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Summary Sheet

Maintaining Ecological Balance Within a Converted Forest Area: A Dynamical Systems Approach to Deforestation, Ecosystems, and Agriculture

Every year, millions of hectares of forest are removed and converted into agricultural land. To model the impacts of this process on the ecosystems that they disrupt, we created a dynamical system model. To model the impacts of various factors on the environment, we track multiple different populations, including the different trophic levels, crop yields, and multiple different species. We also divided the converted forest area ecosystem into three areas to account for the different dynamics in each area: farmland, edge, and forests. Through our model, we seek to investigate the dynamics of the different species in the farmland itself, as well as the edge habitat that forms between the farm and the forest and the forest itself.

To model the impacts of various populations on each other, we primarily use type II functional responses, accounting for the fact that animals take time to process the food that they consume. We also have almost all populations affected negatively by herbicides and pesticides. Lastly, certain species can move between the different areas of the farm, forest, and edge.

Our model behaves realistically in accordance to Rain forest Ecosystem expectations. Balancing different regions as dynamic coupled sets of differential equations. In reality we observed that animals diffuse through region boundaries either exploring for food or traveling due to climate. To represent this problem we model 3 separate equation sets and diffuse populations through region membranes.

Contents

1 Introduction

1.1 Background

Millions of hectares of forest have been removed in the past years, with the primary driver being agriculture. As forests are converted into farmlands, animals and plants alike lose their natural habitats, and food webs and ecosystems are disturbed, if not permanently changed. However, after disruption, there is opportunity for recovery and for a new ecosystem to take its place.

In this new ecosystem, both the needs of the wildlife living within the ecosystem as well as the productivity of the farmland need to be maintained. In addition, there are a variety of different ecological factors (such as the introduction of a new species into the local ecosystem) as well as human decisions that can have cascading impacts on the ecosystem as a whole. Understanding these effects is crucial to creating a sustainable farm while preserving the vitality and biodiversity of the environment surrounding the farm.

Numerous ecological and human factors are involved in these new ecosystems, and each one has the potential to have a domino impact on the system as a whole. For instance, the introduction of a new species can drastically change pollination networks, competition for resources, and predator-prey dynamics, whether it is invasive or purposefully introduced as part of pest management. In a similar vein, agricultural methods like the application of agrochemicals or crop selection can affect the survival of native species as well as the condition of the soil and water.

1.2 Problem Statement

In the following paper, we hope to address the following:

1. Creation of a model involving the food chain to model ecosystem dynamics, incorporating the agriculture cycle and its seasonal dynamics
2. Impacts of herbicide and pesticide use on plant, insect, and bat/bird populations and ecosystem stability
3. Reemergence of species in the edge habitats
4. Incorporation of two different species into the model and their impacts on the ecosystem
5. Effect of removal of herbicide from the environment
6. Effect of addition of bats to the environment and stability
7. A potential species that could improve the balance and stability of the ecosystem
8. Impact of green farming on the ecosystem and each individual component of the ecosystem

2 Assumptions

Our assumptions are as follows:

1. **Leaching is negligible in the edge habitat.** Farmers use herbicides and pesticides in controlled manners, typically row farming, where both herbicide and pesticide are applied in very controlled and regulated manner. As such, in our model, we assume that the edge habitat hqas negligible exposure to pesticides and herbicides. [6] [4]

2. **Herbicide and pesticide is applied bi-seasonally.** Typical farms apply weed and pest control measures in a periodic fashion, to both prevent excess deployment and help promote crop yield in growing seasons. [6] [4] [7] [9]

3. **Simplification of the food web.** To simplify the food web for modeling purposes, we assume that we can capture the ecosystem dynamics relatively accurately by grouping most organisms within the forest and converted forest area into three main categories: producers, consisting of most plant life, primary consumers, consisting primarily of herbivorous animals, and secondary consumers, consisting of mostly carnivorous animals. [11]

4. **Crop Factors.** Only biotic factors influencing crop yields are considered; abiotic and economic factors such as weather, market demand, or farming practices beyond those modeled are excluded.

5. **Static Relationships.** The network of interactions is static; relationships between species do not change over time or context beyond what is modeled.

6. **Predator-prey interactions are best described by Holling type II response functions.** Our model assumes that animals that consume other organisms to grow and reproduce spend time processing their food and also time hunting for their food. Based off this assumption, the most fitting way to represent predation and reproduction is through a Holling type II response function, which factors in the time spent finding and processing food in a wa similar to a chemical reaction.

7. **Pesticides and Herbicides chemically break down over time.** We assume in our model that after pesticide and herbicide is applied, that the pesticide nad herbicide breaks down over time with a constant rate and that there are no other factors affecting the concentration.

3 Model

3.1 Model Overview

For our model, we primarily chose to study the Amazon Rainforest. Of the millions of hectares of forest removed over the past decades, more of it has been in Brazil than any other country [8], and of the deforestation that occurs in Brazil, most of it occurs within the Amazon. As such, we focus our modeling efforts on the conversion of a tropical rainforest into farmland with the idea that doing so allows for a good representation of most of the forest to farmland conversion on the planet.

To model the different smaller-scale ecosystems we expect to see, we separate our investigation into three different areas: farmland, forest, and edge. We allow for limited interaction and movement between these three areas, set by certain diffusion rates that allow for the diffusion of specific populations across the regions. [2]

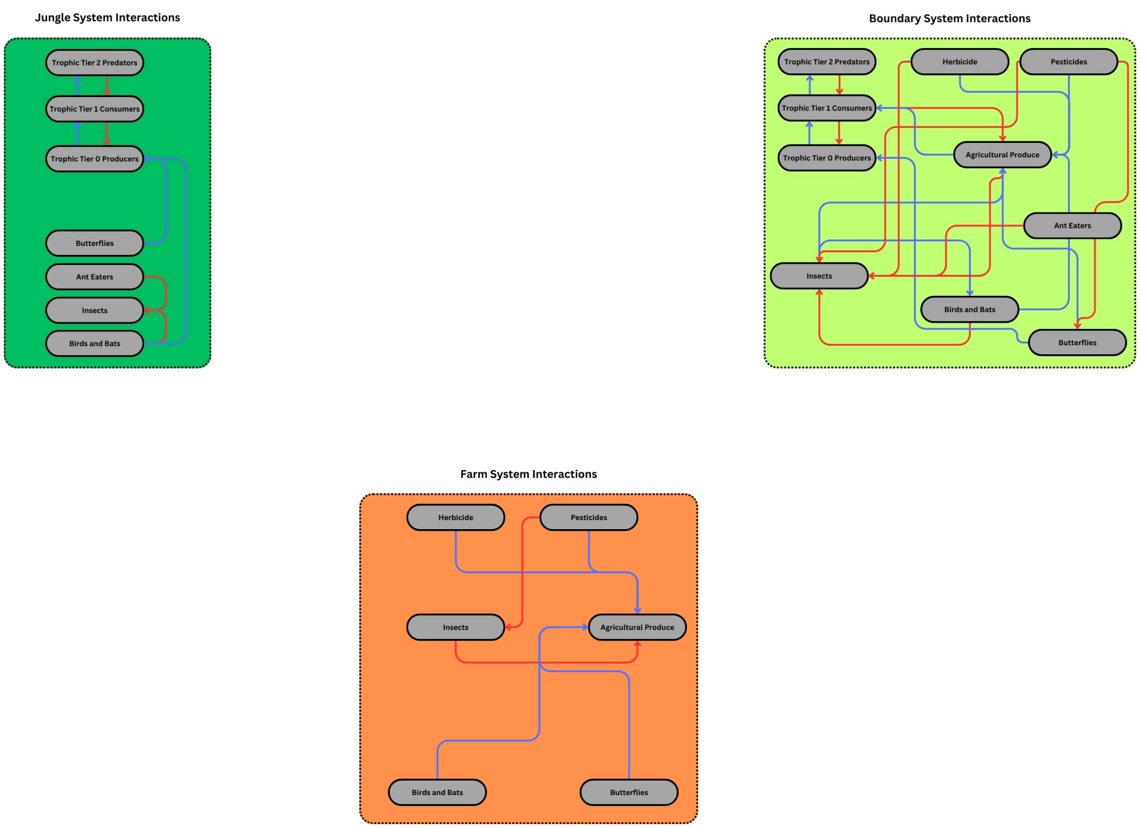

Figure 1: Interactions of Key Species Circles in System Regions (Blue and Red Lines indicate positive and negative interactions between species)

3.2 State Variables

To model the converted forest area ecosystem, we track multiple different populations throughout our simulations.

a) **Producer Population.** This is the population of photosynthesizing plants that act as producers in the food chain. This term is influenced by:

↑ Logistical Growth. We assume that without consumers, producers in the environment will grow with a logistical growth curve.

↓ Consumption. Producers are consumed by both insects and primary consumers alike, which is modeled using a Holling type II functional response.

↓ Toxins. Herbicides and pesticides are toxic to the producers and kill producers proportional to the producer population.

b) **Crop Yields.** This is the yield the farmer receives during harvest.

↑ Cross Pollination. Cross pollination helps improve the quantity and quality of crops, thus improving yield.

↓ Damage. Crops are damaged by animals and insects. Insects consume crops, damaging them in the process, whereas animals damage crops through depredation.

c) **Primary Consumer Population** This is the population of primary consumers that, for simplicity, we will assume consist primarily of herbivores.

↑ Consumption. Primary consumers consume producers, as modeled by a Holling type Ii functional response.

↓ Predation. Primary consumers are predated by secondary consumers.

↓ Natural Death. Some proportion of the population dies through natural causes.

d) **Secondary Consumers** This is the population of secondary consumers, consisting primarily of carnivorous creatures.

↑ Consumption. Secondary consumers consume primary consumers to grow their population.

↓ Natural Death. Some proportion of the population dies through natural causes.

e) **Insects** This is the population of insects that eat or otherwise damage crops and plant life to survive.

↑ Consumption. Insects can consume producers and crops to gain energy to reproduce.

↓ Predation. Bats and various other species eat insects for food.

↓ Toxins. Herbicides and pesticides are toxic to the insects and kill insects proportional to the population of insects and the concentration of the pesticides or herbicides. Pesticides are naturally more effective than herbicides at killing the insect population.

↓ Natural death. Some proportion of the insects die to natural causes.

f) **Herbicide.** This is the concentration of herbicide present in a particular area.

↓ Degradation. Herbicides break down over time through chemical degradation.

g) **Pesticide.** This is the concentration of pesticide present in a particular area.

$\downarrow$ Degradation. Pesticides break down over time through chemical degradation.

h) **Butterflies.** This is the population of butterflies within the ecosystem.

$\uparrow$ Logistical Growth. Without any major natural predators, butterfly population is a logistic function of the ecosystem carrying capacity and their own reproduction rates.

$\downarrow$ Consumption. Butterfly are traditionally eaten by tier I consumers, we model these incestivors in their population dynamics.

$\downarrow$ Toxins. Herbicides and pesticides are harmful to butterflies and cause mortality proportional to their population and the amount of herbicide and pesticide.

i) **Anteaters.** This is the population of anteaters within the ecosystem.

$\uparrow$ Logistical Growth. Ant eaters are a resilient species, whose population heavily depends on the quantity of food in the environment.

$\downarrow$ Death. Ant Eaters have a stabilizing rate of mortality.

j) **Bats and Avian Creatures.** Population of Bats and Birds within the ecosystem.

$\uparrow$ Logistical Growth. Avian populations are determined by the quantity and availability of food, modeled as a limiting growth factor of the population.

$\downarrow$ Death. Birds and Avian creatures have a stabilizing rate of mortality.

$\downarrow$ Toxins. Herbicides and pesticides are harmful to bats and avian creatures via bio-accumulation and cause mortality proportional to their population and the amount of herbicide and pesticide.

3.3 System Variables

Variable	**Description**
I	Insect Population
B	Bats and other Avian Creatures Population
X	Primary Producers
Y	Primary Consumers
Z	Secondary Consumers
U	Butterfly Population
E	Anteater Population
P	Pesticide Concentration
H	Herbicide Concentration

3.4 Dynamical System

$$
\begin{aligned}
\frac{dI}{dt} &= c_3\left(\frac{a_3(A+X)}{1+b_3(A+X)}\right)I - \frac{a_4B}{1+b_4B}I - \mu_I I - \mu_{PI}PI - \mu_{H!}HI \\
\frac{dA}{dt} &= -c_4\left(\frac{a_4A}{1+b_4A}\right)I + \mathbb{K}_P(B+U) - \mu_{destroyed}AY - \mu_{PA}PA \\
\frac{dB}{dt} &= c_5\left(\frac{a_4I}{1+b_4I}\right)I - \mu_B B - \mu_{BH}BH - \mu_{BP}BP \\
\frac{dX}{dt} &= rX\left(1-\frac{X}{k}\right) - \frac{a_1X}{1+b_1X}Y - \mu_P PX - \mu_H HX \\
\frac{dY}{dt} &= c_1\left(\frac{a_1X}{1+b_1X}\right)Y - \frac{a_2Y}{1+b_2Y}Z - d_Y Y \\
\frac{dZ}{dt} &= c_2\left(\frac{a_2Y}{1+k_2Y}\right)Z - d_2 Z \\
\frac{dU}{dt} &= c_6\left(\frac{a_6(A+X)}{1+b_6(A+X)}U\right) - \frac{a_7U}{1+b_7U}Y - \mu_U U - \mu_{UP}UP - \mu_{UH}UH \\
\frac{dE}{dt} &= c_7\left(\frac{a_7I}{1+b_7I}\right)E - \mu_E E \\
\frac{dP}{dt} &= -r_P P \\
\frac{dH}{dt} &= -r_H H
\end{aligned}
$$

3.5 Diffusion Parameters

We use the typical diffusion value of 1-percent per day, as we found this representative of real-time animal move on week-by-week scales.

3.6 Determination of Half Saturation Rate and Maximal Consumption Rate Terms

Rates	Possible Range	Value Picked	Explanation
a_1	0.1 – 1.0	0.1	Maximal consumption rate of producers X by primary consumers Y
b_1	0.01 – 0.1	0.05	Density scaling for the half-saturation in the Y consumption of X
a_2	0.05 – 0.8	0.7	Maximal consumption rate of Y by secondary consumers Z
b_2	0.005 – 0.1	0.006	Density scaling for the half-saturation in Z consumption of Y
a_3	0.1 – 1.0	0.61	Maximal growth contribution to insects I from $(A + X)$
b_3	0.01 – 0.2	0.1	Half-saturation term for insect growth from $(A + X)$
a_4	0.1 – 0.8	0.4	Maximal consumption (or predation) rate on I by B
b_4	0.01 – 0.1	0.06	Half-saturation density for B's predation on I
a_6	0.1 – 1.0	0.9	Maximal growth contribution to butterflies U from $(A + X)$
b_6	0.01 – 0.2	0.1	Half-saturation term for butterfly growth from $(A + X)$
a_7	0.05 – 0.8	0.2	Maximal rate of consumption among relevant species
b_7	0.005 – 0.1	0.013	Density scaling for the half-saturation in that consumption process

3.7 Determination of Parameters

Note that the parameters not sourced are experimentally determined based on model observations, sensitivity analysis, and reasonable range.

Parameter	Possible Range	Value Picked	Explanation
μ_i	0.097 – 0.2	0.097	Natural mortality rate of insects [3]
$\mathbb{K}_P$	$4.79 \cdot 10^{-282}$ – $5.09 \cdot 10^{-282}$	$4.79 \cdot 10^{-282}$	Crop yield increase due to cross pollination [10]
μ_U	0.01 – 0.1	0.04516129032	Natural mortality rate of butterfly
μ_E	0.001 – 0.01	0.00137	Natural mortality rate of anteater
r	0.0001 – 0.5	0.1	Reproduction Rate for Producers
k	0.0001 – 0.1	0.004	Growth rate limiter for Producers
μ_{PI}	0.05-0.5	0.141	Mortality Rate of insects to pesticides [3]
μ_{HI}	0.05-0.5	0.141	Mortality Rate of insects to Herbicides [3] (Note same as above because single value for non natural mortality rate of insects)
μ_P	0.05-0.5	0.1	Mortality rate of Producers to pesticides
μ_H	0.05-0.5	0.1	Mortality rate of Producers to herbicides
μ_B	0.0001-0.001	0.00081481481	Natural Mortality rate of Birds
μ_{BH}	0.0001-0.002	0.001	Mortality rate of Birds to herbicides
μ_{BP}	0.0001-0.002	0.001	Mortality rate of Birds to pesticides
$\mu_{\text{destroyed}}$	0.01-1	0.1	Agrable land destroyed by Primary Consumers
μ_{PA}	0.01 - 1	0.1	Rate at which agrable land destroyed by pesticide
dY	0.001-0.1	0.001	Natural mortality rate of Primary Consumers
dz	0.000001-0.1	10^{-6}	Natural mortality rate of Secondary Consumers
μ_U	0.000001-0.1	0.04516129032	Natural mortality rate of Butterfly [1] Calculated based on natural mortality rate of butterfly
μ_{UP}	0.000001-0.1	0.000001	mortality rate of Butterfly to pesticide
μ_{UH}	0.000001-0.1	0.000001	mortality rate of Butterfly to herbicide
μ_E	0.000001-0.1	0.01	Natural mortality rate of anteater [5] Based on anteater lifespan of 14 years
r_P	0.000001-0.1	0.1	Decline in usage rate of pesticdes
r_H	0.000001-0.1	0.1	Decline in usage rate of herbicide

3.8 Model Visualizations

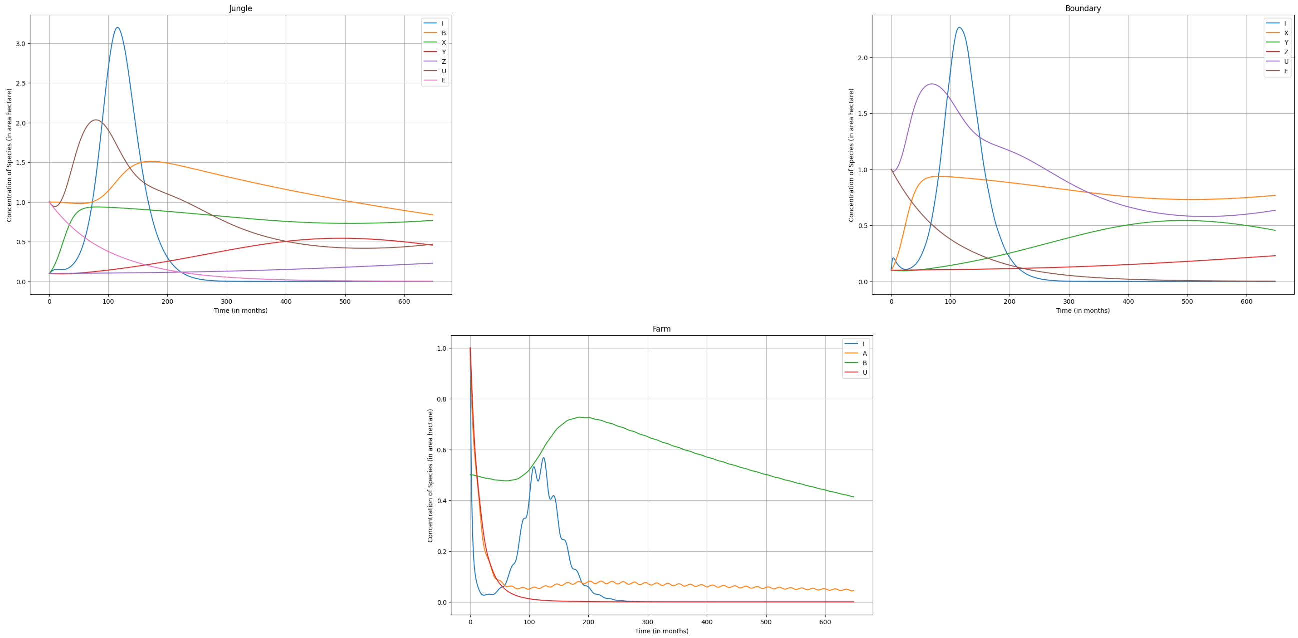

Figure 2: Concentration of Species Normalized in Region, when ”Green Practices” are not used.

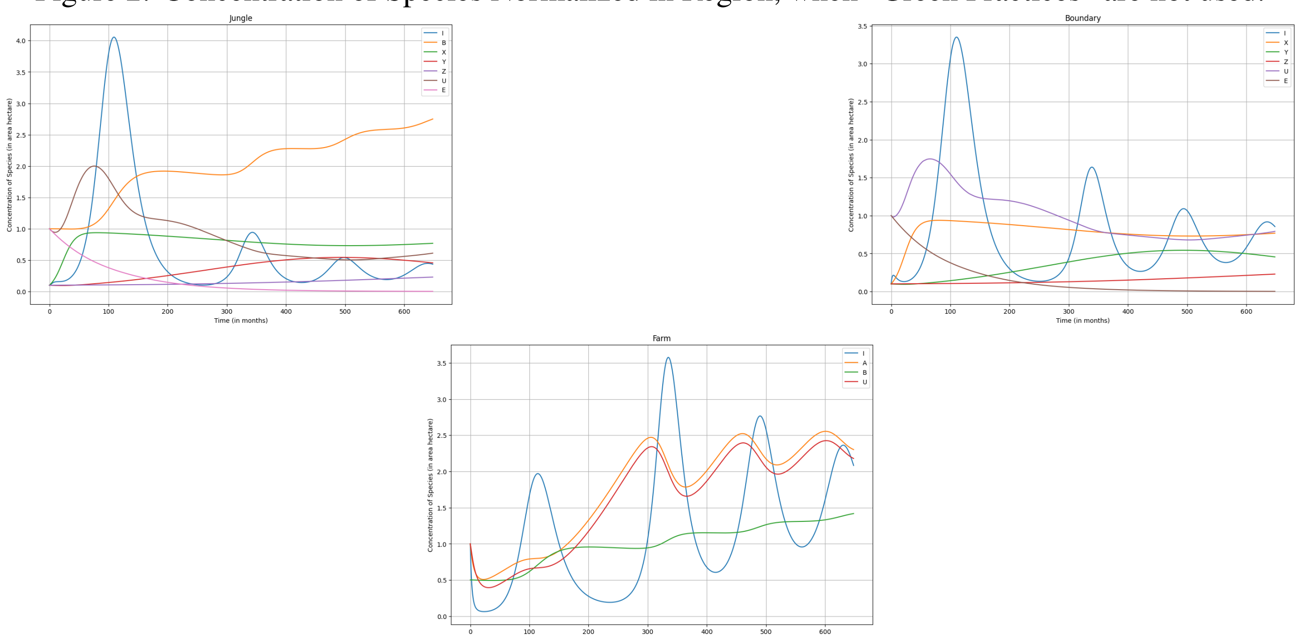

Figure 3: Concentration of Species Normalized in Region, when ”Green Practices” are used.

4 Findings

4.1 Long-Term Behavior

i) **Our system achieves stable dynamics in the Jungle Region.** Stability of this region demonstrates model accuracy in terms of real world scenarios which allow us to correctly use spatial dispersion between species in our systems.

ii) **Endangered Species.** In our model, one of the species which we examine is the giant anteater. Because of the way that we model it, there is no stability for the anteater population in the ecosystem, which makes sense considering their status as endangered even in hospitable habitiats. The only way anteaters survive is with high reproduction rates the wreck the rest of the ecosystem.

4.2 Sensitivity Analysis

We determine the sensitivity of variables using a stochastic sampling method, and approximating partial first and partial total derivatives with respect to parameters. High parameter sensitivity to initial input and low parameter sensitivity with respect to initial parameters displayed as a red and blue gradient respectively

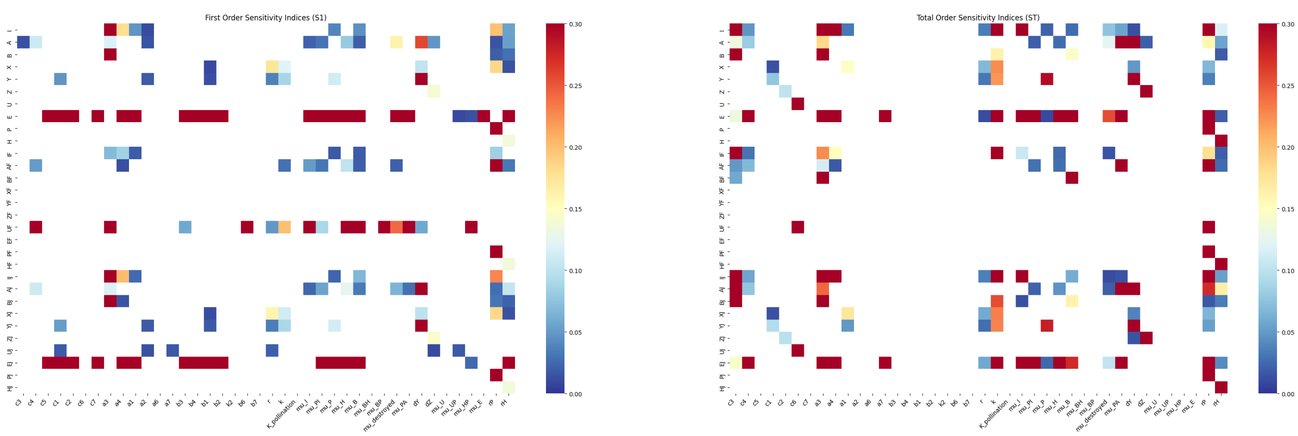

Figure 4: Heat Map Represents First and Total Estimated Partial Derivatives of Parameter Values

4.3 Seasonal Effects

We model harvesting seasons and periodic herbicide and pesticide use. In our model, we see the agricultural cycle primarily affecting the insect population, with the insects population showing a periodic behavior mirroring that of the crop yield. Besides the insect population, there is relatively little to be seen in terms of periodic behavior for the other populations.

4.4 Herbicide and Pesticide Use

We model herbicide and pesticide use as a periodic function to use it to give our model planting and harvesting seasons.

4.5 Bats and Avian Creatures

Bats and Avian creatures can play a very beneficial role in the converted forest ecosystem due to their consumption of agricultural pests, as well as their cross-pollination of plants. To study the impact of bats and other species with similar ecological niches to bats, we introduce bats into our simulations.

4.6 Green Farming Practices

Green farming encompasses a wide range of farming practices that can have a wide variety of impacts on a farm. Here, we will consider three different green farming practices and gauge their impacts on the ecosystem and crop yields. When disallowing green farming practices we see that our population states behave highly erratically. Specific populations like Insects and Butterflies, shown as lines I and B, experiencing population collapse.

The immediate effects are observed in the Farm and Boundary eco-system, with minor effects in the Jungle system due to partial diffusion of populations through the boundary in our model. In our ”Green” ecosystem we observe that due to the supply of Incests, the Bird and Avian populations thrive, adding cross-pollination to generate more crop yield. This is representative of how we use herbicide and pesticide to interact with the ecosystem.

4.6.1 Cover Crops

To model the effect of cover crops on the system, we use multiple crop varieties, varying depending on Region. The Holling Type-II Response Function models the two primary producer, (X and A) where X acts as a natural and native cover species to de-burden the agricultural run off from consumption.

4.6.2 Crop Rotations

Our model handles seasonal crop rotations using a periodic sinusoidal function to mimic different types of crops. We utilize this as a typical response and apply annually to aid soil health. Crop rotation acts as a nitrogen fixing measure, allowing for larger crop bounties over time.

4.6.3 Herbicide-Pesticide Removal

Our model accounts for the effect of herbicides/pesticides on various species through the H and P variables which are multiplied by mortality rate parameters for relevant species and crop yield. Through this, we are able to see the dampening effect on growth of plants that herbicide/pesticide causes.

4.7 Species Reintroduction

To model the reintroduction of species over time, we introduce two new species into our model: butterflies and anteaters. One with a very high reproduction rate (Butterflies) and one with a low reproduction rate (Anteaters). We distinctly use these species as they both play key-roles in ecosystem management, specifically so in our idealized habitat of rain forests.

We observe that irregardless of the scenario, and using sourced parameter that the Giant Anteater population is non-stable and doesn't have a suitable time competing with other local species. This follows empirical data which observes the Anteater as a very non-competitive species where they are primarily labeled as endangered or near-extinct.

The other newly introduced population, the Butterfly, as a mush easier time acclimating to the farm environment. This is likely due to their innate high reproductive capacity. Allowing them to both exist in the ecosystem, and also benefit it symbiotically by acting as another pollinator.

5 Strengths and Weaknesses

Our models has many strengths and weaknesses to consider when analyzing the results:

5.1 Strengths

i) **Our model simulates a complex ecosystem with many different interactions between populations.** Any ecosystem is a complex system of many interactions between the life that is present. Our model accounts of much of the interactions between different populations, and is thus better able to capture the cascading impacts that we expect to see as a result of any sort of change in an ecosystem where all the different organisms impact others, whether directly or indirectly.

ii) **Robustness to Wide Parameter Ranges.** In our model, we see relatively reasonable behavior while the parameters are within the parameter ranges we defined. As such, our model is resilient against inaccuracies in the measured parameters - even if the measured parameters are off, we expect the general qualitative behavior to be roughly the same.

5.2 Weaknesses

i) **Our model does not account for financial costs of certain actions.** In our model, certain factors such as pesticides, herbicides, and organic farming practices will require a financial investment from the farmer. However, our model only focuses on the impacts of these factors on the ecosystem as a whole. As such, certain actions, such as implementing organic farming practices, may be only beneficial in our model, but may not actually be beneficial for farmers when the cost of implementing such actions is considered.

ii) **The food chain is much more complicated that what we represented it with.** Real ecosystems have extremely complex and rich food webs that include many kinds of interactions and groups of organisms that were not included here. These could include detritivores, omnivores, non-apex predator carnivores, and so on.

iii) **Our model does not include mechanisms to simulate the weeds within farms and the impacts of various factors on those weeds.** Weeds are a big influence on crop yields and can sap resources form the crops, decreasing yields. Our model does not have a particularly complex treatment of weed populations, and there are many dynamics with weeds that we did not capture, such as the impact of cover crops on weeds, weed resistances to herbicides, and many more.

6 One Page Letter

To whom it may concern:

Our team has developed a mathematical model to understand the various different interactions between the different populations within a converted forest area ecosystem, as well as the impacts of human decisions on the ecosystem and crop yields. Based off our model, we generally suggest adopting green farming practices when possible, such at utilizing cover crops, crop rotations, and a reduced dependence on herbicides and pesticides.

Utilization of both cover crops and crop rotations will help increase the productivity of the farm as a whole and contribute to the stability of the ecosystem, providing both financial benefits as well as ecological benefits. In addition, these practices will protect your farm against weeds and therefore also help reduce dependence on herbicides, which can help decrease costs for running your farm. It is ultimately up to you to decide whether these choices will be cost-effective for your farm, however our results indicate that using these practices will lead to greater crop yields and a more robust and biodiverse environment.

When a ecosystem has had time to sufficiently mature, certain species, such as bats, can help control the pests on your farm without the use of pesticides. In addition, pesticides also negatively impact the bat population and therefore somewhat counteract the original goal of decreasing the pest population. As such, we recommend that after a converted forest area has had sufficient time for species to reintroduce themselves, that you stop or reduce utilization of pesticides. We believe that this will not have a large impact on the amount of damage that pests inflict on crops while also cutting costs due to not having to buy pesticides.

By practicing these organic farming practices, we are hopeful that your farm will be able to have increased crop yields while farming in a more sustainable and ecologically sound way. It is our belief that having large crop yields and maintaining a stable and healthy ecosystem are not two contradictory goals, but rather synergistic goals, where the improvements in the health of the ecosystem will also lead to improvements in the crop yields of your farm.

Thanks,
Team 2528487

7 Appendix

Find our code here: HERE.

8 References

[1] *Blue Morpho Butterfly*. URL: https://www.rainforest-alliance.org/species/blue-morpho-butterfly/.

[2] *Chaos in a Three-Species Food Chain*. URL: https://sites.ifi.unicamp.br/aguiar/files/2014/10/HP.pdf.

[3] *Do patterns of insect mortality in temperate and tropical zones have broader implications for insect ecology and pest management?* URL: https://pmc.ncbi.nlm.nih.gov/articles/PMC9048698/.

[4] *Fertilizers Pesticides*. URL: https://www.ers.usda.gov/topics/farm-practices-management/fertilizers-pesticides#:~:text=U.S.%20crop%20producers%20use%20a,by%20hand%2C%20to%20manage%20weeds..

[5] *Giant Anteater*. URL: https://www.sfzoo.org/giant-anteater/.

[6] *Herbicide*. URL: https://www.epa.gov/caddis/herbicides.

[7] *Pesticides*. URL: https://www.usgs.gov/centers/ohio-kentucky-indiana-water-science-center/science/pesticides.

[8] Hannah Ritchie. *Deforestation and Forest Loss — ourworldindata.org*. https://ourworldindata.org/deforestation. [Accessed 25-01-2025]. 2021.

[9] Anket Sharma et al. *Worldwide pesticide usage and its impacts on ecosystem - discover Applied Sciences*. Oct. 2019. URL: https://link.springer.com/article/10.1007/s42452-019-1485-1.

[10] *Soybean dependence on biotic pollination decreases with latitude*. URL: https://www.sciencedirect.com/science/article/pii/S016788092300035X#sec0020.

[11] *Trophic level — Definition, Examples, & Facts — Britannica — britannica.com*. https://www.britannica.com/science/trophic-level. [Accessed 26-01-2025].