coral reef ecosystem and for the ability for coral reef ecosystems to be able to provide ecosystem services. Two particularly important ecosystems services for people provided by reefs are coral reef fisheries, which provide ten percent of the fish consumed globally, and the tourism industry associated with coral reef ecosystems, which is estimated to be worth $9.6 billion annually. Artificial reefs have become increasingly more popular in coral reef ecosystem management and conservation. Artificial reefs have been mainly used in the management of fisheries, but other applications have also been found. A significant loss of coral reef fish biodiversity could have prolific consequences.

What are the practical and efficient uses of artificial reefs as a tool to aid in the promotion of biodiversity among coral reef fish communities? I hypothesized that utilizing artificial reefs which are structurally complex would create biologically diverse fish communities, and that this could be done feasibly without extraneous added costs and work by adding rubble to simple artificial reef structures. This topic was explored in the literature and a case study in Koh Tao, Thailand was conducted. In the case study, I hypothesized that adding rubble to simple artificial reef structures would increase the overall biodiversity of the fish communities which would develop at the reef sites and increase the rate at which fish biodiversity would accumulate, without adding excess cost or maintenance to the conservation work already being done. In my study I sought to answer the following questions: (1) How do local fish communities respond to the use of structurally simple artificial reefs? (2) How does increasing the complexity of artificial reefs influence the rate of change of fish biodiversity on the artificial reef sites? (3) Can inexpensive and easy to build artificial reefs create suitable habitats for fish communities? (4) Can structurally complex artificial reefs be built, deployed, and maintained in an economically feasible fashion?

Structurally complex artificial reefs were found to be associated with higher levels of biodiversity in fish communities throughout the literature. A consistent result was found in the case study. I concluded that artificial reef can be used as a tool to promote the biodiversity of fish communities by creating structurally complex artificial reefs. This can be done without adding extraneous costs and added labor, as was shown in the case study. However, the mechanism behind the high levels of fish biodiversity on natural coral reefs appears to be complex with interrelated factors. For artificial reefs to be able to promote fish biodiversity in a comparable way, a better understanding of this mechanism is necessary. Artificial reefs have a role to play in the conservation of fish communities and coral reef ecosystems, but should be used in combination with other conservation and management techniques.

Preface:

I would like to thank my committee members for all of the advice that they have given throughout this project. Without the time and energy that they have given me, it would not have been possible for me to complete this. I would also like to thank the New Heaven Conservation Program in Koh Tao Thailand, and especially Chad Scott and Devrim Gunsel Zahir. Chad Scott developed the conservation program at New Heaven Dive School, and Devrim Gunsel Zahir is the owner of the dive school. This project would not have been possible without the resources and assistance that they made available to me.

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Introduction:

Biodiversity is generally defined to be the variability of genes, species, and ecosystems in a given area. It is a measurement of the totality of life in a specific area (Newmark 2002). Biodiversity has been shown to be positively correlated with many ecosystem services, and there is a large body of evidence suggesting that biodiversity is related to ecosystem process rates (Balvanera et al. 2006). The specific mechanisms and circumstances through which biodiversity affects ecosystems is not understood well, but due to the apparent relationships between biodiversity and ecosystem processes it is valuable to consider biodiversity in management and policy (Hooper et al. 2005). My research question was what are the practical and efficient uses of artificial reefs as a tool to aid in the promotion of biodiversity among coral reef fish communities? I hypothesized that utilizing artificial reefs which are structurally complex would create biologically diverse fish communities, and that this could be done feasibly without extraneous added costs and work by adding rubble to simple artificial reef structures.

It has been shown that biodiversity is declining in many ecosystems throughout the world at alarming rates. In tropical forests alone it is believed that we may be losing species at a rate of two to five species per hour (Singh 2002). Today it appears that biodiversity is declining a thousand times faster than at rates found in the recent fossil record (Balvanera et al. 2006). Coral reef are one of the most biologically diverse ecosystems on Earth, and are often compared with the better known tropical rain forest ecosystems, as they both exhibit immense diversity and ecological complexity (Connell 1978).

Unfortunately, coral reef ecosystems are in decline. This decline is from multiple and interrelated factors, which have many scientists predicting the extinction of many coral species and the death of the majority of the world’s coral reefs by 2050 unless current trajectories change (Bradbury and Seymour 2009; Hoegh-Guldberg et al. 2007). According to the National Oceanic and Atmospheric Administration, NOAA, coral reef ecosystems support millions of different species. So what will happen to all of the species inhabiting coral reef if they go extinct?

The extinction of coral reefs would potentially lead to a loss of global biodiversity at a catastrophic scale (Carpenter et al. 2008). This paper is focused upon the biodiversity of coral reef fish communities, and the possibility for artificial reefs to play a role in the preservation of this diversity. Current issues plaguing coral reef and fish communities and the interconnectedness of these issues are discussed. Artificial reefs and their applications to conservation are examined, and a case study on the fish biodiversity of a set of artificial reefs deployed off the coast of Koh Tao, Thailand is presented.

In the case study, I hypothesized that adding rubble to simple artificial reef structures would increase the overall biodiversity of the fish communities which would develop at the reef sites and increase the rate at which fish biodiversity would accumulate, without adding excess cost or maintenance to the conservation work already being done.

In my study I sought to answer the following questions: (1) How do local fish communities respond to the use of structurally simple artificial reefs? (2) How does increasing the complexity of artificial reefs influence the rate of change of fish biodiversity on the artificial reef sites? (3) Can inexpensive and easy to build artificial reefs create suitable habitats for fish communities? (4) Can structurally complex artificial reefs be built, deployed, and maintained in an economically feasible fashion?

Background:

Background on the coral reef ecosystem:

Over one thousand different species of coral exist. There are two distinct types of coral: hard coral and soft coral. Hard coral, also called stony coral, form coral reefs. Coral reefs range dramatically in size, from tens to thousands of meters across. Coral reefs are composed of calcium carbonate, which is secreted by the coral animals. Only the few outermost cell layers of the coral are alive, with the calcium carbonate skeleton beneath the living tissue. Coral are composed of polyps, which reproduce asexually (although coral are able to reproduce sexually as well) by budding off. This produces colonies of polyps which are able to grow and expand indefinitely. For a colony to begin growing there must be some sort of structure initially for the polyps to grow off.

Coral reefs, occupying only about 0.2% of the ocean floor, are the most biologically diverse marine ecosystems known today (Knowlton et al. 2010). Because of the incredible number of marine species which inhabit coral reef ecosystems, having healthy reefs is crucial for the continuation of marine biodiversity. In recent years a global increase in disease and stress throughout reef systems has led to increased mortality rates of coral. In the Indo-Pacific, coral reef cover has been declining at a rate of 1% per year for the last 20 years and a rate of 2% per year between 1997 and 2003 (Bruno and Selig 2007). A key factor in the decline of coral reefs is the growing concern of climate change, and a number of scientists are addressing the effects it will have upon coral reefs around the world (Bradbury and Seymour 2009; Hoegh-Guldberg et al. 2007). Other areas of concern include increased rates of development in coastal areas, which results in more sedimentation and nutrient runoff into coral reef ecosystems (Fabricius 2005;

Rogers 1990). Overfishing and destructive fishing techniques are also having a negative impact on coral reefs (Bradbury and Seymour 2009).

Background on Coral Reef Fish Communities:

Coral reef fish are fish which live in close proximity to coral reefs. They are incredibly diverse, and sometimes hundreds of different species will be found in a very small area of healthy reef. As a result, coral reef fish are considered to be the most diverse assemblage of vertebrates on Earth (Sale 2002). Within the Indo-Pacific alone there are thought to be 4,000 to 5,000 different coral reef fish species. The mechanism behind the high diversity in coral reef fish communities is unknown (Sale 2002). Two of the current theories are the lottery hypothesis and the recruitment-limitation hypothesis. The lottery hypothesis ascertains that coral diversity in coral reef fish assemblages is the result of competition amongst juvenile fish of different species for space on a reef. This theory argues that many species of reef fish are interchangeable with one another and that availability of habitat is limited (Sale 1978). The recruitment-limitation hypothesis assumes that the mortality of larval recruits, and not competition, limits the number juvenile fish of any given species which inhabit a reef (Victor 1986).

Over the course of her lifetime, a female coral reef fish can lay anywhere from 10,000 to over 1,000,000 eggs (Sale 1980). Mortality rates of offspring are extremely high for all species. After hatching, coral reef fish go through a pelagic larval phase (Victor 1986). When most coral reef fish are in their larval phase they drift around in the open water. The larval phase is different lengths of time for different species, ranging roughly from 9 days to well over 100. The size of the juvenile fish, when it inhabits a reef and is no longer in its larval phase, ranges from 9 to 200 millimeters depending on species (Leis 1991). During the larval phase, coral reef fish have an incredibly high mortality rate due to predation and can disperse very large distances. Dispersal is highly dependent upon physical oceanographic processes such as current, as the fish cannot effectively swim during the early larval phase (Leis 1991).

Issues:

Issues Facing Coral Reef Ecosystems:

Problems contributing to the coral reef decline are multifaceted in nature and include both anthropogenic and natural processes. Stressors are defined as sublethal disturbances (Hughes and Connell, 1999). Some disturbances in coral reef ecosystems are thought to be beneficial as they can trigger the renewal and regeneration of reefs and species diversification (Hughes and Connell 1999; Nyström et al. 2000). However when reefs are exposed to prolonged disturbances, chronic stress, the introduction of new stressors, or multiple stressors simultaneously they can all lead to coral decline (Hughes and Connell 1999; Nyström et al. 2000). Natural stressors include storms such as cyclones or hurricanes (Hughes and Connell, 1999), some coral disease, and El Niño (Bruno and Selig, 2007). Anthropogenic stressors include nutrient enrichment and sedimentation (Szmant 2002), ocean acidification (Hoegh-Gulberg et al. 2007), increasing ocean temperatures (Selig et al. 2010), human traffic (Hawkins and Roberts 1993), over fishing (Roberts 1995), and destructive fishing techniques (McManus et al. 1997). Many of these causes of coral decline are interrelated and have complicated relationships which are not fully understood.

Recent El Niño events have had extensive effects globally on coral reefs. The 1998 El Niño event caused massive coral bleaching around the world, which led to large scale global coral mortality. Mortality associated with this event was 26.2% of coral in the Galapagos Islands, 13.1% in the Gulf of Chiriqui, and 7% off of the coast of Ecuador (Glynn et al. 2001). Bleaching-related mortality from the 1998 El Niño event in India was 26% in Lakshadweep and 23% in Mannar (Arthur 2000). In Maldives, an island chain in Indian Ocean, live coral cover went from 42% before the 1998 El Niño event, to 2% after the event (Edwards et al. 2001). The magnitude of this event has been associated with increased water temperatures, which is most likely a consequence of climate change (Aronson et al. 2000; Hoegh-Guldberg 1999; Selig et al. 2010). Although El Niño is a natural stressor, its combination with anthropogenic stressors such as increased water temperatures has lead to large scale coral reef decline as was seen in the 1998 event (Hughes and Connell 1999).

Nutrient runoff and sedimentation are also contributing to coral decline (Szmant 2002). Primary productivity in the oceans is limited by the ratios of carbon to nitrogen to phosphorus (Redfield 1958). Nutrient runoff from sources such as agricultural fertilization, waste water, and urban runoff changes the ratios and concentrations of limiting nutrients which is often seen to alter marine environments to favor algae. Excess nutrients play a role in causing a shift in coral reef ecosystems from high coral cover and low algal cover to low coral cover and high algal cover (Fabricius 2005). In the presence of excess nutrients, macroalgal grow rapidly, overtaking the coral reef (Stimson et al. 2001). This is usually seen in areas where the presence of herbivores is unusually low, often due to overfishing, which further aids macroalgae (McCook 1999).

Increased sedimentation is another anthropogenic source of coral degradation (Rogers 1990). Excess sedimentation is often observed alongside excess nutrient deposition. Both processes are associated with the development of coastal zones (Fabricius 2005). Often times when tropical areas are developed, parts of the forest must be clear cut to make way for buildings and roads. The root system of vegetation holds together topsoil, keeping it essentially immobilized. Removing vegetation results in increasing soil erosion and mild disturbance events, such as rain, can potentially result in massive amounts of sediment to be washed into the ocean. Excessive sedimentation can result in entire reefs being buried, which results in coral death. Less extreme cases of sedimentation might temporarily decrease water quality or block light, which often results in coral bleaching.

Coral reef ecosystems draw scuba divers and snorkelers from all over the world. The irony of diver's and snorkeler's love for coral reef ecosystems is that their presence at reef sites is a contributing factor to coral decline (Hawkins and Roberts 1993; Hawkins et al. 1999). In a study performed by Hawkins and Roberts (1993) in Egypt it was found that shallow water reefs flats often times get trampled by snorkelers and divers. When trampled and untrampled reef flats were compared, it was found that coral colonies were smaller in trampled areas, there was a higher percentage of damaged coral and fragmented coral in trampled areas, there was a higher percentage of bare rock and rubble in trampled areas, and the total percent of live coral cover was significantly lower in trampled areas. With scuba diving technology advancing and tourist accommodations in areas with dive sites improving, coral reef ecosystems around the world are more available to the masses than ever before. This has resulted in increases in the amount of traffic that coral reef receive all over the world, which means that the damage due to human traffic through coral reef ecosystems is also increasing.

In a different study Hawkins et al. (1999) conducted in the Caribbean, coral communities and fish communities in protected reserves were compared with those at dive sites which had a maximum of 6000 divers per site per year over a three year time period. They found that there was coral decline at both the protected and dived sites over this time period but that there was a 19.2% loss of old colonies of massive coral species at the sites which saw heavy traffic versus only a 6.7% loss in reserves. They also found that there was significantly more fragmented coral at dived sites than at the reserves, and that there were more abraded coral in the high use sites than there were in sites which were dived less often.

It has been estimated that by 2050 the majority of coral reefs will have died (Bradbury and Seymour 2009; Hoegh-Guldberg et al. 2007). As the reefs become increasingly at risk, all of the species which are dependent upon the reefs also become at risk. The effect of a drastic decline in reef ecosystems upon the rest of the planet is unknown, however maintaining biodiversity is considered to be of high importance for the health of any ecosystem (Roberts et al. 2002).

Issues Facing Coral Reef Fish Communities:

Indirect Causes of Decline

Coral reef fish communities are directly connected with coral reef. Not all processes contributing to coral reef decline have a direct impact on fish communities. However many of these processes influence fish communities indirectly. In 2004, Jones et al. published an eight year study on coral reefs in Papua New Guinea. They observed that following a massive decline in coral reef cover (thought to be caused by the combination of coral bleaching, increasing sedimentation from costal runoff, and outbreaks of crown-of-thorns starfish), there was a decline in fish biodiversity in which the abundance of 75% of reef fish species declined. The abundance of 50% of reef fish species declined to less than half of their original population size. Percentage of live coral cover is positively correlated with both numbers of coral reef fish species and with number of individuals (Bell and Glazin 1984). Therefore, any process which significantly decreases coral reef cover will likely decrease reef fish species richness and abundance.

Coral reef bleaching has been shown to have negative effects on coral reef fish communities. Graham et al. (2008) conducted a study in the Indian Ocean on fish communities following the 1998 mass bleaching. Their study included 7 countries and 66 different sites which were spread out over 26 degrees of latitude. They found that decline in coral cover was followed by decline in fish species richness, abundance of corallivores (fish which eat coral), abundance of plankivores (fish which eat plankton), and abundance of fish less than 20cm long. It was known that adult fish were being removed from the ecosystem through fishing and natural mortality, but were not observed to be effected by the bleaching event except for corallivore and plankivore species. Abundance of juvenile fish was reduced following the bleaching event, decreasing the population of fish able to replace the adult fish being removed from the population. This study concluded that the bleaching event caused a time-lag decline in coral reef fish abundance. They also noted that the decline of corallivores and planktivores followed the pattern of the decline of their preferred species of coral.

Direct Causes of Decline:

There are also many processes which cause direct decline in coral reef fish communities. One example of this is ocean acidification, which is directly and negatively affecting coral reef fish communities. Munday et al. (2008) conducted an experiment on larval clownfish and the effects of ocean acidification. By the end of their larval phase, most reef fish species have well developed olfactory organs, and are able to use olfactory cues (smells) to find suitable habitats when they are in the close proximity to those habitats. pH was manipulated in an aquarium setting to test the effect of pH on larval habitat selection. Clownfish are typically found on reefs which are nearby tropical islands, and live in close proximity to sea anemones. Because of this behavior, olfactory cues from sea anemones and three different types of vegetation were used in the experiment. At a pH of 8.15 (current ocean pH), the larvae were strongly attracted to the olfactory cues from the tropical tree and the anemone. There was no preference to areas with or without olfactory cues from the savanna grass, and areas with olfactory cues from the swamp tree were avoided. When pH was decreased from 8.15 to 7.8, larvae became attracted to the olfactory cues from the savanna grass and became strongly attracted to the olfactory cues from the swamp tree. Attraction to the olfactory cues from the tropical tree and sea anemone were significantly weaker than at current pH. When pH was further decreases to 7.6 larvae did not react in at all to any of the stimuli. This has implications for the replenishment of adult fish populations, and the survival rate of juveniles as habitation of some reefs is less optimal than others. As it has been shown that many species of fish, not just clownfish, use olfactory cues to pick habitats, it is possible that ocean acidification will cause decline in the populations of many different coral reef fish species.

Destructive fishing practices are considered by many resource managers to be the largest anthropogenic threat to coral reef ecosystems (Fox et al. 2003). Destructive fishing techniques include blast fishing, poison fishing, trawling and overfishing (McManus 1998). Blast fishing is the process by which fishers drop explosives into the ocean, often times onto a coral reef or into a school of coral reef fish, where they explode, killing a large amount of fish in a very short amount of time. Many fish which are caught in the blast sink to the ocean floor, requiring divers to go down collecting the catch (Pet-Soede et al. 1999). The explosives are typically home made from fertilizers and other easy to obtain materials (McManus 1998), which releases chemicals such as ammonium and potassium nitrate into the coral reef ecosystem (Pet-Soede et al. 1999). Blast fishing is incredibly destructive to both coral reefs and to fish communities, and is an extremely inefficient fishing method. It is an effective means of catching large amounts of fish in a small amount of time, but the explosives do not distinguish between desirable species of fish and the rest of the fish community, or between juvenile and adult fish (McManus

1998). The result is that although there are large yields of sellable fish, there are also massive amount of unsellable fish killed. The explosion fractures the reef, producing a large amount of rubble which buries many of the sellable fish, adding to the inefficiency of the process (McManus 1998). The death of juvenile fish hurts the population because it decreases the ability for the population to replenish after fishing. The death of the undesired species hurts the fish community and the coral reef ecosystem as a whole as it add an unnecessary pressure on the undesired species, decreasing the abundance of the species and potentially the biodiversity of the community.

Blast fishing is also devastating to the coral reef itself. Within a radius of one to two meters surrounding the explosive coral mortality is typically observed (McManus 1998). Considering that coral grow at the scale of 10 cm per year (Shinn 1966) and that blast fishing is repeated often on reefs where it occurs, a one to two meter radius represents a significant amount of area in which to find coral mortality. A study in Indonesia examined coral recovery in areas affected by blast fishing. Nine rubble fields created by extensive blast fishing on coral reef were monitored for over ten years for coral recovery, however no significant recovery was seen at any of the sites (Fox et al. 2003). Blast fishing negatively influences coral reef fish communities in several different ways. It devastates fish populations by massive biomass removal and by altering the population structure. It removes habitat, and it alters community structure by removing large amounts of biomass from a large variety of different species, altering ecosystem dynamics.

Justifications for the Conservation of Biodiversity:

People have been utilizing coral reef resources for thousands of years (Hodgson 1999). However, it is difficult to quantify the total value of reef ecosystems since some reef attributes are not associated with an economic value. Reefs are an open access resource, which is a resource anyone can access at any time. Open access resources are often times overused (Hardin 1968). Tens of millions of people are directly dependent upon coral ecosystems for protein and other resources. The current value of the resources provided by coral ecosystems is somewhere between $172 billion and $375 billion annually (Veron et al. 2009). Biodiversity loss decreases the ability of coral reef ecosystems to provide ecosystem services (Worm et al. 2006). It is therefore important to protect and conserve biodiversity on coral reefs in order to maintain the services which reefs provide.

Coral Reef Fish as a Food Source:

Millions of people are dependent upon coral reef fisheries for food (Newton et al. 2007). One square kilometer of actively growing reef supports a large enough fish community to sustainably be the sole source of protein for 300 people (Jennings and Polunin 1996), however for current catch rates of coral reef fisheries to be sustainable it was estimated that 75,031 km^2 more reef area would be needed on Earth (Newton et al. 2007). Roughly ten percent of the fish consumed globally are caught from coral reefs (Moberg and Folke 1999). There are over 100 countries which have coastlines with coral reefs, many of which are third world countries. In many coastal communities seafood is the primary source of protein, and adequate replacement sources of protein are not available (Newton et al. 2007). If there was a significant reduction in the size of coral reef fisheries, the affects would most likely be felt in third world communities. An annual removal of only five percent of the biomass of any particular fishery has the potential to significantly change community structure in coral reef ecosystems (Jennings and Polunin 1996). Without the coral reef fish communities as a source of protein, significantly more people in the world would have insufficient diets.

Coral reef fisheries are a valuable commodity. The global economic value of coral reef fisheries has been estimated at $5.7 billion, however due to the overexploitation of fisheries the economic value of fisheries in some developing countries has been reduced to zero (Cesar et al. 2003). Many fishing communities are economically dependent upon the sustainability of reef fisheries. In the Philippines, small scale fishers contribute more than $1 billion annually to the local economy (White et al. 2000).

Tourism:

Every year millions of scuba divers travel to reefs around the world. This service alone is creates approximately $9.6 billion (Cesar et al. 2003). Much of this revenue goes into the local economy of coral reef areas (Cesar et al. 2003). White et al. (2000) found that in the Philippines many divers are willing to contribute to local reef management programs in the form of donations or entrance fees. They calculated an annual contribution from divers of $300,000 from just one of the popular dive sites, and that divers already add $1.3 billion annually to the economy in the Philippines from the tourism industry. Many divers are drawn to coral reefs for the diverse fish populations, and if biodiversity was to significantly diminish, this industry would suffer. The overexploitation of coral reef ecosystems by the reef tourism industry is unsustainable, since excessive human traffic on reefs is a cause of reef decline. Without proper management, the tourism industry will collapse completely due to coral destruction.

Medicine:

Most taxa associated with coral reef ecosystems are not very well understood as a result of few species having been collected, studied, or described (Sebens 1994). As so many of the coral reef associated organisms remain a mystery, humans could potentially make huge breakthroughs in the fields of science and medicine with the future study of these organisms and their ecosystem functions. Somewhere between 25% and 50% of all currently marketed drugs originate from natural products and between 1981 and 2006 possibly as high as 66% of all anti-cancer agents were derived from natural products (Kingston 2011). The loss of biodiversity in coral reef ecosystems would likely be the loss of future cures for diseases.

Methods of Coral Reef Fish Conservation:

Allocation of Conservation Resources:

With coral reefs declining all over the world, it must be decided where to focus conservation efforts and limited resources. One approach taken to address the issue of the decline of environments with suitable coral growing conditions was explored by Jordan M. West and Rodney V. Salm (2003). They surveyed current reef sites and identified reefs which were located in areas which were naturally resistant to bleaching and areas where the reef communities were naturally resilient to bleaching. The distinction between naturally resistant and naturally resilient areas made by the researchers is that naturally resistant areas were defined to be areas where the natural environmental conditions would result in very little coral bleaching. Naturally resilient areas were defined to be areas where conditions would likely lead to natural recovery from bleaching events. Identifying reef systems which have the highest likelihood of survival after bleaching will allow these reefs to be given the highest priority in conservation and restoration efforts. This approach may increase the likelihood of survival of those reefs which are most suited to live in the projected ocean conditions. However, it does not offer any solutions for minimizing reef losses in general. West and Salm stressed the importance of preserving marine biodiversity, arguing that protecting these specific areas is a means of maximizing the conservation of global reef biodiversity as ocean conditions continue to change.

A species is endemic to an area if it can only be found in that area. Endemic species are more at risk for extinction than species which have more widespread distributions. Many species which inhabit reefs are endemic, making coral reefs centers of endemism. The biodiversity of the ten coral reefs which are the richest centers of endemism, it was found that they make up only 15.8% of the world's reefs, while consisting of 44.8% to 54.2% of endemic species found on reefs (Roberts et al. 2002). Due to this clustering of at risk species in these biodiversity hotspots some scientists have argued that we should focus our coral reef conservation efforts on the reefs which exhibit the largest amount of biodiversity. This will result in the preservation of as many species as possible in order to maximize biodiversity of surviving reef systems. This requires intimate knowledge of biodiversity of all the different reef systems around the world. To do this efficiently, complete lists of all species inhabiting the reefs would be needed for all reefs in the study area. Such lists do not exist and would be very difficult to develop (Beger et al. 2007).

Marine Protected Areas:

The most commonly executed method of coral reef conservation has been the establishment of marine protected areas. Marine protected areas are defined to be any area of the ocean floor in combination with the water column above it and any biotic or abiotic elements of that space which have been designated by legislation with the purpose of protecting part or the entire described enclosed environment (Joachim and Dominique 2004). This definition is very broad and allows for the designation of a marine protected area for a variety of different reasons. Marine protected areas are typically used for the conservation of marine habitats and species (McNeill 1993). Today there are over 69 countries which have established marine protected areas, however little is known about the effectiveness of this designation with respect to conservation, and there is little consistency in selection and management of the designated areas (McNeill 1993). Various suggestions for criteria by which marine protected areas can be designated have been produced.

One success story of marine protected areas took place in Kenya. Researchers examined the rate of fish recovery in four marine protected areas which in which absolutely no fishing was allowed. They found that in the 37 years that the areas were protected there was a significant increase in both species richness and total and size class density (McClanahan et al. 2007). As was shown in this study, designating a reef as a marine protected area is an effective method of conservation if the primary issue plaguing the reef ecosystem is human activity. However this is not always the case. As discussed earlier, there are many different kinds of issues causing coral reef decline and negatively influencing coral reef fish communities. Not all of these issues are caused by human activity at the reef sites, and not all of these issues can be solved by designating areas where people aren't allowed to go. The ocean is complex and interconnected, and unfortunately it is not possible to isolate deteriorating coral reefs and protect them from issues such as warming ocean temperatures or ocean acidification.

Fish biodiversity is not protected by marine protected areas from degrading environments (Jones et al. 2004). In an eight year study in Papua New Guinea, it was observed that there was a significant drop in the abundance of many different fish species in both marine protected areas and in areas which were open to human activities following a decline in coral cover. In the marine protected areas 50% of fish species were seen to decline in abundance to less than half of their original population size, and in areas open to fishing it was 75% of fish species (Jones et al. 2004). These numbers indicate that there is some benefit to fish communities in having areas where fishing is prohibited, but that having marine protected areas is not going far enough to protect coral reef fish biodiversity. Not all marine protected areas ban fishing of all kinds. Another issue with marine protected areas is that for many areas there are very few regulations put in place and that there is often times little enforcement of these regulations. In the Caribbean many marine protected areas only limit the types of fishing that are allowed to take place, allowing “conventional design” fishing and disallowing commercial trap fishing, and despite this distinction commercial trap fishing still takes place to some extent (Rogers and Beets 2001). In these marine protected areas there was no evidence of any difference between number of species, biomass, or size of fish in the marine protected areas versus the non-protected areas (Rogers and Beets 2001).

Community Based Conservation:

An alternative approach to the top-down, government established marine protected area is to use community based conservation efforts. The cooperation of all involved parties is considered to be a crucial element for the success of conservation efforts (White and Vogt 2000). Often times, when a marine protected area is given this designation there is a lack of cooperation. The regulations set in place by the government are typically poorly monitored and unwanted by local fishermen. The result of these two factors is that marine protected areas often times do not work (Luttinger 1997). Establishing marine protected areas also does not address the effects on coral reef ecosystems by causes of decline such as nutrient runoff and sedimentation (Richmond et al. 2007). Getting local communities involved can address these issues.

McClanahan et al. (2006) conducted a comparison of the effectiveness of different types of coral reef management techniques in Indonesia and Papua New Guinea. They examined national parks (large, government managed and enforced reef areas), co-managed reserves (small reef areas managed by the local community and nongovernment organizations), and traditionally managed reserves (small reef areas managed by the local community alone). In this study they found that all traditionally managed reserves and one of the co-managed reserves had increased fish biomass and an increased average size of fish inside the reserves. They also found that there was a positive correlation between how successful a management technique was with how compliant the local community was. The results of this study suggest that when the people who are using reef resources are able to manage the reef themselves, conservation efforts are more successful.

In an examination of coral reef ecosystem decline in the Philippines since the 1970s, White and Vogt (2000) discuss the successes and failures of conservation efforts. Two areas in particular have been incredibly successful. These areas are legally protected, with government instituted sustainable management regimes in place. However, in these two areas legal protection was accompanied with intensive educational programs and the active involvement of local communities. In particular, local fishermen were encouraged to be actively involved with the management regime. White and Vogt suggest that developing reef more integrative reef management systems which involve multiple parties who are invested in the reefs will result in successful conservation efforts.

Luttinger (1997) reported on a case study in the Bay Islands where local communities developed their own reef management program unprompted. On the main island, Roatán, the local economy shifted from being supported by fishing to being supported by nature tourism which was mostly reef based. This shift was accompanied by rapid development of island. Due to the development and increased human traffic on the coral reefs they began to rapidly decline. Two local communities on the island took it upon themselves to institute a marine protected area, which was incredibly successful. They had no support from national or local government, and managed the marine protected area themselves. The success of this case was attributed to involvement and consensus of the stakeholders before and during the conservation regime.

Alternative Conservation Methods:

Mangrove forests have a large impact of coral reef ecosystems, and should therefore be considered when coral reef management and conservation plans are being designed. Mangroves are tropical trees which inhabit the border between costal and marine environments. They live in areas with shallow, slow-moving, saline water with their roots growing partially or wholly submerged in water. Mangrove forests are able to catch up to 30% of sediment being deposited into the ocean, acting as a buffer against intensive sedimentation for coral reefs (Victor et al. 2004). This has implications for coral reef conservation. Excessive sedimentation is not known to have negative effects on mangrove forests (Victor et al. 2006). Following the removal of mangrove forests in Micronesia to make room for the development of houses, coral mortality was suddenly witnessed 150 meters further into the bay than it had been seen prior to removal (Richmond et al. 2007).

Mangroves are also thought to act as fish nurseries for some species of coral reef fish (Mumby et al. 2004; Nagelkerken et al. 2000). In a study conducted in the Caribbean, Mumby et al. (2004) found that the presence of mangroves increased the survivorship of juvenile fish, and had a strong influence on the community structure of nearby coral reefs. They also found that the biomass of several fish species more than doubled when comparing sites where the adult habitat was connected with mangrove forests with sites where the adult habitat was isolated from mangrove forests. One species of fish was observed to become locally extinct following the removal of mangroves. A study conducted by Nagelkerken et al. (2000) on Bonaire found that mangroves are the most important nursery habitat for several different species of commercially important reef fish. Including mangrove forests in reef conservation plans in areas where mangroves are associated with coral reefs could increase conservation effectiveness.

Land management is also an important factor to consider when developing coral reef conservation and management regimes. Richmond et al. (2007) found that in Guam reefs were in decline due to excessive sedimentation, which was the result of increased erosion from regular forest burnings to clear vegetation. Following this assessment, local communities made efforts to decrease forest burnings. Six years after the initial assessment reef conditions were improving. In addition to decreasing forest burnings, the local community had implemented additional watershed restoration activities and education/community awareness activities to decrease erosion.

Artificial Coral Reefs:

Introduction to Artificial Reefs:

An artificial reef is an object that is intentionally placed on the ocean floor to influence biological, physical, or socio economic processes for some reason relating to marine life. Artificial reefs are often used to attract fish to create new fishing sites. Another common use is for conservation purposes. Some examples of ways which artificial reefs can be used in conservation is the acceleration of the development of a new coral reef by providing physically sound structure for coral settlement and to create new scuba diving and snorkeling sites in attempt to decrease the stress on natural reefs caused by human traffic.

In the United States, artificial reefs have been utilized for the improvement of fisheries for over 100 years, mostly by local communities whose livelihood is dependent upon fishing (McGurrin et al. 1989). Originally artificial reefs were made from easily accessible discarded materials which were placed into the ocean. Little construction or methodology was put into the development or deployment of these reefs, and little was actually known about the effects of placing them in the ocean, aside from the observation that objects placed in the ocean attract fish. In a response to the growing knowledge regarding issues facing coastal resources and ecosystems, artificial reefs have been deployed regularly across the world over the last three decades (Santos and Monterio 2007).

Types of Artificial Coral Reefs and Construction Materials:

There are many different types of artificial reefs being used today constructed out of a wide variety of different materials. Concrete is a very common construction material, as is limestone, ceramic, and various types of metal. Materials of opportunity, or scrap materials, such as retired machinery are often used in the construction of artificial reefs. Materials which are highly durable, stable, and will not leach any toxins into the ocean are ideal for artificial reefs.

Artificial Reefs as Fish Aggregation Devices: Behavioral Preference or Habitat Limitation?

One of the big questions amongst scientists is whether or not artificial reefs actually result in more fish being produced in an ecosystem or if fish inhabit artificial reefs preferentially. This is often referred to as the “attraction versus production” debate. Although there is some evidence for increased production as a result of artificial reefs, most studies on the subject conclude that artificial reefs are acting as fish aggregation devices as opposed to increasing population sizes by providing extra habitat (Bohnsack 1989). However some scientists believe that artificial reefs act as both aggregation devices and as production enhancers, depending upon the specific needs of the species in the specific location (Pickering and Whitemarsh 1997). It is impossible to truly determine which role an artificial reef is playing, as it is impossible to know if the fish which inhabit artificial reefs would have successfully inhabited natural reefs had the artificial reefs not been present (Pickering and Whitemarsh 1997).

Cost of Artificial Reefs:

The cost of building and deploying an artificial reef is dependent upon many different factors such as the materials used, the type of artificial reef being built, and the size of the artificial reef site being built. Despite their variability, creating an artificial reef site tends to be expensive. Artificial reefs can either be built out of raw materials, they can be built out of materials of opportunity, or they can be purchased from an artificial reef manufacturer. Which method utilized will greatly influence the cost of both construction and deployment.

Building artificial reefs out of raw materials can decrease material costs, but require time and man power (which may or may not be free) for construction. Dry cement mix can be purchased for under $1.00 per 10 pounds. To fill approximately one cubic foot with cement, 150 pounds of dry cement mix are needed. So one cubic foot of cement can be acquired for roughly $15.00. However, a mold must then be designed and constructed which could add extra costs and time. Depending in part on what size of artificial reef is being constructed, building it out of raw materials may not be practical.

Materials of opportunity can often be acquired very cheaply or for free. Unfortunately they are not always readily available, and the state that they are acquired in may not necessarily be suitable for deployment in the ocean. An example of this is retired ships, train/subway cars, and military vehicles, all of which have frequently been utilized to build artificial reefs. In the United States there are several companies which specialize in the conversion of retired ships into artificial reef sites. One such company is California Ships to Reefs. They explain that there are many different factors which contribute to overall cost of the conversion such as cleaning the vessel, making it safe for divers, transporting it and sinking it. Depending upon the state of the vessel when they get it, the total price can vary significantly. For people planning on contracting their company to create an artificial reef site, California Ships to Reefs suggest having a $1.6 Million budget.

There are also many companies which specialize in the construction of artificial reefs for sale. Several such companies are Reefmaker, Reef Ball™, Artificial Reef Inc., Eco Reefs, and BioRock™. Reefmaker builds artificial reefs to be sold for personal reef building, which is only legal in the state of Alabama and the Florida Panhandle. Their artificial reefs are built out of Florida Limestone, range in height between 3 and 25 feet, range in weight between 5,000 and 36,000 pounds, and range in price between $1,995 and $2,195. Reef Ball™ builds relatively small concrete artificial reefs for the use of conservationists and researchers and for fisheries management. Their reefs range between 1.5 and 3 feet high, weigh between 30 and 6,000 pounds, and cost between $719 and $11,489.

The size and weight of the artificial reef structure affect the cost of deployment. For artificial reef structures such as those made by Reefmaker and Reef Ball™ specialized equipment is required to safely deploy the structures due to their weight. Cranes are often needed to load such heavy artificial reefs onto boats and to lower artificial reefs to the ocean floor. Specialized boats are also needed, the use of which can be expensive.

Artificial Reefs in Fish Conservation:

Regardless of whether or not artificial reefs actually increase the abundance of fish species, they have a wide variety of useful applications. They have the potential to be incredibly useful in marine conservation, and people all around the world are finding very interesting ways to utilize them to relieve some of the stressors affecting natural coral reef ecosystems and also as remediation for deteriorating coral reef ecosystems.

Relocation of Destructive Human Activities:

Artificial reefs have been successfully used in fisheries in a wide variety of ways. They create new fishing opportunities, are able to reduce user conflicts, and reduce the time and effort needed to fish successfully as a result of being able to strategically place new fishing sites

(Bohnsack 1989). Although it is not possible to say if artificial reefs reduce fishing pressure on coral reef fish communities directly as it is still unknown if the presence of artificial reefs increase fish abundance, they create new fishing sites which are beneficial in the sense that they have the potential to make fisheries more accessible and fishing cheaper and less time consuming to fishermen. This is important because it has been the desperation to obtain large enough catches which has led to many of the destructive fishing techniques which are so detrimental to coral reef ecosystems such as blast fishing and poison fishing. Many fishermen consider blast fishing to be their last resort (Pet-Soede 1999). Despite this, blast fishing still occurs in over 40 countries or island territories and poison fishing occurs in over 15 (McManus 1997). Destructive fishing techniques put more stress on coral reef ecosystems than simply reducing fish biomass. If artificial reefs can be used to decrease the frequency of these techniques being used then they will be benefiting the entire coral reef ecosystem.

Scuba diving puts a considerable amount of pressure on coral reef ecosystems. Artificial reefs can be designed and used as alternative diving sites as a way to reduce the pressure from tourism on natural reefs. It was found that several artificial reef sites in Japan were economically beneficial as artificial dive sites (Wilhelmsson et al. 1998). Shipwrecks have also been serving as diver aggregation devices for years, sometimes being even more popular dive sites than local coral reefs (Treeck and Schuhmacher 1999). Many people are skeptical that divers would accept artificial dive sites as acceptable alternatives to natural coral reefs. A random sample of 1,059 divers was surveyed about their experiences diving on natural and artificial reefs. Divers were found to value their experiences on natural reefs significantly more than their experiences on artificial reefs. Despite this, artificial reef dive experiences were valued enough and have economic values large enough to suggest that artificial reefs are able to relieve natural reefs of a significant amount of pressure associated with diver traffic (Oh et al. 2008).

With all of the issues contributing to coral decline many scientists are predicting an imminent extinction of many coral species within the next 50 years (Knowlton et al. 2010). It is a sad but real possibility that we may not be able to reverse coral reef decline in time. If these estimates are accurate then we ought to consider what can be done to minimize the effects of the disappearance of natural coral reef. Artificial reefs could be an effective tool in this situation. In the event of significant decline of natural coral reef, artificial reefs could be used as an alternative habitat and structure to preserve the coral reef ecosystem as much as possible. One benefit of artificial reefs which does not exist with natural reefs is the ability to selectively choose what coral species are grown on the artificial reef. Coral colonies which have been found to be particularly fit to withstand changing ocean conditions can be grown on artificial reefs in attempt to maximize the potential for survival. Artificial reefs can also be strategically placed in areas which may be least affected by the changing ocean conditions to further increase their chances of survival. It would be tragic if the natural reef ecosystems were lost, but it would be even worse if the biodiversity that is dependent upon coral reef for survival were also lost.

Help to Remediate Damage Caused by Human Activities in Marine Ecosystems:

Artificial reefs have the potential to be very useful in a worst case scenario, but they can also be used to in efforts to prevent the worst case scenario from occurring. Artificial reefs can be used to directly repair damages done to natural reef ecosystems through human activity. One example of this is to place artificial reefs in areas with poor water quality and to grow a community of filter-feeders on the reef (Miller 2002). The community could be designed in such a way as to target the specific compounds in the water contributing to poor water quality. This would be a way to address the issue of excess nutrients which is doing considerable damage to coral reef ecosystems around the world. Strategically growing communities of filter feeders could potentially be used to remove other pollutants such as heavy metals as well (Miller 2002). This method has been implemented in the Caspian Sea to remove waste associated with fish farming cages (Bugrov 1994).

There is a considerable amount of research being done on the ability for artificial reefs to be used in the maintenance and restoration of damaged ecosystems. They have been found to be an effective method of ecosystem restoration in various site-specific situations. A coral reef off the coast of Florida was reduced in areas to rubble by trawling in the area and coral reef fish populations were incredibly low. Trawling is an incredibly damaging form of fishing to coral reef ecosystems. After a series of artificial reefs were put in place some fish populations began to increase again, and there was evidence seen that groupers began using the area for spawning and nursery functions (Seaman 2007). Many European countries have begun utilizing artificial reefs as a means to prevent further trawling in areas in which trawling has been banned, but that too large to effectively monitor (Pickering et al. 1999). Spain is one of the countries which has had an incredible amount of success using artificial reefs in this way. They most commonly use concrete reefs, and place them strategically creating artificial reef fields which have made trawling in these areas impossible and eliminated the need for further regulation (Pickering et al. 1999).

The Use of Artificial Reefs Conservation: A Case Study in Koh Tao Thailand

Introduction:

At the New Heaven Dive School in Koh Tao, Thailand, divers are given the opportunity to play an active role in marine conservation. The dive school has developed a conservation program intended to create opportunities for the people who spend the most time on the reefs to care for the reefs. In their coral reef conservation work, New Heaven builds and deploys many artificial reefs. The majority of the artificial reefs used by New Heaven are built from steel rods welded together. These reefs exhibit little structural complexity. Increasing structural complexity of artificial reefs has been shown to increase the biodiversity of the fish communities which inhabit artificial reefs. Building structurally complex artificial reefs also tends to increase the cost of production of the reefs. I hypothesized that adding rubble to simple artificial reef structures would increase the overall biodiversity of the fish communities which would develop at the reef sites and increase the biodiversity of the fish community without adding excess cost or maintenance to the conservation work already being done.

In my study I sought to answer the following questions: (1) How do local fish communities respond to the use of structurally simple artificial reefs? (2) How does increasing the complexity of artificial reefs influence the rate of change of fish biodiversity on the artificial reef sites? (3) Can inexpensive and easy to build artificial reefs create suitable habitats for fish communities? (4) Can structurally complex artificial reefs be built, deployed, and maintained in an economically feasible fashion?

Figure 1: A map of Thailand and neighboring countries, with the island of Koh Tao marked with a red star in the mid-eastern Gulf of Thailand.

Figure 2: A map of Koh Tao, Thailand, curtsey of Chad Scott, with a red star marking Ao Leuk Bay, the location of my study site.

Many forms of conservation are very technical and expensive, limiting the ability for the average person without a scientific education or special training to be involved. This is especially true of conservation work involving coral reef ecosystems, purely as a result of their location below the ocean surface. The diving community is made up of a group of people who collectively have a great deal invested in coral reef ecosystems, and who have developed the skills required to effectively function under water. New Heaven has recognized the potential of this group of people as a tool in coral reef conservation. By educating volunteering divers in issues associated with coral reef decline and simple conservation techniques they have been able to accomplish a lot with limited funds and resources.

Although the New Heaven Conservation Program focuses most of its efforts on coral reef conservation, there are also many projects associated with other aspects of marine conservation. Some of these are the sea turtle head starter program, the giant clam nursery project, land restoration (to decrease sedimentation), and community educational programs. Most of the work that they do with coral reef conservation involves the construction, deployment and maintenance of artificial reefs.

The artificial reefs which New Heaven makes are made mostly out of steel rods which are welded into different shapes to create structure which coral fragments can then be attached to, but concrete and recycled glass are also used. Coral fragments are collected from surrounding reefs, but are never broken off of healthy reefs. The coral reefs of Koh Tao are heavily dived, and many coral fragments which have broken due to human traffic or natural causes can be found in the sand. Such fragments have a very low change of survival since they are constantly rolled around and covered with sand from wave movement.

This method of coral conservation has been successful for New Heaven, but it does not actively consider the coral reef ecosystem as a whole. I wanted to investigate the possibility of extending the work already being done by the conservation program to include coral reef fish communities.

Methods:

I constructed five cone shaped artificial reef structures, all of comparable size and shape. These structures were designated as structures A, B, C, D and Control. The dimensions of each structure are described in Table 1. All structures were made out of steel rods welded together.

Figure 3: Photo of one of the artificial reef structures sunken at Suan Olan before coral fragments or rubble was added. All five structures had the same basic shape and design. The photo was taken by Chris Dalley of the New Heaven Conservation Program on June 5th, 2013.

Dimensions of Artificial Reef Structures			
Structure	**Height (m)**	**Diameter (m)**	**Hypotenuse Length (m)**
A	1.2	1.4	1.47
B	1.13	1.72	1.33
C	1.43	1.43	1.48
D	1.22	1.38	1.34
Control	1.17	1.16	1.37

Table 1: Dimensions of the artificial reef structures sunk in Koh Tao, Thailand in Ao Leuk Bay at the Suan Olan artificial reef site. All five structures were cone shaped, and constructed out of steel rods.

Myself and the rest of the New Heaven Conservation Program placed the structures in the middle of Ao Leuk Bay in a sandy area away from the natural reef and other established artificial reef structures. The general area in which the structures were deployed contained several established artificial reef structures and is referred to as the Suan Olan artificial reef site. All five structures were initially placed on the seafloor by free diving. Once under water the structures were arranged using scuba equipment.

Coral fragments were collected to attach to the artificial reef structures. During the process of collecting coral fragments, the sands surrounding natural reefs are searched for small fragments of coral which are not attached to stable substrate. Only fragments which had a very low chance of survival were taken and attached to the artificial reef structures. This insured that the project did not negatively impact existing reefs. Fragments were handled as little as possible in attempt to minimize added stress to the coral.

Coral fragments were attached to long sections of rope, which could then be wrapped around the steel rods of the artificial reef structures and secured. These ropes were attached to Structures A, B, C, and D. The control structure was left empty, having no coral fragments attached to it so that any fish colonization of the structures that resulted from the presence of the structure itself could be accounted for.

To add structural complexity to the metal skeleton of the artificial reefs without adding extra costs and minimizing extra time needed to create and deploy the reefs I decided to fill the base of the artificial reefs with rubble after they were deployed. Rubble consists of rocks and dead coral fragments, and is readily available in areas surrounding natural coral reef. Collecting rubble did not disturb the natural reef at which it was collected. Rubble was added inside two of the structures, Structures C and D, to approximately a height of half of a meter.

Following the set up of the artificial reef site I collected data as often as possible over the following four weeks. Data was collected using scuba equipment, cameras and underwater slates. Frequency of data collection was dependent upon weather and ocean conditions as the study site could only be accessed by boat. The frequency of data collection was also limited by the availability of the boat. New Heaven Conservation has full access to a boat, but there were multiple ongoing projects which needed regular maintenance.

Observations were made for the different species observed, the abundance of each species, the size range of the individuals, their location, and whether their behavior indicated if they were transient species or residential species. For the purposes of this study, transient species were defined to be species which were observed within one meter of the structure during the fifteen minute observation, but did not remain within one meter of the structure for the full duration of the observation. Residential species were defined to be species which remained within one meter of the structure during the full observational time.

The first ten minutes of data collection was still. Observations were made while remaining still in the sand approximately one meter away from the structure. The structures were approached slowly so as to kick up as little silt as possible so that visibility would not decline. This also allowed the presence of a person to create as little disruption as possible to the species that were being observed. The last five minutes were devoted to moving observation. Observation of the structure from different sides and angles enabled a more thorough assessment of species. The moving observation also allowed for closer observation in attempt to identify species which were not initially seen. During the moving observation, all movements were slow and reserved so to disturb the fish as little as possible. Photos were taken of as many species as possible during both the still and moving observations for identification purposes.

After underwater observations for all five of the artificial reef structures were made, all observations were compiled into a spreadsheet and photos were separated into files sorted by structure. Species observed were then identified using the physical descriptions and photos. To identify species, a variety of fish identification books specific to the area were used, and cross-referenced with FishBase. Data were collected over a four week time period. The fish species observed during data collection are shown in Figure 4.

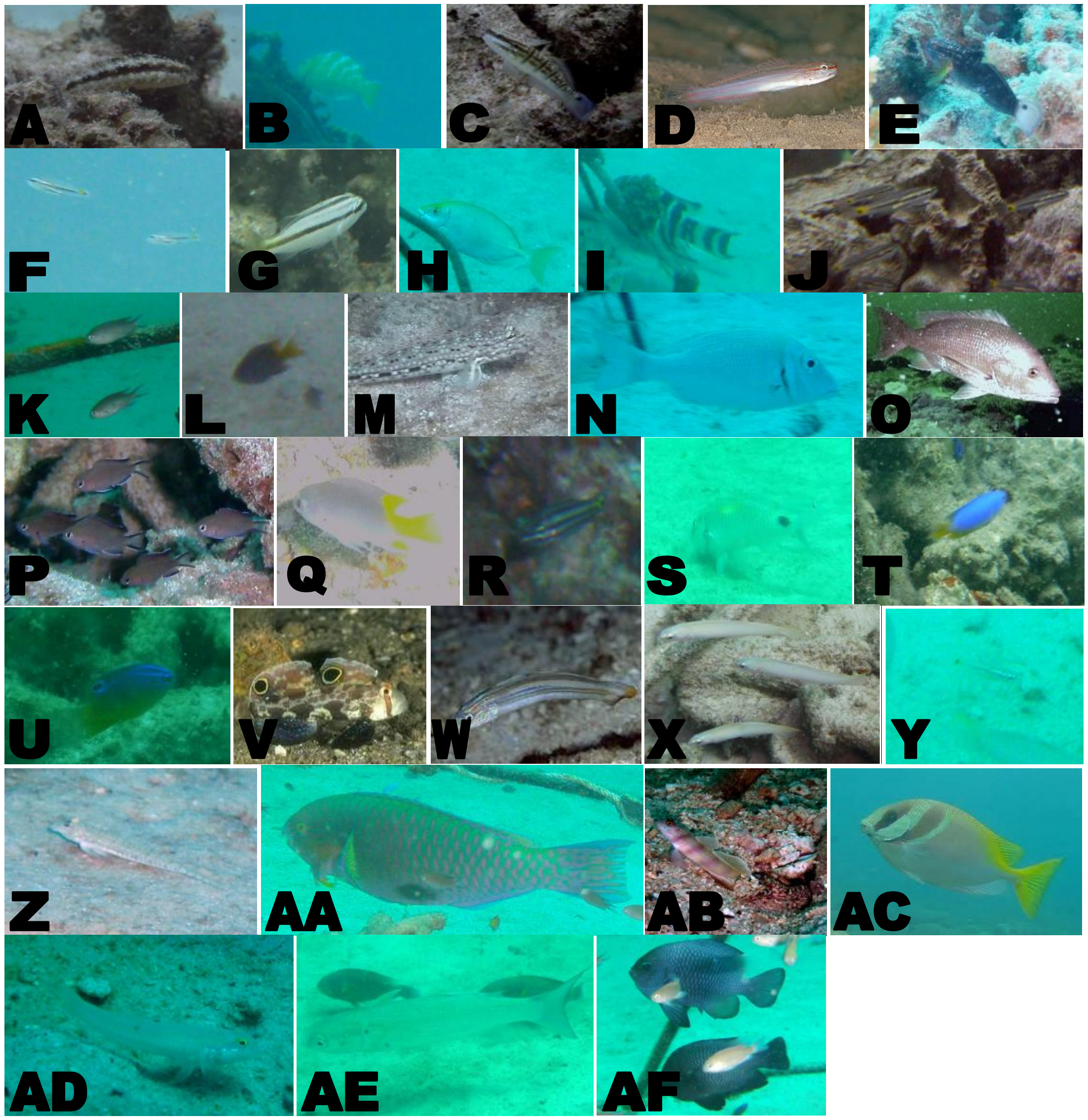

Figure 4: Photos of the fish species observed during data collection over the course of the case study. The labels correspond to the following species. A: Petroscirtes variabilis, B: Abudefduf sordidus, C: Amblygobius albimaculatus, D: Amblygobius descussatus, E: Amblygobius phalaena, F: Apogon fraenatus, G: Apogon quadrifasciatus, H: Caesio cuning, I: Cheilnus fasciatus, J: Cheilodipterus quinquelineatus, K: Chromis ternatensis, L: Chrysiptera rex, M: Istigobius decorates, N: Lethrinus lentjan, O: Lutjanus boutton, P: Neopomacentrus anabatoides, Q: Ostorhinchus sealei, R: Parupeneus indicus, S: Petroscirtes breviceps, T: Pomacentrus coelestis, U: Pomacentrus milleri, V: Pasmmagobius biocellatus, W: Ptereleotris grammica, X: Ptereleotris microlepis, Y: Rhabdamia gracilis, Z: Saurida gracilis, AA: Scarus rivulatus, AB: Amblyeleotris steinitzi, AC: Siganus virgatus, AD: Synodus hoshinonis, AE: Valamugil buchanani, AF: Dascyllus trimaculatus

Once fish species were identified, species richness and species abundance data was utilized to calculate the Shannon-Wiener diversity index for each of the five structures, for each day of data collection. Linear regression analysis was done using Excel to test for a significant relationship between biodiversity and time on each of the five structures. To determine whether or not there was a significant difference between the biodiversity on the three different types of structures an ANOVA was done on the mean values of the Shannon-Wiener diversity index measured on the last day of data collection.

Results:

Linear Regression Analysis

The Shannon-Wiener diversity index was calculated for each structure, on each day that data was collected. Species richness was observed to increase over the course of the study on all of the structures except for the control. The structurally simple artificial reefs (A and B) had fewer species present than the structurally complex artificial reefs (C and D) on every day of data collection except for day 1. Maximum species richness on Structure A was 6 and occurred on day 19. On Structure B the maximum species richness was 7 occurring on day 8. For the Structures C and D, maximum species richness was 12 and 18 respectively, and occurred on day 23 and 27 respectively. Maximum species richness was higher and occurred later on the structurally complex artificial reefs.

The maximum number of individuals observed on the structures was also greater on the structurally complex artificial reefs than on the structurally simple artificial reefs. On Structures A and B the maximum number of individuals were 70 on day 8 and 72 on day 23 respectively.

The maximum number of individuals observed on Structures C and D were 384 on day 23 and 315 on day 19 respectively.

The maximum value calculated for the Shannon-Wiener diversity index was greater on the structurally complex artificial reefs than on the structurally simple artificial reefs. On day 19 on Structure A the maximum diversity index was calculated to be 1.38. On Structure B the maximum diversity index was 1.66 on day 23. The maximum diversity index for Structure C was calculated to be 1.79 on day 23, and the maximum diversity index for Structure D was calculated to be 2.15 on day 27. The data collected is summarized in Tables 2-4 and Figure 5.

Species Richness					
Time(Days)	Structure				
	A	B	C	D	Control
1	1	2	1	2	2
8	5	7	11	10	2
19	6	3	8	11	2
23	5	7	12	17	2
27	4	5	11	18	1

Table 2: The total number of different species observed at each artificial reef structure on each day data was collected is presented

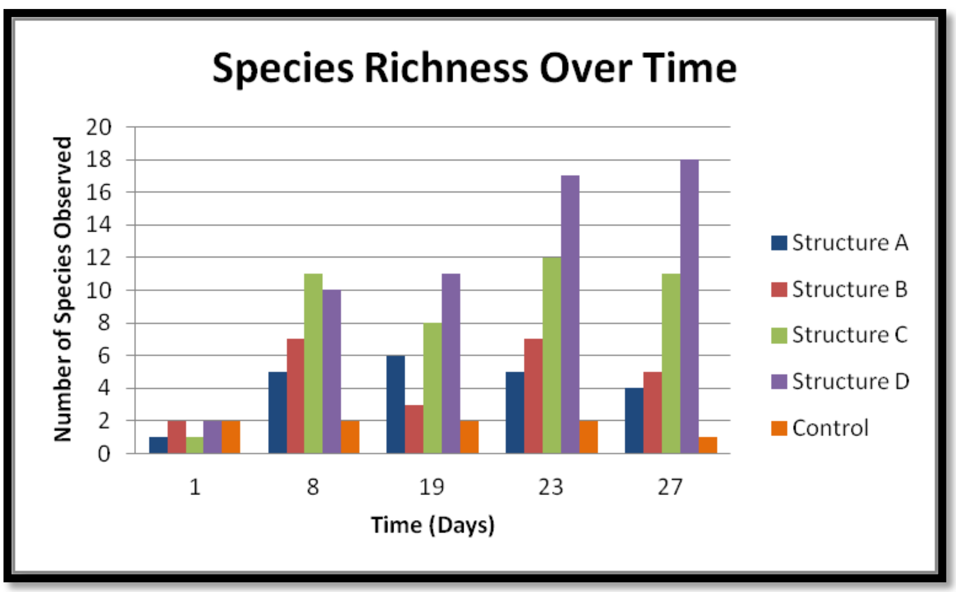

Figure 5: The total number of species observed over time on each artificial reef structure.

Total Number of Individuals Observed					
Time(Days)	Structure				
	A	B	C	D	Control
1	4	4	2	3	4
8	70	61	127	149	13
19	41	29	122	315	4
23	45	72	384	296	4
27	27	30	273	215	5

Table 3: The total number of individuals observed from all species observed at each structure on each day of data collection is shown. The species of individuals is not considered here.

Shannon-Wiener Diversity Index					
Time(Days)	Structure				
	A	B	C	D	Control
1	0	0.562335	0	0.636514	0.693147
8	0.943405	1.194525	1.166551	0.857784	0.271189
19	1.380162	1.021784	1.247162	1.330283	0.562335
23	1.331053	1.659602	1.791218	2.107219	0.693147
27	1.24083	1.187224	1.784348	2.148705	0

Table 4: The Shannon-Wiener diversity index was calculated for each structure and for each day on which data was collected. All calculated diversity indexes are shown in this table. The Shannon-Wiener diversity index considers both species richness and species evenness.

The control structure, which did not have any coral fragments attached to it and was not filled with coral, did not have steadily increasing or decreasing biodiversity during the period of observation. The linear regression done on the data collected for the control structure gave an R-squared value of 0.16 and had a slope of -0.011 units per day. There was no significant relationship found between fish biodiversity and time on this structure (F-test, $p = 0.512$).

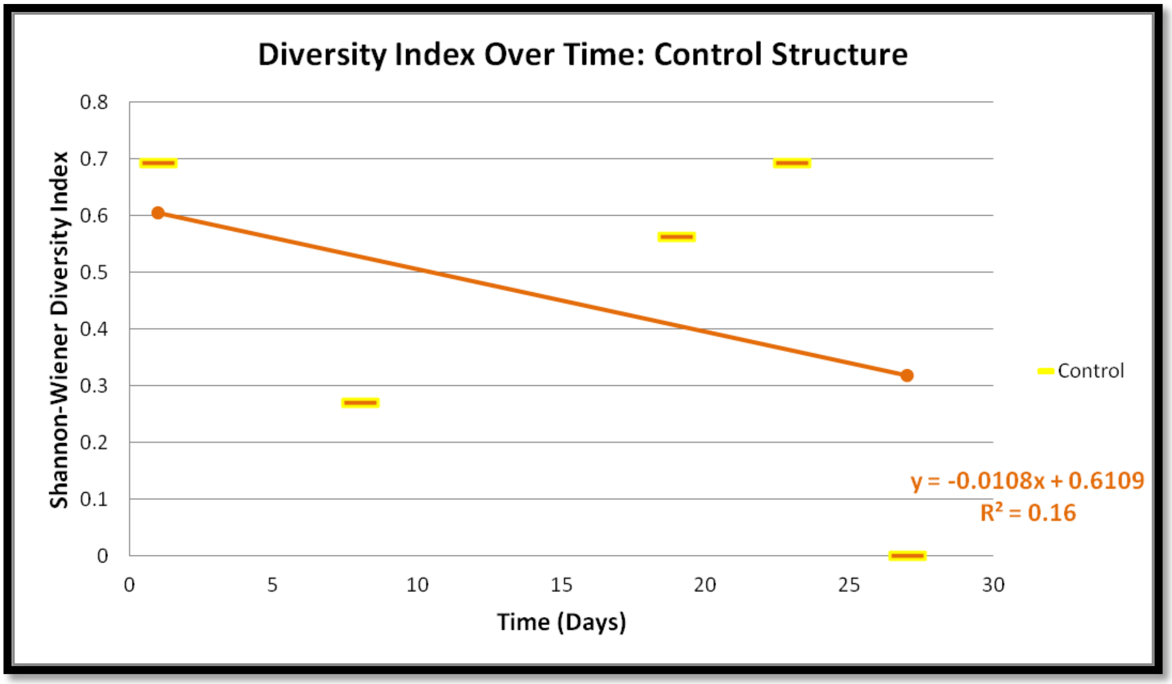

Figure 6: The linear regression of the control structure, no coral fragments and no rubble, yielded $R^2 = 0.16$ and a slope of -0.011. There was no significant relationship found (F-test, p = 0.512).

Structure A had coral fragments attached it, but was not filled with rubble. On structure A fish biodiversity increased initially, from day one to nineteen, and then decreased from day nineteen to twenty seven (Figure 7). Structure A was found to have an R-squared value of 0.755, and a slope of 0.0461 per day. The relationship between time and biodiversity was not found to be statistically significant (F-test, p = 0.056).

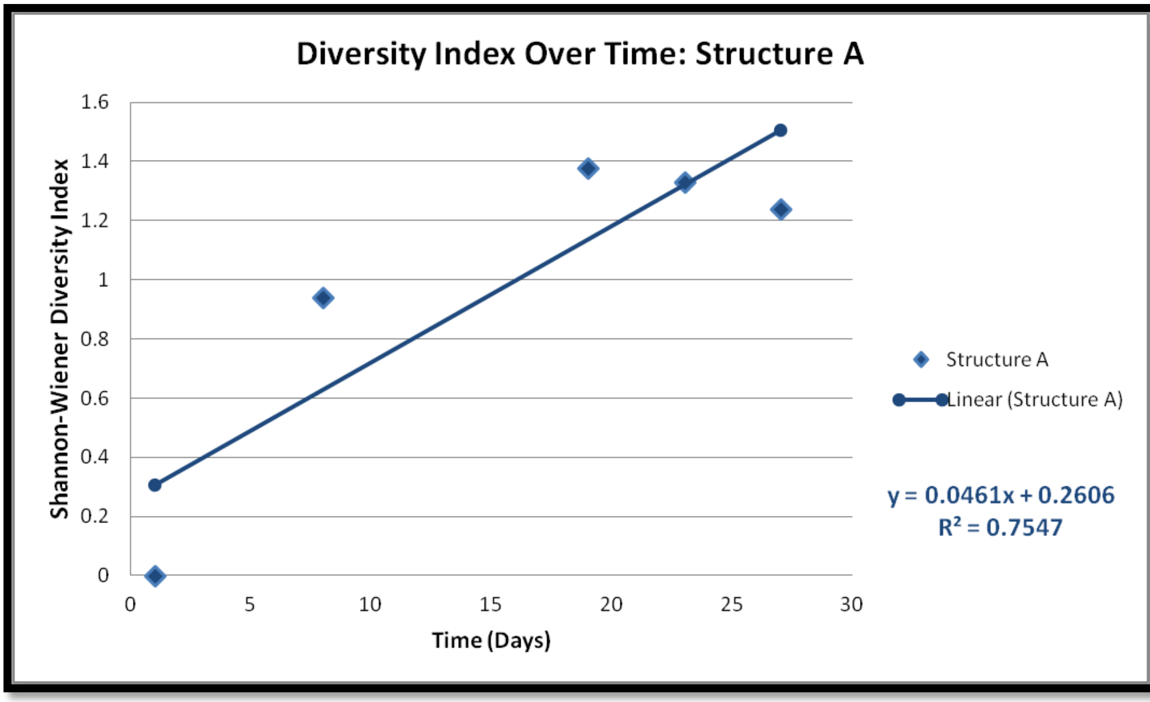

Figure 7: Structure A was one of the structurally simple artificial reefs. It had coral fragments attached to it but was not filled with rubble. Linear Regression for Structure A has R^2=0.755, and is a statistically insignificant relationship (F-test, p = 0.056).

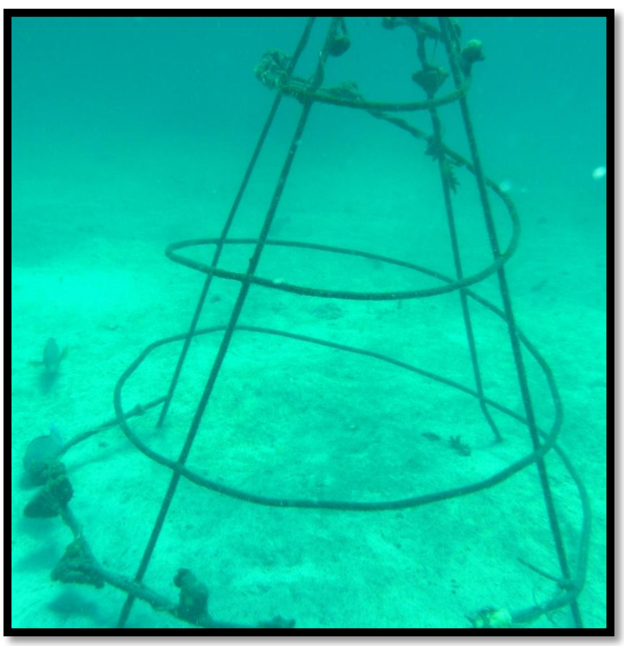

Figure 8: A photo of Structure A, taken by Markus Fitzka of the New Heaven Conservation Program on June 28th, 2013.

For Structure B, biodiversity fluctuated over time, sometimes increasing and sometimes decreasing in biodiversity since the last day data had been collected (Figure 9). Overall there was an increase in fish biodiversity between the first day that data was collected and the last day. The R-squared value for the regression analysis on structure B was found to be 0.496 and the slope of the regression line was equal to 0.026 per day. Structure B did not exhibit a statistically significant relationship between time and biodiversity (F-test, p = 0.184).

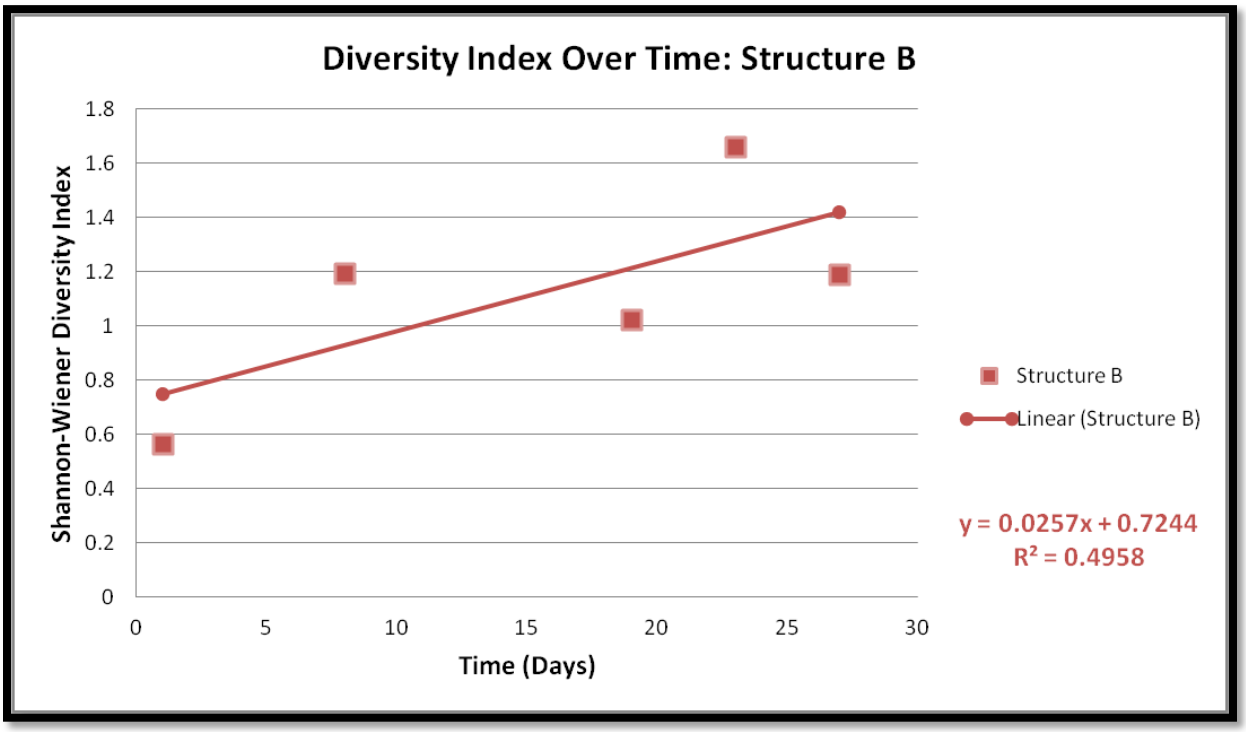

Figure 9: Structure B had coral fragments attached to it, but no rubble. Linear regression for Structure B had R^2=0.496 and a slope of 0.026. The relationship between time and biodiversity was found to be statistically insignificant (F-test, p = 0.184).

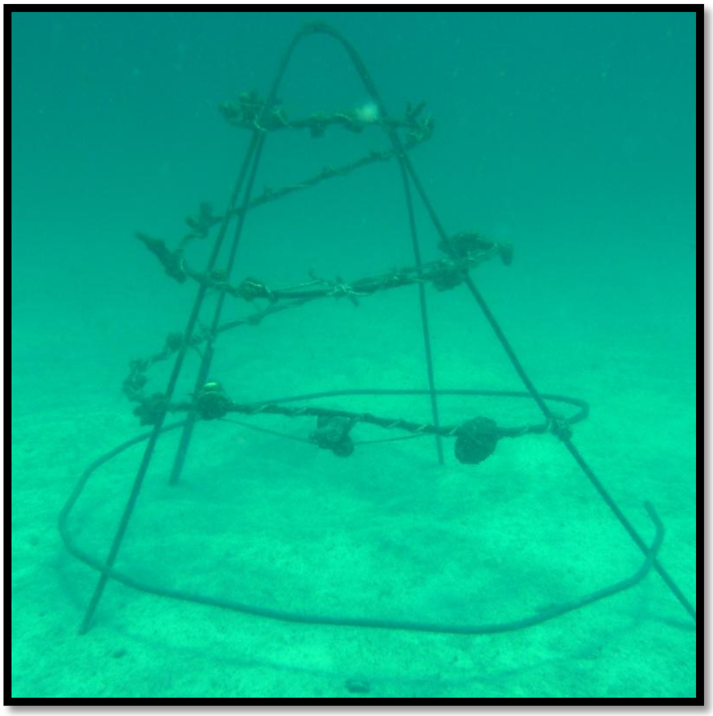

Figure 10: Structure B is shown. This photo was taken by Markus Fitzka of the New Heaven Conservation Program on June 28th, 2013.

Structure C, which had both coral and rubble added to it, yielded a linear regression with an R-squared valued of 0.842 and a slope of 0.062 per day (Figure 11). The diversity index increased until the last day of data collection, on which day the index was calculated to be about 0.007 less than on the previous data collection day. The relationship between time and the biodiversity of fish was found to be statistically significant on this structure (F-test, p = 0.028).

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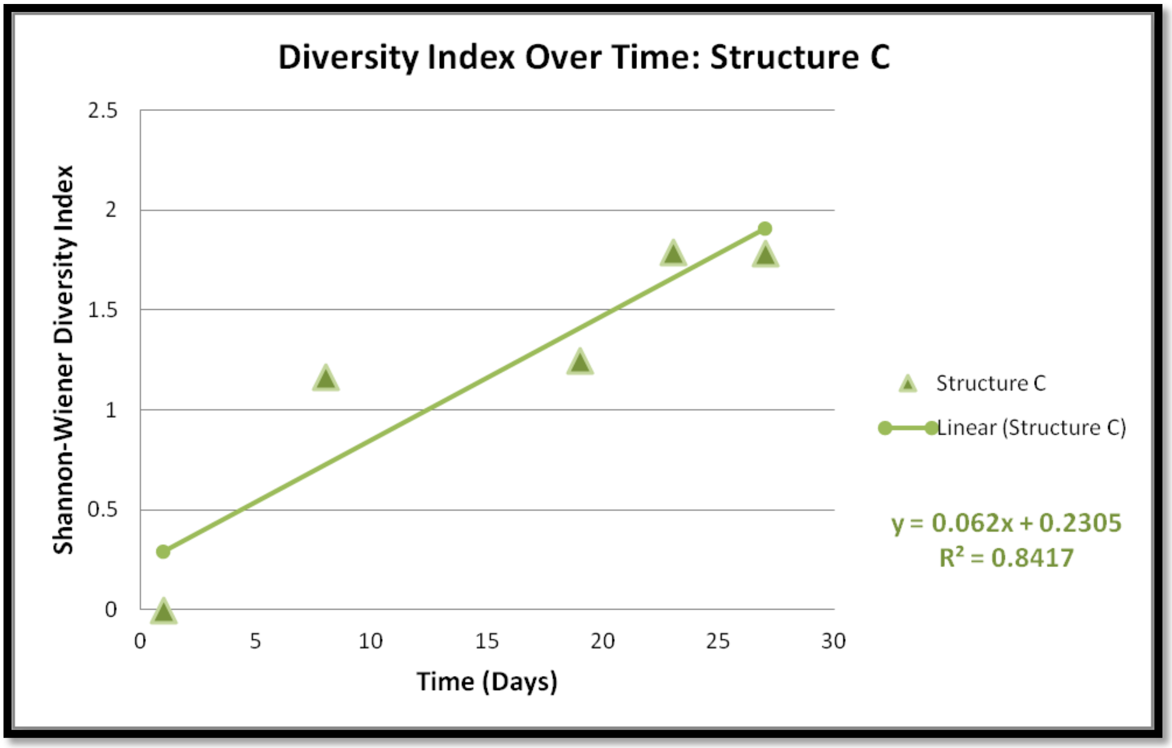

Figure 11: Structure C had coral attached to the structure, and was filled with rubble. The linear regression of Structure C yielded $R^2 = 0.842$ and a slope of 0.062. This relationship was found to be statistically significant (F-test, $p = 0.028$).

Figure 12: A photo of Structure C, taken by Markus Fitzka of the New Heaven Conservation Program on June 28th, 2013.

The biodiversity on Structure D increased throughout the entire study. The final diversity index calculated for Structure D was the largest valued diversity index calculated for any structure during the study. The R-squared value calculated for the linear regression was 0.915 and the slope of the regression line was 0.062 per day. Of all five of the structures, Structure D had the R-squared value which came closest to one. It was found that the relationship between time and biodiversity on Structure D was significant (F-test, p = 0.011).

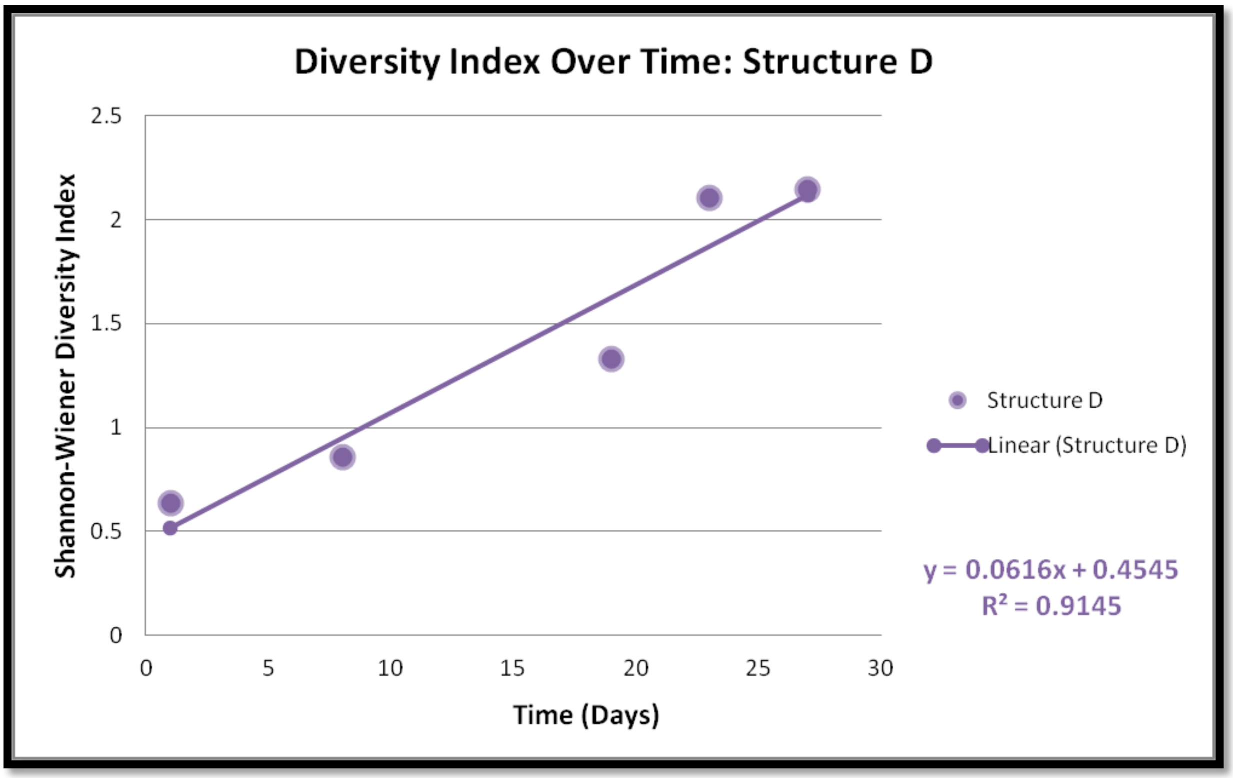

Figure 13: Structure D had coral fragments attached to it, and was filled with rubble. Linear Regression on the data collected for Structure D, which had both coral and rubble added to it, produced R^2=0.915 and a slope of 0.061. The relationship was found to be statistically significant (F-test, p = 0.011).

Figure 14: A photo of Structure D, taken by Markus Fitzka of the New Heaven Conservation Program on June 28th, 2013.

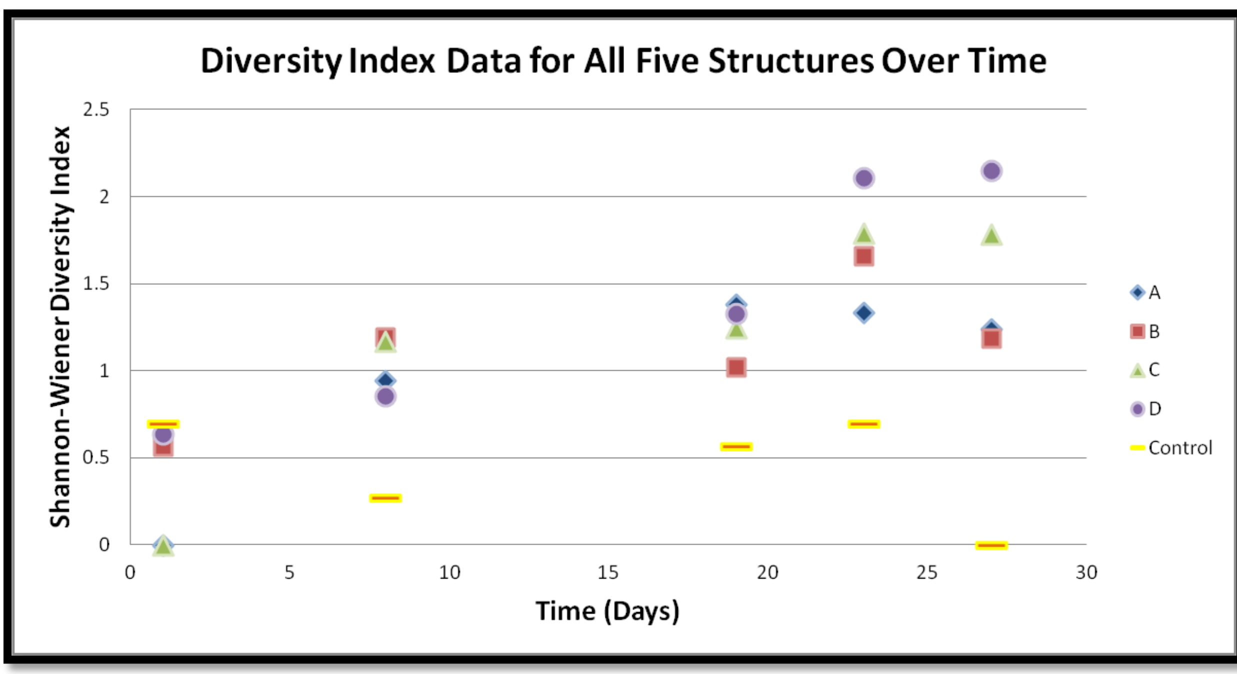

Figure 15: The Shannon-Wiener diversity index data for all five structures plotted together over time.

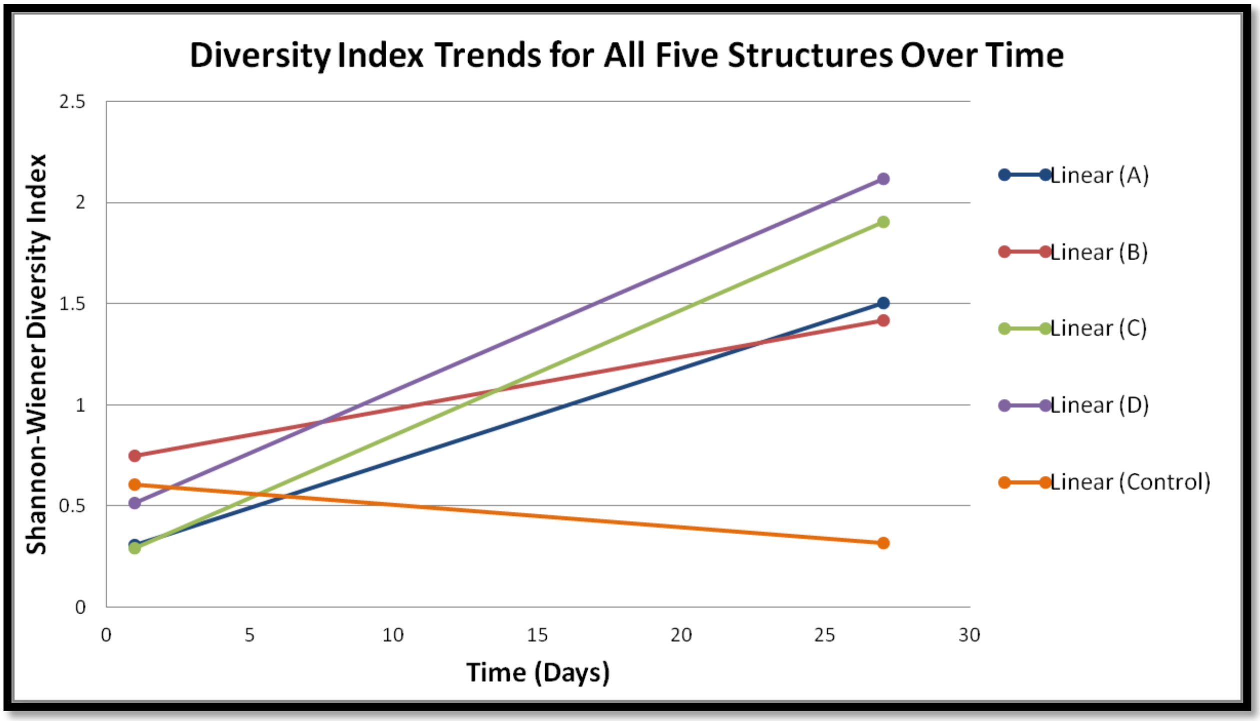

Figure 16: The linear regression trend lines for all five of the artificial reef structures plotted together over time.

Anova

An ANOVA was done in Excel on the final Shannon-Wiener diversity index calculated for structures. The final values of the diversity index for each structure were compared to examine the effect of structural complexity of the artificial reef structures on fish biodiversity. It was found that there was a statistically significant difference between the types of artificial reefs ($p = 0.026$).

As the ANOVA produced significant results further analysis was done to determine which artificial reef structures significantly differed from which other structures. To do this Tukey's HSD test was used on each possible coupling of artificial reef structures. The artificial reef structures which had both coral fragments and rubble (Structures C and D) were found to have a significantly larger amount of fish biodiversity associated with them by the end of the study period than the control structure did ($p < 0.007$). The biodiversity on the artificial reef structures which only had coral fragments (Structures A and B) was not found to be statistically different than the control structure ($p < 0.06$), and the biodiversity on the structures with both coral fragments and rubble compared with the biodiversity of the structures with only coral fragments was not found to be statistically different ($p < 0.10$). For all three couplings of structure type it was found that $p < 0.010$.

Discussion:

The control structure did not successfully act as a fish aggregation device. This is evident from the number of individual fish observed over the course of the study on the control structure. Four fish were seen on day 1 and five fish were seen on day 27, equating to a net increase of one individual for the control structure over the course of the study. The other four structures were successful fish aggregation devices. The maximum number of individual fish observed on Structures A-D on day 1 was four. On day 27 the number of individuals observed on Structures A-D ranged from 27 to 215. There was obviously a much larger fish community on all of the artificial reef structures except for the control at the end of the study than when the study began. Structures A-D being successful fish aggregation devices is not equivalent to them being good fish habitats which will develop into healthy ecosystems, as fish abundance does not take into consideration fish diversity. However, was it a good habitat for the fish aggregating on the structure? For there to be fish diversity there must be fish abundance, and so the control structure appearing to be a bad fish aggregation device indicates that it is also an unsuitable habitat for fish.

There was no relationship between fish biodiversity and time on the control structure (F-test, $p = 0.512$). The slope of the regression line was negative, and the R-squared value was equal to 0.16, indicating that the regression line fit the data very poorly. Structures A and B (coral fragments, no rubble) were not found to have a statistically significant relation between fish biodiversity and time ($p = 0.056$, $p = 0.184$ respectively). Both structures had positive slopes, and relatively high R-squared values ($R^2 = 0.755$, $R^2 = 0.496$ respectively). The biodiversity did not consistently increase, but on both structures there was an overall increasing trend. It is possible that the lack of statistical significance is due to the short amount of time over which data were collected and the small amount of data points for each structure. It seems that there is a relationship between biodiversity and time on this type of artificial reef structure, however further data collection would be needed to determine this as the statistics are inconclusive.

Structures C and D (coral fragments and rubble) were found to have statistically significant relationships between fish biodiversity and time ($p = 0.028$, 0.011 respectively). Biodiversity increased over time on both structures. The R-squared value on Structure C was equal to 0.842 and the R-squared value on Structure D was equal to 0.915, indicating that there was relatively little deviation in the data from the trend line.

The relationship between the biodiversity of the fish communities on each of the artificial reefs over time was stronger on the artificial reefs which were more structurally complex. This is seen in the variation in the p-values for each of the structures. The control structure had the lowest p-value (0.512), indicating that there is a 51.2% probability that any observed trend was purely due to chance. The structures which had coral fragments attached to them but no rubble had p-values that were statistically insignificant. However, the p-values were much smaller than the p-value of the control structure. On Structure A there was a 5.6% probability that the observed trend of increasing biodiversity over time was due to chance, and for structure B there was an 18.4% chance. The most complex artificial reef structures, which had both coral fragments and rubble, had the two smallest p-values (Structure C: $p = 0.028$, Structure D: $p = 0.011$). The artificial reefs which were structurally complex (C and D) had a well defined relationship, whereas the structurally simple artificial reefs (A and B) exhibited an increasing trend in biodiversity over time, but the relationship was statistically insignificant. The structurally complex artificial reefs (C and D) exhibited the strongest relationships of increasing biodiversity.

Fish biodiversity over time exhibiting a stronger relationship on structurally complex artificial reefs and a weaker relationship on structurally simple artificial reefs is supportive evidence for the hypothesis that adding rubble to simple artificial reef structures would increase the overall biodiversity of the fish communities which would develop at the reef sites.

The variation in the calculated diversity index values deviated less from the general trend of the data as the structural complexity of the artificial reefs increased. This was seen in the differences in R-squared values for the different types of artificial reef structures. The smallest R-squared value (0.16) was calculated for the control structure. The R-squared values for the structurally simple artificial reefs (Structures A and B) had larger R-squared values than the control structure and were smaller than the R-squared values for the structurally complex artificial reefs (Structures C and D). This indicates that the trend of increasing fish biodiversity over time varies less on structurally complex artificial reefs than on structurally simple artificial reefs.

This trend is evidence indicating that structurally complex artificial reefs create a more suitable habitat for fish communities than structurally simple artificial reefs. This is supportive evidence for the hypothesis that increasing structural complexity As Structures C and D were very easy to build and the materials used were relatively inexpensive, this is also evidence that structurally complex artificial reefs can be built, deployed, and maintained in an economically feasible fashion.

The final value of the Shannon-Wiener diversity index was found to be significantly different ($p < 0.007$) between the control structure and the structures which had both coral fragments attached to them and were filled with rubble (Structures C and D). A statistically significant difference was not found ($p < 0.06$) between the control structure and the structures which had coral fragments attached to them (Structures A and B). There was also no statistically significant difference found ($p < 0.10$) between the structures with coral (A and B) and the structures with coral and rubble (C and D).

The average values for the final diversity index for the control structure, coral structures, and coral with rubble structures were 0, 1.214, and 1.967 respectively. The conversion of these diversity indexes into values of effective number of species yields 1, 3.37, and 7.15 species respectively. The structures with both coral and rubble (C and D) were found to have a value for the effective number of species which was more than twice as large as that for the structures which had coral but no rubble (A and B). Even though there was not a statistically significant difference between the final Shannon-Wiener diversity index for the coral structures and the coral with rubble structures, it seems that there is a biologically relevant increase in biodiversity. To reject the null hypothesis further research would be needed with a larger sample size.

From the ANOVA, fish biodiversity was found to be greater on more structurally complex artificial reefs with a 90% confidence interval. Fish biodiversity being larger on the structures with rubble and coral than on the structures with only coral indicates that increasing the complexity of the artificial reefs did in fact increase the overall fish biodiversity at the artificial reefs. This is evidence which supports the hypothesis that adding rubble to structurally simple artificial reefs increases the habitat quality for the fish community.

The hypothesis that increasing the complexity of simple artificial reefs by adding rubble to the interior of the structures would result in a larger amount of biodiversity in the fish communities inhabiting the artificial reefs was supported by the data. The relationship of biodiversity over time was stronger on the artificial reefs which were more complex structurally, and the overall biodiversity of the fish communities was larger on the structurally complex reefs one month after deployment. However, in order to confidently reject the null hypothesis that biodiversity was not affected by structural complexity, more research would be needed. A larger sample size and a longer period of observation would provide more conclusive results. Based off of the results from this study I believe that if it could be done on a larger scale the fish biodiversity on the structurally complex reefs would be significantly larger than on the structurally simple reefs.

My results are consistent with the existing body of scientific knowledge. Increasing the structural complexity of artificial reefs has been shown to increase the biodiversity of the fish community on the artificial reef sites (Charbonnel et al. 2002, Sherman et al. 2001; Hackradt et al. 2011; Lingo and Szedlmayer 2006; Hixon and Beets 1989), and more generally, increased fish biodiversity is found where habitat complexity is greater (Gratwicke and Speight 2005; Luckhurst and Luckhurst 1978; Risk 2003). Furthermore, fish abundance has been shown to be positively correlated with habitat complexity (Grigg 1994; Almany 2004). It was also found that more complex artificial reefs had a larger abundance of juvenile fish specifically (Gorham and Alevizon 1989).

In the body of literature addressing the effect of structural complexity of artificial reefs on fish biodiversity, studies range widely in their length, location, and also in the types of artificial reefs being examined. Charbonnel et al. (2002) found that increasing artificial reef complexity increased fish biodiversity at a large artificial reef site (158 m^3) in a study which took place over 11 years in France. Concrete blocks were used to increase complexity on artificial reefs made out of concrete slabs. In their study the complexity of an artificial reef was increased after four years of observation. Six years after increasing the structural complexity fish biodiversity data was collected on that reef as well as on an unchanged reef. Data was collected for a year, and it was found that species richness had doubled, mean number of species observed per census had tripled, density was 10 times larger, and biomass was 40 times larger following structural complexity increase (Charbonnel et al. 2002).

In a two year study conducted by Sherman et al. (2002) in Florida, small concrete artificial reefs (~1 m^3) were used to compare two levels of structural complexity. Sherman et al. also examined the effect of adding a streamer to structurally simple artificial reefs, as an attractant for juvenile fish. 30 artificial reefs were deployed: ten replicates of each treatment. Each artificial reef weighted approximately 850 kg, and had to be deployed using a cane. It was found that on the structurally complex reefs fish abundance, fish species richness, and fish biomass were all significantly greater than on the structurally simple reefs. The streamer had no effect (Sherman et al. 2002).

Lingo and Szedlmayer (2006) conducted a study in which six different levels of artificial reef complexity were compared for differences in biodiversity. This study took place over two years in the Gulf of Mexico, and artificial reefs were made out of a variety of materials including… It was found using the Shannon-Wiener diversity index and the Simpson index that one year after deployment, species richness and abundance were higher on the more complex structures. Two years after deployment fish biodiversity was only significantly less on the least complex structure (Lingo and Szedlmayer 2006).

These studies varied significantly in experimental design, materials, duration and location, but all found that fish biodiversity increased with increased complexity of artificial reef structures. My results are consistent with this. Despite the short length of my study and the small sample size, the structurally complex artificial reefs exhibited a much stronger trend of accumulating biodiversity and had a larger amount of biodiversity when data collection ended. With the exception of Day 1, both species richness and the total number of individuals were greater on the structurally complex artificial reefs throughout the period of data collection.

Location of Species on Simple versus Complex Artificial Reefs

Not every species observed in the study was found on both the simple and complex artificial reefs. 14 out of 33 species observed during this case study (42.4%) were seen during at least one of the observations on either Structure A or Structure B (structurally simple artificial reefs); whereas 31 out of 33 observed species (93.9%) were seen on either Structure C or Structure D (structurally complex artificial reefs). This means that 19 species of fish were found exclusively on the complex reefs, and only 2 species of fish were found exclusively on the simple reefs. Charbonnel et al. (2002) observed new fish species after adding structural complexity to an existing artificial reef. This suggests that species of fish were preferentially inhabiting the structurally complex artificial reefs.

Prevalence of Juveniles and Small Fish

On all five of the structures, the majority of individual fish were small (< 5 cm). On Structures A and B (coral) and also on Structures C and D (coral and rubble) the majority of individual fish seen on each structure were juveniles. It has been shown that reef fish preferentially choose habitats with hole sizes close to their body size (Shulman 1984; Lingo and Szedlmayer 2006; Hixon and Beets 1989). In my case study, rubble provided crevices and passageways in a variety of sizes, but all were relatively small. The lack of large holes on any of the structures is a likely explanation for the abundance of juvenile fish and small fish species compared with larger fish.

Gorham and Alevizon (1989) found that increasing reef complexity resulted in an increased number of juvenile fish occupying the reefs. In their study they added polypropylene streamers to PVC and concrete block artificial reefs in the Florida Keys. Data was collected over the course of one year, and it was found that the reefs with streamers had on average 388 juveniles per census versus the average of 132 juveniles per census on the reefs without streamers (Gorham and Alevizon 1989).

Predation

Predatory fish species were rarely observed on the artificial reefs over the course of the study time. Yellowtailed Trevally sometimes prey upon small fish, but the majority of their diet consists of crustaceans, ostracods and gastropods. None of the other fish species observed during the study are known to prey upon other fish. Predation was appeared to be less on the artificial reefs in my case study as compared with the nearby natural reef. However, since species present at the artificial reef site were only observed for 15 minutes roughly once a week it is entirely possible that predation was occurring at the artificial reef site.

Isolation has been found to be negatively correlated to predation on artificial reefs (Belmaker et al. 2005). The artificial reefs in the case study were highly isolated.

A study conducted by Beuker and Jones (1997) found that habitat complexity mitigated the effect of predation on juvenile damselfish. They examined the relationship between juvenile damselfish survival with the presence or absence of predators on two different levels of reef complexity. The structurally complex reef with predators was not found to have a significantly different survival rate to the structurally simple reef without predators (Beuker and Jones 1997). Although the result of the Beuker and Jones (1997) study cannot be extrapolated to all predator species and all prey species, it does suggest a possible explanation for why fish biodiversity was found to be greater on structurally complex artificial reefs.

The total number of individual fish reached a maximum on all of the structures before the end of the study. On Structures A and B the maximum number of individual was 70 on day 8 and 72 on day 23 respectively. On Structures C and D the maximum was 384 on day 34 and 315 on day 19 respectively. The control structure had a maximum of 13 on day 8. All five structures saw a reduction in the total number of individual fish during the study, which means that either some of the individuals were leaving or some of the individuals were dying.

Both isolation and structural complexity were likely contributing to the rate of predation upon the artificial reef structures. Structural complexity mitigating the effect of predation in this case would explain why there was a larger abundance of juvenile fish on the structurally complex artificial reefs than there was on the structurally simple artificial reefs, but it would not explain why a decrease in the number of individual fish on all five structures was observed. It is also possible that the juvenile fish simply preferred the structurally complex artificial reefs, and that predation did not influence the population size at all, but this would not explain why a decrease in the total number of individuals was observed on the structurally complex artificial reefs was observed. Further experimentation would need to be performed to determine if either hypothesis is true.

Feasibility

For artificial reefs to be useful in conservation they must be feasible to use. Adding complexity to artificial reefs seems to increase the biodiversity of the fish communities which inhabit the artificial reefs. However, building and deploying artificial reefs which are structurally complex can be more difficult than just using simple artificial reef structures. This is not necessary. The materials used to construct the artificial reefs in my study were inexpensive, and quick to assemble. Simple artificial reefs were made more complex structurally by filling the metal skeleton with rubble, which was free and took two divers only half an hour to accomplish. Due to the light weight of the simple artificial reefs, no machinery was needed to deploy them except for a boat, which was needed to get to the dive site already. Since the artificial reefs were hallow, they were easily stacked on top of one another, and did not take up a large amount of space on the boat.

SCUBA diver volunteers were used as the work force for this case study. Since no one who worked on it was paid, the total cost of the study was reduced. SCUBA divers are a largely untapped resource for researchers doing marine conservation work. They can be used to help set up experiments and collect data with minimal training.

Conclusions:

I conclude that artificial reefs can be used in the conservation of coral reef fish species practically and efficiently. Artificial reefs can sustain large and diverse communities of fish. The preservation of the biodiversity of coral reef fish communities is important for the continued use of coral reef ecosystem services and for the sustained health of coral reef ecosystems. Based on the research I conducted, I conclude that artificial reefs have the ability to be used as a tool in this conservation effort. Due to the nature of the problems that coral reef ecosystems are facing, simply creating marine protected areas is not enough. Ocean acidification is unaffected by the creation of marine protected areas. Excessive sedimentation is not affected by the creation of marine protected areas. It is necessary to do more than simply create marine protected areas to truly protect coral reef ecosystems. Artificial reefs can contribute to this effort.

Threat to the coral reefs from climate change and other human activities continues to threaten the species dependent on reefs. A decline in live coral cover results in a decline in the abundance and species richness of coral reef fish. Climate change has created a difficult problem to address in reef ecosystems. Both rising ocean temperatures and ocean acidification are attributed to climate change, and both are having adverse effects on coral reefs. These two factors are difficult to address because they act on a global scale and because they are the unanticipated result of an increased output of carbon dioxide on a global scale. The obvious solution would be to reduce carbon output, but that is much easier theorized than implemented. People all over the planet are heavily dependent upon the burning of fossil fuels, and significantly reducing carbon output will be slow. Coral reef ecosystems are declining now at an alarming rate. Other solutions ought to be investigated.

Artificial reefs offer several unique characteristics to the conservation of coral reef ecosystems. Both their placement and their design can be chosen. This is significant because it is likely that different areas in the ocean will be affected by changing ocean conditions in different ways and at different magnitudes. Being able to choose a location which may be affected less by ocean acidification and rising temperatures will, in theory, give the reef ecosystem a better chance of survival. Choosing the design of artificial reefs allows them to be catered to different needs. If a particular natural reef ecosystem is being degraded by over fishing, destructive fishing techniques, or excessive human traffic then stress on the natural reef ecosystems may be relieved by the development of an artificial reef and the movement of these activities onto the artificial reef. If the populations of fish species are being limited on a particular natural reef, the development of an artificial reef may actually increase the population size of some fish species in the area which could be used to obtain larger sustainable fishing yields. Due to the potential of these applications, artificial reefs can be used in the conservation of coral reef fish communities, and more generally to the conservation of coral reef ecosystems.

The construction and deployment of artificial reefs which will make suitable fish habitats does not need to be incredibly time consuming or expensive. More research is needed in the development of communities which inhabit different types of artificial reefs. It seems likely that not only is structural complexity important in determining the different species which inhabit artificial reefs, but also the type of structure. A sunken ship may attract a completely different community than a structurally complex concrete reef. Depending upon the specific application and specific goals of creating an artificial reef site, different types of artificial reefs are more suitable. However, not all artificial reef projects will be benefited by using a sunken ship.

Affordable, easy to construct, and easy to deploy artificial reefs are possible to create and can be effective for certain project goals.

The use of artificial reefs is one way for citizens who care about the conservation of coral reef ecosystems can become involved in the conservation work. SCUBA divers as a whole are undereducated about the decline in coral reef ecosystems. By educating this community in the problems and what they can do to help, a huge human resource can be mobilized. SCUBA divers have an invested interest in the health of coral reef ecosystems. The use of artificial reefs is a method of coral reef ecosystem restoration in which SCUBA divers are able to participate which minimal training and expertise required. A significant part of the work required for using artificial reefs in conservation efforts is physical labor. Volunteering SCUBA divers can be used for this effectively.

Although I do not believe that artificial reefs have the capability of solving all of the issues facing coral reef ecosystems, I do believe that they have a great deal of potential as a tool in conservation efforts. By combining the use of artificial reefs with other conservation methods the causes of reef ecosystem decline can be addressed.

Suggestions:

Structural complexity is correlated to the biodiversity of coral reef fish communities. However there are many different ways in which structural complexity can be manipulated, and these different ways to manipulate complexity would likely lead to different fish assemblages. Further experimentation ought to be done on different shapes, sizes, and building materials of artificial reefs and what effect those variables might have on both the biodiversity and the composition of fish communities. In addition to examining these factors it would be of use to experiment with the effect on fish communities from manipulating combinations of these variables. Creating artificial reefs which are structurally complex and are made out of a variety of materials, or that have different connected sections which combine different styles of artificial reefs could possible result in a completely different assemblage of fish than one of the variables produces alone.

Longer-term and larger scale studies are also needed on inexpensive and quick to make artificial reefs and their affects on fish communities. If artificial reefs which are quick and easy to build and deploy are ever to be used seriously in coral reef ecosystems conservation, much more research is needed on the long term sustainability of them. It would be counterproductive to create artificial reef ecosystems only to have them destroyed in a tropical storm several years after deployment. For this to be a practical method of coral reef ecosystem conservation, the structures must be able to have a lifetime which is a reasonable length for a reef ecosystem to develop. Since corals grow very slowly but live for thousands of years, it would be completely unreasonable to build artificial reefs which are unable to last for more than a few years. Further research in artificial reef design is necessary to address this concern.

The education of communities surrounding coral reefs and tourists of coral reefs is also necessary. Many of the issues contributing to the decline of coral reef ecosystems are being caused by these people. By educating people, some of these issues can be addressed. Many SCUBA divers and snorkelers do not understand that coral are fragile animals, and therefore do not treat them as such. Excess sedimentation is not an obvious cause of coral reef ecosystem decline. By educating the people who have the largest direct effect on reef ecosystems many of these problems can be addressed.

Many reef ecosystems are being affected by a combination of different stressors. Research ought to be done on the combination of a variety of different management and conservation strategies to investigate which methods work well together and which do not in an attempt to address as many of the issues affecting a particular reef ecosystem as possible. Experiments which combine marine protected areas with community based management and artificial reefs could have significantly different results than simply looking at one of these methods at a time. It seems unlikely to me that there will be one solution found which successfully address all of the different causes of coral reef ecosystem decline. For this reason, there should be research done in the future which institutes conservation method packages which are designed for specific causes of decline for specific reef ecosystems.

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