How Exogenous Stressors Lead to Coral-Algal Phase Shifts

ABSTRACT

Coral reefs are the most productive ecosystems in the ocean. Roughly twenty-five percent of ocean fish depend on healthy reef ecosystems (NOAA) and coral reef ecosystems provide habitat to between one and three million marine species (Sukhdev et. al, 2010). Coral reef ecosystems also provide a range of ecosystem services including coastal protection, fishing, and tourism (Weijerman, 2017). In recent years, anthropogenic stressors have threatened the resilience and quality of coral reef ecosystems, leading to the emergence of coral-algal phase shifts which result in the loss of productivity and biodiversity (McManus and Polsenberg, 2004). A system-dynamics approach is utilized to model two exogenous stressors and their effects on a contained coral reef ecosystem. Though numerous stressors affect coral reef ecosystem health, coral bleaching and fishing are modeled to quantitatively demonstrate how these stressors diminish coral reef ecosystem health both separately and in tandem. Results suggest that reducing bleaching severity through the reduction of anthropogenic causes that increase ocean temperature is most effective in preventing algal-phase shifts.

CONTEXT

There are several stressors that can affect coral reef health and resilience. Stressors include the difficulty of coral reefs to calcify with ocean acidification from increased carbon in the atmosphere, the presence of invasive species, the spread of disease, and damage from hurricanes (Weijerman, 2017). Two additional stressors affecting reef health, specifically evaluated in this study, are coral bleaching and overfishing.

Coral bleaching is a global phenomenon in which rising ocean temperature causes coral to expel their symbiotic zooxanthellae. The foundation of coral reefs begins with the relationship between reef-building coral and photosynthetic algae called zooxanthellae (NOAA). Zooxanthellae provide reef-building coral with food and waste removal, while coral provides zooxanthellae with habitat. Once zooxanthellae are expelled, corals lose their source of nutrients and ultimately starve. Once coral die, algae, which competes for space with coral, can replace coral and proliferate in the system. By mid-century, severe bleaching events are expected to affect approximately seventy percent of all reefs globally and coral cover is expected to decrease by twenty-four to fifty percent by 2100 (Weijerman, 2017). Overfishing, the harvesting of fish populations beyond a sustainable rate, has increased over time due to a rising human population. Overfishing leads to decreases in fish population and fish size, reducing herbivory and grazing of algae. This ultimately also leads to the proliferation of algae within a coral reef ecosystem (McManus, 2004). A simple causal loop diagram, shown below, reflects the relationships within the system.

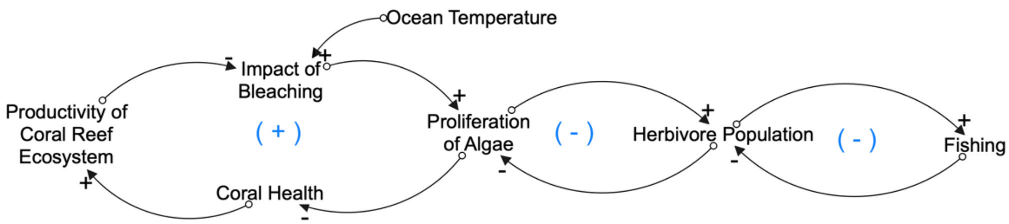

Figure 1. Causal Loop Diagram shows the basic feedback loops between coral, algae, herbivorous fish, bleaching and fishing.

APPROACH

I developed a STELLA model to assess coral reef ecosystem dynamics over a period of 500 days. The model dynamics are assessed in a "closed" 100 meter-squared area in which neither coral and algae can grow beyond this constraint and herbivorous fish can enter and exit the system. In developing a STELLA model, I sought to address the following questions: (1) How does coral bleaching influence coral cover, algal cover, and herbivore population? (2) How does fishing influence coral cover, algal cover, and herbivore population? (3) How do both stressors influence the system and which stressor is more important to direct attention and resources towards? A simple replication of the model is shown below.

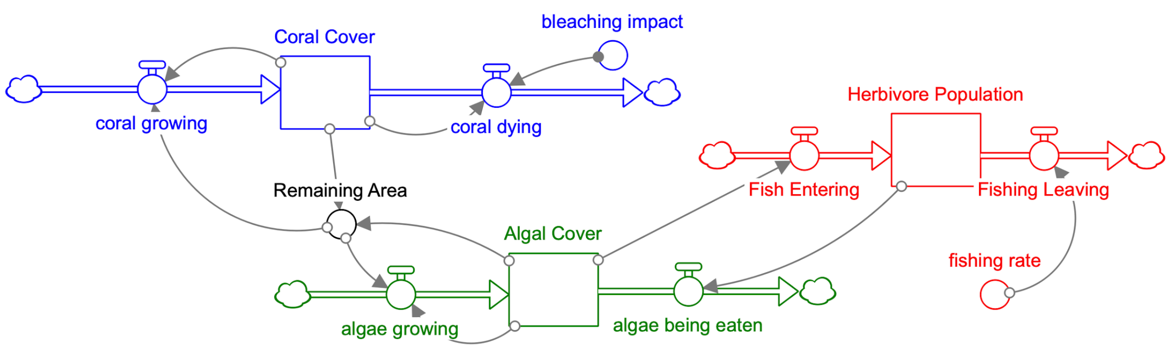

Figure 2. Simplified STELLA model how dynamics between the three populations. The two stressors in the model are bleaching and fishing. Bleaching influences the flow of coral dying and fishing influences the flow of fish leaving the system.

An initial steady state is created in which herbivore population, coral cover, and algal cover remain stable over time. Three tests are run within the model. First, coral bleaching, which intensified with ocean temperature, is modeled on the steady state. Second, fishing is modeled, which increases when the herbivore population is greater than the steady-state population of five fish. Third, both bleaching and fishing are modeled in the system.

RESULTS

An initial steady state was modeled to show the coral reef system without the presence of stressors (Figure 3). Coral cover remains at 48 meters squared, algae cover at 50 meters squared, and the steady state herbivore population is 5 fish. Following the creation of the steady state, effects of coral bleaching were modeled in the system (Figure 4). Coral bleaching depends on ocean temperature, thus when temperature reaches beyond a certain threshold (86.4 F), a bleaching event occurs and kills a large portion of coral. General oceanic trends, show ocean temperature increasing over time, increasing the likelihood of bleaching events. After 500 days, we see coral cover decline to 11.2 meters squared, and algae cover oscillates around 50 meters squared. As algae increases, the herbivore population also increases and begins to oscillate around 24 fish, introducing a coupled predator-prey dynamic.

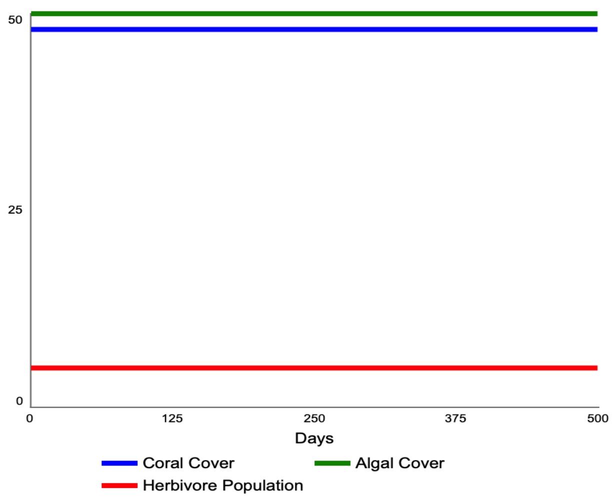

Figure 3. Model in steady state.

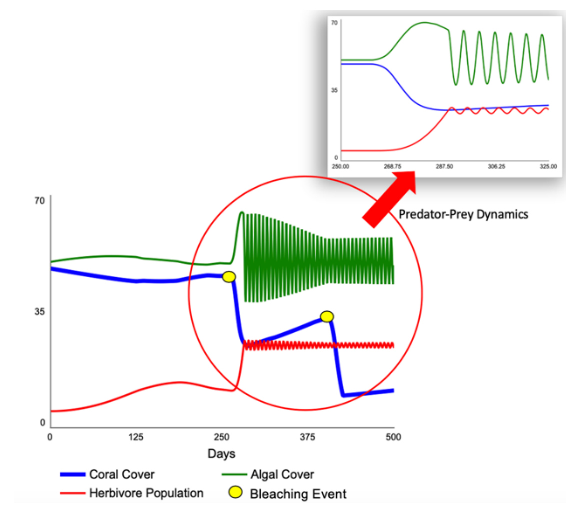

Figure 4. Test one shows effects of bleaching events on model.

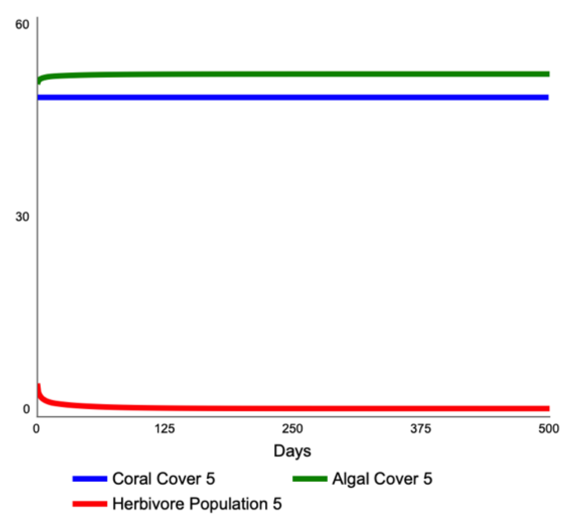

Figure 5. Test two shows effects of fishing on model.

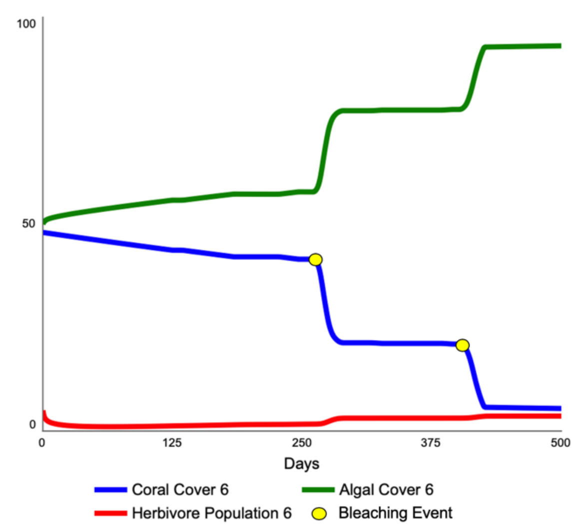

Figure 6. Test three shows effects of both bleaching and fishing on model.

Effects of fishing were then modeled in the system (Figure 5). We see coral cover stay at the steady state cover of 48 meters squared. We see a slight increase in algal cover to 51.5 meters squared, and fish population declines to 1.24 fish. Given the area constraint of the system, even with a reduction in predation, algae cannot grow unless coral die and space is made available. Finally, fishing and coral bleaching are modeled together to assess their aggregate effect on the system (Figure 6). We see coral cover decline to 5.44 meters squared. Algal cover rises to 93.1 meters squared, and herbivore population slightly declines and then slightly increases to 3.62 fish. With both stressors, we see coral cover decline to its lowest rate, and algal cover increases to its highest rate.

DISCUSSION

Coral bleaching alone and in addition to fishing can have a detrimental effect on coral growth. Given that bleaching is associated with high ocean temperatures, as temperatures continue to rise, the frequency of bleaching events will increase. Increased bleaching frequency drives down coral cover because there is less time for coral to rebuild and recover. When coral dies, space availability increases, and algae can fill this gap because algae grow much faster than coral. As shown in Figure 4, without a fishing pressure, the herbivore population increases and achieves a predator-prey oscillation. However, as shown in Figure 6, the herbivore population cannot increase in response to increased food availability due to fishing. Algae can proliferate in the system until there is no space left. Interestingly, Figure 5 shows that fishing alone has little impact on the system. This is likely due to lack of available space. Without any negative impacts to coral, there is no additional space for coral to grow. If we were to see a system without a space limitation, we would expect algae to continue to increase.

CONCLUSION

For both the bleaching test and the final test with both stressors, we see strong evidence for the influence of stressors on coral-algal phase shifts. In both tests, algae dominate the system and coral is unable to recover to its original levels. In order to prevent algal-coral phase shifts, there must be concentrated efforts to reduce the impact of bleaching. Though there are additional stressors than can disrupt the system, for the sake of the model, we should focus attention on bleaching rather than fishing.

Levers for reducing bleaching severity include efforts to reduce the anthropogenic causes that lead to rising ocean temperature. This includes reducing carbon emissions into the atmosphere. However, such efforts must be global in scale, which is difficult to implement. On a local scale, efforts to prevent overfishing, excess nutrient runoff into reef systems, and underwater disturbance can reduce stressors that exacerbate the effects of bleaching. As shown in Figure 6, after bleaching events, fishing keeps coral cover low. Thus, such efforts to prevent algae from rapidly expanding could counteract the detrimental effects of bleaching to some degree. Recently, there have been efforts to engineer techniques to increase coral growth. Such efforts could be utilized to counteract coral loss. Examples of such techniques include the creation of coral nurseries to subsidize coral reefs, though the effectiveness of such techniques is yet to be fully understood.

Overall, this model demonstrates the detrimental effects of anthropogenic stressors on coral reef ecosystems. Policies and technologies must be implemented if coral reefs are to continue to provide their array of ecological and economic benefits.

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