Coral reef degradation in the Philippines: a SD approach




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1. Introduction

Coral reefs, referred to as the 'rainforest of the sea', are disappearing at an alarming rate worldwide (Szmant, 2002). This has severe consequences since they are one of the most diverse ecosystems on the planet and serve as a haven for marine life. 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. As a matter of fact, in many small islands, tourism is the main contributor to GDP and employment (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 (Figure 73). 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.

This paper is a first attempt to help policy makers fill the vacuum created by making decisions based on intuition rather than a deeper level of understanding of coral reef dynamics. It does so by describing a simulation model of a hypothetical coral reef with the focus on explaining the driving forces behind coral reef growth and decay. The theory presented here, in the form of a formal model, is based on the extensive literature available on coral reefs and the author's own insights from studying the coral reef environment in the Philippines. The results of this study provide a new perspective on the processes responsible for coral growth, decay and recovery. It postulates the hypothesis that coral reef degradation is dominantly caused by the reversal of three reinforcing feedback loops which are responsible for coral growth in a healthy coral reef environment but coral decay in an unhealthy environment. Before exploring the human factors which are impacting the coral reef, the paper starts with developing a better understanding of the natural processes that make the coral ecosystem develop. Than the simulation model will show why current coral programs, intervening directly in the natural environment, are ineffective and why programs should intervene in the human environment to reverse the rapid degradation of the coral reef.

2. Methodology

This thesis examines the life cycle of a coral reef system using the method of system dynamics, which was developed by its founder Jay Wright Forrester in the late 1950s at the Massachusetts Institute of Technology (MIT). The method is used to study the complex behavior in industrial and urban systems (Forrester, 1961, 1969). After its success in understanding the complex systems within the industrial and urban setting, system dynamics is now also successfully applied to the study of environmental systems (Ford, 2009; Meadows, Randers, & Meadows, 2004; UNEP, 2011).

While much of the current research on coral reefs is focused on detailed study into individual relationships between species on the coral reef, the purpose of this paper is to combine the results from those specific and detailed studies into a holistic perspective. As such, this paper starts with a literature review to understand the natural growth processes of coral reefs worldwide.

To increase understanding about the variables which are dominantly responsible for degradation in real-life coral environments, a case study approach is used to identify the variables which are deemed most important on multiple coral reef locations in the Philippines. The use of a case study approach is recommended for research topics in which a rich understanding of a problem has to be obtained (Denscombe & Martyn, 2012; Laws & Mcleod, 2004). Furthermore, it will be difficult to create an experimental setting on a realistic scale in which a multitude of variables will be controlled to compare the effects on the coral reef. The case study approach, on the other hand, will enable exploratory research into the causes of coral reef loss on several destinations in the Philippines. The case study approach is also strongly advocated in the system dynamics field, where first-hand knowledge obtained by 'walking the line', leads to a better understanding of problems that exists in real life (Forrester, 1992; Sterman, 2000). The selection of research locations was based on the location's importance as a tourist destination. The locations which are included in the research are presented in Figure 1.

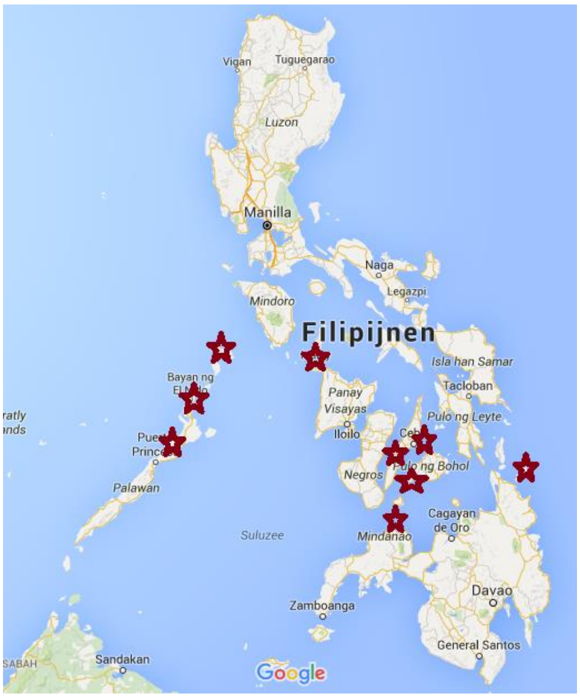


Figure 1 Research locations in the Philippines (from left to right: Port Barton, El Nido, Coron, Borocay, Apo Island, Moalboal, Panglao Island, Mactan Cebu, Siargao Island)

A mixed methods approach has been used to combine qualitative data from interviews and field observations with quantitative data from general statistics and environmental reports. This mixed method approach is useful because the qualitative data obtained can be used to explore causal relations within the system, while the quantitative can be used to find numerical input for the system dynamics model (Luna-Reyes & Andersen, 2003).

The 'De La Salle University' in Manila has supported the research and provided access to stakeholder names and email addresses. The research has used the 'disconfirmatory interview' method (Andersen et al., 2012) to increase the confidence in and validity of the model. Simplified versions of the model combined with textual information have been used to structure the interviews. Interviewees have been stimulated to provide new information, which is currently not included in the model. The use of this method has iteratively led to opportunities to falsify the initial hypothesis about the cause of the problem as new information was obtained. Interviews have been conducted with key stakeholders (Figure 2), as will be presented in the subsequent chapters.

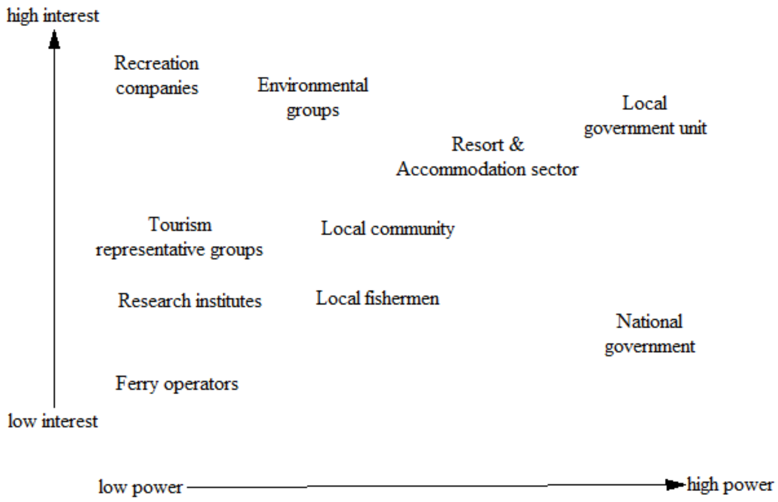


Figure 2 Stakeholder identification grid

Field observations of people's behavior on the island (and specifically around the coral reefs) have been used to gain new insights about causes of the coral reef problem. The people who have been observed include tourists, the local population and business operators (including fishermen).

3. Dynamic hypothesis

This paper proposes the hypothesis (e.g. theory) that coral degradation is caused by the interaction of three reinforcing feedback loops, as described in Figure 3:

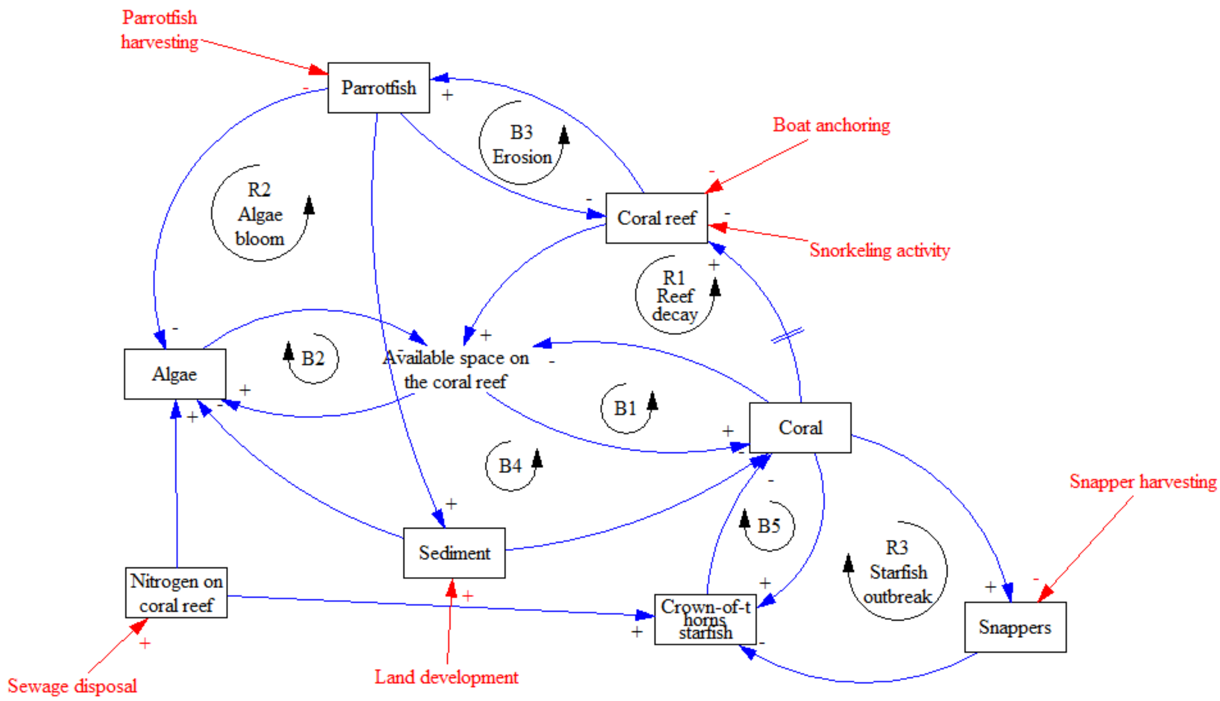


Figure 3 Dynamic hypothesis of coral reef degradation

1) Reinforcing feedback loop R1 'Reef decay', in which a lower occupation of the coral reef by live coral tissue leads to lower coral reef formation. When there is less formation of coral reef, the available space for coral recruits to settle upon decreases.
2) Reinforcing feedback R2 'Algae boom', in which a decreased size of the live coral tissue and coral reef substrate lead to lower growth rates of the parrotfish, which then leads to lower grazing rates on macro-algae on the reef. Lower grazing rates of macro-algae lead to more macro-algae occupation on the reef which then leads to a lower occupation by live coral tissue.
3) Reinforcing feedback R3 'Starfish outbreak', in which a decreased size of the live coral tissue and coral reef substrate lead to lower growth rates of the snapper, which then leads to increased survival rates of the crown-of-thorns starfish (COTS) larvae. An increasing size of the COTS population, the main predator of live coral tissue, leads to a rapid decline of the live coral cover and thereby reduces the formation of the coral reef.

The strength (e.g. dominance) of these reinforcing feedback loops is affected human impacts; by sewage disposal, overfishing, sedimentation and direct coral reef destruction by boat anchoring and snorkeling/diving activities. These human impacts, which have been depicted in red, are both directly and indirectly (through the feedback loops) affecting the sustainability of the coral reef.

If the above hypothesis cannot be rejected, it will have severe consequences for the sustainability of many coral reefs around the world. The hypothesis implicates that even on coral reefs that do not face climate change, natural disasters and other destructive forces (such as illegal fishing methods), rapid degradation is still the most likely outcome.

The results in this paper will describe the process of data collection through which this hypothesis has been developed. According to Popper (1934), each theory should be able to describe an experiment which would be able to falsify the predictions of that theory. Real-life experiences on coral reefs around the world will function as the main experiment with which to falsify the hypothesis of this paper. If a coral reef can be identified on which sewage disposal, overfishing, sedimentation and direct coral reef destruction by boat anchoring and snorkeling/diving activities are present, but rapid degradation is not the result, the theory can be rejected. Furthermore, if, on coral reefs which implement the policies as proposed in this paper, coral reef recovery is not the result, it will also lead to a rejection of the theory.

4. Literature review: understanding coral reef growth

This paper will start with a literature review to better understand the natural growth processes of the coral reef. It will focus on identifying those ecological components which are deemed most important in the creation of coral reef growth under natural environmental conditions.

4.1 The natural growth of an undisturbed coral reef

This chapter describes the marine biology of coral tissue. It explains how the coral organisms develop coral reef structures (calcium carbonate skeleton) and how those structures influence the coral growth. It will also describe how sedimentation, algae growth and fish stocks interact with the growth of the coral. The growth of coral will be simulated on a coral reef without human disturbances. The chapter will end with an explanation of how the growth of an undisturbed coral reef will be used to capture the prevailing trend at the start of all the models as presented in this paper.

4.1.1. Coral tissue biology

Before explaining in more depth the biology of coral growth, the distinction between coral reefs and the coral organisms (or coral polyps), which are responsible for producing them will be explained. This chapter will focus on explaining the driving forces behind the growth of coral polyps, while the next chapter will focus on how those polyps are able to produce a carbonate reef over time.

In essence, the coral polyp is a close relative to the most 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, such as the number of tentacles and forms of reproduction (Sheppard, Davy, & Pilling, 2009). Figure 4 shows the system dynamics model of the growth processes of coral polyps. In the remainder of this chapter, the model and its assumptions will be explained.

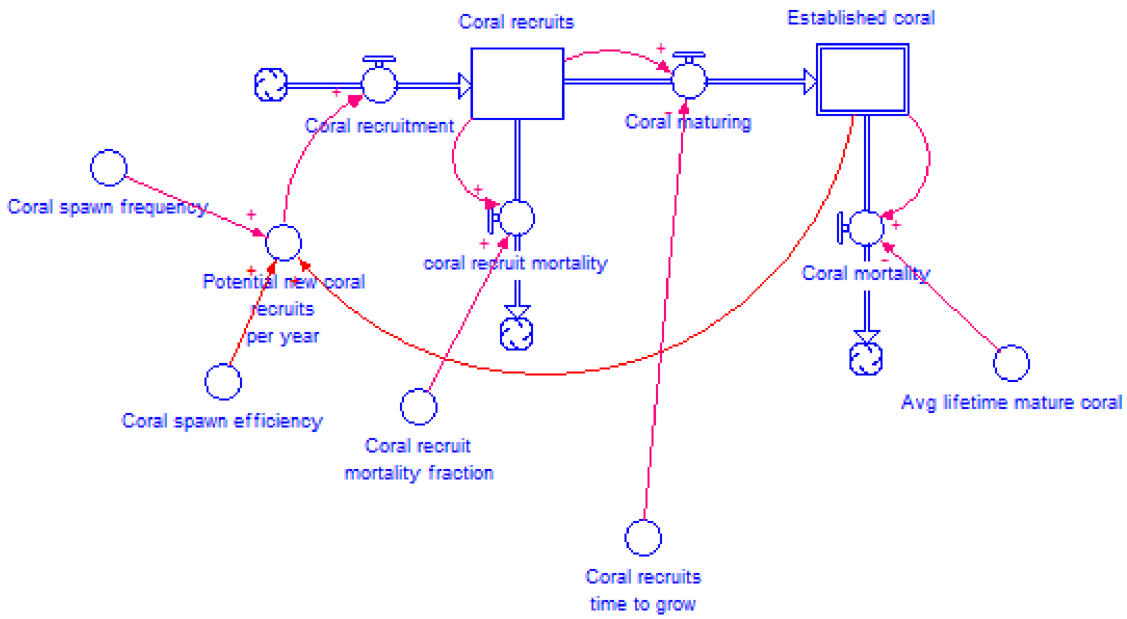


Figure 4 Live coral tissue biology model

There are many different species of coral polyps which live on the reef. In this model, all those different types of coral are aggregated into two main level variables (or stocks). The first level variable is the coral recruits, which are the coral polyps which have only recently settled on the coral reef substrate. The second stock consists of the coral polyps which have grown and matured to become fully settled on the reef substrate (established coral). Both stock values are measured in hectares. The model assumes that in the start of the simulation period, the year 1970, there are 200 hectares of coral recruits and 250 hectares of established coral.

The coral colony grows through the recruitment of new corals. Since in the coral tissue biology model there is not yet a limiting factor on the growth of the coral polyps, the coral recruitment rate is equal to the potential new recruits per year. 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 et al., 2009; Viles & Spencer, 1995).The ‘Coral spawn frequency’ explains how often the established coral colony spawns per year. A time to spawn of ‘1’ means that the colony has a spawning event once per year. Although coral colonies are often spawning on a year-round basis, they mainly reproduce through ‘mass spawning’ events. A synchronized mass spawning effect is assumed to occur once a year (Glud, Eyre, & Patten, 2008; Harrison, 2011). The ‘Coral spawn efficiency’ shows how successful the coral colony is in reproducing. An efficiency of ‘1’ means that the coral colony is able to reproduce their exact current number at each spawning event. In this model, the spawning efficiency is assumed to be 0.5.

The coral recruits must compete with other organisms to acquire and maintain their position on the reef and to continue their maturation process. Some of the coral recruits will not survive this competition (Wood, 1999). The coral recruits who survive must grow until they reach reproductive maturity and become established coral (‘Coral maturing’). The coral mortality outflow assumes that the established coral dies when they have reached their average lifetime. Some polyps might outlive their average lifetime (3 years), while others die younger.

Figure 4 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. Furthermore, there are three minor balancing feedback loops which establish local control on the stocks of coral recruits and established coral. As the population of coral recruits grows, the number of coral recruits which die and become established coral will grow and thereby decrease the stock of coral recruits. The same holds when the population of established coral grows and the number of established corals that will die grows and thereby decreases the population of established coral.

4.1.2 Coral reef formation

While the initial coral polyps attach 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. Where the initial farmers used their excretion to fertilize the land for food production, the coral settlers are capable of building their own house for protection and growth from their excretes (Murchie, 1999). 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 5 shows the process through which the established coral polyps built their own coral reef substrate which then provides a habitat for new coral recruits.

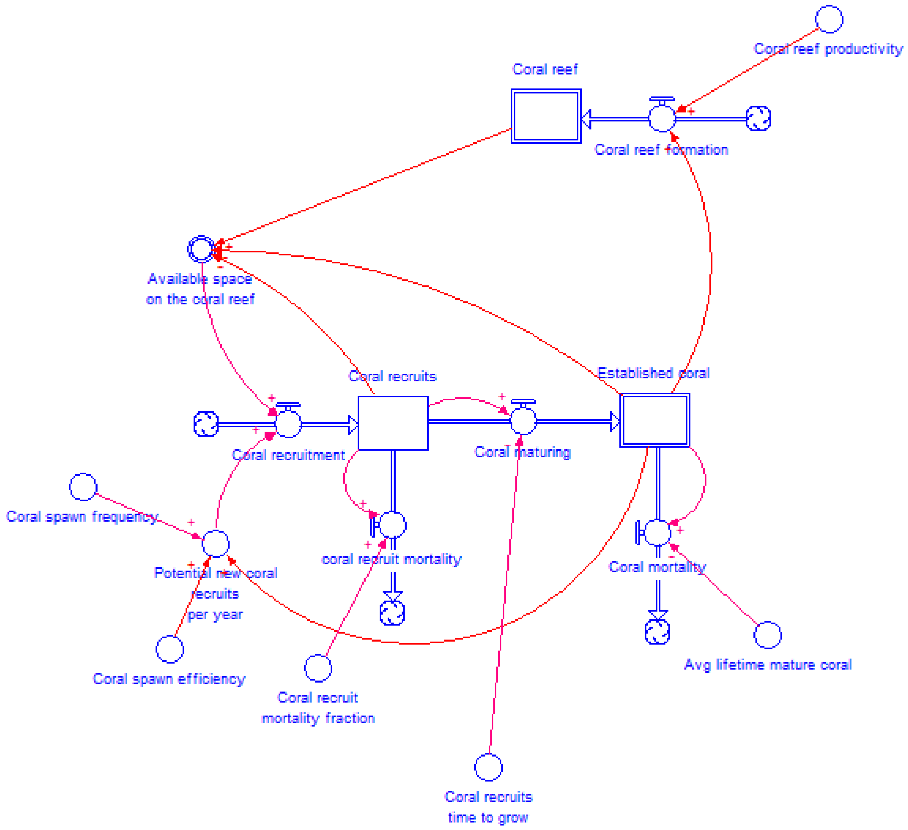


Figure 5 Growth of the carbon coral reef substrate

Although there are a wide variety of hard coral reef structures, similar to the form of the live coral tissue, the model aggregates them into one stock of coral reef. 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). In this model it is assumed that one hectare of established coral produces 0.01 hectares of coral reef per year. This means that it will take 100 years for the established coral to double their size (assuming no reef decay). This is likely still a very optimistic rate of coral reef formation.

The available space on the reef for coral recruitments depends on the total coral reef surface minus the reef which is already occupied by coral recruits and coral polyps. 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. As will be discussed later in this paper, the slow growth rate of the coral reef is a key factor related to the unsustainability of the current developments. Two balancing feedback loops lead to a decreasing availability of space when the coral recruits and established coral grow in size on the reef.

4.1.3 Carbonate sedimentation

The coral reef can decay over time because of natural and human processes. 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 (parrotfish grazing and reef destruction from human activities). Figure 6 shows the system dynamics model of the process through which the coral reef decays naturally and becomes sediment. Sediments make the water milky and it can cover the coral polyps and reef (Sheppard et al., 2009; Talbot & Wilkinson, 2001). The sediment is measured in hectares, which means that more hectares of sediment will mean that a larger part of the coral reef is covered. The sedimentation caused by the natural decay of the reef substrate, however, will only lead to very small amounts of sediments which are not likely to have an impact on coral reef growth rates. When other sources of sedimentation are included, such as parrotfish grazing and boat anchoring, the amount of sediment could start to have a negative effect on the coral growth rates.

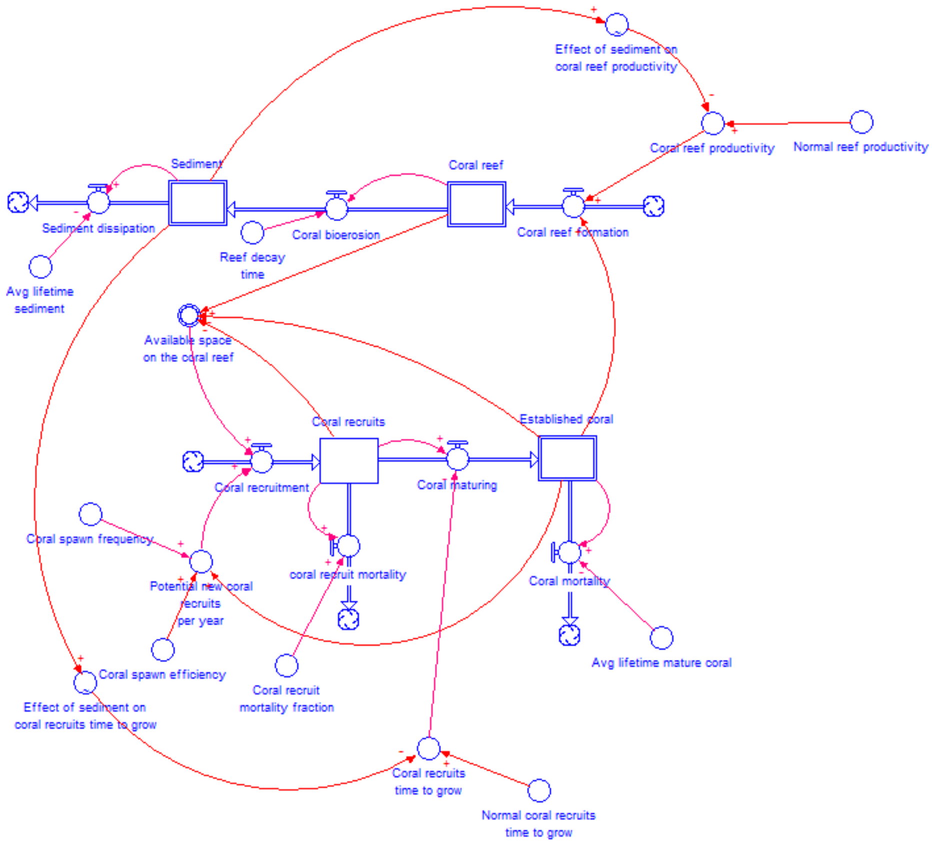


Figure 6 Coral reef decay and sedimentation effects on growth rates

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). The effect of the sediment on the coral reef productivity is assumed to be linear. The sediment on the reef is also affecting the natural growth rate of the live coral cover in two ways (Rogers, 1990; Sheppard et al., 2009):

1) The increased turbidity of the water decreases the light availability needed for the recruit growth
2) It will cost the coral recruits extra energy to fight of the sediment, energy which cannot be used to grow

The sediments are assumed to remain on the coral reef waters for 3 months on average, before dissipating into the open sea. This can vary strongly based on characteristics such as the depth and the current on the reef. It also depends on the distance of the reef from the sediment and the type of sediment. It could be as short as an afternoon or as long as a year (Quimpo, personal communication).

4.1.4 Competition for space with Macro-algae

While in the previous chapters it was assumed that the available space on the coral reef can only be covered by live coral tissue, in reality the live coral tissue faces competition from other species, mainly from macro-algae. In this model 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). Figure 7 shows the competition for space between the coral polyps and macro-algae.

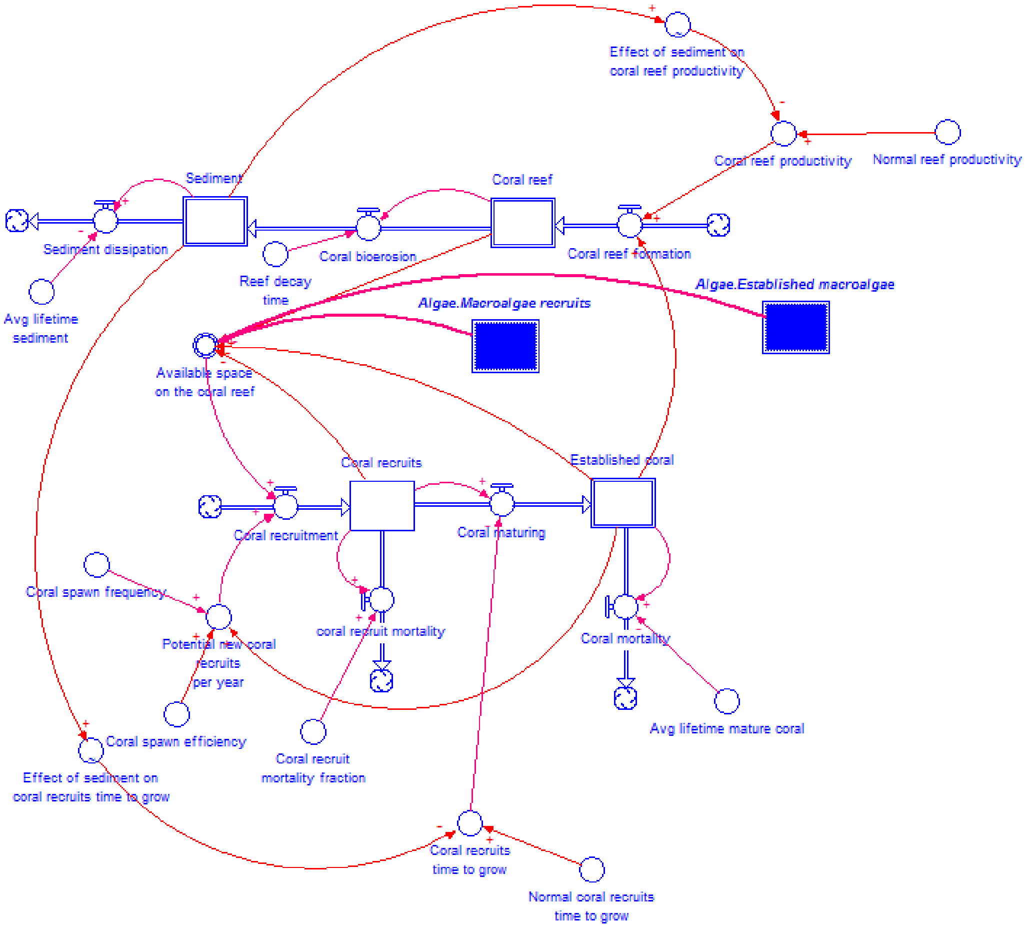


Figure 7 Competition for space between live coral tissue and macro-algae

Figure 8 reveals how 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. There are many different species of algae, globally about 2000-3000. In this model, the algae species which will be represented is the 'Sargassum Siliquosum', a fleshy macro-algae species which is living on many tropical coral reefs (de Wreede, R.E. Klinger, 1990, p. 272; Diaz-Pulido, G., McCook, 2008, p. 5).

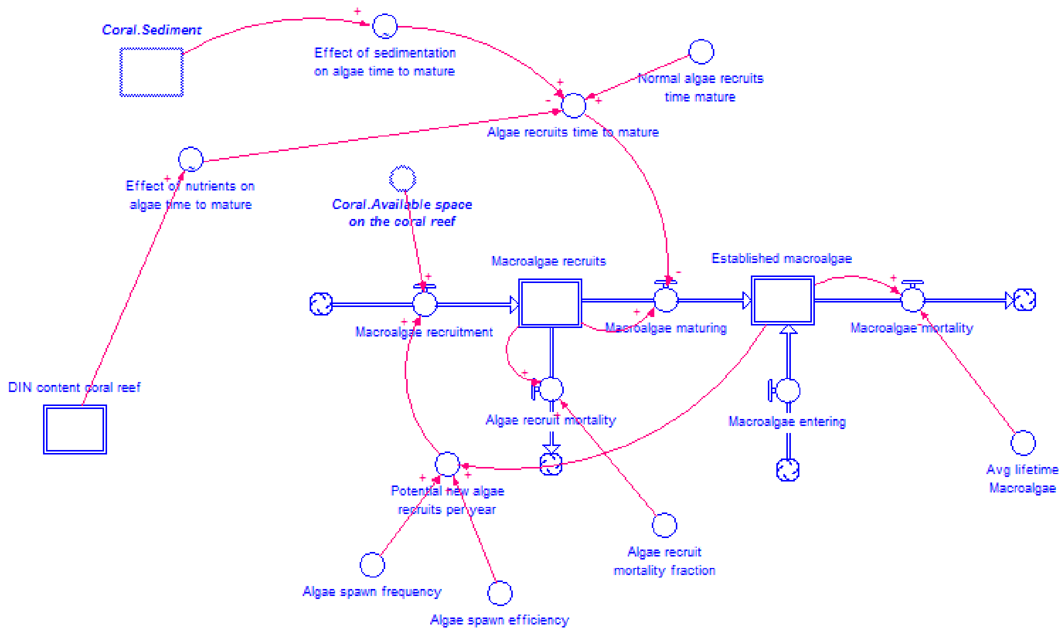


Figure 8 Macro-algae biology model

Under natural environmental conditions, the coral polyps have a competitive advantage over the macro-algae. The time to mature for coral polyps is assumed to be three months, and for algae 18 months. 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). On a healthy coral reef without significant human-induced nutrients entering, the average dissolved inorganic nitrogen content is <0.4 µmol/liter (Lapointe, 1997).

Furthermore, the coral recruits are assumed to have a mortality fraction of 0.5, while the macro-algae recruits have a mortality fraction of 0.8 (de Wreede, R.E. Klinger, 1990, pp. 272–273). Both macro-algae and coral polyps are assumed to have an average lifetime of three years. The inflow of ‘Macro-algae entering’ explains how algae can enter the coral reef from outside of the reef by means of water currents. This inflow has an important function in the model, since without it, the algae will never be able to grow again once it has died off.

4.1.5 Coral reef fish

One of the most important functions of the coral reef is to sustain the life of a wide diversity of fish species. All these different species interact with the coral reef in a multitude of ways. In this chapter, some of the most important coral reef fishes, with regards to the health of the coral reef, have been identified. The next sections will explain their role on the coral reef.

4.1.5.1 The algae-grazers (herbivores)

There are two main coral reef species which feed on the macro-algae species on the coral reef, the parrotfish and the sea-urchin. In the model, only the parrotfish has been modeled. Chapter 7.1 Boundary adequacy test discusses the reasons not to include the sea urchin in the model. 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. The excretion of calcium carbonate by the parrotfish is providing the white sand (coral) beaches on several destinations in the Philippines. 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. There are about 80 species of parrotfish with different characteristics. However, for the purpose of this model, the behavior of those species has been aggregated. Figure 9 shows the important ecosystem function the parrotfish provides by keeping the macro-algae stocks on the coral reef on a low level, thereby increasing available space for coral recruits to occupy. The second figure shows how the parrotfish are also impacting the reef substrate when they graze for algae.

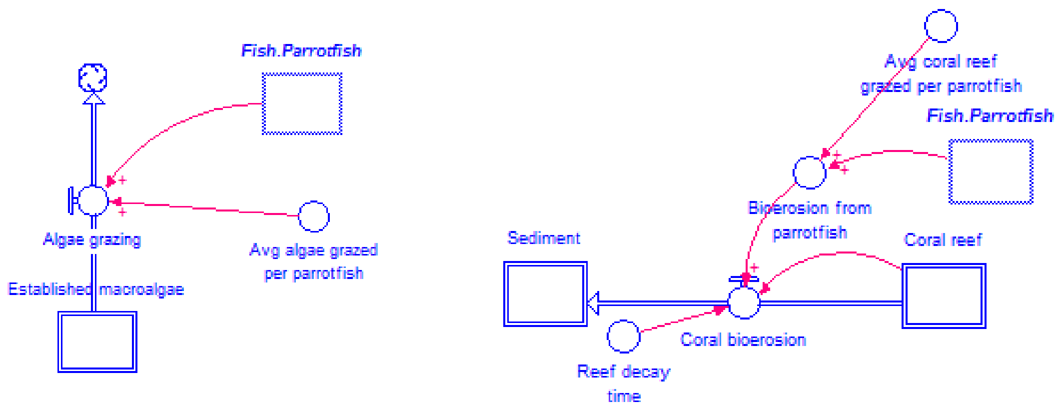


Figure 9 The role of the parrotfish grazers on the macro-algae and coral reef substrate

Mumby (2009), Sheppard (2009) and Hoey (2008) provide an excellent overview of the literature available on grazing rates of the parrotfish on different coral reef locations in the Caribbean. In this model it has been assumed that a parrotfish, on average, grazes 1 m2 of algae cover per month (or

0.0012 hectares/yr) and will have an yearly bio-erosion impact of 3e-07/hectares. This number is much lower than the grazing of algae since the algae is only a small layer while the coral reef substrate can be much thicker.

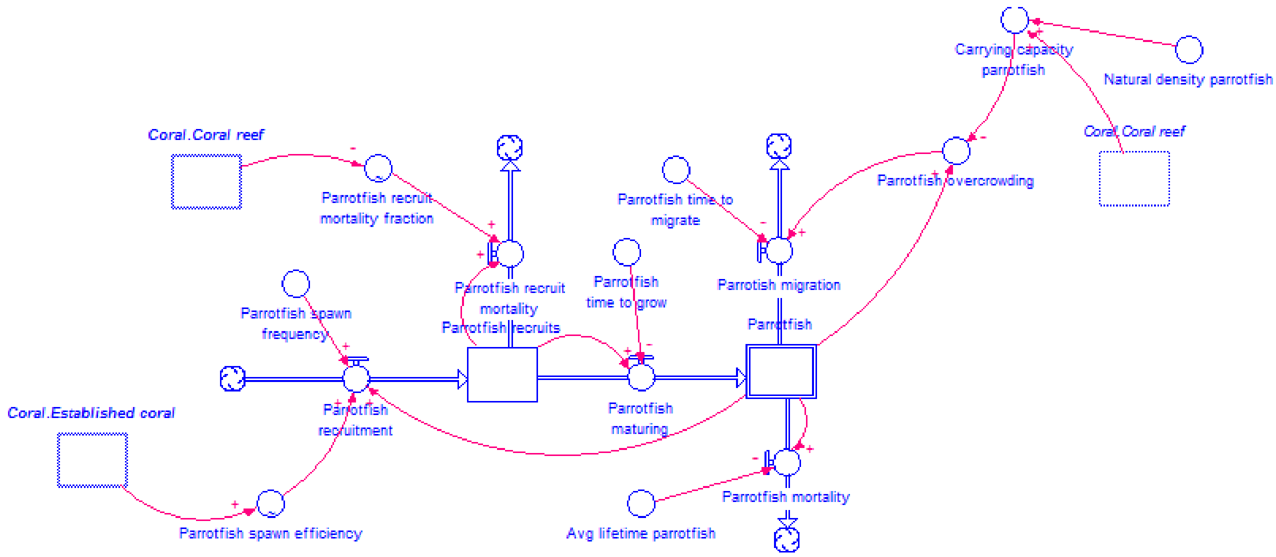


Figure 10 Parrotfish biology model

The biological growth process of the parrotfish, as described in Figure 10, 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). Since there is no specific data on the relationship between the size of the live coral cover and the spawn efficiency, the effect has been assumed to be linear with a highest spawn efficiency of 60% (1000 hectares of coral reef) and a lowest spawn efficiency of 10% (0 hectares of coral reef). When there is no coral reef to settle upon, it has been assumed that 10% of the parrotfish larvae will still be able to settle on the surrounding seagrass.
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). The herbivore parrotfish recruits might use the coral reef as a means for protection during the day, while feeding in neighboring seagrass beds during the night (McCook et al., 2001; Sheppard et al., 2009). Since there is no specific data on the relationship between the size of the coral reef and the recruit mortality, the

effect has been assumed to be linear with a highest mortality fraction of 90% (0 hectares of coral reef) and a lowest mortality fraction of 65% (1000 hectares of coral reef).

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.

4.1.5.2 The coral grazer: crown-of-thorns starfish

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; J. 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. The starfish is named for the dense covering of long, sharp spines on its upper surface. At low densities the COTS is a ‘normal’ part of the reef’s ecology. However, during outbreaks (sometimes in excess of 1,500 starfish/hectare), the COTS is capable of the massive destruction of reef-building corals (Figure 11).

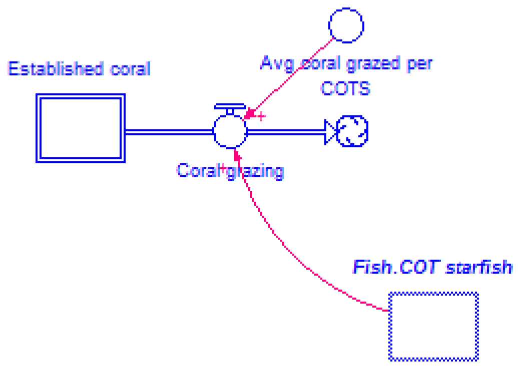


Figure 11 Coral grazing by crown-of-thorns starfish

A COTS almost exclusively feeds on live coral tissue. On individual reefs, COTS outbreaks ‘typically last 3-4 years before the starfish exhaust their food supply, with often dramatic impacts. In some locations, coral mortality may reach 95 percent, with a typical coral cover of 78 per cent being reduced to 2 per cent in 6 months around entire reef perimeters and being replaced by algal communities' (Viles & Spencer, 1995, p. 251). 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). Therefore, on a yearly basis one mature COTS is assumed to graze 0,001825 hectares.

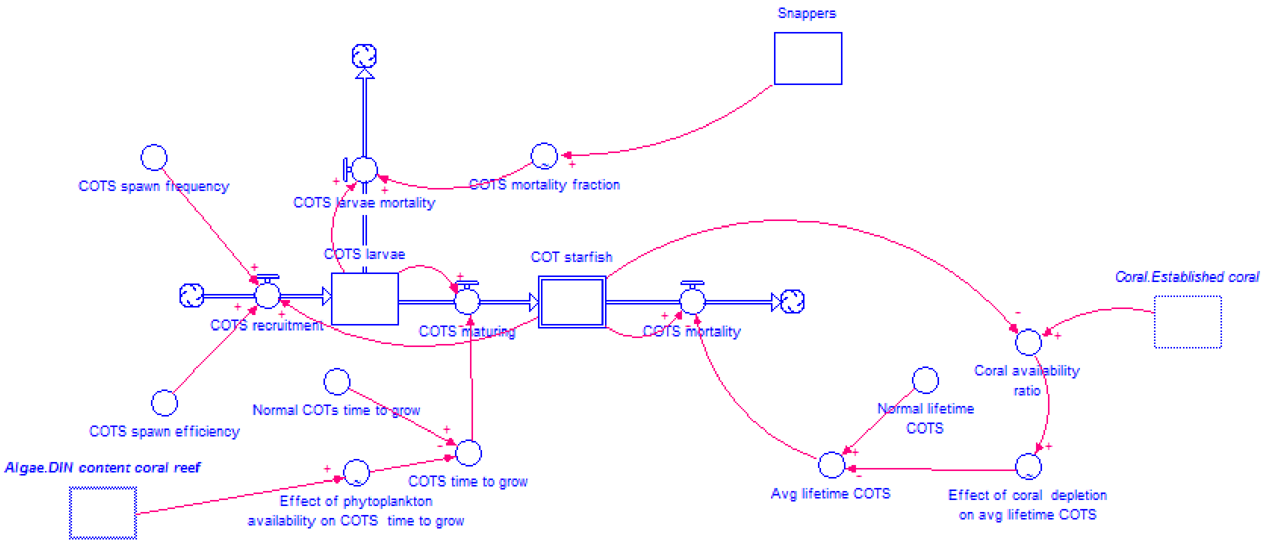


Figure 12 Crown-of-thorns starfish biology model

The biological growth process of the COTS, as described in Figure 12, is similar to the growth process of coral polyps, macro-algae and parrotfish. 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). In this model it has been assumed that the relationship between snapper stocks and the COTS mortality fraction is linear.
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). The effect of coral depletion on the average lifetime of the COTS is nonlinear. When there is still coral available, there is no effect. However, when the total live coral cover has been depleted, the avg. lifetime of the remaining COTS will decrease to become three months (the assumed time that they can live without food intake).
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 (J. Hoey & Chin, 2004; Sheppard et al., 2009; Talbot & Wilkinson, 2001).

4.1.5.3 The snapper population

The snapper has been included in the model because it is one of the most important and popular coral reef fishes in terms of serving as a food source for the local population. Furthermore, the snapper plays an important role in controlling survival rates of the COTS. There are many different species of snappers, with the 'red snapper' as the best known because of its popularity as a source of seafood.

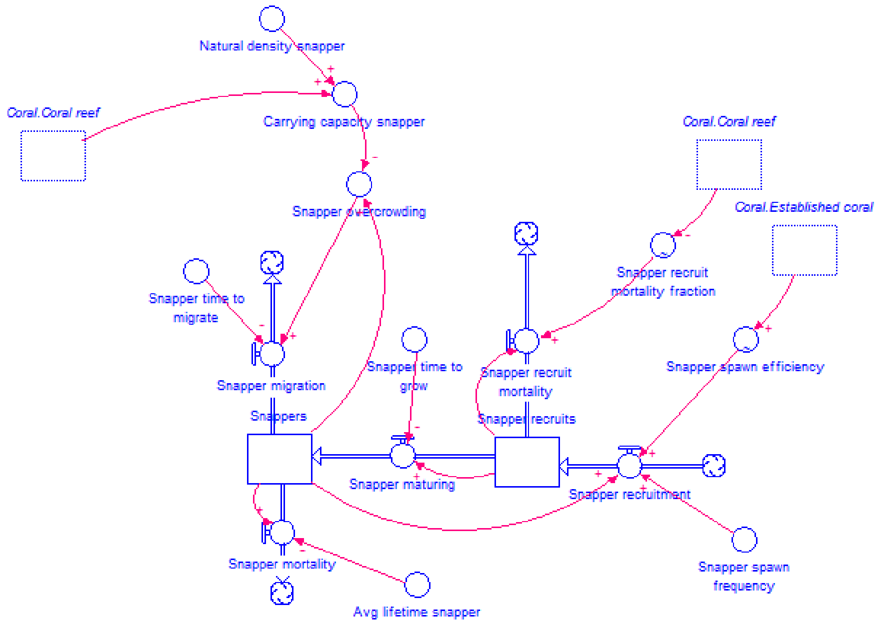


Figure 13 Snapper biology model

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 (Figure 13).

4.2 Simulation results and causal-loop-diagram

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 14). With the assumed causal relationships and parameter values, the coral reef substrate grows from 500 to 570 hectares, while the live coral tissue grows from 250 to 379 hectares. The macro-algae cover declines rapidly from 30 to 0 hectares.

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. Therefore in later chapters, long-term steady growth behavior of the undisturbed coral reef can be compared with the behavior of coral reefs which are affected by human development. The initial transients leading up to steady growth can be minimized by adjusting initial stock values of the main stocks in the model:

Coral reef = 509; Sediment = 0.65; Established coral = 341; Coral recruits = 33; Macro-algae (established & recruits) = 0; Parrotfish recruits = 255051; Parrotfish = 5197200; Snapper recruits = 824475; Snappers = 4270501; COTS larvae = 1889; COT Starfish = 4565

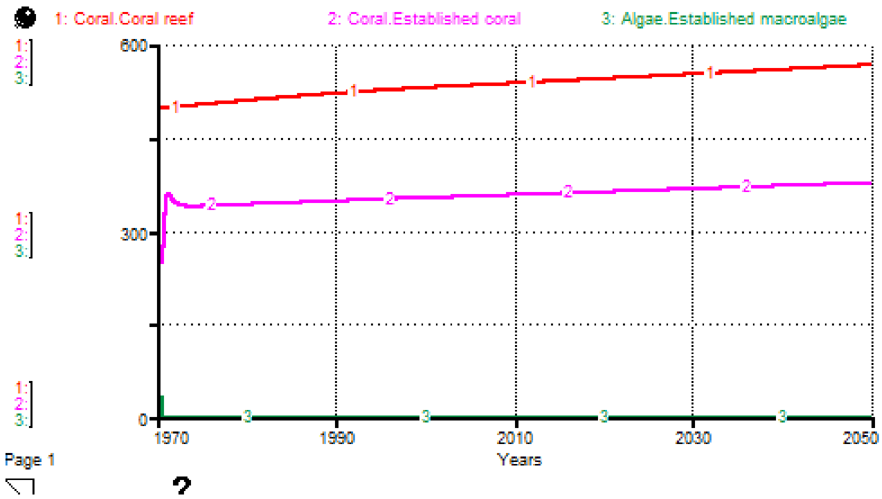


Figure 14 Simulating coral growth on an undisturbed coral reef

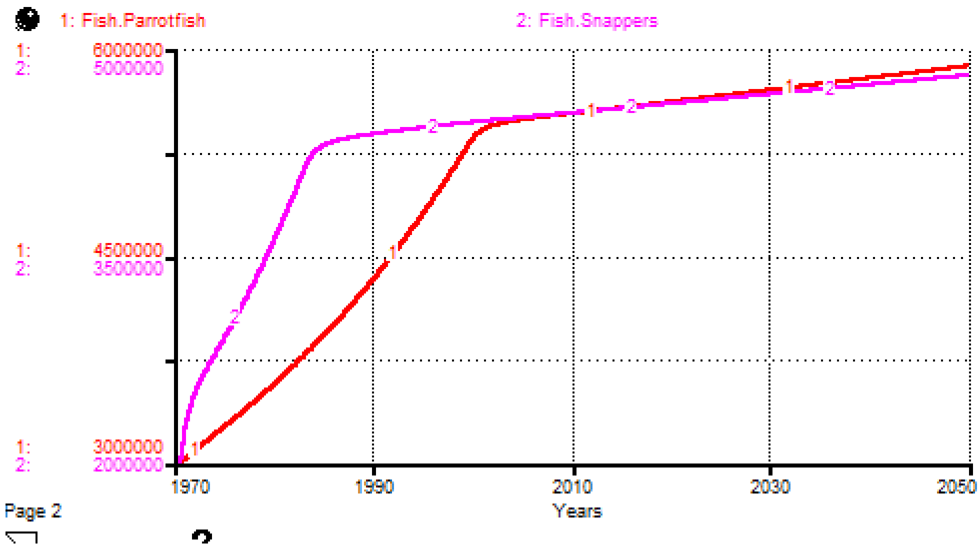


Figure 15 Simulating fish stock growth on an undisturbed reef

The simulations (Figure 15) show similar behavior of the fish stocks, which initially grow rapidly over time, until they reach a steady state growth period in which their fish stocks grow whenever the size of the coral reef grows. The change in the slope of the growth in the parrotfish and snapper population around the year 2000, therefore, is a consequence of the populations reaching their natural density on the coral reef. When they have reached this carrying capacity, the populations will only be able to grow in size whenever the coral reef grows in size. The observed behavior in the undisturbed coral reef system is a consequence of the natural structure of the coral reef (Figure 16). There are three important reinforcing feedback loops, which are leading to a steady growth of the coral reef and the fish stocks over time:

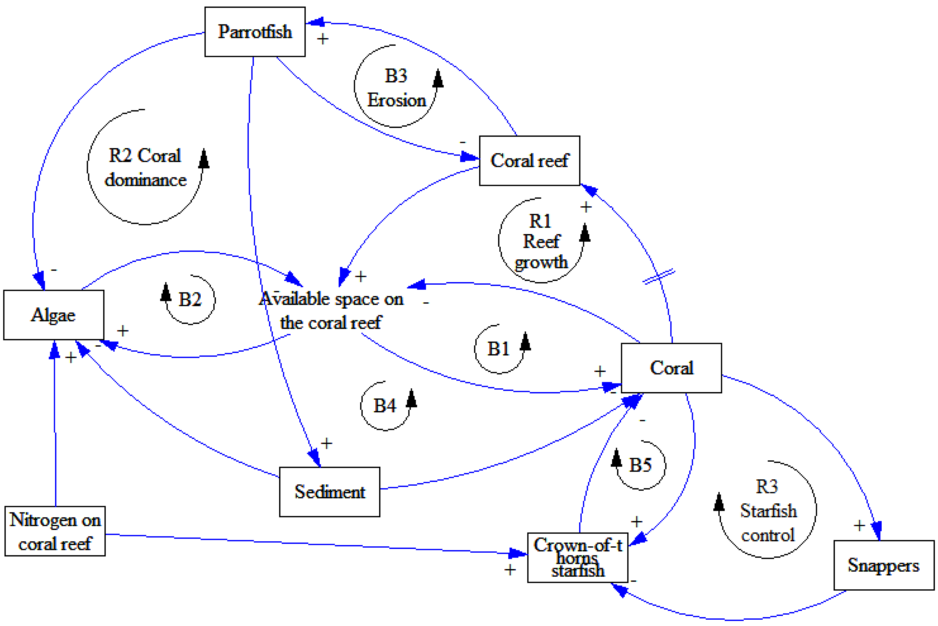


Figure 16 Causal-loop-diagram undisturbed coral reef system

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.

A coral reef can only grow in size when it is dominated by live coral tissue, since macro-algae are not able to build a coral reef substrate. The main drivers for coral tissue dominance over macro-algae dominance are:

1) A low nitrogen content on the coral reef, which decreases growth rates of macro-algae and crown-of-thorns starfish;
2) Sufficient stocks of parrotfish, which keep the macro-algae from dominating the reef substrate; and
3) Sufficient stocks of snappers, which control the outbreaks of crown-of-thorns starfish which could rapidly decrease the live coral cover

Due to the long delay in the formation of the coral reef, the reinforcing structure will, in favorable conditions, lead to steady state growth of the coral reef, the live coral tissue and the fish stocks. However, it can already be theorized from the model structure that, under less favorable conditions, the self-enhancing process on the coral reef could lead to a runaway collapse over time. This would be possible under the assumption that the time it takes to destroy the coral reef is much shorter than the time to build it.

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

5.1 The growth of a coastal population and fishing industry

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. It will start describing the way in which a population grows over time. Thereafter, it will show how this growth of the population leads to more pressures on both the amount of nutrients on the coral reef, the fish stocks and the destruction of the reef substrate.

5.1.1 Population growth

The human population model, as depicted in Figure 17, is remarkably similar to the population models of the live coral polyps, macro-algae and fish species, although the human species reproduces sexually and not through spawning. The population has been disaggregated into three age groups:

1) From 0 to 14 years old;
2) From 15 to 64 years old; and
3) Older than 65

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. Historically, the percentage of women in the population in the Philippines has always been close to 50% (Philippine Commission on Women, 2014). In this model it is assumed that 5% of the women are not fertile. With regards to the total fertility rate, the average number of children per woman in the Philippines is 2.8 in urban areas and 3.8 in rural areas. 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). The life expectancy at birth in the Philippines is, on average, 72 years (Philippine Statistics Authority, 2011).

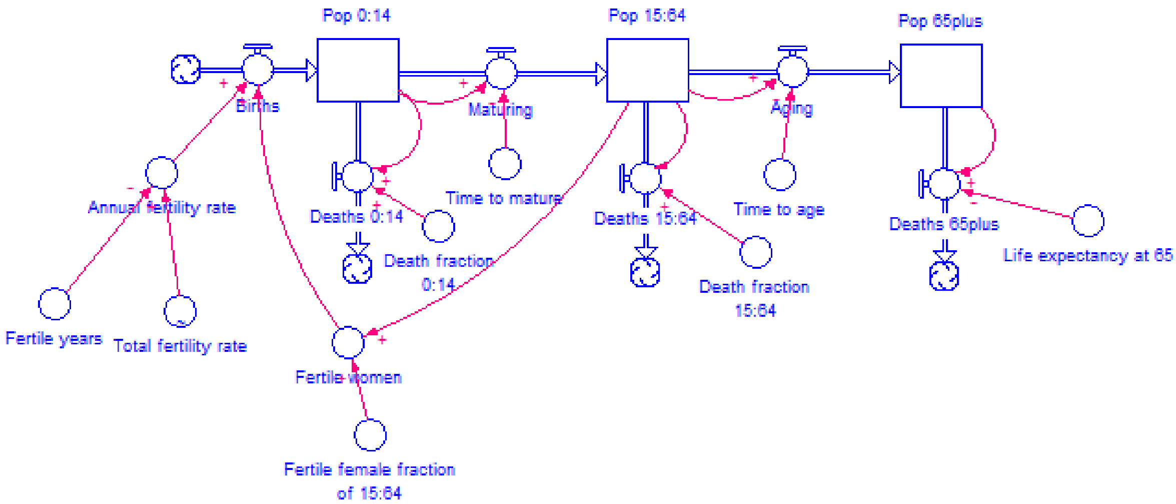


Figure 17 Population growth model

Simulating (Figure 18) the population model with initial population values of respectively 1000; 1000; and 250, shows how the population grows from 2250 in 1970 to 7642 in 2050. It increases by a factor of 3 over a period of 80 years.

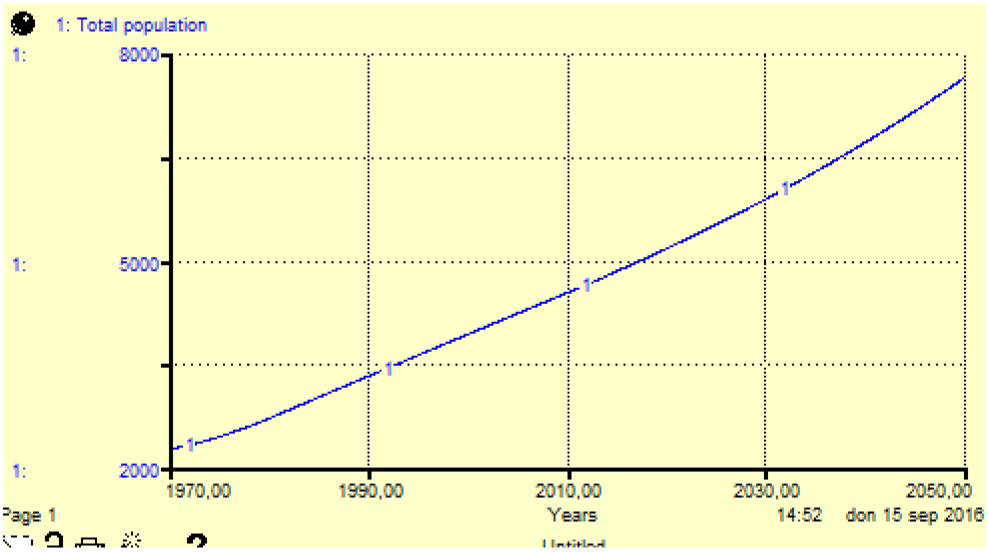


Figure 18 Simulating population growth

5.1.2 Pollution from sewage disposal

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. In Coron Town and parts of Siargao Island, the local population is living in run down houses above the water (Figure 19). Sewage is directly dropped into the water. On other locations, such as El Nido, Boracay and Port Barton, Panglao, Moalboal and Mactan, the sewage from the local population living in towns is transported to the seawater through two or three sewage outfalls (Figure 20, Figure 21 and Figure 22). The abundance of algae around those sewage outfalls clearly shows that these outfalls are not transporting sewage water which has been treated properly.

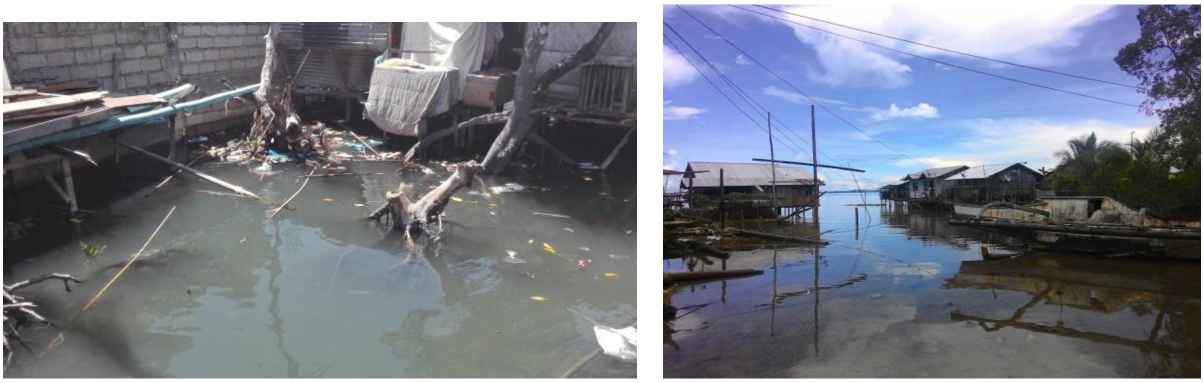


Figure 19 Local population housing settlements in Coron Town and Siargao Island

Figure 20 Sewage disposal and algae bloom on Borocay

Figure 21 Sewage disposal and algae bloom on El Nido

Figure 22 Sewage disposal in Port Barton

In the model (Figure 23), the sewage output from the local population has been modeled based on the total population and an average sewage output of 730 liters per person per year. The share of sewage from the local population which is treated is generally very low in the coastal areas of the Philippines. 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). These septic tanks are available on different levels, corresponding to the level of treatment. 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 share of sewage which is treated properly is assumed to be 10%.

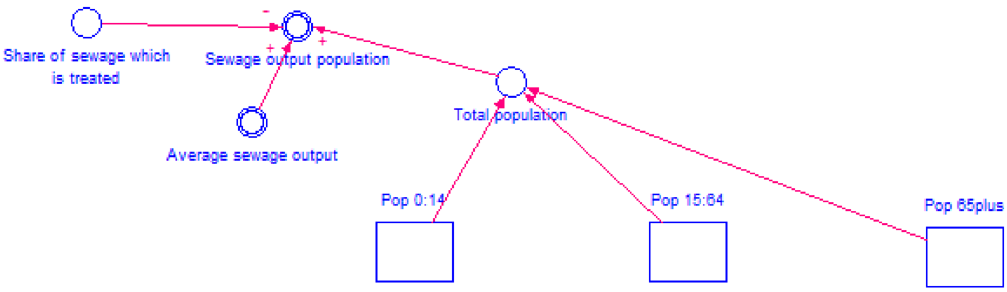


Figure 23 Sewage disposal local population model

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 (e.g. the location where the sewage is disposed). It is assumed that it will take three months for the DIN content to dissipate from the beachfront to the coral reef. This can vary strongly based on characteristics such as the depth and the current among the reef. It also depends on the distance of the reef from the entering of the nitrogen. Figure 24 describes the process through which the inorganic nitrogen dissipates from the sewage disposal to the beachfront and into the coral reef.

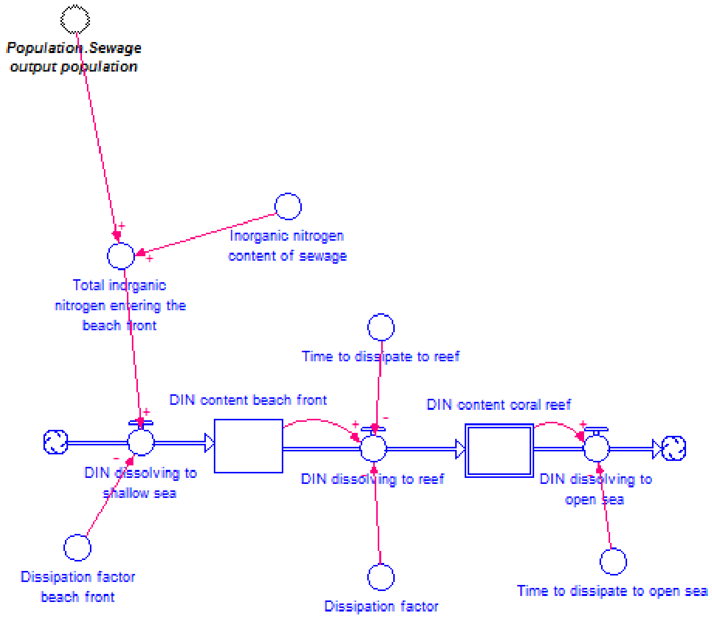


Figure 24 Nutrients entering on the coral reef

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 (Figure 25) when the pressures become high enough and sewage is being disposed on a continuous basis. As discussed in the previous chapters, the DIN content on the coral reef has an important role to play in containing algae bloom and crown-of-thorns starfish outbreaks. However, as the model shows, when the disposal of sewage is stopped, the DIN content on the coral reef will be able to recover to its natural value relatively fast, as the time for the nitrogen to dissipate to the open sea is only three months. This relatively short delay will be discussed further in the proposed policies chapter.

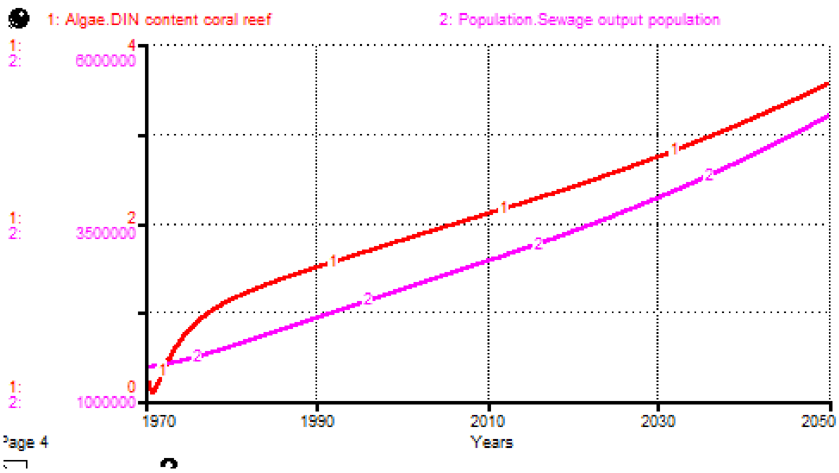


Figure 25 DIN content on the coral reef

5.1.3 Developing a fishing industry

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 26). 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.

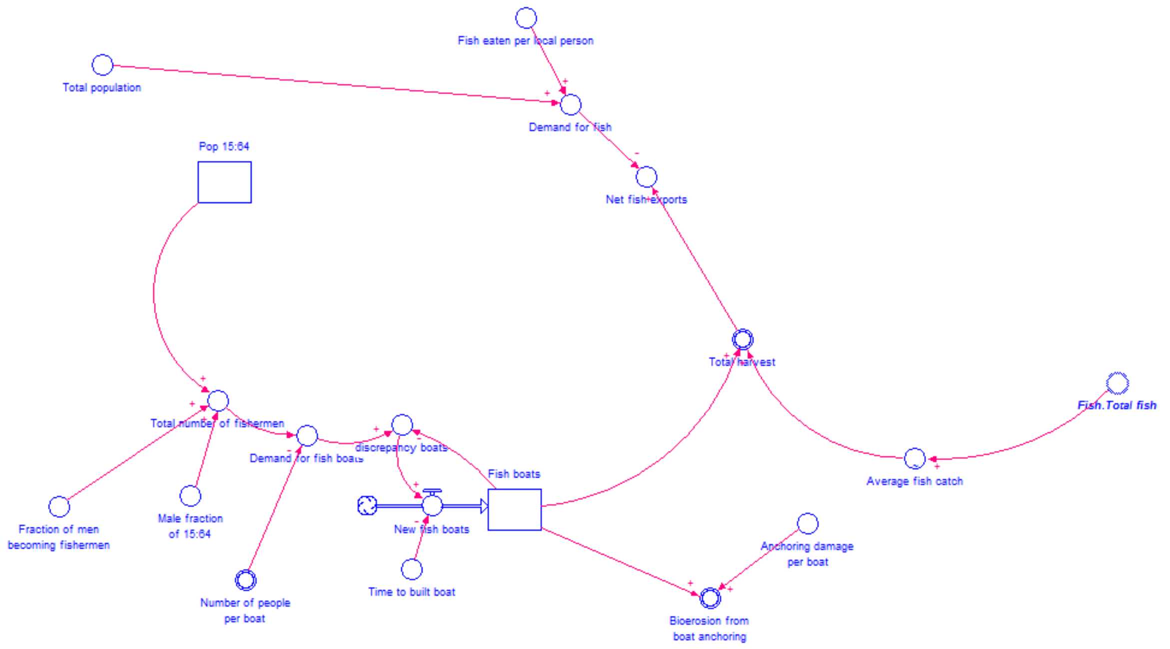


Figure 26 Local fishing community

Based on observations in the Philippines, it has been assumed that 30% of the male population between 15 and 64 years old becomes fisherman. Most of the locations, before developing a tourism industry, could be described as small local fishermen economies. In those economies, a large part of the male population has no other option than becoming fishermen. The 70% who are not fisherman include people in the construction sector, transport sector (tricycles and motorbikes), service industry (shopkeeper, barber etc.) and people with a disability.

The fish industry plays an important role in the degradation of the coral reef through their interaction with important fish stocks. In this model, only the endogenous effect of a growing fish fleet based on a local population dynamics is modeled. Important factors which have been excluded, such as illegal fishing, will be discussed in more detail in chapter 7.1 Boundary adequacy test. This model intends to show how, even with only regular fishing practices by the local population, negative impacts on the coral reef are a likely outcome. The model assumes that the average fish catch per boat is 50 fish per day (or 15600 per year based on 6 days of fishing per week) when fish levels are not depleted. However, when the fish stocks are depleted below 1.000.000 fish, the average fish catch will decline linearly towards zero (Figure 27 and Figure 28). This is because the fish stocks on the (relatively shallow) coral reef are easy to catch, even when their stocks are getting lower. Furthermore, fishermen often don't watch/monitor the fish stocks. They continue fishing until they are depleted.

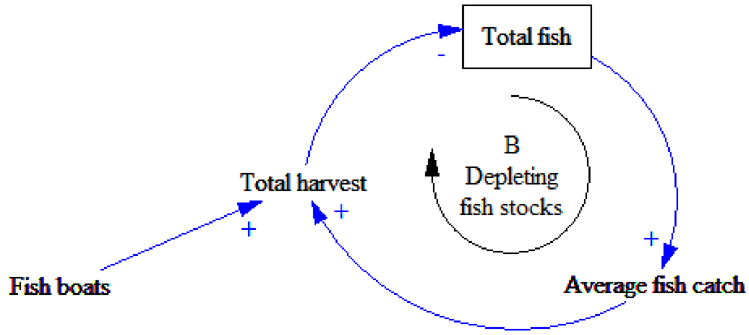


Figure 27 Causal-loop-diagram average fish catch

There is nothing in the model which explains what fishermen do when there is no fish stock for a prolonged period of time. In reality, the fishers will try to fish outside of the reef or eventually might emigrate (assuming they have money to do so). This feedback is not included in the model because it is highly speculative and outside the scope of the model. Because of poverty and limited chances elsewhere, my hypothesis is that most of the people will just limit their intake of fish and start living from chicken and pork sources and meanwhile keep fishing hoping that the fish will come back.

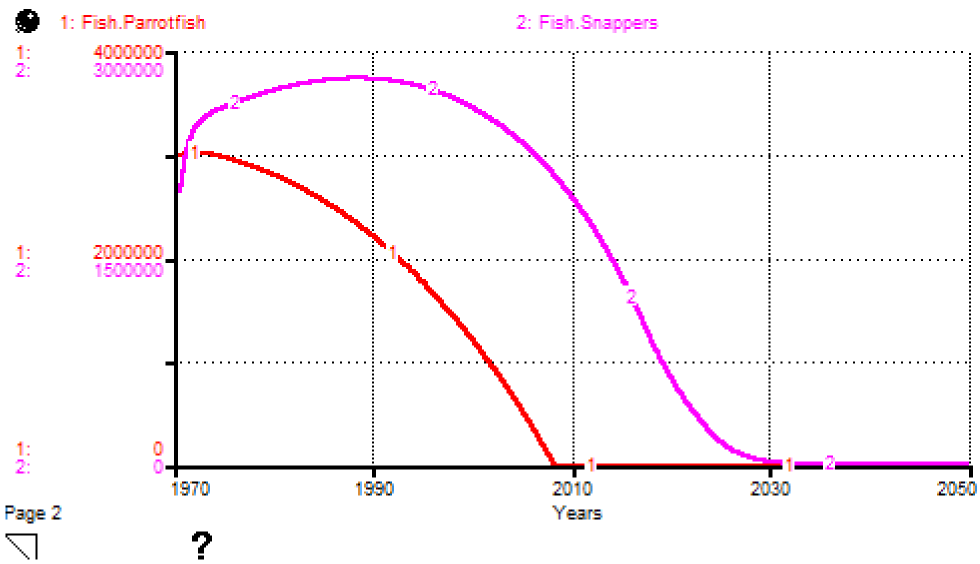


Figure 28 Simulating fish stock growth on a coral reef with a local fishing community

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.

5.2 Simulation results and causal-loop-diagram

Simulating the model with the impacts of a local growing population provides some interesting insights about the interaction between the human and ecological environment. Most counterintuitive is the fact that the coral reef substrate is actually able to grow faster on a coral with a local fishing community than on a coral reef without human impacts. This can be explained by the depletion of the parrotfish, which on a healthy coral reef is an important balancing factor controlling the growth of both macro-algae and the coral reef substrate. Thus it might seem as if it would be beneficial for the coral reef to have a small fishing community developing next to it. However, the parrotfish are not only controlling the growth of the reef substrate but more importantly, also the growth of macro-algae on the substrate. As the simulations in Figure 29 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.

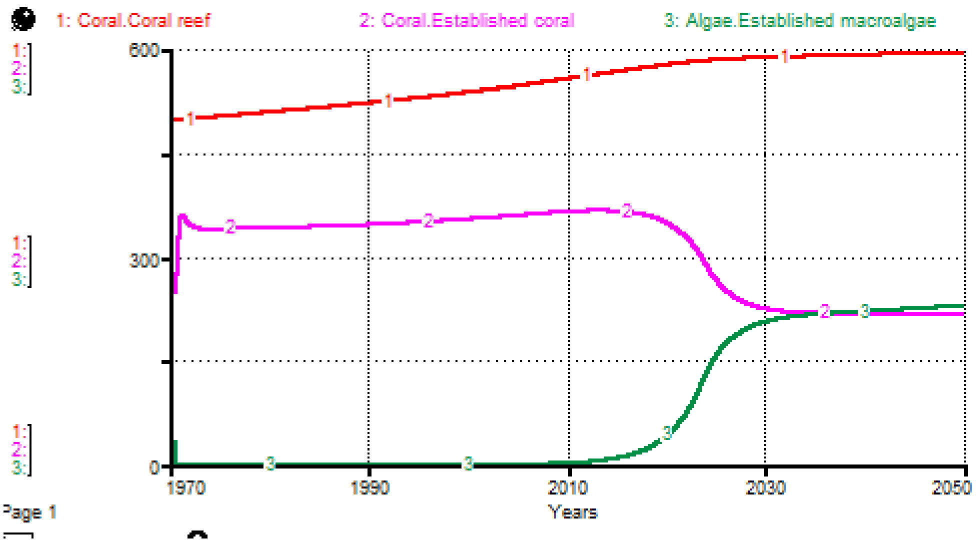


Figure 29 Simulating coral growth on a coral reef with a local fishing community

The long-term impacts of this increasing macro-algae dominance on the reef will also affect the size of the coral reef substrate. 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 30). 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.

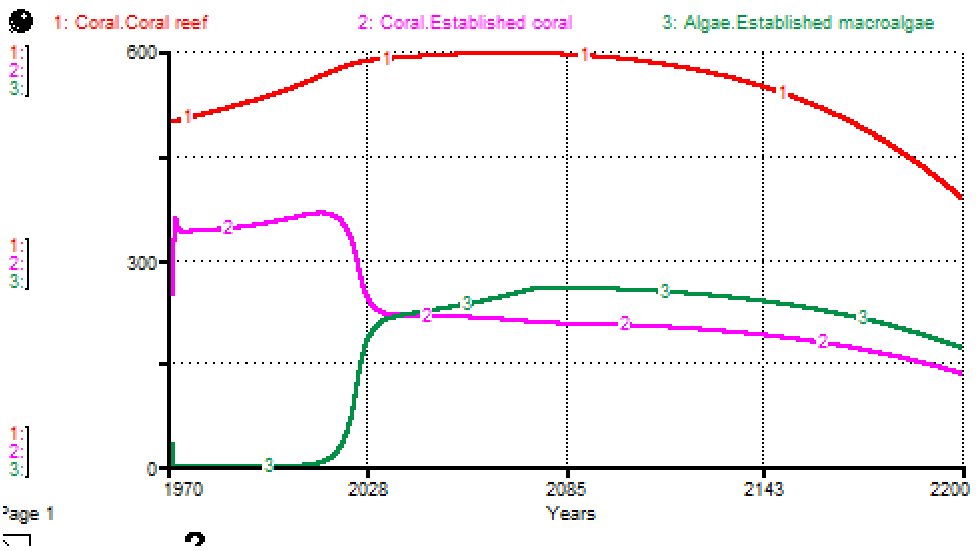


Figure 30 Simulating long-term coral decline on coral reef with local fishing community

Figure 31 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.

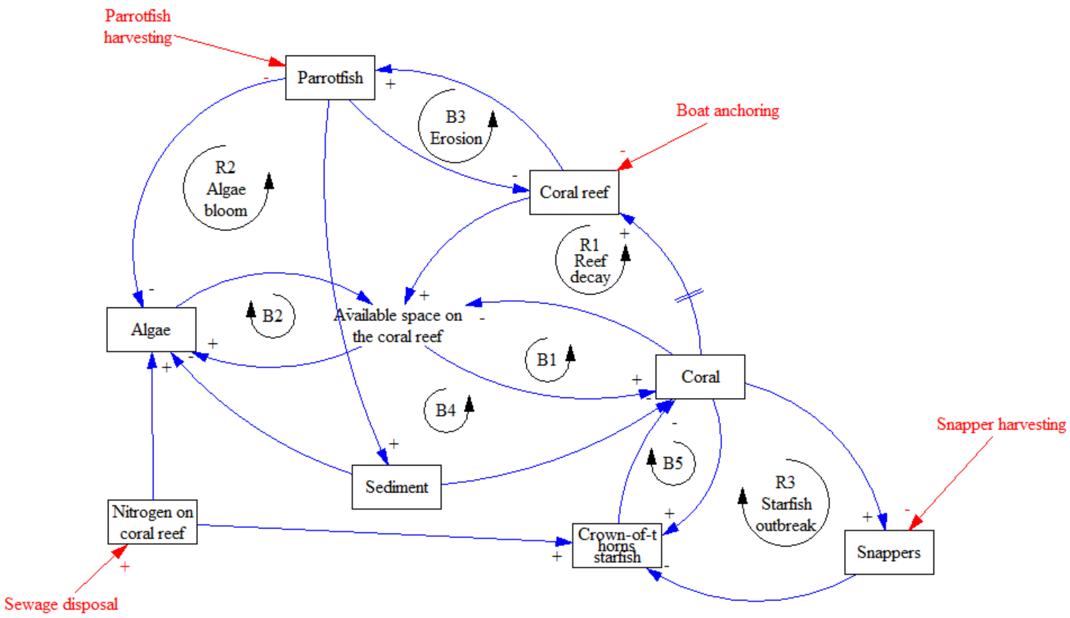


Figure 31 Causal-loop-diagram coral reef with local fishing community

5.3 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 show how a local population, which slowly shifts their economy from fishing to tourism development, will impact the coral reef ecosystem. The goal of this model is to increase a deeper understanding about the multitude of ways this shift is affecting the coral reef, both positively and negatively. It will start with describing the way in which the tourist sector develops over time. Thereafter, it will show how increasing tourist numbers are interacting with the growth process of the coral reef and how they interact with the local population growth on the destination.

5.3.1 Tourism 'boom' in the Philippines

The Philippines has a large untapped potential for tourism, with beautiful islands, a rich cultural heritage and a friendly and welcoming local population. However, growth in tourist arrivals has structurally lacked behind that of even its smallest neighbors like Singapore. Based on the latest numbers from the UNWTO (2015), the Philippines accounted for only 1.3% of tourist arrivals in the Asia Pacific Region in the year 2014. Malaysia (5.8%) and Thailand (10.2%) scored considerable higher, while also 'small' Singapore accounted for 5.1% of total visitors to the region.

The low tourist arrivals could for a large part be explained by a lack of infrastructure capacity. Especially the main airports in Manila and Cebu are already overcrowded and lack far behind airports like Bangkok, Kuala Lumpur and Ho Chi Minh in terms of available services and customer convenience. However, both airports are already in the process of renovation. The new passenger terminal in Cebu, for example, is expected to be ready by June 2018. With infrastructure improving, it can be expected that the Philippines will finally unleash its full tourism potential. Due to a rapid increase in the middle-class of many Asian countries, the growth in international tourists coming from this region is expected to continue in the years to come (Butler, 2009). Especially in Boracay and Mactan, a large percentage of the tourists are already arriving from China and Korea. Furthermore, increasing ASEAN integration would lead to an easier flow of passengers between different countries in South-East Asia (Mencias, personal communication). Finally, the growth in domestic tourism (especially because of young population) is rapid, mainly driven by increasing incomes, an increasing number of low-cost flights and social media effects.

To conclude, the growth in tourist arrivals is bound to grow in the coming years. The only potential negative influences could be natural disasters and/or political instability. However, even with relatively slow growth in tourism in the Philippines up to this point, there are already destinations, such as Boracay and El Nido, which are experiencing significant pressures from growth in tourist arrivals.

5.3.2 Tourism growth on individual destinations

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). Figure 32 describes how these prior visitors influence the amount of new people who would like to visit the destination, e.g. the destination diffusion rate. The destination diffusion rate is the total number of encounters between prior tourists and their relatives multiplied by the probability that a person will choose to visit the destination in the future. It is assumed that there is no limit to the amount of people which can become potential new tourists. This is based on the assumption that tourists to the Philippines come from all over the world, especially Europe (population 750 million), the US (320 million) and increasingly more from other Asian countries, mainly China (1.4 billion), Korea (50 million) and Japan (130 million),

The contact rate is the number of people a tourists interacts with about his holiday after returning. Up until the year 2000, the returning tourists interacted mainly mouth-to-mouth with direct family and friends (+- 20 per year). From 2000, there was a rapidly growing trend towards the use of social media in sharing holiday experiences (Tripadvisor, Facebook, Instagram, etc.). Therefore, people who come back from a holiday nowadays are able to reach a much larger public than before (+- 40 per year). Especially among Asian tourists, there is a constant use of selfie-sticks to share special moments online with friends and relatives. Not every person who encounters a relatives' holiday experience will decide to visit the same location. The adoption rate shows what percentage of people decides to visit the destination in the future based on the interaction with the prior tourist. It is assumed that new experiences will make a tourist, who has visited a certain destination, forget about past experience in three years.

The potential new tourists are the people who have decided to visit the destination in the future and will start organizing their trip. Potential tourists will forget about the destination when they do not have the chance to visit the destination in the next five years. However in that case it is still possible that in the future they become enthusiastic about the destination again by interacting with another prior tourist.

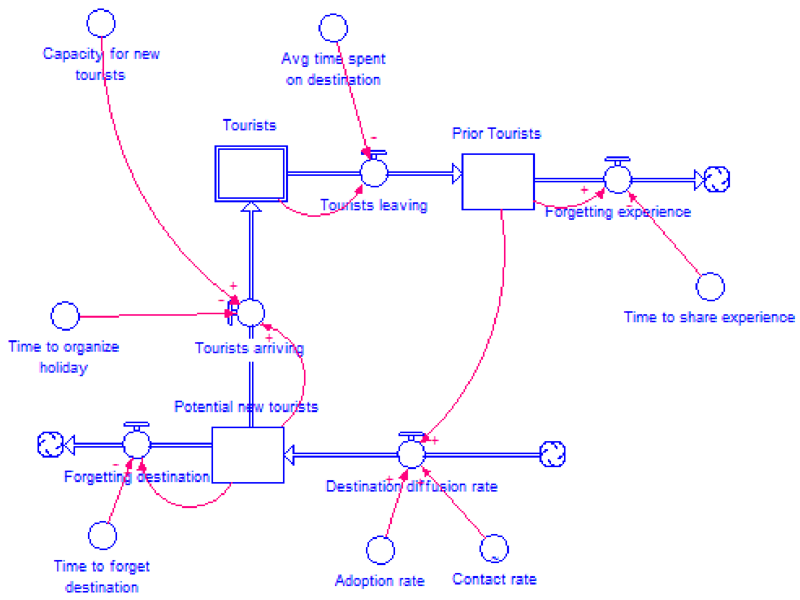


Figure 32 Tourism growth model

The potential number of tourists who want to visit the destination in each given years depends on the number of potential new tourists and the time it takes to organize their holiday. It is assumed that, on average, it will take potential tourists one year to organize a trip to the destination. This one year includes preparing flights, resorts and activities and arranging vacation days. This time is expected to be shorter for domestic tourists (who can visit the destination within 6 months) and longer for foreign tourists (who might need about two years because they also have other long-distance travel plans). However, when there are no rooms available in resorts on the island, the potential tourists will have to postpone their trip. From my experience, with the exception of a small percentage of 'backpackers' who come to a destination without a reservation, most of the tourists will have pre-arranged resort rooms.

Figure 33 describes the process through which the available resort capacity on a destination increases when that destination gets more popular with tourists. In this model, all different kinds of available accommodation options for tourists are aggregated into the stock of tourist resorts. This includes the traditional beachfront resorts, but also hotels, hostels and more off-beach accommodation options. The number of new resorts which are planned to be built is equal to the difference between the demand for resorts and the actual number of resorts on the destination now.

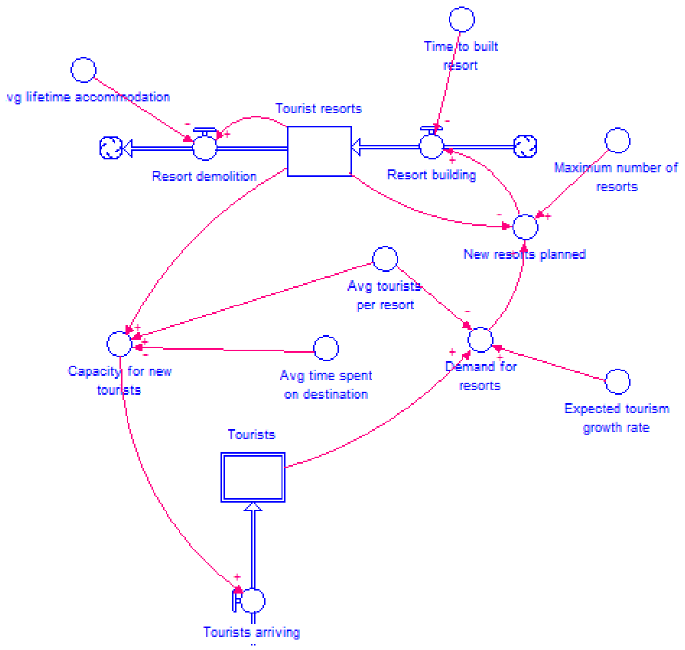


Figure 33 Resort capacity for accepting new tourists

The demand for resorts shows the decision making process of project developers. Project development in the tourist resort sector in the Philippines is often funded by foreign investors in cooperation with a local person due to national laws (only people from the Philippines are allowed to start a business). The project developers often decide to invest in new property based on the number of tourists which are visiting the destination now and the expected growth rate for the next years. It is assumed that, on average, the expected tourism growth rate is 20%. This number can vary in different stages of the tourism cycle, often starting low when a destination is only just discovered, then growing and peaking when destinations get relatively crowded and/or environmental pollution becomes a major problem. These feedbacks are outside the boundary of this model. For example, in Borocay, which has seen tourism development starting already in 1980, tourism is still expected to grow, even when overcrowding and pollution seem to become a bigger problem. Thus the capacity for accepting new tourists increases as the number of tourists on the destinations increases. The model further assumes that after a period of 30 years, the resorts will not be able to serve as a tourist resort any more due to decay of its structural foundation. Then these resorts will be demolished.

It is assumed that there is an absolute maximum of 3200 resorts on the island. This number is based on a destination with a size like that of Borocay (1000 hectares). This number is likely very optimistic, since other (environmental and social) factors are expected to limit tourism growth before that time. Borocay reached tourist arrivals of 1.5 million in the year 2015. With a maximum of 3200 resorts and the assumptions for average time spent on destination and average tourists per resort, Borocay would be able to reach a yearly number of 4 million tourists with this carrying capacity.

However, this number is highly speculative since it is a prediction for a future period. Further research on actual carrying capacities is needed. Figure 34 reveals the exponential growth of the number of tourists on the destination, capped by the carrying capacity around the year 2035. As described, there is no feedback between the state of the environment and the attractiveness of the destination. Therefore the growth pattern of the number of tourists will be s-shaped growth.

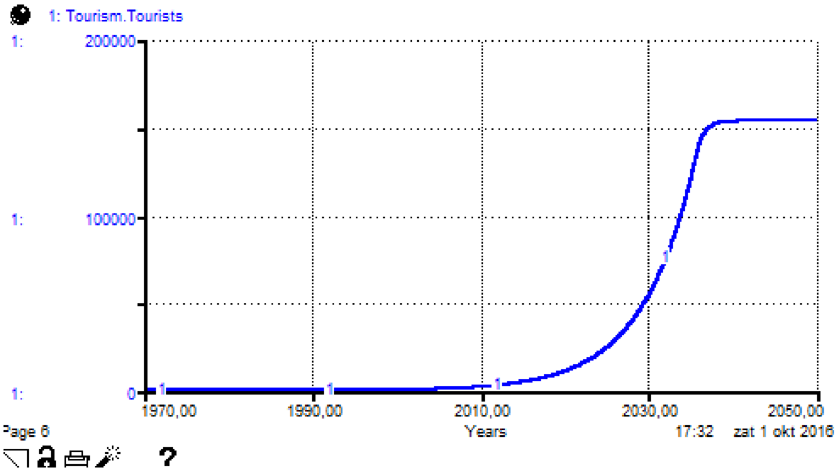


Figure 34 Tourists on the destination

From the model structure, it can be implied that the growth in tourist arrivals is driven by a reinforcing feedback loop, in which word-of-mouth leads to a higher number of people who want to visit the destination in the future which then leads to more word-of-mouth. However, the growth in tourist arrivals is limited by the available resort capacity. The growth in resort capacity, however, is by itself driven by a reinforcing feedback loop in which a higher number of tourists lead to more resorts being built which then leads to a higher number of tourists. Figure 35 describes these two reinforcing feedback loops, and how a small balancing feedback loop decreases the available capacity for new tourists as the resorts become fully booked over time. It is interesting here to note the similarity of this feedback structure to the structure of the coral reef growth, in which high occupancy rates by live coral tissue lead to more coral reef substrate which then increase the available capacity for new coral recruits. The most important difference between tourism growth and the coral reef growth is that the growth of the coral reef takes a very long time, while the time it takes to build a resort is only 1 year. As a consequence, the growth in the number of resorts and tourists can be expected to occur much faster than the growth on the coral reef.

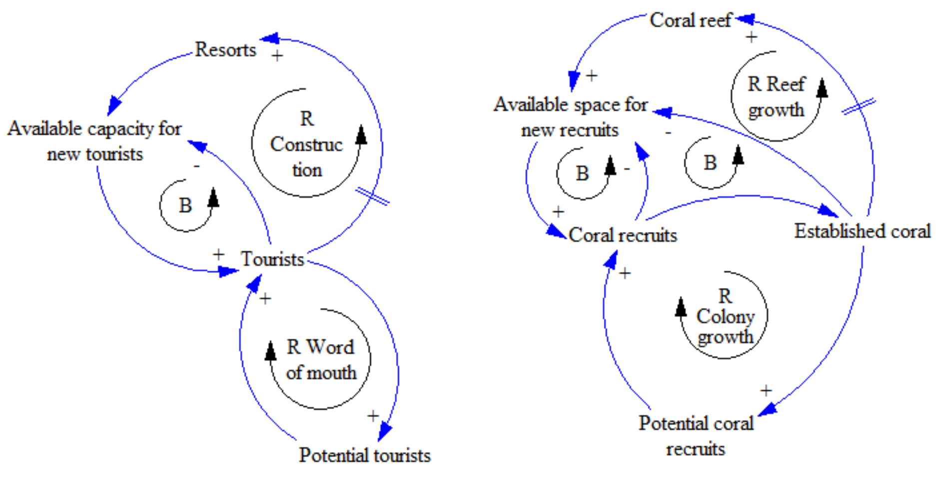


Figure 35 Similarity tourist development and coral reef growth structure

5.3.3 Reducing pressure on fish stocks

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. In this model it is assumed that most of the tourists who visit a coastal destination in the Philippines will also go on an island hopping tour one or multiple times during their holiday. Therefore it is assumed that, on average, of all the tourists who are on the destination on a certain day, 1 out of 5 will go on an activity involving a tourist boat (mostly island hopping). Figure 36 explains how a growing number of tourists will lead to a growing demand for tourist boats.

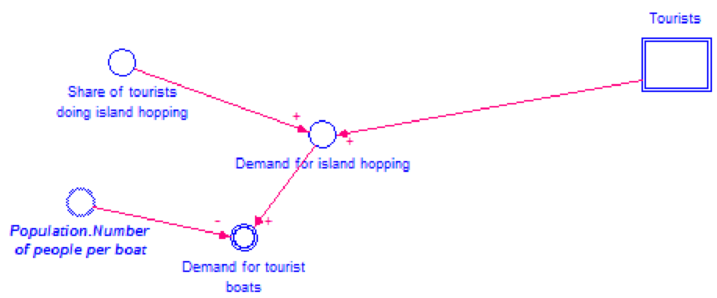


Figure 36 Growing demand for tourist boats

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. Additionally, fish stocks might have been lowered making fishing less attractive. The amount of fishers who are switching depends on the demand for tourist operations and the time it takes to switch. The model assumes that, if tourist demand is high enough, all fishers will switch to tourism.

This is probably not completely true as there will still remain some small local fishermen (often smaller one-person boats). Furthermore, in the initial phase of tourism development there seems to be a kind of transition period, in which boats are being used in hybrid mode, for both fishing and tourist activities. However, on big tourist locations like Borocay and El Nido (Figure 37), almost all of the fishermen have switched to become tourist operator. Observations on the fish market in El Nido show how the available fish is not locally fished but is coming from other locations such as Taytay.

Figure 37 Tourist boats ready for departure (El Nido, Palawan)

Figure 38 describes the process through which the local population on the island switches from the fishing to the tourism industry. It is assumed that it takes, on average, 6 months to switch from working in the fishing industry to working in the tourist industry. This delay includes the time it takes to receive a tourist operating license from the local government unit (LGU) and the time it takes to redesign the boat to be able for tourist transportation. In case the local population decides to go into tourism directly (not first becoming fishermen), they will still go through the same process of building a boat and having to learn how to become a tourist operator. Therefore this process has not been separately modeled. Additionally, since there is no feedback in the model through which tourism growth can reverse, there is no process in the model through which the tourist boats can switch back to becoming a fish boat. Furthermore, it has been assumed that both the fish and tourist boats do not decay over time, instead their broken or old parts will be replaced.

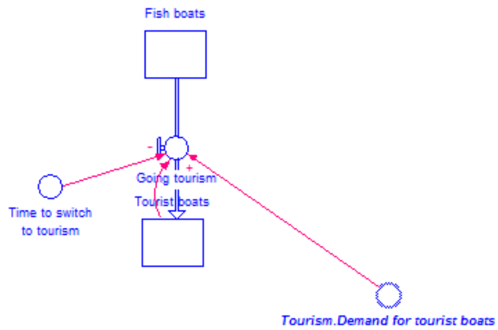


Figure 38 Switching from fishing to tourism

Figure 39 shows how the number of fish boats peak at 24 boats before starting decline when tourism development takes off and more fishermen switch to become tourist operator.

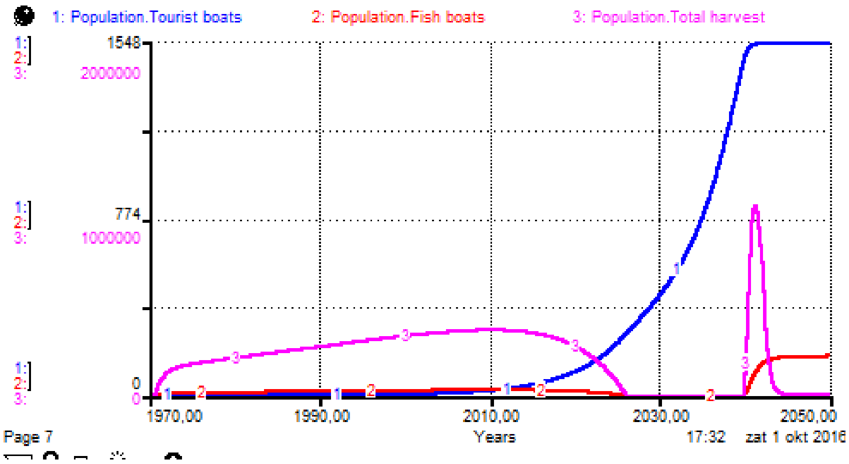


Figure 39 Reducing pressure on fish stocks

5.3.4 Unintended consequences of tourism diversification

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. As described in chapter 5.1.3 Developing a fishing industry, harvesting of fish has a negative impact on the growth of the coral reef. Therefore, the switch to tourism is often seen as a policy to increase the sustainability of the coral reef. 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. These unintended consequences will be described in this chapter.

5.3.4.1 Sedimentation from land development

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 (Figure 40). Even for resorts which are built further away from the beach, sediment from building activities can still be disposed into the sea by the workers. Also when old resorts are demolished, sediment is produced and disposed. It is assumed that, on average, the development of one resort leads to 500 m2 (or 0.05 hectare) of sediment disposal.

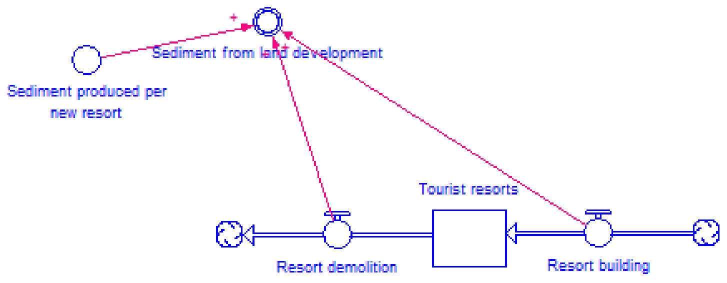


Figure 40 Sedimentation from land development

The most problematic issue with resort development and sedimentation is when the resorts are built close to the beachfront. On some tourist locations, there are regulations which inhibit constructional activity within 30 meter of the shoreline. However, observations revealed that on most locations, there were several resorts built near the shoreline and/or planned to be built near the shoreline. Figure 41 shows a picture of the relatively undeveloped shoreline of Port Barton, which is only recently starting to become a major tourist destination. Figure 42 shows development of a new resort within a few meters of the shoreline on El Nido.

Figure 41 Low level of resort development in Port Barton, Palawan

Figure 42 Developing beachfront resorts in El Nido, Palawan

Figure 43 shows the development of the amount of sediment on the coral reef as a consequence of the construction activity caused by the tourist boom. The peak and the rapid change in slope around the year 2035 is the consequence of the carrying capacity for resorts on the destination. When that carrying capacity is reached, no more new resorts will be built, which then leads to a rapid decrease in the disposed sediment.

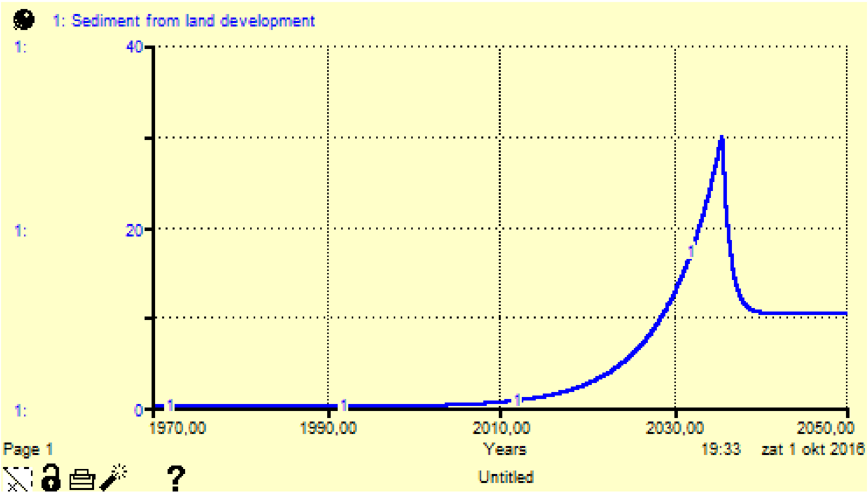


Figure 43 Sedimentation from resort development

5.3.4.2 Sewage disposal tourist resorts

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. In later phases of tourism development, when water pollution starts to become a bigger problem, often plans for sewage treatment systems and regulations for resort owners are getting stricter. Figure 44 describes the process through which a higher number of tourists lead to more sewage disposal. It is assumed that 40% of the resorts treat their sewage in such a way as to offset the inorganic nitrogen content. This 40% consists mainly of the most expensive resorts that have the money available to invest in technology. Many other resorts either directly dispose their sewage into the sea or use septic tanks which are not working properly. 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.

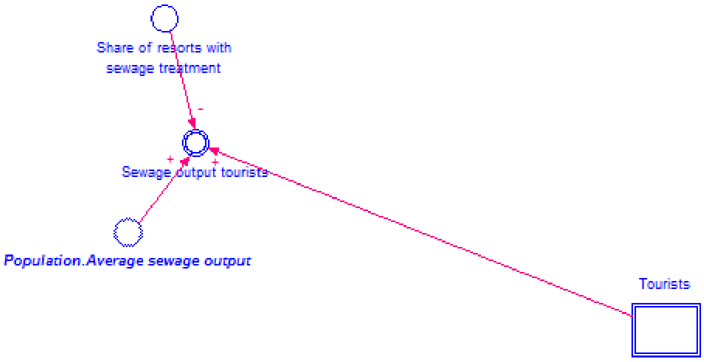


Figure 44 Sewage output tourists

Figure 45 reveals the increased sewage output of the tourist resorts without appropriate sewage disposal.

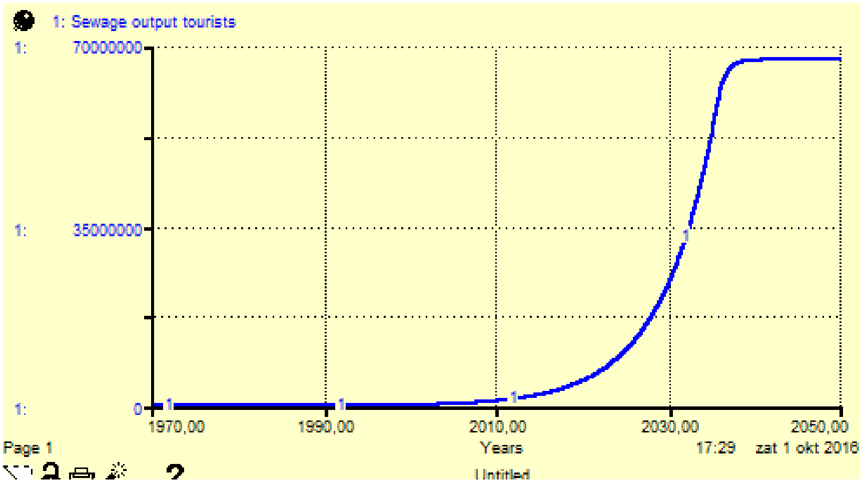


Figure 45 Sewage output from tourist resorts

5.3.4.3 Direct coral destruction by boats and tourists

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 (Bawasanta, personal communication). Especially branching corals and shallow reefs face major impacts from tourist activities. Experience from a tourist in El Nido tells us how boat operators visit the coral reefs during low tide, and the tourists are walking over the coral reef with their boat shoes. Figure 46 describes the interaction between island hopping activities and bio-erosion of the coral reef.

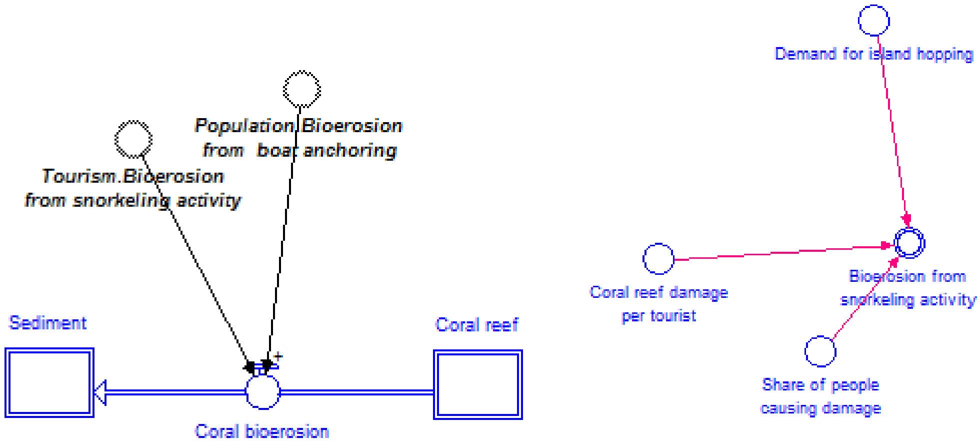


Figure 46 Bio-erosion from tourist activities

In this model it is assumed that, on average, 1 out of 5 (20%) of the tourists causes damage to the coral reef. Education and training are important to warn the people about the importance of not touching the coral reef and how to behave in the water. Especially Korean, Chinese and Japanese divers and snorkelers cause a lot of damage, as they have lack of knowledge and experience on the coral reefs (Bawasanta, personal communication). 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 (Jimenez, personal communication).

Figure 47 shows the damage caused by boat anchoring (fishing boats and tourist boats) and snorkeling and diving activity on the coral reef.

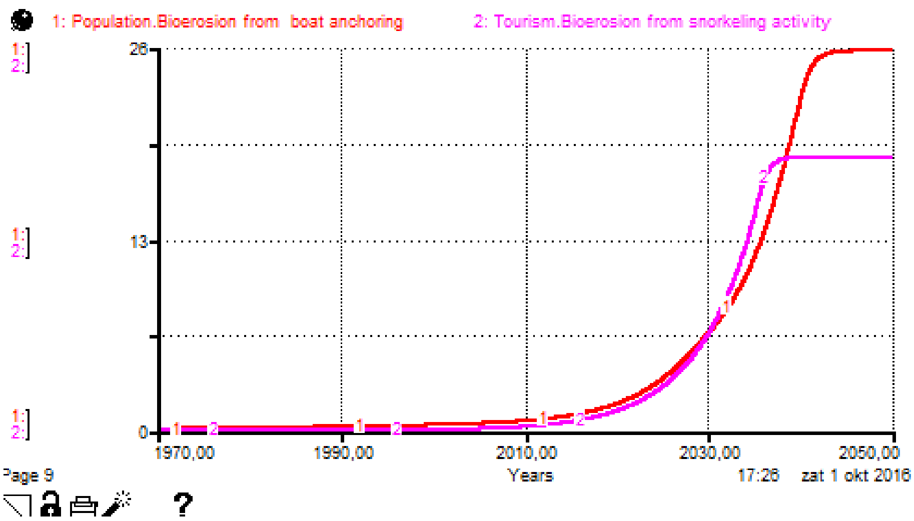


Figure 47 Bio-erosion from tourist activities

5.3.4.4 Fish demand and immigration

As a destination gets an increasing number of tourist arrivals, the number of restaurants will also increase. On most coastal destinations, (reef) fish are a popular source of food, as can be seen in Figure 48 and Figure 49.

Figure 48 Snappers (left) in fish restaurant in El Nido, Palawan

Figure 49 Parrotfish (left top) and snappers (right top) in fish restaurant on Panglao island, Bohol.

However, as explained before, growing tourism development will lead to an increasing number of fishermen which start to switch to become an operator of a tourist boat. Therefore, as experienced on many destinations, an increase in the demand for fish does not necessarily lead to an increase in the harvesting of fish. As a matter of fact, on several locations, increased demand for fish by tourists is now supplied by importing more fish from nearby locations. Figure 50 describes the process through which increased fish demand leads to more imports (e.g. negative exports).

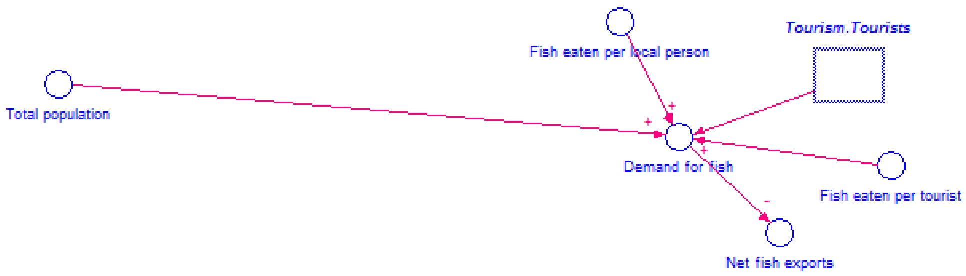


Figure 50 Demand for fish from local population and tourists

Figure 51 shows the divergence of the total harvest of fish and the demand for fish after the year 2010, in which a large part of the fish demand has to be imported from fishermen outside of the destination.

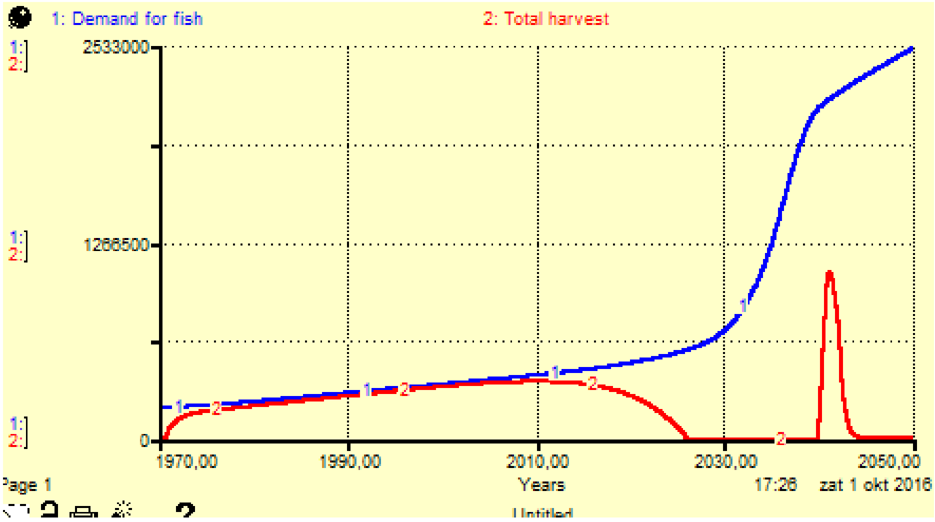


Figure 51 Demand and harvest of fish on the destination

When fish has to be imported or is made available on primary basis to the tourist markets (e.g. resorts buying directly from the fishermen), the price of fish increases. This could lead to the local population decreasing their food intake from fish significantly. They often increase their protein intake from pork and or chicken. This effect is beyond the scope of this model and has not been included in the model.

Another unintended consequence of the 'success' of tourism development is the increased employment opportunities coming mainly from increased demand for tourist activities. Figure 52 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. Therefore, the stock of available people is assumed to be infinite. For example in Coron (Palawan), due to a recent tourist boom many fishermen switched to tourism. However, there was still more demand for tourist boats and new people came to the island to find work. From observations, it became clear that many of the people working in the tourist sector on Borocay, El Nido, Panglao, Mactan and Moalboal were also originally from other areas of the Philippines (often Manila).

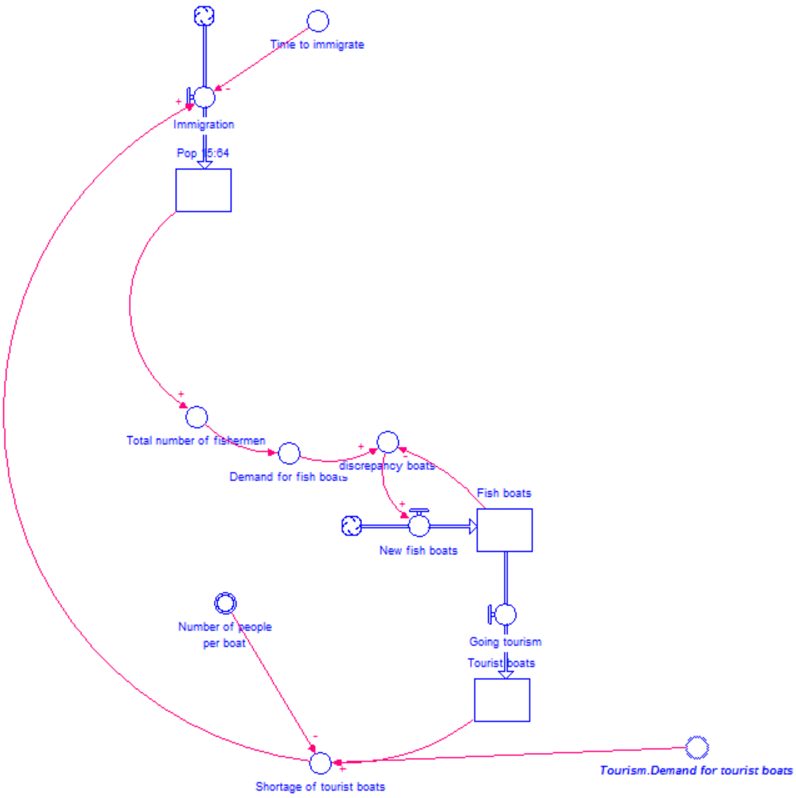


Figure 52 Tourism development and immigration

It is assumed that it will take one year for a person to immigrate. This delay includes administrative procedures and the time it takes to perceive the shortage of jobs. Figure 53 explains how 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.

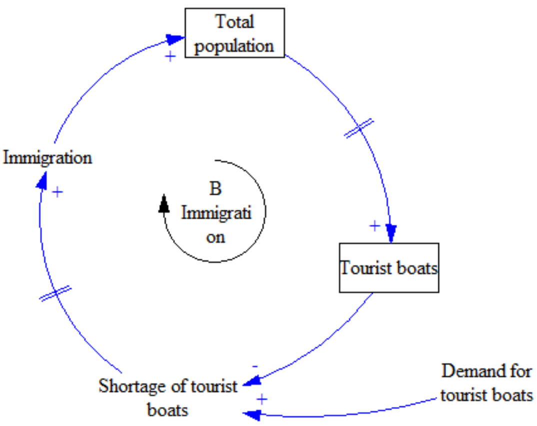


Figure 53 Causal-loop-diagram immigration

Figure 54 shows the growth of the population as a consequence of rapid immigration of workers who come to the destination because of the shortage of labor.

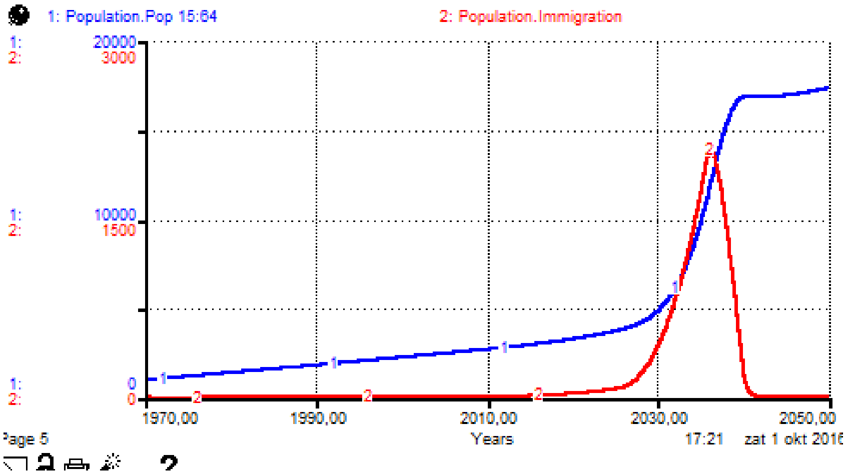


Figure 54 Immigration and local population growth

The increasing immigration can have another unintended and negative impact on the local population. It is possible that, because of limited education and commercial experience, the local population will actually not be hired to work in the tourist sector. Instead, more immigrants with commercial experience will be attracted from cities like Manila. This could potentially lead to increased poverty for the local population, which does not benefit much from the tourism development, while even being impacted negatively by increasing prices of basic services and products (Mencias, personal communication). Some indicators of this problem have been noticed during this study, but this relationship has not been included in the model because it is outside of the scope of this paper.

5.4 Simulation results and causal-loop-diagram

The simulation of a coral reef, as described in Figure 55, explains how the combination of local population growth and tourism development could lead to a rapid degradation and even extinction of the coral reef.

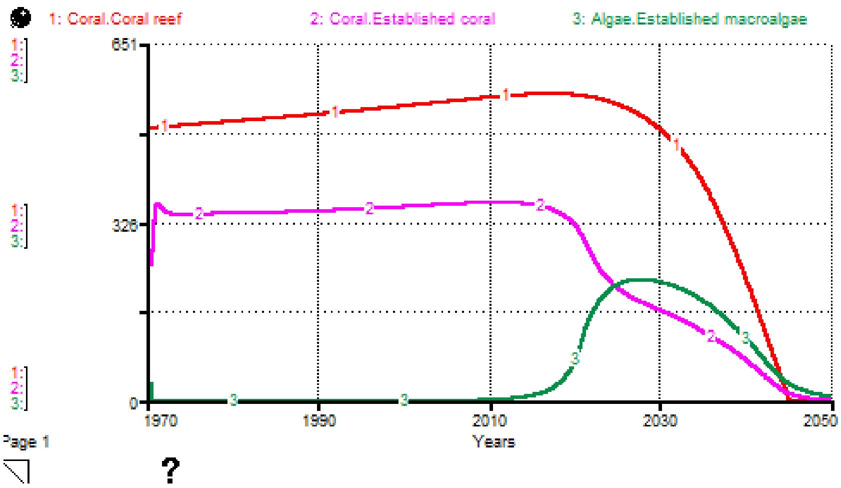


Figure 55 Simulating long-term coral collapse on coral reef with local fishing community and tourism

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 56 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.

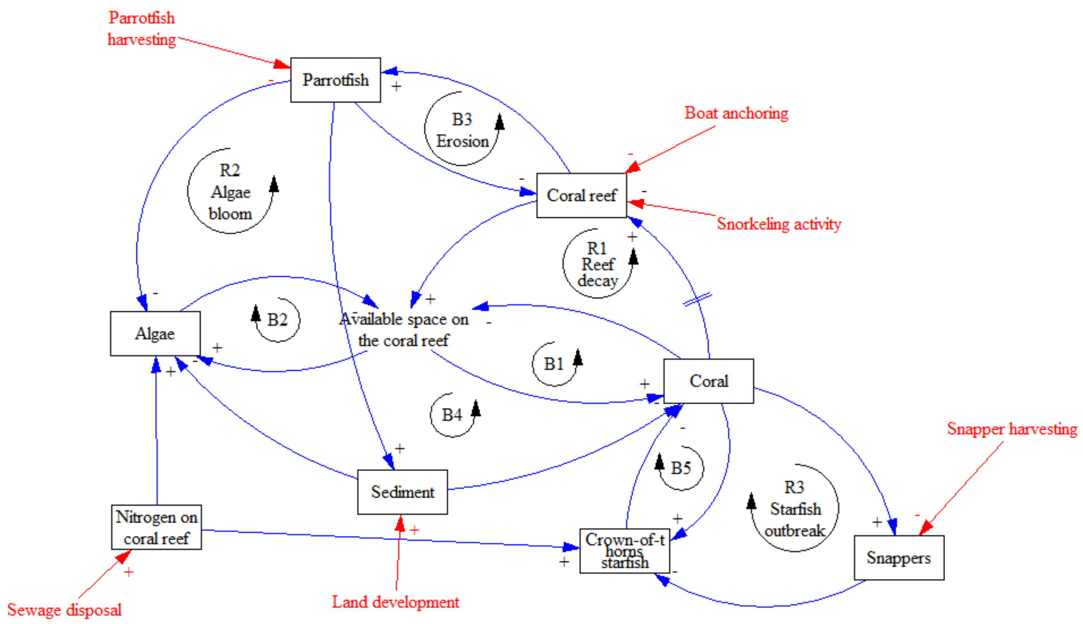


Figure 56 Causal-loop-diagram coral reef with tourism ‘boom’

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.

6. 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. To explore these coral-management programs, the next chapters will introduce the coral programs starting from the year 2000 and their effects over the following 50 years are plotted.

6.1 Artificial reefs and coral replanting

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 (and around the world). In Borocay, for example, a project has been developed on the Coral Garden reef. The project has been deemed successful there as coral recruits have come to occupy the space on the artificial reef (Lumagod, personal communication). On El Nido and Coron (Palawan) similar projects have been initiated (Al Linsangan III, personal communication). Figure 57 describes how the construction of artificial reefs increases the, naturally slow, rate of coral reef formation.

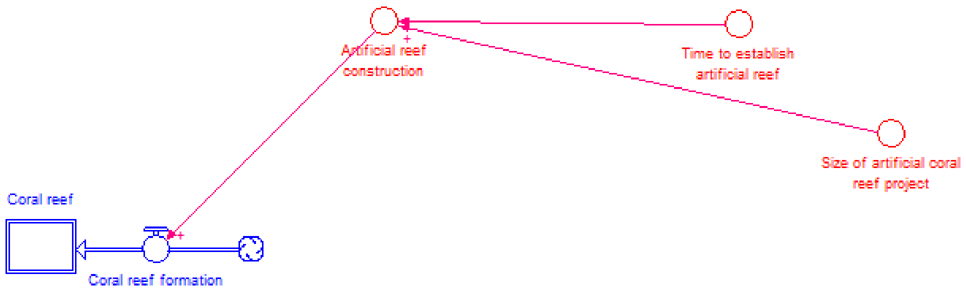


Figure 57 Artificial coral reef program

The size of current artificial reef projects in the Philippines is relatively small compared to the size of the total coral reef. In this model it is assumed that each year, from the start date of the policy in 2000, 1 hectare of artificial reef will be deployed. Figure 58 shows the ineffectiveness of this coral-program, as there is only a minor effect on the pace of the coral degradation.

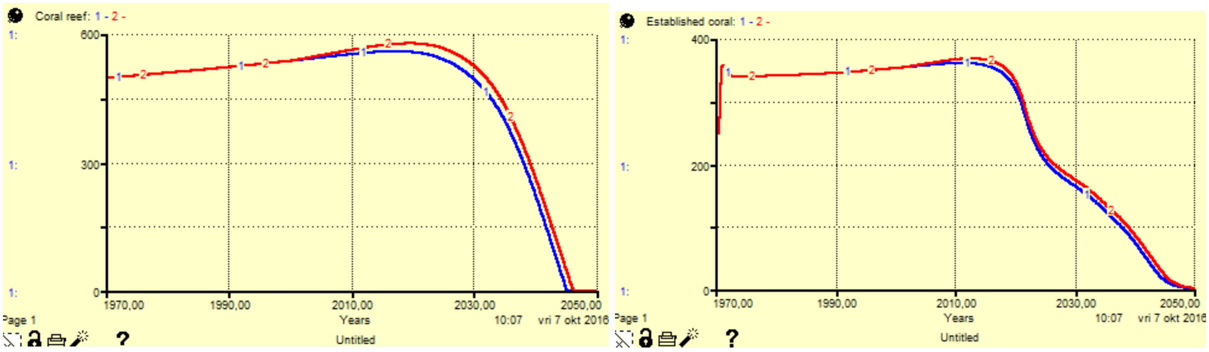


Figure 58 Effect of artificial coral reef program on coral reef and live coral tissue

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. Figure 59 describes the way in which the coral replanting programs increase the size of the live coral tissue.

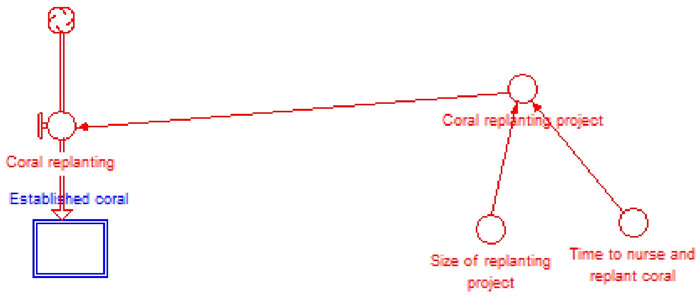


Figure 59 Coral nursing and replanting program

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. In this model it is assumed that similar to the artificial reef project, each year a coral replanting project of 1 hectare is deployed. It is assumed that it will take about one year to complete a coral nursing and replanting project. This year includes the time to nurse the coral recruits until they become established coral (three months), time to remove and re-locate the coral and administrative procedures related to environmental management programs. Figure 60 shows the ineffectiveness of adding the coral replanting projecting to the already existing artificial reef program, as there is again only a minor effect on the pace of the coral degradation. Even when we assume that the size of the yearly programs will be 5 hectares, the simulations in Figure 61 show us that the coral reef will still go towards extinction.

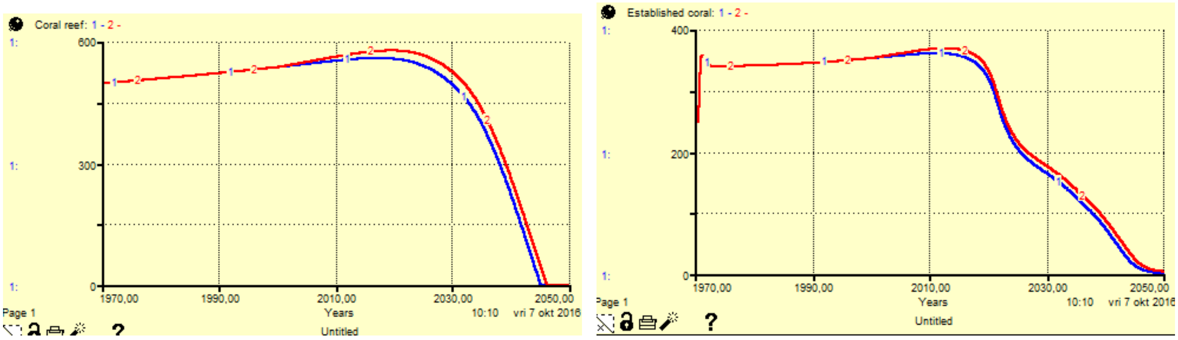


Figure 60 Implementing artificial reef and coral replanting program (1 hectares) simultaneously

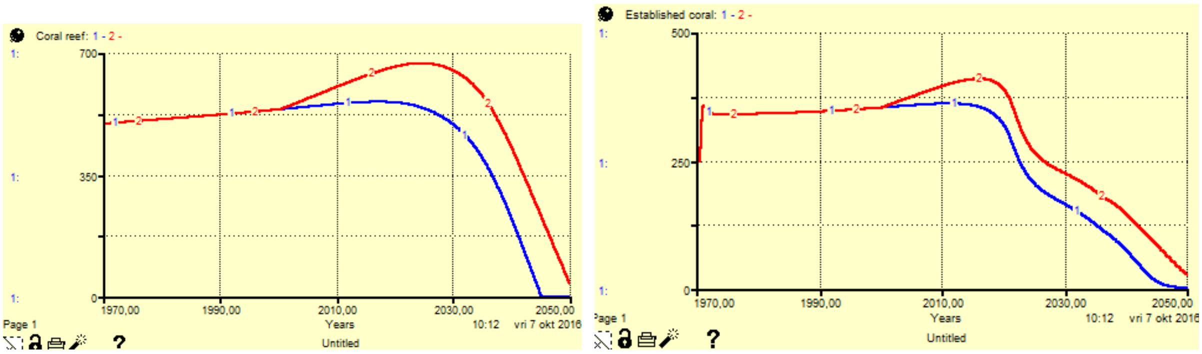


Figure 61 Implementing artificial reef and coral replanting program (5 hectares) simultaneously

6.2 Removing crown-of-thorns starfish

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. It is not possible to directly observe the number of COTS on the coral reef. However, when the number of visible COTS (a derivative of the COTS stock) on the reef increases, policy makers will get alerted. 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.

Therefore, as described in Figure 62, the removal of COTS in the model is not based on the desired number of COTS which have to be removed but on the available capacity to remove them.

On Borocay, in 2006, there was a COTS outbreak in which the coral reef was heavily affected. However, with a delay the COTS were removed to alleviate the pressure on the live coral tissue. From that moment, when there are more than 5 visible COTS, the divers remove them from the main diving sites (Lumagod, 2016). On Coron, the last COTS outbreak has occurred in 2014. Now Coron has a continuous policy of removing COTS when an outbreak is to be expected (Al Linsangan II, 2016).

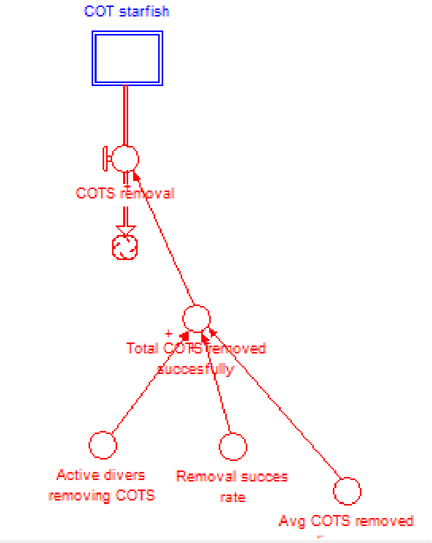


Figure 62 Removing of crown-of-thorns starfish by divers

The total COTS which will be removed each year depend on the active divers removing the COTS, the removal success rate and the productivity of the divers in removing the COTS. It is assumed that there are 20 active divers (collaborating with researchers) to remove the COTS from the coral reef in case of an outbreak. It is assumed that on average, a diver can remove 50 COTS per year (or about one per week). Interviews with several dive shop owners in the Philippines revealed that the divers have only limited time available for working on the project as they are (most of the time) not paid for this duty (only in the form of keeping the coral reef alive in the future). 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. This feedback has not been included in the model. When the COTS are properly removed, the success rate will be '1'. After removing, the COTS can be used as coconut fertilizer (Alcala, 2016). Furthermore, new studies from the James Cook University in Australia reveal that COTS might be killed directly by injecting them with vinegar. It is assumed that currently only 50% of the active divers remove the COTS properly. For example on

Siargao Island, due to a lack of knowledge on how to remove the COTS properly, divers are actually killing the COTS by throwing heavy stones on them.

Figure 63 shows the effect of the COTS removing policy on the number of COTS on the coral reef. While the number goes down, it starts to increase again around the year 2010. Figure 64 reveals how even as the number of COTS are reduced, the effect on the sustainability of the coral reef and live coral tissue is almost neutral.

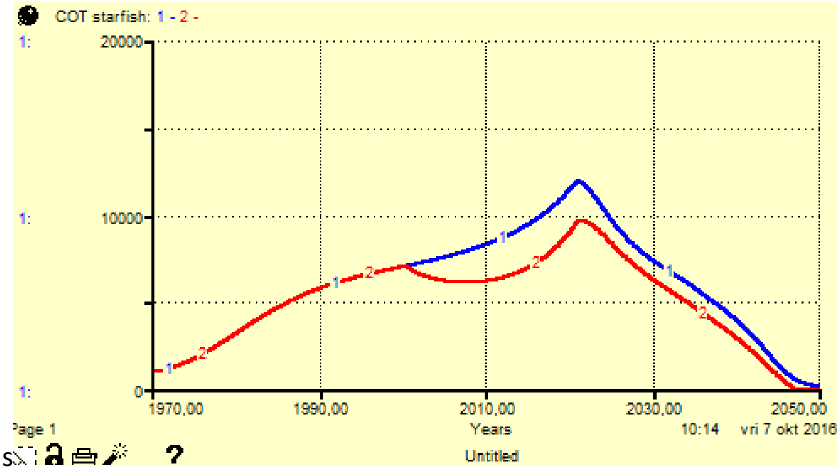
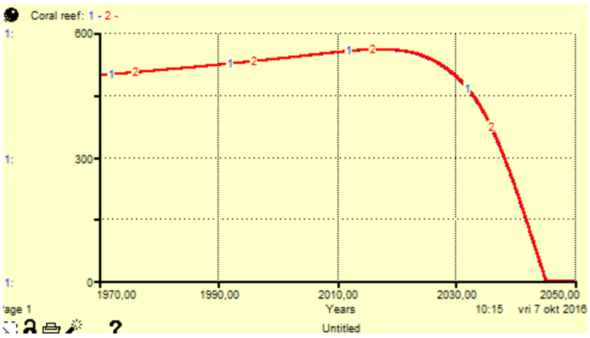


Figure 63 Effect of COTS removing program on COTS stock



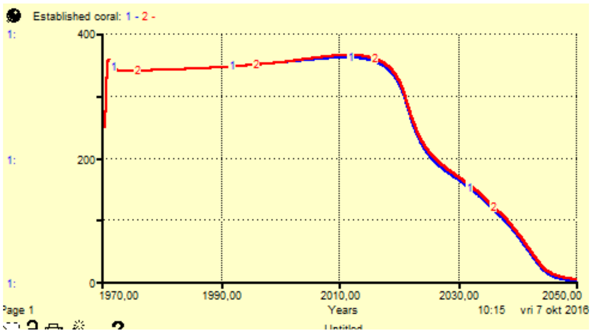


Figure 64 Effect of COTS removing program on coral reef and live coral tissue

6.3 Marine Protected areas

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. As described in Figure 26, the fish industry is generally supply-driven, meaning that the harvesting of fish depends on the number of fishing boats and the average catch per boat. 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. Figure 65 describes the effect of establishing MPA's on a limited area of the coral reef.

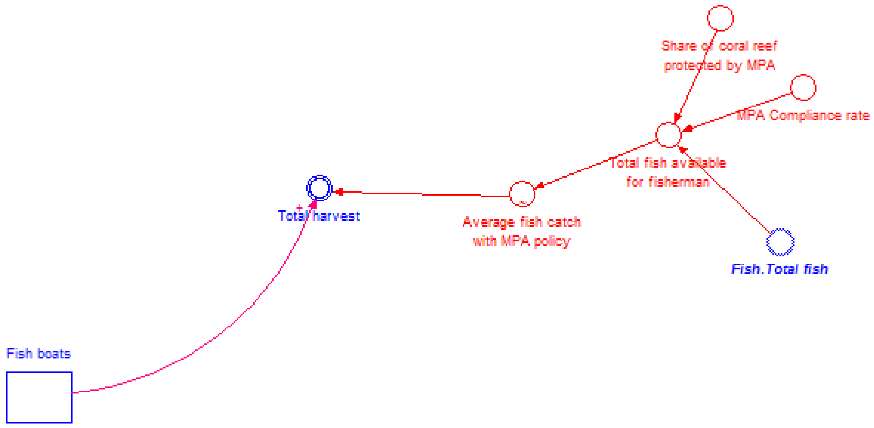


Figure 65 Marine protected area program

When a MPA is established on a coral reef destination, it has the implication that the total fish available for fishermen will be lower (since the fishermen are not allowed to fish in the MPA). This model excludes the spillover effect from increased fish stocks in the MPA which then will increase the fish stocks near the border of the MPA. The nonlinear 'average fish catch' function is similar to the average fish catch without MPA policy. The only difference is that with the MPA policy, the available fish stocks will be lower and therefore the total harvesting will decrease faster than without MPA (thus alleviating pressure on fish stocks).

Assuming that the same amount of fisher boats will now go fishing on a smaller part of the reef, this program alleviates the problem to another part of the reef which will face additional pressures. When it is not implemented on the whole coral reef, or in combination with programs to reduce the number of fishermen, the program will not be as effective as initially intended. The non-protected parts of the coral will now face larger fishing and anchoring pressures from fishing boats.

The problem of the size of the MPA is an important problem on many locations in the Philippines, where MPA programs are often more showcase experiments than large-scale projects. In this model, it is assumed that 10% of the coral reef is protected by MPA regulation (this 10% can shift between different areas within the reef). 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. The compliance rate in the model is assumed to be 60%. Figure 66 shows the effect of both a 10% and 50% marine protected area on the total size of the fish stock. It can be seen that there is a positive effect of the program on the fish stock. In both cases, most of the fish outside of the MPA will go extinct, while only the fish in the MPA survive. Ultimately, around the year 2040, even the fish stocks in the MPA will go extinct as the coral reef, by then, has been completely degraded. As the fish need the coral reef and live coral cover for protection and spawning, the fish stocks will not survive the extinction of the reef.

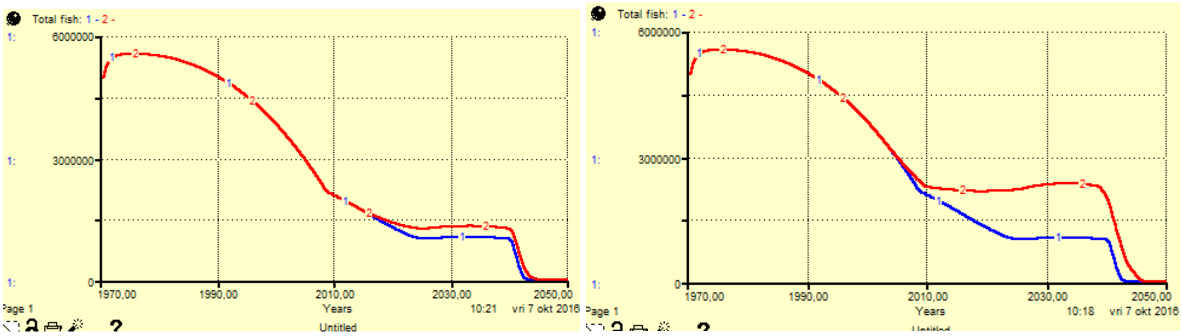


Figure 66 Effect of MPA program on total fish stock (10% protection; 50% protection)

Figure 67 shows the effect of a 50% marine protected area on the sustainability of the coral reef and live coral tissue. The simulations reveal the most important reason, which will discussed in the next section, for why MPAs by themselves, are not the 'holy grail' towards the problem of coral reef sustainability.

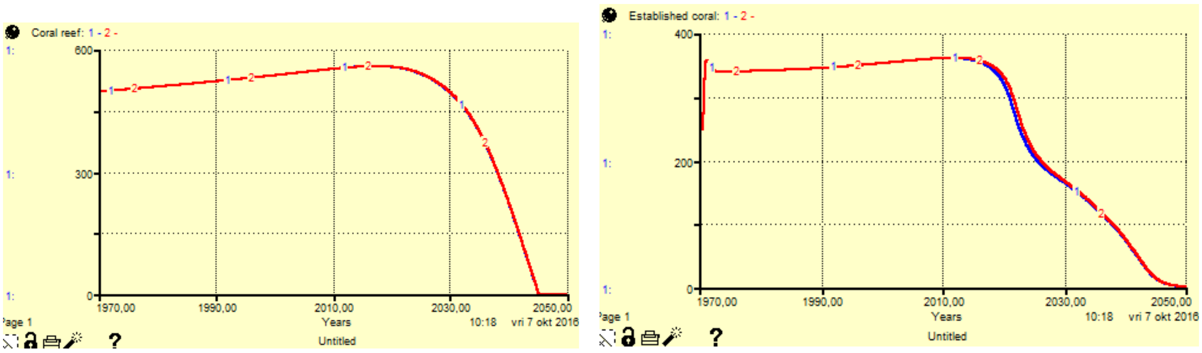


Figure 67 Effect of MPA program (50% protection) on coral reef and live coral tissue

6.4 Simulation results and causal-loop diagram

Figure 68 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.

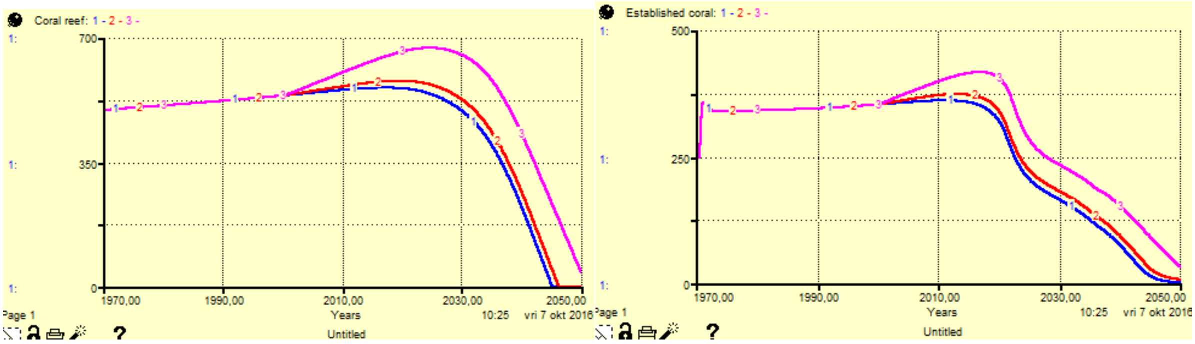


Figure 68 Combined effect of coral programs on coral reef and live coral tissue

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 69.

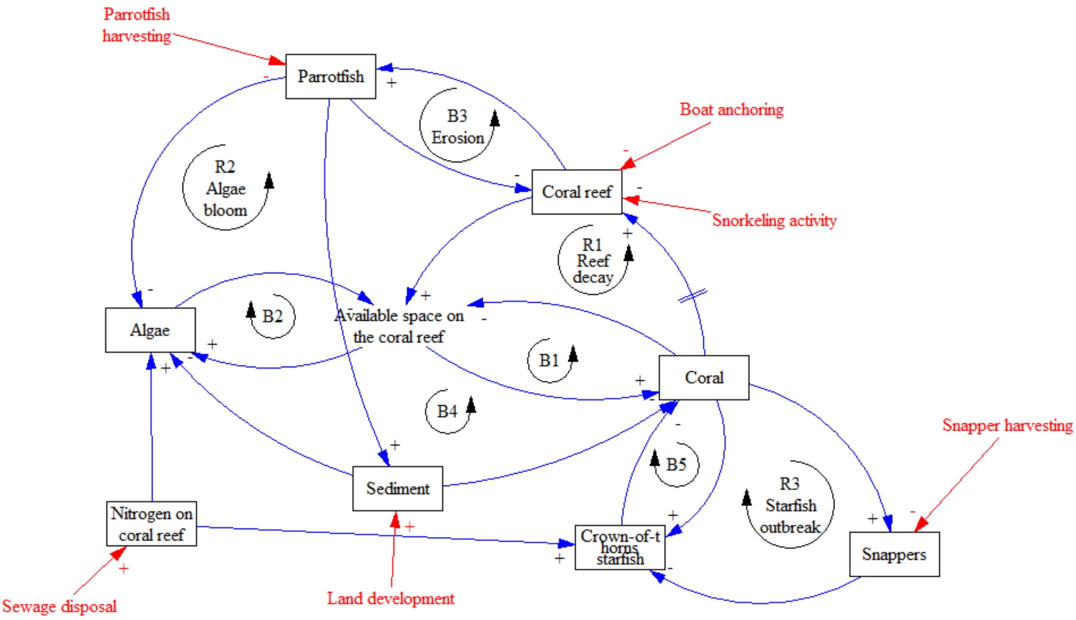


Figure 69 Causal-loop-diagram coral reef with tourism 'boom'

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

7. 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

In accordance with Popper (1934), testing the model will never be able to verify or validate the hypothesis about how the coral reef system works. Testing is mainly focused on trying to reject the model (or parts of the model) and the hypothesis it produces about the real-life behavior of coral reefs. As the main part of the model postulates assumptions about the causal effects between the human environment and the nearby coral reef, scientists and policy makers will be able to adjust model parameters and stock values to their particular 'local' situation and will be able to test the hypothesis. In this way, real-life experiences on coral reefs around the world will function as the main experiment with which to falsify the hypothesis of the model. Additionally, the causal relationships and feedbacks, as described in the model structure, can be tested, rejected and/or improved in laboratory experiments.

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). As has been described in the results chapter, 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.

Since all models are by definition wrong, it is more important to validate the model based on the usefulness related to its purpose (Sterman, 2000). The purpose of this paper has been to increase understanding about the general dynamics of coral reef degradation in the Philippines. Based on this purpose, the model's main goal is to capture and describe those causal relationships which have been identified as most dominant regarding the coral reef degradation in the Philippines. The model therefore excludes several particular, individual and interesting relationships which could also affect the coral reef environment.

The next chapter will describe the tests which have been used to assess the quality of the model and the dynamic hypothesis which have been proposed. The choice of tests has been based on recommendations from the main authors within the field of system dynamics (Barlas, 1996; Forrester, 1961; Sterman, 2000, 2002).

7.1 Boundary adequacy test

As addressed in the methodology chapter, the main hypothesis proposed in this paper is that even on coral reefs which do not face environmental pressure from climate change, rapid degradation is the most likely outcome given current developments. However, this does not mean that the effects of climate change on the sustainability of the coral reef are labeled as unimportant. The IPCC (2014) provides an excellent overview of the major problems the coral reefs are facing regarding climate change. Coral bleaching from rising sea temperatures, ocean acidification from the uptake of CO2 from the atmosphere and a rising sea level are the major impacts on the reef in the years to come. Additionally, higher sea water temperatures might also lead to the more frequent occurrence of typhoons, already a major threat to coral reefs in the Philippines.

Thus it becomes clear that excluding climate change as an input to the model is one of the major issues related to the boundary choice of the model. There are four major reasons why climate change has been excluded from the model:

1) The potential for policy makers, the fishing industry and the tourism industry to use climate change as an 'easy excuse' for coral degradation while local drivers are actually the main cause of the problem (Jackson, Donovan, Cramer, & Lam, 2014).
2) Evidence for the rapid recovery of coral reefs on which local pressures were reduced (for example in MPA's) while at the same time climate change effects still worsened in effect. It might be possible that improving the local conditions of the coral reef might increase their resilience to cope with the more gradual changes caused by climate change.
3) Without climate change impacts, the simulations in the model already lead to a rapid degradation of the coral reef. Adding climate change to the model would not significantly change the behavior of the model, but would most likely only increase the pace of degradation.
4) Extending the model boundary would not change policy recommendations, since climate change impacts are outside of the direct control of policy makers.

Aside from excluding climate change, several other important factors have been excluded from the model while others have been not been included within the endogenous structure of the model. Table 1 gives an overview of the boundary of the model. Some of those factors will be shortly explained.

Endogenous	**Exogenous**	**Excluded**
Live coral tissue	Seawater nutrients	Coral bleaching (temperature)
Coral reef substrate	Spawning frequencies	Ocean acidification
Sediment	Live coral mortality	Sea level rise
Macro-algae	Macro-algae mortality	Natural disasters (typhoons)
Parrotfish	Parrotfish mortality	Coral disease
Crown-of-thorns starfish (COTS)	Snapper mortality	Algae overgrowth

Snappers	Available land for resorts	Sea urchins
Population (+ immigration)	Expected tourism growth rate	Large predators (reef shark)
Fishing industry	Fish eaten per person	Giant triton
Tourists	Death fractions population	Destination attractiveness
Tourist resorts	Fertility rate population	Income population (economics)
Tourist industry	Coral reef damage per tourist	Nutrient cycle on the reef
COTS mortality		Sea grass ecosystem service
Fish migration		Fish immigration

Table 1 Model boundary overview

The exclusion of natural disasters (primarily typhoons) in the model is based on the same argumentation as was provided for excluding climate change. Since typhoons are outside the control of policy makers, the coral reef will be subjected to such disasters now and then in the same way the people in the Philippines are subject to them. However, coral reefs in a healthy local environment are most likely able to recover more often and more rapidly from the impact of typhoons. This can be related to the hypothesis of the paper, in which a coral reef which faces high nutrient levels and low fish stocks will most likely be occupied by macro-algae recruits after a typhoon kills all the live corals and algae on the reef. In a healthy coral environment, on the other hand, coral recruits will be able to occupy the reef after the typhoon as macro-algae growth is controlled by a lack of nutrients and parrotfish grazing.

Aggregation also plays an important role with regards to the boundary of the model. As discussed in the individual chapters explaining model structure, the model does not differentiate between different species of coral (both live tissue and substrate), macro-algae, parrotfish, crown-of-thorns starfish and snappers. Although the author's acknowledges that different species will have different responses to certain developments, choosing this aggregation level is in line with the purpose of the model; to increase general understanding about the reasons for the rapid decline of coral reefs. For example: Although some coral species might be more vulnerable to pressures from algae competition than others, this model is more focused on the macro-level, on which it assumes that, in general, increased survival of algae leads to a less favorable competitive position for coral species. To account for individual differences in species, the model has tried to average individual responses of species into the parameters related to the effect on the aggregated variable. For example, branching corals might be more susceptible to damage by tramping tourists than more rectangular coral species. The parameter value for average coral reef damage per tourists takes the average amount of damage caused by the tourists. Therefore, as disaggregation is not expected to significantly change the model outcomes and policy recommendations, the higher level of aggregation can be justified (Sterman, 2000, p. 864). Within the coral sub-model, the most important factors which have been excluded are:

1) The natural oxygen, carbon and nutrient cycles on the coral reef produced by the interaction of different species and photosynthesis (Mann, 1982). These natural cycles play only a minor role with regard to the rapid degradation of coral reefs compared to the dominant role of manmade pollution, overfishing and anchoring. Furthermore, the effect of seawater nutrients on the growth (or death) of coral polyps has not been included while the effect on macro-algae growth has been included. Although coral polyps are expected to grow faster in sea water with less nutrients (Alcala, personal communication), this effect is relatively small compared to the effect of increased seawater nutrient levels on the growth of macro-algae.
2) While the indirect effect of increased algae competition for occupation of space on the coral reef has been included in the model, the direct effect of macro-algae overgrowth on coral juveniles has been excluded (Birrell et al., 2008; McCook et al., 2001). The reason for the exclusion of the overgrowth effect is that the indirect effect of competition for space on the reef has been deemed more dominant in relationship to the degradation of the coral reefs.

Within the fish sub-model, the most important factors which have been excluded are:

1) Fish immigration, since in the model it is assumed that the fish stocks will only increase through internal reproduction (e.g. spawning). However it could be possible that the fish stocks also increase through immigration of (mature) fish from other coral surrounding coral reefs. Since reproduction has a longer delay than immigration, this could mean that restoring the natural health of the coral reef might lead to a faster recovery of fish stocks than is now assumed by the model.
2) The sea-urchin, which together with the parrotfish, is the main grazer of algae cover on the coral reef. Compared to the parrotfish, however, the sea-urchin is a less popular fish for fishermen as it has large black spines and is a less popular food source for both the local population and tourists (although it is a local delicacy for some locals). On overfished coral reefs, where large predators of the sea urchin (such as the triggerfish) have disappeared, outbreaks of the sea urchin populations are very likely to occur (Mumby, Hedley, Zychaluk, Harborne, & Blackwell, 2006; O'Leary, Potts, Schoenrock, & McClahanan, 2013). Indeed, such outbreaks have been observed during research visits to Coron and Siargao Island. Such an outbreak on Borocay even made the newspaper in 2009 (Godbold, 2009): "The abundance of algae has provoked the growth of exceptionally dense populations of long spine black sea urchins.." Therefore the sea urchin might offset the losses in algae grazing caused by the

depletion of the parrotfish stocks. In that case it would be an important element to include in the model. However, reefs with outbreaks of sea urchins might have the unintended consequence of grazing not only the macro-algae but also the coralline algae, the type of algae which is found in coral polyps and is the responsible for producing calcium carbonate to build the coral reef structure (O'Leary et al., 2013). Furthermore, high densities of sea urchins might make them vulnerable to disease, which could then lead to a rapid die-off of the whole urchin population (Willoughby, 2015). Such a rapid die-off following disease in the sea-urchin population has been observed in the Bahamas in the 1980s, leading to a rapid overtake of the coral reef by macro-algae species (Mumby et al., 2006). In general, it can be concluded that 'the effects of reduced abundance of grazing fishes (on available space for coral settlement) may be initially offset by increased sea urchin grazing, but that higher urchin abundances may ultimately reduce coral cover by their negative influence on post-settlement survival'(O'Leary et al., 2013, p. 165). Therefore, for now, the dynamics of the sea urchin have not been included in the coral reef model. This is due to the increased complexity these dynamics will add to the model while their effects on the decline of the coral reef are expected to balance out on the basis of positive and negative effects. Additionally, the inclusion in the model would not change the policy recommendations: increase fish stocks (including large predators) by decreasing harvesting on the reef.

3) Large predators (such as reef shark, groupers, barracudas and triggerfish) which prey on the coral reef have not been included in the model. These large predators are attracted to the coral reef by the high density of fish to prey on. In that way they play an important role in controlling the growth of smaller fish such as the parrotfish and snappers which have been described in this paper. The large predators have not been included in the model for two reasons. First of all, because of fishing pressure, large predators are often the first fish to go extinct from the reef as they are small in numbers, mature later in life and are slower in growth (Sheppard et al., 2009). Therefore on most coral reefs which are affected by overfishing, large predators will not be able to control the other fish since they will have disappeared themselves. Observations and interviews in the Philippines have revealed an overall low level of large predator availability on the coral reef. Secondly, the fish stocks of snappers and parrotfish are already rapidly depleting, even without a natural predator. Thus it can be said that humans play the most dominant role as 'large predator' of those fish species on the coral reef.
4) The natural predator of the crown-of-thorns starfish has also been excluded from the model. In the Philippines, the Giant Triton has been identified as the main predator of the crown-of-thorns starfish (Alcala; Quimpo, personal communication). The giant triton has not been

included in the model for two reasons. Firstly, giant triton stocks might have been depleted as they are harvested by fishermen, mainly for their shell which is used for souvenirs. While harvesting their shells is now illegal in the Philippines, it is still possible to find large quantities of them in Cebu City (Alcala, personal communication). The second reason why the giant triton has not been included in the model is because their predation rates on crown-of-thorns starfish are very low and most likely they do not feed exclusively on those starfish (J. Hoey & Chin, 2004).

Within the human population sub-model the most important factors which have been excluded are:

1) Illegal fishing by boats that do not belong to the local population has not been included in the model, while it poses a significant challenge for some of the coral reefs in the Philippines (mainly in Palawan and Mindanao). These illegal fishing boats intensify the already existing prisoner dilemma, in which the local fishermen will certainly have no incentive to decrease their harvesting to recover fish stocks. For example during observations in Honda Bay (Palawan, Feb 17) three illegal fishing boats had just been captured by the marines.
2) Illegal fishing practices such as dynamite and cyanide fishing which have been or are still popular on many coral reefs in the Philippines also have been excluded from the model. The use of dynamite destroys the coral reef substrate directly, while the use of cyanide poisons the live coral cover. Illegal fishing practices are often the only way for fishermen to secure the necessary fish catch when fish stocks are depleting (Hilomen, personal communication). On Coron, illegal fishing practices led to a fast degradation of the coral reef until the late 2000s. The Palawan region is popular for fishermen from the Visayas region, where fish stocks often already have been depleted. Larger predator fish, such as the Lapu-Lapu (Barracuda) and groupers were catched using cyanide methods and then sold to Manila and Hong Kong. The effects of illegal fishing were felt on the local market in Coron, where declining fish catches led to increasing prices. In the late 2000s the maritime police became more vigilant. An USA-funded project started in the year 2005 with the objective to increase fish stocks in the Calimianes area. Marine protected areas became a best practice, in which local (traditional) fishermen were still allowed to fish, but no commercial vessels were allowed. Fish stocks recovered in five years (Al Linsangan III, personal communication). On Borocay, tourism development led to a decrease of illegal fishing practices (Lumagod, personal communication). In Port Barton (Palawan) and Siargao (Mindanao), illegal fishing practices are still being used on the coral reef (Aquaholics; Palaka, personal communication). On Siargao Island, which also established fish sanctuaries, fishermen are still fishing inside those protected areas day and night (Palaka, personal communication). The model excludes

both illegal fishing and illegal fishing practices as its goal is to put forth the hypothesis that even with only regular fishing practices by the local population, fish stocks are rapidly depleting on the coral reefs. It should be clear for policy makers that illegal fishing and illegal fishing practices should be banned directly if the sustainability of the coral reef is deemed important.

3) The model also excludes the impacts of agricultural activities and port/harbor activities on the coral reef. Agricultural activities could play an important role in bringing additional supplies of nitrogen (from fertilizer) to the coral reef. However, this model only includes the effect of sewage disposal on the nutrient levels, as it has been deemed more dominant on most destinations. With regard to port activities, many sources of industrial waste could have a negative effect on the health of the coral reef. Additionally, more ships leads to more oil entering the sea water (e.g. refilling). This effect from local (motorized) fishing boats and tourist boats ('bangkas') has also been excluded from the model, but has been observed on many coral reefs in the Philippines. The most important reason not to include the effects of port activities in the model is that their impact will mostly be felt by coral reefs which are adjacent to the port, and which will already have died off. The most important case study on this topic, on Mactan Island, shows how (protected) coral reefs on an island close to the second-largest city in the Philippines (Cebu City) are still able to thrive even though they are relatively close to one of the major trading ports in the Philippines. Even on these coral reefs, the main causes of degradation seemed to be local (water quality, overfishing, sedimentation and anchoring).

Within the tourism sub-model the most important factors which have been excluded are:

1) The effect of sunscreen on the health of the coral polyps. While this effect has historically been mostly a hypothesis, there is now growing scientific evidence that the concentration of ultraviolet protection ingredients leads to increased bleaching of the hard coral cover (Danovaro, Roberto; Bongiorni, Lucia; Corinaldesi, Cinzia; Giovannelli, Donato ; Damiani, 2008; Downs et al., 2016). With increased tourism development, and related island hopping activities, the coral reefs are now facing more pressure from sunscreen. Especially Asian tourists are notorious for the thick layers of sunscreen they use to protect against the sun. It is recommended for local authorities to promote/regulate the use of natural alternatives for sunscreen to take precautionary action against the possible negative effects on the corals. Figure 70 shows an alternative coral-friendly sunscreen lotion, which has been developed in the Philippines. It has been decided not to include the effects of sunscreen in the model for two reasons. First of all, other pressures on the coral reef have been deemed more dominant

with regard to the rapid degradation of the coral reef, which already happened before tourism development started growing. Some of the coral reefs which are now mainly used for tourism and which have taken the necessary measures (such as using sustainably buoys instead of anchors) are actually facing a slowdown of coral degradation. Therefore the effect of sunscreen might not be as dominant as the effects of overfishing and pollution. Secondly, water currents help to dissipate the sunscreen from the coral reef into the open water which might limit the effect on coral health (Al Linsangan III, personal communication).

Figure 70 Human nature ‘Safe Block’ natural sunscreen (reef-friendly) – Siargao Island

2) An important factor which has not been modeled is the feedback between the quality of the environment on the tourist destination and the attractiveness of the destination for new tourists. While it is reasonable to assume that a healthy coral reef is more attractive for tourists than a death coral reef, it is still unsure to what extent the quality of the environment will feed back on tourists’ experiences and new tourists arriving. Tourism development seems to be a complex system and once it has gained momentum it is hard to slow it down, even when the environment which makes the destination attractive in the first place is suffering degradation. Popular tourist destinations will have money available to partly cover up the environmental effects (for example by cleaning algae from the popular beachfronts) and/or diversifying the available attractions on the destination. For example, in Borocay, the most popular and crowded tourist destination in the Philippines, many people assume that environmental pressure will lead to a decline of its attractiveness. However, up to now, tourist arrivals are still rapidly increasing. The same goes for El Nido, which is already experiencing water pollution on its main beachfront but it is expected to get even more popular with new tourists arriving to the Philippines. The main question is to what extent most of the tourists care about the quality of the coral reef. Are the tourists truly interested in the marine environment, or are they ‘just’ taking the tours which are recommended in

travel magazines? To answer this question, more research is required. Therefore in this model it is assumed that there is no feedback between the quality of the environment and the tourist arrivals. Tourism growth is only limited by the available land which can be used for tourist resorts.

7.2 Structure assessment

Structure assessment has been tested iteratively during the modeling process and many of the results are presented in the subsequent chapters explaining the model. All parts of the model have been tested for consistency with the real system. There was one part of the model which violated physical laws. The outflow from the coral reef 'Bioerosion' was initially modeled based on bio-erosion from parrotfish and from tourist activities. The natural decay of the coral reef was not modeled because the other sources of bio-erosion were more dominant during the given reference period. However, in simulations of the model in which there is no parrotfish stock and no tourism, the effect of natural decay has to be included since it can have a considerable impact on the total size of the reef.

None of the stocks in the model can become negative, as this is also impossible in the real system. Furthermore, the model has tried to exclude 'free lunches', in which activities which require resources are being performed in the model without any usage of resource (Sterman, 2000, p. 863). For example in the policy of removing crown-of-thorns starfish, many destinations have a policy of removing them when they reach a certain number on the reef. However, in this model, the policy has been modeled based on the limitation of resources: the number of persons who are available to remove them and their efficiency. In other parts of the model, there are still 'free lunches'; for example, the building and demolition of resorts has been assumed to occur without any workforce. This can be explained by the parameter 'Fraction of men becoming fishermen' from the population sub-model. This parameter accounts for the part of the male population which, among other occupations, could be active in the construction sector. However, in the height of a 'tourist boom', the percentage of people needed in the construction sector might increase rapidly and in that case it should be modeled endogenously and might lead to an increase in immigration and/or an increase in the time to build a resort (in the case of a shortage). These feedbacks might be included in a future version of the model. The same problem situation occurs with the policies of artificial reefs and coral replanting, which have been assumed to happen without any people (mostly scientists or divers) needed to perform them. The model assumes here that these duties will mostly be done by scientists which work under externally-financed environmental programs.

With regards to peoples' decision making, several assumptions have been made. In the tourist sector, for example, it has been assumed that the reason for people to visit a destination is primarily based on their contact with friends and relatives. This might exclude the important effect of destination marketing and/or travel agencies on the attractiveness of tourist destinations. Secondly, the decision of the local fishermen to switch from being fishermen to working as a tourist operator has been modeled without the effects of economic incentives which play an important role in the decision.

7.3 Dimensional consistency

Dimensional consistency of the model equations has been performed by the iThink software. The only part of the model in which the units are a bit harder to understand is in the model structure representing the nitrogen level on the coral reef. In this part of the model, the sewage output from the population is measured in liters/year while the total nitrogen entering the beachfront is measured in µmol/liter/yr. This unit means that a fraction of the total liters of sewage entering contains nitrogen. The parameter 'inorganic nitrogen content of sewage' therefore has the units µmol/liter^2, which basically means the amount of nitrogen/liter of each liter of sewage which is disposed.

7.4 Parameter assessment

All parameters in the model have been assessed on having a real-life counterpart. Parameter values in the model have been based on:

1) Scientific research
2) Expert opinions
3) Author's assumptions
4) Sensitivity analysis

Most of the parameters in the coral, algae and fish sub-models have been estimated using scientific sources or interviews with marine experts in the Philippines. Within the population, tourist and management sub-models, most of the parameters have been estimated based on observations on different destinations (e.g. number of people per boat) in the Philippines, interviews with local stakeholders (share of sewage which is treated), national statistics (fertility rates) and the author's own assumptions (sediment produced per resort). Many of the parameters in the model are still unscientific and need further study. The only parameter in the model which has been estimated using sensitivity analysis is the 'dissipation factor of nutrients on the beach front', as it was unclear to the author which factor it would take for the disposed sewage to dissolve in the sea water on the beachfront.

7.5 Extreme conditions test

Extreme conditions tests have been performed to assess the robustness of the model under extreme circumstances. When the model was tested without any live coral tissue, it became clear that there wasn't really an effect on the size of the coral reef, since the parrotfish were declining in numbers and there was no model structure to take account of the natural decay of the coral reef. After this test, the author has decided to include the natural decay of the coral reef (500 years) in the model. Now, when the model is simulated without live coral tissue, the model behaves as expected: 1) the coral reef will decline faster since there is no more formation of new reef substrate; 2) the macro-algae population will be able to start occupying the reef earlier than before (1990 instead of 2010); 3) fish stocks are depleting more rapidly (within 15 years), as there spawn efficiency will decrease (not completely to '0' since it is assumed that some of the eggs can still survive by nesting in the seagrass); 4) crown-of-thorns starfish will go extinct as their source of good is depleted.

When the model is simulated without both the live coral tissue and the coral reef substrate, the model behaves as expected with 1) No coral substrate, no live coral and no algae; 2) Fish stocks depleting for the largest part within 1-3 years.

When the model is simulated without a snapper population, the model behaves contradictory to expectations. It would be expected that the crown-of-thorns population would grow more rapidly, leading to more grazing on live coral tissue which then would lead to higher occupation of macro-algae. However, when the model is simulated it reveals that with a snapper population, the live coral tissue degrades more rapidly than without snappers. This contradictory behavior can be explained by the feedbacks between the level of the total fish stocks and the harvesting of the local fishermen. When there is no snapper stock, the total fish stock is lower than with a snapper stock, which means that the average fish catch will start to decline more rapidly than when the model is simulated with snappers. Because only a certain fraction of the total harvest are parrotfish, simulating the model without snappers mean that the parrotfish stock will decline less rapidly. Since parrotfish graze on the macro-algae, a higher stock of parrotfish leads to less competition for space between the coral polyps and the algae. Therefore the live coral tissue degrades less rapidly without snappers. When the model would be simulated without snappers, it is therefore necessary to change the parrotfish fraction to '1', assuming that it is the only fish to be caught by fishermen.

When the model is simulated without a parrotfish population, the model behaves according to expectations. Since there is no grazing on algae, the algae cover can increase rapidly, at the expense of the live coral tissue cover. The live coral cover is able to remain a small competitive advantage in terms of occupied space of the reef over the algae, until around the year 2014-2015, when the effects of water pollution lead to an algae-dominated reef. This is caused by the increased growth rates of the algae caused by changes in nitrogen availability and the outbreak of crown-of-thorns starfish also caused by nitrogen availability and the depletion of the snapper stock.

When the model is simulated without tourism development, the coral reef faces only pressures related to local population growth (which grows from '1000' in 1970 to '4620' in 2050). As the simulations in Figure 71 show, the model predicts that the coral reef, initially, is able to sustain itself with a small local fishing community developing next to it.

Figure 71 Simulations coral reef without tourism development

However, after about 30 years of population growth, the sewage disposed on the reef grows in volume and the stock of parrotfish becomes depleted. This leads to an increasing dominance of the two reinforcing feedback loops which lead to a decrease in the live coral tissue: algae bloom and COTS outbreak. In the long run, these feedback loops increase the dominance of the reinforcing 'reef decay' feedback loop, in which decreased cover by live coral tissue leads to decreased formation of coral substrate for new recruits to settle upon. In the long run, a collapse of the coral reef will be the result. An important point of discussion and limitation of the model is the fact that there is no structure in the model which explains what will happen to the local population when the fish stocks are depleted and there is no potential for tourism development. Will the population be able to find other means of living or will they have to migrate to other parts of the Philippine archipelago?

The model has also been tested by simulating the behavior of the coral reef when there is tourism development but no local population. This situation might, for example, be possible on uninhabited or private islands which exist in the Philippines. The simulations show how, without an initial local population, there will be no fishing and therefore fish stocks will increase. With high stocks of parrotfish, the macro-algae will not have a chance to occupy the coral reef, even when the water starts to become polluted from increased sewage disposal from tourist resorts. However, the live coral tissue, although the snapper population is helping to keep the COTS larvae survival rate down, is affected by the outbreaks of COTS, which are growing in numbers because of increased nutrients level on the coral reef. As the live coral tissue declines, coral reef formation starts to decrease as well. Additionally, large impacts from anchoring by tourist boats and tourists during island activities are severely impacting the coral reef substrate starting from around the year 2010. This situation leads to a lower settle rate for coral recruits and finally to extinction of the coral reef. It is interesting to note that, because of tourism development, immigration of labor (e.g. local population) has to occur to work in the tourist sector. This shows that the model takes account for the fact that there cannot be tourism development without a local workforce (‘no free lunch’).

7.6 Integration error

The simulation model uses Euler’s integration method with a DT time step of 0.0625 (or 1/16). Changing the timestep to 1/32 or 1/64 does not alter the simulation results.

7.7 Behavior reproduction

The theory presented in this paper, in the form of a formal model, is based on the extensive literature available on coral reefs and the author’s own insights from studying the coral reef environment in the Philippines. The main focus has been to identify those social-ecological processes which are specifically responsible for coral growth, decay and recovery on multiple locations in the Philippines. Several of those processes have also been identified by other author’s studying coral reefs around the world. The outcomes of the model simulations are hypothetical as the model has not been calibrated based on one specific coral reef environment. As recommended by Forrester (1961, 1969), a modeler should focus on a class of problems rather than individual cases.

Therefore the behavior produced by the hypothetical model could apply to all coral reefs declining worldwide, although it is more specifically focused on the coral reefs in the Philippines. The model is not a blueprint which is applicable to each individual coral system. To use the model directly for policy making, it should be specified and calibrated towards the individual characteristics on the particular coral reef location.

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, population growth and tourist arrivals are available and can be compared to simulation results of the hypothetical coral reef model. Figure 72 and Figure 73 show the most important trends in population size, tourist arrivals and coral cover from the 1980s to 2011. Comparing these trends to the simulation results (Figure 74) 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.

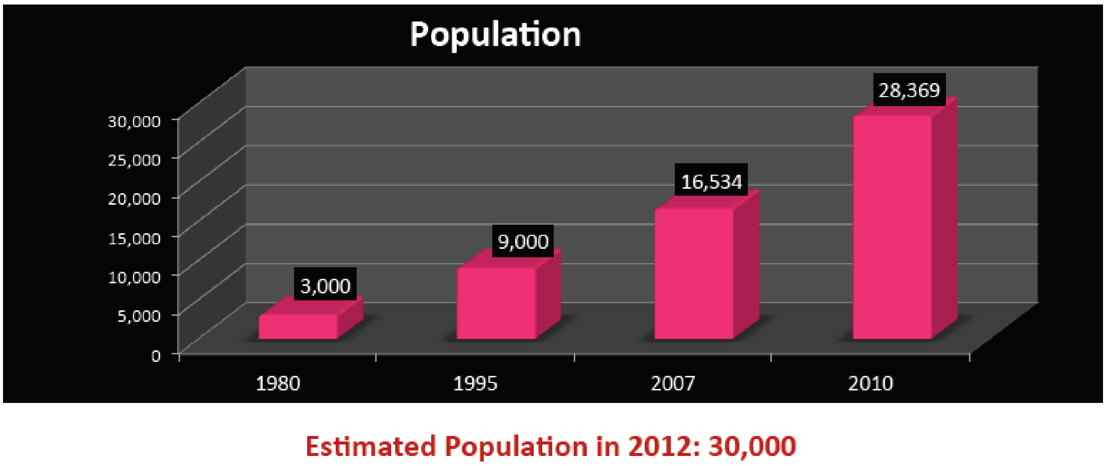


Figure 72 Population growth on Borocay, the Philippines (Fortes, 2014, p. 10)

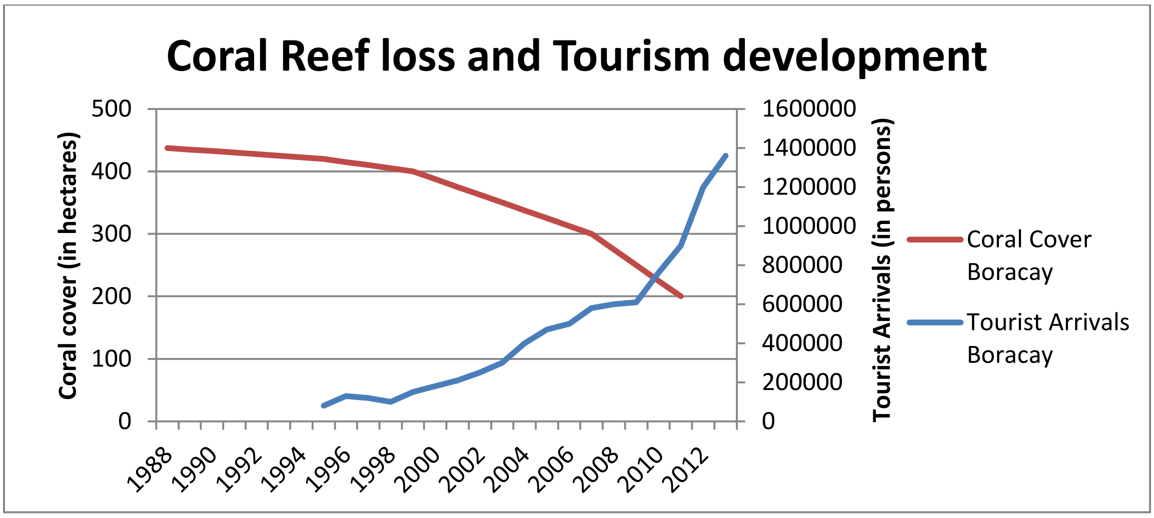


Figure 73 Coral cover and (annual) tourist arrivals on Borocay, the Philippines (Fortes, 2014, p. 12,20)

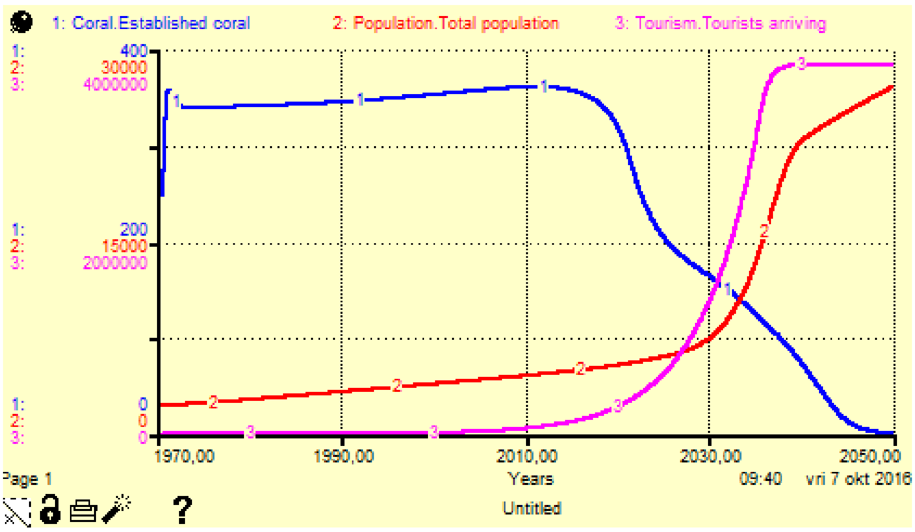


Figure 74 Simulation results of the coral cover, population and (annual) tourist arrivals

On El Nido, which is often seen as the next Borocay in terms of tourism development, similar trends can be observed in Figure 75 and Figure 76.

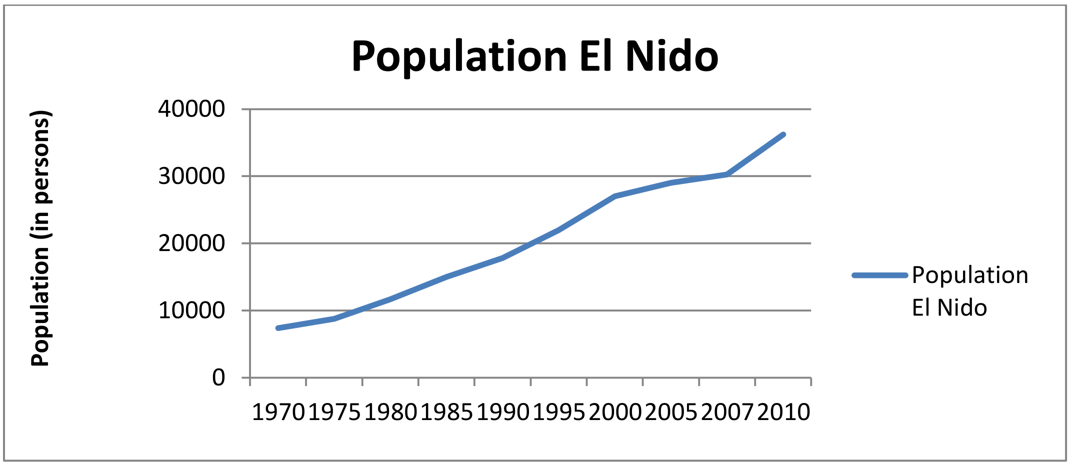


Figure 75 Population growth on El Nido, the Philippines (Municipality of El Nido, 2016, p. 4)

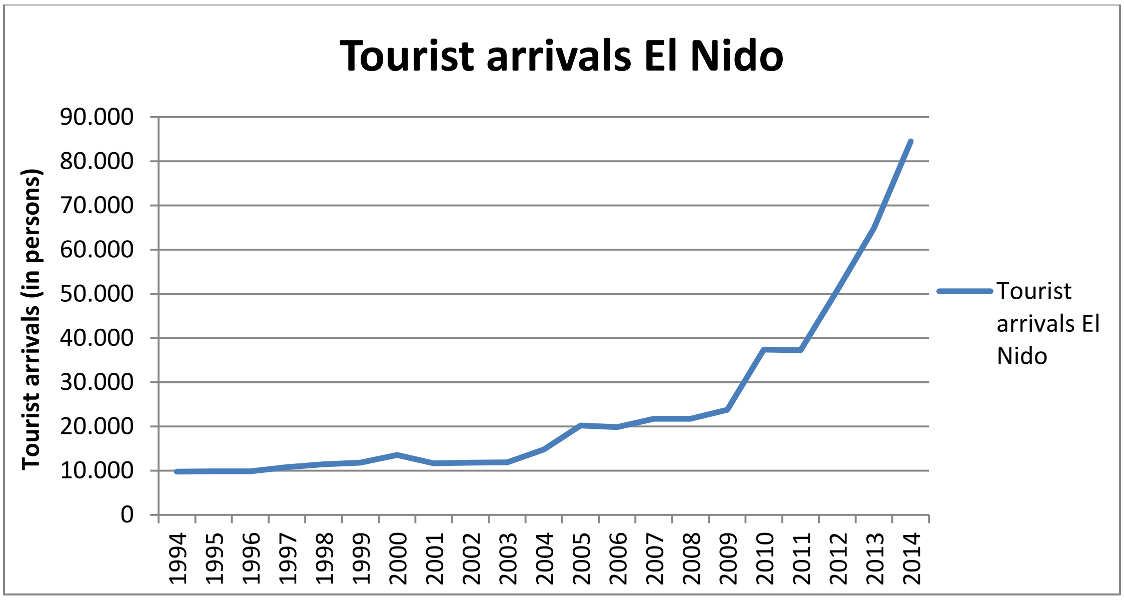


Figure 76 (annual) Tourist arrivals on El Nido, the Philippines (Municipality of El Nido, 2016, p. 10)

With regards to the development of the coral cover over time, there is limited historical data available. Table 2 shows the assessment of the status of the coral reef in the most important tourist bay in El Nido. However, it must be noted that the present state of affairs is based on an assessment from the year 2006.

	BACUIT BAY
1950's	EXCELENT
1970'S	EXCELLENT
1980's	POOR
1990's	GOOD
PRESENT	FAIR

Table 2 Assessment of the status of the coral reefs in El Nido (Palawan Council for Sustainable development, 2006, p. 19)

Figure 77 provides reference data for other growing tourist destinations in the Philippines.

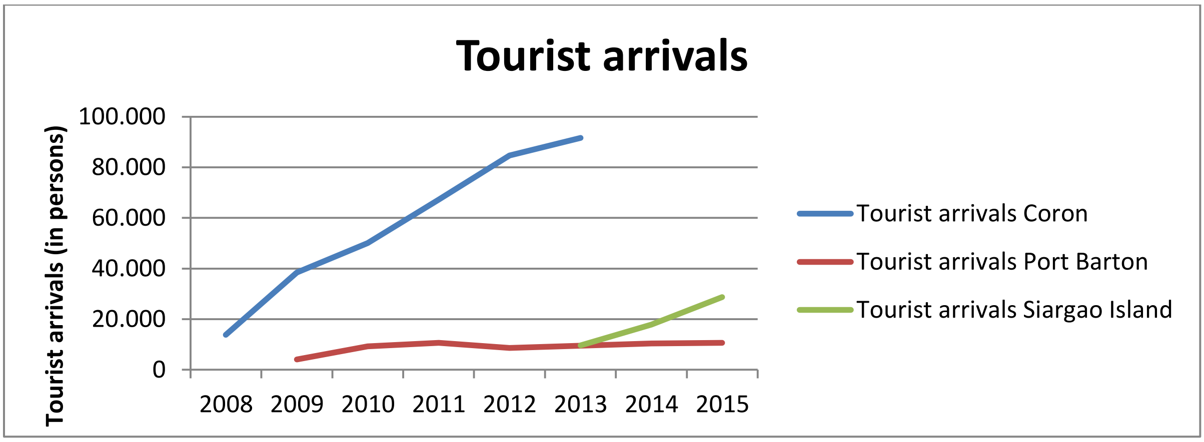


Figure 77 (annual) Tourist arrivals on Coron (Province of Palawan, 2014, p. 13), Port Barton (Tourism office municipality of Port Barton, personal communication) and Siargao Island (Gallantes, personal communication)

Many tourist destinations in the Philippines are expected to experience rapid growth in tourist arrivals in the coming years. The island of Palawan (including destinations like Coron, El Nido and Port Barton) is gaining momentum as a travel destination as it is often seen as the 'last frontier', because of its relative remote and isolated character. It has recently been voted as the best island in the world by the readers of one of the leading travel magazines (Conde Nast, 2015). Tourism development is currently still relatively slow due to limited infrastructure capacity. However, the number of direct flights to Coron is increasing rapidly and a paved road for access to Port Barton is expected to be ready by the end of this year. On the province of Cebu, expansion of the airport capacity is expected to increase the number of tourists arriving to destinations like Mactan Island and Moalboal. Siargao Island is a relatively new and unknown destination but has a high potential for nature and marine based tourism. A new airport on Panglao Island (Bohol) is expected to be finished at the end of 2017, which could lead to a rapid growth of tourist arrivals there as well.

On most of these 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. Figure 78 reveals the results of a recent assessment of the hard coral cover on the most popular tourist town on Siargao Island (General Luna). As described in the boundary adequacy chapter, this rapid decline in hard coral cover is most likely caused by illegal fishing practices (e.g. dynamite fishing). Following the hypothesis presented in this model, the low level of tourism development on Siargao Island will most likely not yet have been responsible for this rapid decline in hard coral cover. There it is possible that certain destinations will already lose their coral reefs before tourism development can take off.

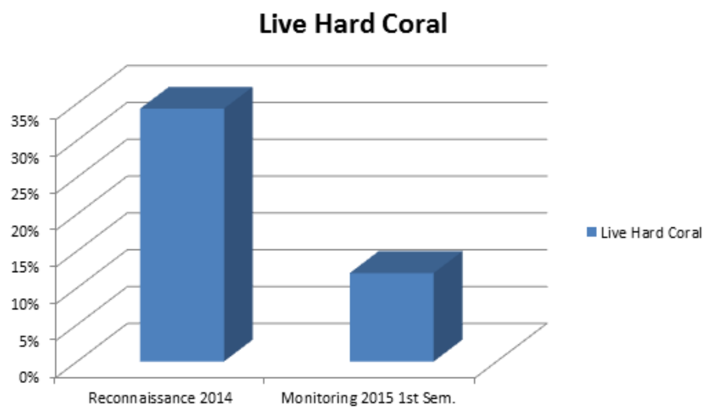


Figure 78 Coral reef cover on General Luna- Siargao Island (Department of Environment and Natural Resources, 2015, p. 11)

7.7.1 Behavior reproduction based on anecdotal evidence

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 and included in this chapter. However, the anecdotal evidence has only limited scientific value since it is prone to the subjective bias of, in this case, the author of this paper.

The conditions as described on an undisturbed coral reef have been observed on one coral reef destination: Apo Island. Apo Island is a small island in the Negros Oriental Province, with a local population of around 300 people and 100 houses. The coral reef is a marine sanctuary (protected area) in which only local fishermen are allowed to fish on a limited basis. All local houses have access to 'level three' septic tanks which clean the sewage. Additionally, there is only one resort on the island, again with good sewage facilities. Observations from the coral reef around the island show:

1) A very high amount of coral reef substrate
2) Highly occupied coral reef substrate by live coral tissue
3) Very limited macro-algae cover
4) Abundant fish stocks, including parrotfish and snappers
5) No reported outbreaks of crown-of-thorns starfish

However, there have been parts of the coral reef on Apo Island which have been degraded, mainly by typhoons. However, these coral populations were able to recover quickly (sometimes within a month).

The conditions as described on a coral reef which is mostly affected by a growing coastal population and fishing industry, but only limited tourism development applies to two coral reef destinations in the Philippines: Port Barton (Palawan) and Siargao Island (Mindanao). Observations from the coral reef and human environment on those destinations show:

1) Coral reef substrate locally damaged by anchoring fishing boats and illegal fishing (dynamite)
2) On Siargao Island, on the coral reef offshore of General Luna, the coral reef seems to have very low occupation by live coral tissue. Although there also does not seem to be much algae cover. There are many sea-urchins grazing on the reef. On Port Barton, the live coral cover is still relatively good, although local impacts have their effects on the coral polyps.
3) Overall water quality around the coral reef is very good. In Siargao Island the water is very blue. However, local outbreaks of macro-algae have been observed in Port Barton (Aquaholics, personal communication).
4) Low fish stocks on the coral reef due to overfishing. In Port Barton, fish is often not available on the fish market (Aquaholics, personal communication).
5) In Port Barton there have not been any crown-of-thorns outbreaks recently, and only a few can be seen on the coral reef (Aquaholics, personal communication). On Siargao Island, there have been recent reports of crown-of-thorns starfish outbreaks.

The anecdotal evidence in Port Barton and Siargao Island show how a local fishing community has affected the health of the coral reef, mainly through overfishing and boat anchoring. With relatively low sewage pressure on the seawater yet, the reinforcing feedback loop R2 'Algae bloom' has gained some strength but is not too dominant yet. Reinforcing feedback loop R3 'Starfish outbreak' has seemed to gain dominance on Siargao Island. This is most likely caused by overfishing of the snappers, which play an important role in controlling the outbreak.

The conditions as described on a coral reef which is affected by both local population growth and rapid tourism development correspond mostly to the two most popular tourist destinations in the Philippines: Boracay and El Nido. Observations from the coral reef and human environment on those destinations show:

1) High levels of water pollution and algae bloom, especially near sewage disposals on the beach
2) Resort construction near beachfront leading to sediment entering the beachfront
3) Occurrence of crown-of-thorns starfish outbreaks
4) Low occupation of coral reef by live coral tissue, many coral rubles and broken coral reef structures
5) Low fish stocks

It is worryingly to conclude that it seems to be the case that El Nido is not learning from the problems which have occurred on Boracay, the destination in the Philippines which was one of the first to develop and grow rapidly. El Nido is now one of the new booming tourist destinations on the popular island of Palawan. The most actual problem on El Nido is the growing pollution of its seawater, most likely caused by a lack of sewage facilities for both the local population and new tourist resorts (Mencias; Al Linsangan III, personal communication). An eye-witness report reveals how the most popular beach on El Nido used to have clear water and visible, alive coral reefs. Now there is no more live coral, many crown-of-thorns starfish and pollution. Following the hypothesis in this paper, the coral reefs most close to human impacts will indeed be the first to degrade.

On Borocay, there was at least a major crown-of-thorns starfish outbreak in 2006 (Lumagod, personal communication). Following the hypothesis in this paper, such an outbreak would be expected as water pollution and fish stocks decline. Until the year 2014, there was no regulation on where to build resorts on Borocay, which leads to many resorts being within the 30-meter distance line of the beachfront. On El Nido, at the moment, new resorts are still being built, even within 10 meters from the beachfront.

On Moalboal, in the province of Cebu, tourism development is growing. Water pollution is starting to become a big problem and coral reefs near the beachfront are already heavily impacted by sedimentation and pollution. There are many death coral, rubles and there is local overtake of macro-algae. On some places near the local settlements, the water looks like a toilet.

On Coron, on the province of Palawan, there is heavy water pollution near Coron Town, where most of the local population lives. There is no sign of any sewage system. Island hopping activities visit Coron Island, which is a bit further away from the front of the town. The water around Coron Island still seems pretty clear. But with increasing pressures it might be possible that the water will be more polluted there as well. Near the harbor in Coron Town, there is now a lot of construction activity and a large part of the area is for sale for investors. What will the future bring for Coron? Island hopping is not so crowded yet as in Borocay and El Nido. Anchors are a problem. There are low fish stocks, but also few algae. This is mainly because of a sea-urchin outbreak, which grazes the macro-algae rapidly. This is a small rejection of the hypothesis, since the model postulates the parrotfish as the only grazer of macro-algae on the reef.

The island of Mactan provides a good example of the failure of current coral management programs when taking into account the health of the complete coral reef. On Mactan, the Shangri-La resort has implemented a (private) marine protected area (of 5.7 hectares) for its guests (Jimenez, personal communication). Within the MPA, no fishing and anchoring is allowed. Furthermore, the MPA program is combined with regular artificial reef and coral replanting projects and COTS removal. In the MPA, the coral reef cover increased from 10-15 percent in 2013 to about 50 percent in 2016. Furthermore, the live coral cover increased while the macro-algae cover decreased (Jimenez, personal communication). Although this program is successful from a local point of view, the surrounding areas do not benefit directly from the program. As the protected coral reef is still facing the adjacent non-protected coral reefs, water pollution, sediment and crown-of-thorns outbreaks will remain a constant threat for the MPA.

Artificial coral reefs, coral replanting, COTS removing and MPAs are important programs on most of the coral reef destinations in the Philippines. For example, on El Nido, there are ongoing projects which focus on coral rehabilitation (Gonzales, 2015). While all efforts to sustain the coral reef should be appreciated, it might be wise to increase the understanding of the major drivers of coral degradation and where to intervene in the system to alleviate these drivers. The next chapters will focus on the ways in which the simulation model and hypothesis of this paper can be used to improve the effectiveness of coral programs to sustain the coral reef.

7.8 Behavior anomaly

To test the strength and importance of important relationships (and structures) in the model, a 'Loop knockout analysis' will be used in combination with extreme condition tests (Sterman, 2000, p. 880). To cut the important reinforcing 'Algae Bloom' feedback loop, the model will be simulated with average algae grazed per parrotfish equal to '0'. In this way, the model assumes that parrotfish will not influence the size of the macro-algae stock by grazing it from the reef substrate. Simulating this scenario reveals the unrealistic behavior of the coral reef, in which the algae can rapidly bloom even when the environmental conditions (e.g. water quality) should still favor live coral cover over algae cover.

The same test can be applied by cutting the important reinforcing 'Starfish outbreak' loop. This loop can be cut by simulating the model with 'average coral grazer per COTS' equal to '0'. When the model is simulated in the extreme conditions where there is very high water pollution and no stock of snappers, the live coral tissue is able to remain alive for a much longer time than would be expected, when a COTS outbreak could rapidly kill all the live coral tissue.

7.9 Family member

The model presented in this paper simulates the behavior of a hypothetical coral reef on a tourist destination in the Philippines. As such, its behavior should be able to generate the behavior of, at least, all the destinations which have been examined during this research. Additionally, there is evidence that coral reefs in the Caribbean are under the same kind of pressure as the coral reefs in the Philippines (Jackson et al., 2014).

Calibrating the model with different parameters and initial stock values should be able to generate different kind of behavior based on individual characteristics on different locations. For example, simulating the model with the data of Apo Island should show healthier coral reef development over time, while simulations with data from Borocay and/or El Nido would most likely show a more rapid degradation of the coral reef. As the model has been simulated with a relatively long reference period (70 years), the theory it presents is able to generate a wide range of behavioral patterns. Simulating the model under different scenarios should, for example, be able to produce both s-shaped growth and growth and collapse.

7.10 Sensitivity analysis

Since the purpose of this paper has been to increase understanding about the general dynamics of coral reef degradation in the Philippines and not exact prediction of coral reef behavior in the short term, the model should be tested on behavior mode sensitivity. 'Behavior mode sensitivity exists when a change in assumptions changes the patterns of behavior generated by the model (Sterman, 2000, p. 883). As discussed before, the pattern of behavior are expected to be similar under changes in the level of aggregation and people's decision making processes. Regarding the boundary of the model, including large predators and sea urchin stocks is not expected to alter the growth and collapse pattern, although it might lead to a slower overtake of the macro-algae and/or a more rapid decay of the coral reef substrate.

'To assess the sensitivity to the parameter values used in the model, the most plausible range of uncertainty in each parameter and nonlinear relationship should be identified, before testing the sensitivity to those parameters under a much wider range' (Sterman, 2000, p. 884). The most important and uncertain parameters and nonlinear relationships have been tested and the simulation results can be observed in Appendix A.

Some interesting insights have been gained from the sensitivity analysis:

1) Coral species with lower average lifetime are most likely to go extinct first
2) Low reef productivity is one of the key reasons why current developments are unsustainable (similar to low formation rates for fossil fuels- unrenewable from a human time perspective)
3) Higher grazing rates of crown-of-thorns starfish could lead to a more rapid mortality of the live coral tissue
4) No sensitivity of macro-algae to parrotfish grazing rates, since the parrotfish will have gone extinct when the macro-algae starts to gain momentum on the reef
5) The effect of nutrient availability on the stock of macro-algae is not so important when the reef is already decaying rapidly. There will be no more space available to occupy.
6) Fish stocks are most likely very sensitive to the effects of live coral tissue on spawn efficiency and coral reef cover on recruit mortality. Since these relationships have no scientific foundation, further research is required.
7) Tourism growth is very sensitive to the expected tourism growth rate of resort developers. This could mean that once one tourism destination in the Philippines has led to great

financial rewards for businessmen, other destinations might have higher growth expectations from the start and will grow more rapidly.

8. The path to coral reef recovery

This chapter explores policies that might reverse coral degradation. 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. Therefore, after exploring several policies, this chapter concludes that reversing coral degradation is only possible by restoring the environmental conditions under which coral reefs can thrive naturally.

8.1 Sewage treatment

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. Figure 79 proposes a policy in which a sewage system is developed on the coral reef destination.

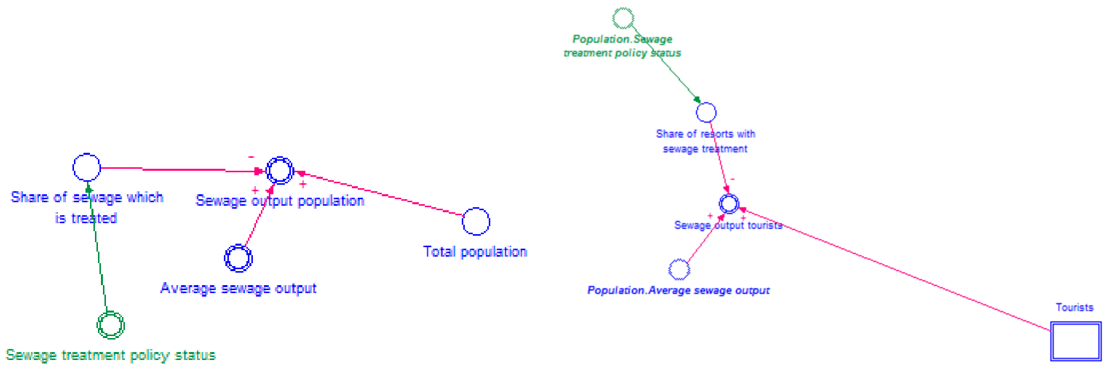


Figure 79 Sewage treatment policy

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. When the sewage treatment policy has been successfully implemented, the share of the local population's sewage which is treated will become 95%. The 5% of the sewage which is still untreated can come from the local population which lives directly above the seawater. In the long term, the people living here might be offered an alternative house further from the reef with an appropriate sewage system. Furthermore, the local population has to be connected to sewage system, preferably free of cost and accompanied with a briefing on how and why they should use it. It is important to make this service free because otherwise most of the people will probably to decide to keep using the seawater for their sewage.

With regard to the tourist sector, it will be possible to establish a policy which will lead to 100% connection to the sewage system. For the success of the policy it will be necessary to have strict regulations which make it obligatory for each resort to be connected to the sewage treatment system. For the resorts, a fee can be charged for this service as their guests, and thus the resorts themselves, will benefit economically from a better environment. It is very important to enforce the regulations by regular checks of the resorts and setting large fines for resorts that do not comply with regulations. Figure 80 shows the positive effect of this policy on the competitive position of live coral tissue against macro-algae.

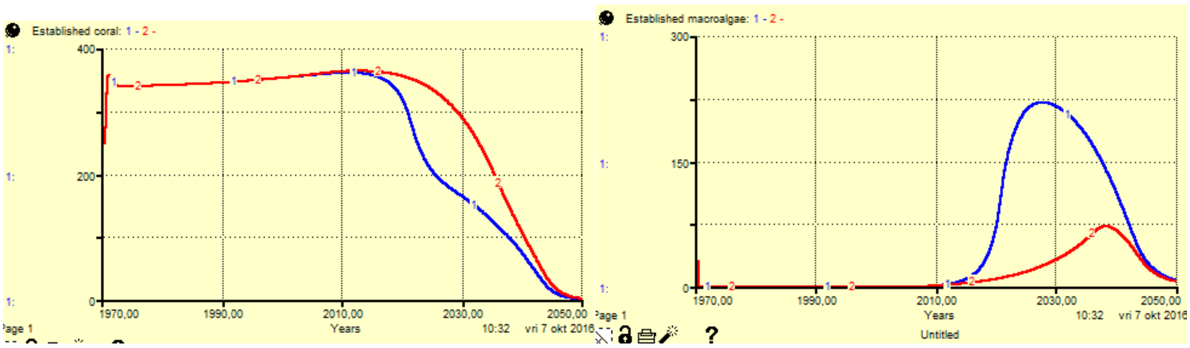


Figure 80 Effect of sewage treatment policy on live coral and macro-algae populations

8.2 Sustainable buoys, glass ceilings and organic sunscreen

As discussed before, it takes a long time for the reef-building coral polyps to develop the reef substrate. Compared with the rapid destruction of the reef caused by anchoring and tramping by tourists, taking measures to prevent those damages could be considered as ‘low-hanging fruit’. The first policy which will be proposed is to use sustainable buoy technology instead of individual anchors for the fishing and tourist boats (Figure 81).

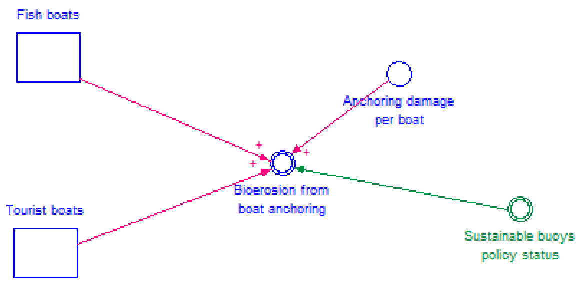


Figure 81 Sustainable buoys policy

When the sustainable buoys policy has been successfully implemented, the damage from boat anchoring will become '0'. 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. Because of the high price of this buoy technology, there is often a risk of theft (Mencias, personal communication). However, combined with the MPA enforcement policy which will be discussed later, the risk on theft will be contained. Furthermore, there are other cheaper alternatives (floating buoys) which prevent damage from boat anchoring and have a lower risk on being stolen.

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 (Figure 82).

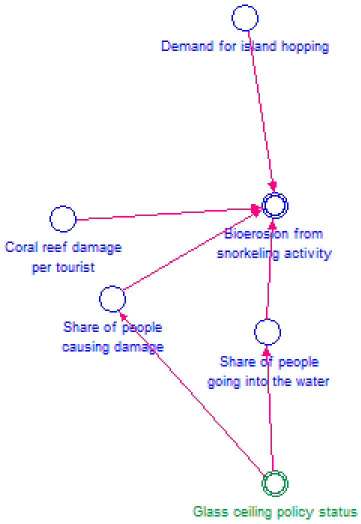


Figure 82 Glass ceiling boats policy

With this policy in place, it is assumed that the share of people who go into the water will decrease to 10% because most of the people will now choose to watch the coral reef and fish from inside of the boat. In this way, they can prevent the stings by jellyfish and listen to the stories of the guide which explains what there is to see on the reef. 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. With this policy, it can therefore be assumed that the share of people who cause damage will decrease dramatically, from 20% to 2%, because most unexperienced swimmers will not be going into the water in the first place, and the people who do go will have to be careful not to break their contractual agreement of appropriate behavior. The agreement, which divers and snorkelers have to read before the trip, they are also obliged to use organic (coral-friendly) sunscreen when going into the water. Although the effect of sunscreen has been excluded from the model, this measure will have an additional positive impact on the sustainability of the coral reef.

Figure 83 shows the high impact these two policies have on the sustainability of the coral reef substrate by reducing the rapid destruction of the reef by tourist activities.

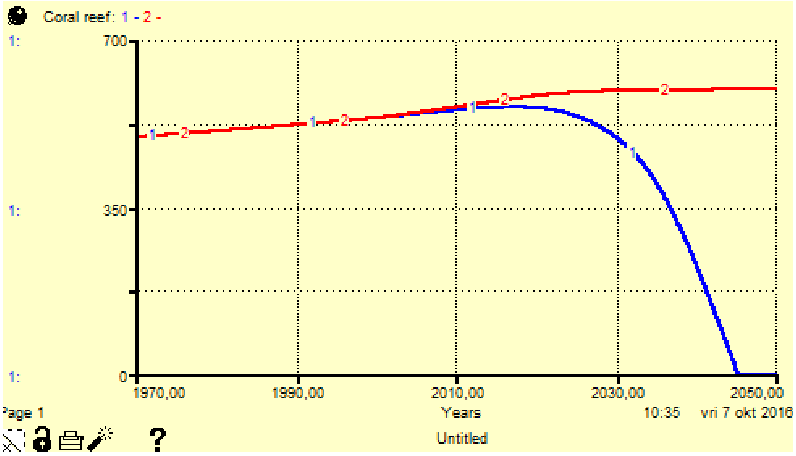


Figure 83 Effect of sustainable buoy and glass ceiling policy on coral reef substrate

8.3 Sediment run-off measures

When the direct destruction of the coral reef substrate has been prevented, another policy should be implemented which focuses on the natural growth rate of both the coral reef and the live coral tissue. 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. A relatively cost-effective measure to de-couple the constructional activity from the sediment disposal is proposed in Figure 84.

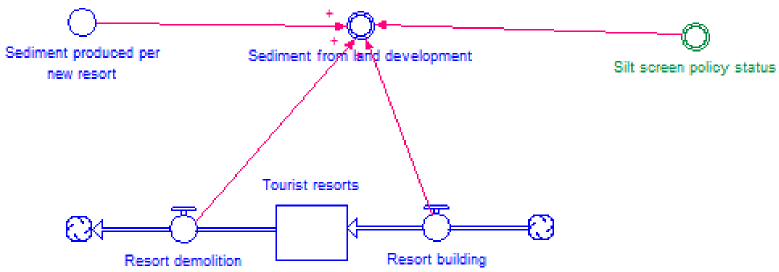


Figure 84 Silt screen policy

The proposed policy consists of implementing 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).

When the silt screen policy has been successfully established, the sediment produced per resort which is built or demolished will decrease 100-fold to 0.0001 hectares. For the success of the policy it will be necessary to have strict regulations which make it obligatory for resort developers to use the silt screen in a proper way. This includes the export of the sediment land inwards when the construction has finished. The silt screen policy should preferably be accompanied by regulations which make it illegal to build within 30-meters of the beachfront.

Figure 85 shows the additional effect the silt screen policy (red line) can have on the productivity of the reef where already sustainable buoy and glass ceiling policies are implemented (blue line). In the case with the silt screen policy, all major causes of sedimentation on the reef have been prevented without jeopardizing tourism development.

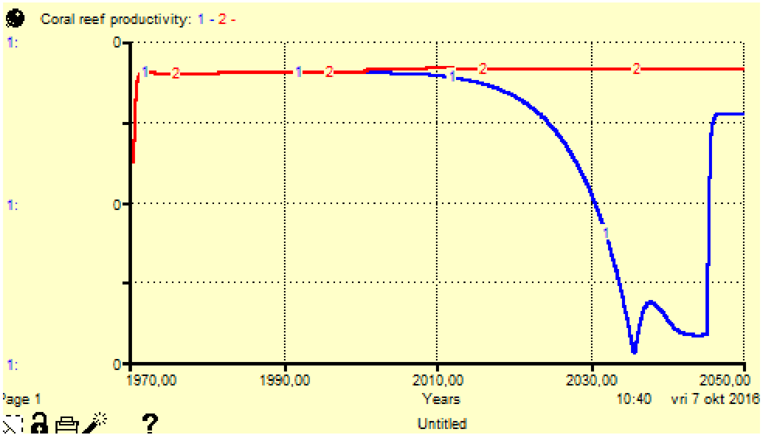


Figure 85 Effect of silt screen policy on coral reef productivity

8.4 Marine protected area with local enforcement

Although the general idea of establishing marine protected areas can be considered highly beneficial for the sustainability of the coral reef, there are some important limitations to their effectiveness in the way they are currently implemented. As discussed in 6.3 Marine Protected areas, the current MPA policies do not take sufficient account for creating alternative livelihoods for fishermen on the reef. Thereby, 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. This program is described in Figure 86.

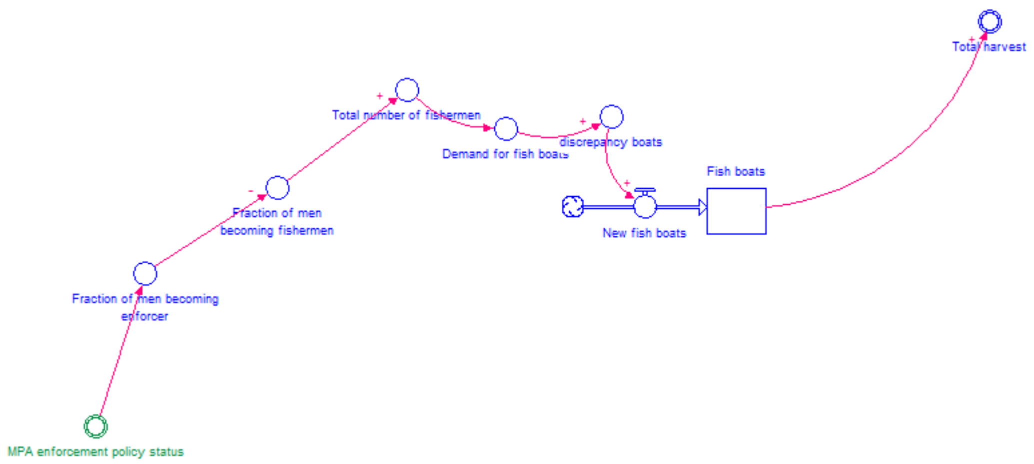


Figure 86 MPA enforcement policy

When there is a policy in place to establish local environmental enforcement on the destination, the fraction of men becoming enforcer will become 10%. This fraction of the workforce will be hired by the local government or national/regional environmental office to enforce the regulations which have been put in place, most notably the marine protected areas. 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. Furthermore, the enforcement program has two additional positive effects, as described in Figure 87.

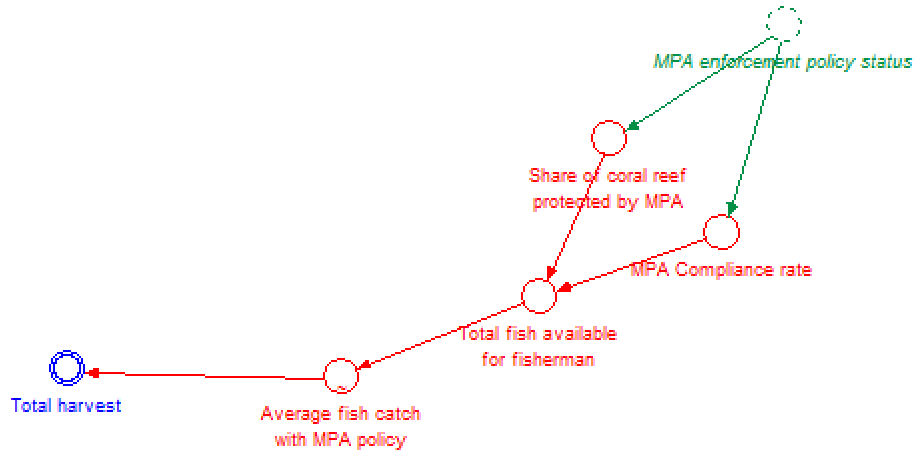


Figure 87 Effect of MPA enforcement on size of MPA and compliance rate

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.

Figure 88 compares the total fish stock under a MPA program without enforcement (blue line), and a MPA program complemented with local enforcement (red line). Although without the other proposed coral programs, the fish stocks will still go extinct, there is potentially a large positive effect of complementing the MPA program with a local enforcement program.

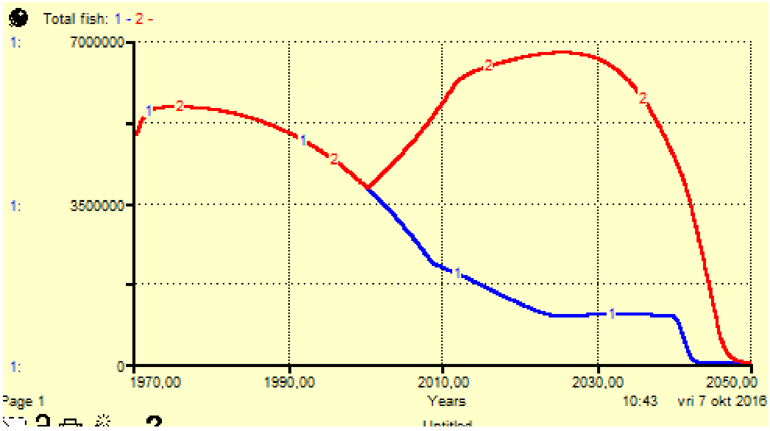


Figure 88 Effect of MPA with enforcement on total fish stock

8.5 Simulation results and causal-loop-diagram

The simulation, as described in Figure 89, 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.

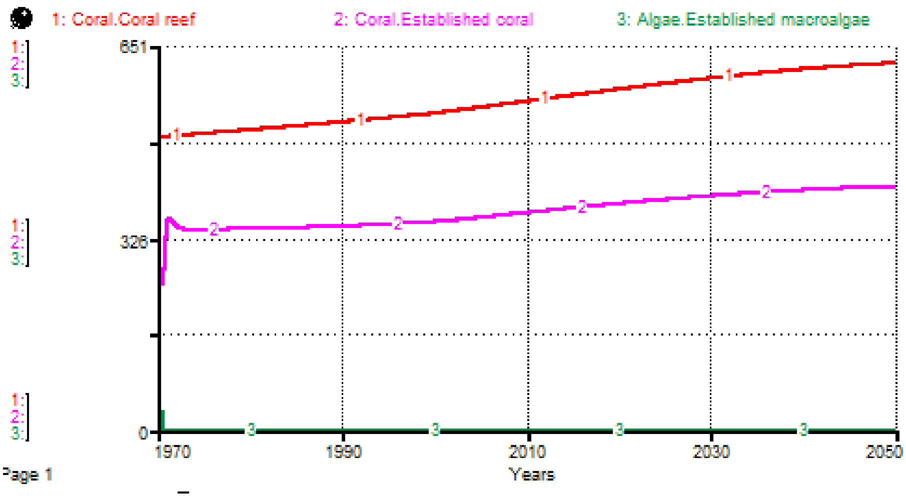


Figure 89 Simulating coral program leading to a sustainable coral reef growth (100% MPA)

Figure 90 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 again able to grow as if there was no human population present besides the coral reef.

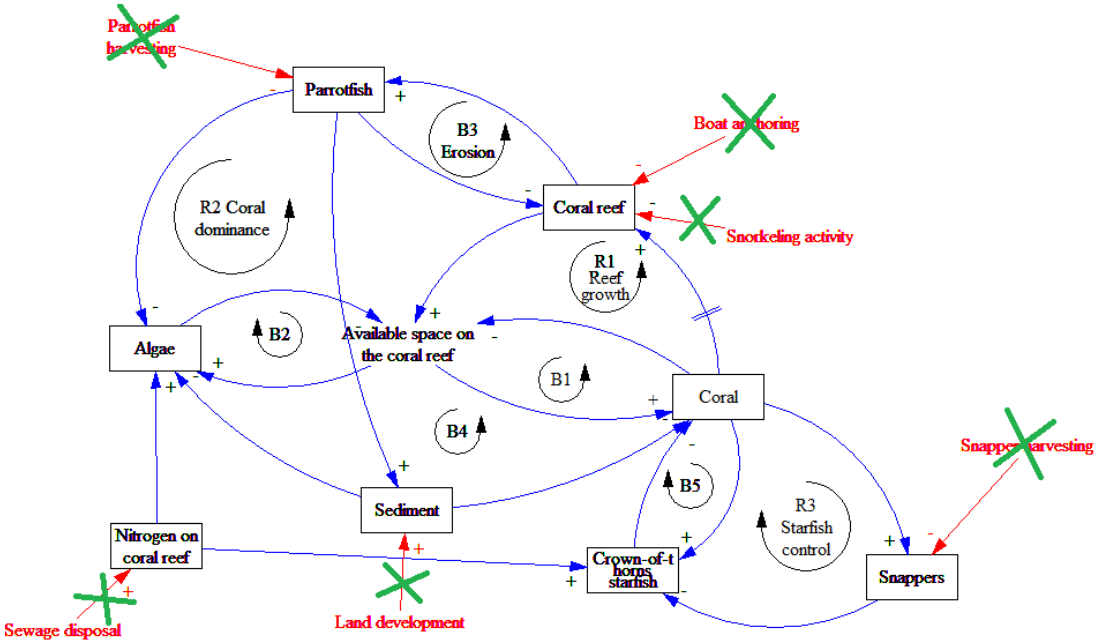


Figure 90 Causal-loop-diagram sustainable coral reef program

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'

Another interesting finding from the simulations, as revealed in Figure 91, is that the coral reef is, counter-intuitively, able to grow even faster when the MPA is only 50% instead of 100% (in combination with other proposed coral programs).

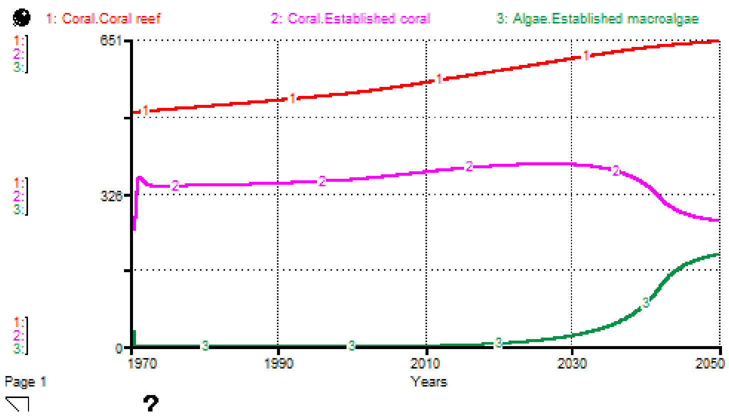


Figure 91 Simulating coral program leading to a sustainable coral reef growth (50% MPA)

However, as can be seen from Figure 91, the faster growth rate of the coral reef is accompanied by a higher occupation of macro-algae on the reef. Both the higher macro-algae occupancy rate and the higher growth rate of the coral reef can be explained by the parrotfish population which goes extinct after 2010. Since the parrotfish grazes not only on the macro-algae, but also on the reef substrate, the simulations show that without the other pressures on the reef, the coral reef might grow faster without parrotfish than with the parrotfish. This is, however, a very controversial conclusion which needs further research. Another problem with the implementation of the 50% MPA is that when the tourism development reaches its carrying capacity around 2040, the growth of the population will then lead to a return of the workforce to becoming fishermen. In the model simulations it can be seen that this will lead to an extinction of the snappers after 2050. This could have further consequences for the stock of COTS. However, this is outside the scope of the model horizon. But it is likely to assume that it is better to implement a 100% MPA. But in that case, what will happen to the local population when tourism development reaches its carrying capacity and there is no possibility to fish on the reef?

The next chapter will explore this question by proposing an alternative model of development which might be applied by coral destinations which are still in the initial phase of tourism development.

8.6 An alternative model of development for new tourist destinations: 'Homestay economy'

The 'conventional' tourism growth model, as discussed in the previous chapters, can be expected to lead to economic benefits for the local population, mainly in terms of employment in the service sector. However, as discussed in 5.3.4.4 Fish demand and immigration, the growth of tourism also leads to immigration of higher or more commercially skilled labor, which then leads to less employment opportunities for the local population. When the prices of basic services and products go up at the same time, tourism growth could have the unintended consequence of increasing poverty rather than reducing it. Although the socio-economic dynamics are beyond the scope of this paper, this chapter will explore an alternative tourism growth model with the goal of improving the inclusiveness of the local population.

Instead of providing benefits to the local population mainly from employment in the service industry, it is also possible put the local population at the center of tourism growth. This could be done by developing tourist accommodation in homestays with the local population instead of in resorts which are often exploited by (non-local) project developers. As much of the profit made in resorts will not end up with the local population, it could be argued that the positive benefits of the coral environment are harvested by non-locals while the locals are stuck with the environmental degradation. Figure 92 shows how, by developing a homestay accommodation model, the growth in tourists is no longer driven by the number of resorts but indirectly by the population on the destination.

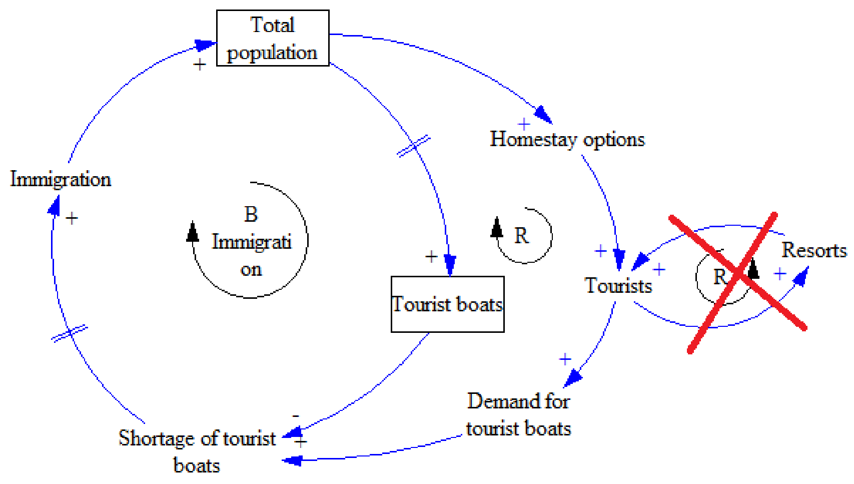


Figure 92 Causal-loop-diagram homestay development

As a result, the capacity for accepting new tourists will increase more in synchronization with the growth of the local population. This will prevent the rapid tourism boom experienced on many locations, which often leads to massive immigration of labor from other provinces. Figure 93 reveals how the number of tourists on the destination grows in accordance with the growth of the local population.

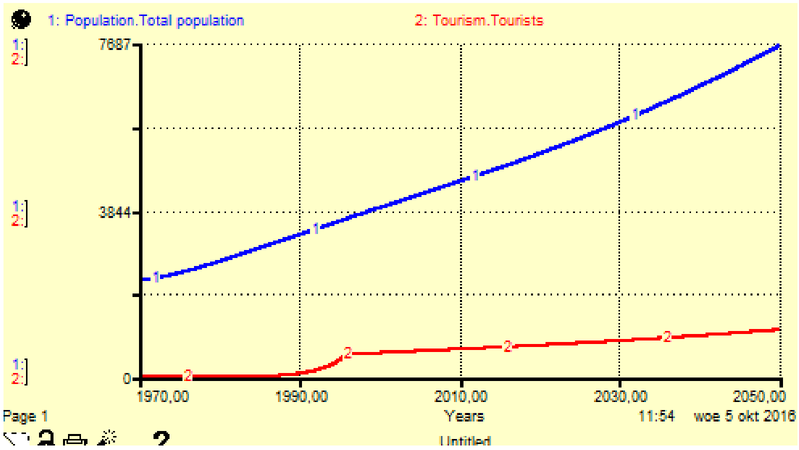


Figure 93 Local population and tourism growth under a homestay development scenario

The model structure under the homestay scenario is provided in Figure 94. It is assumed that 50% of the local households on the destination will be willing and able to participate in the homestay economy program.

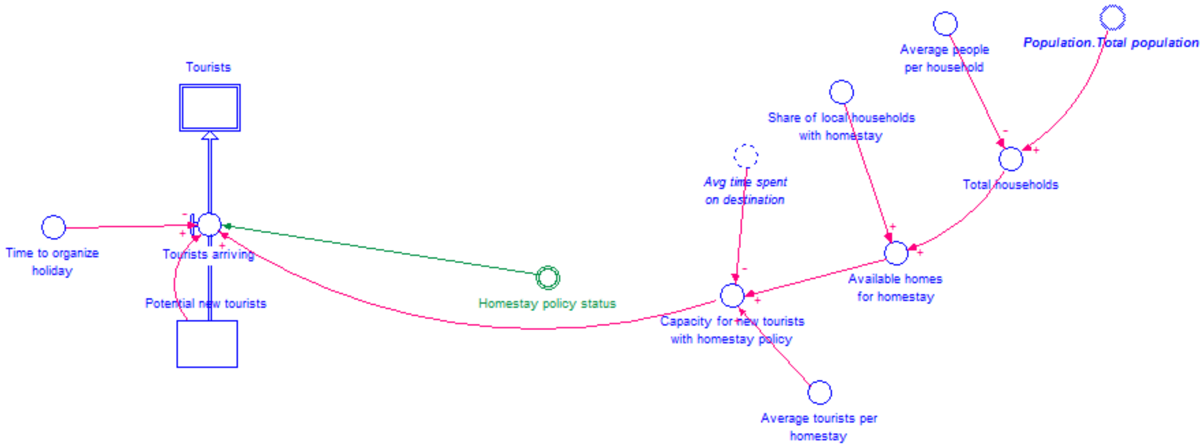


Figure 94 Homestay economy model structure

Similar to the MPA enforcement scenario, developing a homestay economic model will mean that more people in the local workforce can work in the homestay instead of becoming fishermen (Figure 95). It is assumed that the fraction of the male workforce who will become a homestay owner will become 20%. In a homestay economy, the whole family has a role to play in servicing the needs of the tourists; cooking, washing, cleaning, renovation, guide activities, transport activities etc. While tourism growth is much smaller under this scenario, the main advantage is that most of the income will end up with the local population instead of mostly foreign investors.

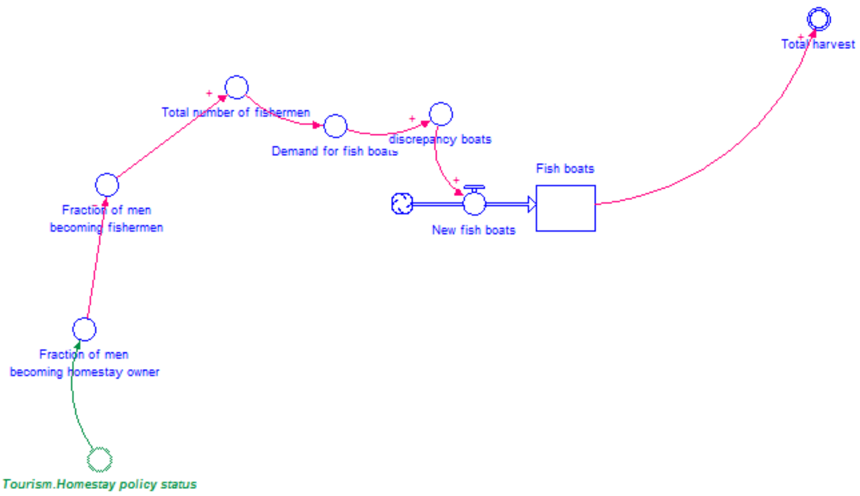


Figure 95 Effect of homestay policy on number of fishermen

The development of a homestay economic model is expected to prevent the large environmental pressures which are occurring under a conventional tourism growth model. Figure 96 shows how even without the other policies discussed before (such as sewage and sustainable buoys), the coral reef and fish stocks can grow sustainably. However, it will be advised to develop the other sustainable coral programs by setting up a tourism tax fund which will be discussed in the next chapter.

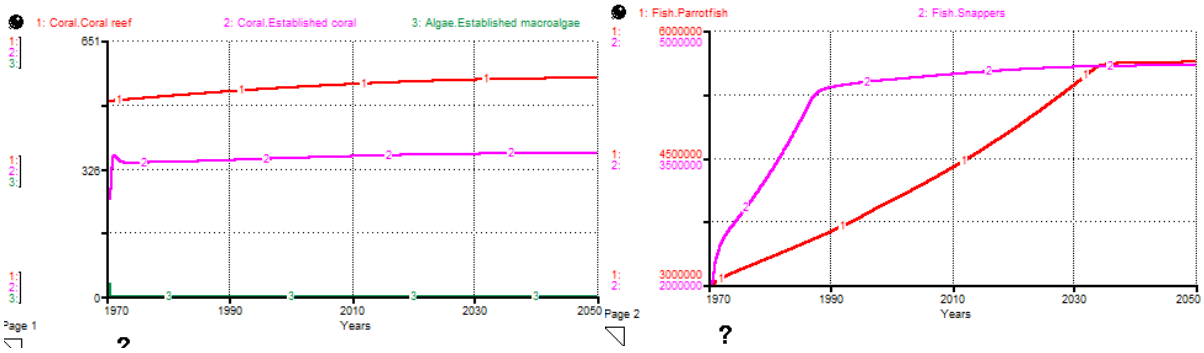


Figure 96 Coral reef and fish growth under a homestay development scenario

Another positive consequence of the homestay tourism model could be that the Pareto principle can be eliminated, in which a small percentage of the tourism destinations in the Philippines receive an un-proportional share of the tourism growth. Instead, the tourists will be dispersed more equally over the widely available coral destinations in the Philippines, many of which are still unknown to most tourists. When a larger share of the workforce will switch to become homestay provider, there will become a need to import fish to fill the growing gap between harvesting and fish demand (Figure 97). The local population can import the fish to cook for their homestay guests, and with the profit they make they can be able to cover the costs of their own fish intake.

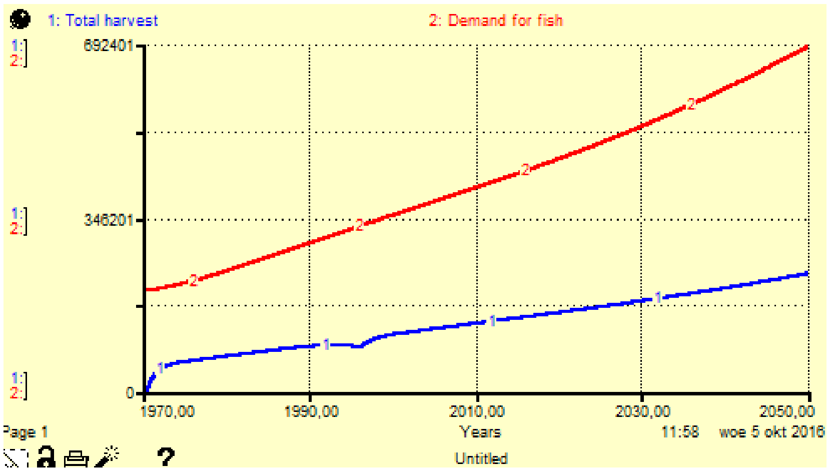


Figure 97 Local population, fishing and tourism growth under a homestay development scenario

9. Implementation

As effective coral programs have now been proposed, the next step would be to explore possible barriers to implementation. The main barriers for implementation are the costs and related financing possibilities for the proposed coral programs. With regard to the conventional tourism growth model, there are several coral programs which could be implemented at a relatively low cost and high pay-off in terms of environmental benefits: the silt screen to prevent sedimentation, the sustainable buoys, glass ceiling boats and organic sunscreen. Implementing the sewage treatment program, on the other hand, will require a relatively large investment.

9.1 The Financing problem: 'Improving the tourist tax system'

On many popular tourism destinations in the Philippines, environmental tax programs have already been implemented. However, there are currently three major problems which inhibit the success of such tax programs:

1) The environmental tax is relatively low. On Borocay, you pay an environmental fee of €1,5 to enter the ferry terminal. On El Nido, you pay an environmental fee of €8 when you go on an island hopping tour. On most other destinations, there is no environmental fee or it is below €5
2) Although the environmental taxes are relatively low, they are the cause of a lot of irritation among tourists (Mencias, personal communication). They are often collected on inconvenient times for tourists, for example when they are waiting in a terminal with their luggage and they have to take an additional counter to pay the fee. Or they are collected before tourists go on a tour and the tourists were not informed that they had to pay the additional fee.
3) Environmental funds not used efficiently:
    a. Funds are not or only partly used for environmental protection
    b. Funds are spent on coral programs which only alleviate the symptoms of the problem. As discussed in this paper, such coral programs have to be sustained as they do not solve the real cause of the problem.

To increase the effectiveness of the environmental tax program in the Philippines, it is advised to restructure the tax procedure. First of all, it would be advised to charge to tourist fee on the resort bill of tourists, instead of when they arrive on the destination. In this way, the process will be more convenient for the tourists. Secondly, the tourist fee should be increased as the natural environment in the Philippines is unique and beautiful. By increasing the transparency of the tourist tax to the tourists they will be less resistant and should understand why it is collected and how it is used. By charging the fee on the resort bill, it will also look relatively smaller compared to charging it on a ferry terminal bill. It might be necessary to centralize an agreement on the height of the environmental fee, to prevent certain destinations from trying to attract more tourists by lowering their fees. When the glass ceiling boat program is implemented, an additional environment fee should be collected for tourists who decide to go in the water for diving or snorkeling activities.

If a destination decides to develop a homestay economy, it could use lower environmental fees, as there will be less risk on a tourist boom and its devastating consequences. It might be interesting to develop a hybrid model, in which a few very expensive resorts with high tourist taxes are combined with homestay accommodation options. With this model, the tourist tax from the resorts can be used to help develop the homestay economy.

Although a higher tourist tax will increase the success of implementation of the proposed coral programs, it might be necessary to complement the tax with other financing schemes. It is advised to start developing a central sewage treatment system before the necessary tax revenues have been collected by the destination. Financing might be required through national and international development programs and loans.

9.2 Implementation success: local support

To increase the success of implementation, it is important to include both the local government and local population in the decision making process. For example, when a destination considers implementing the marine protected area program, it should collaborate with the local fishermen to make the switch to tourism development and environmental protection work smoother. This collaboration should start with an educational program, for which the model developed in this paper might be used, to teach the local population about the dynamics of coral reefs and which role the harvesting of fish plays in the degradation of coral reefs. During the educational program, it is important to show the local population how they will benefit from the proposed programs. For example, by being able to provide a 'free' sewage system and new job opportunities for the local population, the locals can benefit socially and economically from the programs.

9.3 Reducing intervention uncertainty

With the policies which have been proposed in this paper, the focus of the interventions will shift from the natural system to the human system. Interventions in the natural system often involve more uncertainty and risks in terms of unexpected cause-and-effects. As the natural ecosystem itself knows best how to optimize the environment, direct interventions could potentially cause harm to the natural processes. Artificial reefs, for example, might include material which intervenes with the natural processes on the reef. And killing crown-of-thorns starfish but not removing them might lead to an increase in their numbers instead of a decline. The coral programs which have been proposed in this paper are mostly developed based on the precautionary principle. As we don't know exactly how fish stocks and pollution intervenes with the natural system, it is best to limit our negative influences on those factors. In that way, the coral reef will be able to solve most of its problems by its own natural mechanisms.

10. Conclusion

To reverse the rapid degradation of coral reefs in the Philippines it is necessary to develop a better understanding of the natural processes which drive the growth of coral reefs and how these processes have been affected by human development. To understand the natural growth of the coral reef, there are two major factors which should be emphasized:

1) The coral reef needs to be occupied by live coral polyps to grow and sustain itself
2) The process through which reef-building coral polyps excrete the coral reef is very slow from a human perspective

In their natural environment, a coral reef will be able to produce steady growth of both the live coral tissue and the coral reef substrate. This growth is primarily driven by three reinforcing feedback loops:

1) A growing size of the reef excreted by reef-building coral polyps which then leads to more space to occupy for new coral recruits
2) High stocks of parrotfish which graze the macro-algae from the reef and lead to higher occupation by coral polyps. The live coral cover and coral reef lead to higher growth rates of the parrotfish.
3) High stocks of snappers which graze on the larvae of crown-of-thorns starfish, thereby containing an outbreak which could rapidly lead to a loss of the live coral cover. The live coral cover and coral reef lead to higher growth rates of snappers.

When a local population starts to settle around the coral reef, they interact with the three reinforcing feedback loops. A growing population produces increasing volumes of sewage, which are disposed in the sea around the coral reef. This sewage, containing inorganic nitrogen, is affecting the natural growth rates on the reef. Both the macro-algae and COTS thrive in a nitrogen-rich environment. The local population is also having an effect on the fish stocks on the coral reef, as their livelihood is mainly revolved around fishing. As the harvesting reduces the stocks of parrotfish and snappers, the macro-algae and COTS populations will face less severe grazing pressures. Therefore, the combination of increasing nitrogen levels and reduced fish stocks on the reef could, over time, lead to a reversal of the three reinforcing feedback loops identified above:

1) With an increasing dominance of macro-algae, there will be less live coral cover which is needed to sustain the coral reef. This could lead to decay of the reef
2) With decreasing levels of live coral cover and coral reef substrate, the growth rates of both the parrotfish and snappers will decrease. With lower stocks of parrotfish and snappers, the

macro-algae and COTS will be able to grow faster, thereby leading to even less dominance of reef-building coral polyps

The insight that the coral reef system is driven by reinforcing feedback has important consequences for the sustainability of the coral reef. When the reinforcing feedback loops reverse in their direction, they tend to move towards the only stable equilibrium which is left: the extinction of the coral reef and live coral cover. However, when there is only a small population around the coral reef, the path towards extinction might take a very long time. The coral reef substrate might even grow faster for a period because of the removal of parrotfish which also graze on the reef substrate. However, less parrotfish will in the long run lead to more algae dominance and thus an ultimate degradation of the coral reef.

On many coral reefs in the Philippines, local population growth is now accompanied by the growth of tourism development. As more fishermen start to work in the tourism sector, the pressure from fish harvesting is reduced. However, the reduced pressure on fish stocks is not having the desired effect of reversing the coral reef degradation. The growth in tourism is actually leading to even more negative impacts on the coral reef caused by increased sewage disposal, sedimentation from land development, boat anchoring and direct destruction by tourists. Moreover, the growth in tourism can lead to an increase of the local population caused by the import of labor. This will amplify the pressures from the local population on the reef.

So, with a growing local population, the reinforcing feedback loops driving coral reef growth might already be reversed in the direction of coral reef decay. Complementing this trend with the multitude of pressures from tourism means that the coral reef is highly unsustainable and could rapidly go extinct. This is actually the current trend on many coral reef locations in the Philippines, and around the world.

To reverse the rapid degradation of the coral reefs, it is of the uttermost important to reverse the reinforcing feedback loops which are driving the coral reef towards extinction. However, most of the coral programs in the Philippines are not directed to solving the underlying cause of the degradation. Instead, current programs are focused on dealing with the symptoms of the problem by directly intervening in the coral reef system, such as by coral replanting and removing crown-of-thorns starfish. Furthermore, effective policies such a protecting the marine environment, are often not complemented by effective regulation and local involvement.

It can be concluded that the current interventions focused on the symptoms of the problems are not going to reverse the trend of rapid coral degradation. What is needed are programs which focus on restoring the natural environment in which the coral reef is able to restore its own growth processes. Such programs should intervene not in the natural system but in the human system. High leverage coral programs which have been proposed are: sewage treatment, sustainable buoys and glass ceiling tourist boats, sediment run-off measures and marine protected areas complemented with local enforcement. Implementing these programs in an integral way could lead to a de-coupling of human development from environmental degradation. As these programs restore the natural environment which fosters coral reef growth, implementing them will lead to a marginally decreasing need for new interventions in the future.

For coral reef destinations which have not started developing tourism yet, another model of development is proposed in which the growth of tourism is more inclusive for the local population: the homestay economy. With this model of development, most of the income from tourism development will remain with the local population instead of investors.

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.

11. 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.

It should be stated here that the results of this study will need further examination to increase confidence in the model structure, the simulation results and the hypothesis it postulates. Many of the relationships and parameters used in the model are still based on unscientific assumptions. Therefore the simulation results should not be used for predictions. The main question will be to see if more scientific calibration of causal relationships and parameter values will change the fundamental behavior of the coral reef, e.g. if it changes the way in which the growth and decay of the reef is driven by three reinforcing feedback loops. It will specifically be advised to explore the effect of adding the sea urchin, large predator populations and fish immigration from outside of the reef to the simulation model.

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. Local decision makers will then be able to use the model structure and simulations to analyze where the destinations are in terms of coral reef impacts and what can happen to the coral reef when no programs are implemented to increase the sustainability of the coral reef. 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. If the results show a significant difference, the experimental coral reef can serve as a role model for other coral destinations which want to successfully sustain their coral reef environment.

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Appendix A Sensitivity analysis results

1) Average lifetime mature coral (years)

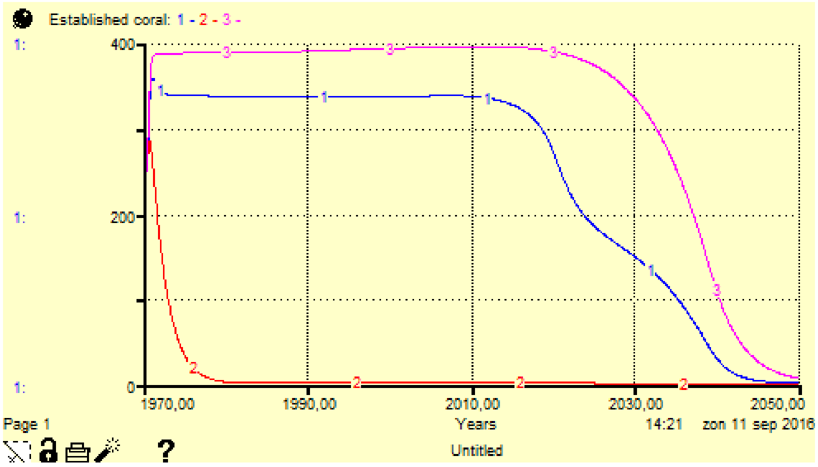


Figure 98 Average lifetime mature coral: 3; 1; 5

2) Normal reef productivity (hectares/hectares-yr)

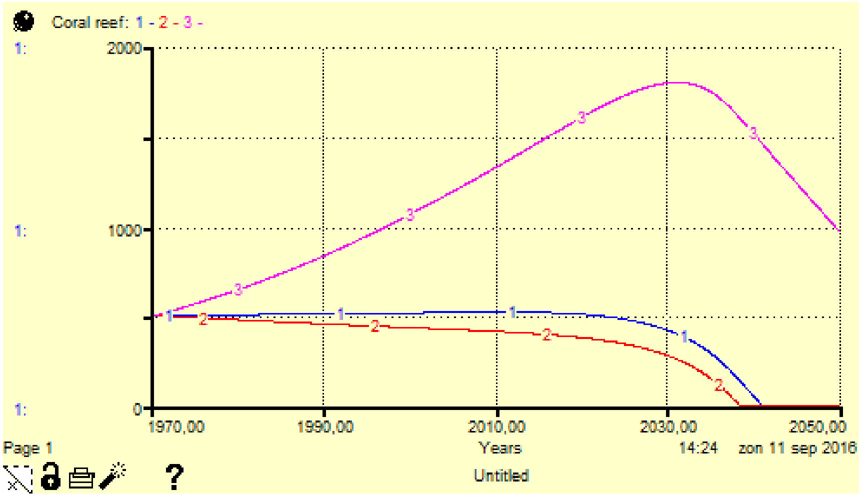


Figure 99 Normal reef productivity: 0.01; 0.001; 0.05

3) Average coral reef grazed per parrotfish (hectares/fish-yr)

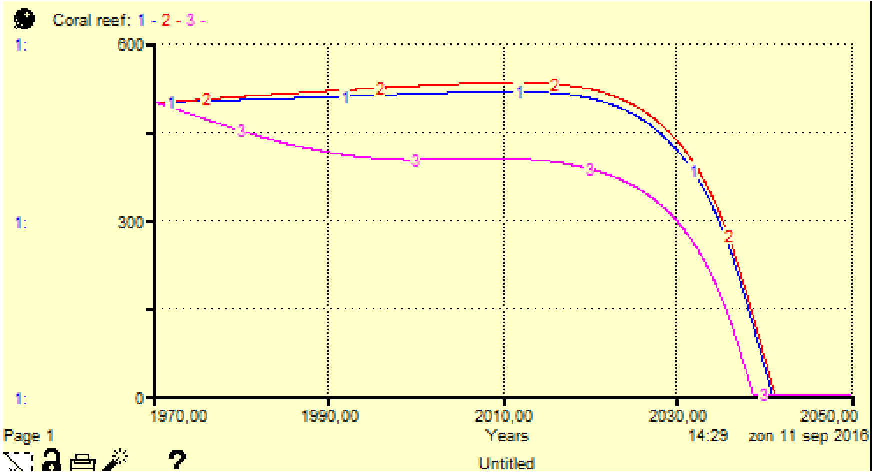


Figure 100 Avg. coral reef grazed per parrotfish: 2e-07; 2e-08; 2e-06

4) Average coral grazed per COTS (hectares/fish-yr)

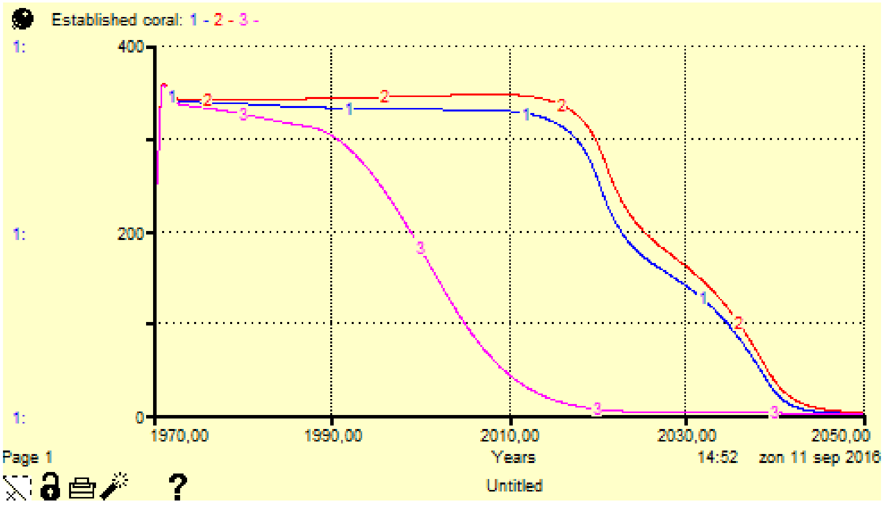


Figure 101 Average coral grazed per COTS: 0.001825; 0.0005; 0.005

5) Effect of sediment on coral reef productivity

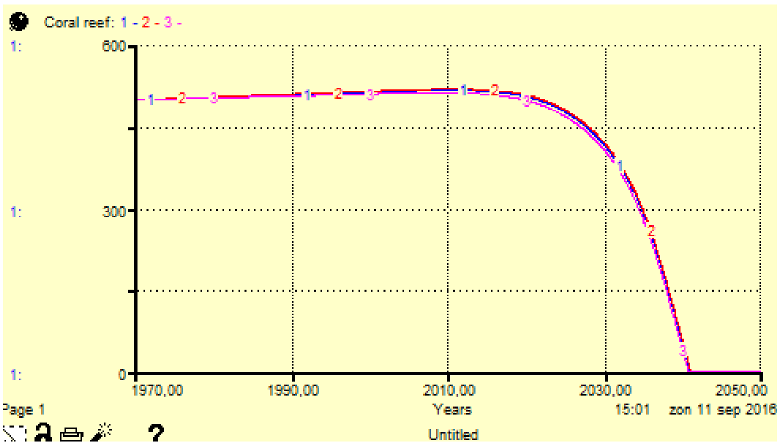


Figure 102 Effect of sediment on coral reef productivity

6) Average lifetime macro-algae (years)

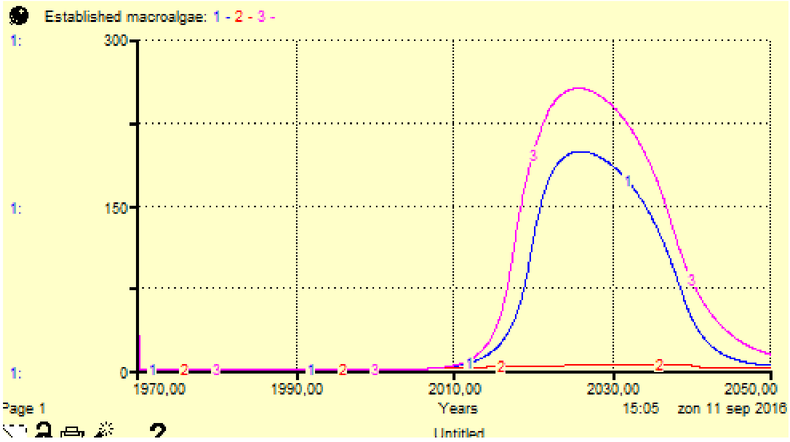


Figure 103 Average lifetime macro-algae: 3; 1; 5

7) Average algae grazed per parrotfish (hectares/fish-yr)

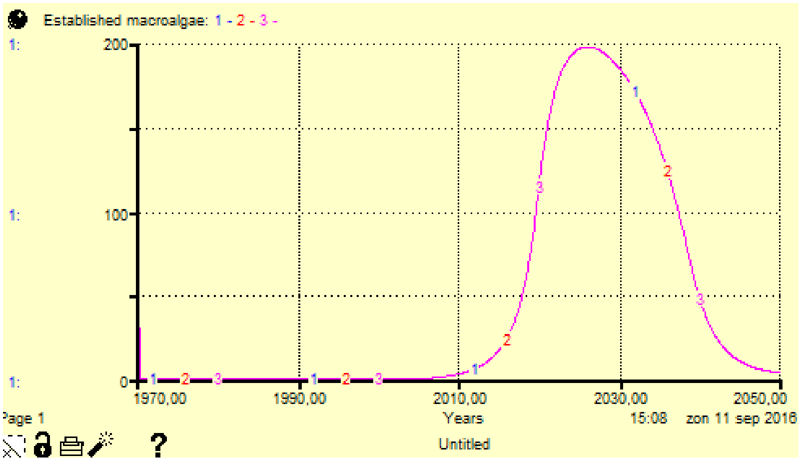


Figure 104 Average algae grazed per parrotfish: 0.0012; 0.0002; 0.0022

8) Effect of nutrients on algae time to mature

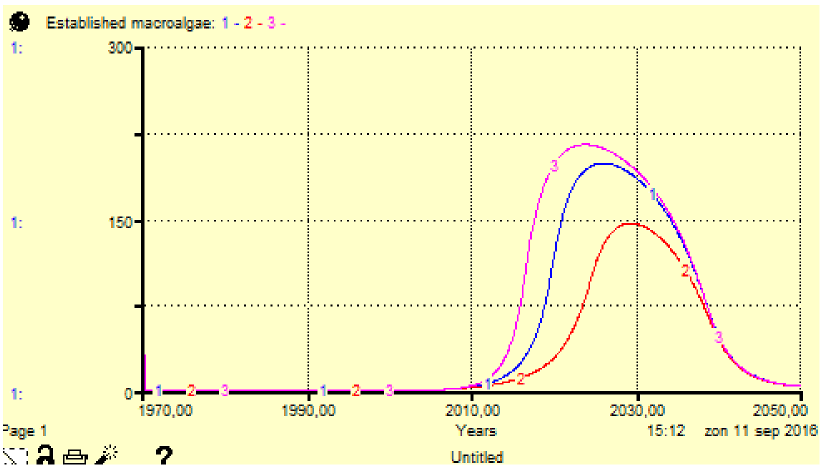


Figure 105 Effect of nutrients on algae time to mature

9) Effect of established coral on parrotfish spawn efficiency

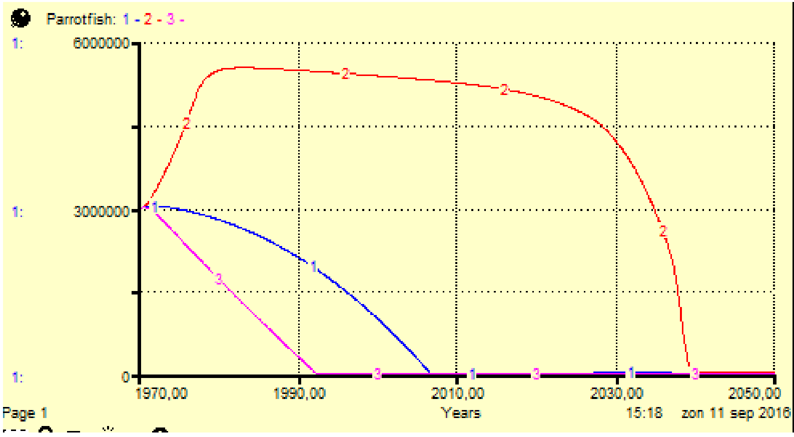


Figure 106 Effect of established coral on parrotfish spawn efficiency

10) Effect of coral reef on parrotfish recruit mortality

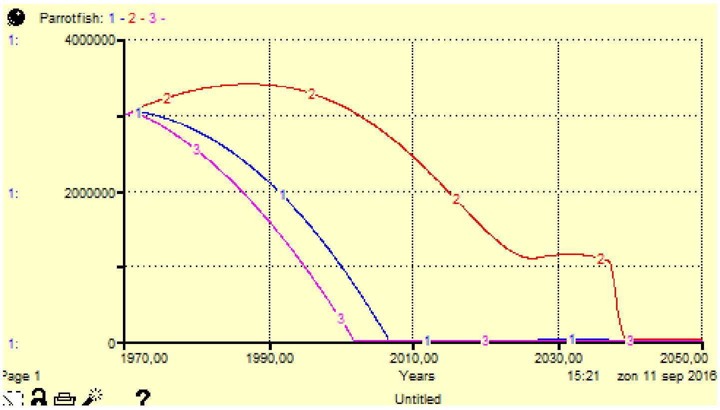


Figure 107 Effect of coral on parrotfish recruit mortality

11) Effect of phytoplankton availability on COTS time to grow

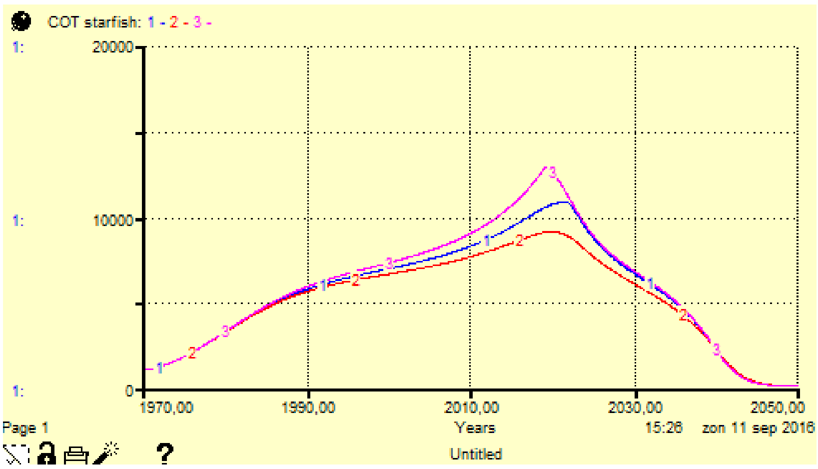


Figure 108 Effect of phytoplankton availability on COTS time to grow

12) Anchoring damage per boat (hectares/boats-yr)

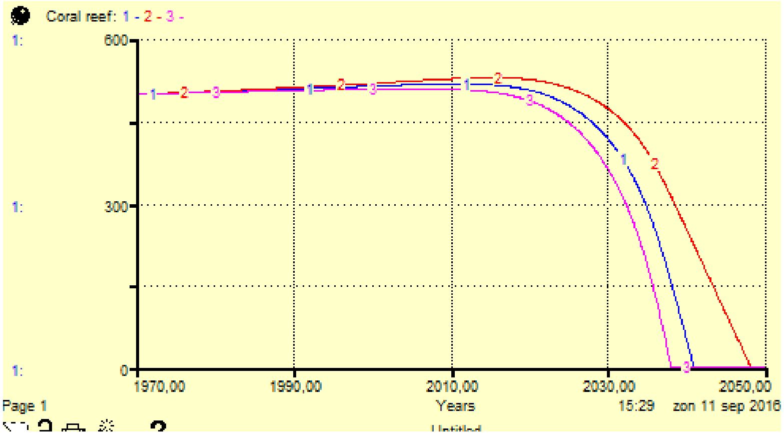


Figure 109 Anchoring damage per boat: 0.015; 0.005; 0.025

13) Adoption rate tourist destination (unitless)

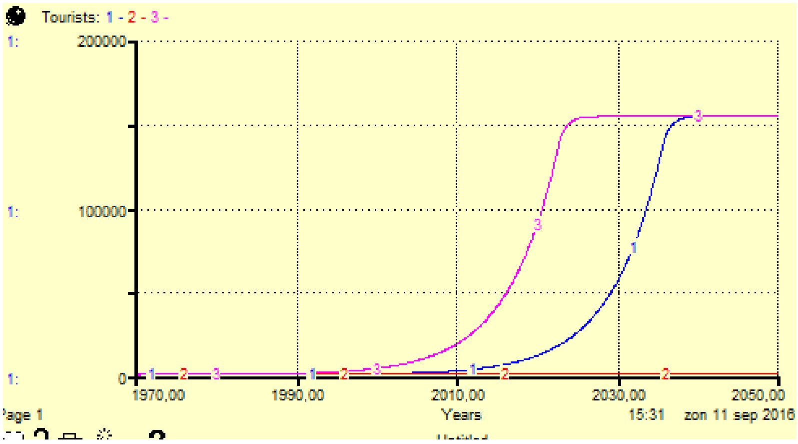


Figure 110 Adoption rate tourist destination: 0.05; 0.01; 0.1

14) Share of people causing damage to coral reef (unitless)

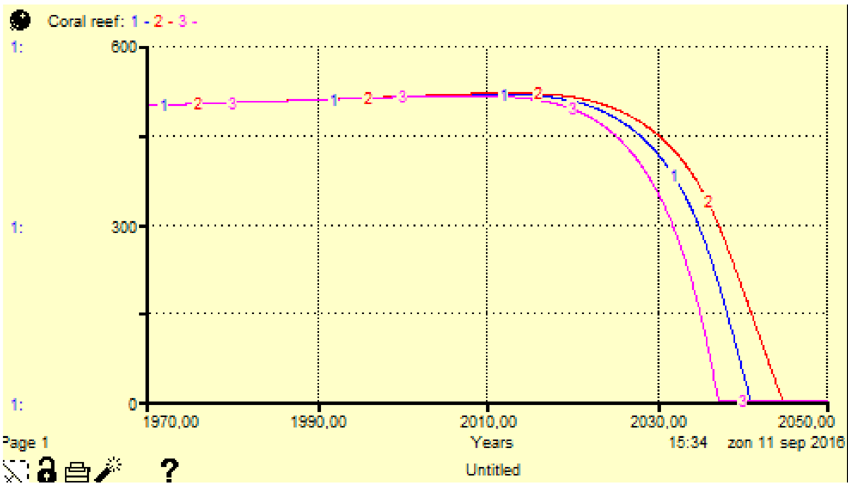


Figure 111 Share of people causing damage to coral reef: 0.2; 0.05; 0.5

15) Expected tourism growth rate (unitless)

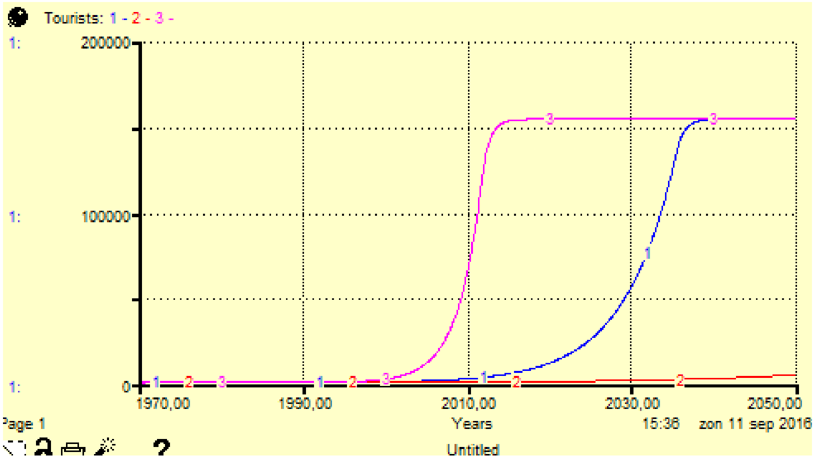
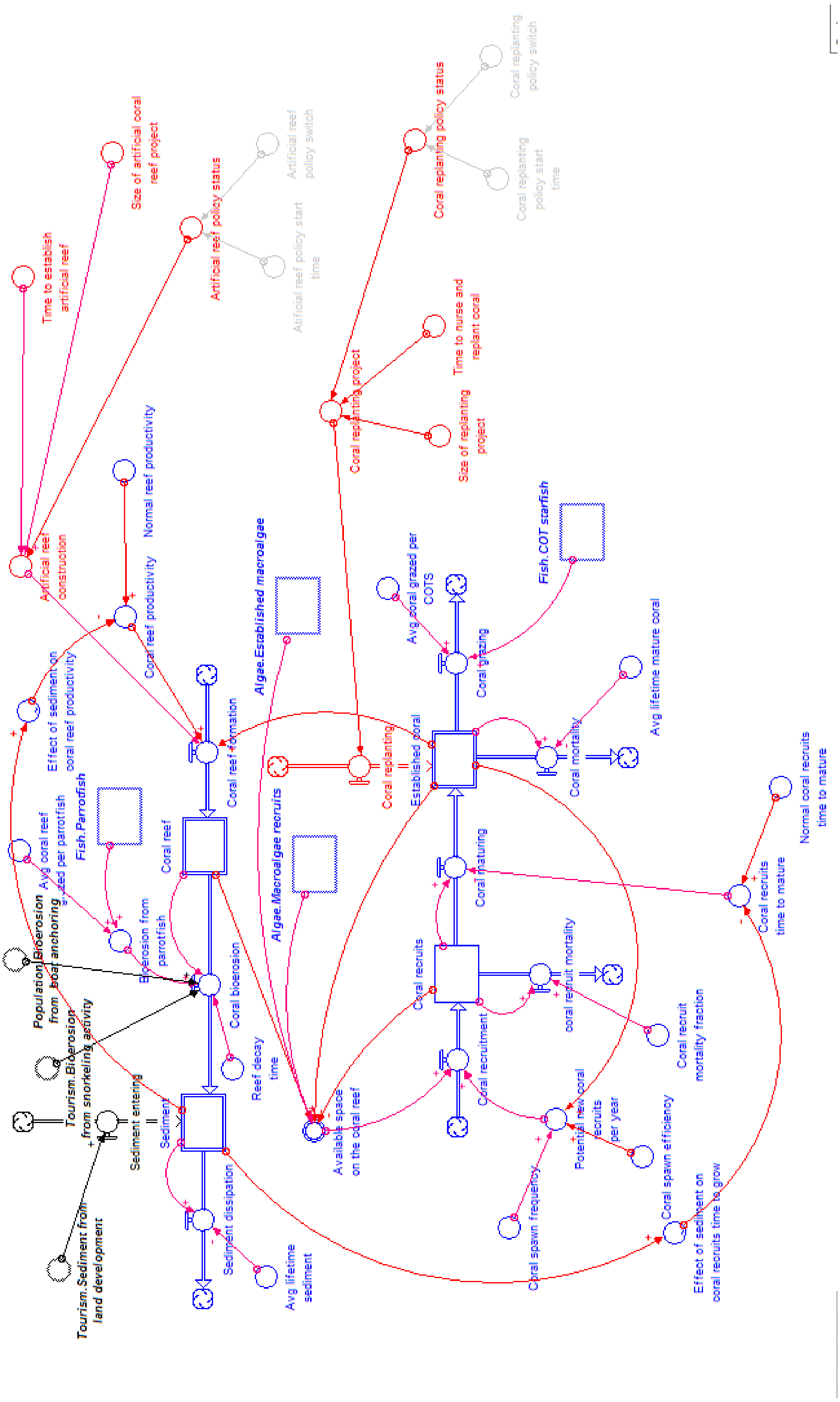
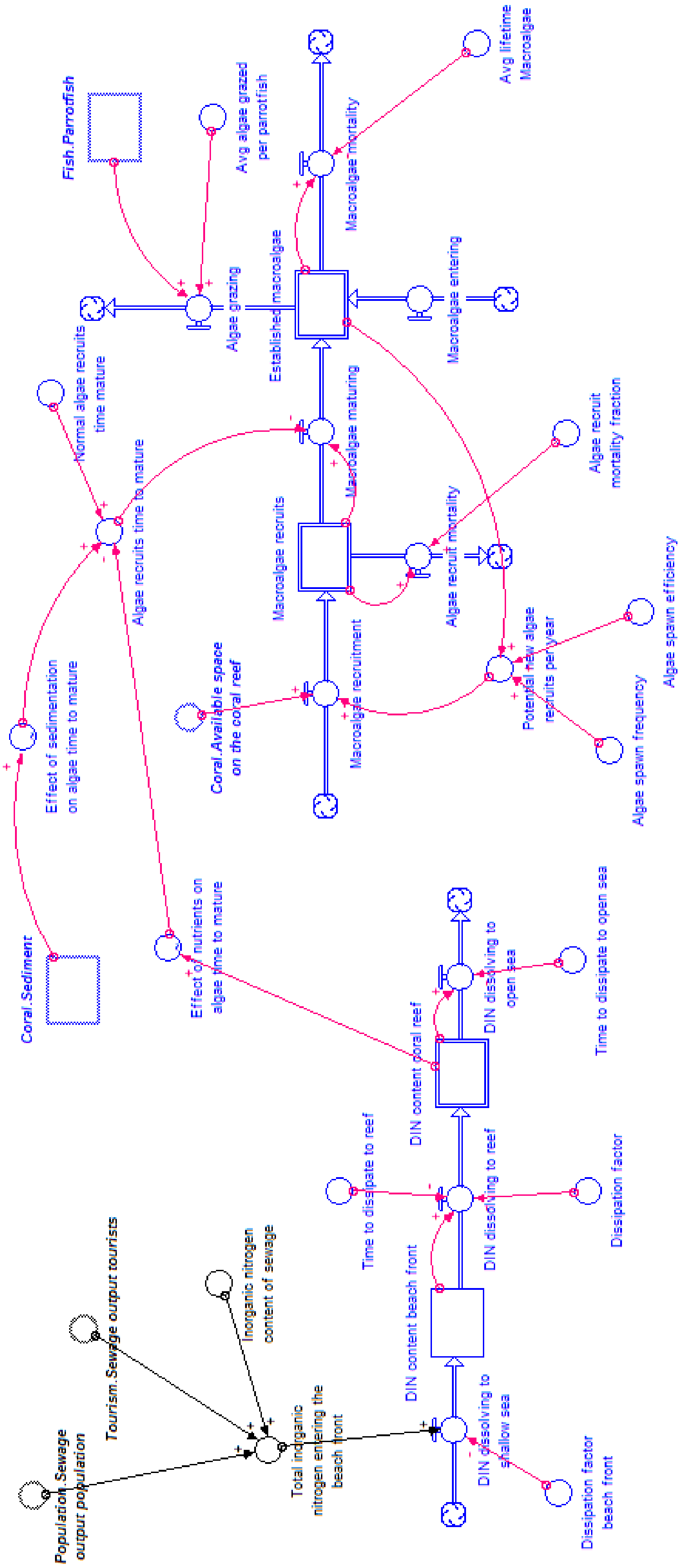


Figure 112 Expected tourism growth rate: 0.2; 0.1; 0.4

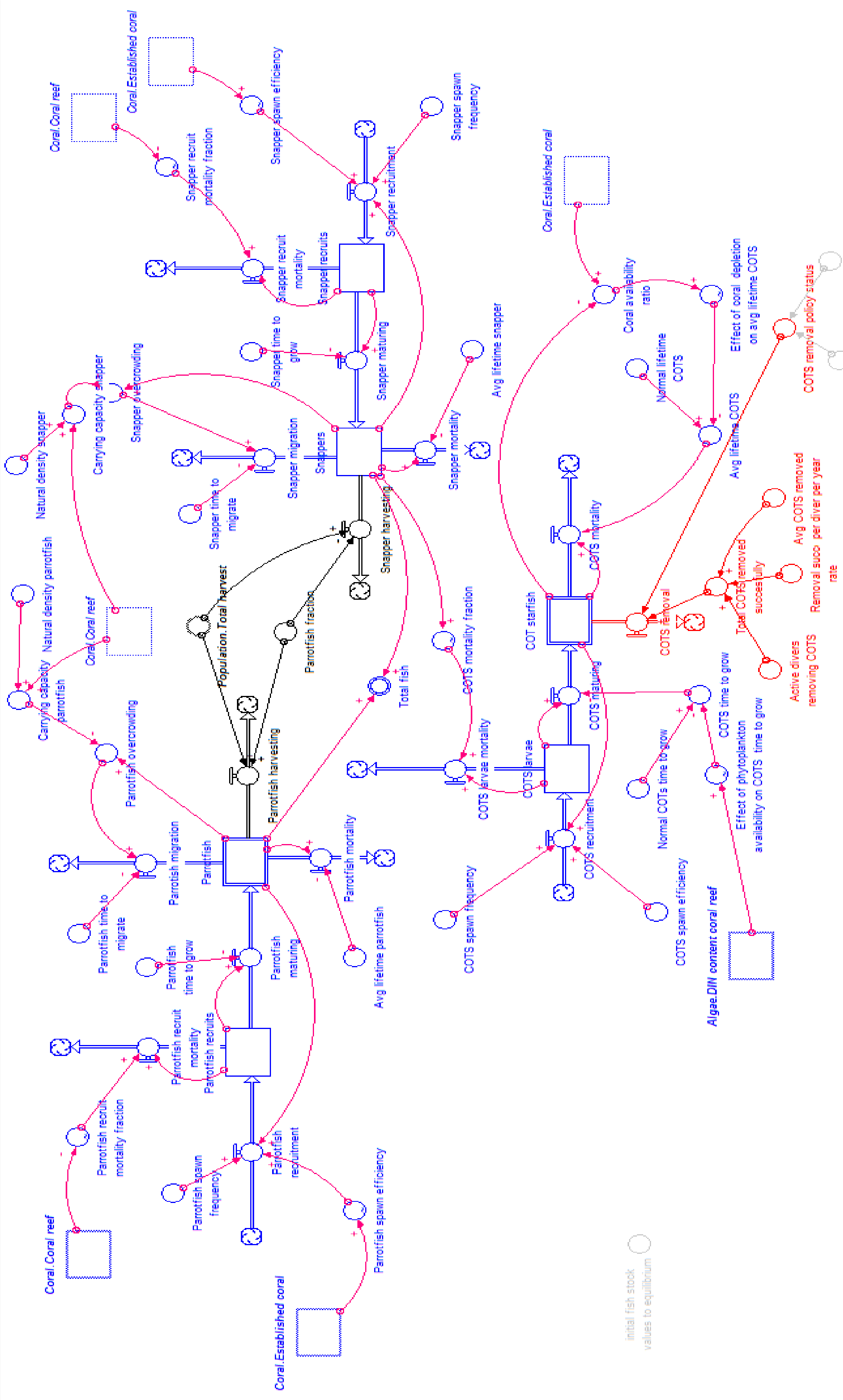
Appendix B Coral sub-model structure (iThink)



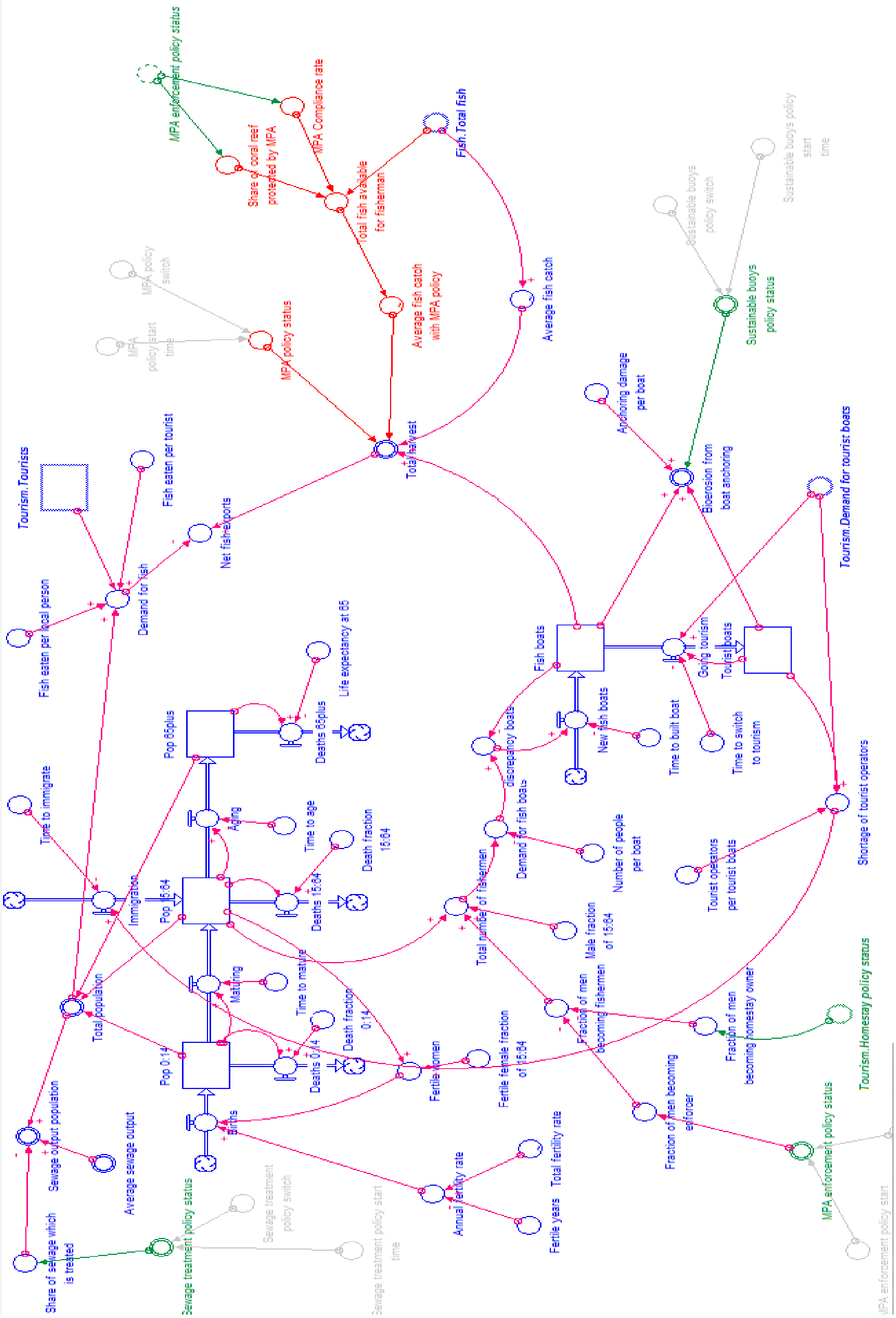
Appendix C Algae sub-model structure (iThink)



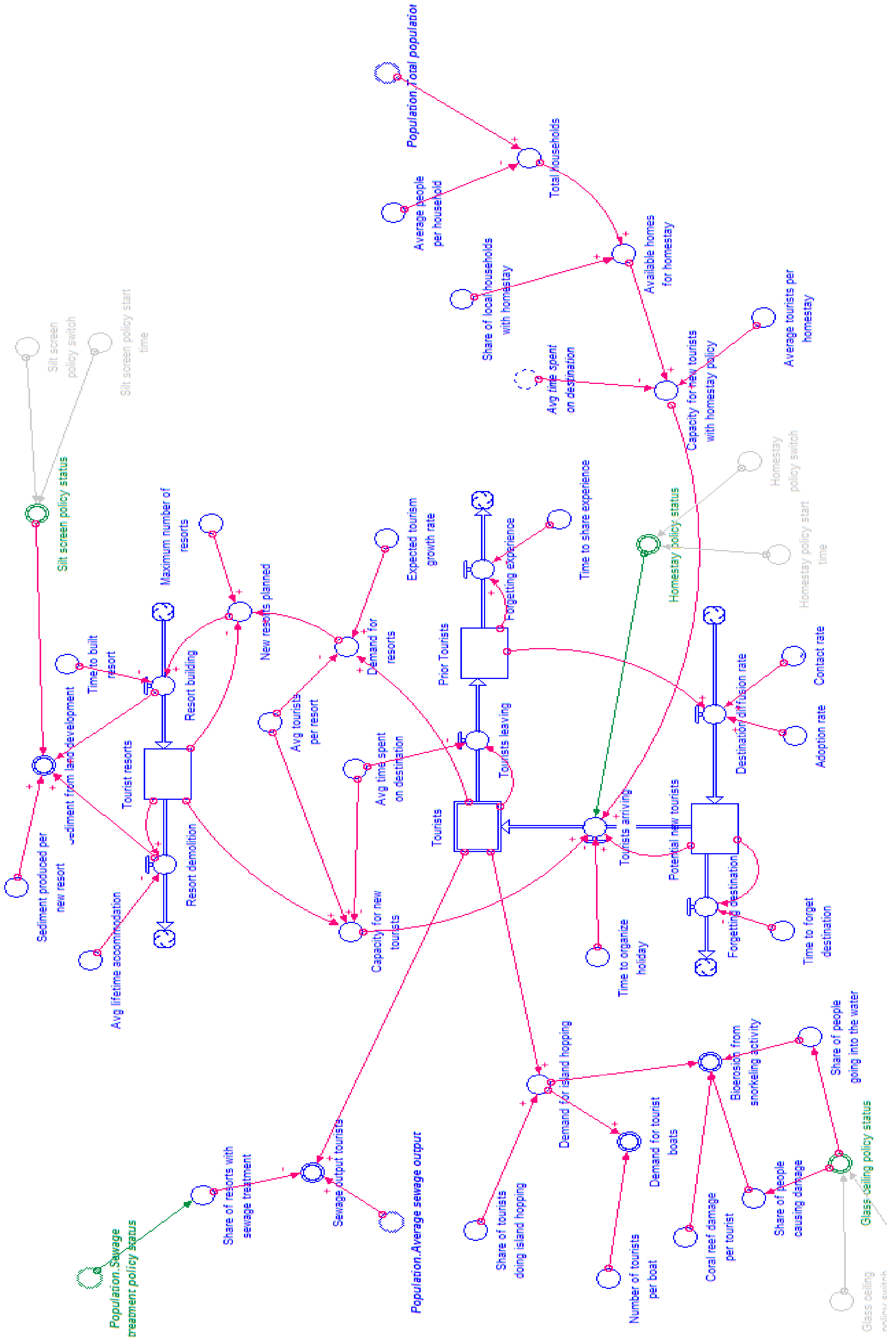
Appendix D Fish sub-model structure (iThink)



Appendix E Population sub-model structure (iThink)



Appendix F Tourism sub-model structure (iThink)



Appendix G Model equations (iThink)

Algae:

DIN_content_beach_front(t) = DIN_content_beach_front(t - dt) + (DIN_dissolving_to_shallow_sea - DIN_dissolving_to_reef) * dt

INIT DIN_content_beach_front = 0.2

INFLOWS:

DIN_dissolving_to_shallow_sea = Total_inorganic_nitrogen_entering_the_beach_front/Dissipation_factor_beach_front

OUTFLOWS:

DIN_dissolving_to_reef = (DIN_content_beach_front/Dissipation_factor)/Time_to_dissipate_to_reef

DIN_content_coral_reef(t) = DIN_content_coral_reef(t - dt) + (DIN_dissolving_to_reef - DIN_dissolving_to_open_sea) * dt

INIT DIN_content_coral_reef = 0.2

INFLOWS:

DIN_dissolving_to_reef = (DIN_content_beach_front/Dissipation_factor)/Time_to_dissipate_to_reef

OUTFLOWS:

DIN_dissolving_to_open_sea = DIN_content_coral_reef/Time_to_dissipate_to_open_sea

Established_macroalgae(t) = Established_macroalgae(t - dt) + (Macroalgae_maturing + Macroalgae_entering - Algae_grazing - Macroalgae_mortality) * dt

INIT Established_macroalgae = (1-initial_coral_stock_values_to_equilibrium)*30 + initial_coral_stock_values_to_equilibrium*0.00001

INFLOWS:

Macroalgae_maturing = Macroalgae_recruits/Algae_recruits_time_to_mature

Macroalgae_entering = 0.5

OUTFLOWS:

Algae_grazing = Fish.Parrotfish*Avg_algae_grazed_per_parrotfish

Macroalgae_mortality = Established_macroalgae/Avg_lifetime_Macroalgae

Macroalgae_recruits(t) = Macroalgae_recruits(t - dt) + (Macroalgae_recruitment - Macroalgae_maturing - Algae_recruit_mortality) * dt

INIT Macroalgae_recruits = (1-initial_coral_stock_values_to_equilibrium)*20 + initial_coral_stock_values_to_equilibrium*0.00001

INFLOWS:

Macroalgae_recruitment = MIN(Potential_new_algae_recruits_per_year,Coral.Available_space_on_the_coral_reef)

OUTFLOWS:

Macroalgae_maturing = Macroalgae_recruits/Algae_recruits_time_to_mature

Algae_recruit_mortality = Macroalgae_recruits*Algae_recruit___mortality_fraction

Algae_recruits_time_to_mature = Normal_algae_recruits_time_mature*Effect_of_sedimentation__on_algae_time_to_mature*Effect_of_nutrients_on_algae_time_to_mature

Algae_recruit___mortality_fraction = 0.8

Algae_spawn_efficiency = 1

Algae_spawn_frequency = 1

Avg_algae_grazed_per_parrotfish = 0.0012

Avg_lifetime_Macroalgae = 3

Dissipation_factor = 15

Dissipation_factor_beach_front = 100000

Effect_of_nutrients_on_algae_time_to_mature = GRAPH(DIN_content_coral_reef)

(0.00, 1.00), (1.00, 0.5), (2.00, 0.4), (3.00, 0.3), (4.00, 0.2), (5.00, 0.1)

Effect_of_sedimentation__on_algae_time_to_mature = GRAPH(Coral.Sediment)

(0.00, 1.00), (80.0, 1.50), (160, 2.00), (240, 2.50), (320, 3.00), (400, 3.50)

Inorganic_nitrogen_content_of_sewage = 0.3

Normal_algae_recruits_time_mature = 1.5

Potential_new_algae_recruits_per_year = Established_macroalgae*Algae_spawn_frequency*Algae_spawn_efficiency

Time_to_dissipate_to_open_sea = 0.25

Time_to_dissipate_to_reef = 0.25

Total_inorganic_nitrogen_entering_the_beach_front = (Population.Sewage_output_population+Tourism.Sewage_output_tourists)*Inorganic_nitrogen_content_of_sewage

Coral:

Coral_recruits(t) = Coral_recruits(t - dt) + (Coral_recruitment - coral_recruit_mortality - Coral_maturing) * dt

INIT Coral_recruits = (1-initial_coral_stock_values_to_equilibrium)*200 + initial_coral_stock_values_to_equilibrium*33

INFLOWS:

Coral_recruitment = MIN(Potential_new_coral_recruits_per_year,Available_space_on_the_coral_reef)

OUTFLOWS:

coral_recruit_mortality = Coral_recruits*Coral_recruit__mortality_fraction

Coral_maturing = Coral_recruits/Coral_recruits_time_to_mature

Coral_reef(t) = Coral_reef(t - dt) + (Coral_reef_formation - Coral_bioerosion) * dt

INIT Coral_reef = (1-initial_coral_stock_values_to_equilibrium)*500 + initial_coral_stock_values_to_equilibrium*509

INFLOWS:

Coral_reef_formation = (Established_coral*Coral_reef_productivity) + Artificial_reef_construction

OUTFLOWS:

Coral_bioerosion = Bioerosion_from_parrotfish+Population.Bioerosion_from__boat_anchoring+Tourism.Bioerosion_from_snorkeling_activity+ (Coral_reef/Reef_decay_time)

Established_coral(t) = Established_coral(t - dt) + (Coral_maturing + Coral_replanting - Coral_grazing - Coral_mortality) * dt

INIT Established_coral = (1-initial_coral_stock_values_to_equilibrium)*250 + initial_coral_stock_values_to_equilibrium*341

INFLOWS:

Coral_maturing = Coral_recruits/Coral_recruits_time_to_mature

Coral_replanting = Coral_replanting_project

OUTFLOWS:

Coral_grazing = Fish.COT_starfish*Avg_coral_grazed_per_COTS

Coral_mortality = Established_coral/Avg_lifetime_mature_coral

Sediment(t) = Sediment(t - dt) + (Coral_bioerosion + Sediment_entering - Sediment_dissipation) * dt

INIT Sediment = (1-initial_coral_stock_values_to_equilibrium)*5 + initial_coral_stock_values_to_equilibrium*0.65

INFLOWS:

Coral_bioerosion = Bioerosion_from_parrotfish+Population.Bioerosion_from__boat_anchoring+Tourism.Bioerosion_from_snorkeling_activity+ (Coral_reef/Reef_decay_time)

Sediment_entering = Tourism.Sediment_from_land_development

OUTFLOWS:

Sediment_dissipation = Sediment/Avg_lifetime_sediment

Artificial_reef_construction = (Size_of_artificial_coral_reef_project/Time_to_establish_artificial_reef)*Artificial_reef_policy_status

Artificial_reef_policy_status = if(Artificial_reef_policy_switch=1)and(time>Atificial_reef_policy_start_time)then(1)else(0)

Artificial_reef_policy_switch = 0

Atificial_reef_policy_start_time = 2000

Available_space_on_the_coral_reef = Coral_Reef-Established_coral-Coral_recruits-Algae.Established_macroalgae-Algae.Macroalgae_recruits

Avg_coral_grazed_per_COTS = 0.001825

Avg_coral_reef_grazed_per_parrotfish = 3e-07

Avg_lifetime_mature_coral = 3

Avg_lifetime_sediment = 0.25

Bioerosion_from_parrotfish = Fish.Parrotfish*Avg_coral_reef_grazed_per_parrotfish

Coral_recruits_time_to_mature = Normal_coral_recruits_time_to_mature*Effect_of_sediment_on_coral_recruits_time_to_grow

Coral_recruit__mortality_fraction = 0.5

Coral_reef_productivity = Normal_reef_productivity*Effect_of_sediment_on_coral_reef_productivity

Coral_replanting_policy_status = if(Coral_replanting__policy_switch=1)and(time>Coral_replanting__policy_start_time)then(1)else(0)

Coral_replanting_project = (Size_of_replanting_project/Time_to_nurse_and_replant_coral)*Coral_replanting_policy_status

Coral_replanting__policy_start_time = 2000

Coral_replanting__policy_switch = 0

Coral_spawn_efficiency = 0.5

Coral_spawn_frequency = 1

Effect_of_sediment_on_coral_recruits_time_to_grow = GRAPH(Sediment)

(0.00, 1.00), (4.00, 1.50), (8.00, 2.00), (12.0, 2.50), (16.0, 3.00), (20.0, 3.50)

Effect_of_sediment_on_coral_reef_productivity = GRAPH(Sediment)

(0.00, 1.00), (4.00, 0.8), (8.00, 0.6), (12.0, 0.4), (16.0, 0.2), (20.0, 0.00)

initial_coral_stock_values_to_equilibrium = 0

Normal_coral_recruits_time_to_mature = 0.25

Normal_reef_productivity = 0.01

Potential_new_coral_recruits_per_year =
Established_coral*Coral_spawn_efficiency*Coral_spawn_frequency

Reef_decay_time = 500

Size_of_artificial_coral_reef_project = 1

Size_of_replanting_project = 1

Time_to_establish_artificial_reef = 1

Time_to_nurse_and_replant_coral = 1

Fish:

COTS_larvae(t) = COTS_larvae(t - dt) + (COTS_recruitment - COTS_maturing - COTS_larvae_mortality) * dt

INIT COTS_larvae = (1-initial_fish_stock_values_to_equilibrium)*250 + initial_fish_stock_values_to_equilibrium*1889

INFLOWS:

COTS_recruitment = COT_starfish*COTS_spawn_frequency*COTS_spawn_efficiency

OUTFLOWS:

COTS_maturing = COTS_larvae/COTS_time_to_grow

COTS_larvae_mortality = COTS_larvae*COTS_mortality_fraction

COT_starfish(t) = COT_starfish(t - dt) + (COTS_maturing - COTS_mortality - COTS_removal) * dt

INIT COT_starfish = (1-initial_fish_stock_values_to_equilibrium)*1000 + initial_fish_stock_values_to_equilibrium*4565

INFLOWS:

COTS_maturing = COTS_larvae/COTS_time_to_grow

OUTFLOWS:

COTS_mortality = COT_starfish/Avg_lifetime_COTS

COTS_removal = Total_COTS_removed_succesfully*COTS_removal_policy_status

Parrotfish(t) = Parrotfish(t - dt) + (Parrotfish_maturing - Parrotfish_mortality - Parrotfish_harvesting - Parrotish_migration) * dt

INIT Parrotfish = (1-initial_fish_stock_values_to_equilibrium)*3000000 + initial_fish_stock_values_to_equilibrium*5197200

INFLOWS:

Parrotfish_maturing = Parrotfish_recruits/Parrotfish_time_to_grow

OUTFLOWS:

Parrotfish_mortality = Parrotfish/Avg_lifetime_parrotfish

Parrotfish_harvesting = Population.Total_harvest*Parrotfish_fraction

Parrotish_migration = Parrotfish_overcrowding/Parrotfish_time_to__migrate

Parrotfish_recruits(t) = Parrotfish_recruits(t - dt) + (Parrotfish_recruitment - Parrotfish_maturing - Parrotfish_recruit_mortality) * dt

INIT Parrotfish_recruits = (1-initial_fish_stock_values_to_equilibrium)*1500000 + initial_fish_stock_values_to_equilibrium*255051

INFLOWS:

Parrotfish_recruitment = Parrotfish*Parrotfish_spawn_frequency*Parrotfish_spawn_efficiency

OUTFLOWS:

Parrotfish_maturing = Parrotfish_recruits/Parrotfish_time_to_grow

Parrotfish_recruit_mortality = Parrotfish_recruits*Parrotfish_recruit_mortality_fraction

Snappers(t) = Snappers(t - dt) + (Snapper_maturing - Snapper_harvesting - Snapper_mortality - Snapper_migration) * dt

INIT Snappers = (1-initial_fish_stock_values_to_equilibrium)*2000000 + initial_fish_stock_values_to_equilibrium*4270501

INFLOWS:

Snapper_maturing = Snapper_recruits/Snapper_time_to_grow

OUTFLOWS:

Snapper_harvesting = Population.Total_harvest*(1-Parrotfish_fraction)

Snapper_mortality = Snappers/Avg_lifetime_snapper

Snapper_migration = Snapper_overcrowding/Snapper_time_to_migrate

Snapper_recruits(t) = Snapper_recruits(t - dt) + (Snapper_recruitment - Snapper_maturing - Snapper_recruit_mortality) * dt

INIT Snapper_recruits = (1-initial_fish_stock_values_to_equilibrium)*1500000 + initial_fish_stock_values_to_equilibrium*824475

INFLOWS:

Snapper_recruitment = Snappers*Snapper_spawn_frequency*Snapper_spawn_efficiency

OUTFLOWS:

Snapper_maturing = Snapper_recruits/Snapper_time_to_grow

Snapper_recruit_mortality = Snapper_recruits*Snapper_recruit_mortality_fraction

Active_divers_removing_COTS = 20

Avg_COTS_removed_per_diver_per_year = 50

Avg_lifetime_COTS = Normal_lifetime_COTS*Effect_of_coral__depletion_on_avg_lifetime_COTS

Avg_lifetime_parrotfish = 7

Avg_lifetime_snapper = 20

Carrying_capacity_parrotfish = Coral.Coral_reef*Natural_density_parrotfish

Carrying_capacity_snapper = Coral.Coral_reef*Natural_density_snapper

Coral_availability__ratio = MAX(Coral.Established_coral/COT_starfish,0)

COTS_mortality_fraction = GRAPH(Snappers)

(0.00, 0.15), (1e+006, 0.3), (2e+006, 0.45), (3e+006, 0.6), (4e+006, 0.75), (5e+006, 0.9)

COTS_removal_policy_start_time = 2000

COTS_removal_policy_status = if(COTS_removal_policy_switch=1)and(time>COTS_removal_policy_start_time)then(1)else(0)

COTS_removal_policy_switch = 0

COTS_spawn_efficiency = 0.5

COTS_spawn_frequency = 1

COTS_time_to_grow =
Normal_COTs_time_to_grow*Effect_of_phytoplankton_availability_on_COTS__time_to_grow

Effect_of_coral__depletion_on_avg_lifetime_COTS = GRAPH(Coral_availability__ratio)

(0.00, 0.025), (0.2, 1.00), (0.4, 1.00), (0.6, 1.00), (0.8, 1.00), (1.00, 1.00)

Effect_of_phytoplankton_availability_on_COTS__time_to_grow =
GRAPH(Algae.DIN_content_coral_reef)

(0.00, 1.20), (1.00, 1.00), (2.00, 0.8), (3.00, 0.6), (4.00, 0.4), (5.00, 0.2)

initial_fish_stock_values_to_equilibrium = 0

Natural_density_parrotfish = 10000

Natural_density_snapper = 8000

Normal_COTs_time_to_grow = 2

Normal_lifetime_COTS = 15

Parrotfish_fraction = 0.5

Parrotfish_overcrowding = MAX(0, Parrotfish-Carrying_capacity_parrotfish)

Parrotfish_recruit_mortality_fraction = GRAPH(Coral.Coral_reef)

(0.00, 0.9), (200, 0.85), (400, 0.8), (600, 0.75), (800, 0.7), (1000, 0.65)

Parrotfish_spawn_efficiency = GRAPH(Coral.Established_coral)

(0.00, 0.1), (200, 0.2), (400, 0.3), (600, 0.4), (800, 0.5), (1000, 0.6)

Parrotfish_spawn_frequency = 2

Parrotfish_time_to_grow = 3

Parrotfish_time_to__migrate = 1

Removal_succes__rate = 0.5

Snapper_overcrowding = MAX(0, Snappers-Carrying_capacity_snapper)

Snapper_recruit_mortality_fraction = GRAPH(Coral.Coral_reef)

(0.00, 0.9), (200, 0.85), (400, 0.8), (600, 0.75), (800, 0.7), (1000, 0.65)

Snapper_spawn_efficiency = GRAPH(Coral.Established_coral)

(0.00, 0.02), (200, 0.08), (400, 0.14), (600, 0.2), (800, 0.26), (1000, 0.32)

Snapper_spawn_frequency = 2

Snapper_time_to_grow = 2

Snapper_time_to_migrate = 1

Total_COTS_removed_succesfully = Active_divers_removing_COTS*Avg_COTS_removed_per_diver_per_year*Removal_succes__rate

Total_fish = Snappers+Parrotfish

Population:

Tourist_boats(t) = Tourist_boats(t - dt) + (Going_tourism) * dt

INIT Tourist_boats = 0

INFLOWS:

Going_tourism = (Tourism.Demand_for_tourist_boats-Tourist_boats)/Time_to_switch_to_tourism

Fish_boats(t) = Fish_boats(t - dt) + (New_fish_boats - Going_tourism) * dt

INIT Fish_boats = 0

INFLOWS:

New_fish_boats = discrepancy_boats/Time_to_built_boat

OUTFLOWS:

Going_tourism = (Tourism.Demand_for_tourist_boats-Tourist_boats)/Time_to_switch_to_tourism

Pop_0:14(t) = Pop_0:14(t - dt) + (Births - Maturing - Deaths_0:14) * dt

INIT Pop_0:14 = 1000

INFLOWS:

Births = Fertile_women*Annual_fertility_rate

OUTFLOWS:

Maturing = Pop_0:14/Time_to_mature

Deaths_0:14 = Pop_0:14*Death_fraction_0:14

Pop_15:64(t) = Pop_15:64(t - dt) + (Maturing + Immigration - Aging - Deaths_15:64) * dt

INIT Pop_15:64 = 1000

INFLOWS:

Maturing = Pop_0:14/Time_to_mature

Immigration = Shortage_of_tourist_operators/Time_to_immigrate

OUTFLOWS:

Aging = Pop_15:64/Time_to_age

Deaths_15:64 = Pop_15:64*Death_fraction__15:64

Pop_65plus(t) = Pop_65plus(t - dt) + (Aging - Deaths_65plus) * dt

INIT Pop_65plus = 250

INFLOWS:

Aging = Pop_15:64/Time_to_age

OUTFLOWS:

Deaths_65plus = Pop_65plus/Life_expectancy_at_65

Anchoring_damage__per_boat = 0.015

Annual_fertility_rate = Total_fertility_rate/Fertile_years

Average_fish_catch = GRAPH(Fish.Total_fish)

(0.00, 0.00), (200000, 5200), (400000, 7800), (600000, 10400), (800000, 13000), (1e+006, 15600)

Average_fish_catch_with_MPA_policy = GRAPH(Total_fish_available_for_fisherman)

(0.00, 0.00), (200000, 5200), (400000, 7800), (600000, 10400), (800000, 13000), (1e+006, 15600)

Average_sewage_output = 730

Bioerosion_from__boat_anchoring = (Fish_boats+Tourist_boats)*Anchoring_damage__per_boat*(1-Sustainable_buoys__policy_status)

Death_fraction_0:14 = 0.001

Death_fraction__15:64 = 0.002

Demand_for_fish = (Total_population*Fish_eaten_per_local_person)+(Tourism.Tourists*Fish_eaten_per_tourist)

Demand_for_fish_boats = Total_number_of_fishermen/Number_of_people_per_boat

discrepancy_boats = MAX(0, Demand_for_fish_boats-Fish_boats)

Fertile_female_fraction_of_15:64 = 0.45

Fertile_women = Pop_15:64*Fertile_female_fraction_of_15:64

Fertile_years = 35

Fish_eaten_per_local_person = 90

Fish_eaten_per_tourist = 0.5

Fraction_of_men_becoming_enforcer = IF(MPA_enforcement_policy_status=1)THEN(0.1)

ELSE(0)

Fraction_of_men_becoming_fishermen = 0.30-Fraction_of_men_becoming_enforcer-Fraction_of_men_becoming_homestay_owner

Fraction_of_men_becoming_homestay_owner = IF(Tourism.Homestay_policy_status=1)THEN(0.2)

ELSE(0)

Life_expectancy_at_65 = 7

Male_fraction_of_15:64 = 0.5

MPA_Compliance_rate = IF(MPA_enforcement_policy_status=1)THEN(1)

ELSE(0.6)

MPA_enforcement_policy_start_time = 2000

MPA_enforcement_policy_status = if(MPA_enforcement__policy_switch=1)and(time>MPA_enforcement_policy_start_time)then(1)else(0)

MPA_enforcement__policy_switch = 0

MPA_policy_status = if(MPA_policy_switch=1)and(time>MPA__policy_start_time)then(1)else(0)

MPA_policy_switch = 0

MPA__policy_start_time = 2000

Net_fish_exports = Total_harvest-Demand_for_fish

Number_of_people_per_boat = 15

Sewage_output_population = Total_population*Average_sewage_output*(1-Share_of_sewage_which_is_treated)

Sewage_treatment_policy_start_time = 2000

Sewage_treatment_policy_status = if(Sewage_treatment__policy_switch=1)and(time>Sewage_treatment_policy_start_time)then(1)else(0)

Sewage_treatment__policy_switch = 0

Share_of_coral_reef_protected_by_MPA = IF(MPA_enforcement_policy_status=1)THEN(1)

ELSE(0.1)

Share_of_sewage_which_is_treated = IF(Sewage_treatment_policy_status=1)THEN(0.95)

ELSE(0.1)

Shortage_of_tourist_operators = (Tourism.Demand_for_tourist_boats-Tourist_boats)*Tourist_operators_per_tourist_boats

Sustainable_buoys_policy__start__time = 2000

Sustainable_buoys__policy_status = if(Sustainable_buoys__policy_switch=1)and(time>Sustainable_buoys_policy__start__time)then(1)else(0)

Sustainable_buoys__policy_switch = 0

Time_to_age = 50

Time_to_built_boat = 1

Time_to_immigrate = 1

Time_to_mature = 15

Time_to_switch_to_tourism = 0.5

Total_fertility_rate = GRAPH(TIME)

(1980, 5.10), (1986, 4.40), (1992, 4.00), (1998, 3.70), (2004, 3.50), (2010, 3.30)

Total_fish_available_for_fisherman = (1-Share_of_coral_reef_protected_by_MPA)*Fish.Total_fish*MPA_Compliance_rate

Total_harvest = IF(MPA_policy_status=1) THEN(Fish_boats*Average_fish_catch_with_MPA_policy)

ELSE(Fish_boats*Average_fish_catch)

Total_number_of_fishermen = Pop_15:64*Male_fraction_of_15:64*Fraction_of_men_becoming_fishermen

Total_population = Pop_0:14+Pop_15:64+Pop_65plus

Tourist_operators_per_tourist_boats = 4

Tourism:

Potential_new_tourists(t) = Potential_new_tourists(t - dt) + (Destination_diffusion_rate - Tourists_arriving - Forgetting_destination) * dt

INIT Potential_new_tourists = 0

INFLOWS:

Destination_diffusion_rate = Prior_Tourists*Contact_rate*Adoption_rate

OUTFLOWS:

Tourists_arriving =
IF(Homestay_policy_status=1)THEN(MIN((Potential_new_tourists/Time_to_organize__holiday),Capacity_for_new_tourists_with_homestay_policy))

ELSE(MIN((Potential_new_tourists/Time_to_organize__holiday),Capacity_for_new_tourists))

Forgetting_destination = Potential_new_tourists/Time_to_forget_destination

Prior_Tourists(t) = Prior_Tourists(t - dt) + (Tourists_leaving - Forgetting_experience) * dt

INIT Prior_Tourists = 0

INFLOWS:

Tourists_leaving = Tourists/Avg_time_spent_on_destination

OUTFLOWS:

Forgetting_experience = Prior_Tourists/Time_to_share_experience

Tourists(t) = Tourists(t - dt) + (Tourists_arriving - Tourists_leaving) * dt

INIT Tourists = 10

INFLOWS:

Tourists_arriving =
IF(Homestay_policy_status=1)THEN(MIN((Potential_new_tourists/Time_to_organize__holiday),Capacity_for_new_tourists_with_homestay_policy))

ELSE(MIN((Potential_new_tourists/Time_to_organize__holiday),Capacity_for_new_tourists))

OUTFLOWS:

Tourists_leaving = Tourists/Avg_time_spent_on_destination

Tourist_resorts(t) = Tourist_resorts(t - dt) + (Resort_building - Resort_demolition) * dt

INIT Tourist_resorts = 4

INFLOWS:

Resort_building = New_resorts_planned/Time_to_built_resort

OUTFLOWS:

Resort_demolition = Tourist_resorts/Avg_lifetime_accommodation

Adoption_rate = 0.05

Available_homes_for_homestay = Total_households*Share_of_local_households_with_homestay

Average_people_per_household = 7

Average_tourists_per_homestay = 2

Avg_lifetime_accommodation = 30

Avg_time_spent_on_destination = 0.04

Avg_tourists__per_resort = 50

Bioerosion_from_snorkeling_activity = Demand_for_island_hopping*Coral_reef_damage_per_tourist*Share_of_people_going_into_the_water*Share_of_people_causing_damage

Capacity_for_new_tourists = (Tourist_resorts*Avg_tourists__per_resort)/Avg_time_spent_on_destination

Capacity_for_new_tourists_with_homestay_policy = (Available_homes_for_homestay*Average_tourists_per_homestay)/Avg_time_spent_on_destination

Contact_rate = GRAPH(TIME)

(1950, 20.0), (1963, 20.0), (1975, 20.0), (1988, 20.0), (2000, 20.0), (2013, 40.0), (2025, 40.0), (2038, 40.0), (2050, 40.0)

Coral_reef_damage_per_tourist = 0.003

Demand_for_island_hopping = Tourists*Share_of_tourists_doing_island_hopping

Demand_for_resorts = (Tourists*(1+Expected_tourism_growth_rate))/Avg_tourists__per_resort

Demand_for_tourist_boats = Demand_for_island_hopping/Number_of_tourists_per_boat

Expected_tourism_growth_rate = 0.2

Glass_ceiling_policy_start_time = 2000

Glass_ceiling_policy_status = if(Glass_ceiling__policy_switch=1)and(time>Glass_ceiling_policy_start_time)then(1)else(0)

Glass_ceiling__policy_switch = 0

Homestay_policy_start_time = 1970

Homestay_policy_status = if(homestay__policy_switch=1)and(time>Homestay_policy_start_time)then(1)else(0)

Homestay__policy_switch = 0

Maximum_number_of__resorts = 3200

New_resorts_planned = MIN(Demand_for_resorts,Maximum_number_of__resorts) - Tourist_resorts

Number_of_tourists_per_boat = 20

Sediment_from_land_development =
(Resort_building+Resort_demolition)*Sediment_produced_per_new_resort*(1-
Silt_screen_policy_status)

Sediment_produced_per_new_resort = 0.05

Sewage_output_tourists = Tourists*Population.Average_sewage_output*(1-
Share_of_resorts_with_sewage_treatment)

Share_of_local_households_with_homestay = 0.5

Share_of_people_causing_damage = IF(Glass_ceiling_policy_status=1)THEN(0.02)

ELSE(0.2)

Share_of_people_going_into_the_water = IF(Glass_ceiling_policy_status=1)THEN(0.1)

ELSE(1)

Share_of_resorts_with_sewage_treatment =
IF(Population.Sewage_treatment_policy_status=1)THEN(1)

ELSE(0.4)

Share_of_tourists_doing_island_hopping = 0.2

Silt_screen_policy_start_time = 2000

Silt_screen_policy_status =
if(Silt_screen__policy_switch=1)and(time>Silt_screen_policy_start_time)then(1)else(0)

Silt_screen__policy_switch = 0

Time_to_built_resort = 1

Time_to_forget_destination = 5

Time_to_organize__holiday = 1

Time_to_share_experience = 3

Total_households = Population.Total_population/Average_people_per_household