Exploring the effectiveness of policies to reverse rapid coral reef degradation in the Philippines

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Abstract

Coral reefs around the world are facing rapid degradation caused by the impacts of climate change and growing pressures from coastal communities. In recent years, the topic has gained more attention and this has led to the implementation of coastal management programs. However, the question remains open whether these Initiatives are able to reverse the rapid decline of the reef. In this paper, the dynamics of coral reef growth and decline are explained by using a comprehensible simulation model. This model helps readers to better understand the interrelationships between the ecological environment and the human developments around the reef. Through a case study on coral reefs in the Philippines, the paper helps policy makers to evaluate the effectiveness of current coastal management programs.

Key words: coral reefs, environmental protection, coastal management, ecosystem

1. Introduction

Coral reefs, referred to as the 'rainforest of the sea', are disappearing at an alarming rate worldwide (Szmant, 2002). As one the most diverse ecosystems, coral reefs are of utmost importance in terms of ecosystem services. The value of those benefits coming from coral reefs has been estimated at nearly US$ 30 billion each year worldwide, mainly from tourism, fisheries and coastal protection (Cesar, Burke, & Pet-soede, 2003). If continuity of those ecosystem services is to be sustained, the processes responsible for the rapid degradation of coral reefs must not continue in their current course.

Although all humans derive direct and/or indirect benefits from coral reefs, there are communities which are specifically dependent on their services. Among those are small island communities, since their economy is often strongly focused around the tourism and fishing industry (Mimura et al., 2007). The Philippines is an archipelago of 7107 islands containing one of the most biodiverse coral reefs in the world (Burke, Selig, & Spalding, 2002). Many of the islands are highly dependent on fishing and tourism and are facing rapid coral degradation. Boracay is one of the main touristic attractions in the Philippines. Visitor numbers and construction projects have been booming over the last decade. On the environmental side, a strong decrease in coral reef cover has been reported from around the year 2000, as can be seen in Figure 1.

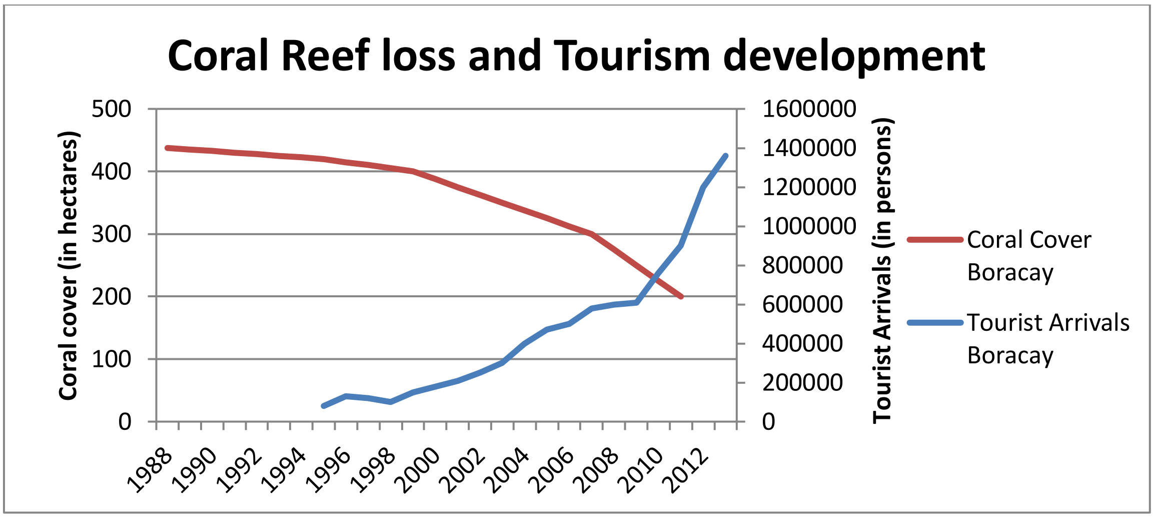

Figure 1 Coral cover and (annual) tourist arrivals on Borocay, the Philippines (Fortes, 2014, p. 12,20)

The economic importance of the coral reef function has been acknowledged on the island and therefore policies have been put in place to restore its function. One of those policies has been the employment of artificial reefs. However, the fundamental question that remains is to what extent the artificial reefs are addressing the major cause of the coral reef loss (Fortes, 2014).

There is strong agreement among researchers that coral reef decline is caused by a complex combination of local-scale human-imposed and regional-scale climate processes (Buddemeier, Kleypas, & Aronson, 2004; Nyström, Folke, & Moberg, 2000; UNEP, 2006). Here it is argued that local impacts on the ecosystem, such as overfishing and pollution, can lead to less resilience of the ecosystem to cope with regional climatic pressures such as ocean warming and acidification. Therefore reef structures close to people's habitats seem to be under more pressure than similar reef structures further away.

Although there is strong support for the role of tourism development in the deterioration of coral reef ecosystems on Boracay (CECAM, 2015), it is still uncertain how they are interrelated. Furthermore, there might be other causes which could be responsible for the degradation. But the interactions between human activity and ecological processes are so complex that intuition alone is not enough to make decisions regarding the reversal or prevention of coral degradation.

The rest of this paper is organized as follows. Chapter two explains the processes through which a coral reef grows under natural environmental conditions. Chapter three explains how the growth of a small fishing community next to the coral reef has an impact on the natural growth processes of the coral reef. In chapter four, the positive and negative impacts from a switch from a fishing industry to a tourism industry are discussed in detail. Chapter five elaborates on model testing. Chapter six helps to increase understanding about the failure of current coral management policies in the Philippines based on model simulations and feedback analysis. Higher leverage policies to sustain the coral reef are discussed in chapter seven, while chapter seven concludes with a discussion of the research.

2. The natural growth of an undisturbed coral reef

In essence, the coral polyp is a close relative to the common ancestor of all the most advanced animals on earth, the jellyfish (Murchie, 1999, p. 99). Like the hunter-gatherer humans who decided to become settlers and live of the land using agriculture, the coral polyp developed from the nomadic jellyfish to build an environment in which it could settle and live from its own resources. Those initial jellyfish attached themselves to rock formations or other hard substrates, often close to islands or continents. From there a process of evolution evolved the settlers into a wide range of coral species with different characteristics. Figure 2 shows the model of the growth processes of coral polyps.

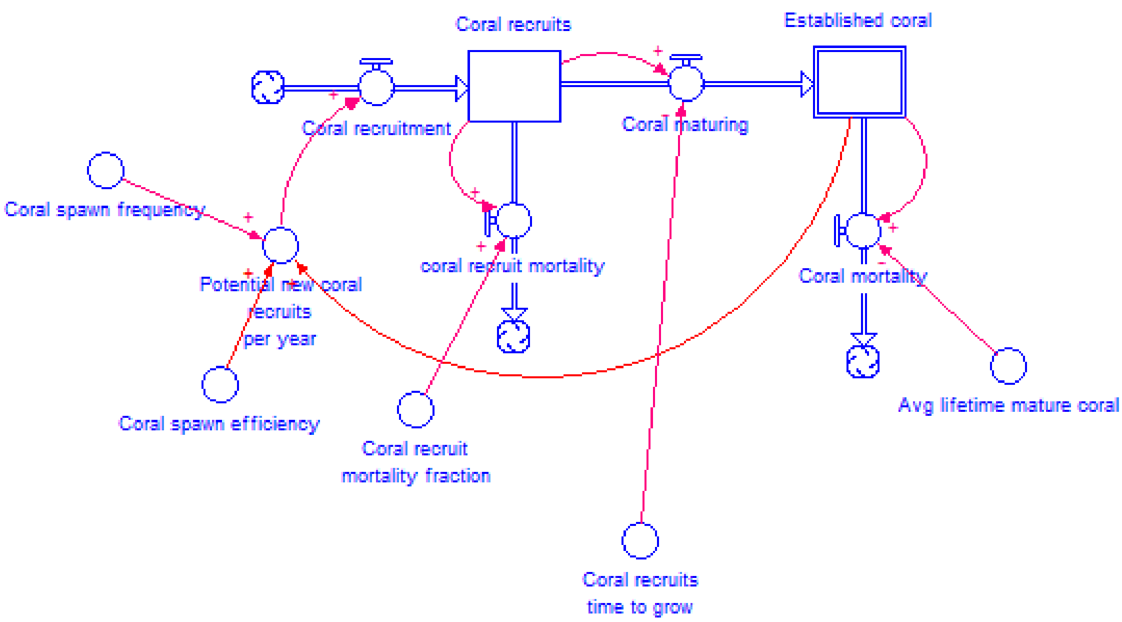

Figure 2 Live coral tissue biology model

The coral colony grows through the recruitment of new corals. Coral polyps can reproduce both sexually and asexually. Most coral species reproduce through spawning. When the corals spawn, they release both eggs and sperm into the water and some of them get fertilized when they find a location to attach (Sheppard, Davy, & Pilling, 2009; Viles & Spencer, 1995). Figure 2 shows an important reinforcing feedback loop in which an increasing population of established coral leads to an increase in the potential new recruits each spawning event, which then leads to a higher number of coral recruits maturing into established coral. If there would not be any limits on coral recruitment, this feedback loop could lead a rapid growth of the coral colony.

While the initial coral polyps attached themselves to suitable rock formations, the next phase of their growth starts from their ability to excrete carbonate substrate, on which new coral polyps can settle. When the coral reef, produced by excreting calcium carbonate, grows in a cumulative manner, it can give rise to massive formations over time (Mann, 1982; Sheppard et al., 2009; Viles & Spencer, 1995). Figure 3 shows the process through which the established coral polyps built their own coral reef substrate which then provides a habitat for new coral recruits.

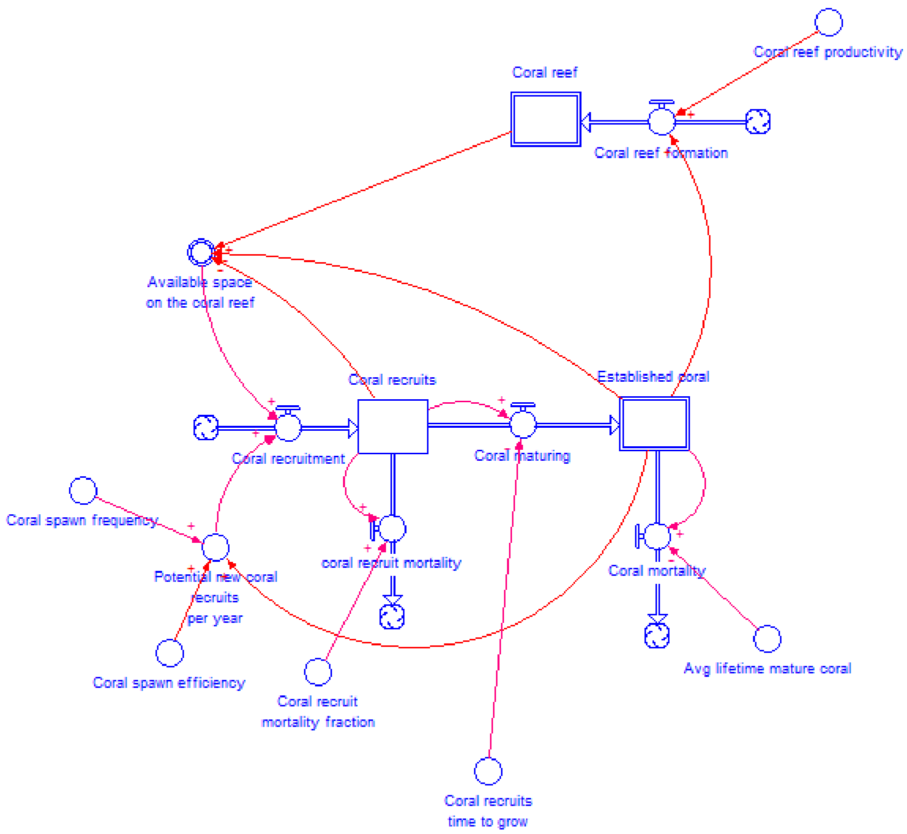

Figure 3 Growth of the carbon coral reef substrate

The coral reef grows in size through 'Coral reef formation'. This reef-building process, however, is very slow by human standards. Under good conditions (clear waters and abundant carbon availability), coral reefs (circular corals) grow 1-2 centimeter per day (Alcala, personal communication). Since a growing coral colony leads to higher coral reef formation, which then leads to more space available for new coral recruits, a reinforcing loop is closed. However, due to the slow process of coral reef formation, this reinforcing loop will not lead to a rapid growth of the coral reef and its occupying coral polyps.

Figure 4 shows the model of the process through which the coral reef decays naturally and becomes sediment. Sediment makes the water milky and it can cover the coral polyps and reef (Sheppard et al., 2009; Talbot & Wilkinson, 2001). It is assumed that the coral reef substrate will naturally decay over a period of 500 years. In this part of the paper, more dominant factors of coral decay are still neglected.

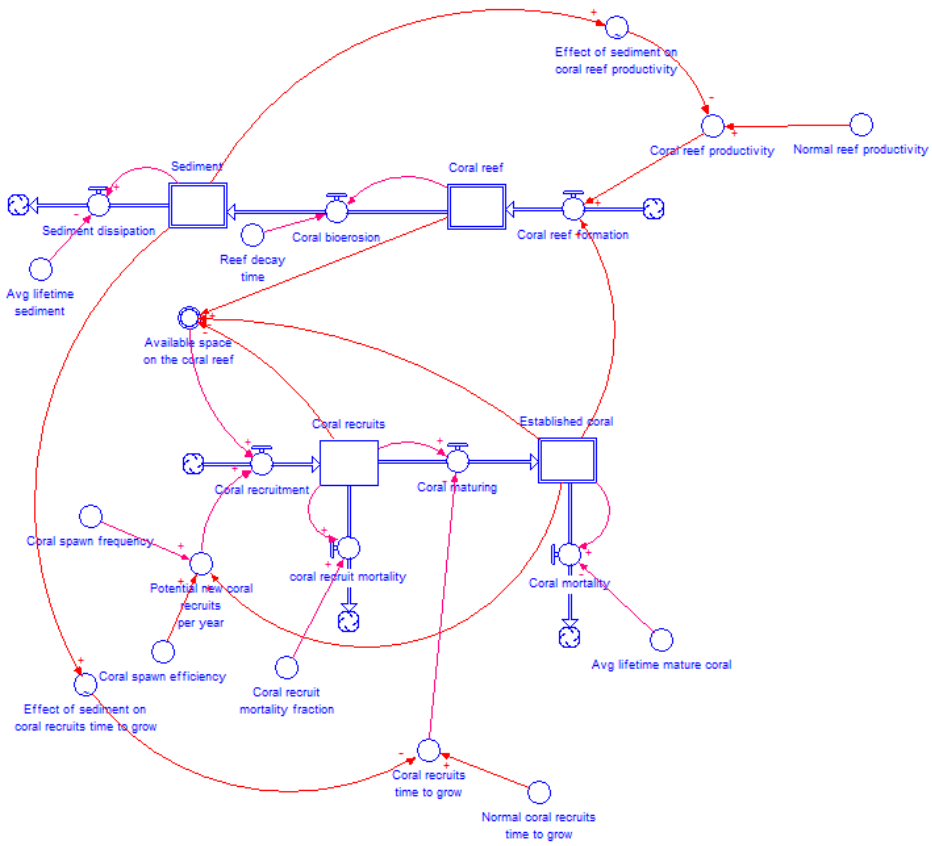

Figure 4 Coral reef decay and sedimentation effects on growth rates

The 'cloud' of sediment on the coral waters limits the availability of sunlight available for the coral reef; one the most important factors in determining the coral reef calcification productivity. Coral reefs do not grow very well or at all on locations with a high amount of sediments, such as close to major rivers (Birkeland, 1997; Rogers, 1990; Talbot & Wilkinson, 2001; Wood, 1999).

While in Figure 3 it was assumed that the available space on the coral reef can only be occupied by coral recruits and established coral, in reality, the live coral tissue faces competition from other species, mainly from macro-algae. Figure 5 shows the competition for space between the coral polyps and macro-algae.

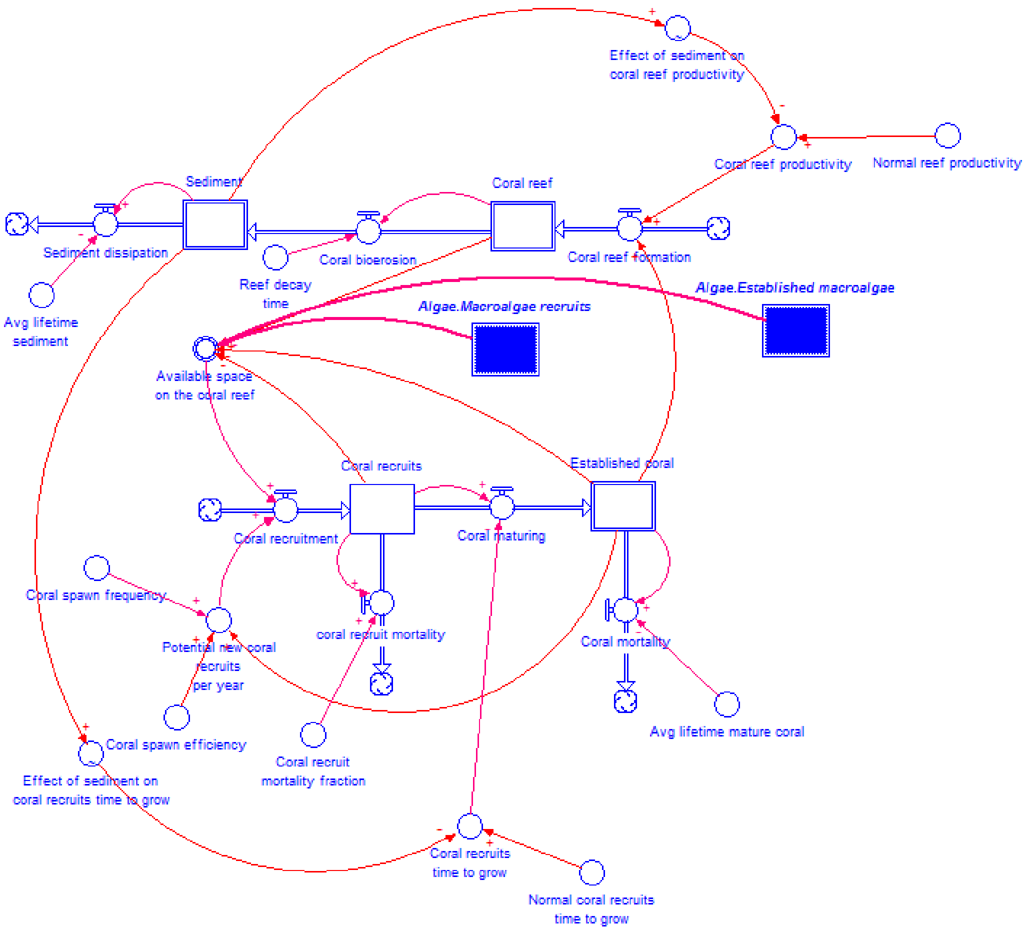

Figure 5 Competition for space between live coral tissue and macro-algae

It is assumed that the corals and algae compete for space on the reef, but not for the nutrients which are available on the coral reef. Furthermore, there is no real evidence that the growth of algae is directly affecting coral mortality (Birrell, Mccook, Willis, & Diaz-Pulido, 2008; McCook, Jompa, & Diaz-Pulido, 2001; Sheppard et al., 2009; Viles & Spencer, 1995; Wood, 1999). As Figure 6 describes, the biological growth process of algae is very similar to that of the live coral tissue. The algae colony grows through spawning (reinforcing feedback loop), but is also limited by the available space on the coral reef for new recruits to settle upon. Under natural environmental conditions, the coral polyps have a competitive advantage over the macro-algae. However, the growth rate of the algae can increase when environmental conditions change. An increased nitrogen (in combination with other nutrients such as phosphate) content of the sea water surrounding the coral reef leads to an increased growth rate of marine plants such as algae, which are highly nitrogen-limited and therefore tend to grow slower in low-nitrogen coral environments (Mann, 1982; McCook et al., 2001; Sheppard et al., 2009; Talbot & Wilkinson, 2001; Wood, 1999). The dissolved inorganic nitrogen content (DIN) is the combination of nitrate, nitrite and ammonia contents of the coral reef sea water. This is an important level variable which has an influence on the growth processes of different species on the coral reef. High nutrients level in the seawater favor the growth of macro-algae over coral species (Talbot & Wilkinson, 2001).

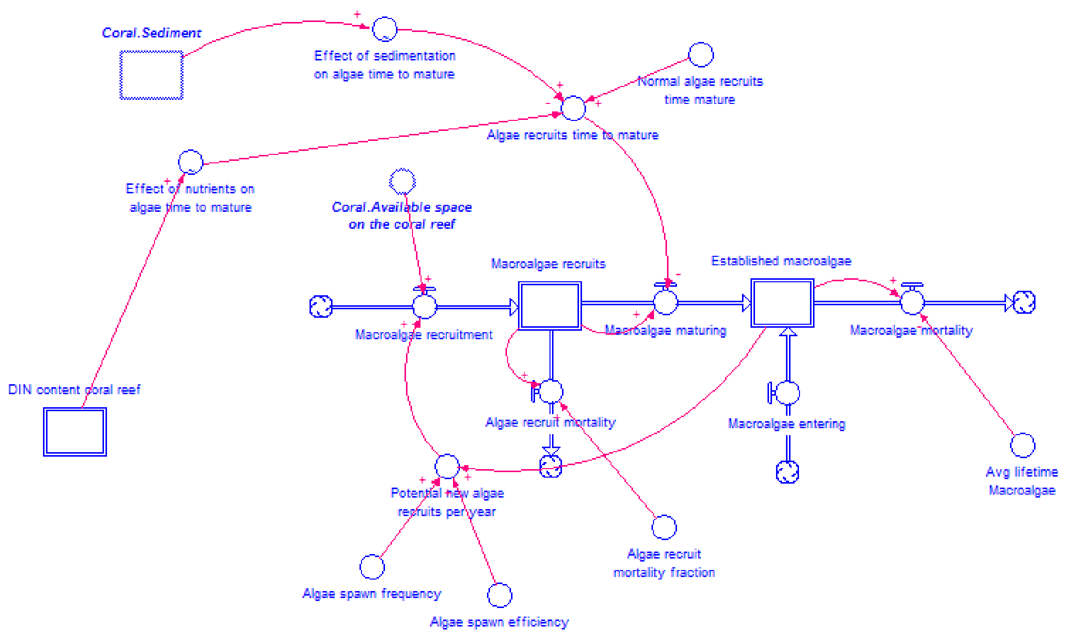

Figure 6 Macro-algae biology model

There are two main coral reef species which feed on the macro-algae species on the coral reef, the parrotfish and the sea-urchin. The parrotfish, with their mouthparts with strong teeth, graze on the coral reef substrate to find food sources, mainly algae, other plants and bacteria (National Geographic, 2016; Sheppard et al., 2009, p. Ch. 6.3, 34). During feeding on the algae, the parrotfish can digest the inorganic calcium carbonate and its stomach content can consist of up to 75% of this material before it is excreted[1]. The presence of a sufficient stock of parrotfish on the coral reefs helps to keep the reef substrate from being dominated by algae species instead of live coral cover. The biological growth process of the parrotfish, as described in Figure 7, is similar to the growth process of coral polyps and macro-algae. The parrotfish stock grows through spawning and decreases through recruit and adult mortality. However, additionally there are three important feedbacks between the parrotfish and the coral reef ecosystem:

1) The larger the cover with live coral polyps, the higher the spawn efficiency since the live coral provides the fish larvae with settlement cues and a location to settle upon (Sheppard et al., 2009).

[1] The excretion of calcium carbonate by the parrotfish is providing the white sand (coral) beaches on several destinations in the Philippines

2) The larger the coral reef area, the lower the recruit mortality fraction since the coral reef provides the recruits with a complex structure in which it can hide from predators (Alcala, personal communication).
3) The carrying capacity of the parrotfish at any moment in time depends on the size of the coral reef and the natural density of the parrotfish per hectare of coral reef. This natural density is related to the natural habitat dynamics of the parrotfish. When the carrying capacity of the parrotfish is exceeded, it is assumed that part of the parrotfish population will migrate to surrounding coral reef areas.

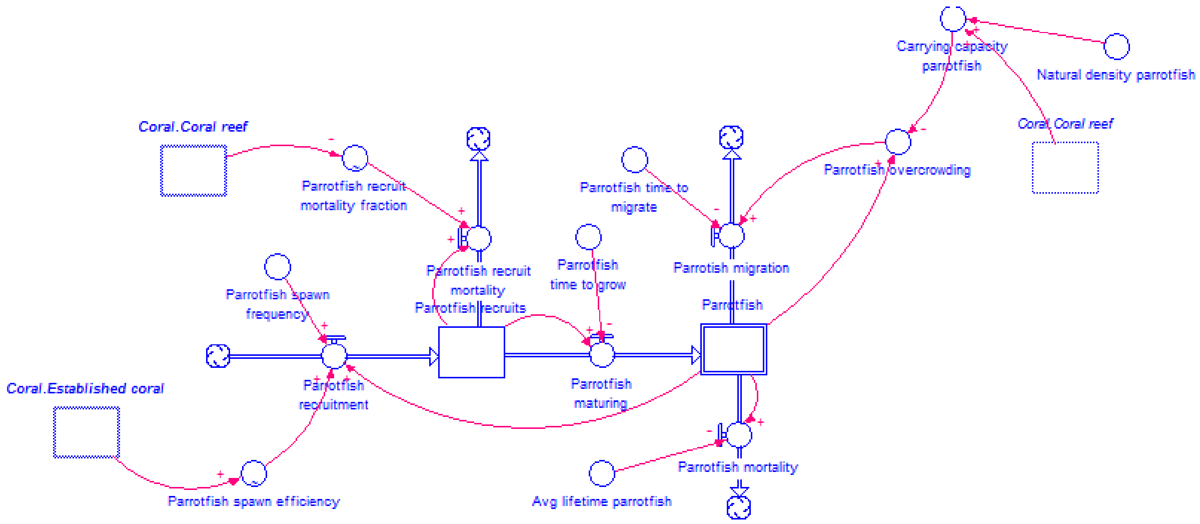

Figure 7 Parrotfish biology model

The crown-of-thorns starfish (COTS) is one of only a few animals that feed on living coral tissue and is one of the major natural predators of Indo-Pacific corals (Great Barrier Reef Marine Park Authority, 2014; Hoey & Chin, 2004; Sheppard et al., 2009; Viles & Spencer, 1995). It feeds on the live coral by everting its digestive system and excreting a mixture of enzymes. An average sized adult (40 cm) can kill up to 478 square cm of live coral cover per day through its grazing activities (University of Michigan, 2016). The biological growth process of the COTS, as described in Figure 8, is similar to the growth process of coral polyps, macro-algae and parrotfish.

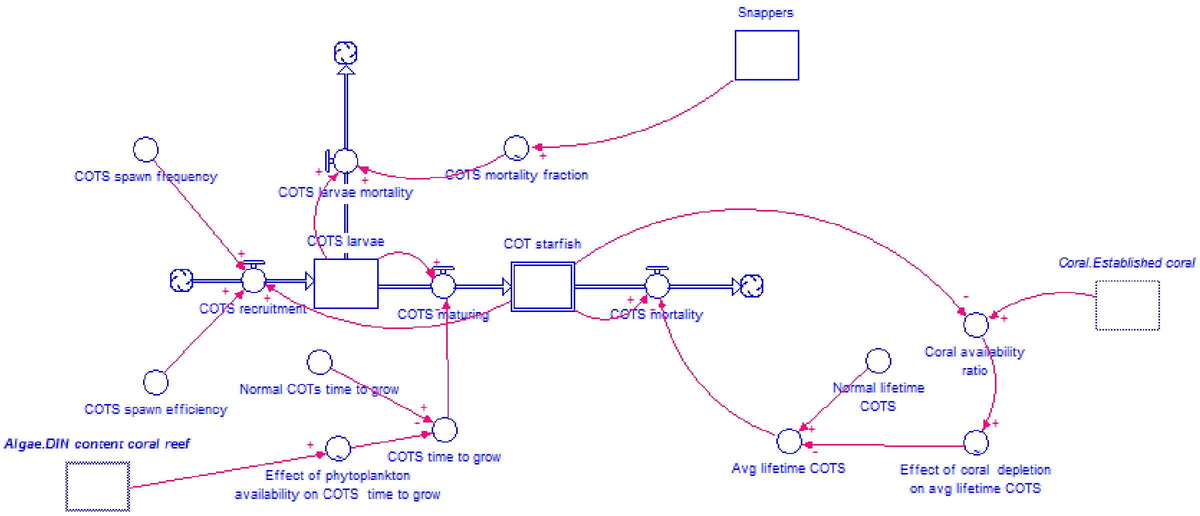

Figure 8 Crown-of-thorns starfish biology model

The most important new relationships and feedbacks within the biology model of the starfish are:

1) The larvae mortality fraction is influenced by the stock of snappers, which have an important coral function in eating little organisms on the reef (Hilomen, personal communication). The COTS larvae are a food source for the snappers and other fish on the coral reef (Talbot & Wilkinson, 2001).
2) The mortality of the mature COTS is influenced by the availability of live coral tissue, their main food source, on the reef. During a COTS outbreak, the starfish rapidly consume all the live coral on the reef, before disappearing as sudden as they have come (Sheppard et al., 2009).
3) On a healthy coral reef with low nutrient levels, it takes the COTS larvae two years to mature. However, when nitrogen levels (DIN) increase, the availability of plankton which feed on nutrients increases as well. As a result, the COTS larvae, which feed on plankton, can grow faster and reach maturity earlier (Hoey & Chin, 2004; Sheppard et al., 2009; Talbot & Wilkinson, 2001).

The snapper has been included in the model because it plays an important role in controlling survival rates of the COTS. Additionally it is one of the most important and popular coral reef fishes in terms of serving as a food source for the local population. The biology of the snapper stock has been modeled in the same way as the biology processes of the parrotfish, with migration based on carrying capacity and feedback between the coral cover and reef and the growth of the snappers.

Simulating the model without human impacts, leads to a steady growth of both the coral reef and the live coral cover over a period from 1970 to 2050 (Figure 9). The steady state growth behavior captures the prevailing trend at the time of the model (1970) for both the undisturbed coral reefs and the coral reefs on which local population and tourism dynamics will slowly start to evolve.

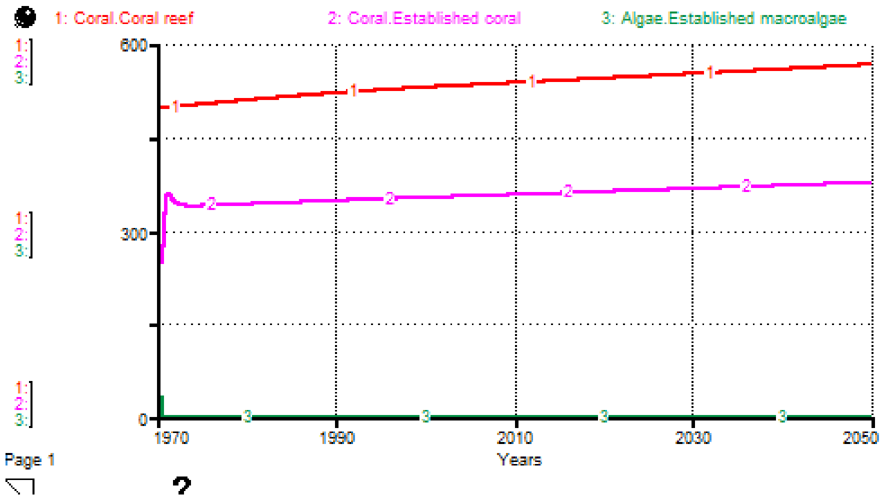

Figure 9 Simulating coral growth on an undisturbed coral reef

The observed behavior in the undisturbed coral reef system is a consequence of the natural structure of the coral reef (Figure 10). There are three important reinforcing feedback loops, which are leading to a steady growth of the coral reef and the fish stocks over time:

1) Reinforcing feedback loop R1 ‘Reef growth’ in which on a coral reef dominated by live coral tissue instead of macro-algae there will be more coral reef formation, which then leads to more space to occupy for new coral recruits;
2) Reinforcing feedback loop R2 ‘Coral dominance’ in which high coral reef and live coral stocks lead to higher recruit survival rate and spawn efficiency of the parrotfish, which leads to growing stocks of parrotfish and increased grazing on macro-algae. When macro-algae is grazed continuously by the parrotfish, the coral polyps will be able to occupy most of the available space on the reef. However, the more parrotfish leads also to more grazing on the reef substrate (B3 ‘Erosion’) which then decreases the size of the reef. This balancing feedback loop limits the strength of the reinforcing reef growth feedback loop; and
3) Reinforcing feedback loop R3 ‘Starfish control’ in which high coral reef and live coral stocks lead to higher recruit survival rate and spawn efficiency of the snappers, which then leads to lower survival rates of the crown-of-thorns starfish larvae. When there are less starfish larvae that survive, possible COTS outbreaks are prevented.

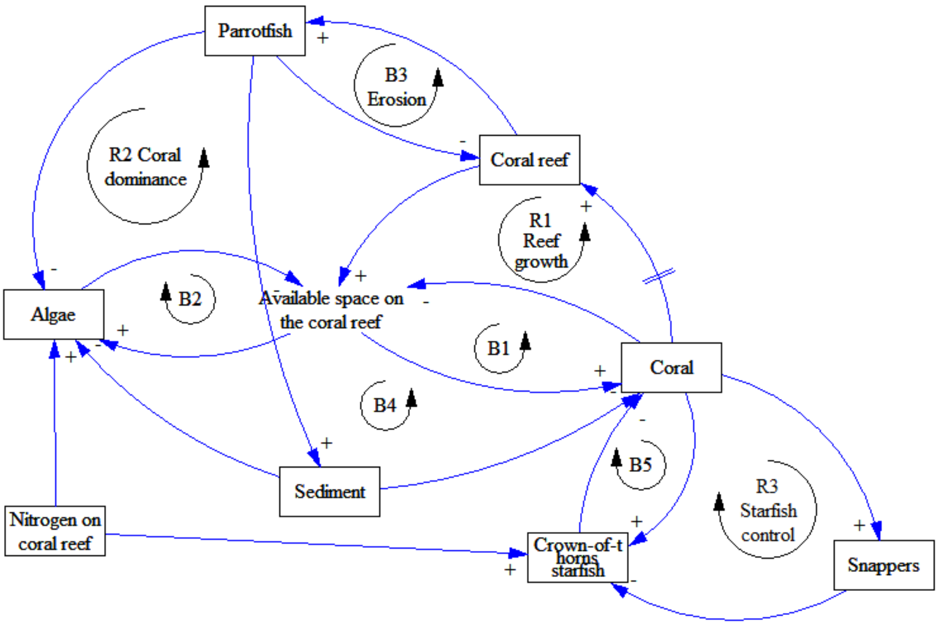

Figure 10 Causal-loop-diagram undisturbed coral reef system

3. Case study: understanding the drivers for coral reef degradation in the Philippines

This chapter will start describing the processes through which an initial small population which settles around the coral reef could lead to population growth and pressures on the coral reef environment. Figure 11 describes the growth of a local population in the Philippines.

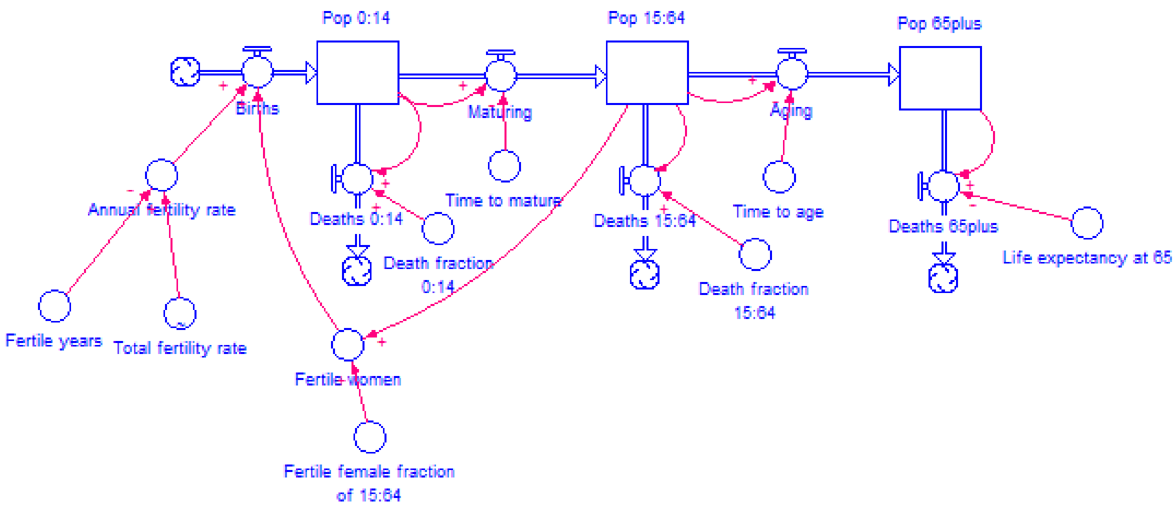

Figure 11 Philippines population growth model

The number of children that gets born each year depends on the number of fertile women from the population 15:64 and their annual fertility rate. Fertility has gradually decreased over the past 20 years from 5.1 children per woman in 1983 to 3.5 in 2003 and to 3.3 in 2008 (National Statistics Office, 2008, p. 3).

As the local population grows in size, so does the amount of sewage which is produced. In the Philippines, the ocean often serves as a bathroom for many people. Observations show heavily polluted waters near coastal settlements. While a central sewage treatment plant and system is almost always absent, even only few families have access to so-called 'septic tanks' (e.g. small-scale sewage systems). Even when septic tanks are used, they often overflow or leak into the ground and sewage can still enter the sea water in that way.

The sewage output from the local population has severe implications on the nutrient levels in the sea waters surrounding the coral reef. When the sewage is first disposed, it will have an almost direct effect on the dissolved inorganic nitrogen content (DIN) on the sea water near the beach front. Figure 12 describes the process through which the inorganic nitrogen dissipates from the sewage disposal to the beachfront and into the coral reef. Although the inorganic nitrogen disposed by the local population will become dissipated due to the high volume of seawater, it can still affect the overall DIN content on the coral reef when the pressures become high enough and sewage is being disposed on a continuous basis.

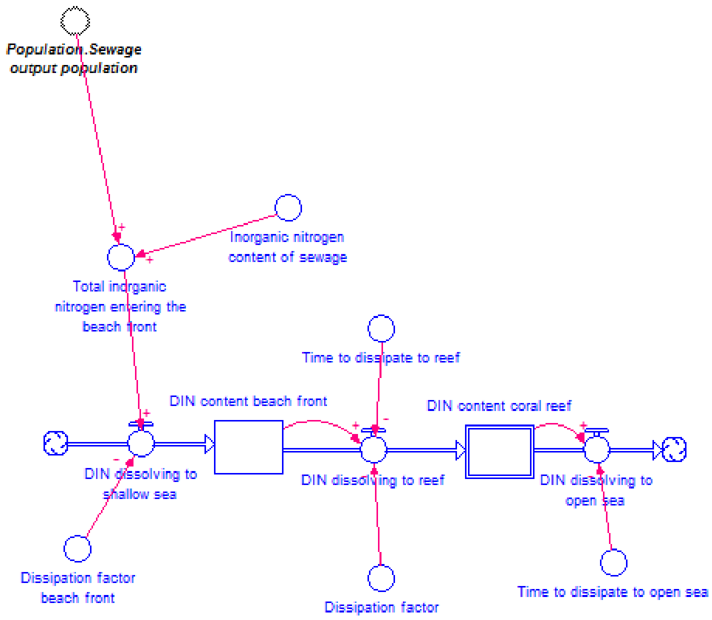

Figure 12 Nutrients entering on the coral reef

Many coastal communities in the Philippines are dependent on the sea as the provider of their main source of protein. A growing population, therefore, leads to a higher demand for fish (Figure 13). However, on many locations in the Philippines, the harvesting of fish is mainly supply driven. This means that the total harvest depends not on the demand for fish by the local population, but on the number of fishing boats and the average fish catch per boat. The difference between the demand for fish by the local community and the total harvest accounts for the export of fish. For initial small fishing communities, fish exports make up a significant portion of the economy.

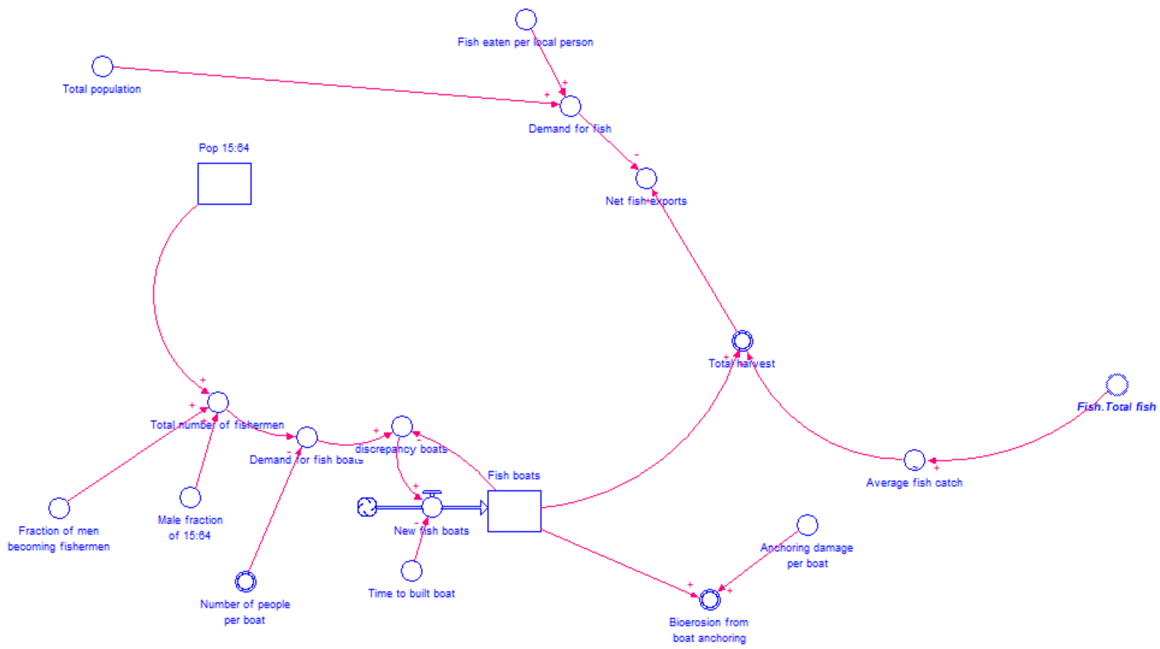

Figure 13 Local fishing community

The fish industry plays an important role in the degradation of the coral reef through their interaction with important fish stocks. The model assumes that fishermen will keep fishing until fish stocks are depleted. However, the average fish catch is expected to decline when fish stocks become more depleted. Besides intervening with the fish stocks on the coral reef, the growth of the number of fishermen is also having a direct effect on the coral reef because of the dropping of anchors which destroy the coral reef substrate.

Simulating the model with the impacts of a local growing population provides some interesting insights about the interaction between the human and ecological environment. As the simulations in Figure 14 reveal, from around the year 2010 the macro-algae starts to increase its relative dominance on the reef compared to the live coral tissue. This is caused by a combination of increasing nitrogen availability on the coral reef and the depletion of the parrotfish.

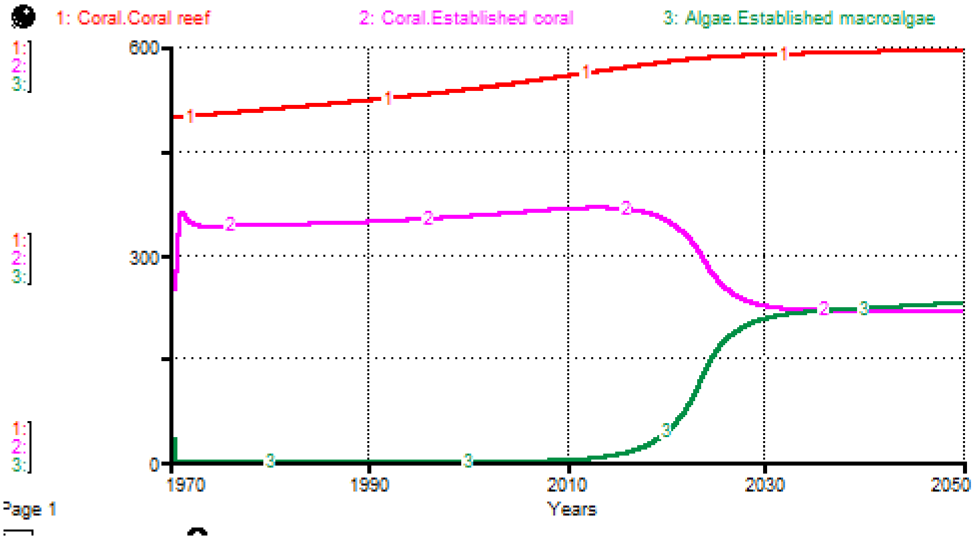

Figure 14 Simulating coral growth on a coral reef with a local fishing community

Extending the reference period from 2050 to 2200 show how lower dominance of reef-producing coral polyps on the reef lead to a decline of the coral reef substrate, and consequently a decrease in the available space for both live coral and macro-algae recruits to occupy (Figure 15). In the long term the coral reef is not sustainable as reinforcing feedback loop R1 'Reef decay' will slowly push the coral reef to extinction, the coral reefs' only stable equilibrium.

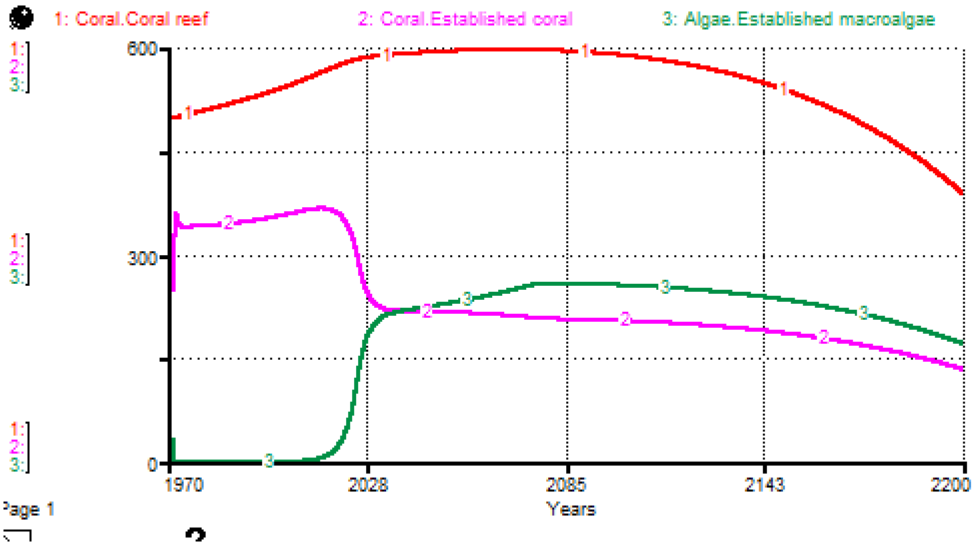

Figure 15 Simulating long-term coral decline on coral reef with local fishing community

Figure 16 reveals how the human interaction (in red) with the coral reef ecosystem leads to a change in the polarity of the reinforcing feedback loops:

- R1 from 'Reef growth' to 'Reef decay'
- R2 from 'Coral dominance' to 'Algae bloom'
- R3 from 'Starfish control' to 'Starfish outbreak'

It is important to note here that the growth of a local fishing community has reversed the natural growth process on the coral reef. However, as described above, because of the limited size of the population, the process of the coral reef going extinct can still take considerable time.

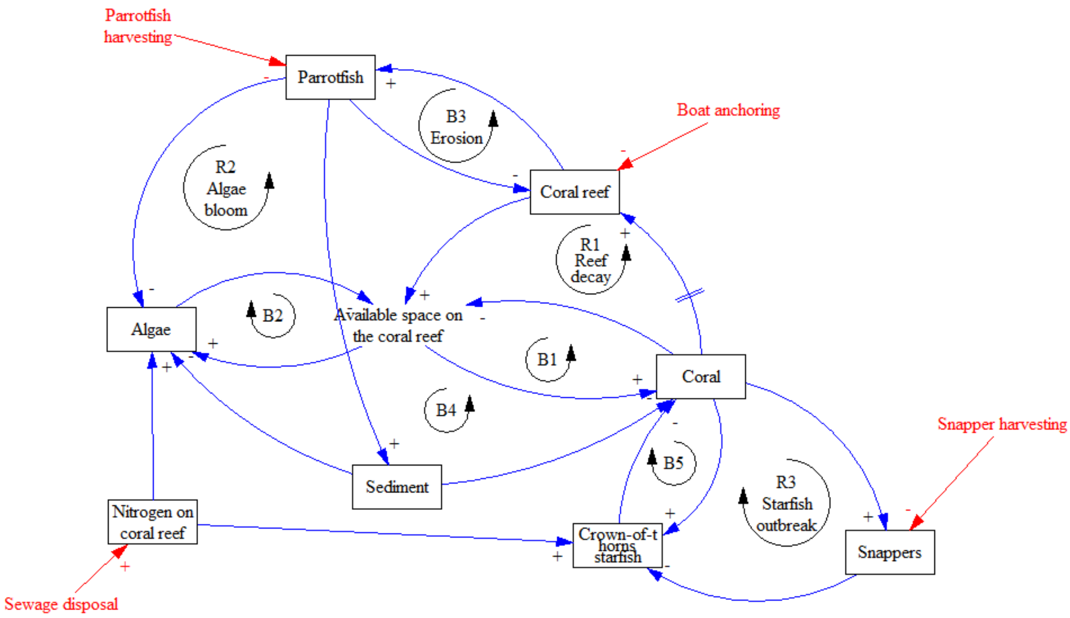

Figure 16 Causal-loop-diagram coral reef with local fishing community

4. Tourism development as an alternative for the fishing industry

While still relatively unexplored, the archipelago of the Philippines has a large potential for tourism growth. For the local population, which has to cope with decreasing fish stocks, the development of tourism can be seen as an alternative way of making a living. The shift from mainly a fishing industry towards tourism might therefore be seen as a potential solution to at least one part of the negative effects of the local population on the coral reef.

This chapter will help to increase a deeper understanding about the multitude of ways this shift is affecting the coral reef, both positively and negatively. The model assumes that the growth of tourist arrivals on a certain destination is based on increasing popularity of that destination due to word-of-mouth effects. After tourists return from their holiday (and assuming they were satisfied), they interact with other people (friends and relatives).

In the Philippines, island hopping is one of the most popular tourist activities. During island hopping tours, groups of tourists are going on a boat to different islands, visiting beaches and coral reef areas. The tourists can either go diving or snorkeling in the coral reef area. Based on a growing demand for tourist boats, more and more fishermen will decide to switch from operating a fishing boat to operating a tourist boat. The fishermen decide to change mostly because using a boat for tourist activities is financially more attractive than using a boat for fishing. On major tourist locations like Borocay and El Nido, almost all of the fishermen have switched to become tourist operator. With more local people working in the tourism industry, the number of active fishermen starts to decline. It can be expected that pressure on fish stocks will go down as a result. However, although the switch to tourism reduces pressure on the fish stocks, it also leads to other processes which are potentially harmful for the coral reef.

The first unintended consequence from tourism development is the effect of land development on sediment levels on the coral reef. When new resorts are built, land has to be cleared. During land clearing and construction of resorts, sediment is produced and disposed into the water. The most problematic issue with resort development and sedimentation is when the resorts are built close to the beachfront.

An increase in the number of tourists can also lead to higher nutrients level on the coral reef, in the same way that a growing population increases those nutrients. On many locations in the Philippines, much of the sewage from tourist resorts is not properly treated due to a lack of a sewage system. It is very expensive for individual resorts to invest in the proper technology needed (Mencias, personal communication). Furthermore, there are often no policies in place to stimulate such investments.

Although the switch to tourism development reduces the harvesting of fish stocks, it will not reduce the anchoring damage by boats, as the boats are now used for tourism activities on the same coral reef. Additionally, a lot of coral reef damage is caused by divers and snorkelers, who step, kick, hold, kneel and stand on the reef during island hopping activities. Additionally a relatively large portion of them are not able to swim, thereby leading to a higher chance of standing on the reef. Also student divers, first-time divers and irresponsible guides have more impact on the reef.

Another unintended consequence of the ‘success’ of tourism development is the increased employment opportunities coming mainly from increased demand for tourist activities. Figure 17 describes how the growth of demand for tourist activities could lead to a shortage of the number of fishermen (e.g. workers) who can fill the demand. When such a shortage of labor is structural, it could lead to immigration of workers. Since there is poverty on many islands in the Philippines, opportunities for better life conditions will lead to a high willingness to migrate. Thus increased tourism development can have an effect on the growth rate of the local population on the island, which thereby can increase al the effects of the local population which have been described in the previous chapter.

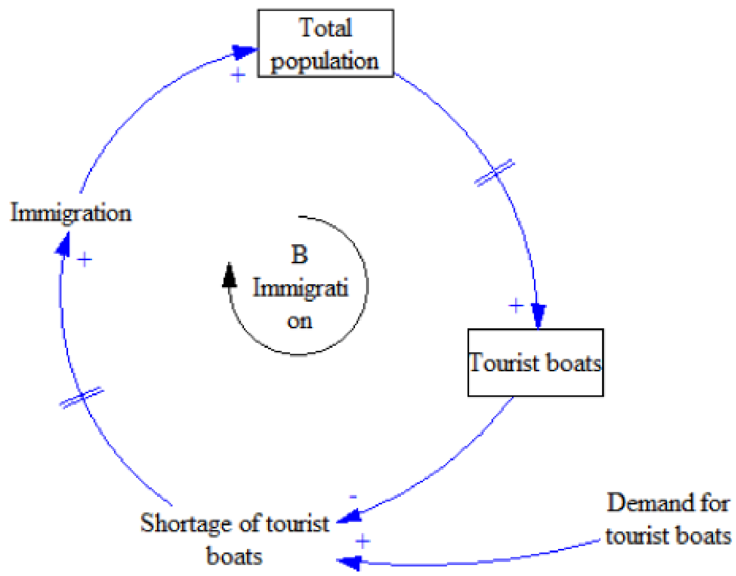

Figure 17 Tourism development and immigration

The simulation of a coral reef, as described in Figure 18, explains how the combination of local population growth and tourism development could lead to a rapid degradation and even extinction of the coral reef.

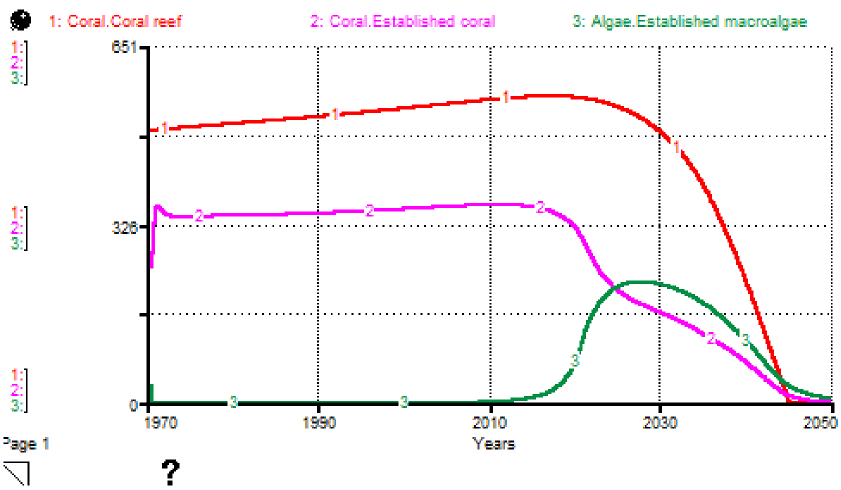

Figure 18 Simulating long-term coral collapse on coral reef with local fishing community and tourism

As discussed in the start of this chapter, tourism development is often seen as the 'holy grail' for local communities to help conserving coral reefs by reducing pressure from fishing. However, comparing the causal-loop-diagram in Figure 19 with that of only a local fishing community helps us explain why the growth of tourism actually leads to a more rapid degradation of the coral reef.

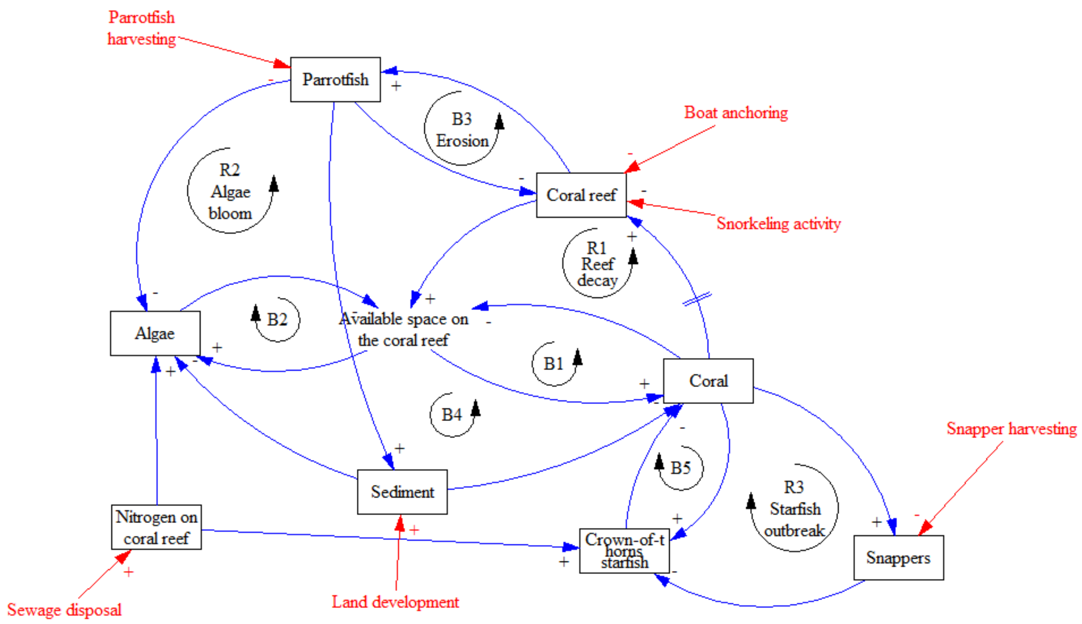

Figure 19 Causal-loop-diagram coral reef with tourism 'boom'

The switch to tourism seems to reduce the strength of reinforcing feedback loops R2 'Algae bloom' and R3 'Starfish outbreak' by reducing the harvesting of both parrotfish and snappers. However, the growth of tourism has several unintended consequences through which it actually strengthens the dominance of those loops:

1) A higher numbers of tourists lead directly (and directly through immigration) to a higher disposal of sewage which increases the growth rate of macro-algae and crown-of-thorns starfish.
2) The construction of tourist resorts leads to more sediment entering the coral reef, which reduces the growth rates of both the live coral tissue, the macro-algae and the coral reef substrate
3) An increased number of island hopping both leads to increased direct destruction of the coral reef by anchoring and tourist tramping.

The feedback loop analysis and simulations reveal how reducing pressure on fish stocks is not enough to restore the fish stocks, as the growth of the fish stocks depends on the size of the coral reef and live coral tissue. With the coral reef substrate and live coral tissue degrading because of tourism development, fish stocks will also degrade in the same rapid pace although the direct effect of harvesting is reduced.

5. Case study: understanding why coral programs fail in the Philippines

The preceding chapter has shown that a diversification strategy towards tourism development, by itself, is not an appropriate strategy to reverse coral reef degradation. Most likely, tourism development has even increased the pace at which the coral reef is degrading. During the last few years many different coral-management programs have been developed in an effort to restore the condition of the coral reef. Artificial reefs, coral replanting and marine protected areas are the most common used efforts. Most of these programs appear to have failed, or at least they did not seem to have the intended effect of reversing coral reef degradation. In fact, conditions on the coral reef seem to have worsened while these programs were in place. Is it possible that the management programs did not improve the status of the coral reef, or even had a negative effect?

The model of coral reef growth and decay has been equipped to simulate various coral-management programs. With this addition, human-induced artificial coral reefs and coral replanting projects can be introduced. Furthermore, the removing of crown-of-thorns starfish and the establishment of marine protected areas can be included in the simulations.

Artificial reefs are human-made structures which are performing the same ecological function as real coral reefs produced by coral-producing polyps. Artificial reef projects have been initiated in many locations in the Philippines. Artificial reef projects are often complemented by coral nursing and replanting programs. In a coral replanting project, young coral recruits which live under detrimental environmental pressure are removed from the coral reef and then nursed under artificial conditions (either in a separate laboratory or another more healthy part of the coral reef). When the young coral recruits have grown to become established coral, they are replanted on the coral reef. As with the artificial reefs, the size of the current coral nursing and replanting projects in the Philippines are relatively small compared to the size of the total coral reef.

The outbreak of crown-of-thorns starfish (COTS) populations are now widely considered as a major threat to the coral reef. Because of the urgency needed to prevent a COTS outbreak from eating all the live coral tissue in a short period of time, policies are in place to remove the COTS when the threat of an outbreak is observed. However, on most locations, the removal policy is still supply-limited, as there are only a certain amount of divers which are able to remove the COTS.). It is very important to remove the COTS completely from the coral to eradicate the problem. It has been argued (Alcala, personal communication) that when u cut a COTS in pieces, their separate parts will be able to multiply themselves. This will worsen the problem rather than solve it.

The establishment of Marine Protected Areas (MPA) is often considered to be the 'holy grail' in terms of sustaining the health of the coral reef. A marine protected area (or MPA) is an area on the coral reef which is protected from a severity of human pressures. The main goal is to preserve and recover fish stocks by completely or partly limiting fishing activities within the area. As an additional benefit, the damage from boat anchoring will decrease as there will be no or less fishing boats on the reef. As such, in general, the MPA program is perceived to help restore fish stocks and reverse the degradation of the coral reef. However, if we look at the way the fish industry works in the Philippines, there might be some unintended consequences of the MPA program. The MPA program reduces the available area for fishermen to fish, but it does not, by itself, reduce the number of fishing boats. Therefore, when the MPA program is only protecting a part of the coral reef, this means that the other parts of the coral reef will receive additional pressure from fishing boats. The non-protected parts of the coral will now face larger fishing and anchoring pressures from fishing boats.

Since it is almost impossible to implement an MPA over the whole coral reef area, the limited size of the projects is a great barrier to better results in terms of reversing coral degradation. Another problem with the MPA programs is related to enforcement. In many cases, MPA programs are limited to surrounding a part of the coral reef with buoys which signal the frontier of the reef which is protected. However, often there is no surveillance on the reef or it stops during the night. Therefore fishers are still able to fish inside the coral reef. The general problem is a lack of funds to support enforcement or the lack of inclusion of the local fishermen and population into the decision making on the coral reef area.

Figure 20 shows how even the combination of artificial reefs, coral replanting, COTS removing and marine protected areas are not able to reverse the rapid degradation of the coral reef. The second (red) line shows the simulation results with the most realistic coral management project sizes, while the third (pink) line shows the results when the size of the projects will be increased to 5 hectares/year for the artificial reefs and coral replanting and 50% for the MPA.

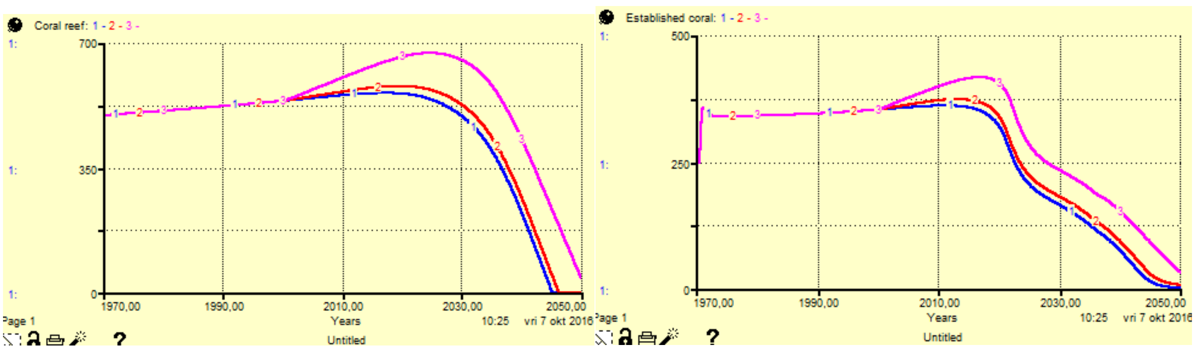

Figure 20 Combined effect of coral programs on coral reef and live coral tissue

The reasons for the ineffectiveness of the current coral programs can be understood by referring back to the causal loop diagram as presented in Figure 21.

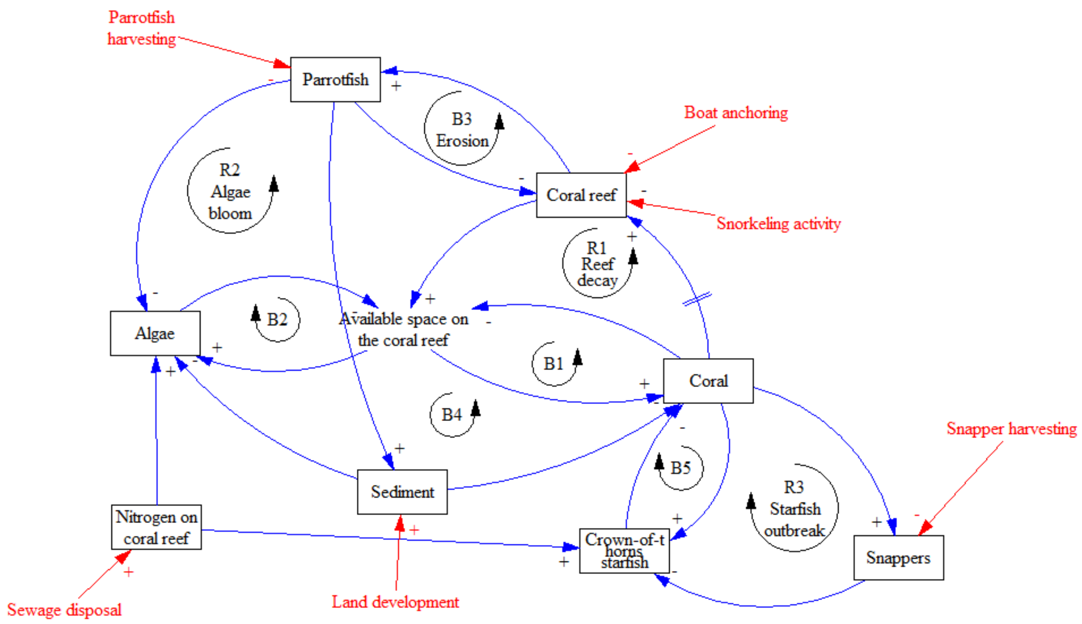

Figure 21 Causal-loop-diagram coral reef with tourism 'boom'

The most important factors for the limited effectiveness of the current coral programs are:

1) The artificial reef program is addressing the reinforcing feedback loop R1 'Reef decay' by increasing the growth of the coral reef artificially. Increasing the size of the coral reef is then intended to lead to more space to occupy for coral recruits who then once again take over the role in building the coral reef. However, the program neglects the reinforcing feedback loop R2 'Algae bloom' in which the dominance of algae growth over coral growth will lead to more of the available space being occupied by macro-algae instead of live coral polyps. As such, the artificial reef program needs to be maintained as there is limited natural reef-building. Additionally, the artificial reef program does not take into account the devastating effect of increased anchoring and snorkeling activity on the coral reef.
2) The coral replanting program faces the same problem as the artificial reef program. It focuses on the R1 feedback loop while not taken into account the R2 feedback loop. This means that the coral recruits have to be nursed artificially in healthy conditions before being replanted on the coral reef. However, when back on the coral reef, they will face direct pressure from crown-of-thorns starfish outbreaks (R3 'Starfish outbreak') and indirectly through a decreased recruitment rate of their recruits because of algae competition.
3) The COTS removal program reduces the pressure on the live coral tissue. However, it does not take into account reinforcing feedback loop R3 in which lower stocks of snappers lead to a higher survival rate of the starfish. Furthermore, the program does not alleviate the

problem of water pollution, which is contributing to both a higher growth rate of the starfish and the macro-algae.

4) The MPA program is implemented to help reduce the strength of the algae bloom (R2) and starfish outbreak (R3) loop by reducing the pressure on both the parrotfish and snapper stock. The main reason the MPA program often fails is that it focuses on the health of the coral reef from a local perspective instead of taking into account the whole coral reef. While the program works effectively for reducing the pressures on the coral reef within the protected areas, it actually increases the pressures on the coral reef outside of the protected area.
5) A combination of the programs mentioned above is having some positive effect on the health of the coral reef, but is not able to reverse the rapid degradation and ultimate extinction over time. The programs fail to take into account a multitude of increasing human pressures on the coral reef which strengthen rather than weaken the dominance of the reinforcing feedback loops which are responsible for the rapid degradation of the coral reef:
    a. The increasing nitrogen content on the coral reef caused by sewage disposal
    b. The increasing sediment level on the coral reef caused by resort construction
    c. The destruction of the coral reef by anchoring and tourist activities

6. Model testing

The coral reef model has been tested on an iterative basis during the modeling process and the final version is the result of:

1) Testing the model to theory
2) Testing the model to real-life experience
3) Testing the model behavior to model structure

It must be acknowledged that in this stage the model does not qualify as a scientific model but rather as an exploratory model (Homer, 1996). Many of the hypotheses about relationships in the coral reef environment have been formulated with little or no empirical foundation. Further testing of the model in practice and experiments will therefore certainly lead to a falsification of at the least parts of the model. However, these new insights can be then be postulated in a more accurate version of the model. In that way, the acceptance of any new version of the model is always conditional to the state of knowledge at that moment in time.

The results of the model simulation can be compared to the actual behavior of coral reefs in the Philippines. The most popular tourist destination in the Philippines, the island of Borocay, provides the best case study to assess the behavior of the model. Historical data on coral cover and tourist arrivals are available (see Figure 1) and can be compared to simulation results of the hypothetical coral reef model. Comparing these trends to the simulation results (see Figure 18) of the model show a general similarity in behavior, in which a growing population and tourist size has been accompanied by a rapid decline in coral cover. On El Nido, which is often seen as the next Borocay in terms of tourism development, similar trends can be observed. However, with regards to the development of the coral cover over time, there is limited historical data available. On most of the relatively 'new' tourist destinations, there is a lack of structural assessment of the quality of the marine environment. With expected growth in local population and tourism, monitoring of marine resource is highly recommended.

Since there is only limited data available on the most important ecological health indicators on the coral reefs in the Philippines, anecdotal evidence has been collected (Bartelet, 2017). However, the anecdotal evidence has only limited scientific value since it is prone to the subjective bias of the author.

7. The path to coral reef recovery

The previous chapters showed the harmfull effects of constructing marine protected areas without providing alternative ways of living for the local population. This chapter shows that the positive effects of protecting the marine environment can be achieved while at the same time the local population can prosper. The problem of coral degradation is related to deteriorating environmental conditions.

Most of the current management problems are symptom-based, while they ignore the underlying cause of the problem. For example, removing COTS and replanting coral polyps will not have an effect on the deeper reasons for why the COTS and macro-algae are growing rapidly on the reef: water pollution. Therefore, for a coral program to be sustainable, it should include policies which focus on restoring the nitrogen content of the coral reef waters. Since it will be unattainable to remove all local population and tourists surrounding the coral reef, a policy should be proposed in which the growth in population and tourist numbers is de-coupled from pollution of the sea-water. A successful sewage program should consists of building one large or several smaller central sewage treatment plants, which will be connected to both the local population and the tourist resorts.

Compared with the rapid destruction of the reef caused by anchoring and tramping by tourists, taking measures to prevent those damages should be implemented. The first policy which will be proposed is to use sustainable buoy technology instead of individual anchors for the fishing and tourist boats. The most well-known example for sustainable anchoring is to make use of a 'Mooring buoy': a buoy to which boats can attach themselves on the coral reef so that they do not need to anchor themselves on the coral reef. The mooring buoy is safely attached to the seabed without destroying the reef.

The second policy, aimed to prevent the direct damage caused by tourists during island hopping activities, is to develop glass ceilings on the island hopping boats. On marine sanctuaries in Florida, in the United States, boat tours with glass bottoms are already operated successfully. When the glass ceiling boat policy has been successfully implemented, it is proposed to combine it with an additional cost for divers and snorkelers who decide that they do want to go into the water. These people will have to read and sign a precautionary agreement in which they are obliged to fulfil the environmental regulations on the coral reef (e.g. not touching the ecosystem). When the divers or snorkelers misbehave, they will get a fine. In the agreement, which divers and snorkelers have to read before the trip, they are also obliged to use organic (coral-friendly) sunscreen.

With the 'tourist boom', there has been a large surge in construction activity which led to high levels of sediment on the coral reef which negatively impacts the growth rates of the coral. It is advised to implement construction regulation which makes it obligatory to use silt screens during the building and demolition of resorts. A silt screen is an artificially made screen which prevents erosion of sediment during land development (Talbot & Wilkinson, 2001). The silt screen policy should preferably be accompanied by regulations which make it illegal to build within 30-meters of the beachfront.

The MPA policy has the unintended consequence of shifting the extra burden of the protected reef to the unprotected part of the reef. Additionally, enforcement of the MPA policy is often lacking, thereby leading to a continuation of fishing activities within the protected area. To fulfil the full potential of the MPA policy, it is proposed to complement the current MPA program with an additional program. First of all it is important to decrease the number of active fishermen on the reef. This can be done by hiring part of the local fishermen to perform surveillance activities on the MPA. The enforcers will surveillance the border of the marine protected area to prevent illegal fishing. Furthermore, they will also enforce the compliance with the sewage treatment, construction and island hopping regulations. The enforcement program will lead to a decrease on the active fishermen on the reef, and will thereby decrease the unintended consequence of increasing pressures on the non-protected reef. When more of local fishermen are hired to work in environmental enforcement, it is assumed that the size of the MPA project can be increased because there will be more local support for the policy. Secondly, with local fishermen working in environmental enforcement, it can be expected that the compliance rate will increase, as there is now local support for the MPA program.

The simulation, as described in Figure 22, explains how it is possible for a coral reef destination to reap the positive benefits of human development without the negative consequences for the environment. The simulation show the sustainable behavior of the coral reef when the coral programs, as described above, are all implemented starting from the year 2000.

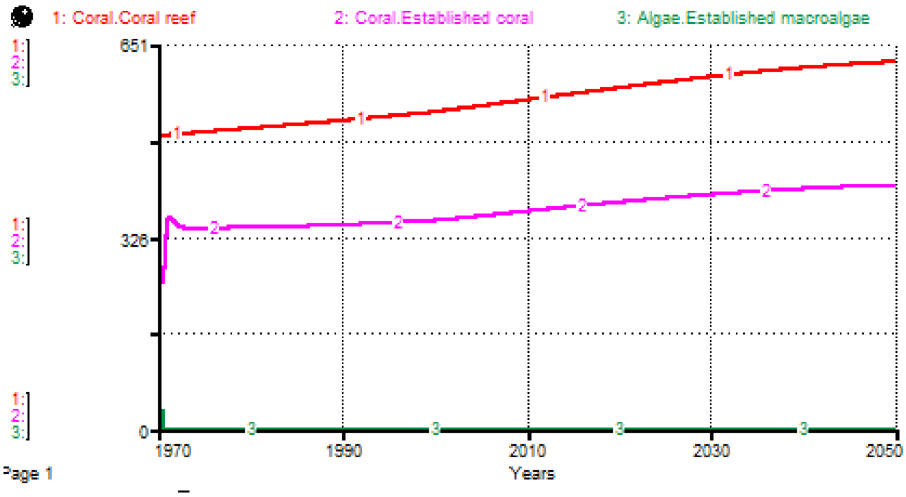

Figure 22 Simulating coral program leading to a sustainable coral reef growth (100% MPA)

Figure 23 helps explain why the simulations of the reef with the proposed coral programs show similar results to that of a coral reef without human pressures. Instead of intervening directly in the natural system, the proposed coral program focuses on alleviating the environmental pressures which originate in the human system. Thereby, as the human and tourism development are de-coupled from environmental impacts, the coral reef will be able to grow as if there was no human population present besides the coral reef.

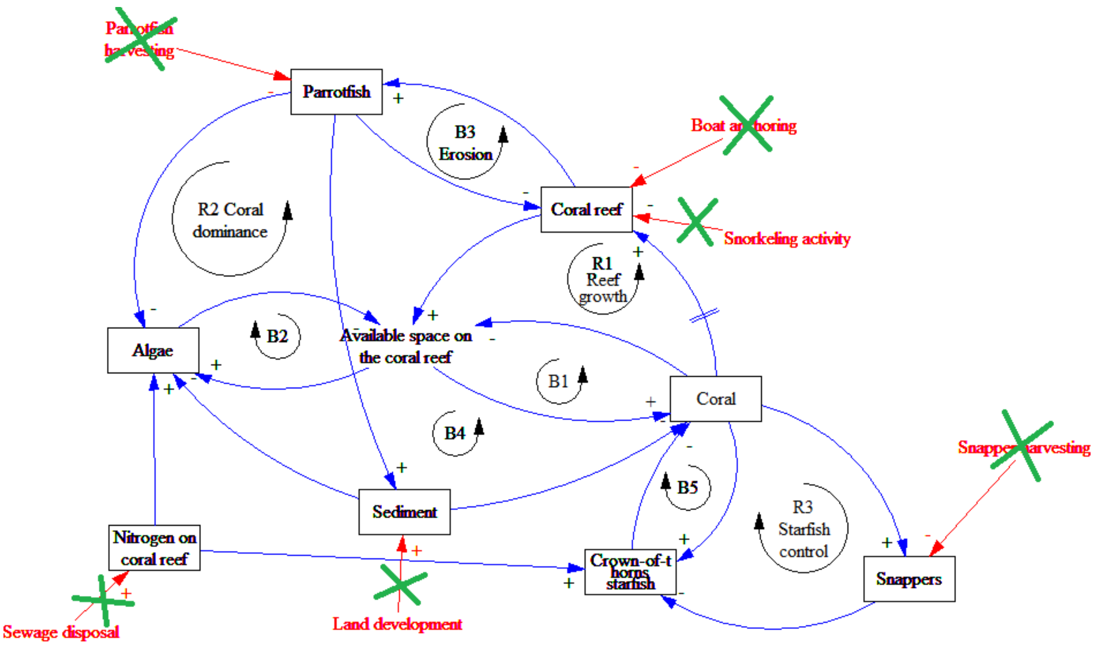

Figure 23 Causal-loop-diagram sustainable coral reef program

Therefore, the elimination of the human pressures means that the three reinforcing feedback loops which drive the coral system, will switch back into their desired direction:

1) From 'reef decay' to 'reef growth';
2) From 'algae bloom' to 'coral dominance'; and
3) From 'starfish outbreak' to 'starfish control'

To implement the policies as proposed above, it will be necessary to improve the tourism tax system. It is proposed to improve this system by making it more transparent, convenient and effective. When these conditions are met, it is recommended to increase the tourism tax to help stimulate the necessary coral programs as soon as possible. Most likely, the income from tourist taxes will have to be supplemented by financial aid through national and/or international agencies.

8. Discussion

This paper has explored the hypothesis that even on coral reefs which do not face climate change, natural disasters and other destructive forces, rapid degradation is still the most likely outcome. In this paper, a simulation model has been developed based on scientific and anecdotal evidence about the growth and decay of coral reefs in the Philippines. As the simulation is still in the exploratory stage, it consists of:

1) Detailed scientific information about ecological variables and relationships
2) New causal relationships about ecological variables and relationships with limited scientific evidence and data
3) New causal relationships about human development and interaction with the ecological variables

The simulation results and initial anecdotal evidence from coral reefs in the Philippines have not been able to reject the hypothesis of the paper. This could potentially have large consequences for the way we think about the sustainability of many coral reefs around the world. The results of this study extend previous findings that conclude that coral reefs close to people's habitat seem to be under more pressure than similar reef structures further away. The study has identified the driving forces through which human development interacts with the increasing pressures on the reef. By understanding these drivers, this research has been able to provide interventions through which human development might be de-coupled from coral reef degradation.

The main contribution of this study has been to increase understanding about how the ecological processes on the coral reef are interrelated and can produce complex and unexpected behavior. The paper has explained the coral reef degradation in terms of shifting dominance of the same processes (e.g. feedback loops) which lead to both coral growth and decay. It has identified the most important human drivers which cause the shifting dominance. This understanding on a systems level helps to increase understanding about what policies are most effective in reversing the degradation of the reef.

The results of this paper have both theoretical and practical implications. On a theoretical level, the model and the hypothesis it postulates can be used as a general theoretical framework to identify areas to do further research. The model, as such, can stimulate a more effective allocation mechanism for deciding on future research areas. On a practical level, the results of this study can be used to develop a training program for local decision makers to increase their understanding about the growth process of coral reefs and how their own decisions interacts with these processes. The findings of this study can be especially relevant for new tourist destinations to develop a precautionary approach to human development around the reef as to prevent the devastating consequences to the reef which have been experienced on more developed destinations.

Future research should aim to increase the confidence in the model structure and simulation results by increasing the scientific accuracy of its causal relationships and parameter values. It would also be beneficial to conduct further research on other tourist destinations around the world, such as the Caribbean, to try to reject the hypothesis or parts of the hypothesis as has been postulated in this paper. Finally, experimental research can be conducted in which the most important variables of coral reef health are compared for a coral reef on which the coral programs as proposed in this paper have been implemented and a coral reef where no new programs have been implemented.

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