Environmental Impacts on the Great Barrier Reef

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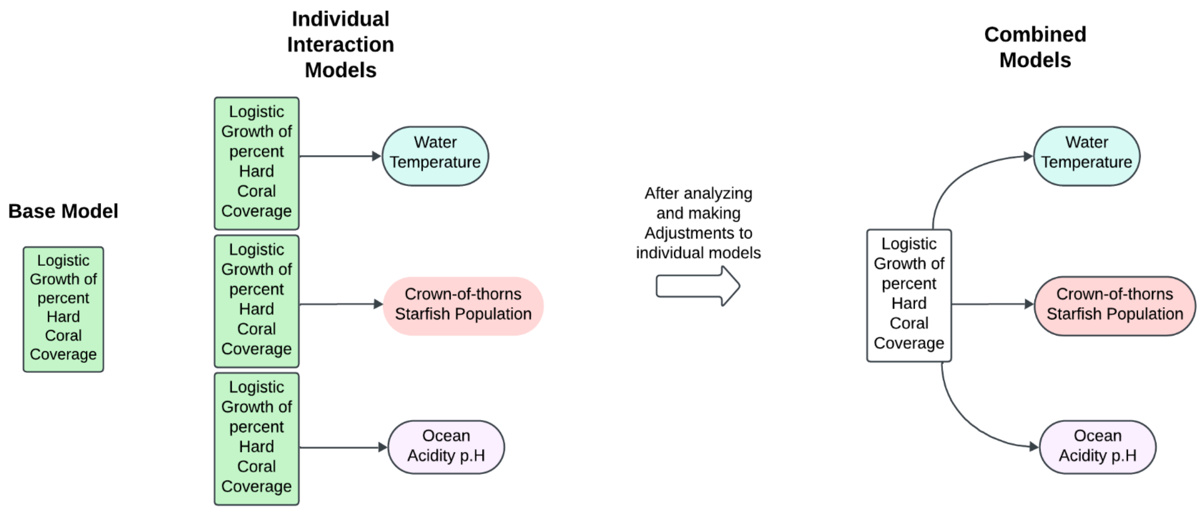
Introduction

The Great Barrier Reef is a complex ecosystem that has been undergoing dramatic fluctuations in the past few decades. The Australian Institute of Marine Science (AIMS) collects monthly data on the condition of the Great Barrier Reef using the metric of percent hard coral coverage, and we posed the question: What environmental factors cause the percentage of hard coral coverage to change, and by how much? By answering this, ecological conservation organizations can focus their efforts on mitigating harmful influences on the Great Barrier Reef, prioritizing the most dangerous threats, and predicting how they will affect the percentage of hard coral coverage with our model.

We assumed that hard coral coverage accurately indicates the overall health of the Great Barrier Reef and that the average hard coral coverage of the Central and South Great Barrier Reef is representative of the overall health of the Great Barrier Reef, which AIMS backs. Furthermore, the results of our preliminary research led us to conclude that the most influential variables on the Great Barrier Reef's condition are water temperature, Crown-of-thorns starfish density, and ocean acidity measured in p.H. We assume that these are the most important factors, hence other potential threats are ignored by our model. To determine how these factors affect the Great Barrier Reef, we chose parameters that are scientifically backed.

All of our models are discrete models of time step "t" years. We start by modeling the hard coral coverage by itself, using a logistic growth model. From there, we make individual models to understand the interactions between the percent hard coral coverage and all of the influencing variables. After finalizing parameters and making model adjustments, we combine all models to produce our final model accounting for all the chosen variables.



Results and Analysis

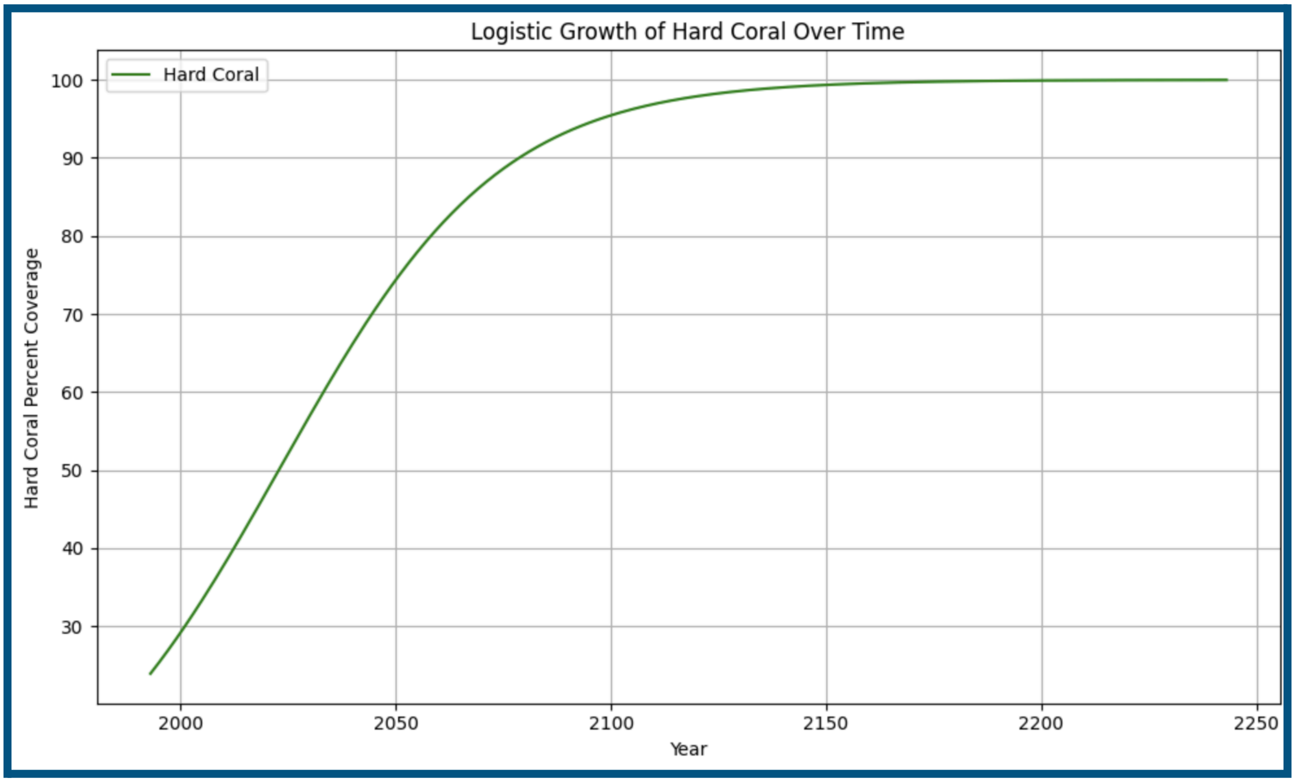
Base Logistic Model for Coral Coverage

Assumptions

To establish a foundation for our further analysis, we elected to model coral coverage logistically and discretely over time. This required us to make a few key assumptions: the growth rate is unhindered by other environmental factors, the coral coverage follows a logistic growth pattern, and this constant growth rate is about 0.039 = r (Osborne et al., 2011). It is important to note that this growth rate is an average, as coral growth rate varies in the real world. However, in establishing a base model, simplicity is key, leading to our omission of such variance.

Modeling

To create a model consistent with these assumptions, we employed the standard logistic growth equation $x(n) = x(n - 1) + r * (1 - x(n - 1)/K)$, where r is the growth rate, K is the carrying capacity, and x(n) is the coral coverage at time n. In the data for coral coverage provided by the Australian Institute of Marine Science (2015), they collected total coral coverage as a percent. As such, our carrying capacity is 100%; K = 100. To find an accurate starting value for our coral coverage, we took the average of all values in our starting year of 1993 (since we are modeling discretely), as there were several reports scattered throughout each year. The results are displayed below:



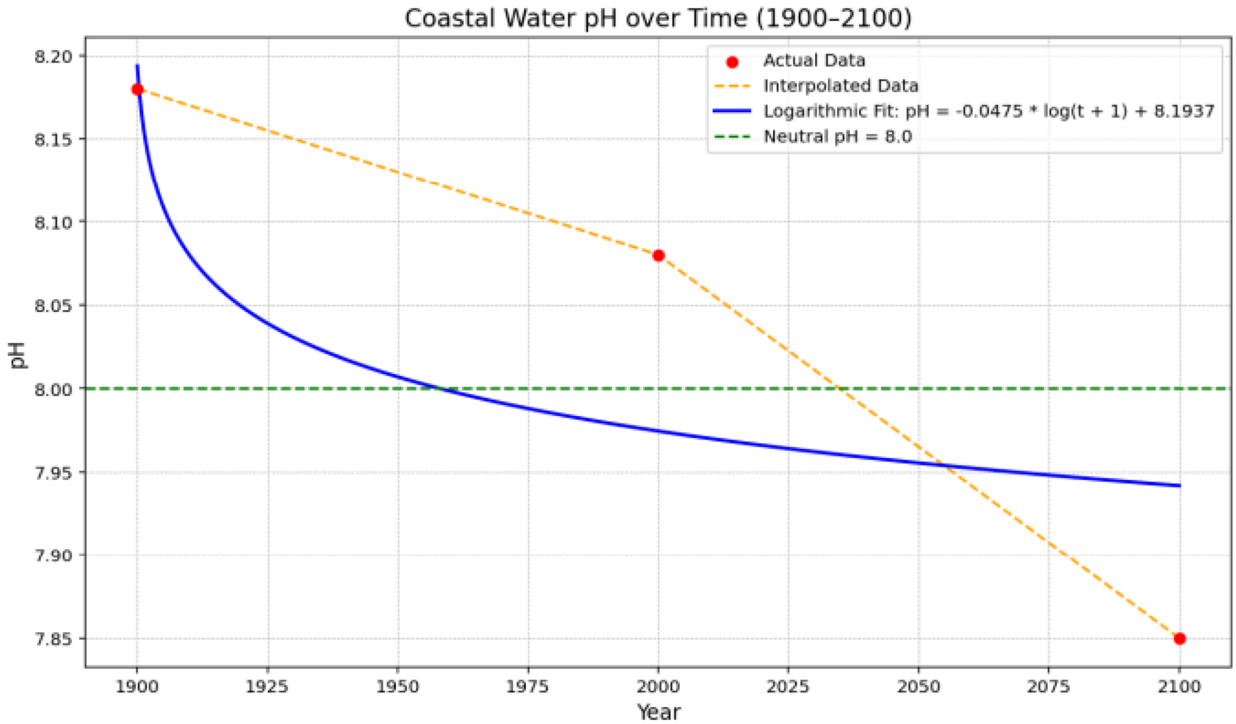
Acidity and Hard Coral Cover

Acidity Change Over Time.

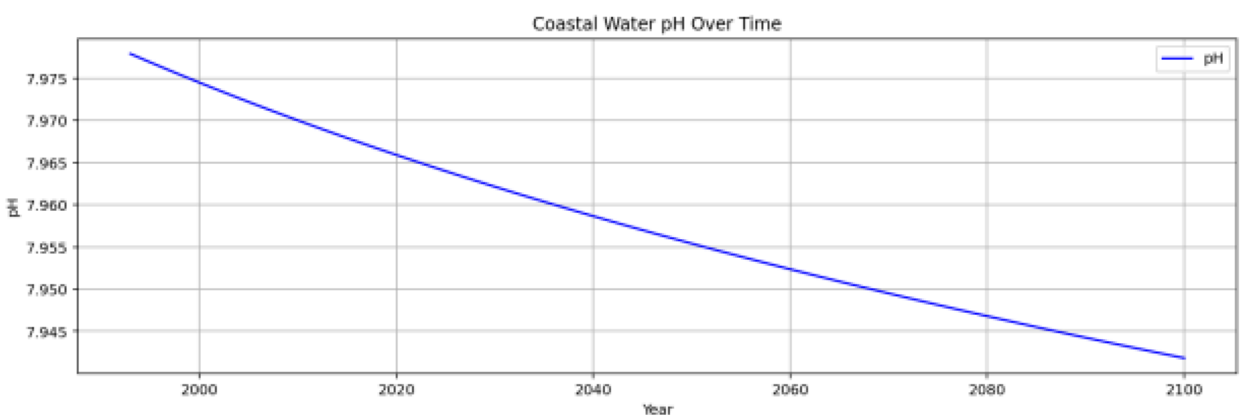
To model how ocean water acidity affects the hard coral coverage on the Great Barrier Reef, we first consider the pH of the ocean over time. According to a study on coastal ocean carbonate acidic systems, the pH in coastal water from 1900 to 2000 decreased from 8.18 to 8.08, and it is supposed to decrease from 8.08 to 7.85 from 2000 to 2100 (Lerman et al., 2016).

Modeling Change in Acidity.

We first assume that pH is naturally modeled logarithmic since the concentration of hydrogen ions becomes 10 times higher for every unit decrease in pH. Since the provided data only provides 3 data points, taking a logarithmic line of best fit was chosen to be the best course of action to get a model for pH change over time. The logarithmic line of best fit is displayed below:



The logarithmic best-fit line equation is given by: -0.0475*log(t+1) + 8.1937. We use log(t + 1) to avoid issues that may arise from getting an undefined value of log(0). Furthermore, since we are considering the years 1993 and onward in our hard coral coverage model, we can constrict the model to those years. We then end up with the following model:



How Increasing Acidity Affects Coral Growth Rate.

According to Woods Hole Oceanographic Institution (2018), as acidity in ocean water increases, corals find it harder to build their skeletons. These skeletons help reinforce coral and are an important factor when it comes to their growth. They also mention that the coral continues to demonstrate upward growth, however since their skeleton formation suffers, it takes longer for them to grow. This means that we should consider how the increasing acidity (decrease in pH) in ocean water leads to a decrease in coral growth rate.

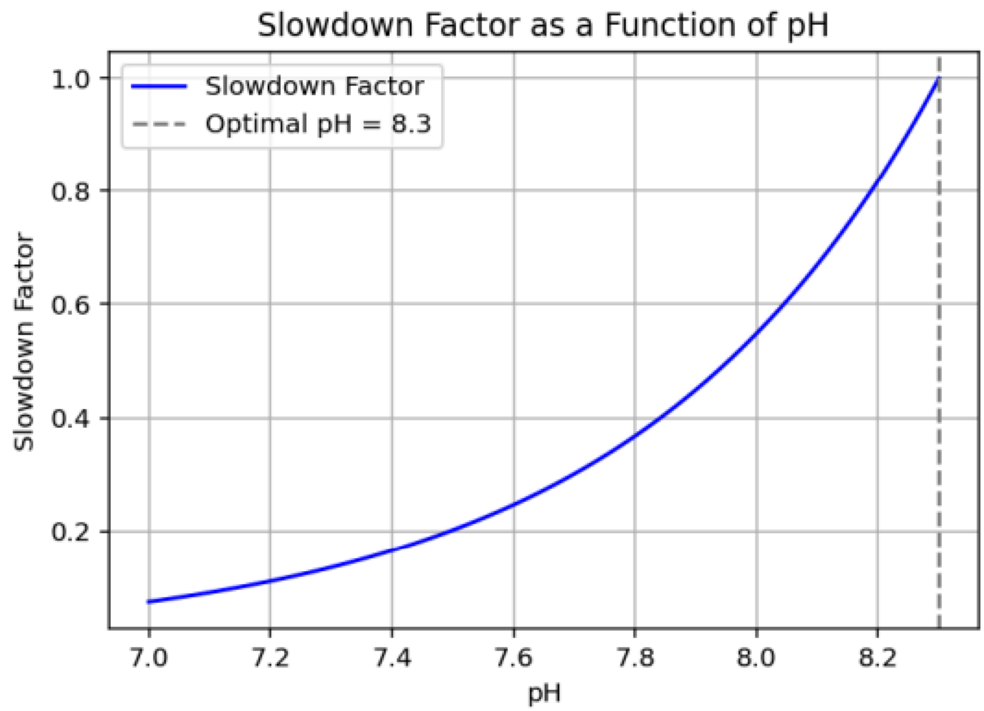
Modeling Decrease in Coral Growth Rate Due to Increasing Acidity.

From the logistic base model of coral growth created at the beginning, we know that the coral growth rate is represented by 0.039 or a 3.9% growth rate per year. According to Barkley et al. (2017), many carbon dioxide manipulation experiments have shown that coral growth and calcification are extremely sensitive to pH drops. To model this extreme sensitivity, we can consider an exponential decay method to model the decline in coral growth rates as pH drops.

First, we must figure out the optimal pH for coral growth. According to Delbeek (2020), corals usually calcify and thrive at pH ranges around 8.2 to 8.5. We can assume that the optimal pH for coral growth is 8.3 and that as the pH lowers from 8.3, the coral growth rate is slowed down by pH. Thus we can consider to following equation to calculate a coral growth rate slowdown factor based on decreasing pH per year:

$$e^{\left(-2\cdot\left(8.3-pH(t)\right)\right)}$$

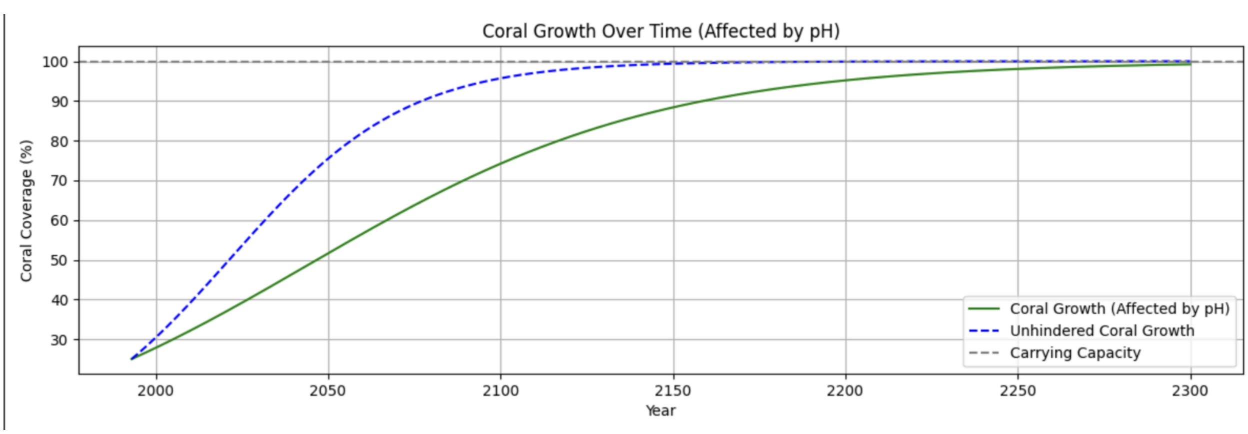
This is an exponential equation that changes the slowdown factor based on the distance of the pH from the optimal value of 8.3. The further the pH drops from 8.3, the greater the slowdown effect. In addition, the -2 in the exponent determines the sensitivity of coral growth to the pH. If the value was -3 or greater, the coral growth would slow down considerably faster due to pH drops. On the other hand, if the value is -1, the coral growth would not properly reflect the sensitivity of coral growth to pH drops. From model testing, -2 seemed to be the right value. A model of the slowdown factor affected by pH is given below:



When applying this slowdown factor to the growth rate per year, the updated growth rate equation will be given by:

$$R = 0.039 \cdot e^{\left(-2 \cdot \left(8.3 - pH(t)\right)\right)}$$

This shows how the slowdown factor is being applied to the unhindered growth rate of the base logistic model. Applying the updated growth rate to our base logistic model, we get :



From the graphs, we can see that the coral growth rate due to pH levels decreasing is significantly lower compared to the unhindered coral growth rate graph. This is due to the effect of the slowdown from pH drops on the unhindered coral growth rate.

Considerations of Updated Coral Growth-Acidity Model.

Although our updated model demonstrates reasonable results, some factors were not considered in the model for the sake of simplicity. One consideration is that there is no increase in growth rate if the pH is greater than the optimal 8.3. We only look at a decrease since that is the realistic expectation of ocean water pH. Additionally, according to the site Reef2Reef (2021), there is a possibility that the coral growth rate may become negative if pH drops to values lower than values around 7.6. This is because coral could dissolve due to high acidity levels. We do not consider it for this case since the graph and projected coral pH over time tell us that it will be a long time until the pH drops below 7.6. The effects will not be witnessed in the period of our model.

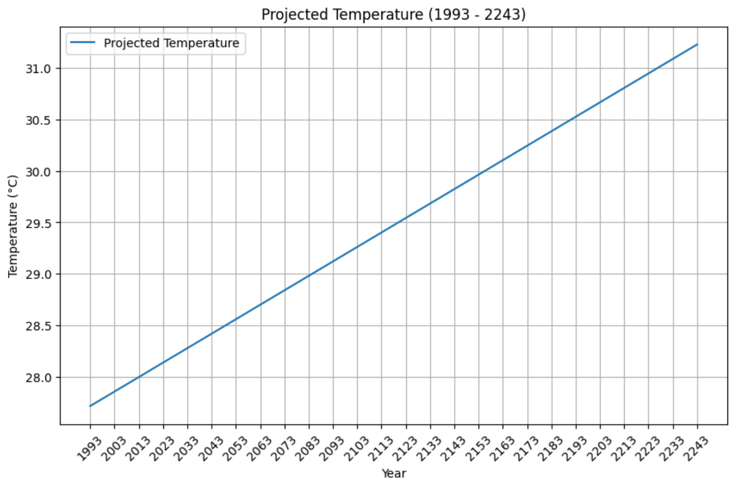
<u>Temperature and Hard Coral Coverage</u>

Background on Temperature Change and Effect on Coral

Increased temperatures can lead to a risk of coral bleaching, which occurs when corals get rid of helpful algae that live in them, causing them to become fully white and increasing the risk of coral death (NOAA, 2010). Based on an analysis of sea temperature data for the Southern and Central Great Barrier Reef regions during the warmest months from 1980 to 2023, we found an average increase of about 0.014 degrees Celsius per year (Embury et al., 2024). We assumed that we could expect a continued increase at this rate.

Assumptions and Modeling Methods

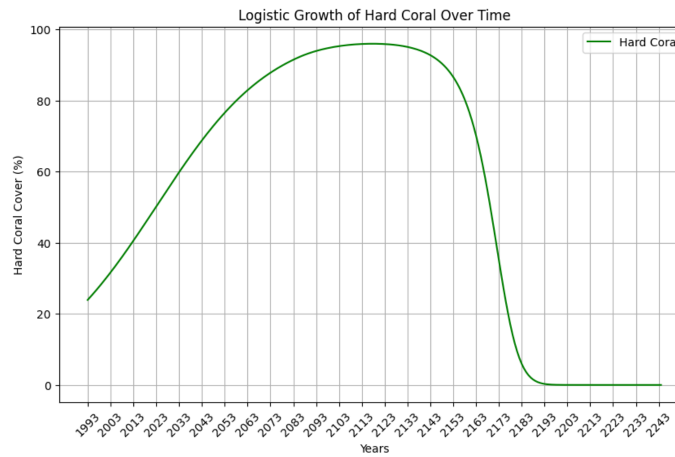
For modeling purposes, we examined the Southern and Central regions of the Great Barrier Reef due to the limited availability of data for the Northern region. We defined the Southern region as roughly between -23.91 and -19.55 degrees latitude and 148.88 to 152.67 degrees longitude and the Central region as roughly between -19.72 and -15.75 degrees latitude and 145.57 to 149.12 degrees longitude, based on the location of coral sample sites. Our modeling assumes that these regions are rectangular for simplicity even though they are slightly irregularly shaped due to the curvature of the Earth. We chose to focus on the sea temperature during the warmest months of December through April, which we referred to as summer sea temperature, because of the potential for bleaching to occur during these months. The aforementioned analysis suggests an increase in temperature of about 0.014 degrees Celsius per year between 1980 and 2023. We modeled this increase linearly, which is likely a relatively conservative model. We began our temperature model in 1993 to match our coral data. The starting temperature for 1993 of about 27.71 degrees was calculated by taking the mean of the summer temperatures from 1988 to 1998. Using these assumptions we created an initial temperature model.



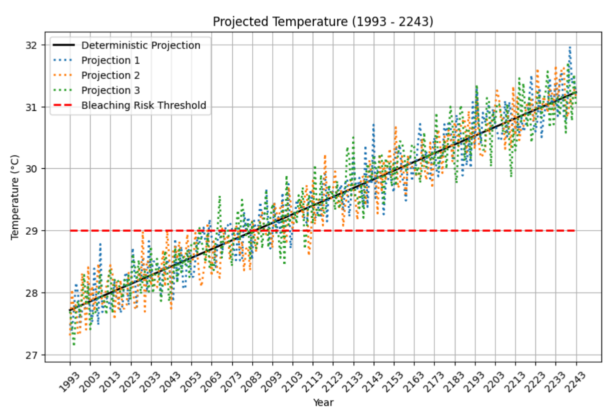
For the interaction between temperature and coral cover, we assumed that bleaching occurs starting at a 29-degree average over the five warmest months based on information from the Great Barrier Reef Foundation (2024). We also assumed that bleaching would only occur during those five months with the warmest sea temperatures. We implemented this as a penalty on coral cover for temperatures above 29 degrees using exponential decay so that the penalty increases rapidly for much higher temperatures. We also assumed that hard coral cover was initially 23.92 percent in 1993 based on a mean of all the samples in the region from 1993.

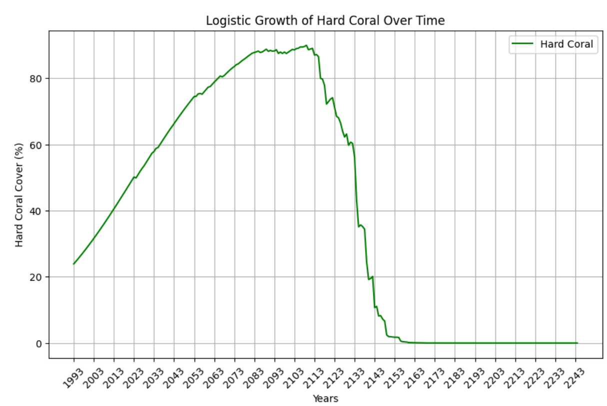
For average summer temperatures at or below 29 degrees, the growth rate of the hard coral cover remained at .039. For temperatures above 29 degrees, we adjusted the growth rate as follows:

$$r = .039\left(2 - e^{1.5\left(temperature - 29\right)}\right)$$

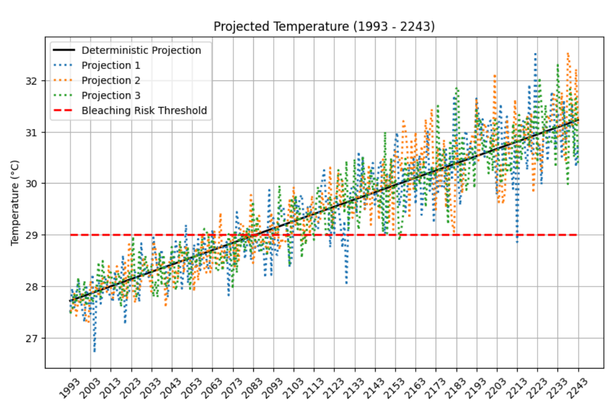


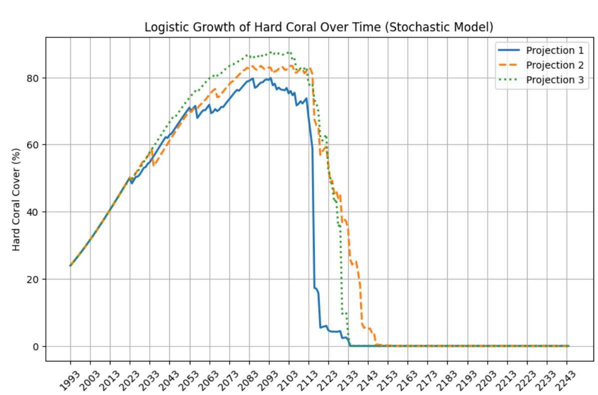
Analysis of the temperature data from 1980 to 2023 yielded a standard deviation of about 0.31 degrees for summer sea temperature. We assumed that stochasticity would be normally distributed based on the central limit theorem. This led to a revised model.





Since the variance of temperature also increases over time due to climate change (Olonscheck et al., 2021), we assumed that the standard deviation will increase by 0.001 degrees per year. We revised the stochasticity to reflect this.





Analysis and Conclusions

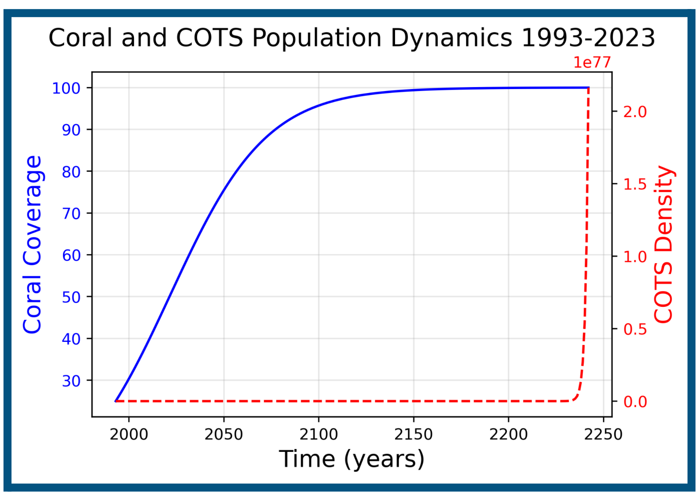
The temperature model suggests that due to the effects of bleaching alone, the environment in the Southern and Central Great Barrier Reef region will likely be unable to sustain any substantial hard coral cover after the middle of the 22nd century. This implies a collapse of reefs and the ecosystems that rely on them.

<u>Crown of Thorn Starfish and Hard Coral Coverage</u>

The Crown of Thorn Starfish (COTS) is a natural predator of hard coral (Fisher, 2022). They dissolve the coral into nutrients giving life to the starfish but killing the coral. Here we will model a predator-prey relationship.

Base Model for Crown of Thorn Starfish

In our base model, which we have chosen to model discreetly with our time interval of 1 year, we will begin by assuming each starfish couple (male and female) has 2 babies together. We assume that no starfish die. This will lead to the starfish population doubling every year, **growing exponentially**. We can model this with the equation below. Where n is the number of years and f(n) describes the number of starfish in the population.



$$\boxed{f(n) = 2f(n-1)}$$

Base Model Analysis

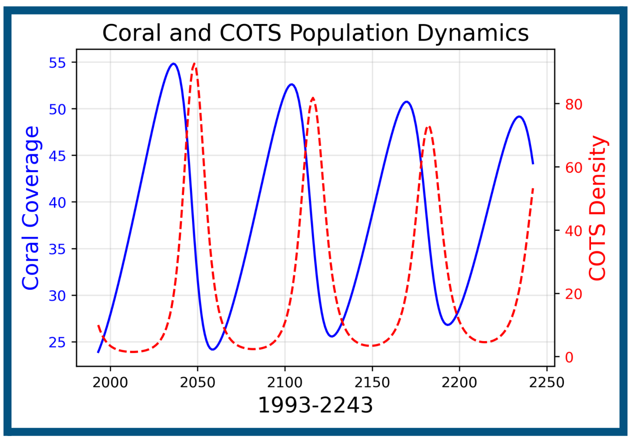
In this first model, we assumed the starfish grew exponentially with no restriction. As you would imagine, the starfish population explodes and approaches infinity. The model also shows the coral reaching 100% seafloor coverage quite peacefully following its logistic growth, despite the ever-increasing number of predators. These results are very unfeasible and do not reflect real life. This model fails to show the starfish interact with the coral through feeding which damages and kills the coral. We also assumed the starfish live forever, this is also not accurate. Let's adjust our assumptions in a second model to account for the first model's limitations.

Predator-Prey Model

To adjust for our predator-prey relationship between the Crown of Thorn starfish and the coral, we must change our assumptions. In this revised model, we will now assume that the starfish's growth rate will be proportional to the population of the starfish. We assume g to be the growth proportion, with $\mathbf{g = 0.12}$. We also assume that the starfish naturally die at a rate of $\mathbf{d_2}$**, 0.45,** each year. For coral, we assume its growth rate decreases in proportion to the population of the starfish with some proportion d_1, with $\mathbf{d_1 = 0.001}$. This decrease is added onto the previous logistic growth of the coral, with c(n) describing the coral population, **k** being the carrying capacity of 100 and **r** being its intrinsic growth rate of 0.039. Using our data we let c(0) = 23.92% (AIMS 2015) , and f(0) = 10 per hectare. These assumptions give us the following model.

$$c(n) = c(n-1)\left(1 + r\left(1 - \frac{c(n-1)}{k}\right) - f(n)d_1\right)$$

$$f(n) = f(n-1)\left(1 + gc(n) - d_2\right)$$



Predator-Prey Model Analysis

In the predator-prey model, we can see evidence of a predatory interaction between the starfish and its prey, the coral. Given an initial seafloor coverage of 23.92% and only 10 starfish per hectare, the coral can grow quickly, but with not enough coral initially, the starfish start to die. This doesn't last long due to the coral's quick growth as soon there is enough food and the starfish rapidly surge in population and devour the coral causing a massive decline in the coral population. This decline leaves little food for the starfish to grow and they start to die again. It was very clear in these oscillations that the model was able to show a predator-prey relationship much more clearly than our first.

We also noticed that each peak got slightly lower each oscillation and each low got slightly higher and higher. This begged the question, do these populations stabilize? Here are our fixed point calculations.

Recall the model for the starfish population and coral model.

$$f(n) = f(n-1)(1 + gc(n) - d_2)$$

$$c(n) = c(n-1)\left(1 + r\left(1 - \frac{c(n-1)}{k}\right) - f(n)d_1\right)$$

A fixed point will be when $f(n) = f(n-1)$ and when $c(n) = c(n-1)$. Let f_* be the starfish fixed point and c_* be the coral coverage fixed point. Then to solve for the fixed points we having the following.

$$f_* = f_*(1 + gc(n) - d_2)$$

$$1 = 1 + gc_* - d_2$$

$$0 = gc_* - d_2$$

$$-gc_* = -d_2$$

$$c_* = \frac{d_2}{g}$$

Here we have the fixed point for coral coverage is:

$$c_* = \frac{d_2}{g} \quad c_* = \frac{starfish\ death}{starfish\ growth} \quad c_* = \frac{0.45}{0.012} = 37.5$$

The fixed point for for starfish:

$$c_* = c_*(1 + r\left(1 - \frac{c_*}{k}\right) - f_*d_1$$

$$1 = 1 + r\left(1 - \frac{c_*}{k}\right) - f_*d_1$$

$$0 = r\left(1 - \frac{c_*}{k}\right) - f_*d_1$$

$$f_*d_1 = r(1 - \frac{c_*}{k})$$

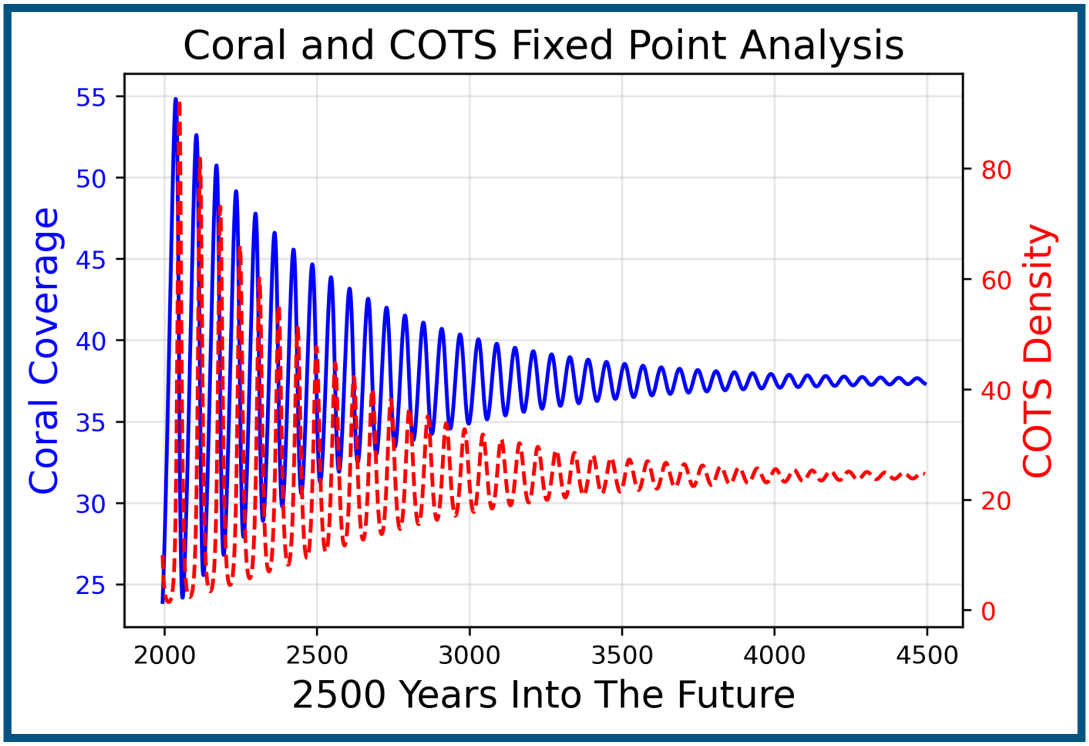
$$f_* = \frac{r(1 - \frac{c_*}{k})}{d_1}$$

Plugging in $c_* = \frac{d_2}{g}$ we have:

$\mathrm{f}_* = \frac{r(1-\frac{d_2}{gk})}{d_1} \quad f_* = \frac{coral\ growth\ (1-\frac{starfish\ death}{starfish\ growth\ *\ carrying\ capacity})}{coral\ death}$

$$f_* = \frac{.039(1 - \frac{.45}{.012*100})}{.001} = 24.375$$

Our fixed point analysis showed that after a long time, the coral fixed point is at 37.5% and the starfish population density would go to 24.375. Let's plot this 2500 years into the future to visually assess its stability.



Coral coverage does converge to the fixed point of 37.5 and the starfish do converge to 24.375.

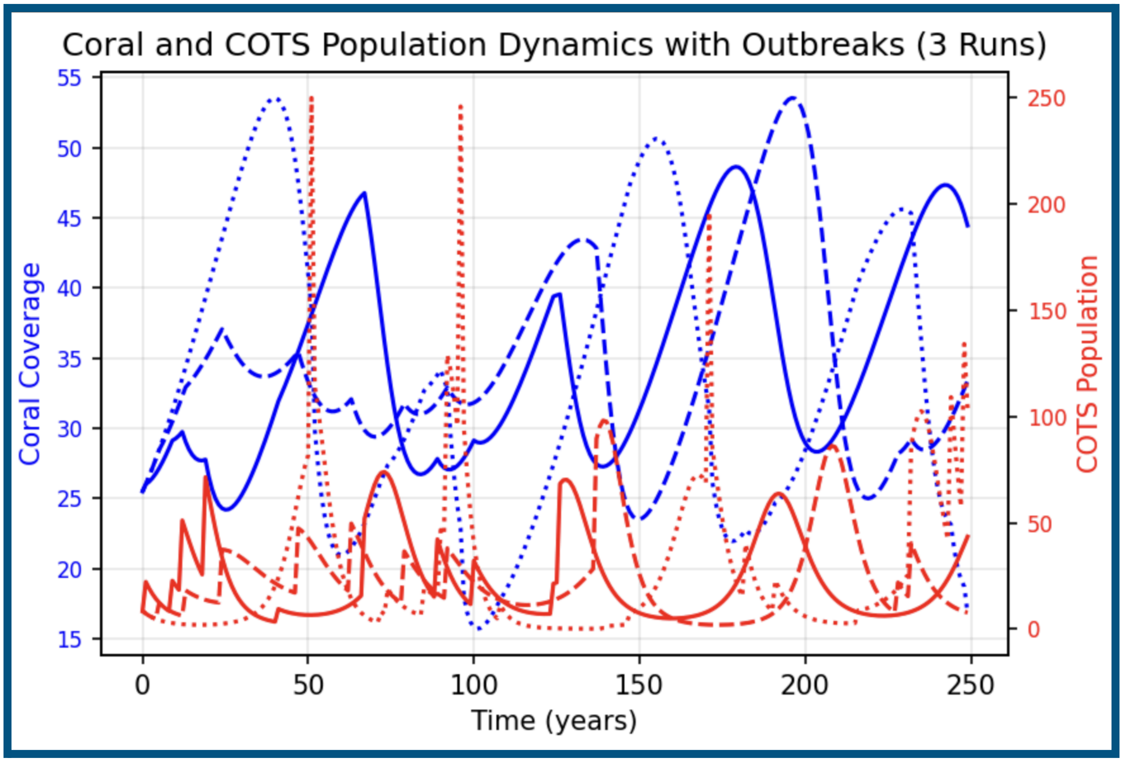
Predator Stochasticity

In this third and final iteration of the model, we included stochasticity to the starfish growth population as data over the years has shown starfish outbreaks (Fisher, 2022). Through our assumptions, we set the outbreak chance to be .05 each year (1 outbreak every 20 years) with the outbreak to be multiplying the population by N(3, 0.1). To combat this the Australian government has initiated programs to send divers to manually kill the starfish to control the population (Less 2024). We have added this into our model by cutting the population of starfish by N(.5, 0.1) if the population went above 150. We will simulate this in three runs.

COTS Dynamics $(f(n))$

$$P(X = \omega) = \begin{cases} 0.05 & \text{if } \omega = 3, \\ 0.95 & \text{if } \omega = 1, \end{cases}$$

$$f(n) \begin{cases} \omega \cdot f(n-1)\Big[1 + 0.012 \cdot c(n-1) - 0.45\Big], & \text{if } f(n-1) \leq 125 \\ \omega \cdot f(n-1) \cdot \mathcal{N}(0.5, 0.1)\Big[1 + 0.012 \cdot c(n-1) - 0.45\Big], & \text{if } f(n-1) > 125 \end{cases}$$



Combined Model

Combining All Variables and Assumptions.

To create a model that integrates all variables, we took the same logic behind the individual models and merged them. One key consideration was how temperature and pH affect the starfish population, which was discussed during the question section of the presentation. Research by Tan et al. (2017) indicates that the crown-of-thorns starfish are not significantly affected by the range of temperatures, and while the pH can affect larvae development and decrease their size, our forecasted pH does not drop low enough (< 7.4pH) in our forecast range to cause them harm. So we assume that the pH and temperature do not directly affect the crown-of-thorns starfish in our forecasted years. All assumptions from previous models were assumed for the combined model as well.

The Model.

In this model, we use the same predator-prey model and keep the coral coverage logistically modeled; however, the growth rate of the coral is a piecewise-defined exponential function of both pH and temperature. We use the same exponential multipliers from the previous models that "turn on" when the pH and/or temperature reach harmful levels, less than 8.3 pH and greater than 29 degrees Celsius. The Crown-of-thorns starfish still have stochastic outbreaks and population control if they exceed a density of 125. The figure below displays the piecewise-defined function for coral coverage and three stochastic runs of our model.

Coral and COTS Population Dynamics with Cases

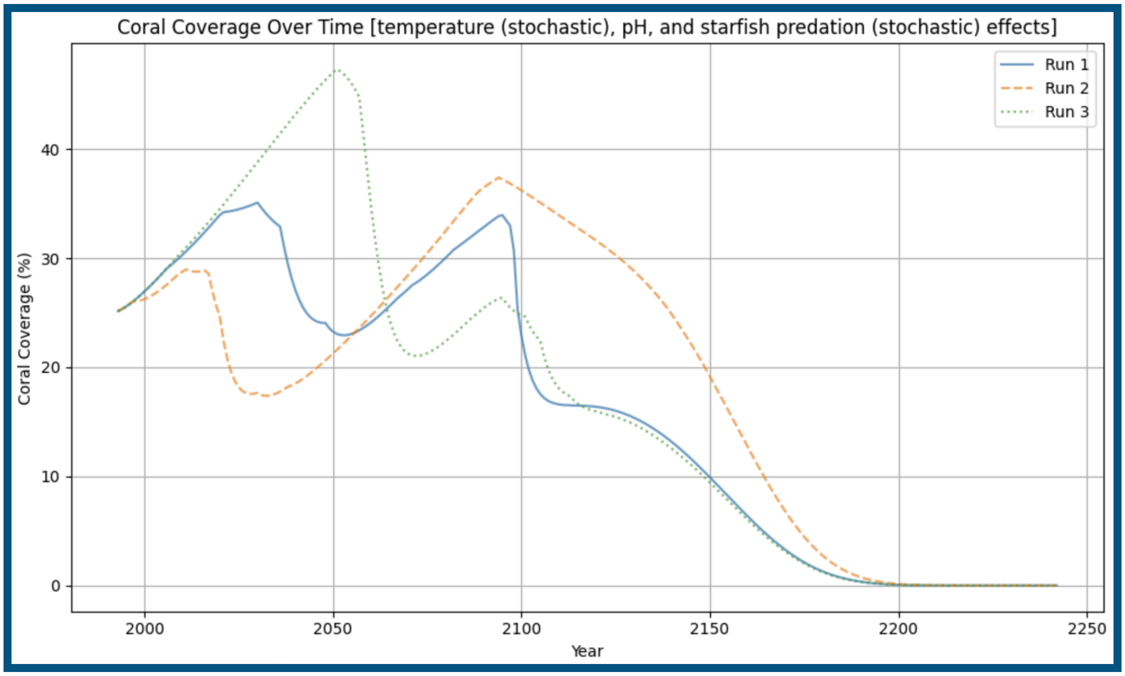
Coral Dynamics ($x(n)$)

$$x(n) = \begin{cases} x(n-1)\left[1 + 0.039\left(1 - \frac{x(n-1)}{100}\right) - 0.001 \cdot y(n-1)\right], & \text{if pH} \geq 8.3 \text{ and temp} < 29 \\ x(n-1)\left[1 + e^{-2(8.3-\text{pH})} \cdot 0.039\left(1 - \frac{x(n-1)}{100}\right) - 0.001 \cdot y(n-1)\right], & \text{if pH} < 8.3 \text{ and temp} < 29 \\ x(n-1)\left[1 + e^{-2(8.3-\text{pH})} \cdot 0.039\left(1 - \frac{x(n-1)}{100}\right) \cdot \left(2 - e^{1.5(\text{temp}-29)}\right) - 0.001 \cdot y(n-1)\right], & \text{if pH} < 8.3 \text{ and temp} \geq 29 \\ x(n-1)\left[1 + 0.039\left(1 - \frac{x(n-1)}{100}\right) \cdot \left(2 - e^{1.5(\text{temp}-29)}\right) - 0.001 \cdot y(n-1)\right], & \text{if pH} \geq 8.3 \text{ and temp} \geq 29 \end{cases}$$

COTS Dynamics ($y(n)$)

$$P(X = \omega) = \begin{cases} 0.05 & \text{if } \omega = 3, \\ 0.95 & \text{if } \omega = 1, \end{cases}$$

$$y(n) \begin{cases} \omega \cdot y(n-1)\left[1 + 0.012 \cdot x(n-1) - 0.45\right], & \text{if } y(n-1) \leq 125 \\ \omega \cdot y(n-1) \cdot \mathcal{N}(0.5, 0.1)\left[1 + 0.012 \cdot x(n-1) - 0.45\right], & \text{if } y(n-1) > 125 \end{cases}$$



Analysis.

In the earlier years, the predator-prey model dominates the coral coverage model. The model oscillates up and down just like the predator-prey model. The stochastic peaks of the starfish outbreaks and the Australian diver interventions are evident. However, as time increases, our forecasted pH and temperature values decrease and increase respectively. Once they hit their thresholds the coral growth rate becomes a function of pH, temperature, or both. The pH makes the coral grow slower and the temperature makes the population go into exponential decay by bleaching the coral. The variable dominating the model in the later years is temperature, actively killing off all the coral.

Conclusions

Model Implications.

We have identified ocean acidification (pH), temperature, and crown-of-thorns starfish as threats to the Great Barrier Reef and the integrity of its coral. With our models, conservational efforts can be made in a mathematically driven manner. For instance, The Australian government can implement population control methods on the crown-of-thorns starfish when they reach a certain population size–that size being a value our model can help determine.

One particular result of note was the forecasted temperatures wiping out the coral population, the decay starting around the year 2100. Knowing that rising temperatures are the biggest long-term threat to reef integrity, conservational forces of the Great Barrier Reef should focus their efforts on addressing global warming. If temperatures keep increasing as forecasted, the Great Barrier Reef will be wiped out due to coral bleaching.

It's worth mentioning that ocean acidification is also a side effect of climate change. When carbon dioxide is released into the atmosphere, the global temperature rises and the ocean absorbs carbon dioxide, which makes it more acidic. So, if climate change and the burning of greenhouse gases can be lessened, two of the variables harming the Great Barrier Reef the most (low pH and high temperature) will be mitigated.

Future work.

There are many ways to approach modeling the Great Barrier Reef. While we have identified three environmental factors, there are a lot of variables remaining that also impact the Great Barrier Reef. Some of these include pollution & poor water quality, overfishing, and coastal development. Modeling these variables could introduce new insights that our current combined model may lack. Another angle to approach the problem could be to examine how different conservation strategies affect coral coverage. For example replantation: How much coral do we need to plant to make a significant difference in the overall coral coverage of the Great Barrier Reef?

One limitation of our model was using lines of best fit for both the pH and temperature. There are many ways to model these variables and there are more sophisticated techniques that researchers have used; however, most are outside of the scope of this class.

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