Coral Bleaching: Pale Remnants and Stark Warning

Project Module Associated with
2nd *Edition, Introduction to Computational Science:*
***Modeling and Simulation* by**

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Prerequisite for Projects 1 and 2: Module 4.2, "Unconstrained Growth and Decay"
Prerequisite for Projects 3 and 4: Module 4.3, "Constrained Growth"
Prerequisite for Project 5: One of Module 10.3, "Spreading of Fire;" Module 10.4, "Movement of Ants–Taking the Right Steps;" or Module 10.5, "Biofilms: United They Stand, Divided They Colonize."
Prerequisite for Projects 6 and 7: Module 11.2 on "Agents of Interaction: Steering a Dangerous Course"

Introduction

Off the coast of northeastern Australia is one of the marvels of the natural world—the **Great Barrier Reef** (**GBR**). The GBR grows on the edge of the continental shelf, separated from the coastal plain by water. During the past 6 to 8000 years, the sea level has risen, flooding the continental shelf between the edge of the reef and the mainland.

Visible from space, the reef, which is a collection of about 3000 coral reefs, hundreds of coral cays, and mangrove islands, stretches along the Australian mainland for about 2300 km (over 1400 miles). The GBR covers about 344,000 square kilometers (about half the area of Texas). There are some 600+ species of coral, more than 1600 species of fish, 30 species of whales and dolphins, and thousands of species of macroinvertebrate animals, besides the corals, including molluscs, sponges, worms, jellyfish, etc. There are also countless species of macroalgae (seaweeds) and microscopic life (GBRMP 2012). Besides the animals that are established residents, the reef nourishes the early, developmental stages of many transient residents. The reef domain supports nesting of sea turtles, breeding/birthing of some whales, and breeding colonies of birds, as well.

Remarkably, coral reefs, even as extensive as the GRB, are formed by **colonies** of individual coral animals, each one only a few millimeters in diameter. These colonies, made up of **stony corals**, secrete calcium carbonate exoskeletons for support and protection. The mass of each reef is made up of layer upon layer of calcium carbonate, deposited over millennia by successive colonies of these reef-building (**hermatypic**) corals. The living coral forms the outer surface (Castro and Huber 2016).

Stony corals belong to the phylum Cnidaria, which also includes many species of jellyfish, anemones, and soft corals (e.g., sea fans). Like other Cnidaria, stony coral individuals are constructed with a fairly simple body plan—two layers of cellular tissue, usually separated by a noncellular layer (**mesoglea**). The cellular layers include the interior **gastrodermis** (**endoderm**), lining the gastric cavity (gut), and the exterior

exodermis (**ectoderm**). Two body forms are typical for members of this phylum—a swimming form, called the **medusa**, and an attached form, called the **polyp** (Figure 1). In both cases, there is an opening (mouth) into a blind pouch, called **coelenteron** or **gastrovascular cavity**, surrounded by a ring of tentacles and sometimes oral arms. The corals only have the polyp body form, living attached by way of a **basal plate** to something solid (Castro and Huber 2016).

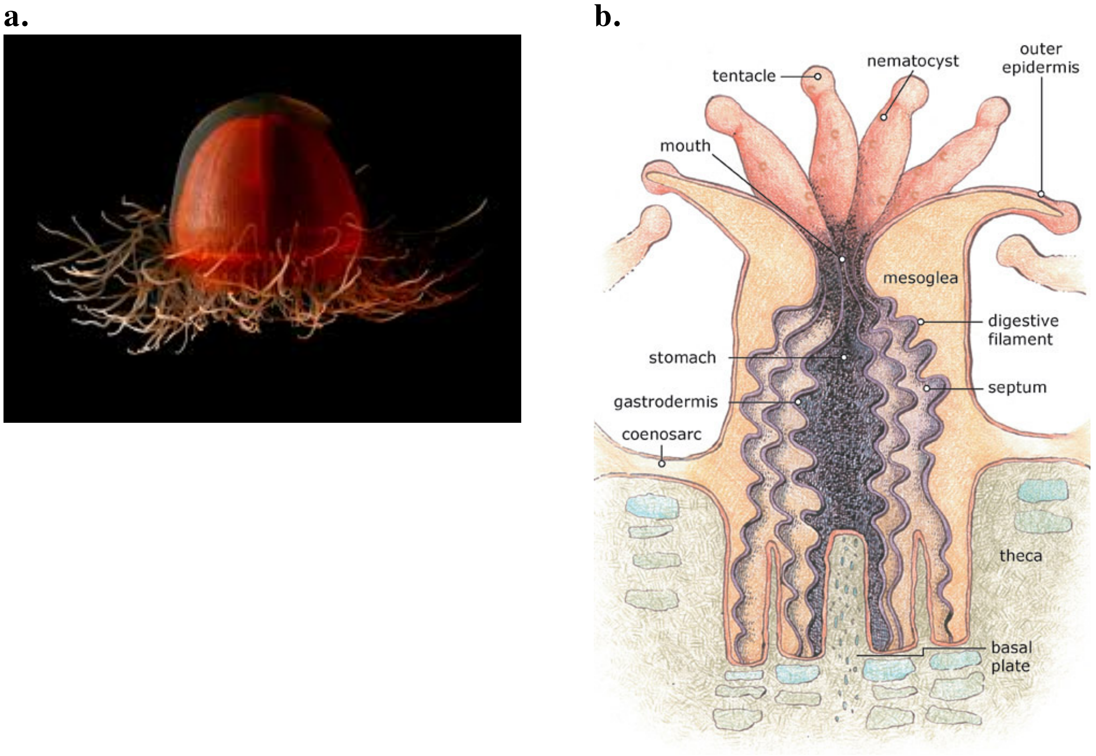

Figure 1 **a.** Medusa (NOAA 2008) **b.** Polyp (NOAA 2005)

The reef-building corals find nourishment from the surrounding seawater. The tentacles are armed with specialized cells, called **nematocysts**, which contain barbed, sticky, and venomous threads. Contact with a small organism floating in seawater triggers the release of the threads from the nematocysts, which paralyze, entangle, or attach the prey (Figure 2). The prey is then drawn into the mouth and into the gastrovascular cavity. The gastrodermis contains various types of glandular cells. Some of these cells secrete digestive enzymes, which help to digest the prey. Other cells absorb soluble nutrients or phagocytize small particles of food. The gastrovascular cavity has vertical folds, or **mesenteries**, which may extend as filaments from the mouth. These **filaments** have nematocysts and glandular cells for capture and digestion of prey, and they can also help to prevent competing organisms from invading the coral's territory (Castro and Huber 2016).

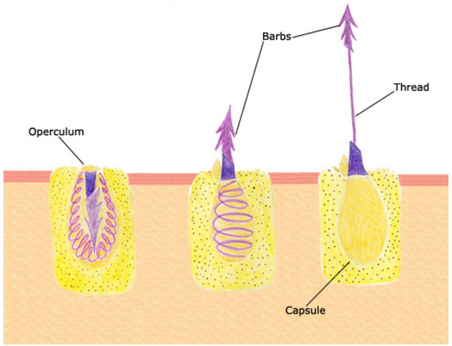

Figure 2 Nematocysts with its firing sequence (NOAA 2005)

Coral polyps also have an internal source of nourishment. Within the upper reaches of the gastrodermis, held inside some of the gastrodermal cells are small, unicellular photosynthetic organisms—**dinoflagellates**. These dinoflagellates have two life forms—a free-living, flagellated form and a form that lives symbiotically in vacuoles of the gastrodermis of a coral (called **zooxanthellae**). The pigments of these zooxanthellae are responsible for the coloration of living coral colonies. Although, zooxanthellae may also be associated with other marine animals, such animals do not build reefs. To biologists, a **symbiotic relationship** represents interactions between two species of organisms, where both organisms benefit from those interactions. In this case, besides CO_2, produced by respiration of the coral tissues, the dinoflagellates utilize other nutrients (e.g., nitrogen and phosphorous) accumulated by the coral. In exchange, the zooxanthellae produce organic products from photosynthesis that the coral can use for energy or the synthesis of other organic compounds (Henkel 2010; Smithsonian Ocean Portal).

Stony corals may reproduce sexually. In many cases, the eggs and sperm are released synchronously into the sea water, where fertilization takes place. Development proceeds to produce a small larval form, called the **planula**. The planula settles on a suitable substrate and continues its metamorphosis to become a polyp. The polyp will begin producing its exoskeleton, grow, and then divide asexually (**budding**) to produce another polyp (Figure 3). Undisturbed, each polyp will grow and divide forming a colony. All of the polyps remain interconnected by an extension of the body wall called the **coenosarc**. Through these connections the polyps can share such things as digested materials and nerve impulses. Reefs are composed of countless numbers of coral colonies (Castro and Huber 2016).

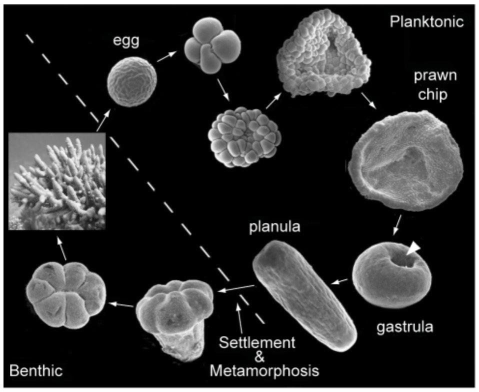

Figure 3 Coral life cycle (Hayward et al. 2011)

For a coral reef to develop, a number of requirements must be satisfied. Active coral growth normally takes place in fairly shallow (< 25 M), warm (> 23° C, but < 29° C), and rather clear water where sufficient light will penetrate to promote the photosynthetic activity of the zooxanthellae. Consequently, reefs are associated with shallower, warmer zones surrounding continents or islands, or perhaps atop underwater volcanic mountains (seamounts). Temperature tolerance varies for different types of zooxanthellae, which partially accounts for the reefs developing below 25 M and outside the normal temperature range. We know that corals can adapt somewhat to varying temperatures. However, in very shallow waters, where there is abundant sunlight, or in coastal areas, where runoff from power plants occurs, temperatures may exceed tolerance and damage the reefs. Salinity, as well as temperature influences calcium deposition rates, so most reefs are found within salinities of 32 to 40‰ (Castro and Huber 2016, Henkel 2010).

Because of the occurrence of reefs near coastal zones, sediments often interfere with the penetration of light to the zooxanthellae but also may foul the polyps themselves. Consequently, reefs associated with coastal areas with considerable human activity may have their growth and development impaired.

During the early part of 2016, Australia was conducting flyover surveys of the Great Barrier Reef. Professor Terry Hughes, director of the Australian Research Council Centre of Excellence for Coral Reef Studies, confirmed that about 99% of the reefs making up the GBR showed evidence of coral bleaching. After personally spending four days participating in the survey, Dr. Hughes said "It was the saddest reef trip of my career." Much of the bleaching in the northern reaches of the reef were quite severe, with some of the reef dead (Normille 2016).

This story prompts several questions:

- What is coral bleaching?
- What causes it?
- Why is this episode of bleaching of so much concern?

As we learned earlier in the introduction, the zooxanthellae, sequestered within the gastrodermal cells of the coral, are important suppliers of energy compounds. The pigments of these symbionts also color the flesh of the coral polyps. Bleaching is the result of the expulsion or destruction of the zooxanthellae by the gastrodermal cells. If the pigments are not present, the calcium carbonate skeleton shows through the translucent polyps, giving them a bleached appearance.

Why would the polyps make such a drastic move? Bleaching of coral reefs generally reveals that the reefs are under stress. Although many stressing factors may influence the lives of the coral animals, temperature appears to be the most common one. Although adapted to warm temperatures, corals may have reasonably narrow ranges of temperature tolerance. Glynn (1991) demonstrated that only a 1-2° C increase over the highest mean temperature for a given location may lead to coral bleaching. Temperature may also work synergistically with increased levels of UV radiation to promote stress.

Lesser (1996), found that zooxanthellae, cultured under elevated temperature and UV exposure, produced elevated concentrations of excess O_2 (byproduct of photosynthesis), which was converted into very high concentrations of **reactive oxygen species** (**ROS**), including superoxide radicals and hydrogen peroxide. Such reactive compounds can interact with myriad cellular components (e.g., proteins, DNA, etc.), causing great damage. Sufficiently damaged cellular molecules can inhibit normal cellular functions that may stymie growth or even kill the cell. Normally, aerobic cells have enzymes which interact with ROS to detoxify them, but these enzymes become overwhelmed if the ROS levels become too high. So, it seems that the coral polyps, in an effort to prevent damage to their own cells, get rid of the zooxanthellae that are producing the toxins.

With changes in climate that produce higher water temperatures, coral reefs are coming under a great deal of stress. Strong El Niño events, which result in warmer surface waters in the Pacific, only aggravate the problem. Scientists are alarmed at the current health status of the world's coral reefs, because under prolonged stress, the reefs may die. Widespread loss of coral reefs and the communities they support would be catastrophic, causing fantastic losses of biodiversity, altering countless animal and plant populations, dislocating marine food chains, ravaging local human communities reliant on the the reefs for food, and devastating tourism-based economies.

Macroalgae, Algal Turfs, Parrotfish, and Corals

For the models in this module, we consider an area where three organisms–macroalgae (seaweed), corals, and algal turfs–completely cover the seabed. Thus, with M, C, and T representing with the fraction of macroalgae, corals, and algal turfs, respectively, we have $M + C + T = 1$. Thus, the sum of their rates of change is zero: $dM/dt + dC/dt + dT/dt = 0$. Knowing the first two derivatives, we can calculate the third (Blackwood et al 2010).

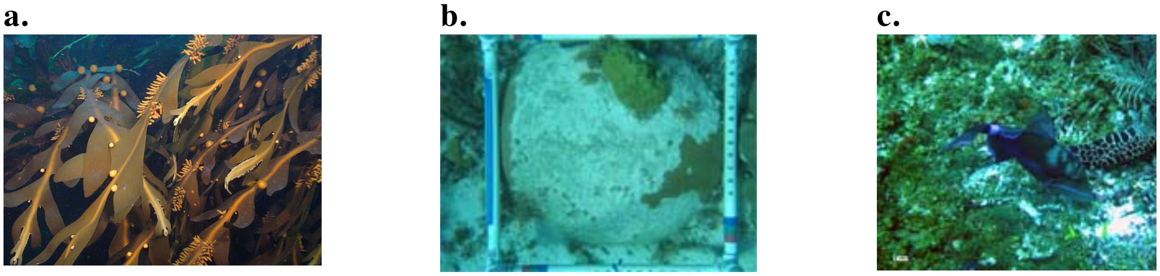

Figure 4 **a.** Macroalgae (USAP 2010) **b.** Algal turf (EPA 2016)
c. Fish feeding on algae (EPA 2016)

Both macroalgae and corals grow over algal turfs. In both these cases, interactions occur, macroalgae with algal turfs and corals with algal turfs. In another interaction, the aggressive macroalgae can also overgrow corals. When corals die, algal turfs colonize that area; so that the death of one leads to the birth of the other. Parrotfish graze on both macroalgae and algal turfs. However, their consumption of the former is helpful to corals because such grazing gives rise to algal turfs, which corals can overgrow. Moreover, when parrotfish consume algal turfs, neither macroalgae nor coral can grow over the area vacated by the algal turfs. Thus, the model does not need to have a term for the grazing of algal turfs. The rate, g, at which parrotfish graze on algae assumes algae cover the entire region. $g/(M + T)$ is the per capita grazing intensity. For the rate of change of macroalgae, we are concerned with the proportion of macroalgae grazed, or the fraction of grazing of algae (macroalgae and algal turfs) that affects macroalgae. If macroalgae and algal turf do not cover the entire area, i.e. $M + T < 1$, the per capital grazing intensity increases as the fish concentrate on eating the remaining algae (Blackwood et al 2010).

Parameter	**Value**	**Description**
a	0.1 y^{-1}	Rate at which macroalgae directly overgrow coral
d	0.44 y^{-1}	
g	$0 \leq g \leq 1$	Rate at which parrotfish graze, assuming algae (macroalgae and algal turf) cover the entire region
r	1 y^{-1}	Rate at which coral overgrows algal turf
v	0.8 y^{-1}	Rate at which macroalgae directly overgrow algal turfs

Table 1 Parameters (Blackwood et al 2010) based on (Mumby et al. 2007)

We can also include the dynamics of parrotfish explicitly in our model with P representing parrotfish abundance. A constrained growth model is natural, but we should temper that value to be a function of coral cover. Thus, we multiply X, the maximum carrying capacity, by $K(C)$ a nondimensional function of C, whose positive value is less than or equal to 1. In Projects 3 and 4, we consider various scenarios that result in different formulations of $K(C)$. Coral is helped by fish grazing, so our model should also include the impact of fishing with f being fishing effort, or the fraction of P fished each year. The models for dM/dt and dC/dt (and dT/dt) remain the same as described above, except grazing intensity should depend on parrotfish abundance with a function of P,

$g(P)$, replacing the constant g. Obviously, when there are no parrotfish, $g(P)$ should be zero. Moreover, we will assume that the maximum possible grazing intensity is one and occurs when P equals the maximum carrying capacity, X. Table 2 lists additional parameters involving parrotfish abundance (Blackwood et al 2010).

Parameter	**Value**	**Description**
f		Fishing effort
$g(P)$	$0 \leq g(P) \leq 1$	Rate at which parrotfish graze, assuming algae (macroalgae and algal turf) cover the entire region, as a function of P
$K(C)$	$0 < K(C) \leq 1$	Achievable fraction of X
s	$0.49\ \mathrm{y}^{-1}$	Growth rate of parrotfish assuming no fishing effort
X		Maximum carrying capacity of parrotfish

Table 2 Parameters involving P (Blackwood et al 2010) based on (Mumby et al. 2007)

Projects

1. **a.** Develop a system dynamics model for M, C, and T, graphing each, using the information in the first and second paragraphs of section "Macroalgae, Algal Turfs, Parrotfish, and Corals" and the parameters in Table 1. Do not include the dynamics of parrotfish but consider their effect through the term involving g.

b. Consider the impact of grazing rate on coral cover, where initially coral covers less than 56% of the area. Running the simulation until equilibrium, describe the graphs for $g = 0.00, 0.15, 0.35, 0.55$, and 1.00, and discuss the results.

c. Calculate the equilibrium formulas for C and T when M is 0. Recommendation: Assigning $M = 0$, start with dC/dt to calculate an equilibrium formula for T, and then use that calculation in the equation $M + C + T = 1$.

d. Find an approximate value of g, g_{crit}, where coral die out and macroalgae overrun the area for values less than g_{crit} and where coral cover tends to the equilibrium of Part c and the macroalgae die out for values greater than g_{crit}.

e. Consider the impact of a coral bleaching event or a hurricane that does not damage the reef structure, including the algae, but only the coral. Have the impact occur at year 7 and destroy half of the coral. Describe the graphs for $g = 0.00, 0.15, 0.35, 0.55$, and 1.00, and discuss the results.

f. Repeat Part e for a destruction level of 20%.

g. For a fixed value of g at which the coral usually thrives, consider an impact as described in Part d at year 7 and another at year 14 with various coral-destruction levels. Discuss the results.

h. Consider the impact of a hurricane that damages the reef structure, including the macroalgae, as well as the coral. Have the impact occur at year 7 destroy 20% of the coral and the macroalgae. Describe the graphs for $g = 0.00, 0.15, 0.35, 0.55$, and 1.00, and discuss the results.

2. **a.** Develop a system dynamics model for M, C, and T, graphing each, using the information in the first and second paragraphs of section "Macroalgae, Algal Turfs, Parrotfish, and Corals" and the parameters in Table 1. Do not include the dynamics of parrotfish but consider their effect through the term involving g.

b. Find an approximate value of g, g_{crit}, where coral die out and macroalgae overrun the area for values less than g_{crit} and where coral cover tends to $(r - d)/r$ and the macroalgae die out for values greater than g_{crit}.

c. Consider the situation where grazing intensity starts at g_0, a value much lower than g_{crit}, and rises linearly to g_{final}, a value greater than or equal to g_{crit}, over a 10-year period. After year 10, have the grazing intensity remain at g_{final}. Investigate the system for various values for g_0 and g_{final}. Discuss coral recovery, particularly in relationship to situations in which macroalgae gain dominance. Discuss the implications for preventative measures.

3. **a.** Develop a system dynamics model for M, C, T, and P, including the dynamics of parrotfish, and graph the results. Initially, have coral cover less than 56% of the area. Assuming that habitat is the primary limiting factor for the parrotfish, perhaps following a coral-damaging hurricane, have $K(C)$ equal C. Under various initial conditions, describe the graphs over a 25-year period with no fishing. Discuss the results.

b. Calculate the equilibrium formulas for C and T when M is 0. Recommendation: Assigning $M = 0$, start with dC/dt to calculate an equilibrium formula for T, and then use that calculation in the equation $M + C + T = 1$.

c. Consider the impact of fishing on this model. Determine a critical value for fishing effort beyond which the coral reef is in extreme danger.

4. **a.** Develop a system dynamics model for M, C, T, and P, including the dynamics of parrotfish, and graph M, C, and the grazing rate. Initially, have coral cover less than 56% of the area. Assuming that food is the primary limiting factor for the parrotfish, perhaps following a bleaching event or a hurricane that does not damage the coral, have $K(C)$ equal $1 - zC$, with $0 \le z < 1$. With $M = 0$, an initial grazing rate of 0.05, and various values for z, describe the graphs over a 25-year period with no fishing. Discuss the results.

b. Calculate the equilibrium formulas for C and T when M is 0. Recommendation: Assigning $M = 0$, start with dC/dt to calculate an equilibrium formula for T, and then use that calculation in the equation $M + C + T = 1$.

c. With $M = 0.35$, $C = 0.2$, and an initial grazing rate of 0.05, describe the graphs over an 80-year period with no fishing. Discuss the results.

d. Repeat Part c except with a fishing effort of 0.25. Discuss the results their implications.

5. **a.** Develop a cellular automaton model for M, C, and T using the information in the first and second paragraphs of section "Macroalgae, Algal Turfs, Parrotfish, and Corals" and the parameters in Table 1. Do not include the dynamics of parrotfish but consider their effect through the term involving g. Running the simulation 40 time steps (years), display the final percentages of macroalgae, coral, and algal turfs.

b. Consider the impact of grazing rate on coral cover, where initially coral covers less than 56% of the area. Run the simulation for $g = 0.00, 0.15, 0.35, 0.55$, and 1.00 at least 100 times, averaging the results. Discuss the results.

6. Repeat Project 5 using an agent-based model.

7. Repeat Project 3 using an agent-based model.

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