Modeling Coral Reef Bleaching

Lila Brown, Xander Michaels, Maggie Hintz, Bryan Jacobs

Presentation Outline

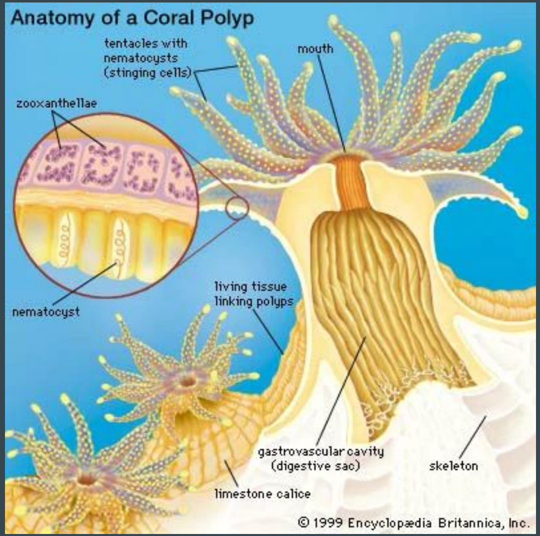
- Introduction
- Model parameters
- Reintroduce original model
- New model
- Equilibria analysis
- Sensitivity Analysis
- Results
- Discussion

Abstract

Zooxanthellae are a symbiotic dinoflagellate that inhabits coral, providing oxygen, and other photosynthetic products to the coral which can then be used for other chemical reactions. Zooxanthellae generally live near their upper lethal temperature limits, and so small increases in ocean temperatures can cause major bleaching events in zooxanthellae populations. Scientists often use coral bleaching rate as evidence of climate change due to the known effect that increases in ocean temperatures have on zooxanthellae. For our project we looked at the relationship between zooxanthellae population percent and changes in ocean temperature. We modeled an ocean temperature increase of 2° C over a period of 100 years and looked at the effect that this temperature change had on three different zooxanthellae types, each with their own carrying capacities and epsilon values (epsilon is competitive dominance of the various algal types). Our model found that as temperature increases, the competitive dominance of Z1 decreases while the competitive dominance of Z2 increases, allowing Z2 to outcompete the other zooxanthellae types. Our model also shows that the overall population percentage of all three zooxanthellae types decreases as the temperature continues to increase over a period of 100 years.

Introduction

- In our project we developed a model to discover the relationship between increases in ocean temperature and the population percentage of zooxanthellae.
- The goal of our project is the see what impact temperature increases have on zooxanthellae carrying capacity and competitive dominance, so that we can observe how zooxanthellae respond to average increases in overall temperature.



Why does it matter?

- Increases in ocean temperature cause bleaching, therefore, bleaching rate can be used as evidence of global warming.
- Coral reefs rarely recover after zooxanthellae die.
- Wildlife depend on coral reefs
    - Support organisms at the base of ocean food chains
    - Shelter, spawning grounds, protection from predators
- People depend on coral reefs
    - Absorb force of waves and storm surges keeping coastal communities safe
    - People rely on reef dwelling species as primary source of income/food
    - Reef tourism brings in billions of dollars per year and supports thousands of jobs
- From 2014-2017, 75% of the worlds tropical coral reefs experienced enough heat stress to trigger bleaching, for 30% this was enough to kill coral

Model parameters

Lotka-Volterra competition equations

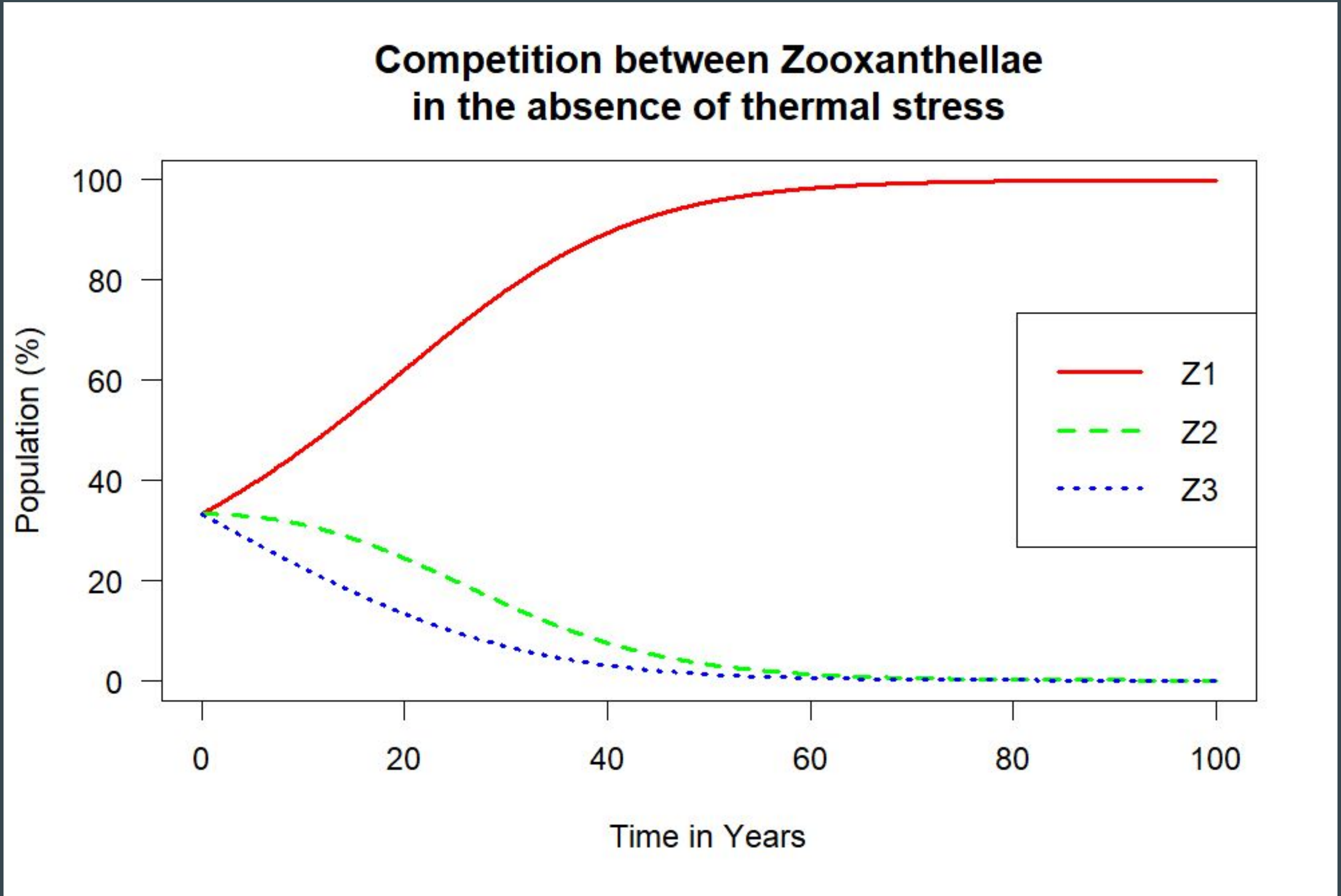
Zi: population density of the *i*th zooxanthellae type

R: reproduction rate

K: carrying capacity of the coral unit

ε: competitive dominance of various algal types

$$\frac{dZ_1}{dt} = RZ_1(K - Z_1 - Z_2 - Z_3)$$
$$\frac{dZ_2}{dt} = RZ_2(K - Z_1(1+\epsilon) - Z_2 - Z_3)$$
$$\frac{dZ_3}{dt} = RZ_3(K - Z_1(1+\epsilon) - Z_2(1+\epsilon) - Z_3)$$



Competition between Zooxanthellae
in the absence of thermal stress
Population (%)
100
80
60
40
20
0
0
20
40
60
80
100
Time in Years
Z1
Z2
Z3

Model Parameters (With Thermal Stress)

$$\frac{dZ_1}{dt} = RZ_1(K_1 - Z_1 - Z_2(1+\epsilon_2) - Z_3(1+\epsilon_3)) \tag{1}$$

$$\frac{dZ_2}{dt} = RZ_2(K_2 - Z_1(1+\epsilon_1) - Z_2 - Z_3(1+\epsilon_3)) \tag{2}$$

$$\frac{dZ_3}{dt} = RZ_3(K_3 - Z_1(1+\epsilon_1) - Z_2(1+\epsilon_2) - Z_3) \tag{3}$$

$$\frac{dT}{dt} = 0.02 \tag{4}$$

$$\frac{dK_1}{dt} = \frac{-362}{T} \cdot 0.02 \tag{5}$$

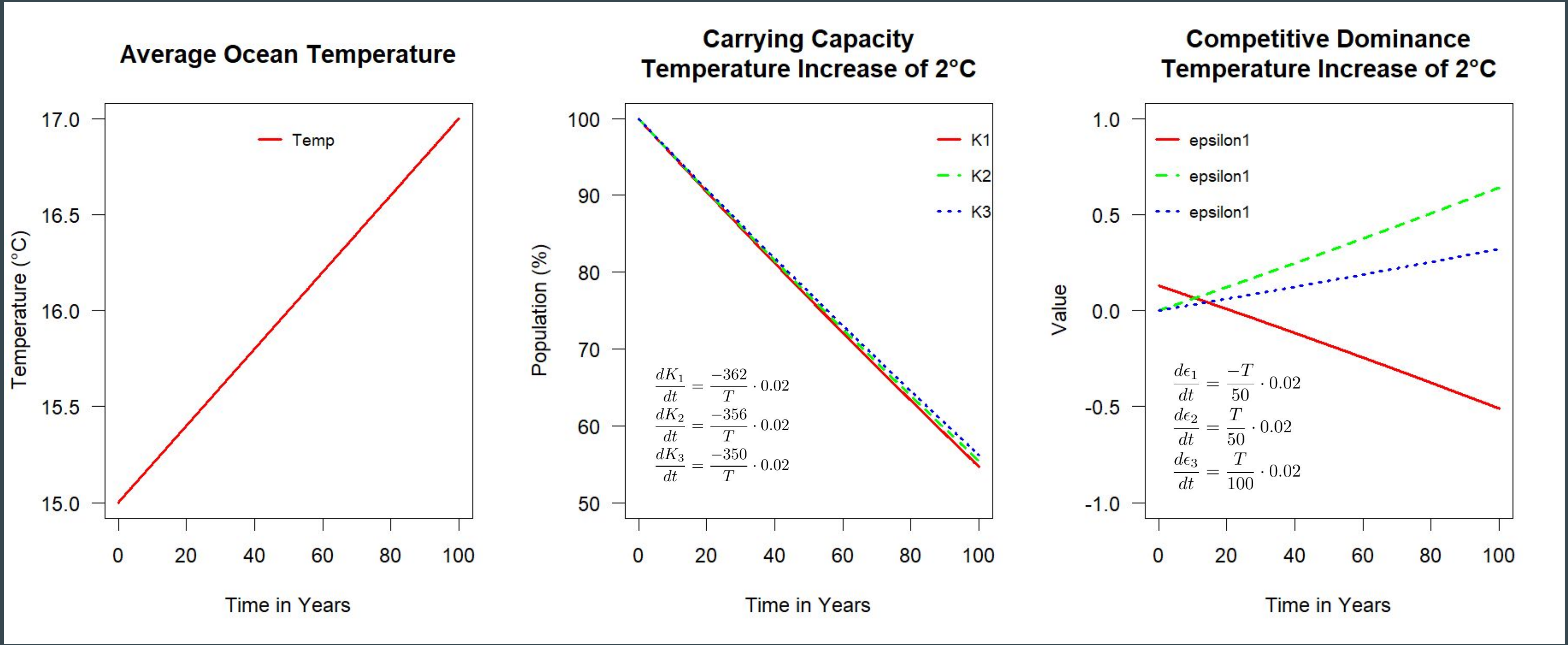
$$\frac{dK_2}{dt} = \frac{-356}{T} \cdot 0.02 \tag{6}$$

$$\frac{dK_3}{dt} = \frac{-350}{T} \cdot 0.02 \tag{7}$$

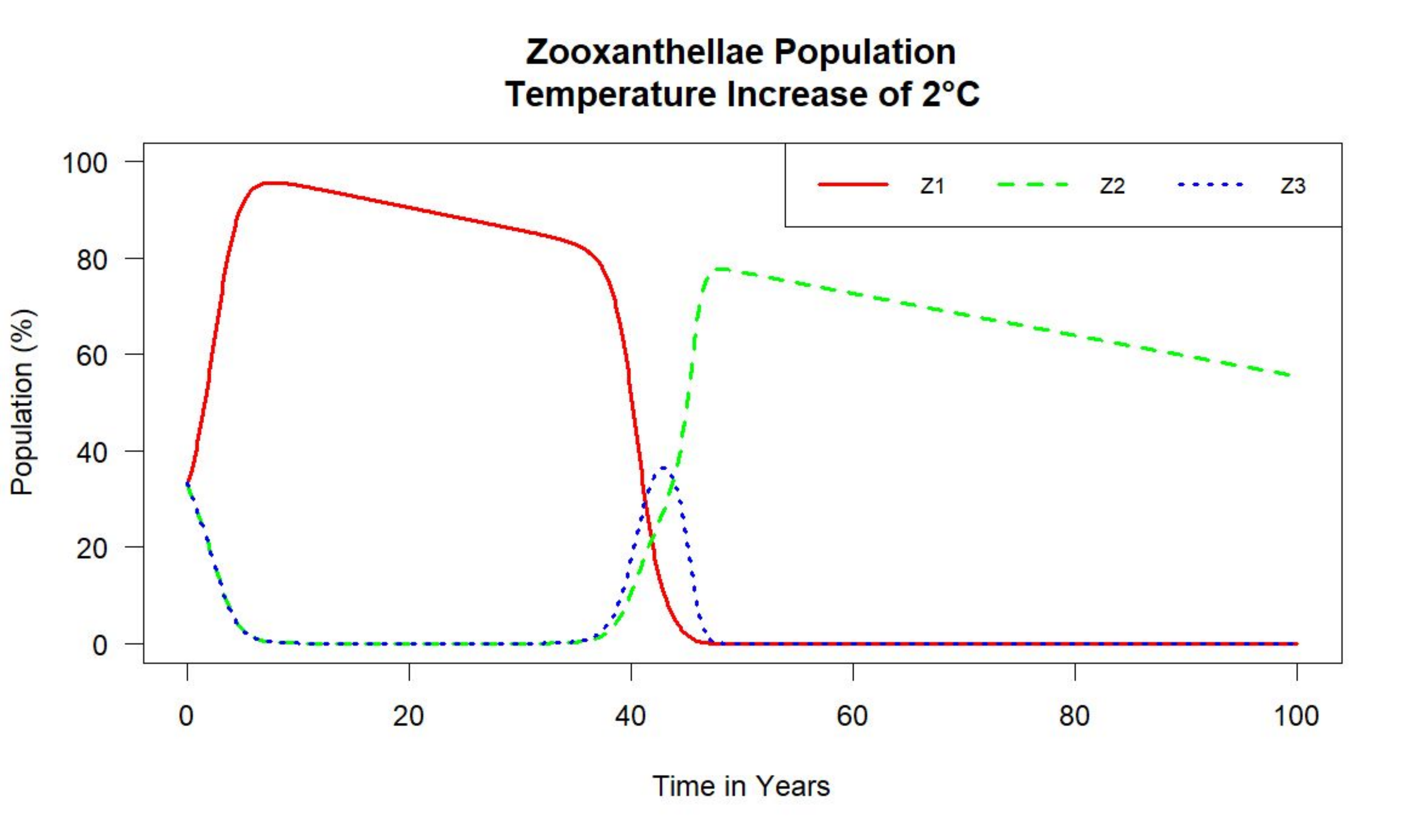
$$\frac{d\epsilon_1}{dt} = \frac{-T}{50} \cdot 0.02 \tag{8}$$

$$\frac{d\epsilon_2}{dt} = \frac{T}{50} \cdot 0.02 \tag{9}$$

$$\frac{d\epsilon_3}{dt} = \frac{T}{100} \cdot 0.02 \tag{10}$$



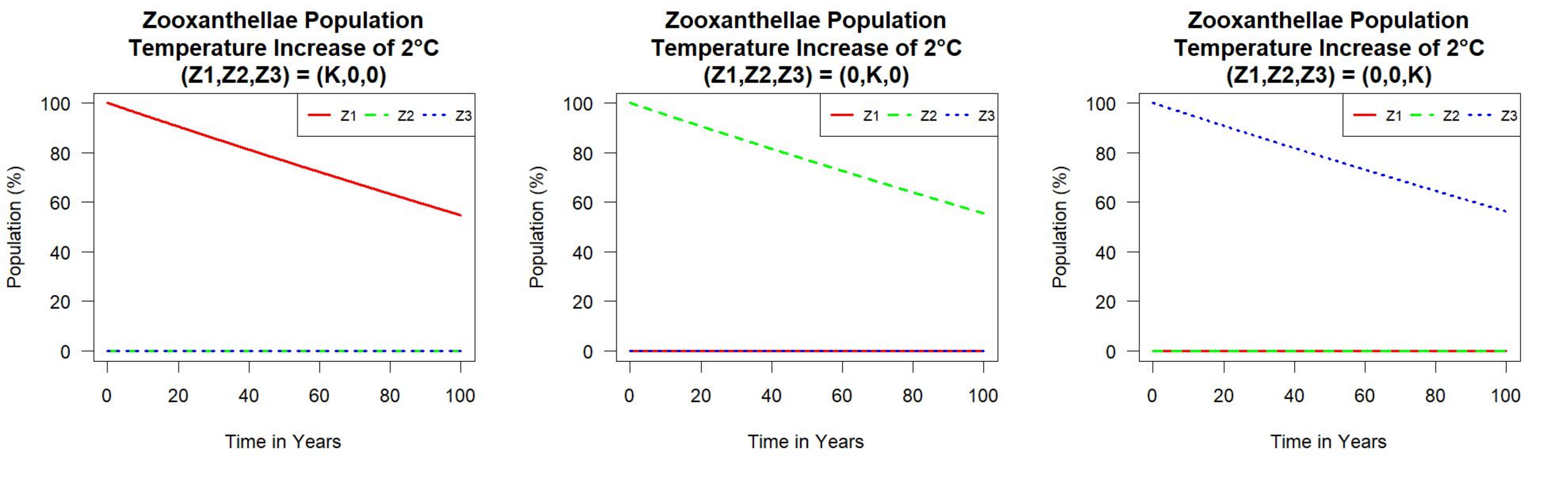
Average Ocean Temperature
Temperature (°C)
Time in Years
Temp
15.0
15.5
16.0
16.5
17.0
0
20
40
60
80
100
Carrying Capacity
Temperature Increase of 2°C
Population (%)
Time in Years
K1
K2
K3
50
60
70
80
90
100
$\frac{dK_1}{dt} = \frac{-362}{T} \cdot 0.02$
$\frac{dK_2}{dt} = \frac{-356}{T} \cdot 0.02$
$\frac{dK_3}{dt} = \frac{-350}{T} \cdot 0.02$
Competitive Dominance
Temperature Increase of 2°C
Value
Time in Years
epsilon1
epsilon1
epsilon1
-1.0
-0.5
0.0
0.5
1.0
$\frac{d\epsilon_1}{dt} = \frac{-T}{50} \cdot 0.02$
$\frac{d\epsilon_2}{dt} = \frac{T}{50} \cdot 0.02$
$\frac{d\epsilon_3}{dt} = \frac{T}{100} \cdot 0.02$


Zooxanthellae Population
Temperature Increase of 2°C
Z1
Z2
Z3
Population (%)
100
80
60
40
20
0
0
20
40
60
80
100
Time in Years

Equilibrium

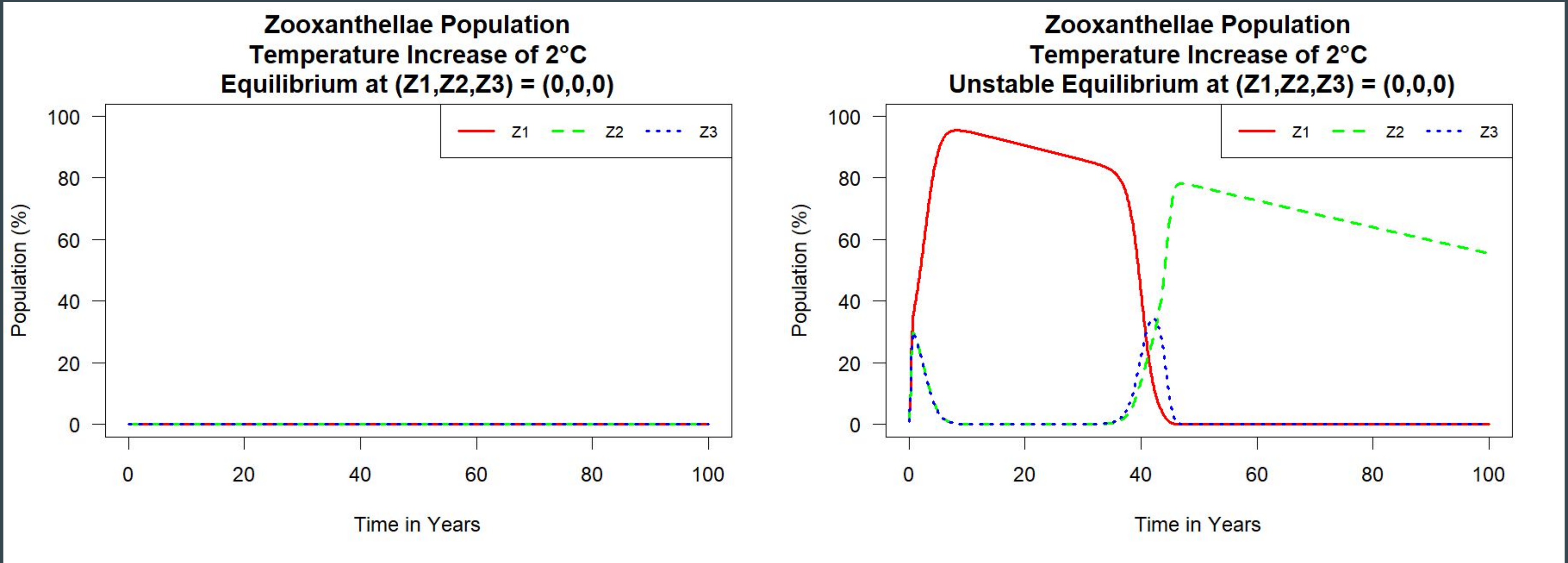
Since K is changing over time, the only possible equilibrium is when all populations start at 0.

i.e. (Z1, Z2, Z3) = (0, 0, 0)

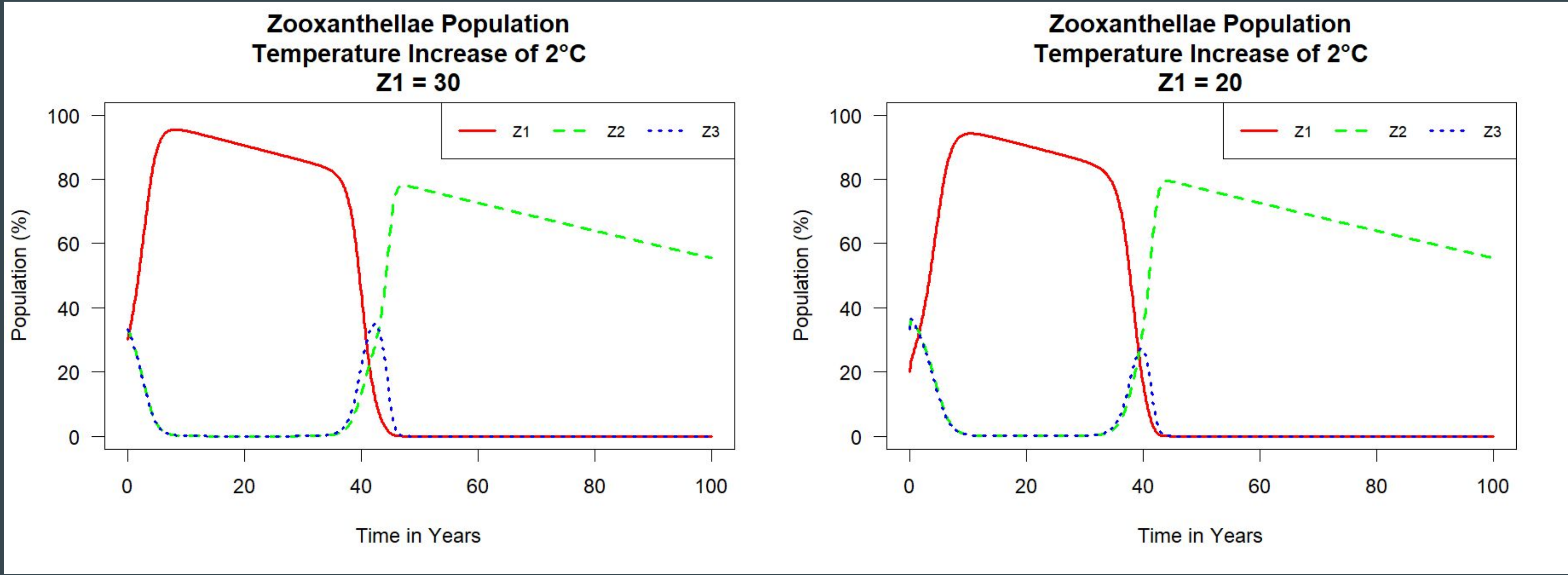


Equilibrium Analysis

Equilibrium at (Z1, Z2, Z3) = (0, 0, 0) is unstable

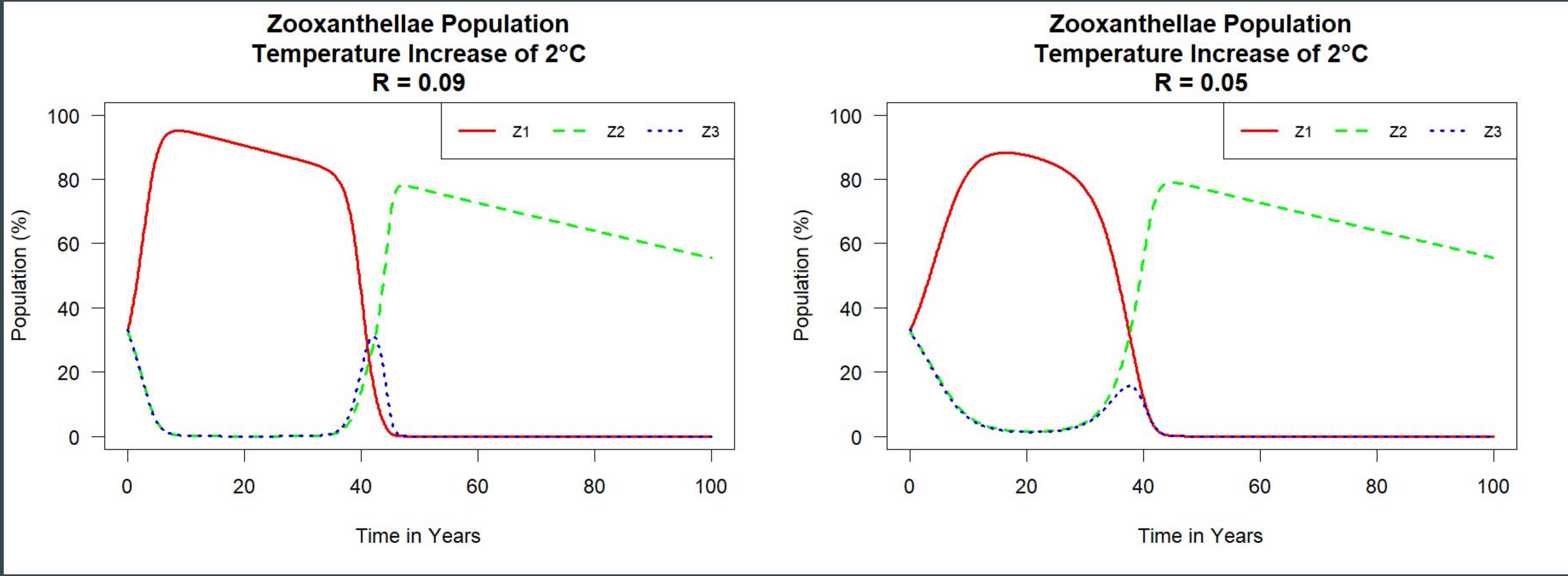


Sensitivity Analysis of Z1



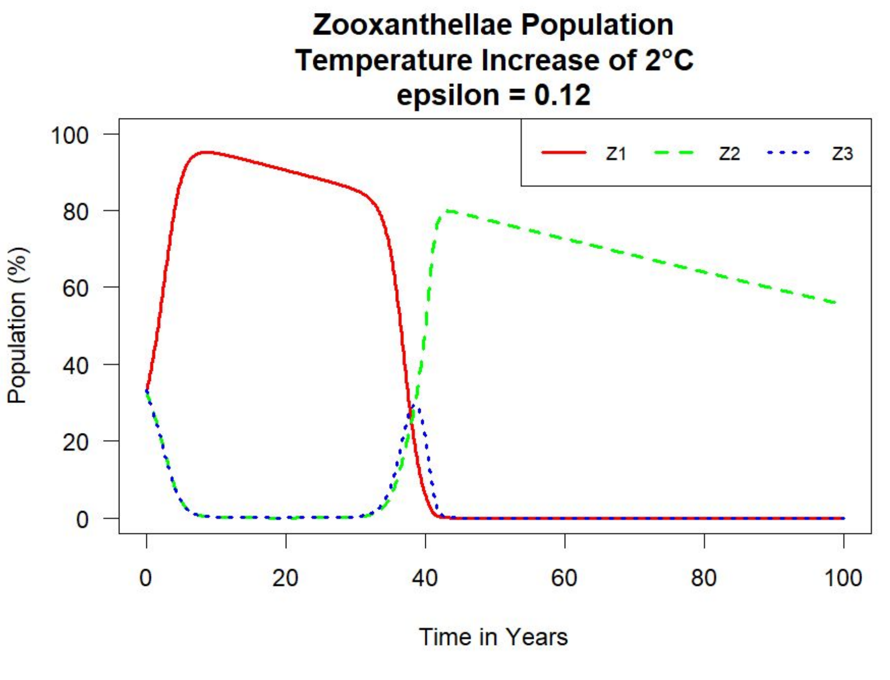
Z1 = 33 in original model

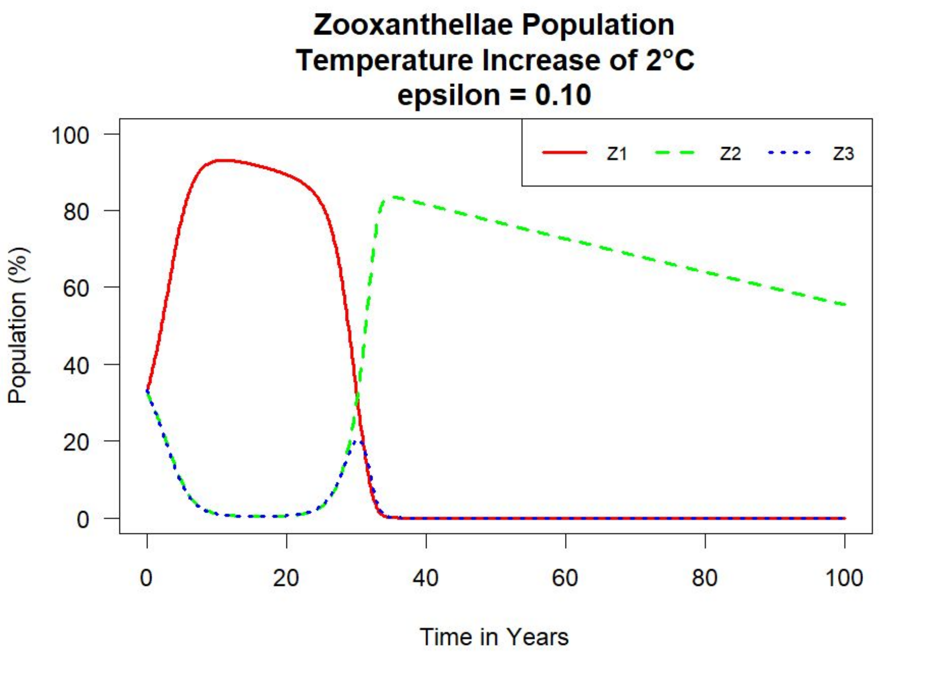
Sensitivity Analysis of R



R = 0.1 in original model

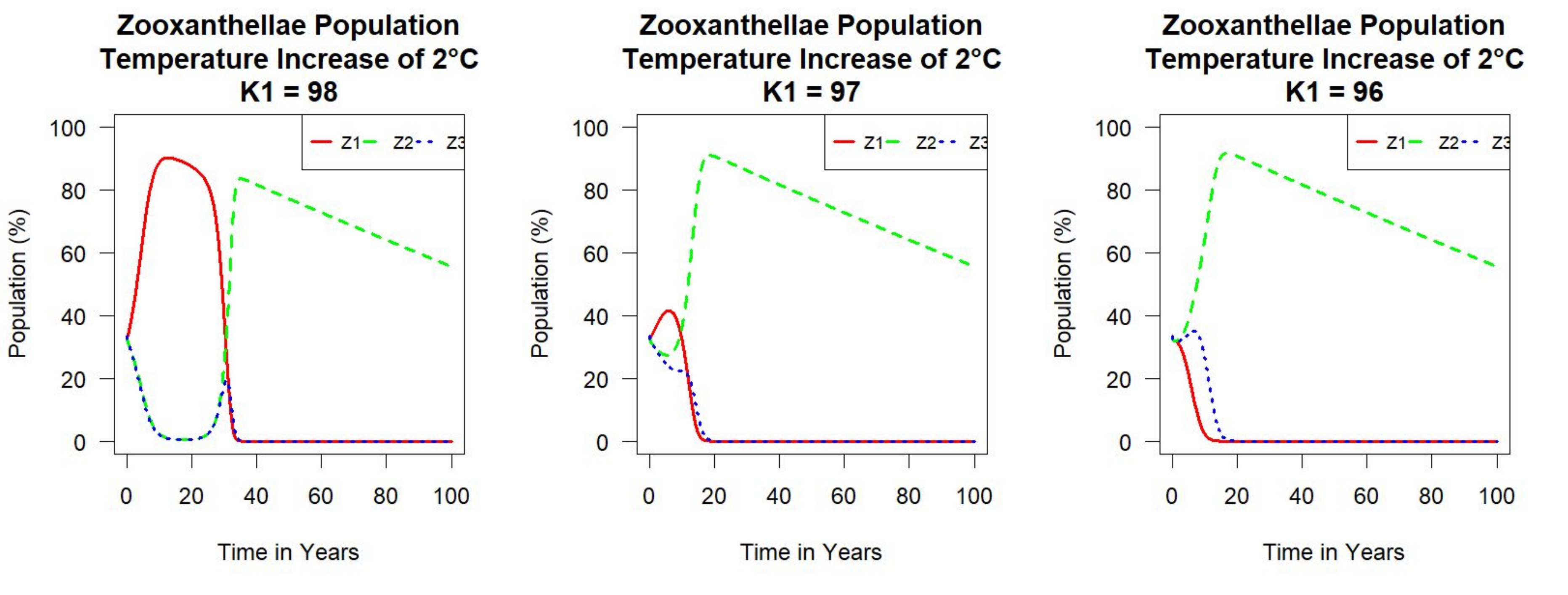
Sensitivity Analysis of ε1





ε1 = 0.13 in original model

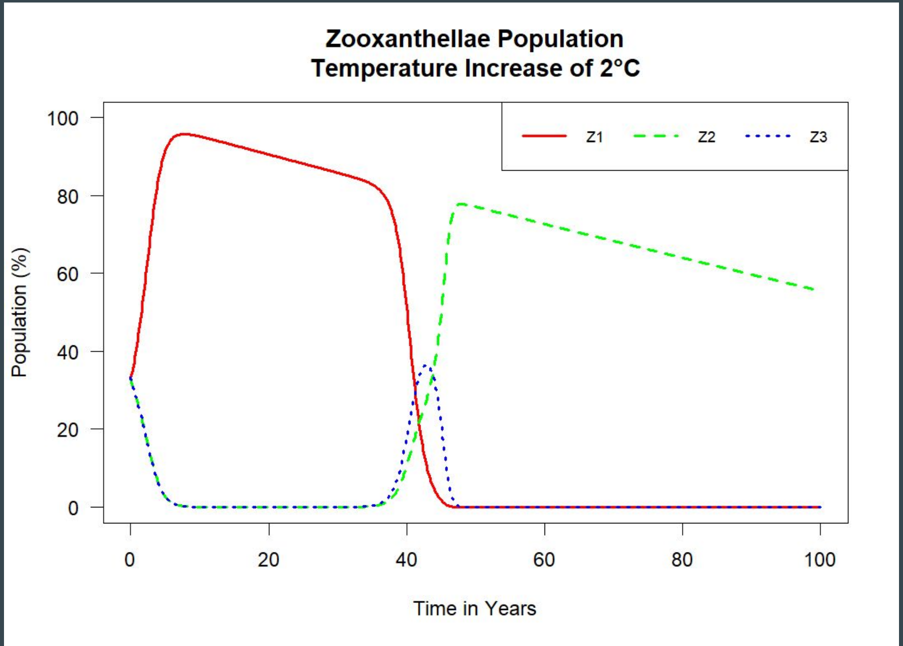
Sensitivity Analysis of K1



K1 = 100 in original model

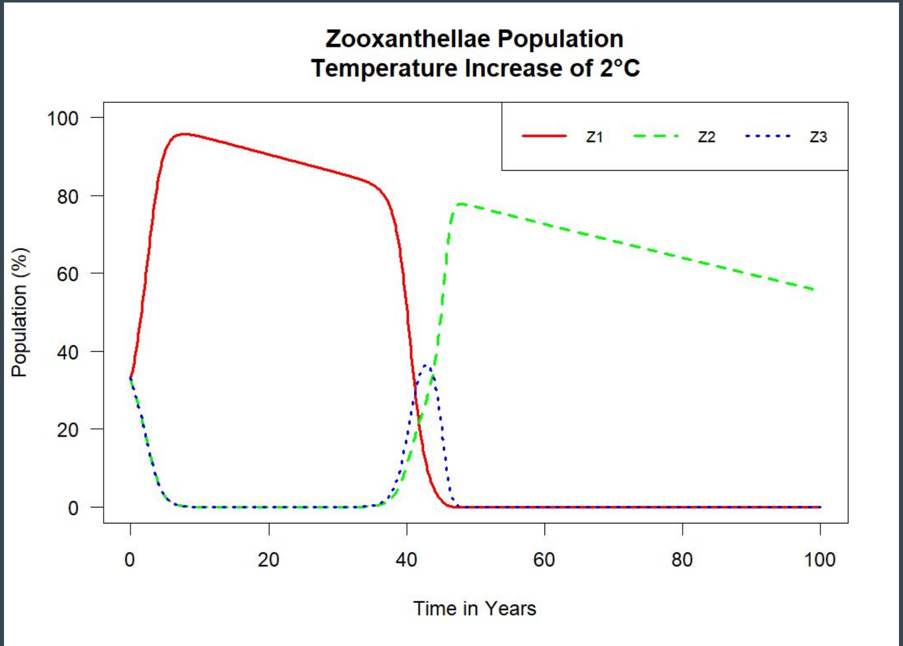
Results

- Carrying capacity for all 3 zooxanthellae types decreases as temperature increases by 2℃ (down to 55 %).
- Z1 is able to out-compete Z2 and Z3 until approx. t = 40 years (temperature increase of 0.8 ℃).
- Z3 population begins to rise at approx. t = 40 years, reaches maximum population percentage of 35%, but quickly drops back down to zero within 10 years.
- Z2 outcompetes Z1 and Z3 starting at t = 45 years. Z2 quickly reaches carrying capacity at approx. t = 50 years, before it quickly declines as temperature continues to increase.



Discussion - Results

- Z1 thrives at cooler temperatures. After temperature increases 0.8 ℃ Z1 loses competitive dominance over Z2 and Z3.
- Z2 thrives in warmer temperatures, and its competitive dominance increases following temperature increase of 0.8 ℃.
- Increasing competitive dominance of Z2 could be due to more efficient nutrient uptake at higher temperatures.
- As temperature increases, more and more zooxanthellae are expelled from coral unit until it is left completely bleached.



Discussion - Impact

- Impact on Wildlife
  - Nearly every species in a coral reef ecosystem depends on corals, whether it be for food or shelter
  - When corals are lost as a results of bleaching, declines in genetic and species diversity occur
- Socio Economic Impact
  - Many millions of people depend on coral reefs for the goods and services they provide.
  - If coral bleaching becomes more severe, it has been estimated that economic losses to tourism, fisheries and biodiversity could reach up to $40 billion, $23 billion and $22 billion respectively
- Personal Impact
  - Do you want your grandchildren to see healthy coral reefs?

References

(2012). *Anatomy of a Coral Polyp* [Diagram]. Algae Research and Supply. https://algaeresearchsupply.com/pages/how-do-coral-get-their-zooxanthellae

Bleaching Impacts | Reef Resilience. (n.d.). Reef Resilience Network.

https://reefresilience.org/stressors/bleaching/bleaching-impacts/#:~:text=Bleached%20corals%20are%20likely%20to,are%20killed%20by%20bleaching%20events

Buddemeier, R.W., Fautin, D.G., Ware, J.R. (1996). Patterns of coral bleaching: modeling the adaptive bleaching hypothesis. *Ecological Modelling*, *84*(1-3), 199-214. https://doi.org/10.1016/0304-3800(94)00132-4

Coral Bleaching [Diagram]. National Oceanic and Atmospheric Administration. https://www.scribbr.com/apa-examples/image/

CWPPRA. (2019, February 13). *Competitive dominance*. CWPPRA. https://cwppra.wordpress.com/2019/02/13/competitive-dominance/

Hancock, L. (2022). Everything you need to know about coral bleaching—and how we can stop it. World Wildlife Fund. https://www.worldwildlife.org/pages/everything-you-need-to-know-about-coral-bleaching-and-how-we-can-stop-it#:~:text=Why%20does%20coral%20bleaching%20matter

US Department of Commerce. (2020, November 5). *What is coral bleaching*? Oceanservice.noaa.gov.

https://oceanservice.noaa.gov/facts/coral_bleach.html#:~:text=When%20water%20is%20too%20warm

Vevers, R. (2016). *Fire Coral Bleaching* [Photograph]. Vox. https://www.vox.com/science-and-health/2017/4/18/15272634/catastrophic-coral-bleaching-great-barrier-reef-map

Zooxanthellae [Photograph]. Tetiaroa Society. https://www.tetiaroasociety.org/biosphere-tetiaroa/zooxanthellae

Zooxanthellae Physiological Physical Characteristics. coraldigest. (n.d.). https://www.coraldigest.org/index.php/Zooxanthellae

Acknowledgements

Pictures taken from SUNY Geneseo Professor pages