Limits to reef growth

Dynamic behavior of (sub)tropical social-ecological coral reef ecosystems in the Anthropocene

Pepijn Kruseman Aretz

Delft University of Technology

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by

Pepijn Kruseman Aretz

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Thesis committee:	Prof. dr. J.H. Slinger,	TU Delft, Chair
	Dr. ir. F.M. d'Hont,	TU Delft, First supervisor
	Dr. J.A. Annema,	TU Delft, Second supervisor

This thesis is confidential and cannot be made public until July 10, 2023.

Preface

Before you lies the thesis 'limits to reef growth: dynamic behavior of (sub)tropical social-ecological coral reef ecosystems in the Anthropocene', for obtaining the Master's degree in Complex Systems Engineering and Management. It is the culmination of my hard work from January to July 2023.

For my bachelor thesis, I choose to do a water-related subject with a System Dynamics (SD) method. Little did I know, this was the beginning of increased interest in water-based systems. Now, a few years later I am researching social-ecological coral ecosystems, again with System Dynamics as one of the methods. The reason I keep coming back is, because SD explains and describes phenomena in the same way as I view the world, and thus, connecting my thoughts to my understanding. Secondly, water-based systems are often very complex systems with huge societal challenges, and I love to take on that challenge.

I am very grateful to have taken on this challenge with my committee: Floortje d'Hont, Jill Slinger, and Jan-Anne Annema, as they enabled me in my ambition to make this a successful thesis and get the best out of myself. I have really enjoyed working with you, Floortje, I think we work well together and to me our conversations felt equal, without you shying away from giving me that push, when it was needed, which I have found truly valuable. I also want to thank you for your dedicated feedback. Furthermore, I want to thank you, Jill, for being always open for me to walk by and have a conversation on whatever was needed. I always left with more knowledge than I initially thought to be coming for, which was brilliant. Lastly, Jan-Anne, as someone who is less familiar with the subject, I very much appreciated your feedback from another perspective. For example during the mid-term, which helped me see what was clear to me, but not to others.

I also want to take a moment to thank Paul Peters and my interview respondents. Paul, you voluntarily have taken time out of your busy schedule to help me with my thesis. You understood the purpose of my thesis, and aided me with your knowledge on marine biology, which has enormously improved my understanding of coral reefs. For that I thank you. Secondly, I want to thank my respondents, for sharing their knowledge with me. I hope I have done your expertise justice with my thesis.

Lastly, I want to thank my family for helping me during the toughest times of the thesis (the last week before the Green-light deadline), and my friends for the lunch conversations on the TU campus and the support during the process.

Coral reefs are a beautiful phenomenon and a beautiful subject for a thesis, and with this I hope to defending the beauty, that cannot defend itself, even if its just a little bit. I wish for you to feel the same enthusiasm and curiosity, from learning about the wonders that are coral reefs, as I did.

Pepijn Kruseman Aretz
Delft, June 2023

Summary

Global average hard coral cover has declined from 33.3% to 28.8% in the last 20 years (UNEP et al., 2020). While efforts have been made to protect marine resources through SDG 14 (UNFCCC, 2018), the global High Seas Treaty adopted in 2023 falls short in safeguarding crucial coastal ecosystems, which are characterized by high biodiversity and productivity. Coastal ecosystems, including coral reefs, serve as breeding grounds for marine life and support the livelihoods of over a billion people. Unfortunately, coral reefs are approaching their physical ecosystem boundaries. Urgent action is required to reduce carbon emissions, halt degradation, and initiate restoration and conservation efforts. Restoring coral reefs not only benefits ecology but also provides essential ecosystem services, such as food security, tourism, and coastal protection. Artificial reefs have emerged as a potential intervention, but their long-term implications on social-ecological coral reef systems require careful consideration, as reckless intervention can cause damage to the delicate balance in the system. The research study aims to understand the dynamics of (subtropical) social-ecological coral reef systems, and in doing so learn about the physical boundaries to coral reef growth, and the serve as a basis for future intervention in coral reefs. Through a multidisciplinary approach, the following main research question, and the subsequent sub-questions are answered:

What is the dynamic behavior of (sub)tropical social-ecological coral reef systems in the Anthropocene?

1. *What variables and relations determine the long-term dynamics within (sub)tropical social-ecological coral reef ecosystems?*
2. *What long-term dynamics shape the marine environment of (sub)tropical social-ecological coral reef ecosystems?*
3. *What are the implications of key patterns of dynamic behavior for long-term intervention in (sub)tropical social-ecological coral reef ecosystems?*

The methodology involves a mixed-methods approach, combining literature reviews, expert interviews, cognitive mapping, and system dynamics modeling to determine the variables, relations and dynamics. Figure 1 shows the outcomes and the activities of the research and how they will contribute to answering the research questions. The literature review is conducted using search terms related to ecology, society, and system dynamics. Various databases are used, including Nature, Science, Google, and Google Scholar, along with snowballing methods to find relevant articles. The expert interviews are semi-structured, allowing participants to share their specific expertise on variables and relations within coral reef systems. The interview information is extracted through cognitive mapping using the List Extension Method. The use of list extension diagrams to process interviews is a unique contribution of this research and an innovation in terms of connecting interview information to computer-based system dynamics modelling. The insights from the literature review and the list extension diagrams are synthesized to create the qualitative stock-flow diagram, see figure 2. The qualitative stock-flow model helps to conceptually understand the dynamic behaviors within social-ecological coral reef systems. The qualitative stock-flow model is converted into the quantitative coral reef system model, which aims to gain insight into key patterns of dynamic coral reef behavior, such as dominant interactions between variables, and find implications of key behavioral patterns in long-term intervention.

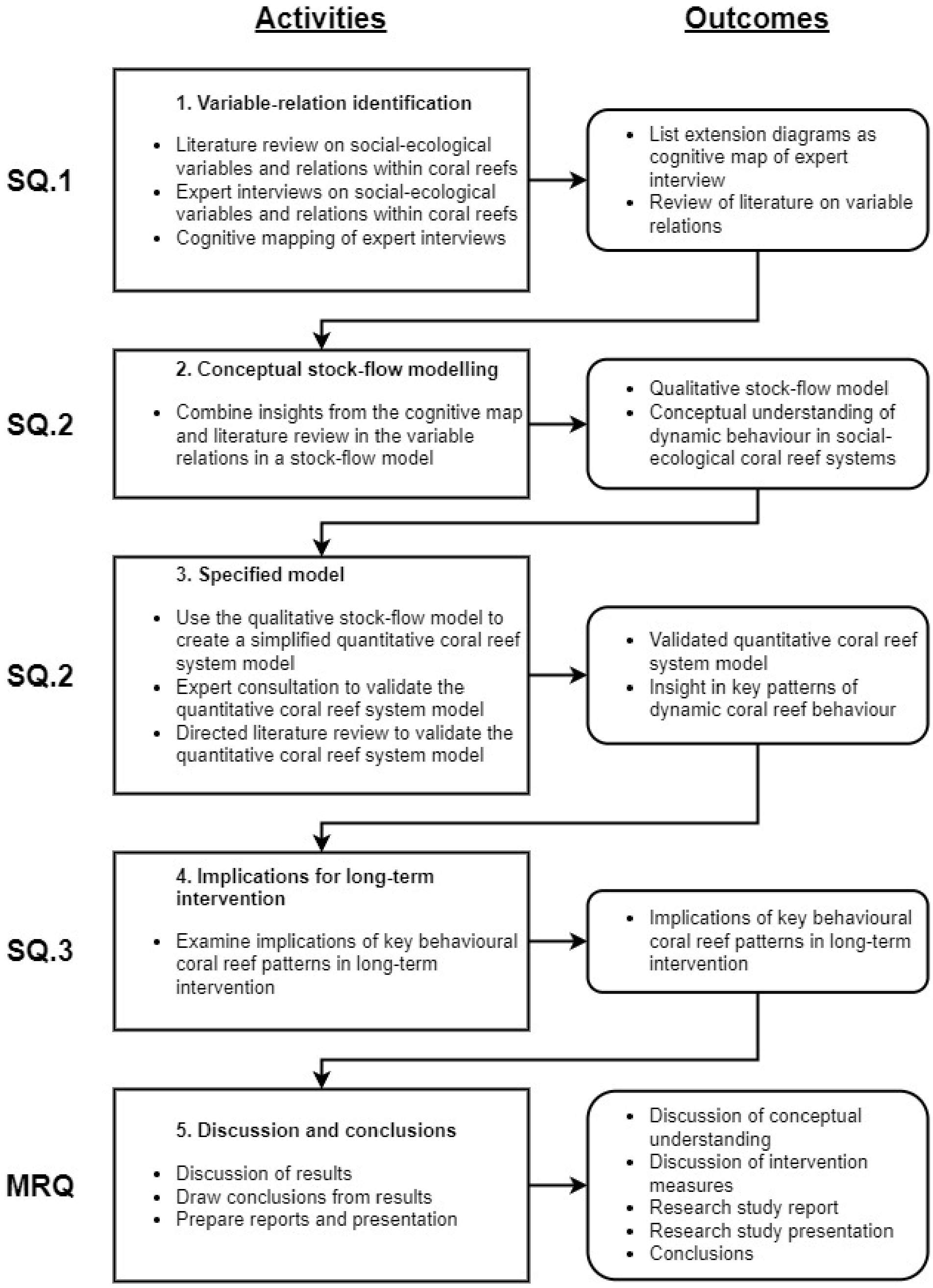

Figure 1: Activities are shown on the left and outcomes on the right. The outcomes are used as input for the new activities (inspired by Videira et al. (2012)).

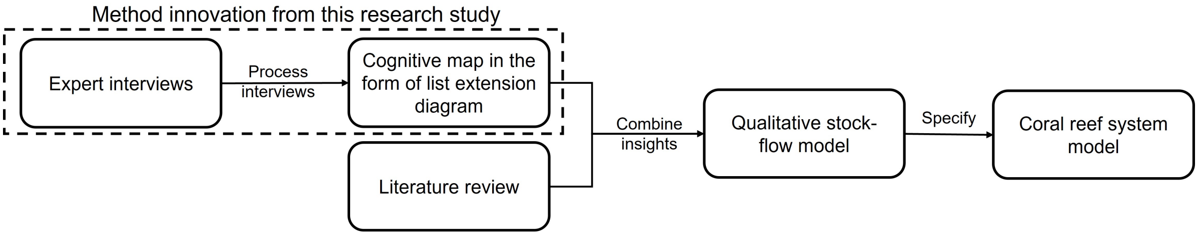

Figure 2: The expert interviews are processed through creating list extension diagrams from the cognitive maps of the interviewee's, which is a unique contribution of this research study.. The list extension diagrams (appendix D) and the literature review are combined into the qualitative stock-flow diagram (appendix E). The qualitative stock-flow model is specified into the coral reef system model.

The qualitative stock-flow model combines ecological and social dynamics, focusing on factors such as fisheries, pollution, and tourism. The model highlights the interplay between green algae, corals, coralline algae, and herbivorous fish as the main ecological feedbacks. The conflict arises between the fast-growing green (macro)algae and the slower-growing corals and coralline algae, which compete for surface area in the reef. However, herbivorous fish feed on green algae, helping to control their growth and providing shelter for corals and coralline algae. Climate change impacts this dynamic, favoring green algae due to warming temperatures, ocean acidification, and rising sea levels. The model also considers additional processes that affect coral reef expansion, such as carbonate framework production and erosion. Anthropogenic activities like tourism, pollution, and overfishing can cause further damage to coral reefs by disrupting trophic food web interactions and causing damage to coral reef assemblages.

The qualitative stock-flow diagram revealed several key structures that determine the behavior of social-ecological coral reef systems. One significant interaction is the competition between macroalgae and hard coral cover for reef surface area. The population dynamics of these organisms can be described using a logistic function, where the growth rate of the population depends on the difference between births and deaths and is influenced by the current population size and the carrying capacity of the system. When the occupied surface area approaches the carrying capacity, population growth slows down. In the case of competing populations, like corals and macroalgae, they balance out over time. If one population has a higher growth rate, it can dominate by occupying all available surface area, limiting the growth of the other population. Additionally, corals and macroalgae compete through extrusion, overgrowth, shading, and allelopathy. The competitive interactions for surface area can be described using the competitive Lotka-Volterra equations. These equations incorporate the effect of one species on the population growth of the other species. Depending on the rates of interaction, the populations can either move towards a dominant state or reach an equilibrium point, where the populations stabilize. Populations can also overshoot the carrying capacity, resulting in a collapse and eventual stabilization around the carrying capacity, forming a stable 2-cycle.

Macroalgae, being r-selective species with higher reproduction rates, should theoretically dominate reefs. However, their growth is suppressed by herbivores, leading to a predator-prey dynamic between herbivorous fish and macroalgae. This dynamic follows predator-prey Lotka-Volterra equations, and the populations exhibit boom-and-bust behavior over time. Environmental conditions, which act as coral stressors, influence the growth rates of corals and macroalgae. Increased stressors such as fishing, pollution, tourism, and climate change can trigger hysteresis in coral reefs, causing shifts between coral dominated and algal dominated states. Interventions, such as modifying stressors, manipulating thresholds, and altering feedback, can help prevent undesired phase shifts and maintain healthy coral dominated states in social-ecological coral reefs. In general, understanding the structures and interactions within coral reef systems is crucial to predicting and managing their behavior and resilience in the face of environmental stressors.

To determine key behavior patterns and examine the implications for intervention, the coral reef dynamics model consists of two subsystems: the predation subsystem and the competition subsystem. The predation subsystem focuses on the predator-prey dynamics between herbivorous fish and macroalgae. It utilizes existing Lotka-Volterra models to describe this interaction. The biomass of herbivorous fish increases through growth and spawning, which is influenced by the structural complexity of the reef, specifically coral abundance. The competition subsystem deals with the competition between macroalgae and corals for surface area. The density of occupied surface area affects the growth and spawning of both coral and macroalgae. Additionally, macroalgae can affect coral death through overgrowth, shading, abrasion, and allelopathy, while corals can extrude macroalgae. The competition subsystem considers the effects of crowding and the interactions between the species. An important insight into the effect of crowding is the difference in density dependence between macroalgae and corals. While corals rely on both macroalgae and other corals for density dependence, macroalgae rely only on other macroalgae, because they can overgrow coral substrate.

The coral reef system model incorporates both predator-prey Lotka-Volterra dynamics and interspecific competitive Lotka-Volterra dynamics, which rest on certain assumptions. However, not all assumptions of these functions apply to the model. For the predator-prey dynamics, the assumptions related to ample food supply for prey, food supply dependency of predators, rate of change proportional to population size, and limitless predator appetite are applicable. However, the coral reef system model has additional assumptions that influence its behavior. Notable assumptions include the immortality of corals (except for death caused by bioerosion, boring, or physical damage), overgrowing not contributing to crowding, inclusion of age distribution between juvenile and mature coral cover, stable bioeroding and boring organisms, lack of migration between regions, and assumption of coralline algae as coral cover. These assumptions, along with others listed in table 5.3, shape the behavior of the model. While the coral reef system model exhibits some behavior anomalies, it also demonstrates characteristics of real systems, such as lag cycles in predator-prey dynamics. In the experiments, the effect of anthropogenic stressors is examined. The experiments show that continuous stressors change the population equilibria between corals, macroalgae, and herbivorous fish. Furthermore, increasing the impact and frequency of coral death events reduce reef resilience. The combined effects of anthropogenic stressors cause reefs to degrade and coral-algal phase shifts to occur in the 21st century.

This research study builds upon previous work by Hughes et al. (2017), which highlights the importance of considering multiple stressors and their combined effects on coral reef ecosystems. It emphasizes the need for long-term insights into the effects of climate change and other stressors on reefs, and increases understanding of the multiple drivers and feedbacks in changing coral reefs. The qualitative stock-flow model developed in this study serves as a basis for further understanding of social-ecological coral reef systems and intervention measures to protect coral reefs worldwide. Conceptually, artificial reefs could be used as tool, if their effectiveness is impactful enough and possesses the ability to counteract the effect of global stressors on coral growth and death. System dynamics modeling shows promise as a tool for coral reef research, capturing interactions, feedback, and non-linearity in social-ecological systems. However, dealing with uncertainty and validating models remain critical points. By using modelling to improve long-term understanding, intervention can be done taking account of the delicate balance within the ecosystem itself. The increased understanding can be used to prevent coral reefs from physical boundary transgression and to return to the safe operating space for coral reefs in the Anthropocene.

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Nomenclature

Abbreviations

Abbreviation	Definition
AIMS	Australian Institute of Marine Science
AR	Artificial Reef
GCRMN	Global Coral Reef Monitoring Network
ICRI	International Coral Reef Initiative
MRQ	Main research question
ppm	Parts Per Million
SD	System Dynamics
SDG	Sustainable Development Goal
SQ	Sub-Question
SES	Social-Ecological Systems
UN	United Nations
UNEP	United Nation Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change

Table 1

Symbols

Symbol	Definition	Unit
r ...	Growth rate	[ha]
K ...	Carrying capacity	[ha]
N ...	Population	[ha] or [kg]
S ...	Surface area	[ha]
α ...	The effect an individual of species X has on the population growth of species Y	[1/year]
β ...	The effect an individual of species Y has on the population growth of species X	[1/year]
γ ...	Prey per capita growth rate	[1/year]
δ ...	Rate at which predators consume prey	[ha/kg/year]
ϵ ...	Predators per capita death rate	[1/year]

Symbol	Definition	Unit
ζ	Rate at which predators increase by consuming prey	[kg/ha/year]
...		

Table 2

1
Introduction

Climate change, loss of biodiversity, and pollution have taken their toll on coral reefs around the world, and while coral reefs cover only 0.2% of the seafloor, they support at least 25% of marine species and millions of people worldwide through ecosystem services (UNEP et al., 2020; Hughes et al., 2017; Woodhead et al., 2019, p.16). In 2020, the United Nations issued a report on the status of coral reefs of the world. The report stated that the global average hard coral cover has decreased from 33.3% to 28.8% (UNEP et al., 2020, p.32).

In 2015, the United Nations agreed to conserve and sustainably use the oceans, seas and marine resources for sustainable development (SDG 14) (UNFCCC, 2018). Eight years later, in 2023, the first worldwide treaty to protect some of these resources has been adopted, in which countries agree to protect the marine environment and cooperate to that end. Although the treaty is a step in the right direction, it leaves out critically important coastal ecosystems. While the high seas (i.e., all parts of the mass of saltwater surrounding the globe that are not part of the territorial sea or internal waters of a state) form the vast majority of marine environment, the coastal zone specifically is characterized by high biodiversity and productivity. Coastal ecosystems consist of (coral) reefs, intertidal zones, estuaries, lagoons, mangroves, etc. Coastal ecosystems in general, and coral reefs specifically, serve as the breeding ground for coastal and high seas species. An estimated 25% of all marine life are dependent on coral reefs at some point in their life-cycle and around a billion people rely on coral reef provided resources. Therefore, marine conservation and sustainable development should consider the coast and its coral reefs.

Coral reefs are slowly but surely reaching its limits, as they are incrementally approaching the transgression of their ecosystem boundaries. The boundaries define "the safe operating space for humanity with respect to the earth system and are associated with the planet's biophysical subsystems or processes" (Rockström et al., 2009). Transgression of ecosystem boundaries may substantially alter the functioning of ecosystems in which human civilization has emerged (Steffen et al., 2015). Climate change, rate of biodiversity loss and interference with the nitrogen cycle have already surpassed their ecosystem boundaries, while the boundaries of global freshwater use, change in land use and ocean acidification are in sight (Rockström et al., 2009; Mathias et al., 2017). As a result of the changes, the current geological period is referred to as the Anthropocene. The environmental changes pose an immense challenge for coral reefs, which will have to be steered away from the biophysical boundaries (Graham et al., 2013). A large driver behind the approach of biophysical boundaries is the rise in global mean average temperature, caused by greenhouse gas emissions (Hughes et al., 2017). Rigorous carbon emission reduction over coming decades is vital, for safeguarding the 2 °C in global mean temperature rise (Rogelj et al., 2016a; Mathias et al., 2017), set by the 2015 United Nations Paris Agreement (UNFCCC, 2015). It is unlikely that this goal will be met (Rogelj et al., 2016b), but even if it is, immediate intervention is needed to halt the degradation and start restoration and conservation of the affected ecosystems.

Restoration and conservation of coral reefs not only benefit ecology, but also contribute to human activity through ecosystem services. Reefs, and in particular coral reefs, can be viewed as intricate social-ecological systems in which interrelations between human society and nature exist. For example, millions of people depend on coastal waters and reefs for food and resource security, ocean recreation and tourism, and coastal protection (Ferrario et al., 2014; Hughes et al., 2017; Free et al., 2022; Carlot et al., 2023). With hard cover corals being on the decline worldwide due to combinations of stressors, the biophysical conditions of the ecosystem change, effectively causing huge challenges for coastal communities. Ocean acidification decreases zooplankton abundance, which serves as source of nutrients for corals, fish and planktivores (Smith et al., 2016). Coral bleaching events and climate change have also sparked last chance tourism (Piggott-McKellar & McNamara, 2017). Loss of the reefs' structural complexity can cause extreme wave heights to occur far more frequently threatening coastal communities (Beck et al., 2018; Carlot et al., 2023). Decisive action will be required to avert further biophysical boundary transgressions of the ecosystem.

There is still potential for coral reef restoration and conservation in the future (Cinner, Huchery, et al., 2016; Saunders et al., 2020; Webb et al., 2023; Knoester et al., 2023b). Global (temperature and acidification) and local stressors (fishing, pollution, etc.) exist, however, the variety of stressors do not occur in one place (Harborne et al., 2017), i.e. the effect of the variety of stressors differs per area. To mitigate the effects of these stressors, and identify positive interventions, an improved understanding is needed between the interacting drivers and the coral reef ecosystem behaviors (Hughes et al., 2017). Reducing the effects of drivers on a local level could induce the reversal of the phase shifts away from the system boundaries (Graham et al., 2013). One has to keep in mind that reef restoration and conservation is effective, but not 'the silver bullet' to the anthropogenic impact on earths ecosystems, stemming from greenhouse gas emissions (Webb et al., 2023). Ostrom et al. (2007) warned for falling in panacea traps. No one blueprint exists for social-ecological systems, like coral reefs, as these systems can have pervasive systemic uncertainty and differing social-ecologic contexts (Brochier et al., 2021).

Hughes et al. (2017) calls for systemic action by identifying opportunities, such as redefining management goals, manipulating ecosystems, building institutions for governance, fostering innovative partnerships and changing social norms. Any of these interventions can potentially give more sustainable solutions, but intervening in the complex dynamics that exist within and beyond the reef ecosystems is challenging, as the intervention effects (probably) will extend to the wider social-ecological system (Graham et al., 2013; Hughes et al., 2017). One example of effective reef ecosystem manipulation that is often called for (Pickering et al., 1999; Belhassen et al., 2017; Brochier et al., 2021; Higgins, 2022), is the implementation of artificial reefs. Artificial reefs (AR's) are man-made structures placed underwater to mimic some characteristics of natural reefs (Pickering et al., 1999; Belhassen et al., 2017; Layman & Allgeier, 2020). But before system action is taken, the holistic system, the complex dynamics, the reef ecosystem, and its relation to the wider social-ecological system, therefore, the main research question (MRQ) is:

What is the dynamic behavior of (sub)tropical social-ecological coral reef systems in the Anthropocene?

To answer the main research question, the research study is divided in the following three sub-questions (SQ):

1. *What variables and relations determine the long-term dynamics within (sub)tropical social-ecological coral reef ecosystems?*
2. *What long-term dynamics shape the marine environment of (sub)tropical social-ecological coral reef ecosystems?*
3. *What are the implications of key patterns of dynamic behavior for long-term intervention in (sub)tropical social-ecological coral reef ecosystems?*

The research approach in chapter 2, which introduces the research study's methodology and methods, and explains how the sub-questions and main questions are answered. Chapter 3 contains a review of the literature on social-ecological coral reef systems. In chapter 4, the literature review is combined with data from the list extension diagrams that were extracted from the expert interviews to create a qualitative stock-flow model. In chapter 5, the qualitative stock-flow model is specified into a quantitative model known as the "coral reef system model", and experiments are set up to investigate the system behavior. Finally, in chapter 6, the conclusions are discussed, as well as a reflection on the research study.

2

Research approach

In this chapter, the methodology of the research is explained. Section 2.1 gives an overview of the methodology and the chosen methods: the literature study (2.2), interviews (2.3), and system dynamics come forth as the most suitable methods and are described in more detail in the respective paragraphs. The case study (selection) are introduced in 2.5.

2.1. Research methodology

To advance the discussion on the effectiveness of interventions in coral reef ecosystems, it is crucial to investigate the interconnectedness of the entire coral reef system and its complex social-ecological relations. Hughes et al. (2017) highlights that "incorporating both human social systems and ecosystems in models reveals added complexity and a broader range of dynamics, opening up new possibilities for sustainable solutions." Therefore, this research focuses on understanding the social-ecological dynamics of (sub)tropical coral reef ecosystems from a relatively high aggregation level. Given the inherent complexity of these systems, a systems thinking approach is particularly emphasized in this study. While various methods exist for studying social-ecological systems (Biggs et al., 2021), this research adopts a system dynamics modelling approach (as described in sections 2.4) to explore the fundamental behavioral patterns within coral reef systems. The research aims to scope, conceptualize, and analyze the systemic variables, processes, and driving behaviors involved.

A mixed-methods approach is selected to scope, conceptualize, and analyze the social-ecological coral reef system. The methods include literature reviews, expert interviews, expert modelling via cognitive mapping and system dynamics modelling, as supported by Biggs et al. (2021, p.75). In figure 2.1, the methodology of the research is introduced. The first step is identifying the variables and relations, which make up the dynamic of social-ecological coral reefs. Coral reef systems have intricate variables and relations, which can be explored and explained. Through a literature review, expert interviews and subsequently the cognitive mapping of the expert interviews, a better image of the complex interrelations is formed. The cognitive maps are made in the form of the list extension diagrams. The literature review and list extension diagrams are combined to create a qualitative stock-flow model using system dynamics modelling. Doing the literature review and expert interviews concurrently aides the knowledge gain in the variable relations phase, as a feedback occurs between the knowledge gained in the interviews and the literature. Learning about a phenomenon in an interview aides the literature study and vice versa. The combined conceptual stock-flow model already offers understanding of the dynamic behavior within social-ecological coral reef systems. The qualitative stock-flow model is specified into a quantitative stock flow model, named 'coral reef system model'. The coral reef system model is validated through expert consultation and a directed literature review comparing behavior of real ecological systems to the modelled behavior. The validated model can give insight in key patterns of dynamic coral reef behavior in the social-ecological coral reef system. The insight in key patterns can give implications for intervention, such as the use of (large-scale) artificial reefs. After which the main research question is answered through a discussion and conclusions of results.

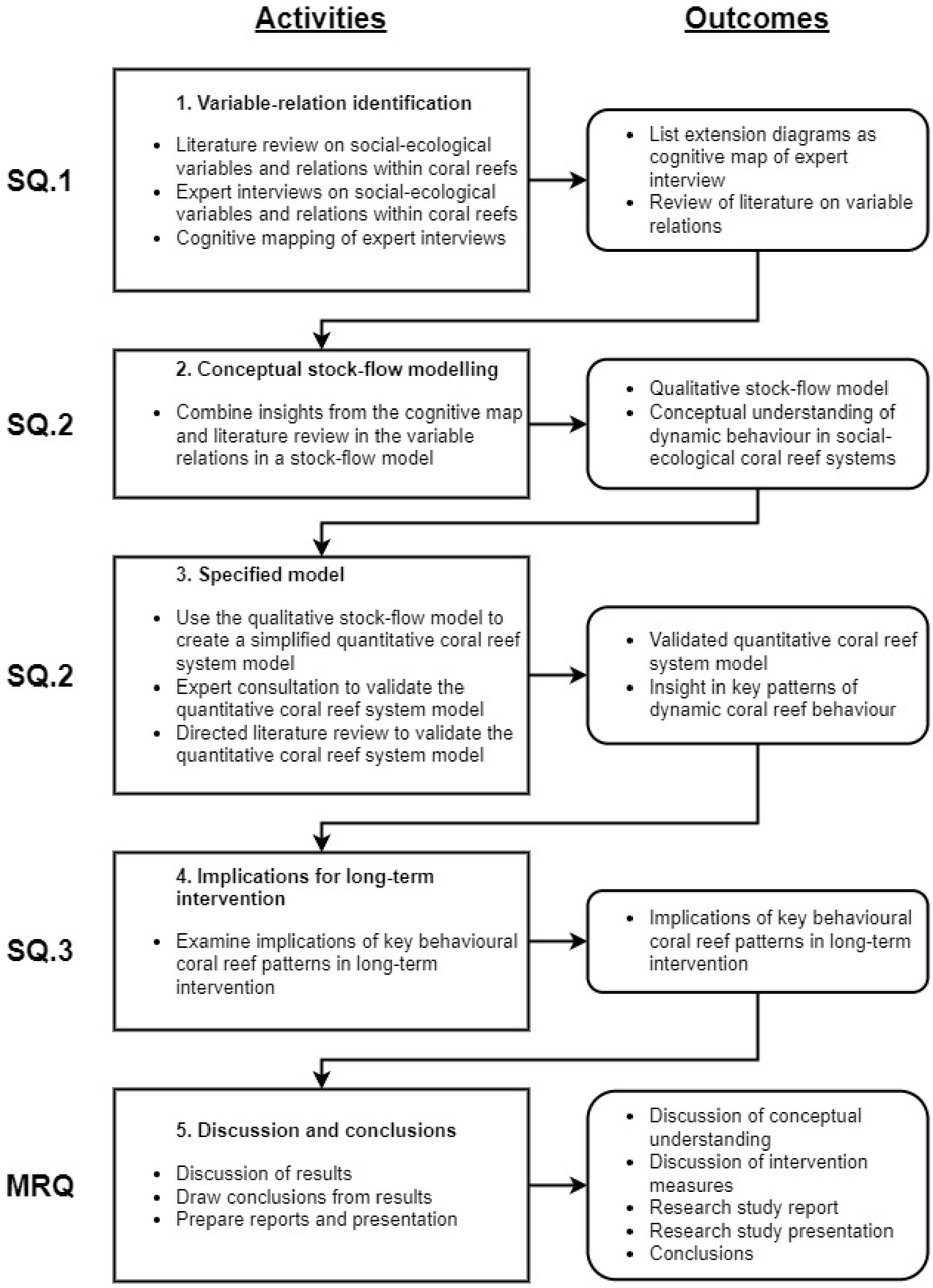


Figure 2.1: Activities are shown on the left and outcomes on the right. The outcomes are used as input for the new activities (inspired by Videira et al. (2012)).

2.2. Literature study approach

For this research, literature on coral reef systems needs to be scoped to access desired publications within the field. Although reefs exist worldwide, (social-ecological) coral reef systems and artificial reefs is a relatively small research field. With a small pool of authors, researching intensively and extensively on the subject. To tap into the literature, a strategy is set up, in which preferred search terms, literature databases, and snowballing methods are determined. With the goal of giving a holistic perspective of the existing knowledge on social-ecological coral reef systems and artificial reefs, the net is initially casted widely.

To cover the research field, a scoping has been done of the search terms. The table covering the search terms is found in appendix A. The terms are divided in three categories: ecology, society, and system dynamics. The ecology terms involve terms, which are related to the ecology of coral reefs, e.g. carbonate budget, sea level rise. The societal terms cover the involvement of human activity in coral reefs, e.g. pollution, fisheries. The System Dynamics terms are related to the method for analysis of the social-ecological system, as explained in section 2.4. The list of search terms is concise and little synonyms are used for the different concepts, because of how they are deployed. A combination of the search terms are used to find the most relevant articles on the topic and the relevant articles are used to snowball within the references. Reason being the small field of coral reef systems and the existence of several prominent authors and journals in the field. Expertise is centered in the countries, which reefs experience unwanted effects, e.g. coral bleaching in the Great Barrier Reef in Australia. As a result, some articles are heavily cited, or published in a journal with a high impact factor. Through this method, recent, credible, and relevant articles can be sought out.

The databases used for the initial search are Nature, Science, Google, Google Scholar, and TU Delft library. Nature and Science are high impact factor journals and have a large database of (social-)ecological articles. Prominent authors in the field of coral reef systems publish in these journals. Making it a decent starting point for the article search, which later on can be used for the snowballing. Google and Google Scholar are large databases, they are used to increase the article coverage. The TU Delft library is used looking for books on a specific topic. After the initial search, with the search terms, snowballing is executed with the help of the Connected Papers software. The software supports the snowballing process. A third way of finding relevant literature, is asking respondent for literature recommendations. The respondents are experienced in the field and often up-to-date with literature in the field. All articles are collected in a log, keeping track of the used search terms and database to find a specific literature piece. In the case of snowballing, the prior article is listed. The literature log can be provided on request.

2.3. Design of Expert Interview and Cognitive Mapping approach

The expert interview and cognitive mapping methods are combined in the methodology to combine the scoping and conceptualization. In this section, the set-up, the conduct, and the wrap-up of the combined method. For the interview a semi-structured approach was chosen. Social-ecological systems can be complex and experts can have differing expertise on, for example, variables, relations, locations. The semi-structured interview opens up the conversation within their expertise, and limits the potential for wrong information. First, the profile and gathering of the participants is described. Secondly, the conduct of the interview and, lastly, validating the interview information.

Coral reefs are marine social-ecological systems. Information is needed on the ecological as well as the social variables and relations. For the ecological variables and relations, a marine biologist is needed. As the ecological interactions make up a large part of the system, interviewing multiple marine biologists may reduce bias. As a limitation of interviews is that people's opinions and perceptions are subjective and therefore require corroboration from other sources such as instrumental or other observation-based approaches (Biggs et al., 2021). Marine biologists often also have insight in the social relations to the system. To reduce subjectivity also various other participants should be gathered, such as long-time volunteers, ocean wave experts, artificial reef experts, experienced coral reef divers, systems engineers with coral reef experience. Participants can have multiple expertise's.

As the result of the semi-structured interviews is to gain information on the scope as well as the expert's cognitive map, the interview script should be set-up accordingly. The full script can be found in appendix B. Approximately one day before the interview, a message is send to the participant. In the message, a teaser is given for the participant to spark enthusiasm, and a system archetype is explained, as means of introducing the scope, and the variables and relations. Furthermore, already recording permission is asked through the informed consent form (appendix C). In the case of an online interview, a meeting invitation is send. Secondly, the interview itself consists of three variables: the warming-up, the dynamic relations, the finish. In the warming-up, permission for recording is asked as declared in the data management plan and the informed consent form, which can be provided on request. Moreover, the purpose of the research is introduced, as well as the interview schedule. Before moving to the experience of the participant's personal/professional background and experience with social-ecological coral reef systems. Subsequently, the interview moves to the second part, the dynamic relations. Questions are asked based on the expertise of the participant. A template of the questions' form is given in appendix B. In the finish, the participant is thanked and the information provided is summarized and investigated for completeness. The participant's remaining questions can be asked and stocktaking is done on the possibility of a validation meeting later on in the research. Following the interview, after approximately one day a post-interview message is send reiterating the gratitude. Transcripts and recordings are handled according to the data management plan (available on request) and informed consent form. The information is analyzed through the analysis technique: List Extension Method, which is explained in the subsequent paragraph. At the end of the interview, the interviewer asks the participant for participation in a validation meeting in a later stage of the research. The goal of the validation meeting is to get feedback on the synthesized diagram of the interviews and the literature study, and the subsequently created coral reef system model. Social-ecological coral reef systems are complex, and therefore a strong validation supports the conceptualization. As preparation for the interviews the author does two mock-up interviews. In the mock-up interviews the structure and style are tested to try and maximize the potential benefit from the interviews. Some adaptations to the script were made after. In section 6.3, the changes that are made to the script are reflected on.

The extraction of the information from the cognitive mapping in the interview is done using a system dynamics approach, which is explained further in section 2.4. The interview covers the interviewee's cognitive map of a coral reef system, but it is not yet instantiated. The cognitive map consists of variables and relations which are important in coral reefs and the use of artificial reefs. Causal loop diagrams and feedback analysis function as conceptual diagrams within system dynamics. Causal relations and feedback as provided by the interviewees are analyzed, using the 'List Extension Method'. It is a conceptual analysis technique, which lends itself well for the extraction of variables and relations. List extension is based on the idea of starting with a small list and gradually extending it until a diagram emerges. The column headed 'Model list' is the starting point for developing a diagram. It contains the name of a variable which it is the purpose of the model to explain. This list of one item is now extended by writing in the column headed 'First Extension' the names of the variables which directly and immediately influence the variable in the model list, adding the appropriate arrows and signs (Coyle, 1996)". Extensions are added to the diagram until the external variables are reached. List extensions are appropriate for the extraction of variables and relations from the cognitive maps in the interviews, because the diagram shows the causality and feedback in the cognitive map of the interviewee. Furthermore, a cognitive map in an interview is built incrementally over the course of the conversation. The list extension method allows to follow that same course, and add or adjust variables and relations during creation. The use of list extension diagrams from the cognitive map for processing interviews is an innovation of this research study. As explained before, list extension diagrams lend itself well for the description of causal relations described by respondents, and is very suitable to connect the interview information to the computer-based system dynamics modelling, because list extension diagrams can be translated to other system dynamics models.

2.4. System Dynamics approach

For the analysis of the social-ecological coral reef dynamics, a System Dynamics Modelling approach is adopted. According to Biggs et al. (2021), system dynamics modelling provides a rigorous approach for studying how causal interactions within a social-ecological systems lead to dynamics at the system level. System Dynamics (SD) is an approach to understanding the nonlinear behavior of complex systems over time using stocks, flows, internal feedback loops, table functions and time delays (J. W. Forrester, 1994), and is applicable to many systems with social and physical components. While SD originally was applied to mainly technical and socio-technical systems, in recent decades, the usability of SD to simulate social-ecological systems is proven (Meadows et al., 1972; Martin & Schlüter, 2015; Elsawah et al., 2017; Uehara et al., 2021). This section describes how SD is used within this research.

Aside from list extension diagrams, system dynamics has other sub-methods for the analysis of social-ecological dynamics. Closely related to the list extension diagrams, causal loop diagrams, and the feedback analysis methods is the stock-flow model. The stock-flow model is another method for analyzing dynamics in complex systems and has been used in some well-known works to describe the variables and relations in the dynamics between society and the natural environment (J. W. Forrester, 1971; Meadows et al., 1972). stock-flow models consist of stock, flow and auxiliary variables. Stock variables are system variables which can accumulate. Flow variables represent rates, meaning they are measured over an interval of time. Auxiliary variables are neither a stock nor a flow themselves, but have an influence stocks and flows. Using stock-flow models can happen qualitative as well as quantitative (Wolstenholme, 1999).

This research study uses a qualitative stock-flow model, as a conceptual model, for combining the variables and relations of the literature review with the ones of the list extension diagrams, see figure 2.2. It facilitates a similar to analysis to causal loop diagrams, the feedback interactions are harder to identify as the variables are depicted as processes rather than causal influences (Wolstenholme, 1999). Combining the insights from the list extension diagrams and literature review, creates a stronger conceptual model of the social-ecological systems, and reduces subjectivity and uncertainty. Both a stock-flow model and list extension diagram are closely related causal loop diagrams and feedback analysis, and both consist of variables and relations for coral reef dynamics. The similarities in diagram characteristics make it possible to compare the dynamics. The conceptual stock-flow model gives a conceptual understanding of the main dynamic behaviors in social-ecological coral reef systems.

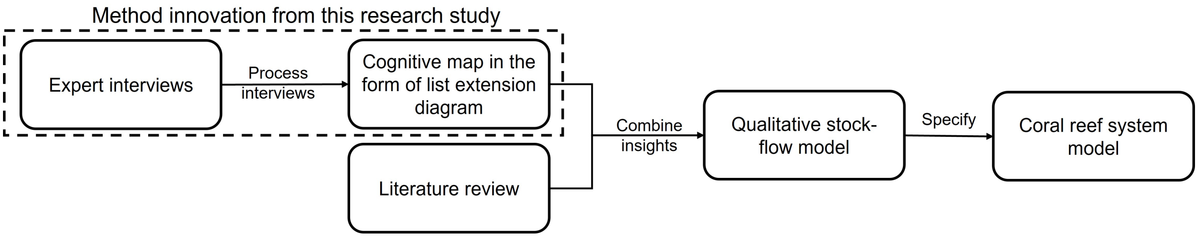


Figure 2.2: The expert interviews are processed through creating list extension diagrams from the cognitive maps of the interviewee's, which is a unique contribution of this research study. The list extension diagrams (appendix D) and the literature review are combined into the qualitative stock-flow diagram (appendix E). The qualitative stock-flow model is specified into the coral reef system model.

The reason for choosing a stock-flow model for combining insights from the literature review and list extension diagrams, is that literature on marine ecological systems often refers to abundances and rates. The process has a central position in ecological literature, instead of the causal relations. As a result, the stock-flow model is the more appropriate method for visually depicting the variables and relations than for instance a traditional causal loop diagram. Although stock-flow diagrams are harder to interpret than causal loop diagrams, the clear distinction between stocks and flows improves applicability and conceptual clarity for the case of coral reef ecosystems, which is beneficial for understanding and analyzing system behavior.

The combined qualitative stock-flow model is specified to a quantitative model. With the required data, the quantitative stock-flow model simulates the behavior of the social-ecological coral reef system over time. In this study, a quantitative stock flow model, the coral reef dynamics model, is specified from the conceptual qualitative stock-flow model, see chapter 5 for a description of the coral reef dynamics model. Furthermore, (large-scale) artificial reef intervention could be added to the model to compare the dynamic behavior pre- and post-intervention and gain key insights in patterns of behavior. The behavior comparison serves as the basis to identify potential long-term implications of the intervention on coastal flood protection and reef ecosystems, and thus answering the main research question.

2.5. Case study

2.5.1. Case study selection

For the research study, a case study is selected. System dynamics models can show the intricacies of system structure and behavior, but usually through the case-specific analyses, making the local context important when modelling. In this research study, the case study needs to have vulnerability to climate change, social-ecological relations between the coral reef and humans, potential for artificial reef intervention.

In figure 2.3 from Nicholls & Cazenave (2010), "the areas which are vulnerable to coastal flooding caused by future or climate-sea level rise. At highest risk are the coastal zones with dense populations, low elevations, appreciable rates of subsidence, and/or inadequate adaptive capacity." A case study in the pressured areas has potentially larger restorative impact compared to sites outside of the vulnerable areas. Most regions which are prone to coastal flooding are (sub)tropical areas surrounding the equator. Therefore, the chosen case study is in the (sub)tropical climate region.

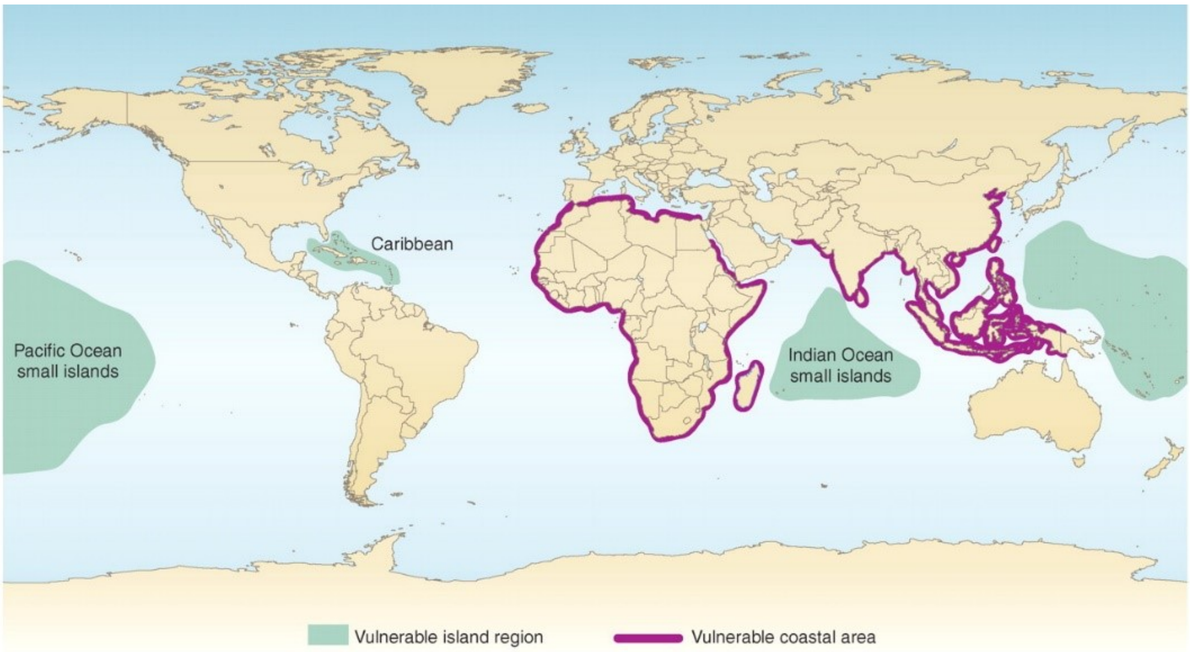


Figure 2.3: Vulnerability of coastal regions worldwide, adopted from Nicholls & Cazenave (2010)

Furthermore, the case study should include social-ecological relations. Many coral reefs are social-ecological systems and serve as ecosystem service. Section 3.3 describes the relations between coral reefs and humans. The most common social-ecological interactions are fishing, pollution, tourism. The case study needs to include the set or subset of social-ecological relations to be able to answer the research questions.

The intervention with (large-scale) artificial reefs should be considered carefully. Ecosystems, especially marine ecosystems, have a delicate balance, and artificial reefs cannot combat climate change effects. However, locally artificial reefs can have potential to replace the disappearing substrate. Furthermore, the artificial reefs can locally increase recruitment success. Combinations of disappearing substrate and decreased recruitment, often lead to coral coverage degradation. Therefore, the research study focusses on a case study with degraded coral coverage.

2.5.2. Study site

The study site, which complies with the criteria, is the marine area of Shimoni, Kenya and the small island in front of the coast, which are part of the territorial waters of Kenya, see figure 2.4. The area lies in the southern tip of the country. The area includes the Kisite-Mpunguti Marine protected area (KMMPA), as delineated by the Kenyan Wildlife Service (KWS), and adjacent islands and reefs, named Sii island, Wasini island, Masulini, Mwamba Mkuu, Mipwa, Mijira and Kichwa Mtu (Kenyan Wildlife Service, 2015). The area is roughly 200 km^2, being approximately 20 kilometers long and 10 kilometers wide. The area has a rich diversity of marine plants and animals some of which are threatened (Kenyan Wildlife Service, 2015).

Figure 2.4: The site of Shimoni, Kenya adapted from Center for Global Discovery and Conservation Science (2023)

As seen in section 2.5.1, The coastal area of Kenya is relatively vulnerable to the effects of climate change, such as sea-level rise. Although the whole of Kenya is vulnerable, the north and the southern tip are the most vulnerable for floods and droughts(Marigi, 2017). Making it possible for artificial reefs to potentially make a relatively large impact, by protecting the coast.

Furthermore, the area is home to some small local communities, which depend on the coral reefs as a source of income and food production. Income generation is done through tourism, such as snorkeling and diving, and the fishing activity in the area is an important source of food. Thus local livelihoods are highly dependent on these reefs. For these reasons, already some small-scale artificial reef research pilot projects have been implemented in the area: 'REEFolution' and 'Reefsystems' which are both based in Shimoni, Kenya (REEFolution foundation, n.d.; ReefSystems, n.d.). Both research projects have strong connections with the Netherlands through collaborations with the University of Wageningen and Boskalis.

3 Literature Study

3.1. Reefs: the underwater rainforest

Reefs are among the worlds' most biodiverse and productive ecosystems, often described as 'the rainforest of the ocean'. They serve as a spawning ground for many aquatic species, by providing essential food and shelter (Spalding et al., 2001, p.27). A large part of marine life are dependent on coral reefs at some point in their life-cycle. A reef is a ridge of material at or near the surface of the ocean, and can occur naturally (Spalding et al., 2001, p.15). Natural reefs are made of rocks or carbonate layers, and consist of biotic and abiotic processes. Biotic processes are connected to living organisms, such as marine animals and plants. Abiotic, on the other hand, involves non-living processes, for example, erosion and sedimentation. The processes balance to create the reefs. The most well-known and widely distributed type of reef is the coral reefs, However, also other types exist, including oyster reefs, muscle reefs and sponge reefs.

Coral reefs, as the name indicates, are dominated by corals. A coral is an invertebrate animal belonging to animalia kingdom in biological taxonomy. They are made up of large amounts of genetically identical polyps. A polyp is a sac-like animal of around a few millimeters in diameter and a few centimeters in height (Spalding et al., 2001, p.15). Together the polyps and a skeleton form the coral. Two types of corals exist: soft corals and hard corals. Soft corals are made up of fleshy mass and a wood-like core, often resembling plants. While hard corals have a hard calcareous skeleton, and resemble rocks more (Spalding et al., 2001, p.15, p.33), see figure 3.1. Both types live in colonies and are stationary during their adult life. Coral reproduction can happen via two methods: asexually and sexually (Spalding et al., 2001, p.33). Asexual reproduction happens when a piece of coral breaks, for example during a storm. The broken coral fragment can regrow into a genetically identical coral clone. In sexual reproduction, corals produce eggs and sperms (gametes) and excrete them in the water. The gametes combine to form coral larvae (planulae), which disperse via currents to form new colonies. Spawning follows a full moon and water temperatures must have risen enough to stimulate the maturation of the egg and sperm bundles (Spalding et al., 2001, p.49). The timing of spawning is also impacted by the length of the day, the tide and salinity levels in the water (Spalding et al., 2001, p.23). Spawning only happens at night and lasts from a few days up to a week. The focus lies on the hard coral type, as the calcareous structure is more vulnerable to climate change effects.

Figure 3.1: The exterior difference between a soft coral (left) and a hard coral

The coral colonies slowly become reefs over long time periods, due to the slow reproduction process. There are three main types of coral reefs: fringing reefs, barrier reefs, and atolls(Spalding et al., 2001, p.17), see figure 3.2. Fringing reefs are the most straight-forward reeftype. The corals lie close to the shore on a shallow plateau with crest dropping steeply to the seafloor. Barrier reefs are usually older structures, where a deeper water channel has formed between the land mass and the shallow coral reef. An atoll are usually formed from volcanic islands, which subside over geological time periods. The reef that was formed around the volcanic island remains, creating a shallow ring with a lagoon in the middle. The worldwide coral reef distribution is mostly surrounding the (sub)tropical regions, between the tropic of Capricorn and the tropic of Cancer (Spalding et al., 2001, p.18). As many coral species rely on the sunlight to grow. Symbiotic microalgae, called zooxanthellae, perform photosynthesis inside the skin of corals, providing it with necessary oxygen and carbohydrates to grow (Spalding et al., 2001, p.31). Cold water corals exist, but they are less wide-spread and less vulnerable to the effects of climate change, such as sea-level rise and average temperature rise (Nicholls & Cazenave, 2010). For this reason, the focal point of the research will be hard coral in (sub)tropical regions.

Figure 3.2: There are three types of coral reefs: fringing reef (left), barrier reef (middle), and atoll.

3.2. Changing climate

Anthropogenic climate change has a severe impact on (sub)tropical hard coral reefs, through average water temperature increase, oceanic CO2 absorption, and sea level rise (Hughes et al., 2003; Mumby & Steneck, 2008; Rockström et al., 2009; Hughes et al., 2013; Harborne et al., 2017; Hughes et al., 2017, 2018). These are referred to as global stressors, because of their globally straining effect on coral reef health. Like many species, corals have adapted to the existing environmental conditions, as Darwin observed in 'The Structure and Distribution of Coral reefs' in 1842 (Darwin, 1842). The corals with the most beneficial genetics for the environmental conditions are the ones that survived. However, in recent years, the change in environmental conditions is changing in such rapid pace, that corals are unable to adapt (Webb et al., 2023).

Global warming raises atmospheric temperatures, and likely will continue to do so for the coming decades. Current scenarios place the temperature increase in 2100 between 1 and 2 degrees Celsius relative to 1850-1900, with the threshold of 1.5 °C, agreed upon in the Paris agreement, being surpassed for multiple decades (Pörtner et al., 2022). Average global temperature increase is not a good indicator for local tropical coral reef health (Hughes et al., 2017). However, the effects are felt, heterogeneously, throughout the globe (Hoegh-Guldberg et al., 2007). Sub(tropical) coral reefs have a temperature resistance, based on the species and the individual genetics, which is highly region dependent (Hughes et al., 2018). Similar for all regions is that transgressing the temperature, which corals typically can withstand, slows the growth and can cause mortality through coral bleaching (Spalding et al., 2001, p.59). Coral bleaching is a biological phenomenon in which corals expel their microalgae, the zooxanthellae. The zooxanthellae, as mentioned earlier produce oxygen and carbohydrates for the coral to grow. With corals disconnected from the zooxanthellae, their food consumption becomes very limited, if the high temperatures persist for too long the corals starve to death. The duration of this period is, depends on the region, the species, the individual (Brown et al., 2019). Thus, it is not the average oceanic water temperatures that directly impact individual coral colonies. Instead, intensity and duration of extreme temperature events, rapidly increased by global warming and climate change affects coral reefs (Claar et al., 2018; Spalding et al., 2001), limits corals ability to adapt to the rise in extreme temperature events (Webb et al., 2023).

Secondly, anthropogenic climate change is driving decreasing pH levels in oceans by emitting high quantities of carbon dioxide into the atmosphere (Hoegh-Guldberg et al., 2007; Anthony et al., 2011; Diaz-Pulido et al., 2012; Smith et al., 2016). Around 25% of the emitted carbon dioxide is dissolved in the oceans (Hoegh-Guldberg et al., 2007). Through a balance reaction, carbon dioxide and water turn into carbonic acid, see reaction 3.1 (Hoegh-Guldberg et al., 2007, p.1738). As the concentration of carbon dioxide increases, so does the concentration of carbonic acid in the ocean. Carbonic acid releases a proton, which can react with carbonate in the water, see reaction 3.2 (Hoegh-Guldberg et al., 2007, p.1738). Corals are calcareous animals. Their skeletons are made from calcium carbonate, which they extract from the ocean water (Spalding et al., 2001, p.15). However, the carbon dioxide is tipping the balance in the equations such that the calcium carbonate in the water reacts to individual carbonate and calcium molecules (reaction 3.3) (Hoegh-Guldberg et al., 2007, p.1738). The decrease of calcium carbonate abundance in the water slows the growth rate of the calcareous species, such as hard corals. As the pH decreases the growth slows more and more. The effect varies per location, species and individual Anthony et al. (2011). The threshold level for major changes to coral communities indicates 480 ppm of atmospheric carbon dioxide (Hoegh-Guldberg et al., 2007). Coral communities could shift from non-carbonate reef communities. From 2007 to 2021, the atmospheric carbon dioxide level rose from 380 ppm (Hoegh-Guldberg et al., 2007) to 410 ppm (Masson-Delmotte et al., 2021, p.4). Current projections are indicating with high certainty that the atmospheric carbon dioxide levels will surpass the 480 ppm threshold in the coming decade (Masson-Delmotte et al., 2021).

$$CO_2 + H_2O \rightleftharpoons HCO_3{}^- + H^+ \tag{3.1}$$

$$CO_3{}^{2-} + H^+ \rightleftharpoons HCO_3{}^- \tag{3.2}$$

$$CaCO_3 \rightleftharpoons CO_3{}^{2-} + Ca^{2+} \tag{3.3}$$

Thirdly, sea level rise is effectively drowning coral reefs in some cases. Thermal expansion and melting of ice caps, as a result of the global warming, are increasing the water volume the water is occupying. The increased water volume makes the average water levels rise all around the world (Cazenave & Llovel, 2010). At the coast the water will run higher up the beach, and the reef water depth will relatively increase to the coast. Today the sea level is 13-20 centimeters higher than it was relative to 1900 (Masson-Delmotte et al., 2021). Coral reef can submerge if their growth capacity to keep up with sea level rise is insufficient (Perry et al., 2012, 2015, 2018). Coral reefs can grow vertically through cementation and lithification processes, if the net carbonate budget is positive the accretion processes outweigh the erosion processes in the reef. The net carbonate budget is a good indicator for a reefs capacity to grow with sea level rise, combatting the negative effects of sea level rise on coral reefs, such as larger wave exposure and reef submergence (Perry et al., 2018). Reef submergence affects the growth potential of corals as the light intensity decreases with the depth. However, there are also some indications that sea level rise has positive effects on coral communities. The increased water depth can decrease the harmful effect of thermally induced bleaching, as the water temperature decreases with the water depth (Perry et al., 2015; Brown et al., 2019). Furthermore, until recently, the maximum depth at which coral reefs could exist, due to a limited light intensity, was thought to be 60-70 meters, but in 2023 scientists discovered a thriving reef near the Galapagos Islands at a depth of 600 meters. The discovery gives hope for coral reefs to be able to withstand possible negative effects of sea level rise in the long term (Guardian, 2023).

3.3. Anthropogenic footprint on reefs

Until now only ecological climate change drivers have been discussed, but coral reef ecosystems are not isolated systems. Anthropogenic impact extends the effects of climate change. Although, ocean acidification and sea level rise have the potential to have discerning effects on the long term, the most pressing challenges for coral reef biodiversity are global warming, overfishing, and pollution (Hughes et al., 2003; Graham et al., 2013; Harborne et al., 2017; Hughes et al., 2017). Overfishing, pollution, tourism are local drivers of change in coral reef ecosystems (Ban et al., 2014). All over the world, humans rely on services provided by coral reefs. They provide services such as food generation, income generation, coastal flood protection, and recreation (Belhassen et al., 2017; Woodhead et al., 2019; Webb et al., 2023; Carlot et al., 2023). The many and varied beneficial services to humans provided by the natural environment and healthy ecosystems are called ecosystem services (Woodhead et al., 2019). However, the extraction of resources and use of the ecosystem services coral reefs provide are harmful to the reefs' sustenance (Rogers et al., 2015).

The overuse of coral reefs lies in them being a common pool resource. The term common pool resources comes from economic goods theory. Common pool resources are goods that are high in substractability, implying one individual's use of the resource reduces the level of the resource available for other users, i.e. one fish cannot be consumed twice. Secondly common pool resources are goods that have high difficulty of exclusion, e.g. reefs protect coastlines from storms (Ostrom, 1990). All inhabitants living near the coastline benefit, and it is impossible to include some and exclude others. For a long time coral reefs have functioned as common pool resources, but uncontrolled depletion of common pool resources induces the 'tragedy of the commons' (Hardin, 1968; Ostrom, 1999). It entails the phenomenon in which common pool resources, to which access is not regulated by formal rules or fees/taxes levied based on individual use, tend to become depleted. If users of such resources act to maximize their self-interest and do not coordinate with others to maximize the overall common good, exhaustion and even permanent destruction of the resource may result, if the number of the users and the amount they demand exceeds what is available. Reef degradation, caused by overfishing and pollution, is a prime example of this phenomenon. Hence, reefs are not merely ecological systems, but social-ecological systems (Ostrom, 2009; Cinner, Pratchett, et al., 2016; Gurney et al., 2019; Barnes et al., 2019). Social-ecological systems (SES) are a concept for understanding the intertwined nature of human and natural systems in this new, interconnected and interdependent way (Biggs et al., 2021)."In a complex SES, subsystems such as a resource system, resource units, users, and governance systems are relatively separable but interact to produce outcomes at the SES level, which in turn feed back to affect these subsystems and their components, as well other larger or smaller SESs" (Ostrom, 2009). As a result of the interconnectedness, studying social-ecological systems benefit from strong delineation of system variables and a strong conceptual understanding.

Humans and reefs are interconnected in various ways. The most prominent ways they interact is through fishing activity, pollution and touristic activities. To understand the effects of local anthropogenic interactions, the balance residing within reefs needs to be understood first. Coral reefs rely on a delicate trophic balance, biodiversity is high and every species has a function in the reef. A very important dynamic within reefs is the interspecific competition between corals and macroalgae (e.g. kelp, turf) (Dell et al., 2016; Johns et al., 2018). Corals and macro algae compete for surface area within the reef. Macroalgae are a fast growing small organism, which is benefitted by high nutrient warm systems

(Zaneveld et al., 2016). They have a short reproduction time. Corals, on the other hand, have slow reproduction cycles and are benefitted by low nutrient systems (low in phosphorus, nitrogen and iron) and have a long life expectancy (Spalding et al., 2001). This difference is described by the theory of r/K selective species. The r/K selection theory relates to the selection of combinations of traits in an organism that trade-off between quantity and quality of offspring. The focus on either an increased quantity of offspring at the expense of individual parental investment of r-strategists, or on a reduced quantity of offspring with a corresponding increased parental investment of K-strategists, varies widely, seemingly to promote success in particular environments (Pianka, 1970). The letters r and K are derived from the formula on population dynamics, in which r represents the growth rate and K the carrying capacity of the system, see also equation 4.1. Corals are K selective species, while macroalgae are r selective species. Without intervention macroalgae would likely dominate reefs. However, due to a symbiotic relationship between corals and herbivorous fish, corals are able to successfully grow and reproduce. Macroalgae are preyed upon by herbivorous fish, restraining macroalgal population growth, and clearing surface area for corals to grow (Hoey & Bellwood, 2011). Corals provide a service to the herbivorous fish by providing a structural complexity. Structural complexity creates shelter from predators and spawning grounds for fish (Graham et al., 2013). Corals are also preyed upon themselves, by bioeroding organism, such as parrotfish, sea urchins, seaturtles and starfish (Mumby et al., 2006; Perry et al., 2012). The bioeroding organisms and herbivorous fish are preyed upon by their own predators to create a trophic food web in coral reefs, figure 3.3 shows an exemplary conceptual food web (Rogers et al., 2015). The trophic balance between predators and prey refrain reefs from turning to monoculture, which would interfere with their function as habitat and spawning ground for a large variety of species.

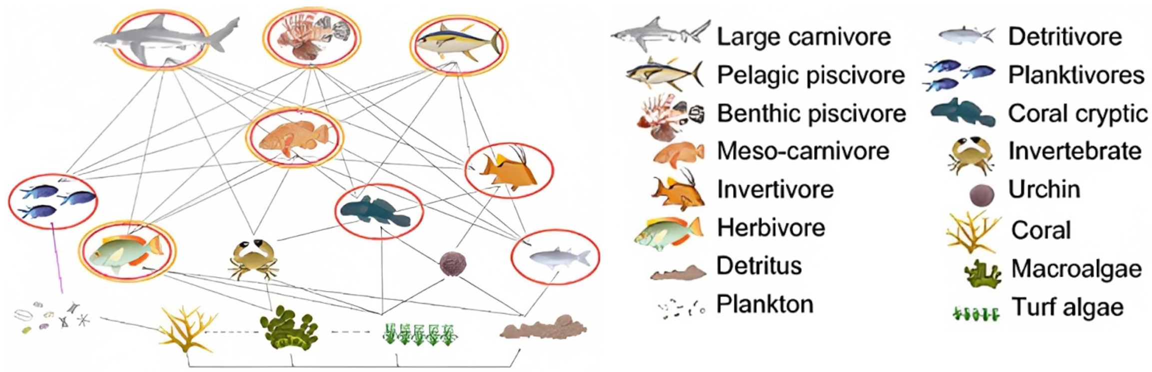


Figure 3.3: An conceptual trophic food web example in a coral reef, adopted from Rogers et al. (2015)

In recent years, anthropogenic actions have disrupted coral reefs and shifted the balance within reefs from coral dominated systems to algal dominated systems (Hughes et al. 2017, p.86; Van De Leemput et al. 2016, p.858). An impactful interaction between reefs and humans is overfishing (Mumby et al., 2006; Zaneveld et al., 2016). Fishing has two ways of impacting reefs: direct and indirect impact. The direct impact of fisheries is the physical damage to corals. Dragging nets and dynamite fishing harms reefs by breaking down coral assemblages (Barnes et al., 2019). On a large scale this can have a severe impact. An indirect effect of fishing is the removing of keystone species from the trophic pyramid (Mumby et al., 2006). By removing a keystone species, trophic cascading can occur. Removing predators releases lower trophic levels of predation, and enormous boom and busts of trophic levels can occur within an ecosystem. Fisheries often start with the largest species, meaning the large predators and large herbivorous fish, until the population is depleted severely. At that moment, another phenomenon kicks in, called 'fishing down the food web' (Pauly & Watson, 2009). The phenomenon is the process whereby fisheries in a given ecosystem, "having depleted the large predatory fish on top of the food web, turn to increasingly smaller species, finally ending up with previously spurned small fish and invertebrates" (Pauly & Watson, 2009). As a result, the food web becomes less diverse and monocultures can occur.

A monoculture type which is gaining prominence around the world, is an macroalgal dominated system. With herbivorous being depleted, macroalgae have more growth opportunity, and an ecosystem phase shift can occur from coral dominated systems to algal dominated systems (Hoey & Bellwood, 2011).

Another anthropogenic interaction is the pollution coastal areas. Many types of pollution can be thought of, but in this research the focus lies mostly on nutrient pollution. Nutrient pollution is the disposal of nutrients into coastal waters (Zaneveld et al., 2016). The most common form of nutrient pollution is waste disposal and open sewage. Sewage water is rich in nitrogen and phosphorus. Macroalgae are benefitted by the increased nutrients in the water and the growth rate rises. Furthermore, septic sewage can decrease the pH of coastal waters, which affects coral growth rates as well. With nutrient pollution the conditions are favoring macroalgal growth (Hughes et al., 2017, p.86). This could have severe consequences and could spark large phase shifts when combined with fishing.

A final impactful interaction between humans and reefs is tourism. Tourism also can have a variety of different effects. Boating, pollution physical damage, oceanic jewelry, and coastal construction can decrease coral coverage and increase algal coverage (Olale et al., 2020). Tourist to increase their satisfaction like to visit the places with the highest coral cover and widest variety in biodiversity. Although tourism is considered a low to moderate stressor (Piggott-McKellar & McNamara, 2017), often the visitations are at the detriment of local coral cover (Lin et al., 2023). On the other hand, tourism generates income for local inhabitants and governmental organizations, which could be put to use for restoration purposes (Obura et al., 2021). Some places are already restricting the access to some areas in light of environmental protection (T. P. McClanahan et al., 1999), but with coral reefs still also the environmental protection from tourism needs to be reviewed.

The short-term depletion of the resources that coral reefs provide, puts humans at long-term risk with their own actions. Short term depletion of fishing stock threatens species with existing, and therefore threatens the food stock of millions of people and animals around the world. Furthermore, many places rely on reefs, as a form of coastal protection during storms, especially island states (Beck et al., 2018). With coral coverage eroding, the wave energy dissipating functionality erodes as well (Carlot et al., 2023). Reef restoration and sustainable reef use provides enormous long-term benefits, and is imperative to prevent coral-to-macroalgae phase shifts, because reversing phase shifts, when they have occurred, is more difficult than preventing phase shift by staying below threshold levels (Hughes et al., 2017, p.86).

3.4. Prevention is better than cure

Guiding coral reefs through a period of increasing world population and globalization, will be the key for coral reefs to sustain throughout the 21st century. Local and global anthropogenic stressors are creating reef conditions in which corals are unable to dominate. As a result, marine species will become less abundant and diverse. Restoration efforts need to be combined with broader management of anthropogenic drivers for the decline to halt. Influencing the drivers can be done by changing social norms, fostering innovative partnerships, building institutions for governance, and redefinition of management goals (Hughes et al., 2017).

One particularly interesting method for restoration of reefs is the use of artificial reefs. Artificial reefs are man-made structures placed underwater to mimic the substrate of natural reefs (Pickering et al., 1999; Belhassen et al., 2017; Layman & Allgeier, 2020). Corals need structural complexity such as rock to attach to and to grow, but once areas erode completely, a sandy beach remains. Therefore, re-introduction of structural complexity is necessary. Artificial reefs can be used to re-introduce the needed complexity and enable corals be reinstated in the area. Artificial reefs can be constructed in different shapes, sizes and materials, as researched by Hylkema et al. (2021), who lists various artificial reef structures and their popularity in research projects. However, this research study will not focus on one specific artificial reef structure, because earlier research has indicated that the preferred structure is dependent on local context (Higgins, 2022; Komyakova et al., 2019). Instead, the introduction of restoration efforts needs to be combined with tackling the drivers behind local stressors, such as fisheries, pollution and tourism. In line with Hughes et al. (2017)'s argument, this research study focusses on understanding the system by developing a system model.

"In reality, however, the world is not so simple. Both the science and governance of coral reefs are in great need of stronger conceptual and methodological frameworks for understanding and managing multiple drivers and their combined impact". The development of heuristic models shows promise in understanding the role of multiple drivers and feedbacks in environmental change. For instance, by simultaneously modeling multiple drivers, the combined effects become more apparent (Hughes et al., 2017). This leads to transitions from a coral-dominant state to alternative states where both coral and non-coral states can occur. Ultimately, the conditions reach a point where only a macroalgal dominant state is possible. The model identifies a generic "safe operating space" for coral reefs, as defined by Rockström et al. (2009), where corals remain dominant as long as multiple drivers are kept below threshold levels that arise from their combined effects. This finding is particularly relevant to the emergence of new drivers that impact ecosystems and add to the impact of pre-existing stressors, which are likely to become more severe over time (Hughes et al., 2017). The model could then serve as a platform for seeing how restoration efforts stretch the threshold levels and their impact over longer time periods.

Research into the physical boundaries of the ecosystems can aid management decision-making by improving insight into the complex dynamics in social-ecological systems. Especially for ecosystems, like coral reefs, which are approaching their physical boundaries, insight in boundaries can have huge potential for prevention and restoration (Rockström et al., 2009). By changing human actions, ecosystems can be steered away from boundary transgression and return to the safe operating space (Steffen et al., 2015). Therefore, this research study takes a physical boundary perspective in examining coral reef dynamics, hopefully contributing to human actions taking the the limits of (coral reef) ecosystems into consideration in the Anthropocene.

4 Conceptual models

4.1. Synthesis conceptual list extension diagrams

From the respondent interviews, six conceptual list extension diagrams are created based on their mental map of a social-ecological coral reef system, see appendix D. In this section, the similarities and differences between the diagrams are discussed.

In the model list of the list extension diagram, the model variables are introduced. Coral coverage and coastal flood protection are most mentioned in this list. Coral coverage appears to be a good indicator for coral reef health. Respondents mostly refer to hard coral coverage in this case. Hard coral coverage also relates to the coastal flood protection. Corals are natural wave breakers and dissipate wave energy. Furthermore, some respondents mention livelihood pressure as a driver of reef unbalancing This can be explained by positioning the coral reef as a ecosystem service. The interaction of ecosystem service environments with humans makes it both a driver and model variable, for example fisheries improve the local livelihood, making it a model variable, but currently livelihood pressure pushes local inhabitants to overfish, depleting the valuable resource, making it also a driver. In this interaction lurks a limits to growth feedback, where livelihood pressure is both a driver and model variable.

The hard coral coverage is extended, in the list extension diagram's first extension, by coral death, coral growth, and coral spawning. Especially, growth and death are impacted by many factors. Starting with the growth, coral coverage is impacted, according to many respondents, by the solar intensity and the water depth. Zooxanthellae in the corals perform photosynthesis for which they need light. Lower solar intensity decreases the zooxanthellae's ability to do so. As a result, the coral lacks energy in the form of carbohydrates. Growth slows down with the energy levels in the coral. The solar intensity also depends on the water depth. Increasing water depth reduces the solar intensity. One way the water depth increases at the moment is sea level rise. Sea level rise could play a factor in decreased growth rates of coral reefs. Lastly, the ocean acidity plays a role in decreasing growth. As participants mentioned carbonate dissolves if the water's acidity increases, and as corals have calcium carbonate skeletons, the accretion of the carbonate slows down.

Coral death, on the other hand, is impacted by overfishing, tourism, macroalgae, nutrient pollution, bleaching, storms, disease, and coral predation. Overfishing and tourism have a direct relation to coral death. Fishing, depending on the type of fishing gear used (rod, net, dynamite) can cause physical damage. Similarly, tourism degrades coral coverage by snorkeling, diving, and boating damage. Although respondents mentioned that through regulation the physical damage to reef can be confined, illegal fishing activity still exists in many places. Illegal activity happens mostly due to the local livelihood pressure. An indirect effect of the fishing is the keystone species removal from the food chain. Respondents mentioned that the removal of, especially, herbivorous fish increases macroalgal cover. Macroalgae compete with corals for available surface area and can overgrow corals, essentially starving them by light deprivation. A feedback interaction is lower coral cover also decreases herbivorous fish abundance, as the fish use coral's structural complexity as shelter and spawning ground. Secondly, macroalgae increase pathogenic micro-organisms, spreading coral diseases. Combined with increased macroalgal growth from nutrient pollution, reefs can be overgrown with algae. Furthermore, climate change induced temperature spikes were mentioned as a major worldwide factor of coral death. Water temperatures rising above in the temperature resilience of a coral species, cause zooxanthellae to leave the coral starving them and removing their color and the corals white skeleton becomes visible, hence the name bleaching. Corals are very low in energy levels at that point and become highly vulnerable. Bleaching in combination with tropical storms can be detrimental to reefs. Entire reefs can be swept away if the these phenomena coincide. The reef's regeneration is very slow, and will not be able to grow back up to the same level, because bleaching events are increasing in severity and frequency. Lastly, corals are also part of the reef's food web. Bioeroding and boring organisms, like starfish, parrotfish, and sea urchins, predate on coral. Coral dominated reefs are made from carbonate layers. It balances between carbonate production processes, such as hard coral growth, and carbonate erosion processes. The bioeroding and boring organisms erode coral assemblages. This is not problematic, if net the carbonate accretion is higher than the erosion. However, removal of keystone predators can create mono-cultures of eroders. If the conditions sustain a reef can be eroded in a few years.

4.2. Qualitative stock-flow model description

From the literature and the list extension diagrams, a qualitative stock-flow model is made, see appendix E. In the stock-flow model the ecological dynamics are combined with social dynamics, such as fisheries, pollution and tourism.

The main ecological feedback occurs in the dynamic between green algae, corals and coralline crustose algae, and herbivorous fish. Green algae (or macroalgae) are a r-selected species and are in conflict with corals and coralline, which are K-selected species, as explained in section 3.3. The corals and coralline algae are in interspecific competition with the green algae (or macroalgae) for land area. Green algae can grow on top and around corals and coralline, causing shading, abrasion and allelopathy, all of which are affecting the coral's ability to grow (Van De Leemput et al., 2016). An important distinction is corals are density dependent on both green algae and other corals, while green algae are only bound to density dependence by other green algae, due to their ability to overgrow coral substrate. In combination with their short reproductive cycle, a system can quickly become dominated by green algae, if it is not for the symbiotic relationship between herbivorous fish and corals/coralline algae. Green algae serve as a food source for herbivorous fish, reducing the growth limiting effects of green algae and corals. In turn corals and coralline algae provide shelter in the form of structural complexity, for example for fish to rest or reproduce (Van De Leemput et al., 2016). The structural complexity of corals and coralline practically means that reefs have many nooks and crannies for small herbivorous fish. The green algae are most appetizing to herbivorous fish during the early stages of their life. The palatibility decreases as green algae mature (Van De Leemput et al., 2016).

Green algae, corals and coralline algae are affected by the effects of climate change. The water temperature warming, ocean acidification and sea level rise are mostly favoring the green algae over the corals and coralline. If the water temperature rises above a certain locus-varying temperature threshold, coral and coralline calcification rates drop (Hoegh-Guldberg et al., 2007; Diaz-Pulido et al., 2012). Corals and coralline are made from calcium carbonate, also called the carbonate framework (Perry & Alvarez-Filip, 2018). Therefore, lower calcification rates mean lower growth rates. Furthermore, when corals are under temperature stress for increased periods of time, the mortality increases. Green algae on the other hand, as a r-selected species, are more resistant against temperature increases (Zaneveld et al., 2016), and due to their short reproductive cycle the natural selection of algae with higher temperature resistance are prevailing. Secondly, ocean acidification, the process of carbon dioxide being absorbed by oceanic waters, decreases the pH of the ocean. Similar to ocean warming, lowering pH decreases the calcification rate, and increases growth rates for green algae (Hoegh-Guldberg et al., 2007). Lastly, the sea level rise will increase the water depth. The symbiotic micro-algae, called zooxanthellae, perform photosynthesis inside corals (Perry et al., 2018). Corals use the energy from the photosynthesis to grow. With the sea level rise increasing, lower volumes of sunlight reach the corals, decreasing growth rates in corals (Perry et al., 2018). The short reproductive cycle of green algae, on the other hand, makes them more adaptable to sea level rise, because it gives them the ability to transport to near shore more quickly.

Aside from green algae, there are more processes, affecting coral reef expansion. A reef consists of carbonate framework production processes and carbonate framework erosion and removal processes (Perry & Alvarez-Filip, 2018). The balance between these processes is called the 'carbonate budget'. A net positive carbonate budget means the reef is expanding, as well horizontally as vertically. Vertically increasing the carbonate framework is a way for reefs to combat sea level rise (Perry et al., 2018). The production processes consist of primary framework production (coral growth), secondary framework production (coralline growth), and cementation and lithification. The erosion and removal processes consist of substrate grazing (bioeroding organisms, such as parrotfish and sea urchins), endolithic boring (sponges, bivalves, worms, cyanobacteria), physical erosion (storms, hurricanes), chemical dissolution (Perry et al., 2012; Perry & Alvarez-Filip, 2018; Seds Online & Perry, 2022). Similar to the herbivorous fish, the bioeroding and boring organism abundance is kept under control by a population of predators. In general, the carbonate budget is good proxy for assessing coastal flood protection, because if the reef is able to grow with the sea level rise, its wave energy dissipating characteristics stay intact and lowering risk of flooding (Perry & Alvarez-Filip, 2018). However, storms and hurricanes are not taken into account in this conceptual model, as they will be considered as a external sudden disruption of the coral reef system.

Apart from the physical erosion from storms and hurricanes, also anthropogenic activity can cause damage to coral reefs. Physical damage can occur when tourist are snorkeling or diving in the reef, and accidentally damage it. One individual tourist is not problematic. However, a continuous flow of tourism activity can have a significant damaging effect over time (Piggott-McKellar & McNamara, 2017; Drius et al., 2019; Lin et al., 2023). Tourism is not the only societal activity affecting coral reefs. Pollution and overfishing exacerbate degrading climate change effects on corals. Coral reefs are, notoriously, low nutrient systems. Pollution, for example in the form of open sewage systems, increase the nutrients in the system, creating a high nutrient system and increasing the acidity. All of which tip the scales in favor of green algae abundance. Overfishing, on the other hand, decreases the herbivorous fish and predator abundance. As a result, a monoculture of boring or bioeroding species can occur, and a secondary affect is that green algae consumption decreases. A combination of pollution and overfishing can change a coral reef from a coral dominated system to an algae dominated system (Zaneveld et al., 2016; Van De Leemput et al., 2016).

4.3. Link between the structure and behavior

In the conceptual diagrams from the literature study and the interviews, a few structures in social-ecological coral reef systems came forward as being determinative for the system behavior. A main interaction is the competition between macroalgae and hard coral cover. These organisms are competing for reef surface area. The populations follow a logistic function, see equation 4.1.

$$\frac{dN}{dt} = rN(\frac{K-N}{K}) \tag{4.1}$$

In equation 4.1, the population over time (*dN/dt*) is described by the growth rate *r*. The growth rate of the population is the difference between the births and the deaths. The change of the population is also dependent on the current population and the carrying capacity of the system. For example, in the case of coral, they can only occupy the available reef surface area, which is a limited variable. Therefore, population growth slows down when more space is occupied. The carrying capacity (*K*) is taken into account through the fraction of the available surface area (*(K-N/K)*). If the occupied surface area approaches the carrying capacity, then growth slows down. Vice versa, when the occupied surface area is low, growth becomes high. The logistic function is depicted in figure 4.1 (left).

For a single population without a positive growth rate, the population reaches the carrying capacity over time. However, with competing populations, such as corals and macroalgae, the populations balance out over time. A population with a high growth rate, might become dominant as it can quickly take up all the surface area, which is then no longer available for the other population. The density of species

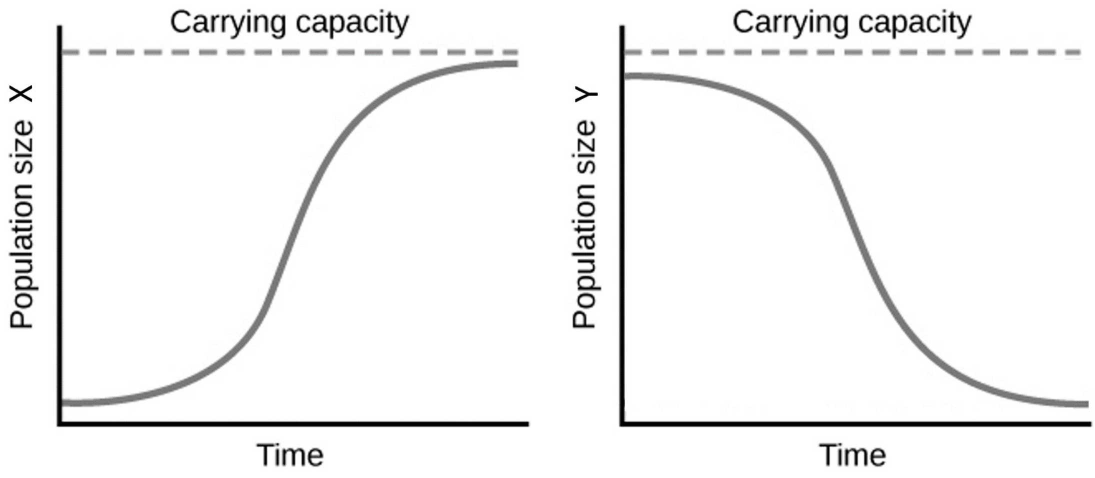


Figure 4.1: Ecological populations often follow a logistic function until the system carrying capacity. Competing populations (x and y) balance out over time depending on environmental conditions.

does not allow for increased growth. In the case of corals and macroalgae, the growth rates depend on the environmental conditions. As mentioned in chapter 3, the temperature and pH of the water influence, growth rates. Furthermore, nutrient pollution can inflate macroalgal growth rates. Apart from the density dependence, macroalgae and corals also compete through extrusion, overgrowing, shading, and allelopathy. The interspecific competition for the surface area, can be described by the competitive Lotka-Volterra equations, which are equation 4.2 and 4.3. The equations are similar to the logistic equation, however, the numerator is now extended by the effect of an individual of one species has on the population growth of the other species, e.g. α is the effect an individual from species Y has on the population growth of species X, and the opposite is true for β in equation 4.3.

$$\frac{dN_x}{dt} = rN_x(\frac{K_x - N_x - \alpha N_y}{K_x}) \tag{4.2}$$

$$\frac{dN_y}{dt} = rN_y(\frac{K_y - N_y - \beta N_x}{K_y}) \tag{4.3}$$

In figure 4.2 are typical interspecific competitive Lotka-Volterra functions shown graphically as the isoclines of two species plotted as function of the population of species X and Y. By setting the one or the other population size to 0 the isocline can be found. The isoclines show the population size of itself and of the competitor. The competitive exclusion principle, also known as Gause's law, is a proposition that two species which compete for the same limited resource cannot coexist at constant population values. When one species has even the slightest advantage over another, the one with the advantage will dominate in the long term (Hardin, 1960). The domination of one of two species can be seen happening in figure 4.2. The populations move either towards a dominant state of one or the other up until the carrying capacity for that species is reached, with exception of the stable point where the isoclines cross.

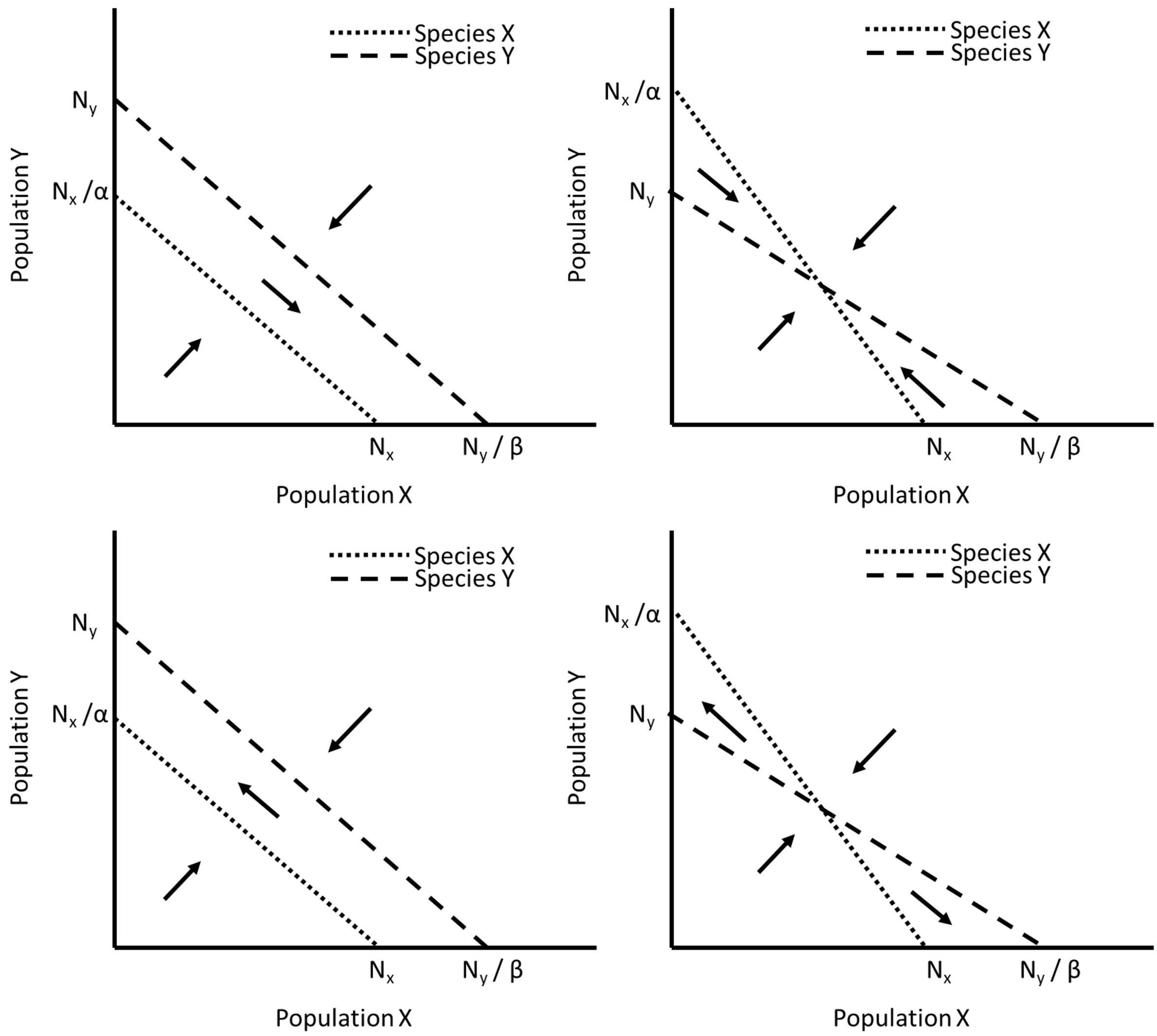


Figure 4.2: The Lotka-Volterra equations for interspecific competition can be turned into isoclines. The populations either move to a state where one of the two species is eradicated or a balance point where the isoclines cross (adapted from Taylor & Crizer (2005)).

Populations can also overshoot carrying capacity, see figure 4.3. This happens typically when growth rates are very high in discrete modelling. The population will increase very rapidly, such that the carrying capacity is overshot. After the overshot the population collapses until beneath the carrying capacity. Eventually it balances out around the carrying capacity, which is called a stable 2-cycle. Stable 2-cycles are not only observed in modelling, but can also be found in nature. Sinervo et al. (2000) from the University of California found a stable 2-cycle in lizards populations.

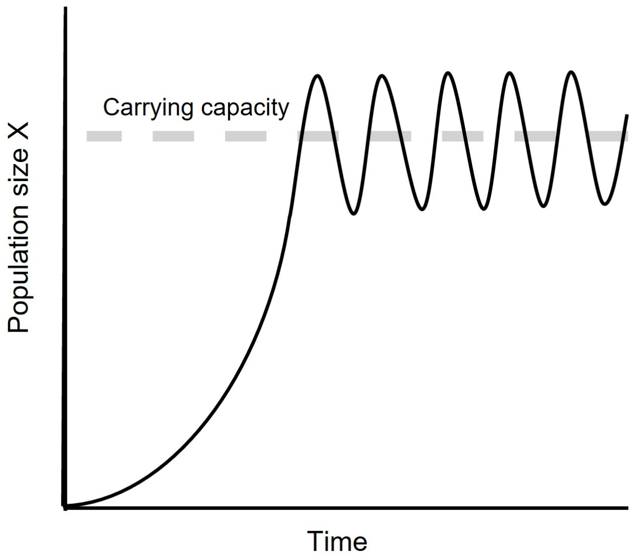


Figure 4.3: With high growth rates the population size can overshoot and collapses, after a while the population stabilizes in this pattern around the carrying capacity, a phenomenon called stable 2-cycle (inspired by Sinervo et al. (2000)).

Macroalgae, in general, have a higher reproduction rate than corals, as macroalgae are r-selective species and corals are K-selective species, see section 3.3. Through this logic most reefs should be algal dominated. However, another important dynamic is restrains the macroalgal population. The literature and the interviews indicated that macroalgae growth is suppressed by herbivores. Herbivorous fish consume algae in the reef and from the corals, leaving surface area for corals to grow. Macroalgae can overgrow corals, and shading and abrasion can cause the coral growth rate to decline. The structure between the herbivorous fish and macroalgae is a predator-prey dynamic, also called predator-prey Lotka-Volterra equations (Perkins et al., 2022). This is a second type of Lotka-Volterra functions. The populations change over time according to the following equations:

$$\frac{dx}{dt} = \gamma x - \delta xy \tag{4.4}$$

$$\frac{dy}{dt} = \epsilon xy - \zeta y \tag{4.5}$$

The prey population over time, equation 4.4, can be described by the population density (x), and predator population density (y). The prey's parameters, γ and δ, describe, respectively, the prey per capita growth rate, and the rate at which predators consume prey. In the predator equation (4.5), the predator's parameters, ε, ζ, respectively describe the predator's per capita death rate, and the rate at which predators increase by consuming prey. Depending on the height of the rates, the behavior of the predator and prey population differs. Figure 4.4 shows an example of predator-prey populations over time (left). On the right a phase diagram is shown, which plots the population of the prey and the predator. The phase diagram shows the equilibrium points of the populations. Characteristic for predator-prey behavior is the boom-and-bust behavior of the populations over time. High predator populations increase the predation rate, lowering the prey population. Critically decreasing the prey population, increases the predator death rate. The pattern replicates over time, if the phase diagram is a closed loop equilibrium. The macroalgae and herbivorous fish populations are likely to combine the logistic behavior and the predator-prey behavior, resulting in a fluctuating logistic function. Coral is not likely to fluctuate as much, and will follow the logistic function.

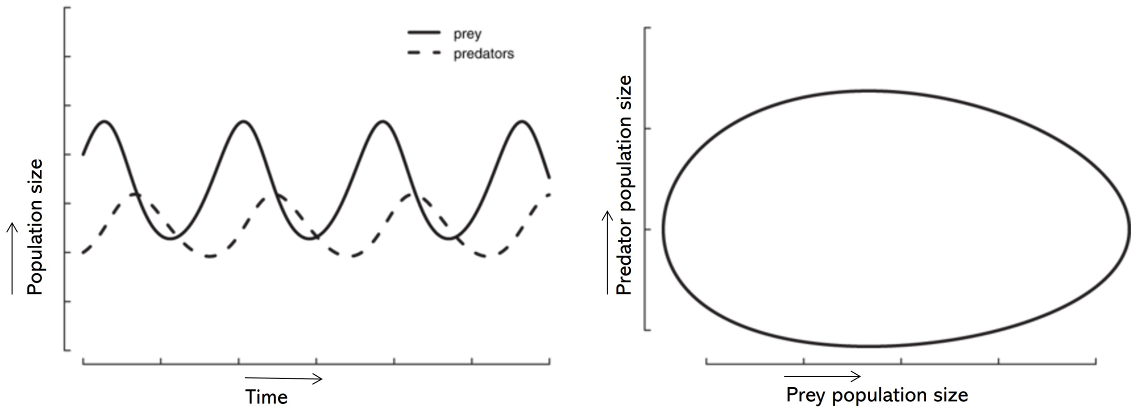


Figure 4.4: The Lotka-Volterra equations give boom-and-bust behavior of the predator and prey population over time (left), because the path of a moving point traces a closed solution trajectory in the phase plane (right), adapted from Bischof & Zedrosser (2009).

As mentioned earlier, the growth rates depend on some environmental conditions. The environmental conditions are a type of coral stressor, i.e. coral degradation driver. The global and local stressors, like fishing, pollution, tourism, and climate change effects can trigger hysteresis in coral reefs (Blackwood et al., 2012; Bhattacharyya & Pal, 2015). Hysteresis is the shift of an one alternate stable state to the next under similar conditions. A shift to another state is not always undesirable, only when that state is deemed to be worse. In the case of coral/algal phase shifts, coral-dominant states are deemed preferable due to their high productivity and biodiversity. Hysteresis happens when drivers become strong. In figure 4.5, from Hughes et al. (2017), a coral reefs response to increased drivers is modelled. Increased drivers can drive the system towards the interface between the coral and algal dominated states. At the interface, the system can (phase) shift from one state to another under the same conditions, also called a tipping point. These drivers are not the only drivers, but illustrate the phenomenon well.

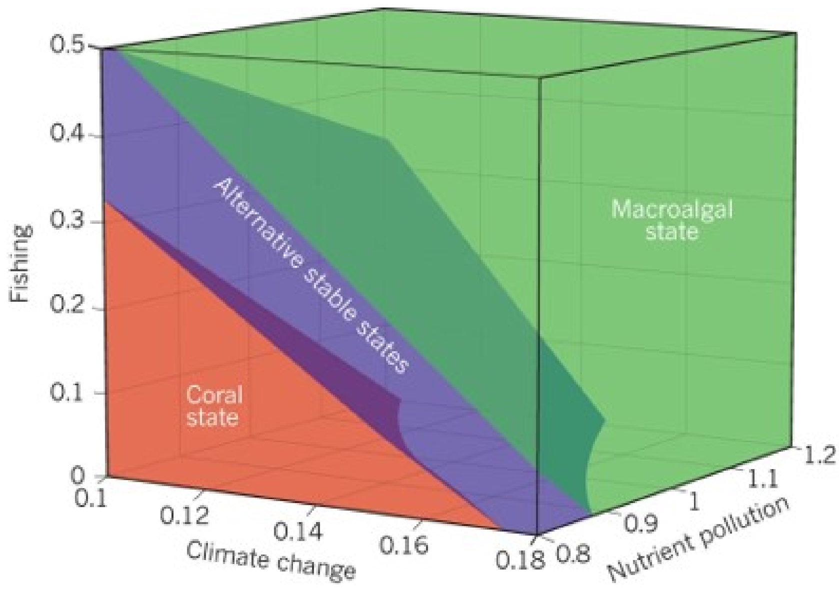


Figure 4.5: Systems can shift from a coral dominated state to a macroalgal dominated state by changing environmental conditions. In the intersection a system can suddenly shift from one state to the next (adopted from Hughes et al. (2017)).

Intervention in the system can contribute to preventing the phase shifts, see figure 4.6. "The x-axis represents one or more drivers of change, including climate change, pollution and overfishing, and the y-axis is the resultant state (at equilibrium) of the social or ecological system. (Hughes et al., 2017)"In figure 4.6, hysteresis is shown in the left figure, where two equilibrium states exists for the same strength of drivers, and the tipping point is at the top of the curve, because at the dashed line both healthy and degraded states can exist for an intermediary range of drivers. The first way of preventing hysteresis to an algal dominant state is by modifying the drivers. Decreasing fishing pressure and remove open sewage systems are ways of modifying the drivers. Secondly, thresholds can be manipulated, e.g. by introducing artificial reef structures in eroded reefs to increase reef growth rates. Lastly, feedback can be altered to prevent a sudden phase shift. Social-ecological systems consists of many positive feedback interactions, examples include providing government-backed incentives for fishers to exit a fishery when stocks decline (Hughes et al., 2017).

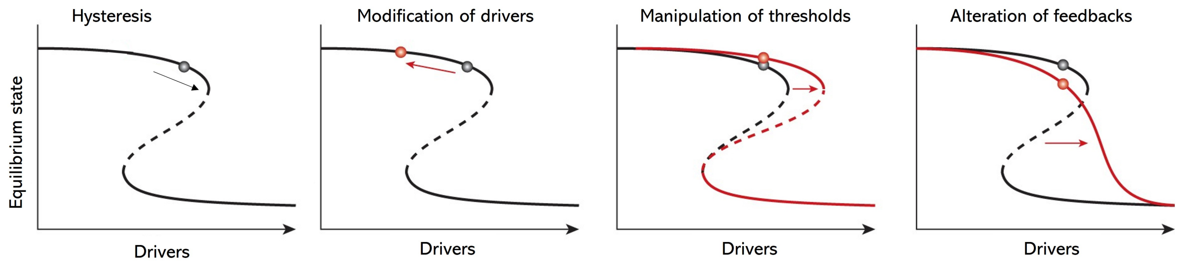


Figure 4.6: System hysteresis is avoided in three ways of intervention: modification of drivers, manipulation of thresholds, alteration of feedbacks (adopted from Hughes et al. (2017)).

5

Coral reef dynamics model

5.1. Subsystems

In this section, the subsystems of the coral reef dynamics model are described, the values and formulas are presented in appendix G. The model consists of two subsystems. Firstly, 'the predation subsystem' describes the predator-prey dynamic between herbivorous fish and macroalgae. For this model existing Lotka-Volterra models were used in system dynamics. Secondly, 'the competition subsystem' describes the competing interest of algae and herbivorous fish for surface area in the reef. A full picture of the model can be found in appendix F.

The predation subsystem, figure 5.1, consist of a herbivorous fish biomass. The biomass increases with the herbivorous fish growth. The biomass growth can occur through mass increase of individuals, but the most common way is through spawning. Herbivorous fish growth increases, when structural complexity increases, due to coral abundance. The relation between structural complexity increase and fish growth is non-linear, as coral coverage increases, and more coral patches are connected, then herbivorous fish growth increase exponentially. Here the predation subsystem links to the competition subsystem, because it depends on the fraction of surface area occupied by coral. Like in the logistic equation the size of the growth is dependent on the current population size as well. Herbivorous fish can die of old age, but it is more common to fall prey to a predator. The herbivorous fish consume the macroalgae. In a respective area a reference macroalgae biomass exists. The herbivorous fish growth rate is dependent on the macroalgae biomass fraction relative to the reference level, which is called the herbivorous fish fractional growth rate. As a result, herbivorous fish growth will be proportional to the fraction of macroalgae. Herbivorous fish death happens through natural (also herbivorous fish predation taken into account) and fishing. Macroalgae death, on the other hand, depends on the Macroalgae fractional consumption rate. The fractional consumption rate is proportional to the herbivorous fish relative to reference levels of herbivorous fish. Macroalgae growth rates are relatively high, up until the available surface area has reached the carrying capacity, which ties into the competition subsystem.

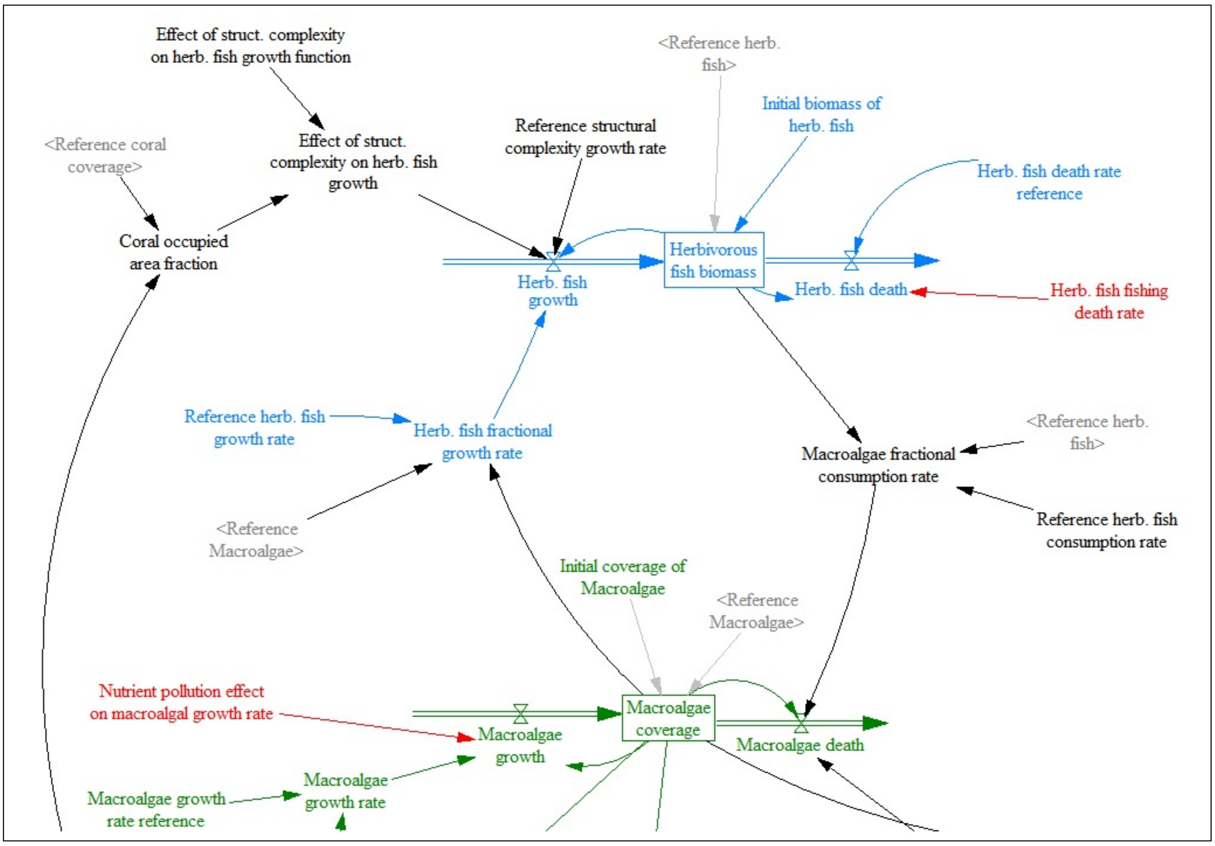


Figure 5.1: The predation subsystem consists of herbivorous fish and macroalgae stocks. Herbivorous fish affect macroalgae death through consumption, and through macroalgal consumption the herbivorous fish biomass grows.

The competition subsystem consists of the competition between macroalgae and corals. As mentioned in the conceptual stock-flow diagram, appendix E, the coral and macroalgae compete for surface area, as a form of interspecific competition. There are two effects at play in the interspecific competition. Firstly, the species are competing for surface area, so there is a density dependent effect. The more surface area is covered, the harder it becomes for coral and algae to settle in a certain spot. The maximum land area limits the surface available for growing, and the occupied area is the fraction of the macroalgae and coral sum and the maximum land area. The increased density means an increased effect of crowding on the growth and spawning. The density dependent effect differs for macroalgae and corals. The macroalgae crowding effect depends on other macroalgae, while corals depend on macroalgae and coral densities. The effect of crowding function is not a linear function, because when little surface area is the covered, the effects are insignificant. However, when the reef becomes very dense, the effect is very large. A distinction is made between mature coral cover and juvenile coral cover, as the maturity time for corals to become adults is long, and the delay has an effect on growth patterns. The second effect of the interspecific competition is the effect the species have on each other. Macroalgae can affect coral death by overgrowing, shading, abrasion, and allelopathy, while corals can extrude macroalgae. Macroalgae compete with algae via overgrowing. The fractional overgrowing rate stimulates coral death through the fraction of macroalgae over reference macroalgae levels. Similarly, the corals can extrude macroalgae, proportional to the coral coverage over the reference coral coverage. With the conditions changing the coral and macroalgae populations are affected. Nutrient pollution increases macroalgae growth rates and decreases coral growth, spawning efficiency and recruitment. Ocean acidification increases the effects of boring and bioeroding species. Anthropogenic activity causes physical degradation. Similarly, bleaching storms and disease cause physical degradation, but they are discrete events, instead of a continuous effect.

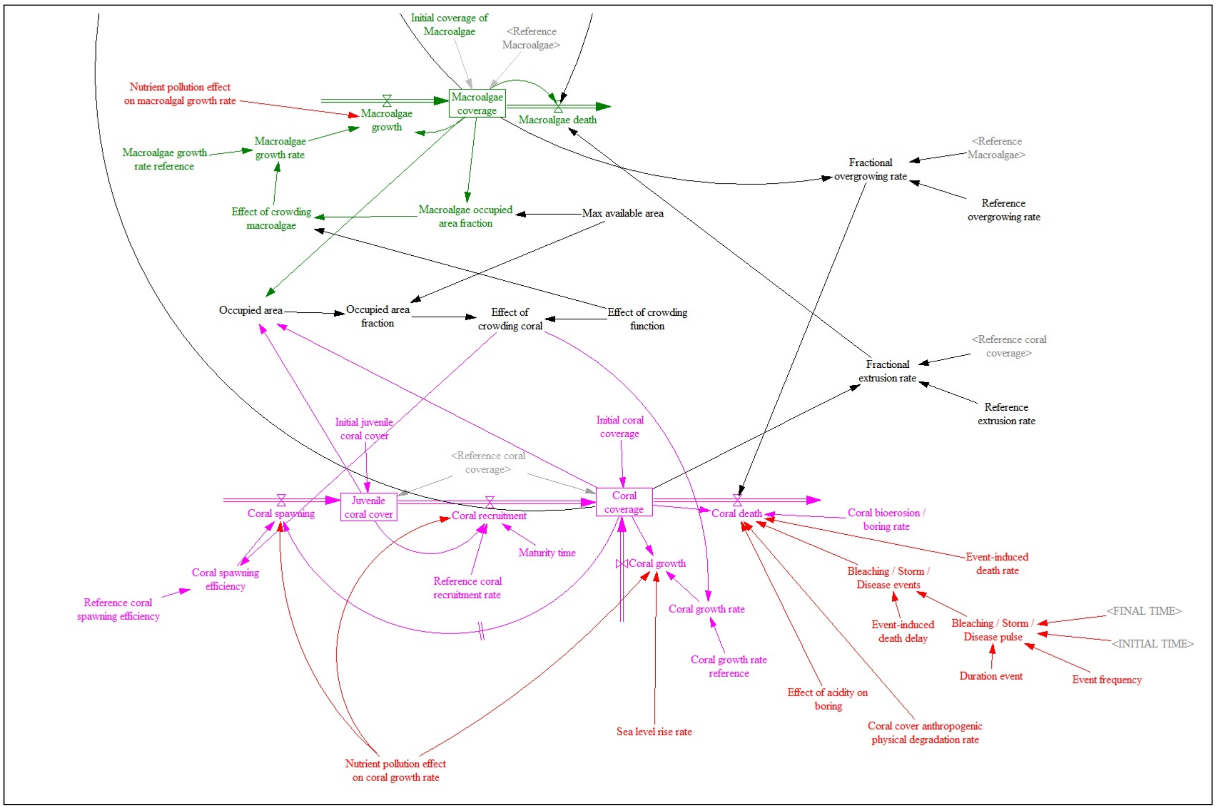


Figure 5.2: The competition subsystem shows the competition of macroalgae and coral for reef surface area.

5.2. Model assumptions

In the coral reef system model, both predator-prey Lotka-Volterra dynamics and interspecific competition Lotka-Volterra dynamics are modelled. The Lotka-Volterra functions are a conceptual description of real world phenomena and thus rest on some assumptions. Firstly, predator-prey Lotka-Volterra assumptions and their applicability in this model are discussed. Secondly the assumptions for interspecific competition Lotka-Volterra are considered. Finally, the most important, non-Lotka-Volterra related, assumptions are introduced.

In traditional predator-prey Lotka-Volterra functions, the equations rest on the following six assumptions. However, in the case of the coral reef system model not all six apply. In table 5.1, a checkmark is given to the applicable assumptions. Firstly, the prey population finds ample food all the time. In this model, it is assumed that the water holds enough nutrients for the macroalgae to sustain their growth rate. Macroalgae growth is limited by density dependence, but not the food source. Secondly, food supplies of the predator population do not depend entirely on the size of the prey population. The crux is in the word 'entirely', because the predator population does depend on macroalgae for food, but it is also influenced by the structural complexity of the corals. Thirdly, the rate of change are all dependent on the population in the time step, because both the growth and death depend on the population for herbivorous fish as well as macroalgae. Furthermore, the environment can change over time to favor one species or the other. The change in the environment is actually a very important driver in the social-ecological coral reef systems, and the experimenting with the environmental change is highly relevant for the research, e.g. temperature, pH, sea-level rise might favor one of the species and can change over time. It is assumed, though, that genetic adaption is inconsequential. In reality, genetic adaption could play a role. Herbivorous fish could adapt to the environmental changes by anthropogenic climate change (Munday et al., 2008). Also, macroalgae can adapt relatively quickly due to their short reproductive cycles. Genetic adaption is not taken into account, because the sustenance of herbivorous fish biodiversity and abundance is more reliant on habitat degradation, than on genetic adaption. Additionally, genetic adaption can vary widely per species (Munday et al., 2008). Assumption 5 is applicable to the coral reef system model, the herbivorous fish will keep consuming the macroalgae.

For individual fish this might not be true, but over longer time periods, such as in this research study, this can be assumed to be true. Lastly, the spatial and age distribution are not taken into account, only the herbivorous fish biomass and macroalgae coverage is instantiated. The variation of multiple herbivorous fish and macroalgae species is represented in the same single variable.

No.	Assumptions predator-prey Lotka-Volterra functions	Applicable
1.	The prey population finds ample food at all times.	✓
2.	The food supply of the predator population depends entirely on the size of the prey population.	X
3.	The rate of change of population is proportional to its size.	✓
4.	During the process, the environment does not change in favor of one species, and genetic adaptation is inconsequential.	X
5.	Predators have limitless appetite.	✓
6.	Both populations can be described by a single variable. This amounts to assuming that the populations do not have a spatial or age distribution that contributes to the dynamics.	✓

Table 5.1: The table holds the six assumptions that are part of predator-prey Lotka-Volterra functions, and their applicability to the coral reef system model.

The interspecific competitive Lotka-Volterra functions also have inherent assumptions, see table 5.2. The seventh assumption is that all values in the interaction matrix are positive or 0. Meaning the interaction effects (α and β) need to be positive. A positive effect means, in this case, that the harmful competition exists between the species. In the coral reef system model, the interaction effects are (1) the extrusion of macroalgae by corals and (2) the overgrowing, shading, abrasion and allelopathy of corals by macroalgae. Assumption eight states that the population of any species needs to grow in the absence of competition, unless its at the carrying capacity. In the coral reef system model, the growth of macroalgae and corals is only constrained by the carrying capacity. In this model, the macroalgae and the corals have the same carrying capacity: the maximum available reef surface area. Therefore, the model complies with the second assumption.

No.	Assumptions interspecific competitive Lotka-Volterra functions	Applicable
7.	All values in the interaction matrix are positive or 0 (α and $\beta \geq 0$ for all x, y).	✓
8.	The population of any species will increase in the absence of competition unless the population is already at the carrying capacity ($r > 0$ for all x and y).	✓

Table 5.2: The table holds the assumptions that are part of interspecific competitive Lotka-Volterra functions, and their applicability to the coral reef system model.

The model has some assumptions, unrelated to the assumptions of Lotka-Volterra functions. Table 5.3 displays the inherent assumptions of the coral reef system model. The most important assumptions (10, 13, 18, 19, and 23), because they potentially heavily influence model behavior, while others have a much smaller effect. Overgrowing is modelled as not contributing to crowding and therefore to density dependence. In reality coral provide a substrate for algae to grow on, meaning surface area can be occupied twice. However, the double occupation is only a temporary state, as the outcome is either coral death if the overgrowing persists, or the algae gets eaten by herbivorous fish. As the modelling time is multiple years, these temporary states are not taken into account as crowding effects, but only as coral/algal interaction effects. Assumption 13 is closely related to assumption 6, but in the interspecific competition, unlike in the predator-prey dynamic, there is an age distribution between juvenile and mature coral cover, as it can take several years for corals to reach maturity. The maturity time is averaged for different species. Realistically, there is variation, but as corals are a K-selected species most of them have similar long reproductive cycles. Another assumption that might influence behavior is the stability of bioeroding and boring organisms. Bioeroding and boring organisms rely on coral as a food source and shelter. It is assumed that the death rate from these organisms remains stable over time, because the population of these organisms remains stable relative to the coral coverage. Furthermore, a lack of migration is assumed between different regions. Coral reefs rely on nearby regions for genetic diverse reproduction. In this model, genetic diversity is not taken into account and therefore also no coral larvae migration. Fish migration could also occur, but it is assumed that net migration in and out of the area is zero. Macroalgae and mature coral are unable to migrate. Lastly, the corals and macroalgae are viewed as 2-Dimensional objects, instead of the 3-Dimensional objects they are. This assumption may result in a failure to represent biomass estimates needed to assess trophic ecology and reef function (Kornder et al., 2021). However, in this research study the emphasis is not on the estimating future populations, but showing the change in behavior of populations under various conditions. The size of the population influences the population dynamics, but is mostly decided through growth and death rates of species.

No.	**Other assumptions used in coral reef system model**
9.	Corals are immortal for dying of senescence, as their life expectancy is far greater than the modelling time. Coral death is through bioerosion, boring or physical damage from storms, tourism or fishing.
10.	Overgrowing does not contribute to crowding.
11.	Herbivorous fish death rate consist of natural death and predation.
12.	Abundance is modelled, but not diversity.
13.	Maturity time is averaged for the different species of coral.
14.	Reference levels of coral, macroalgae and herbivorous fish are site dependent.
15.	Available surface area pertains only to the area which is available for macroalgae and coral growth, as they is the space relevant for density dependent effects.
16.	Palatability effects for herbivorous fish during macroalgae maturing is assumed constant
17.	Effects of coralline algae on coral spawning and growth are assumed constant.
18.	Bioeroding and boring organisms are assumed relatively stable in abundance and diversity relative to the coral abundance.
19.	There is a lack of migration between regions.
20.	The effect of bioerosion and boring organisms on juvenile coral cover is taken into account through the coral spawning efficiency.
21.	Coralline is assumed as coral cover, as they respond similar to environmental conditions and predation.
22.	Corals grow in all directions.
23.	Corals and macroalgae are viewed 2-Dimensional, from a surface area perspective, not including 3-Dimensional stacking effects of corals.

Table 5.3: The other assumptions that are used in the coral reef system model.

5.3. Verification & validation

Verification and validation are critical processes in the field of system dynamics modeling. Verification focuses on checking the accuracy, correctness, and consistency of the model, while validation evaluates the model's performance against real-world data or expert knowledge. Together, these processes ensure the quality, reliability, and usability of the model. Verification in SD helps identify and rectify errors, ensuring that the model equations, formulas, and structure accurately represent the intended relationships and behaviors. By conducting thorough verification, potential sources of bias, inconsistency, or miscalculations can be detected and corrected, increasing the model's overall accuracy. Validation, on the other hand, assesses the model's ability to replicate the real-world system it represents. By comparing the model's outputs to empirical data or expert judgment, validation helps establish the model's credibility and its usefulness as a decision-making tool. It provides evidence of the model's reliability and its ability to capture essential dynamics and patterns of the real system (Sargent, 2013; J. Forrester & Senge, 1979).

5.3.1. Verification

To verify the coral reef system model, the model settings, units, equations, structure, and behavior are examined. Model settings and units are explained, equations and structure are checked for correctness with the qualitative stock-flow model, and behavior is compared to conceptual behavior from section 4.3. The table of variables and equations can be found in appendix G.

The model was created in the software Vensim PRO x64 version 9.3.5 (Ventana Systems inc., 2022b). In this version of Vensim, the model settings, which need to be set, are the time boundaries, the units for time, the base date, date display, and the integration type. for the model a unit year is chosen as the model will be run over the course of the current century. The initial and final time of the model are, respectively, 2023 and 2100. The date display format is YYYY-MM-DD with the base date being 2023-01-01. The current century is chosen as time boundaries for the model, because this century will be determinative for the future of coral reefs (Hoegh-Guldberg et al., 2007). The time step is set on 0.0625 years, which amounts to a time of around 3 weeks per step. The time step was chosen, because the reference growth rate of algae is around 4 to 6 weeks. A smaller time step than the growth prevents discrete behavior. Furthermore, Euler is the integration type, because Runge-Kutta assumes continuously differentiable functions, and some abrupt changes related to interventions may be simulated. In the coral reef system model, no equations are used which create discrete behavior changes. However, in the experiments a PULSETRAIN function is used, therefore, Euler with a small time step is better equipped to simulate the behavior.

Consistent dimensions indicate consistent implementation of model equations

The coral reef system model units for all variables are instantiated in the table in appendix G, and equations pass the dimensional-consistency test (J. Forrester & Senge, 1979). Both coral and macroalgae are in hectares, as the coverage is identified for a surface area. Herbivorous fish biomass is measured in kilograms. Biomass is also measured over a surface area, however, in this case, the total biomass for the area is entered, making it unnecessary to take this into account in the unit. The inflows and outflows of the stocks are the stock's unit over time, in this case 'ha/year' or 'kg/year'. The spawning efficiency and all rates in the model have the unit '1/year'. The unit '1/year' is a simplified version of the full unit, e.g. the full unit of the growth rate of coral is ha/ha/year, because the unit describes the amount of hectares a hectare of coral can produce in a year, but the unit can be mathematically simplified to '1/year' as the hectare terms cancel out. Furthermore, the model contains to lookup functions, which ought to be dimensionless. The input for both lookups is a fraction, where the numerator and denominator have the same unit, making the lookups dimensionless.

Consistency with Lotka-Volterra equations and the qualitative stock-flow model indicate correct model structure

To check the variable equations, a structure-verification test is used (J. Forrester & Senge, 1979). Equations should reflect the relations in the stock-flow diagram accurately. Checking the equations indirectly checks the model structure as well. If the equations match the structure of the qualitative stock-flow diagram and the structure of predator-prey (Swart, 1990; Crookes & Blignaut, 2016; Ventana Systems inc., 2022a) and interspecific competition models or formulas, then so does the structure of the coral reef system model.

In predator-prey modelling, the predator growth rate is dependent on a fractional growth rate. The fractional growth rate depends on the fraction of prey abundance over the reference prey abundance at a certain time step. This reflects the effort a predator has to do to find a prey. In this case, the effort a herbivorous fish has to do to find macroalgae. The prey consumption rate is dependent on a fractional consumption rate. The fractional consumption rate depends on the fraction of predator abundance over the reference predator abundance at a certain time step. This reflects the predator density effect on prey abundance. For the coral reef system model, the herbivorous fish abundance relative to the reference level will determine the macroalgae death rate. However, in the qualitative stock flow model, it also becomes apparent that macroalgae and herbivorous fish do not live in an isolated system, and the growth and death is not solely dependent on growth and consumption rates. Structural complexity of coral influences herbivorous fish growth rates as well. The structural complexity is an addition effect, because for herbivorous fish to grow there need to be structural complexity as well as a food source, such as macroalgae. If one or the other are missing, herbivorous fish growth rates drop drastically. However, fish populations will not go to zero. The double dependency of herbivorous fish is incorporated in the formula this way, without the effect of herbivorous fish dying out when macroalgae or corals cease to exist. The effect of structural complexity on herbivorous fish growth is not a linear effect, but an exponential as the effort decreases for fish to spawn and shelter, if coral density increases. When the predator-prey dynamic is isolated the populations of fish and macroalgae show the characteristic predator-prey behavior of boom and bust cycles. When the predator-prey submodel is linked to also create the interspecific competition the behavior changes, and the boom and busts stabilize over time.

In interspecific competitive models, two species compete for a resource, in this case surface area. Due to the low amount of SD models available with competitive Lotka-Volterra, the coral reef system model equations are checked through the competitive Lotka-Volterra equations, see equation 4.2 and 4.3. According to the competitive Lotka-Volterra and the qualitative stock-flow model, the structure of macroalgae and corals in the coral reef system model, the growth should depend on a growth rate, the population size, and the fraction of available carrying capacity, including the effect of the competitor on the population growth. The available carrying capacity is the available surface area in the reef. Macroalgae affect coral death by overgrowing, shading, abrasion, and allelopathy. Corals, on the other hand, affect macroalgal death by extrusion. Both macroalgae and coral growth and death are dependent on the population sizes and growth/spawning factors. Coral is split in juvenile cover and mature coral, because a significant delay of 5 years exists for the corals to mature. However, both the spawning and the growth depend on the available surface area, therefore, still, satisfying the competitive Lotka-Volterra equations. The behavior for the corals is similar to the logistic function and the isoclines in section 4.3. In the case of corals, the available surface area is dependent on other corals as well as macroalgae, because corals cannot grow in places where others have already rooted. Herein lies a difference with macroalgae, because macroalgae can overgrow corals. Therefore, macroalgae, unlike corals, are only bound by the density-dependence through other macroalgae. Macroalgae behavior also shows the logistic behavior, however, because macroalgae is part of both the interspecific competition and the predator prey dynamic, it generates a fluctuating logistic function, until it stabilizes at a population value.

Model behavior abides by population carrying capacities under extreme conditions
Furthermore, through an extreme-conditions test, the robustness of the model is tested (J. Forrester & Senge, 1979). To test the robustness of the coral reef system model, the growth, death and spawning rates of the herbivorous fish, macroalgae and corals are doubled or halved. Increasing growth rates should increase the exponential growth or death of populations. In the coral reef system model, the growth and death rates change the behavior in the sense that it changes the dominant population the development of the population, however, the populations still abide by the carrying capacities and negative population sizes do not occur. The extreme condition test did reveal one flaw in the model structure. The increase in spawning efficiency had no effect on the juvenile coral coverage. The test revealed that the growth and maturing of corals need to be taken apart to make the effect appear, because the flow of the juvenile coral cover to coral coverage was not related to the juvenile coral cover. With the growth and maturing split into two flows the effect of the spawning appears.

5.3.2. Validation

For the validation, a parameter-verification test, behavior anomaly test, and behavior sensitivity test are done. The tests are complementary as first parameters are checked, followed by checking if the behavior with those parameters is valid, and lastly the sensitivity of the behavior for those parameters, creating a complete picture of the validity of model parameters and behavior.

The model parameter values fall within a plausible range
The parameter-verification test compares parameters to real-life knowledge of the system. System dynamics models should strive to describe real processes. Numerical parameter verification involves

determining if the value falls within a plausible range of values for the actual time. parameters often do not change over time. In the case of the coral reef system, it is assumed that reference growth, death, and recruitment rates do not change over time and are therefore parameters. In appendix H, the parameters, which are entered in the coral reef system model, are listed in a table. The table describes the parameter, the value and unit, and the reference for the value. Some parameters are validated through literature, other values from the expert validation meeting. In the list, also some variables are included, which change over time, nutrient pollution, sea level rise, acidity, fishing rates, and anthropogenic physical degradation can change over time, but are still included for completeness.

Very high macroalgae growth rates drive anomalous behavior at the start of the simulation

The behavior anomaly test compares model behavior to real behavior. Frequently, the model contains anomalous behavior compared to real systems. In the case of the coral reef system model, the test is important to validate the population behavior. The model shows to forms of anomalous behavior. Firstly, at the start of the simulation a rapid change in population size occurs for all three populations, depending on the configuration of the parameters the population either rapidly increases or decreases in the first year of the simulation, see figure 5.3. The population of macroalgae explodes in the first year of the simulation, because the herbivorous fish follow a quarter lag cycle behind the macroalgae, their population explodes a few years later. At some point the populations find an equilibrium. Right before the equilibrium the macroalgae and herbivorous fluctuate a from the predator-prey Lotka-Volterra model structure. Eventually the fluctuations die out over time.

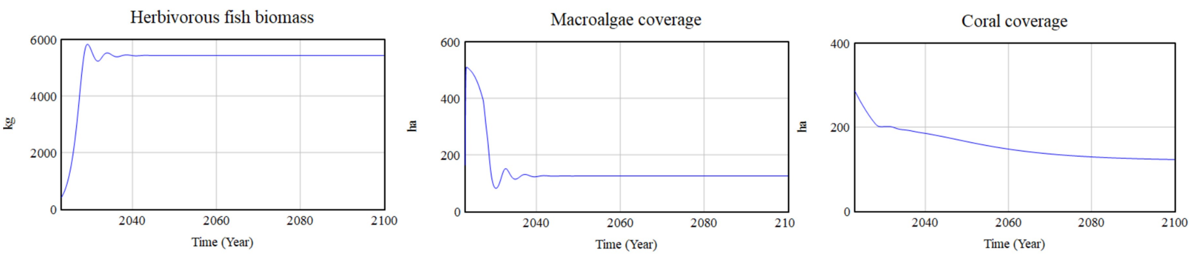


Figure 5.3: The population behavior at the start of the simulation is anomalous as the populations change very rapidly and stabilize later on.

In figure 5.4, the macroalgae growth rate reference is changed is set to a much lower value (from 11 to 1). The enormous fluctuation at the start of the simulation has now disappeared, and the populations still finds an equilibrium, and the fluctuations of the macroalgae and herbivorous fish populations still die out over time. It is realistic for ecosystems to find a equilibrium in the populations over time. However, the large increase of herbivorous fish and macroalgae at a high macroalgae growth rate are not representative for real ecosystems. The coral reef system model does not deal well with very high growth rates, because populations can explode within a matter of years.

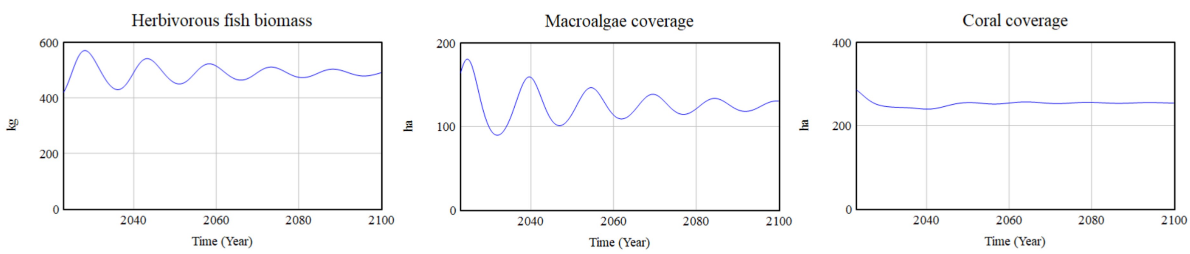


Figure 5.4: The anomalous behavior at the start of the simulation disappears when the macroalgae growth rate reference is set to a much lower value.

Altogether, the model generates some surprising behavioral anomalies. However, some characteristics of real systems are also seen in the simulations. Similar to real systems, there exists a lag cycle between the predator and the prey populations. In ecological models that exclusively focus on ecological interactions and do not incorporate any changes in traits of prey or predator species, These models also anticipate a quarter lag relationship in the dynamics between predator and prey biomass (Rosenzweig & MacArthur, 1963). Population growth is controlled by negative feedback operating with a time lag. In the coral reef system model, herbivorous fish populations also follow a quarter lag cycle to the macroalgae population. However, the ratio of herbivorous fish needed to keep macroalgae populations under control does not reflect real systems. Knoester et al. (2023a) reported the difference between fished, marine reserves, and no-take zone areas in terms of fish and algae biomass. In the no-take zones a fish population around 420 kg biomass can keep a macroalgae population in check. However, the coral reef system model does not report the same order of magnitude. Likely, this is the result of the models sensitivity to growth/death rate changes, and because the herbivorous fish population in the model depends largely on the macroalgae population. The high macroalgae growth rate is causing the anomaly in the start of the simulation. In figure 5.4, the simulation with the lower macroalgae growth rate gives behavior which is more representative in terms of populations sizes. The variation in population size of herbivorous fish biomass and macroalgae coverage are relatively similar in that case. T. R. McClanahan et al. (2007) reports the effect reef fish recovery in marine protected areas. In a number of decades the reef fish populations can grow many times over for all different type species. Macroalgae have higher growth rates than herbivorous fish, and macroalgae blooms can occur within a 100 days (Humphries et al., 2020). Coral coverage varies slow as is to be expected due to the low growth rates. The changes in simulated population sizes are relatively representative for changes in real population sizes after the simulation start anomaly.

Phase shifts occur at very high growth and death rate variations

The behavior anomaly test revealed a sensitivity to growth and death rates of the different species. In figure 5.5, the growth and death rates of the macroalgae, herbivorous fish, and corals are varied by 10 percent over 200 simulations (The varied parameters are: Herb. fish death rate reference, Reference herb. fish growth rate, Reference herb. fish consumption rate, Macroalgae growth rate reference, Coral growth rate reference, Coral death rate, Reference coral recruitment rate, Reference coral spawning efficiency). The population sizes show a large sensitivity to the variation in growth and death rates. However, the phase shifts from coral dominated systems to coral dominated system are not occurring when the variation is 10 percent. The populations sizes shift by approximately 10 percent as well. When pushing the system even further, the variations start to become larger.

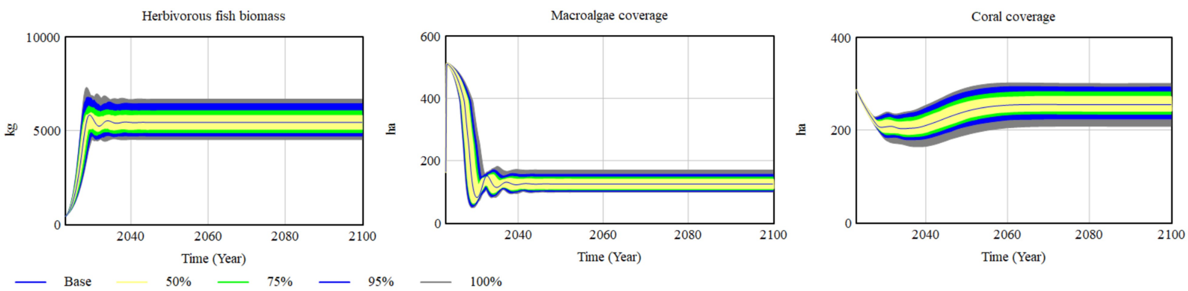


Figure 5.5: The variation of the coral growth, spawning and recruitment rates and the macroalgae growth rate by 10% shows that the growth rates influence population dynamics, but do not cause a coral algal phase shift.

Figure 5.6 shows the simulated behavior over 200 simulations, when the growth and death rate parameters are varied by approximately 50 percent. As expected the variation between the simulations now becomes much larger. The phase shifts now become visible as well. Depending on the conditions in the simulation, the system can either be a coral dominated system or a algal dominated system, which is the behavior also seen in real ecosystems. Anthropogenic stressors are causing extreme effects on ecosystem growth and death rates, and the large variety within the simulated behavior can be expected for real systems as well, depending on the height of stressor effects.

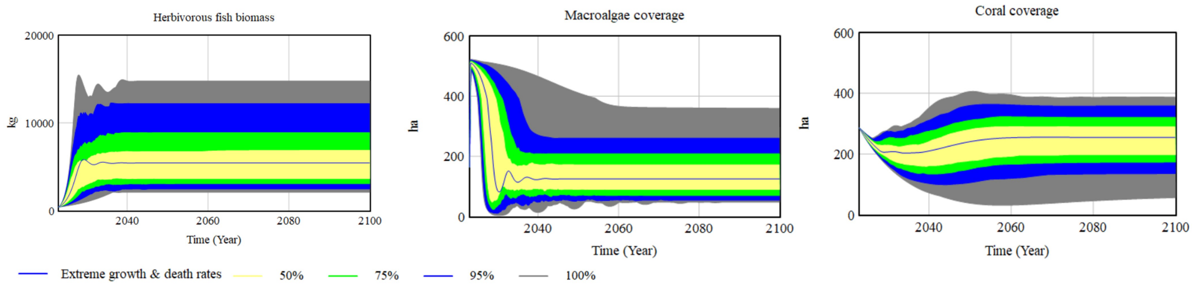


Figure 5.6: The variation of the coral growth, spawning and recruitment rates and the macroalgae growth rate by 50% shows that the change in growth and death rates can cause a coral-algal phase shift.

In the behavior-anomaly test, the start of the simulation anomaly disappeared with a much lower macroalgae growth rate, see figure 5.4. If the growth and death rate of the macroalgae, herbivorous fish, and corals are varied by 10 and 50 percent again, but now with the lower macroalgae growth rate, the simulated behavior follows figure 5.7 and 5.8 respectively. The magnitude in behavior change between the 10 percent variation and the 50 percent variation is similar to the case with the high macroalgae growth rate. In the 10 percent growth and death rate variation simulation, figure 5.7, the population sizes again also vary around 10 percent. The effect is exacerbated in the case of 50 percent parameter variation.

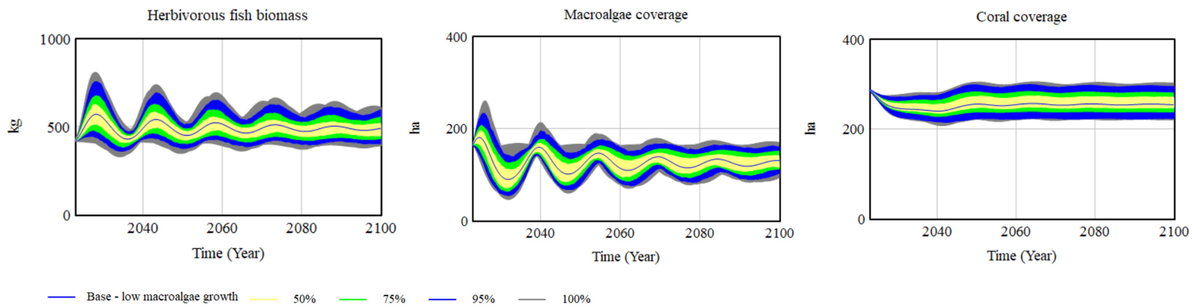


Figure 5.7: With a low macroalgae growth rate and a variation of 10 percent in the growth and death rates, the population sizes still vary over time, with the quarter lag cycle reappearing.

With the variation of 50 percent the simulation still phase shifts happen between coral dominated systems and algal dominated systems. However, now the quarter lag cycles between herbivorous fish and macroalgae appear in the simulation as well. Although the macroalgae growth rate is not representative for a real system in this case, the behavior shown in figure 5.8, is representative for the sensitivity of coral reef ecosystems under anthropogenic stressors. Low anthropogenic stressors create ecosystem conditions beneficial for corals, and the system will become dominated by corals instead of macroalgae.

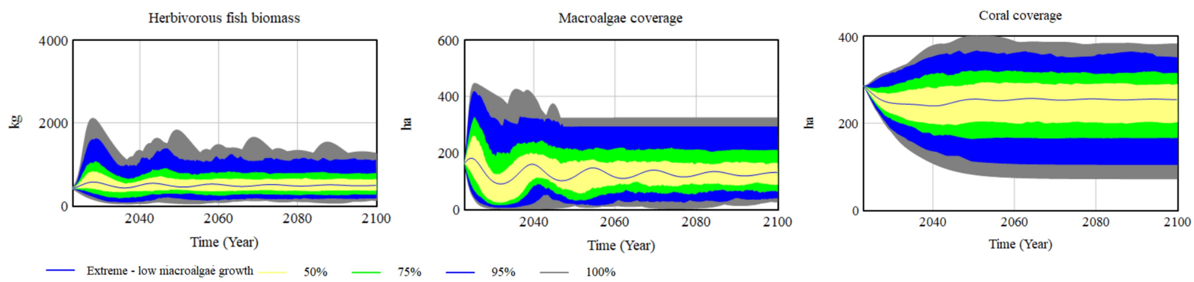


Figure 5.8: With low macroalgae growth and a high variation in growth and death rates, the phase shift occurs again with the quarter lag cycle.

5.3.3. Expert verification & validation

Verification & validation by respondent D

The effect of structural complexity on the herbivorous fish growth is clear. It is a simplification of the effect of that structural complex habitats provide food, shelter, and place for spawning for fish. Fish have a death rate and fishing death rate which is clear. A interesting thing is that reference herbivorous growth rates are not the same per habitat and growth rates can fluctuate over time. Usually they are not a set number. Furthermore, a reference ecological system does not exist and they differ widely and can be in different states. The effect of this simplification should be taken into account in the discussion.

Furthermore, grazing efficiency increases when the density of macroalgae increases, this should be caught in the model. This dynamic is already captured in the predator-prey dynamic. Where the herbivorous fish growth rate increases, if the macroalgae rise above the reference macroalgae.

Moreover, there were two nomenclature suggestions. Firstly, the name 'occupied area capacity fraction' should maybe change to availability. Capacity indicates the capacity of substrate to receive macroalgae and coral. However, in reality it is the coral and macroalgae looking for available space. One is from the viewpoint of substrate and the other of the corals and macroalgae. The nomenclature changes the perspective. For this case the perspective from corals and macroalgae is more relevant. Also, the name 'coral cover physical degradation' should be more specific. Physical degradation can happen also through storms and other effects. In this case, it refers to anthropogenic effects on the coral reef. Making it more clear will make the distinction between this variable and the variable 'Bleaching / Storm / Disease event-induced death rate'.

For coral spawning events, this is more a discrete event and can be more or less successful. The successfulness could, for example, rely on a stressed population of corals. It might be worth to create a stressed population of corals which are affected by disease/bleaching and therefore, limit growth and spawning. This period of being stressed can have an interested effect on the dynamics. What happens, for example during a El Nino event, where the water becomes a lot warmer.

Ocean acidification effect op boring and bioerosion, with an increase pH the boring and bioerosion effect becomes higher, as it takes less pH difference for the sponges to dissolve the carbonate structure of the corals. This is an effect that also can be taken into account.

For validating the behavior of the model, it would be wise to look into literature on the ratio between herbivorous fish and macroalgae. A lot has been published also on population dynamics of corals and this should also be available to compare to the behavior. Lastly, it needs to be reviewed what the perturbation at the start of the model is caused by. Shifts this large do not occur often in ecological systems, only during extinction events or other similar occasions.

5.4. Experiments

In this section, the experiments are done to determine key patterns of behavior, such population responses to changing stressor effects. The experiments are done with a lower macroalgal growth rate, as it was more representative for real behavior. Furthermore, a distinction is made between continuous stressor and discrete stressor effects. Continuous stressors continuously pressure coral reef ecosystems over time, such as continuous flow of tourists, nutrient pollution, and sea level rise. Discrete stressors are a short duration event impacting the ecosystem, such as disease outbreaks, bleaching events, and storms. In the first experiment, the effect of anthropogenic stressors on coral reef populations is shown. In the second experiment, the effect of discrete events on coral coverage is tested. In the final experiment, the combined effects of continuous and discrete stressor are examined.

5.4.1. Continuous stressor effects push the ecosystem populations to new equilibria.

In this experiment, the coral reef system is pressured by several continuous stressor effects. In this case, the nutrient pollution effects on macroalgae and corals, the fisheries effect, negative effects of sea level rise, and the effect increased acidity has on boring species. The parameters for these values can be found in appendix H. For the experiment, first a simulation is done without the stressor effects (Base). Secondly, the stressor effects are added. Finally, the fishing pressure is increased to much higher levels.

In figure 5.9, the result from the simulations are shown. Depending on the stressor effect the reef populations find an equilibrium. In the base simulation, high levels of coral coverage and low levels of macroalgae populations are found. This is in line with the idea of a healthy coral reef, where corals can thrive. In the anthropogenic stressor simulation, the populations sizes shift and a new equilibrium is found, in which corals are no longer the dominant species. Both species still exist, however, the coral abundance is far lower than in the base simulation. Herbivorous fish are seemingly unaffected by the increased stressors, until the fishing pressure is increased even further. In the 'increased fishing pressure' simulation a clear macroalgal dominated state is created, where corals disappear almost completely over time. The herbivorous fish population do not die out completely, but the population is less productive. In the experiment, the stressor effects are kept constant over time, which is likely not the case in real systems. However, the results show that increased anthropogenic stressor push the system towards new equilibria, in which corals are not the dominant species.

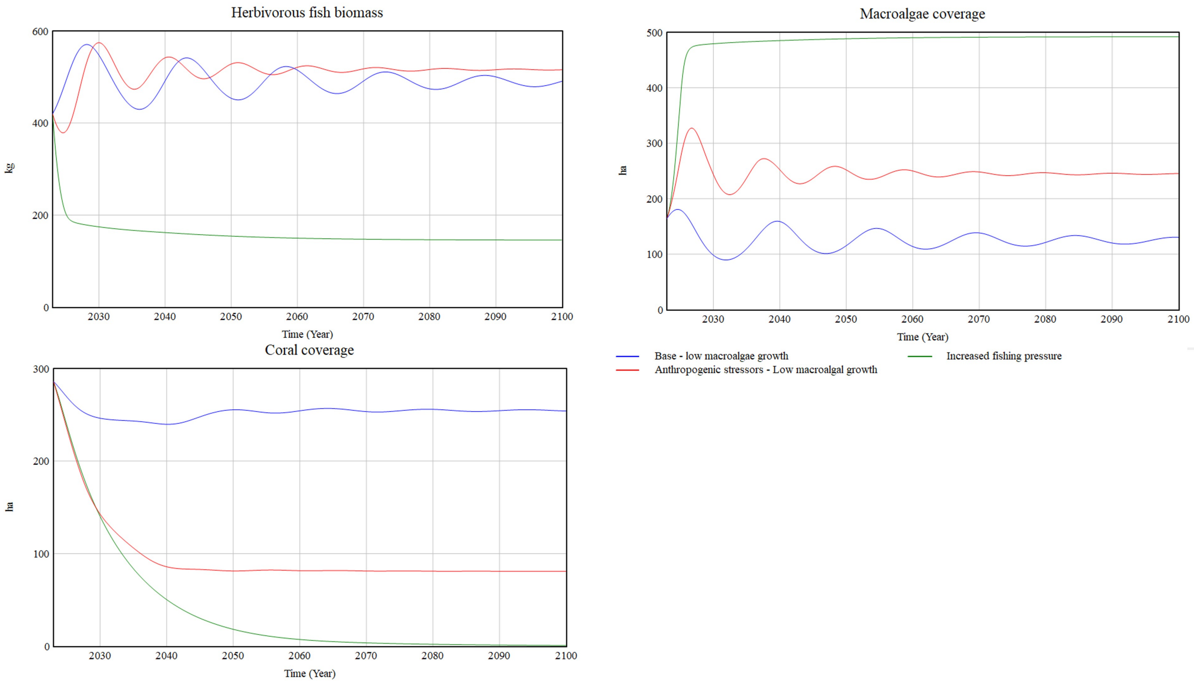


Figure 5.9: Coral populations find a lower equilibrium with the increased stressor effects over time. Macroalgae, on the other hand, find a higher equilibrium. Herbivorous fish are seemingly unaffected by the anthropogenic stressors. However, when the fishing pressure is increased to high levels also fish become heavily affected.

5.4.2. The increase in intensity and frequency of bleaching event drives coral degradation.

In the second experiment the impact of coral death events is simulated. Corals are impacted by disease, storm and bleaching events. The events are short discrete period of high coral death. The effect of events will be shown by means of simulating bleaching events. The experiment is started by creating highly beneficial conditions for corals, meaning low macroalgae growth rates, low anthropogenic stressor effects, and high available area for corals to grow. These are conditions for corals to thrive and creates a coral dominated system. Secondly, the bleaching events are simulated. The results can be seen in figure 5.10.

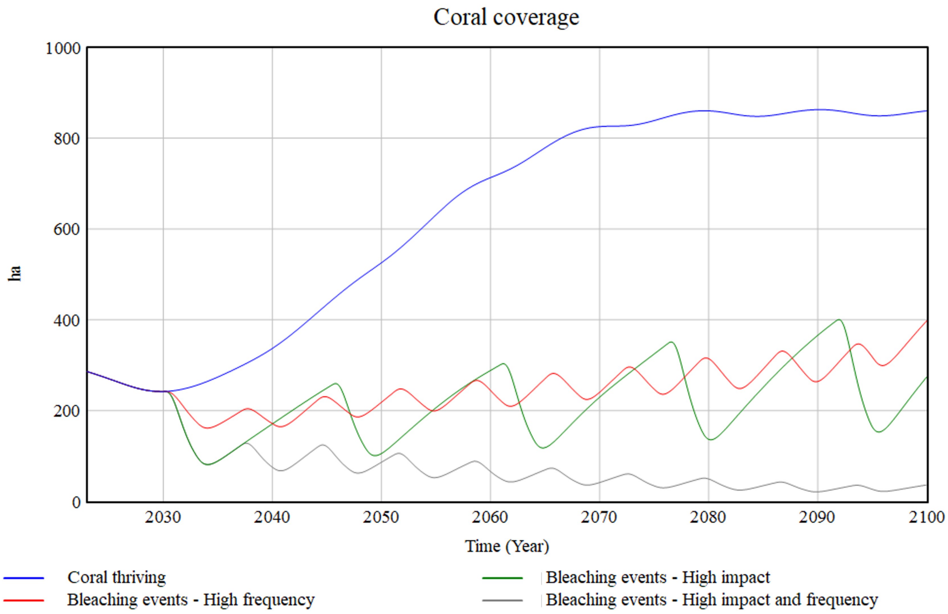
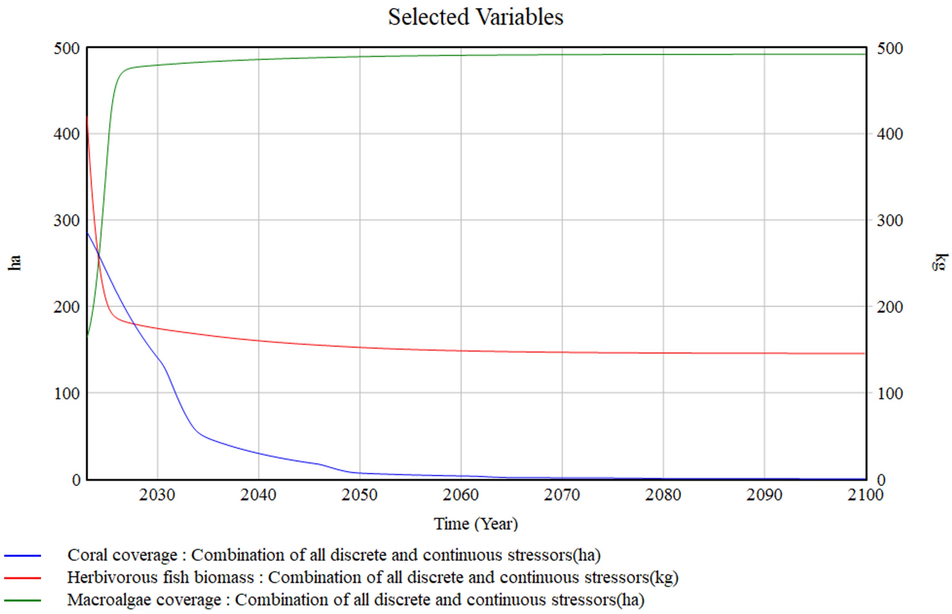


Figure 5.10: Coral coverage decreases when the intensity and frequency of bleaching events increase, at some point corals are unable to bounce back from the event, and degradation starts setting in.

In the figure, four simulations are shown: Coral thriving, bleaching with high frequency, bleaching with high impact, bleaching with both high intensity and high impact. In the simulations with bleaching the coral coverage is fluctuating. In the simulations with only one of high impact and high frequency, the coral is able to regrow just enough for it to have a upward regression line. When bleaching events occur both with high impact and high frequency, coral is not able to recover to the point of growth and the coral coverage decreases over time, i.e. coral resilience has decreased to the point of degradation. Anthropogenic global warming increases both the impact and intensity of bleaching events, which will make corals less biodiverse, as coral species with low temperature resistance will die out first, and less abundant as certain areas will bleach faster due to their location, e.g. a location which has a lower water depth.

5.4.3. Combined effects of discrete and continuous stressor effects.

In this experiment, the effect of continuous and discrete anthropogenic stressor effects are tested. Based on the results of the former experiments, it is likely not beneficial for coral populations, which is confirmed by the results from the simulation in figure 5.11. In the experiment, the reef finds an equilibrium, in which corals are completely eradicated, herbivorous fish are less productive, and macroalgal populations are thriving. Again this experiment was done under constant stressor parameter values, but the results indicate that the stress humans are putting on coral reefs will result in coral-algal phase shifts, if anthropogenic pressure is not lifted. In reality, it is unlikely that coral reefs will disappear all over the world, but coral abundance will be a lot less. However, it is probable that reefs will disappear locally in some places, which will create new ecosystems. The new ecosystems will likely be less productive in terms of herbivorous fish populations.


Selected Variables
500
400
300
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Time (Year)
Coral coverage : Combination of all discrete and continuous stressors(ha)
Herbivorous fish biomass : Combination of all discrete and continuous stressors(kg)
Macroalgae coverage : Combination of all discrete and continuous stressors(ha)

Figure 5.11

6 Discussion, conclusions & reflection

6.1. Discussion

These results give a conceptual understanding of the variables, relations, and behavior at play in (sub)tropical social-ecological coral reefs, and quantitative indications for the occurrence of shifts in coral reef ecosystems under stressors. The findings concerning the interactions in social-ecological coral reef systems build on the elegant work of Hughes et al. (2017), which explores the future prospects for coral reefs in the Anthropocene. In their literature review, they explore future coral reef dynamics and opportunities for action. This research study takes a step in the direction of finding a safe operating space for coral reefs (see Rockström et al. (2009)) by investigating multiple drivers and feedbacks in environmentally changing coral reefs, and by looking at combined effects of multiple drivers simultaneously. The fact that this research study conceptually modelled the interrelations in coral reefs, serves as a basis for further understanding (potential intervention measures of) coral reefs worldwide, which could lead to local action to protect reefs from further degradation and boost their capacity to survive climate change.

The approach, described in the study, allows for follow-up analyses in other contexts. One of the challenges of working with marine coastal systems is the large variability. Systems differ in species and environment. However, the qualitative stock-flow diagram can be used and adapted to fit other contexts. Taking into account many variables and relations in the qualitative stock-flow model, a first estimation of the implications of intervention measures, such as artificial reefs, can be researched. However, the success of such an intervention lies not only in ecological effectiveness, but also depends on complex socio-economic interrelations (Brochier et al., 2021). The qualitative stock-flow model can be expanded to gain understanding of both the implications on the social-ecological systems as on the socio-economic systems, such as strong feedback effects in weak governance systems or high levels of illegal activities (Mackinson et al., 1997; Cinner et al., 2011; Uehara et al., 2021). The qualitative stock-flow model provides the opportunity to link the socio-economic subsystems to a ecosystem dynamics. Furthermore, the coral reef system model shows a first attempt to quantitatively describe coral reefs over longer periods of time. With corals sighing under the pressure of climate change this century, insight in long-term dynamics is gaining importance (Hughes et al., 2017).

As the field of coral reef research moves from observational studies to experimental studies to test methods for coral preservation when battling the hard conditions of the 21st century, there is a growing need for insight in the relatively long-term effects of climate change and other stressors on reefs. Uncertainty about the long-term pathway of corals is halting potential intervention. In the field, many short-term experimental artificial reef studies have been conducted to see impacts on ecosystems (Boström-Einarsson et al., 2020). The (short-term measures) effectiveness of these combined with insight in long-term coral reef ecosystem development can provide a strong basis for restoration. This study already made a start by creating the coral reef system model, but a stronger push for this type of research can elevate the benefits of current coral reef research. Moreover, the field of coral reef research is a relatively small research field, and suffering because it is unfamiliar.

Coral reefs have been overlooked, due to the 'out of sight of mind' mentality that corals are facing, especially in social-ecological contexts. Research can contribute more to creating awareness in the public.

A unique contribution of this research is the use of list extension diagrams for processing the interviews. The use of the list extension diagrams serves as a good method for representing the causal relations described in answers of participants. Moreover, list extensions diagrams are easily converted to other system dynamics (SD) model types, acting as a bridge between interviews and computer-based SD modelling. SD as a tool for coral reef research has potential to lift some of the uncertainty surrounding long-term effects. Hughes et al. (2017) called for stronger heuristic models for analyzing multiple stressor effects in reefs. SD offers the freedom to explore these long-term stressor interaction effects, such as was done in the coral reef system model from this study. However, the modelling of these systems require careful consideration of the strengths and limitations of the modelling method.

SD is a strong tool for describing the feedback in the system, and calculating the non-linear effects, which characterize social-ecological coral reef systems. Studies have been conducted on individual stressor-stressor effects, such as by Diaz-Pulido et al. (2012) and Ban et al. (2014). The ability of SD to combine the insights on these stressor-stressor interactions as well as calculate population behavior based on the effects, and its ability to tailor the scope to the purpose of the research provides added value for a research field with complex interactions. By simulating effects on population behavior some insight on long-term dynamics can be gained. In this research study, SD was used for the case of the marine area of Shimoni, Kenya. The qualitative stock-flow model is adaptable to other reefs and reef types as well, and can serve as a basis for further modelling of coral reefs, because the case study site was not determinative for the model design. The dynamics described in the qualitative stock-flow diagram can be found in coral reefs all over the world. The coral reef system, model on the other hand, will work best for fringing and barrier reefs, because the problems atolls are experiencing are often related to sea-level rise, the carbonate budget and the water depth of the reef, while the coral reef system model is more scoped towards population shifts in reefs. Although, coral-algal phase shifts can also occur in atoll reefs, it is often not the main focus.

Although this type of modelling suits complex systems like coral reefs quite well, dealing with uncertainty remains a critical point in the use of SD. One way of reducing the uncertainty in future research, could be the use of 'Exploratory Modelling and Analysis' (EMA), by increasing the number of runs, the uncertainty decreases. However, one should be very wary to take the simulations as objective truth for future ecosystems. Due to the complex nature of the system, validation of models can create challenges. Models in general do not depict reality only a simplification thereof, in the case of SD it needs to be made very clear for which set of parameters and assumptions the model can give insight. Water-based systems, specifically coral reefs, exhibit more dynamical behavior than land-based systems due to the fluidity of the medium, and restoration of water-based systems is, therefore, perceived as prone to failure (Saunders et al., 2020). Also in this research study, validation proved to be tricky endeavor. Population behavior needs to reflect real systems representatively, however, due to the large amount of interactions and feedbacks, as well as very high macroalgal birth rates, the coral reef system model becomes sensitive to changing growth and death rates. Furthermore, parameters, such as growth rates and death rates are not constant over time, herein assumptions can be made. In this case, some important assumptions come from the Lotka-Volterra equations on predator-prey and interspecific competition interactions. So although SD is strong in describing feedback, simulating models needs additional work to represent real-life systems better.

At the end of the day, SD has the potential to be a strong tool for coral reef research, as it is capable of catching the interactions, feedback and non-linearities, which the social-ecological coral reef systems are filled with, but SD can also be a means to eliciting interdisciplinary expert knowledge, as evidenced by the cognitive mapping method through list extension diagrams designed and employed in this study. Lastly, SD has been shown to be a communicative tool in natural resource management, able to gain some traction and create awareness for coral reef restoration action and put coral reefs 'in sight and in mind'.

6.2. Conclusions

In order for (sub)tropical coral reefs to pull through the 21st century, reef stressor effects need to be mitigated. A better grasping of the interrelations and dynamics existing between coral reefs and humans, can contribute to understanding the potential long-term effects of future interventions, such as artificial reefs. Thus, creating a basis for restoration of coral reefs.

The variables and relations, determining the long-term dynamics within (sub)tropical social-ecological coral reef ecosystems, are represented in the qualitative stock-flow model, developed in this study. Coral reefs consist of interacting plants, animals, and humans, and some of their interrelations are more important than others coral reef restoration. The qualitative stock-flow model shows the critical factors and the interrelations in reefs. Corals and macroalgae are competing for their spot in the reef. Herbivores consume macroalgae, and in exchange corals provide place for herbivores to protect them from predators. Unfortunately, external pressures, such as ocean acidity, sea level rise, storm frequency, and temperature-induced bleaching events, cause coral death to exceed coral growth (i.e. coral reef degradation), and with it, degrade ecosystem function. Ocean acidity decreases carbonate accretion rates and increases chemical bioerosion effects. Sea level rise can hinder light from reaching microalgae inside corals, but can also cool corals in times of heat stress. Ocean warming have increased storms' intensity and frequency, causing brittle corals to break. Furthermore, extreme water temperatures cause coral dieback. In addition, overfishing, tourism, and pollution push the ecosystem towards coral degradation. Overfishing creates imbalance in reef biodiversity, tourism causes physical degradation to hard coral cover, and pollution induce harmful algal blooms, spreading coral disease and overgrowing corals. The dynamics, resulting from the variables and relations, can acts as limiting factors on coral reefs.

The long-term dynamics, shaping the marine environment of (sub)tropical social-ecological coral reef ecosystems, are explained in the conceptual dynamics analysis of the qualitative stock-flow model, unveiling that populations of corals, macroalgae, and herbivorous fish rise to their respective carrying capacities in the ecosystem. In the interspecific competition between macroalgae and corals, the available surface area is restricting further growth of the species, and the dominant species is determined by the environmental conditions. The conditions determine dominance, because they affect the growth and death rates of species. Corals have risen over thousands of years, because the ecosystem conditions in the Holocene era were more beneficial for coral growth than for macroalgal growth. Low nutrient systems, herbivorous fish presence, and pleasant water temperatures, are good conditions for corals to grow. Conversely, corals adapted to these conditions. Now, moving into the Anthropocene age, the delicate balance shifts (Hughes et al., 2017). Stressors are changing carrying capacities and growth rates, favoring macroalgae over corals, and disturbing the lag cycle between macroalgae and herbivorous fish populations. The coral reef system model indicates that it is not an individual stressor threatening ecosystem balance, but, instead, the combination of stressor effects, potentially damages the ecosystem catastrophically.

The implications of key patterns of dynamic behavior for long-term intervention in (sub)tropical social-ecological coral reef ecosystems can give coral a fighting chance by addressing the damaging dynamic behavior changes. By lowering carbon dioxide emissions and extraction of earth's resources, a push towards sustainable resources use can be realized. However, climate change effects are delayed, and corals are under pressure now, with likely exacerbating environmental pressure to rise in the remainder of the 21st century. Therefore, the use of measures stimulating coral growth and lowering coral death, can give corals the edge needed to pull through. Artificial reefs are an invention, stretching the survival of coral fragments and introduces substrate for corals to attach, effectively increasing coral growth potential, as is seen in the qualitative stock-flow model. Another option is to halt positive feedback mechanisms, preventing exponential degradation of coral reef ecosystems. The experiments of the coral reef system model indicated that the continuation stressors will harm coral reefs heavily throughout the century. Coral reef ecosystems might shift from a coral dominated state to an algal dominated state, with a less productive herbivorous fish population. The combination of event-induced coral deaths and continuous stressor effects lower coral resilience to levels of exacerbating degradation. The effect will depend on the impact and frequency of stressors, intervention to lower the impact can contribute to halting the downfall of coral reefs.

Understanding the dynamic behavior of (sub)tropical social-ecological coral reef systems in the Anthropocene will play a role in maintaining coral reefs, because it serves as a basis for understanding intervention effects. Artificial reefs, for example, can locally increase the limits of coral growth in social ecological coral reefs. However, an artificial reefs should not be used on their own. The qualitative stock-flow behavior analysis showed their use is stay of execution, if the climate change trajectory remains unchanged, and will only act as a temporary symptomatic solution. Although some coral species can withstand stressors better than others, physical boundary transgression will, ultimately, affect all reefs. Scaling back anthropogenic impact on reefs now, gives reefs breathing space and increases resilience for difficult times to come. Making the Anthropocene not only an era of transgression of physical boundaries, but also of re-entry of the safe operating space for ecosystems. Thankfully, it is unlikely that coral reefs will disappear completely, but they will become less widespread and productive. However, the degree of abundance and productivity is still in our own hands, and will improve recovery of reefs in the future.

6.3. Reflection

Firstly, a reflection is given on the research process, including changes in methodology, research goal, modelling purpose, in advance identified risks, and the research study's contribution to society. Secondly, a reflection is given of the personal process, which includes reflection on the effect of motivation, personal skills, and personal risks on the research.

6.3.1. Reflection on research process

The research study underwent a few changes to the research process along the way, because new insights required the process to change. During the course of the research, the (beforehand created) plan proved not always useful for the goal of the research, and sometimes strategies had to be adapted and other times, they worked very well. In this section will be reflected on the success and challenges within this research study, and what lessons can be taken for other research processes.

One of the predetermined risks was the setting up of the interviews. Experts on coral reefs usually have busy schedules. The strategy to minimize the risk was to create a list of names of people and organizations to contact and to start very early on with contacting the experts. This strategy proved to be fruitful, and six interviews were set up within a timeframe that was reasonable to take them into account in the study. At the beginning the aim was 3-5 interviews, the strategy proved to effective. Another effective strategy in setting up the interview is making use of the social network around you, and making use of the social network to contact the people will increase the chances of them agreeing. This strategy is not a guaranteed recipe for success, but minimizes risk of ending up empty-handed.

Secondly, for the cognitive mapping in the dynamic relations part of the interview, the plan was to draw the relations on paper. However, in the two practice interviews, it quickly became apparent that this takes the interviewer's focus away from the conversation. Vital for this research study is to steer the conversation towards interviewee's knowledge within their own personal experiences, which also relates the subject of the research. Having your attention being drawn to writing down the relations and variables will therefore have an unwanted effect on the conversation and in the end decrease the effectiveness of the interview. For this reason it was chosen to only have pen and paper for sketching a certain type behavior a respondent wants to show, but for the rest of the conversation stay in the moment and let the interview take its natural course. The conversation will be more dense with information and when agreed with the respondent can be replayed to extract the information, so the information is not lost. The cognitive mapping still happens, but the map stays cognitive, unless written clarification is needed. After the interview, the information could be extracted from the recording with the List Extension diagram.

Thirdly, for the processing of the literature review information, it was planned to create a separate diagram, with the information of the literature. The literature review diagram would be combined with the information from the List extension diagrams to create a conceptual model. However, during the course of working on the literature diagram, the realization came that interviews also inform the literature study, and the literature study inform the interviews, because the interviews and literature study were executed over the same period. Due to the great amount of overlap between the interviews and the literature, the diagram that was created was already a synthesis of insights from literature and interview information. Therefore, it was chosen to not create a separate diagram for the literature review, but instantly synthesize the literature review information with the list extension diagrams into, what is now, the qualitative stock-flow model. The literature review is processed in textual form, ridding the research process of superfluous modelling, which can be time-consuming, and freeing up valuable research time. The qualitative stock-flow diagram is now iteratively built, by going back and forth between literature and interviews. The iterative approach, in the end, increased quality of the model, as insights were added and adjusted the current version. However, I think this approach worked well in this particular case, because the information from the literature review and the interviews contains many similarities, making synthesizing straight forward. In cases where information is much more conflicting the synthesis might not come so natural. Therefore, the aforementioned approach might only work in research fields, which are relatively aligned, like is the case for coral reefs.

Another change, over the course of the research, was a slight change to the the model purpose. The intention was for the model to inform on long-term effects of artificial reefs on coastal flood protection as well as ecology. The model purpose has shifted to informing on the ecosystem state instead. Reason being that insights on the workings of coastal flood protection relied on ecosystem states. Coastal flood protection is heavily related to sea level rise and frequency and intensity of storms. Sea level rise increases water depth, which decreases the wave energy dissipating function of coral reefs, while storms severely damage coverage also decreasing this function. However, a proxy exists for analyzing the wave energy dissipating function of reefs. A net positive carbonate budget indicates a healthy reef, which is resilient against sea level rise and storm effects. a net positive carbonate budget relies on the health of the coral reef ecosystem. Therefore, the model purpose shifted to the ecosystem dynamics, as this can be used as a proxy for the coastal flood protection. In this case newly acquired insights on the structure of the system informed the model purpose to better align the purpose with the research goal. A lesson for further research is that leaving some room to adapt the research study to new information can increase the research quality. Especially in cases where authors have limited expertise on the research subject beforehand.

One of the main learning experiences in this research process, is taking a more iterative approach to validation of the coral reef system model. In this research study, the validation was executed when the model was finished. However, in complex social-ecological systems modelling strong validation is necessary to be able to reflect the real-world system representatively. In complex cases, a more iterative approach to the validation might reduce modelling time and creates the strong validated model that is required. In this particular study, the iterative approach could have come from intermediate meetings with experts. The coral reef system is validated through an expert validation and validation tests, however, multiple iterative expert interviews would have created a stronger validation. One approach would have been to apply the same strategy of the setting up of the interviews to the validation meetings, and show the progress and built the model from there.

The other predetermined research process risk was the collection of data. This proved to be less of a struggle than thought beforehand. This was due to the strong conceptual start of the research. During the course of the literature review, it is unavoidable to also find literature on data in social-ecological systems. The literature could be used later on during the setting up of the coral reef system. Furthermore, the experts in the field often were familiar with interesting articles or researchers, which could be looked at. Therefore, the groundwork of around six weeks of gaining conceptual understanding had already been laid. In research which does not take the conceptual approach first, it might be wise to plan significant time for data search.

Finally, insight in dynamic behavior of (sub)tropical social-ecological coral reef ecosystems can support humans in maintaining vital ecosystems. However, still steps forward have to be made, in terms of awareness and policy. Specialized companies already possess advanced engineering techniques to improve coral reef ecosystems. However, knowledge on the effect in the social-ecological dynamics of coral reef ecosystems are missing, which are pivotal for success. Furthermore, higher priority in policy making is needed, but in the face of climate change adversity, where coral reefs are not the only threatened ecosystem. It can, understandably, be difficult for policymakers to prioritize, trade-off, and balance resources. Increased awareness, though, might contribute to finding the right balance for preserving these vital ecosystems, and with it, its ecosystem services for society.

6.3.2. Reflection on personal process

For the reflection on the personal process, I discuss personal successes, pitfalls, and motivation, to draw lessons from this process for future endeavors. By means of examples, I will demonstrate how these occurred in this research study.

The best decision in the research, in my opinion, I made at the very start. I started the first few days with setting up all administrative tools, which allowed me to work in a structured manner. This included setting up four logbooks I was going to use during the course of the research: the activity logbook, the contact logbook, the literature study logbook, and the data collection logbook. Later on also the mental model logbook was added on the recommendation of my supervisor. The logbooks allowed me to document my activities throughout the research, and I found it helped to structure thoughts, break tasks into smaller pieces, and decreases procrastination. Furthermore, a template was created for writing the research report, allowing me to have a place to assemble all the pieces of work activities. As this is a personal process, it might not work for everybody. The structured approach worked for me, because it suits my personality as I like to work ambitiously, goal-oriented and disciplined. Taking those initial days for these administrative task, has paid back in the quality of the research.

In my ambition, goal-orientation, and discipline also hides some of the personal risks, which have reared their head. In my ambition, it happens that I become fixated on reaching a goal and get hung up in an aspect of the research. At the start this has been of the predetermined risks, and in modelling the stubbornness did come forth. The writing of the report was suffering under the endless adaptions to the coral reef system model, until it would have been perfect. However, one of the clichés of modelling is that it is never perfect and never finished. As the mitigation strategy for this personal risk, I relied on the committee to push me through this phase. In this case, my supervisor pushed me away from creating the perfect model and start on the writing, which in the end has been the right choice for finishing in time. Relying on another person to identify this moment, and responding to this indicator, was the right strategy and paid off in this case. Another perspective one can take on being stuck in the model building phase is: did you, in your over-ambition, take up too much work? In the end, I think I estimated the workload correctly, but personally I believe in pushing oneself to do better leads to personal growth, as you learn by taking small steps out of your comfort zone. One way of doing so is setting a high ambition level, which is why I do not regret the decision to do so. However, it can potentially also lead to disappointment, when things do not turn out satisfactorily. Finding the right balance between ambition and over-ambition can be tricky, and is a learning process still. A possible way of dealing with this is to create a social safety net, preventing you from going overboard. In this case this can be a thesis committee.

Finally, a common struggle for people doing relatively long-term research is to stay motivated during the course. One simple way for me to stay motivated is having chosen the right subject. Choosing a subject I was passionate about, lowered the barrier to start working on the research. Furthermore, I learned that social contacts during the course of the research is a good way for me to stay intrinsically motivated. Doing the interviews and learning from experts on coral reefs, gave the research variation in task, which prevents slipping into a rut. During the course of the research, I felt decreased intrinsic motivation in the modelling of the coral reef system as the daily tasks lacked variety. I already mentioned that the iterative validation meetings, would have benefitted the model building period, however, the social aspect of the validation meetings also adds to the variety in the research activities. The social aspect and variety would have contributed to maintaining high levels of intrinsic motivation during the personal process of the research.

Looking back on the overall process, I am relatively satisfied. My goal for a thesis was to try choose a subject in which I felt I could make a difference, which, in my opinion, is achieved. The research field is relatively small and the need for attention is high. Contributing my efforts to places, which are in dire need, gives me that feeling of satisfaction. I think I pushed myself to make that contribution. This is also the reason I cannot say I am entirely content since, to me, pushing yourself to the limit entails giving your entire effort—in this case, your time—to the task at hand. However, having this perspective means that there is always some things, where you thought you could have done better. Likely, devoting 100% of your efforts to a cause, will give unsatisfactory results, as it can be self-destructive. Turning this feeling off is difficult, but for me it helps to remind myself of what my mother, as a medical professional, used to say, about providing first aid: You first have to help yourself, before helping others. In other words, self-destructive actions will limit your ability to contribute to helping others. I think this applies to more situations, whether it is providing first aid or writing a thesis, which is why, overall, I can be proud of my efforts.

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A

Table of search terms

Ecology	Society	System Dynamics
Anti-phase	Artificial reefs	Boundary adequacy
Algae	Building with nature	Causal diagram
Artificial reef(s)	Coastal flood protection	Causal loop diagram
Atoll reef	Coastal flood risk	Competitive
Barrier reef	Ecosystem services	Conceptual diagram
Biodiversity	Fisheries	Dynamic
Bioerosion	Food production	Feedback
Bleaching	Management	Fixes that fail
Carbonate budget	Nature inclusive design	List extension diagram
Carbonate budget	Nutrient pollution	Lotka-Volterra
Climate change	Pollution	Predator prey
Coral	Protection	Relations
Coral larvae	Restoration	Shifting the burden
Coral reef(s)	Social-ecological system	Stock-flow diagram
Coralline	Tourism	Success to the successful
Density dependence		System
Disease		System archetypes
Ecosystems		Tragedy of the commons
Erosion		Variable
Food web		
Fringing reef		
Hysteresis		
Macroalgae		
Nutrients		
Ocean acidification		
Overgrowing		
R and K selection		
Recruitment		
Reproduction		
Sea level rise		
Sedimentation		
Stable-2-cycle		
Storms		
Structural complexity		
Temperature		
Trophic		
Trophic cascading		
Trophic structure		

Table A.1: The table of search terms is divided in three categories: Ecology, Society, and System Dynamics. The terms are combined within and between categories to create suitable search terms.

B

Script Expert Interview

1 day prior to the interview:

1. Message interviewee on the meeting
2. Introduce the system archetypes and explain interest in talking about the relations
3. Show enthusiasm for the interview
4. In case of online interview, send invite link

START INTERVIEW
Part A: Warming up

1. Ask if the person agrees to record the interview either audially or audio-visually and if they agree to sign the informed consent form.
2. Explain the schedule for the interview (Typically 45 minutes, but dependent on expert availability)
3. Explain research (what the study is about (subject, geographic and time boundaries), relevance, goal, reason for interview)
4. Interviewee ((Professional) background, tasks, work, experience)
5. (Optional: Organization (vision, goal, structure, business activities))

Part B: Dynamic relations

1. Link the interest in dynamic relations to the research objective and show the system archetypes
2. Ask questions on the structure, relations, behavior and boundaries in time and space:

   A If you look at the relations as depicted, what would you change / add / remove?
   B What variables would you change / add / remove ?
   C What factors play a role in . . . ?
   D What specific relations needs deeper understanding?
   E What level of detail is needed for understanding?
   F On what scale do these relations have an effect?
   G Could you draw the relation as you think it is?
   H Could you tell me something about the relation between . . . and . . . ?
   I What behavior do you think this relation exhibits?
   J How predictable do you think this relation is?
   K What size / order of magnitude do you think this variable / relation is?
   L Over what time period do these variables affect each other?
   M What is the speed / rate with which this variable changes?
   N Which of the variables / relations is most important for the behavior of the system?
   O How important is this relation / variable?
   P How much does this variable / relation depend on that variable / relation ?
   Q How does this variable / relation effect . . . ?
   R What is a unit used for measuring this variable?

S Is the relation between . . . and . . . continuous, or is there a start and stop?
T How strong is the relation between these variables?
U When does the effect of this variable start / stop?
V What happens when this variable goes to zero / infinity?
W On what level of aggregation would you notice the effect of this relation?
X What actors are able to influence this variable?
Y How is this system / relation / variable influenced by actor?

PART C: Finish

1. Ask if they have any questions for me
2. Summarization
3. Feedback on completeness (Gaps in information of discussion)
4. Benefit for the interviewee (Sharing of the thesis)
5. Acknowledgement
6. Ask if they are interested in doing a follow up interview in about 2 months for the purpose of validation

END INTERVIEW

1 day after the interview:

1. Message thanking the person for the interview
2. Add in the message a short summary of the interview
3. Reiterate the sharing of the thesis if they showed interest

***Necessities in-person interview:**

1. Copy of Informed consent form
2. Dictaphone, camera
3. Copy of system archetype relations
4. Pen and blank paper

***Necessities online interview:**

1. Digital copy of informed consent form
2. Digital copy of system archetype relations
3. Programme for drawing (e.g. DrawIO, Powerpoint)
4. Drawing pad connected to computer

C

Informed consent form

Informed consent form

You are being invited to participate in a research study by Pepijn Kruseman Aretz from the Faculty of Technology, Policy and Management at TU Delft. The study is part of as a thesis graduation project for the Master of Complex Systems Engineering and Management.

The purpose of this research study is to explore the effects of artificial reefs on the coastal ecosystem and will take the form of an interview. The data, including video/audio recordings and interview transcripts, will be reviewed and analyzed for the study.

The interview data and any personal information will be stored for the duration of the project. As with any online activity the risk of a breach is always possible. To the best of our ability your answers in this study will remain confidential.

We will anonymize personal data and reporting only their function as expert.

Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any questions. Data will be destroyed after the conclusions of the research, approximately 5 months.

____________________________ ____________________________ __________

Name of participant Signature Date

I, as researcher, have accurately presented the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

____________________________ ______________________ __________

Researcher name Signature Date

Pepijn Kruseman Aretz – p.d.krusemanaretz@student.tudelft.nl

D

List extension diagrams

D.1. Respondent A

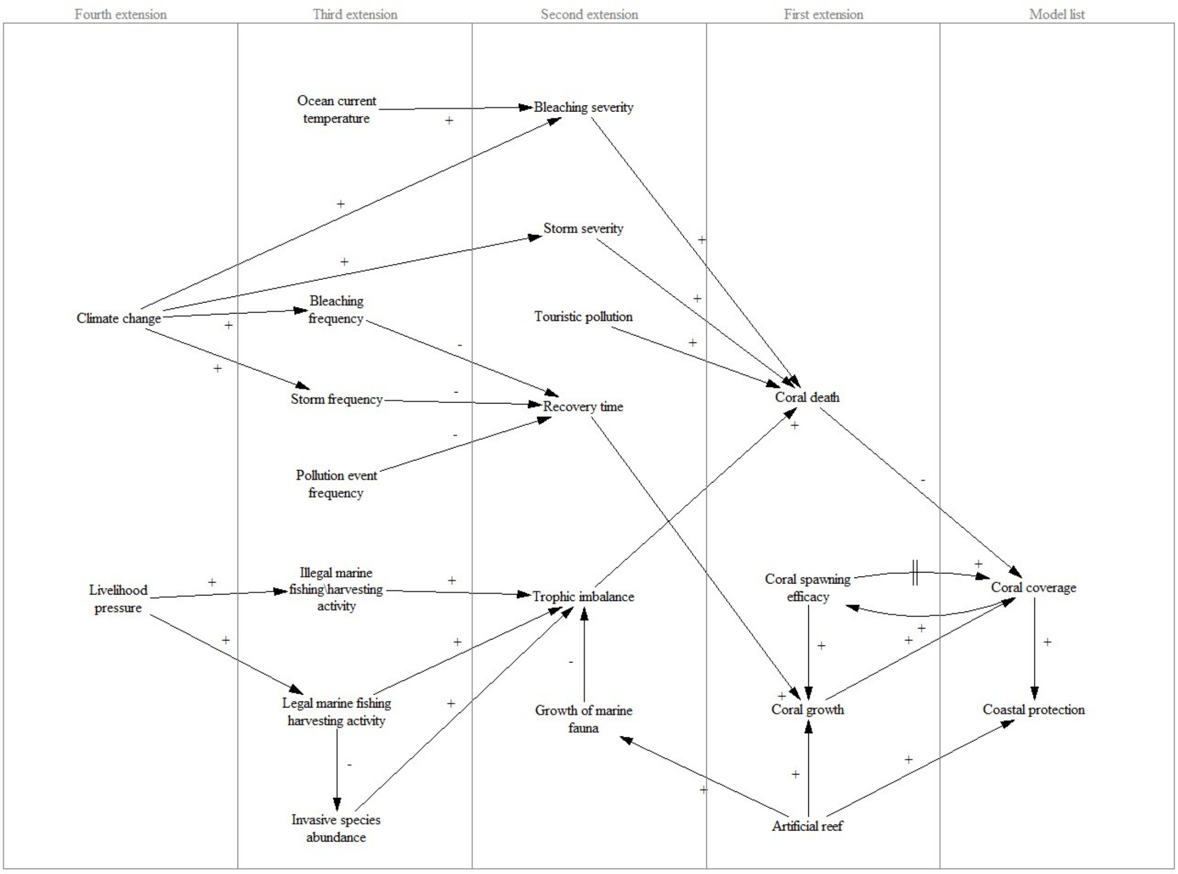

Figure D.1: List extension diagram from Respondent A's interview

What is present in the diagram?
In the list extension diagram of respondent A, the model variables are the coastal protection and coral coverage. Artificial reefs have a dual goal in this regard by improving both the coastal protection, and the coral and marine fauna, like fish and invertebrates beside corals. Corals grow with a certain growth rate and the more corals there are the faster the coral growth, as well as an increased coral spawning efficacy, displaying the archetype 'success to the successful'. However, due to the relatively slow growth rate of corals, it takes some time for corals to develop to the point that they can reproduce themselves,

causing a delay between the spawning efficacy and the coral coverage.

On the other hand corals are under pressure by many different things: pollution, tourism, bleaching, storms and overfishing. An important dynamic according to respondent A is the degradation of coral resilience, due to the increased storm and bleaching severity and incidence, as a result of climate change effects. Higher incidence of bleaching, storms and pollution events gives coral reefs less recovery time. A lower recovery time means that corals are not able to recuperate fast enough or not up to the right level, resulting in behavior where coral coverage decreases like a sawtooth down below. The effects are exasperated by human activity from tourism and pollution. Tourism causing a slow continuous decline in health through pollution and damage. Similarly, fisheries are causing a decline by tipping the balance in the trophic structure of the reef, giving more room for dominancy of invasive species or the creation of a monoculture on the reef. Monocultures can be particularly damaging for delicate systems like coral reefs. Harvesting and fishing happens legally as well as illegally. The reefs often serve as primary source of food or income, and dependence on the reef for survival is high. Due to this livelihood pressure, locals will risk the punishment from the illegal activity to continue fishing.

Interesting in conclusions from this interview are that there is an archetype found. 'Success to the successful' this is not only true for the corals, but also for the other invertebrates and fish. When the reef is in balance, meaning the diversity and abundance is within a natural range, this battle for dominancy is not threatening to the reef. However, when the imbalance increases due to other pressures, like marine harvesting practices, then a species can become dominant, creating a hurtful monoculture in the reef. Furthermore, there is a clear distinction between discrete events and continuous events. Discrete event frequency is increasing, creating less recovery time for the corals. In these periods of discrete degradation events (bleaching, storms, pollution events), the coral coverage decreases rapidly in a short time. Continuous pressures, like pollution and fishing create a more fluent degradation.

What is missing in the diagram?
Notably that the effects of algae was very little mentioned. The trophic imbalance was mentioned, however, algae play such a large role and is often the dominant species in the monoculture. Especially in areas in which overfishing is a problem.

Furthermore, there is no real mention of coral diseases, which thrive under higher water temperatures and is one of the reasons for the bleaching events to be so disastrous to coral health. Corals become much more susceptible to the coral diseases during high temperature events.

D.2. Respondent B

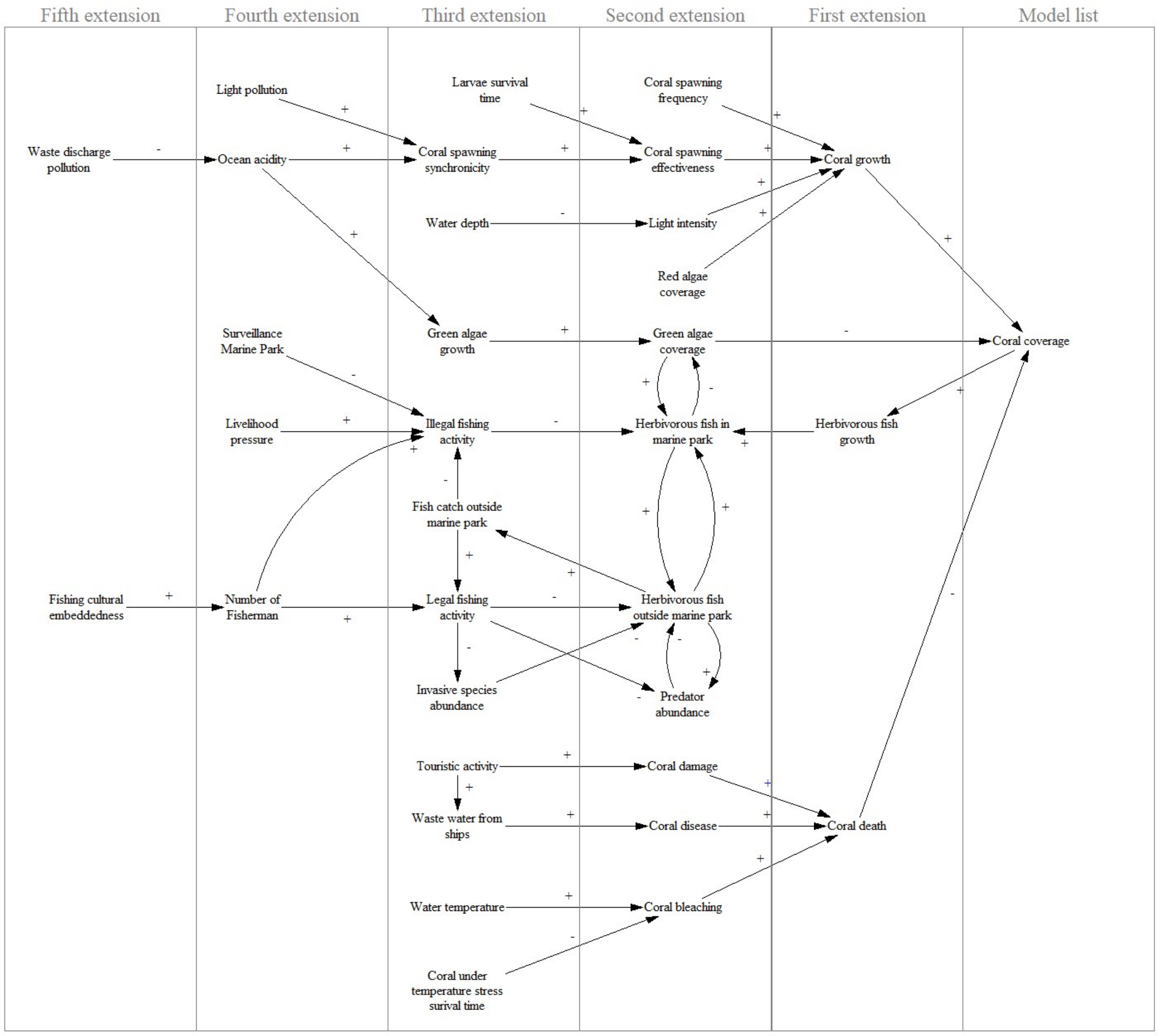

Figure D.2: List extension diagram from Respondent B's interview

What is present in the diagram?
From the conversation with respondent B, the list extension diagram was drafted. From the conversation a clear distinction between coral growth and coral reproduction was identified. Coral spawning is a 1 or 2 day event per year in which all corals release their coral larvae. The synchronicity of this event for all corals is highly important as the coral eggs and sperm need to combine for sexual reproduction. However, the cells do not survive for more than around 24 hours in the hostile ocean environment. A desynchronized event can drastically lower the spawning effectiveness. The timing of this event is influenced by the phase of the moon. However, in the area of Cozumel, where respondent B was situated during his/her volunteer work, he/she experienced coral spawning over 3 days, caused by the increased acidity of the water from open sewage systems and the light pollution from the coastal built environment, fading the light from the moon. The growth of coral reefs is the other manner for increased coral coverage, where the corals grow in size. Both coral spawning and coral growth increase the coral biomass on the ocean.

The coral coverage was affected by the algae abundance in the ocean, but a distinction had to be made between the two types of algae: Green algae and red algae. Green algae are in competition with corals for space on the reef and also can grow on the corals. Corals depend on the herbivorous fish to eat the green algae from their skin to have unaffected growth. Red algae, in specific Coralline, is an important algae for the growth of corals and young corals can settle more easily in places with a high density of coralline for them to be able to use for growth.

The dependency on the herbivorous fish made the corals also vulnerable, because if the overfishing becomes to severe, it can overgrow the corals and in the end will have a negative effect on the coral coverage. In the area there was high fishing activity, legal as well as illegal activity. Fishermen were not allowed in the marine park, however, still everyday people tried to fish in illegal spots and had to be patrolled away. Mainly due to the cultural embeddedness of the fishing in the area and the livelihood pressure on the locals, they still tried to fish in protected areas. Some invasive species were allowed to be fished in the area, e.g. the lionfish. The invasive species threaten the biodiversity as they have few predators.

Keeping the trophic balance in the reef is one of the main dynamics. All species have their function. By removing a keystone species a trophic cascading effect can be induced, which in the end is disastrous for the diversity and the abundance of certain species in the reef. Lastly, respondent B said the corals have a strong interaction with the water temperature. If the temperature ascends above the threshold of 30 degrees Celsius for 2 weeks the corals start to bleach, depriving them of much-needed nutrition. If the coral bleaching takes too long the coral start to die. Touristic activity is also a factor that can cause coral death through abrasion or disease. Boats function as disease carriers, through the intake of waste water from different areas and bringing it over to other ecological systems.

What is missing in the diagram?
One of the large things that is missing is the erosion. Sedimentation was mentioned in relation to construction works. However, there was no mention of bio-erosion, which is an important dynamic for the reef. Furthermore, there is also no real mention of the effect of sea-level rise on the reefs. Also the interaction in the trophic balance could be more specific. There are actually more types of micro-algae, not only red algae. There is very little mention of corallivores as well eating the coral.

It is possible that some of these interactions are not as prominent in the places that respondent B visited. However, some omitted factors are global stressors, which are also at play in Cozumel, Thailand and Madagascar.

D.3. Respondent C

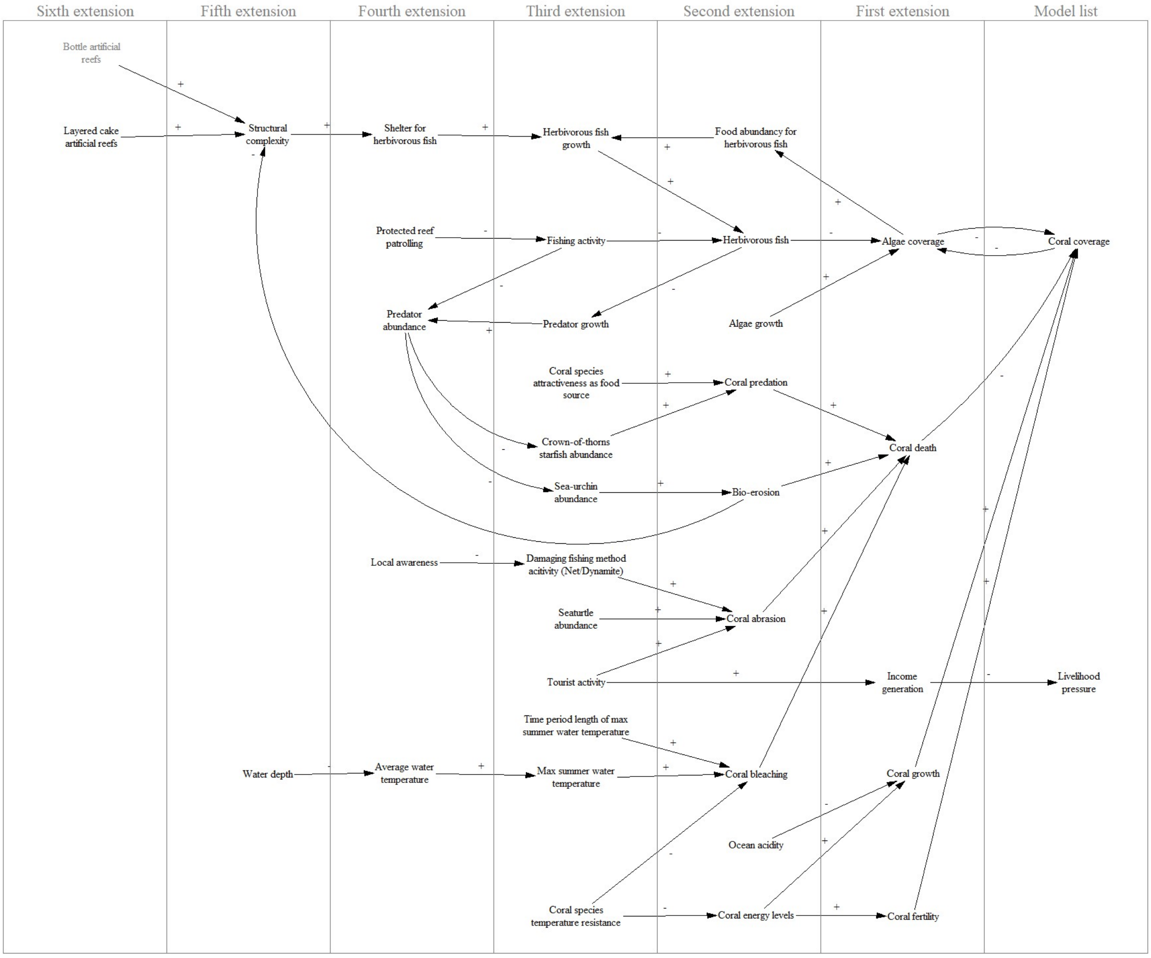

Figure D.3: List extension diagram from Respondent C's interview

What is present in the diagram?
This list extension diagram was created from the interview with respondent C. The respondent has done coral restoration efforts in Southern Kenya for 7 years and is a marine biologist. The restoration was done through a coral nursery where coral was grown until it was large enough to be placed in the artificial reef structures in the actual reef. The artificial reefs were bottle artificial reefs and layered cake artificial reefs. The artificial reefs provide the structural complexity which is needed for herbivorous fish to shelter, recover and sleep. The herbivorous fish provide a function for the coral by eating the algae, which grow on them.

However, in Southern Kenya there are some local stressors and global stressors threatening the coral species. The most impactful stressors are the overfishing, bleaching and bio-erosion. Overfishing is decreasing the herbivorous fish abundance, but also the predator abundance. For example the harvesting of giant triton and the giant wrasse, which indirectly increase the Crown-of-Thorns starfish and sea urchin abundance, because they lost their natural predator. The trophic imbalance induces other feedbacks and pushes the reef further from balance. For example, the starfish eats hard corals and the sea urchins cause bio erosion, which can erode a reef in a matter of years if it becomes a plague. The eroded are can be taken over by algae or be turned into sand if all structural complexity is lost. Other effects are the sea turtles which lay on the artificial bottle reefs, causing abrasion to the corals. Abrasion can also occur through certain methods of fishing or tourist activity. It has to be taken into account that tourist activity, also boost income and reduces local livelihood pressure. In Kenya, the part which is deteriorated by tourist is only local as tour operators are all taking them to the same location. So tourist activity impact is limited to the visited area of the reef.

A larger impact is the coral bleaching. The water depth determines the water temperature. The corals closer to the surface will bleach first. Bleaching depends on the maximum water temperature of the area and is measured in degree heating weeks. 1 degree heating week means that the water temperature is 1 degree above the maximum summer water temperature for 1 week. Roughly, the bleaching starts at 4 degree heating weeks and corals start to die at 8 degree heating weeks. However, the temperature does vary per species as some species have better temperature resistance than others. One of 4 coral species in Kenya is not used for the coral restoration as the potential is to low due to the low temperature resistance of that particular species.

Placing corals at lower depth may reduce temperatures, however, could also affect coral energy levels. The energy is likely needed to sustain the temperature resistance. As a result the temperature resistance could reduce at lower depth as well. Furthermore, reduced energy levels could also affect coral fertility of growth, but this needed some further investigation according to respondent C.

What is missing in the diagram?
In the diagram, ocean acidity was mentioned as a factor impacting the growth. Nutrient pollution in the area is less of a problem in the area of Kenya. Therefore the acidity is a lower impact stressor than some of the others. Respondent C mentioned that the acidity was a longer term problem and the direct threat of the coral bleaching is where most of the efforts were directed at.

D.4. Respondent D

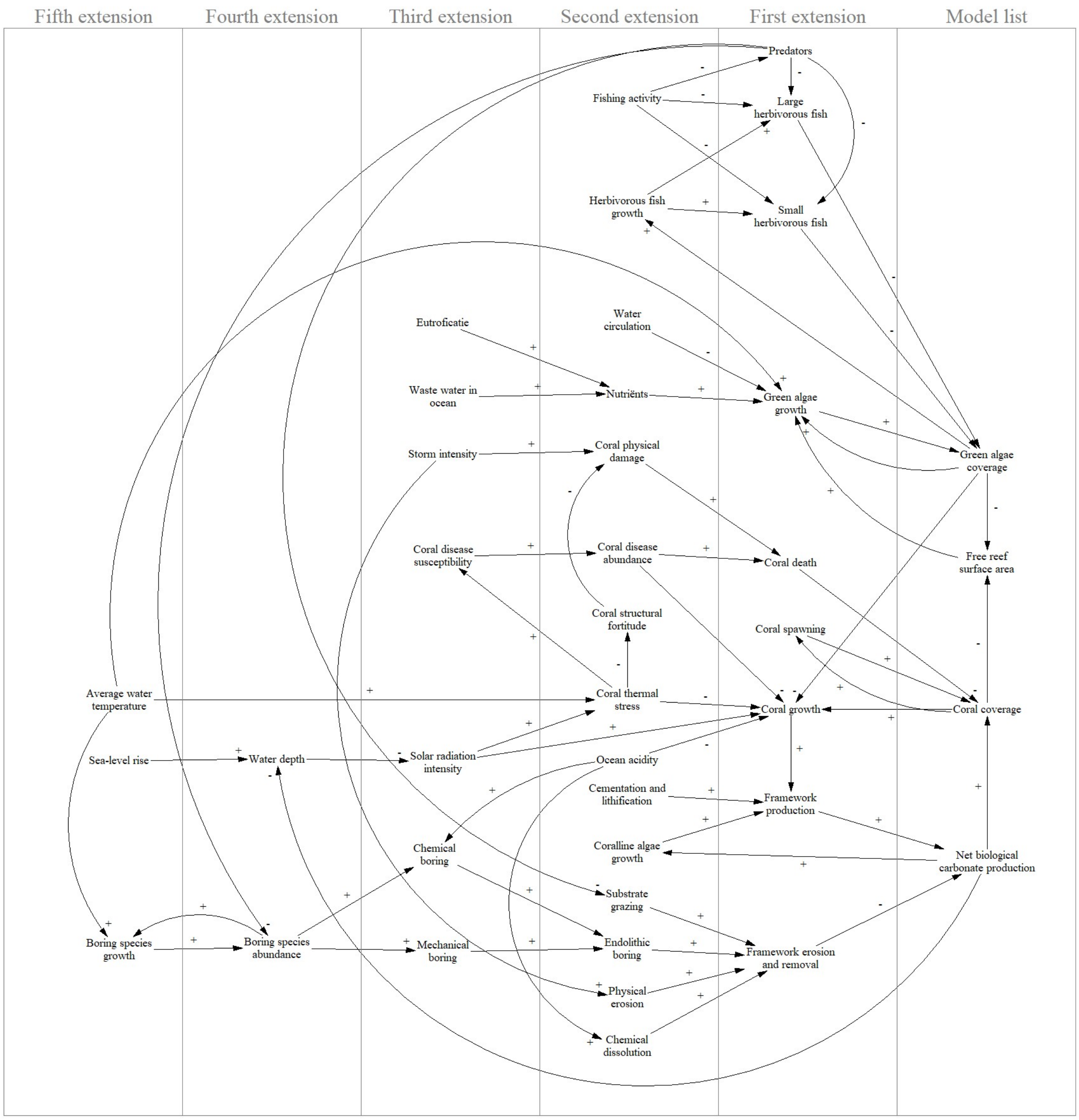

Figure D.4: List extension diagram from Respondent D's interview

What is present in the diagram?
The list extension diagram of respondent D is quite extensive. The diagram holds quite some marine biology jargon. The most notable characteristic is the high amount of feedback in the interactions. Lots of feedback occurs in the trophic pyramid, where through feedback happens through trophic cascading effects. Furthermore, there are some success to the successful archetypes between all these different species, but mainly between green algae and corals.

An important part of the diagram is the depiction of the carbonate budget. The carbonate budget consists of the processes producing carbonate framework in the reef and the processes eroding and removing carbonate framework from the reef. The framework is the substrate of which the reef is made. It gives the reef structural complexity and a net positive biological carbonate production is a very good indication of a healthy reef, because processes are balanced and the coral species are dominant in the reef ecosystem. Dominance of corals creates a very large biodiversity which is good for fish and other marine life. The production processes of carbonate are coral growth, cementation and lithification and coralline algae growth. The erosion processes are the substrate grazing by certain marine species, the endolithic boring by boring species, physical erosion to the substrate and the corals and chemical dissolution. These processes are influenced by the factors at play at the global level: Ocean acidity, Sea-level rise, average ocean temperature.

Average ocean temperature increases put corals closer to the bleaching threshold. Under thermal stress corals excrete their zooxanthellae algae, which they need to produce food via photosynthesis. Thermal stress also decreases coral growth, because they do not have the energy to grow. Ocean also decreases growth rate as the calcification of calcium-carbonate decreases under lower pH, as coral skeletons are made of calcium carbonate, their growth is impaired. The sea-level rise drowns reefs, because the water depth increases and the solar radiation which is needed for the photosynthesis of the zooxanthellae is less. However, the lower solar radiation also means that coral bleaching is likely less common, cancelling out some of the effect.

Furthermore, local stressors of storms, pollution and overfishing are really affecting the ecosystem. Increased amount of nutrients and high ocean temperatures create favorable conditions for green algae to grow. In theory, algae would be eaten by the herbivorous fish. However, due to the overfishing the fish population has decreased as well, giving the algae the opportunity to grow exponentially and take over the reef in a short amount of time. Corals do notoriously well in low nutrient systems and somewhat lower temperatures. When bleached, the coral loses structural fortitude and if this happens together with storms than this has disastrous consequences for the coral coverage, because the corals are eroded away. With all the conditions increasingly favoring the growth of algae and affecting the corals, coral biodiversity is seriously threatened.

What is missing in the diagram?
From the interview with respondent D, it became clear that the coral biomass can grow by regular growth, sexual and asexual reproduction. However, the effects on coral spawning are not as widely discussed as some of the other processes. Overall the diagram is relatively complete, with many of the stressors being in the diagram and the ecology being very specific.

D.5. Respondent E

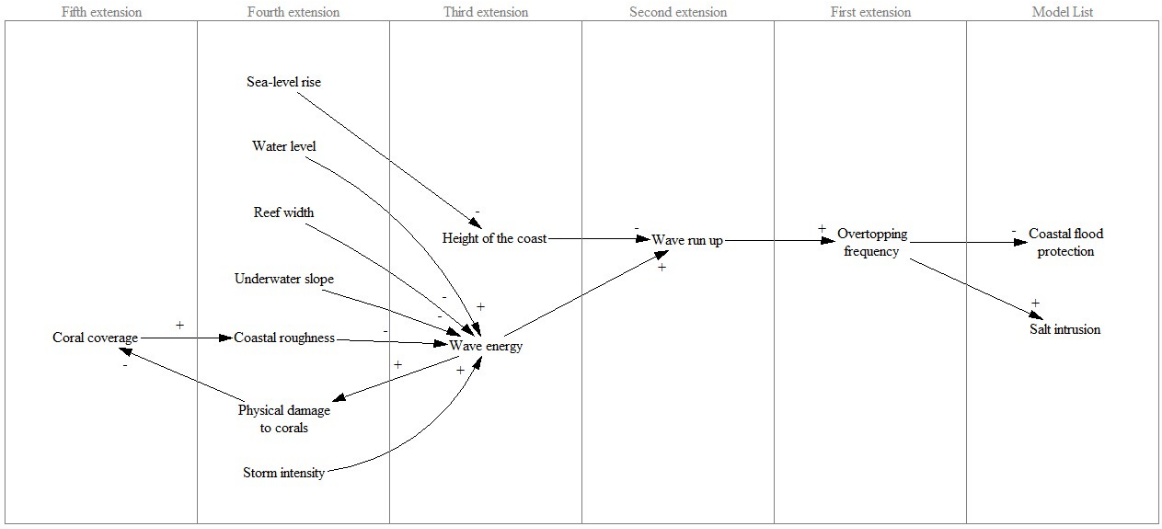

Figure D.5: List extension diagram from Respondent E's interview

What is present in the diagram?
In the diagram of respondent E, the focus is largely on the wave energy dissipating qualities of the coasts. The diagram is mostly applicable for the interactions during storms. The coastal shape, roughness, and water level are important parameters for the implications of the wave energy and direction. The effects are not always the same. Generally the effects are as mentioned in the diagram. Roughness can be increased by an increased coral coverage. As corals are complex structures. The structural complexity increases the wave energy dissipating aspect of reefs.

A good proxy for the coastal flood protection is the wave run-up. The wave run-up is the height at which the water is pushed up the coast. If the water overtops the crest than flooding can occur. With increasing sea-level rise the height of the coast relative to the ocean declines and overtopping is likely to occur more frequently. As a result, oceanic salt might intrude fresh water reserves, rendering some atoll island states inhabitable. At the same time, the risk of flooding will increase.

There is some feedback in the diagram. Storms are able to damage the coral coverage, which provides roughness to the coast. If reef becomes increasingly damaged over time, its wave energy dissipating characteristic might decline.

What is missing in the diagram?
As respondent B is an expert ocean waves, the focus of the diagram is on the wave energy dissipation interactions on coasts. However, many of the ecological and social interactions are missing which are important for the continuous behavior of reefs. The diagram is focused mostly on what happens during storms and recurrence of storms.

D.6. Respondent F

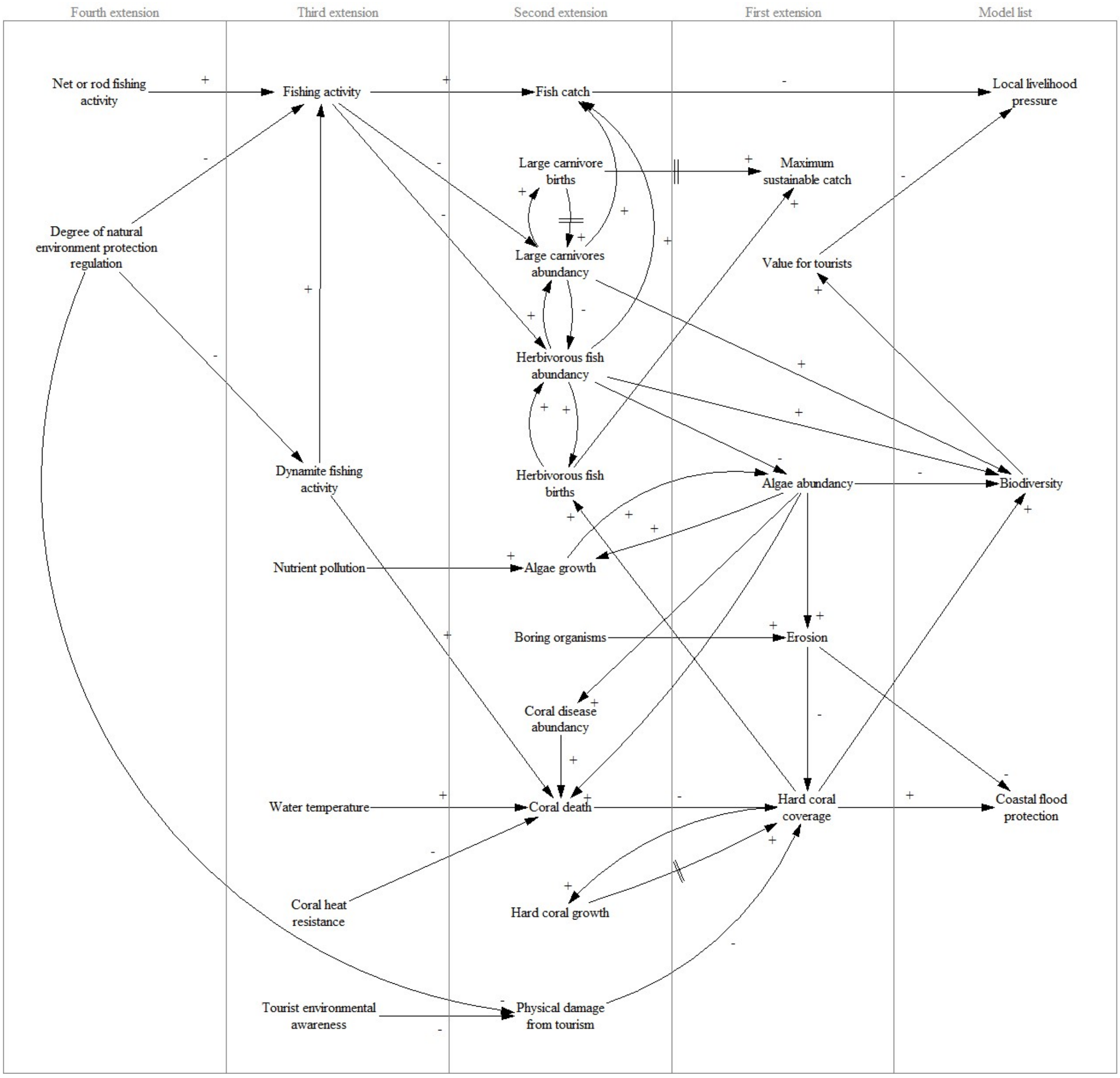

Figure D.6: List extension diagram from Respondent F's interview

What is present in the diagram?
In the diagram of respondent F, there is a separation between the local and the global variables that play a role. A variable that plays a role on the global level is the temperature. Depending on the species and the region corals start to bleach and can die. Locally, there is very little that can be done to combat this effect. However, the local stressors are variables that can be controlled. The local stressor with the largest impact, according to respondent F is the overfishing. Overfishing is a local stressor but happens all over the world and reefs have mostly a nursery function and are unable to function as a primary food source for large amounts of people worldwide. Some local towns would be able to use it as a food source. Increasing the fishing activity even further, can cross the threshold of the maximum sustainable catch. The maximum sustainable catch is the threshold to which the reef can regenerate the fish catch through natural processes. In current years, the threshold was surpassed with fisherman seeing their catch per unit effort to decrease. Several forms of fishing are used, currently net or rod fishing is most popular. Historically, and still in some places, dynamite fishing was used, causing devastation to coral structures, and fish populations. Not only the target species were caught, but also all kinds of other fish died, creating huge impact on reefs. In addition the first species to be targeted were the large carnivores, which take over 50 years to grow to appropriate size, causing a significant delay and a missing link in the trophic pyramid.

Often, if the large carnivores are fished away, herbivorous fish can also become targeted. With the removal of these key stone species the fish abundancy decreases to levels to which algae are not eaten away significantly enough. Hard coral and algae are in competition for underwater space. Algae overgrowing coral can cause increased erosion (e.g. boring organisms)and coral diseases, ending in a lower coastal flood protection at the coast.

Locally, often there is also nutrient pollution from sewage systems or physical damage from tourism, depending on the level of awareness amongst tourists, which affect algal growth and hard coral coverage. The richness of the biodiversity in the ecosystem is, in the end, what provides the value for the tourists. However, with the degradation of the coral reefs increasing value for tourists and catch of fisherman are on the decline. Incrementally increasing livelihood pressure for local communities. The local stressors can be combatted with some forms of environmental protection regulation. However, often these measures improve the environment drastically, but also have a large impact on the local communities with their sources of income being restricted, and eventually increasing livelihood pressure again.

What is missing in the diagram?
In the interview, there was less focus on the global factors of acidification, which was mentioned briefly, and sea-level rise. Another important variable in some locations is the occurrence of storms, which in combination with bleaching can have disastrous effects. The trophic cascading was mentioned, however, there was more emphasis on the large carnivores and less on other trophic levels.

E

Qualitative stock-flow model

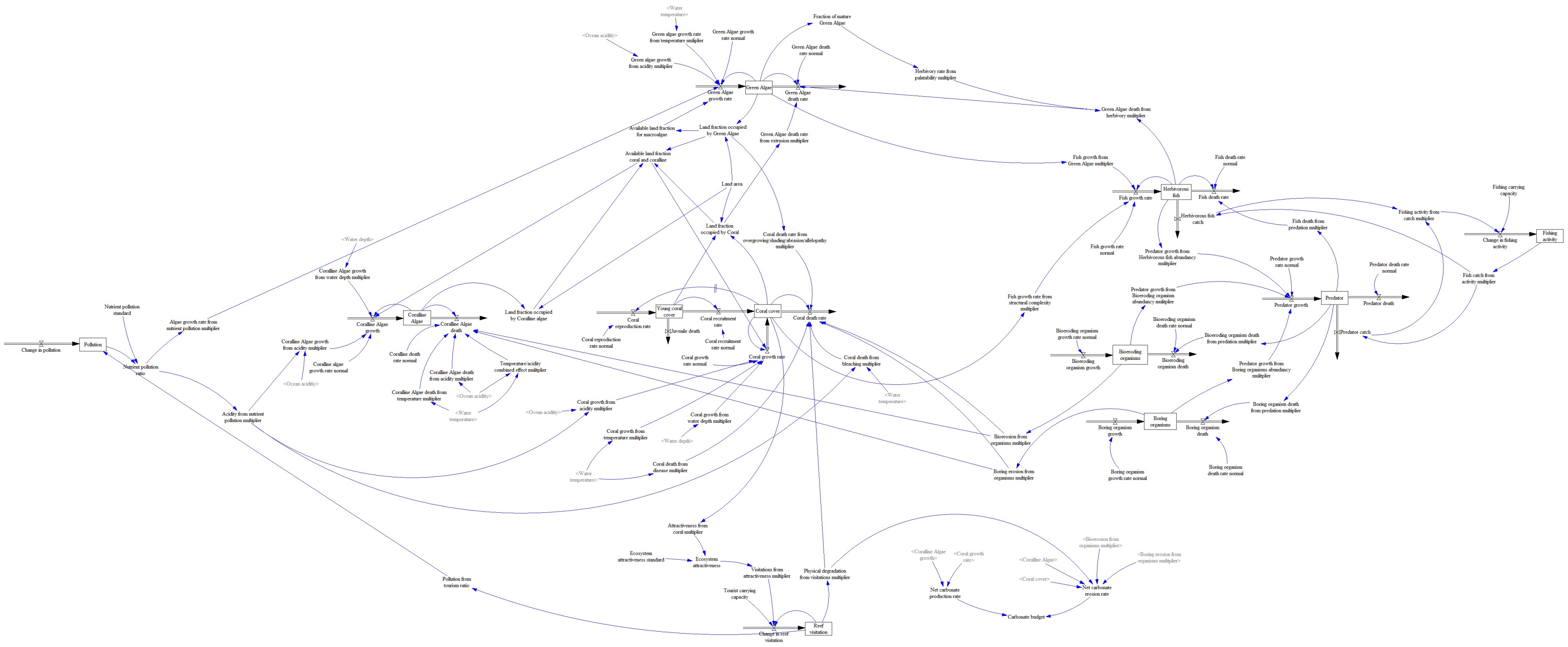

Figure E.1: Stock-flow conceptual diagram from literature

F

Coral reef system model - full figure

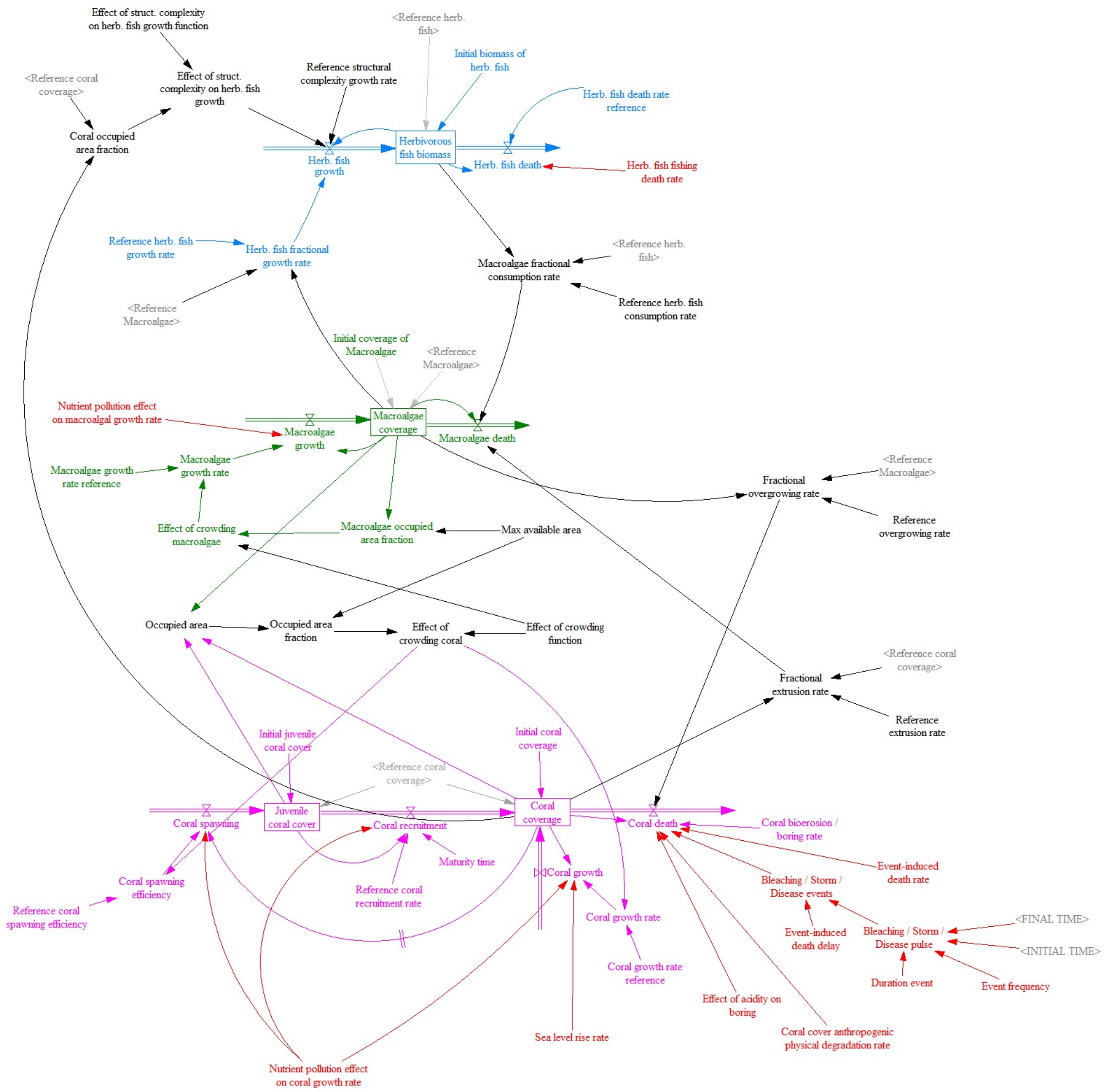

Figure F.1: In the figure the full coral reef system model is displayed with the links between the predator-prey submodel and the interspecific competition submodel

G

Coral reef dynamics model equations

Variable	Equation / Parameter	Unit
Coral bioerosion boring rate=	0.038	1/Year
Event-induced death rate=	0.2 OR 0.5	1/year
Coral cover anthropogenic physical degradation rate=	0.005	1/year
Initial juvenile coral cover=	0.05	Dmnl
Coral death=	Coral coverage * ("Coral bioerosion / boring rate" + Fractional overgrowing rate + ("Event-induced death rate" * "Bleaching / Storm / Disease events") + Effect of acidity on boring + Coral cover anthropogenic physical degradation rate)	ha/Year
Coral growth=	Coral coverage * (Coral growth rate * Nutrient pollution effect on coral growth rate - Sea level rise rate)	ha/Year
Coral growth rate=	Effect of crowding coral * Coral growth rate reference	1/Year
Coral recruitment=	DELAY3(Juvenile coral cover * (Reference coral recruitment rate * Nutrient pollution effect on coral growth rate), Maturity time)	ha/Year
Reference coral recruitment rate=	0.08	1/Year
Coral growth rate reference=	0.059	1/Year
Coral spawning=	(Coral spawning efficiency * Nutrient pollution effect on coral growth rate) * Coral coverage	ha/Year
Coral spawning efficiency=	Reference coral spawning efficiency * Effect of crowding coral	1/Year
Reference coral spawning efficiency=	0.16	1/Year
Occupied area fraction=	Occupied area / Max available area	Dmnl
Occupied area=	Coral coverage + Juvenile coral cover + Macroalgae coverage	ha
Macroalgae occupied area fraction=	Macroalgae coverage / Max available area	Dmnl
Juvenile coral cover=	INTEG (Coral spawning-Coral recruitment, Initial juvenile coral cover * Reference coral coverage)	ha
Macroalgae growth rate=	Effect of crowding macroalgae * Macroalgae growth rate reference	1/Year
Macroalgae growth=	Macroalgae coverage * (Macroalgae growth rate + Nutrient pollution effect on macroalgal growth rate)	ha/Year
Nutrient pollution effect on macroalgal growth rate=	0.11 OR 1.1	1/Year
Effect of crowding function(	[(-100,0)-(100,1)],(-100,1),(0,1),(0.498471,0.877193),(0.746177,0.657895),(1,0),(100,0)	Dmnl
Max available area=	528	ha
Effect of crowding coral=	Effect of crowding function(Occupied area fraction)	Dmnl
Effect of crowding macroalgae=	Effect of crowding function(Macroalgae occupied area fraction)	Dmnl
Macroalgae growth rate reference=	1 OR 11	1/Year
Maturity time=	5	Year
Nutrient pollution effect on coral growth rate=	0.93	1/Year
Sea level rise rate=	0.002	1/Year
Macroalgae death=	Macroalgae coverage * (Macroalgae fractional consumption rate + Fractional extrusion rate)	ha/Year
Herb. fish growth=	Herbivorous fish biomass * ("Herb. fish fractional growth rate" + "Effect of struct. complexity on herb. fish growth" * Reference structural complexity growth rate)	kg/Year
Herb. fish death=	Herbivorous fish biomass * ("Herb. fish death rate reference" + "Herb. fish fishing death rate")	kg/Year
Effect of struct. complexity on herb. fish growth=	"Effect of struct. complexity on herb. fish growth function"(Coral occupied area fraction)	Dmnl
Effect of structural complexity on fish growth function(	[(0,0)-(1,1)],(-100,0),(0,0),(0.244648,0.679825),(0.495413,0.850877),(1,1),(100,1)	Dmnl
Reference structural complexity growth rate	0.01	1/Year
Coral occupied area fraction=	Coral coverage / Reference coral coverage	Dmnl
Herb. fish fractional growth rate=	Reference herb. fish growth rate * (macroalgae coverage / Reference Macroalgae)	1/Year
Coral coverage=	INTEG (Coral growth+Coral recruitment-Coral death,Initial coral coverage * Reference coral coverage)	ha
Fractional overgrowing rate=	Reference overgrowing rate * (Macroalgae coverage / Reference Macroalgae)	1/Year
Reference coral coverage=	286	ha
Initial coral coverage=	1	Dmnl
Reference Macroalgae extrusion rate=	0.01	1/Year
Reference overgrowing rate=	0.01	1/Year
Fractional extrusion rate=	Reference extrusion rate * (Coral coverage / Reference coral coverage)	1/Year
macroalgae fractional consumption rate=	"Reference herb. fish consumption rate" * (Herbivorous fish biomass / "Reference herb. fish")	1/Year
Herb. fish death rate reference=	0.35	1/Year
Herb. fish fishing death rate=	0.02	1/Year
Herbivorous fish biomass=	INTEG (Herb. fish growth-"Herb. fish death", "Initial biomass of herb. fish" * "Reference herb. fish")	kg
Reference herb. fish=	420	kg
Initial biomass of herb. fish=	1	Dmnl
Initial coverage of Macroalgae=	1	Dmnl
Macroalgae biomass=	INTEG (Macroalgae growth-Macroalgae death, Initial coverage of Macroalgae * Reference Macroalgae)	ha
Reference herb. fish growth rate=	0.25	1/Year
Reference herb. fish consumption rate=	0.8	1/Year
Reference Macroalgae=	164	ha
Effect of acidity on boring=	0.005	1/Year
Bleaching / Storm / Disease events=	SMOOTH3("Bleaching / Storm / Disease pulse", "Event-induced death delay")	Dmnl
Bleaching / Storm / Disease pulse=	PULSE TRAIN(2030, Duration event, (FINAL TIME - INITIAL TIME) / Event frequency, 2095)	Dmnl
Event frequency=	5 OR 11	Dmnl
Event-induced death delay=	1	Year
Duration event=	3	Year
FINAL TIME =	2100	Year
INITIAL TIME =	2023	Year
SAVEPER =	TIME STEP	Year [0,?]
TIME STEP =	0.0625	Year [0,?]

Table G.1: On the right the variable name is listed. For every variable the equation or parameter value is listed with the unit in the final column (left).

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Parameter reference table

Parameter	Value (Unit)	Reference
Coral bioerosion / boring rate=	0.038 (1/Year)	The bioerosion rate is for Kenyan reefs is around 1-45% of the carbonate accretion (coral growth + coral recruitment). On average bioerosion is around 20%, according to Carreiro-Silva & McClanahan (2001).
Event-induced death rate=	0.2 OR 0.5 (1/Year)	Lambo & Ormond (2006) reports that severe bleaching events can kill 50 - 90% of the coral cover. Storms can damage 1 - 45% of the reef (Carter et al., 2022). Disease kill around 3-4 % in an outbreak (Church & Obura, 2006). Depending on future climate change scenarios, intensity and frequency can change. For the experiments a value of 0.2 for low and 0.5 for high was used.
Event frequency	5 OR 11 (Dmnl)	Low frequency would mean a bleaching event every 15-years. High levels would mean at least one bleaching event every 10 years.
Coral cover anthropogenic physical degradation rate=	0.005 (1/year)	In Knoester et al. (2023b), the difference between coral cover in the marine park and outside the protected area is around 25% cover. The park was created 50 years ago. Over that period, the unprotected area has degraded and estimated 0.5% per year. Depending on population scenarios, intensity can change.
Initial juvenile coral cover=	0.05 (Dmnl)	Juvenile coral cover in carribean reefs lie between 8 - 20 % of the total coral cover. The reference value should be closer to 20% in healthy reefs (Vermeij et al., 2011). In the model, is chosen to start at a value of around 5% of the reference coral population.
Reference coral recruitment rate=	0.08 (1/Year)	An estimated 8 % of coral larvae survive the first year (Cameron & Harrison, 2020; Johns et al., 2018)
Coral growth rate reference=	0.059 (1/Year)	Coral growth rates vary from around 2 cm per year to around 10 cm per year. The average being 6cm per year, assuming that they grow in all directions, it takes 100 / 6 years for it to fill a square meter, which is around 17 years. The growth rate is 1/17
Reference coral spawning efficiency=	0.16 (1/Year)	Around 16% of coral larvae settle, according to Cameron & Harrison (2020); Johns et al. (2018).
Nutrient pollution effect on macroalgal growth rate=	0.11 (1/Year)	Zaneveld et al. (2016) shows the increase the in macroalgae cover over a period of 4 years, it increases around 25%. This amounts to a exponential growth rate of around 11%. In the cases of high macroalgal growth rate this variable is set to 1.1. In the low cases, it is set to 0.11. This amounts to 10% of the growth rate in both cases. Depending on population and climate change scenarios, intensity can change.
Max available land area=	528 (ha)	According to Knoester et al. (2023b), the max available land area is around 58% of the total area. The available land consist of hard coral cover, macroalgae cover and hard substrate. However, to make the model run smoother, it is set to the sum of reference population values plus the initial juvenile population (0.48x1.1e4).
Macroalgae growth rate reference=	11 OR 1 (1/Year)	Kelly et al. (2017) shows the algae growth rate for several species of macroalgae in Hawaii is around 0.03 gram per gram per day. However, those same species also occur in Kenya (Bolton et al., 2007). Assuming that the growth rate does not change, the growth rate per year is around 11. However, in the validation a growth rate of 1 was more representative.
Maturity time=	5 (Year)	Respondent D stated that coral maturity times vary from 1 - 10 years, but on average it takes 5 years for corals to reach maturity.
Nutrient pollution effect on coral growth rate=	0.93 (1/Year)	Zaneveld et al. (2016) shows that nutrient pollution has a coral tissue loss effect of 25% ± 10 over 4 years. This amounts to an effect of around 7% on the growth rate of corals per year. Depending on population and climate change scenarios, intensity can change.
Sea level rise rate=	0.002 (1/Year)	In itself sea level rise can drown coral reefs. However, the effect can become net positive in combination with increased bleaching (Brown et al., 2019). Depending on future climate change scenarios, intensity and frequency can change. The effect is mild relative to other stressors though, a value of 0.002 is estimated per year.
Reference coral coverage=	286 (ha)	Knoester et al. (2023b) reports that the reference hard coral coverage is around 26% of the total area (0.26x1.1e4).
Initial coral coverage=	1 (Dmnl)	According to Knoester et al. (2023a), around 14% of the total coverage on average is hard coral coverage in the Mpunguti reserve.
Reference Macroalgae extrusion rate=	0.01 (1/Year)	According to some respondents and Nugues et al. (2004), coral extrusion is a relatively uncommon phenomenon. Therefore, it is set to 0.01, as this is very low compared to other death effects.
Reference overgrowing/shading/abrasion/allelopathy rate=	0.01 (1/Year)	Algal interaction effects are usually only very impactful, after bleaching events when coral is weakened (Diaz-Pulido et al., 2009). Therefore, a small effect of 0.01 is estimated under normal conditions.
Herb. fish death rate reference=	0.35 (1/Year)	The lifespan of fish varies widely per species. The average lies around 10 years (Brandl et al., 2018). However, due to predation the life expectancy is assumed to be halved.
Herb. fish fishing death rate=	0.02 (1/Year)	Kiaka (2008) reports on the biomass fish catch per area per month. In Mpunguti the catch amounted to 14400 kg per year. If we assume a biomass of 420 kg per ha over the 11 square kilometers in Mpunguti. The total fish biomass is 462000. Meaning roughly 14400 / 462000 is caught, which is around 3%. Fishing intensity can differ though. In the experiments the variable is increased to 0.4
Reference herb. fish=	420 (kg)	Knoester et al. (2023a) reports the herbivore biomass in various levels of regulations. Reference levels for herbivorous fish are around 420 kg per ha
Initial biomass of herb. fish=	1 (Dmnl)	Knoester et al. (2023a) reports a average biomass of 200 kg per ha in Mpunguti. However, in the model is chosen to set it to reference levels.
Initial coverage of Macroalgae=	164 (ha)	Reference macroalgae are around 14%. We match that value as an estimation for the population size.
Reference herb. fish growth rate=	0.25 (1/Year)	Herbivorous fish growth rates differ massively between species. The average is around 6 months, but fish are not pregnant immediately back to back. Therefore, the herbivorous fish growth rate is set to 0.25.
Reference herb. fish consumption rate=	0.8 (1/Year)	Knoester et al. (2023a) reports on the macroalgae consumption per level of regulation.
Reference Macroalgae=	164 (ha)	According to Knoester et al. (2023b), the reference macroalgae cover is around 14% of total cover (0.14x1.1e4).
Reference structural complexity growth rate	0.1 (1/Year)	Herbivorous fish spawning varies significantly over the different species. An estimation of around growth of 10% biomass per year is made.
Effect of acidity on boring	0.005 (1/year)	Chemical boring becomes more damaging to coral as the pH of the water lowers to due ocean acidification.
Event-induced death delay	1 (Year)	The impact of the bleaching is delayed by a year, as the coverage does not decrease from one day to the next, but it changes over time.
Duration event	3 (Year)	The duration of the event is set to multiple years as the effect of events on the coral death is not instant but happens over time. The parameter can vary depending on the type of event.

Table H.1: On the right the parameter name is listed. For every parameter the value is listed with the unit, and in the final column (left) the reference for the parameter value is introduced.

Delft University of Technology

TU Delft