Evaluating the Effect of Pest Control in a Discrete Ecosystem with Three Species

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Introduction

0.1 Model

In this project, the macroscopic behaviour of three competing species in a discrete predator-pray model on a large unobstructed flat area is studied. The simulation examines a piece of land, referred to as the board, with periodic boundaries to be able to represent a larger area. The board is divided into n amount of cells, referred to as tiles, where a filled-in tile for a specific species represents a focused population density at that point.

0.2 Question

In the real world a majority of species would be extinct if not for evolutionary pressure on a large time frame. However, in the short-term all species live in a dynamic equilibrium. Realistically, this equilibrium is characterized by having more plants than animals, more pray than predators. The first goal is to find this realistic equilibrium for the computer simulation.

Secondly, human desires often want certain species eradicated from set locations, for example, pests near crops. With human intervention in mind, this simulation will test and evaluate the effect of periodic pest control. The question is if pest control is beneficial for plants, especially in a location where multiple species consume the plants. Given that no other species migrate onto the board, this simulation ultimately evaluates the effectiveness of periodic use of pesticides in an isolated location with a plant, a herbivorous pest, and an omnivore.

0.3 Realism

Initially at time $t = 0$ a useful plant is planted on a fertile island. Present on the island are pests that consumes this useful plant. A top predator omnivore arrives immediately, able to consume both of the other species. Among many selections, the pest could be an aphid and the omnivore a ladybug.
To mimic reality, all types of species, referred to as entities on the board, have some energy E correlating to the amount of food they have consumed. For all entities this energy decays with each simulation step, however, as the plant density of a region

usually does not die for a long time on fertile land, plants have much greater energy than pests and omnivores. The herbivore pest consume plants to increase their energy with amount Eat_plant_h. The omnivore can consume both plants and pests gaining the same Eat_plant_o and Eat_pest_o respectively.

Imagining each tile as empty if not dense with a certain species, and filled if dominated by one, the simulation only adheres to the macroscopic group behaviours of the species. In order for an animal group to reproduce there is a minimum amount of energy needed, Rep_needed_h and Rep_needed_o. Furthermore, there is a lesser energy cost reproducing. Hence, upon reproduction the tile loses an amount of energy Rep_cost_h and Rep_cost_o. A continuously well-fed group does not want to migrate. However if animals are near each other they create migratory pressure. In the simulation this give the animals a slight direction in their reproduction towards food. Plants can reproduce freely to nearby tiles at all times.

As a population grows with migratory pressure it should expand. The board is assumed to be fertile land and empty tiles are simply not densely populated by any species. Hence in the model the reproduction can be made in any direction touching the reproducing tile. In order to mimic omnivores' generally slower reproduction rate, pests' faster rate and plant's ability to spread pollen vastly, in each step there is a probability for them being able to reproduce in every nearby empty tile. This is assumed to be greatest for plants, lesser for pests, and the least for the omnivores.

This randomized reproduction mimics how nature will push the migration of species, due to the wind for plants or due to natural circumstance for animals, in a random manner on a small perspective. Upon birth a tile will have a set amount of energy and hence survive a while, realistically enjoying the food present in the non-food-dense tile, until dying. The energy needed for reproduction is always set higher than the energy given upon birth for a tile so that all animals need to eat to reproduce.

Lastly, pest control will be introduced as a wide spread human intervention. Targeted chemical treatment will eradicate a large percentage of the intended pest population, but will also hamper others to a lesser degree. Each time step is perceived as a certain number of days and the climate is assumed to be stable enough to not affect the simulation. As human intervention usually occurs periodically, it is parameterized with constant modulo t_{kill}

0.4 Game Rules

As the simulation is discrete certain rules have to be selected for which entity first gets to reproduce and eat. Reasonably the omnivore is the top-predator and reproduce first, the pest second, and the plants third. For consumption pests are imagined faster than omnivores and is prioritized. Lastly, all entities of the same kind consuming another tile receives the same amount of energy from the consumption.

Board size plays a massive role on the impact of the randomness. The chance of a lump of pray escaping a wall of incoming predators is much larger if there by chance occurs a hole in the wall. Before beginning this paper the following 20x20, 30x30, 40x40, 50x50, 60x60, 70x70, and 80x80 tile dimensions were tested and the critical point was around 30x30. A larger board becomes less sensitive in terms of species going extinct however take longer to simulate. As a trade-off the board is fixed at 50x50 tiles.

0.5 Parameters

Variable Names	Plant	Pest	Omnivore
Chance of Reproducing	P_p	P_h	P_o
Energy needed for reproduction	Rep_needed_p	Rep_needed_h	Rep_needed_o
Energy cost of reproduction	Rep_cost_p	Rep_cost_h	Rep_cost_o
Energy attributed upon birth	Birth_energy_p	Birth_energy_h	Birth_energy_o
Energy gained by consuming		Eat_plant_h	Eat_plant_o Eat_pest_o
Consumtion Rules		One pest can directly eat one plant	One omnivore can eat one plant. Two omnivores can eat pest

1 method

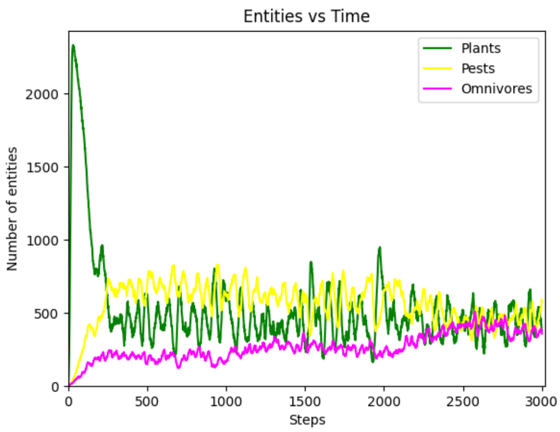
1.1 Measurements and analysis

After each step then number of each type of entity is recorded. In the end their population is plotted against time.

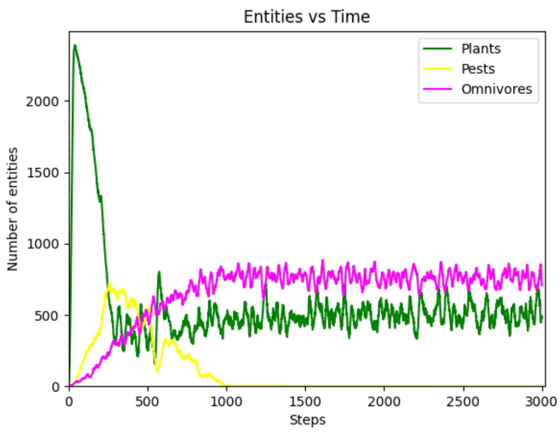
1.2 Different types of Equilibrium

The board's configuration can end in a few different way. If the plants die out at some point all pests and omnivores decay and the island becomes uninhabited. Additionally, pests and omnivores can die out alone leaving the other two in equilibrium. If none dies out the outcome becomes a dynamic equilibrium between the remaining species. Starting with the following parameters for the first image in Figure 1 some form of dynamic equilibrium is reached. Interestingly and somewhat counter-intuitively, increasing the energy of pests, by increasing their energy upon birth, cause them to go extinct faster. This can be attributed to them becoming easier pray for omnivores. Slow migration and a too great of a population cause their extinction. Decreasing the rate of reproduction for plants cause omnivores to go extinct as they are the slowest to reproduce and need the plants to reproduce in their direction. Most rarely all plants become extinct, however if longevity is maximized for all animals this occurs, leading to absolute extinction. With the following set as

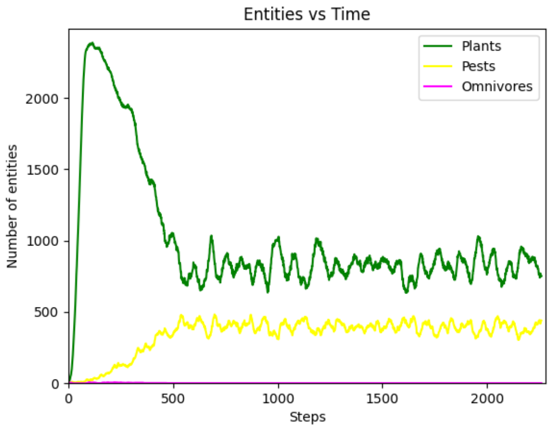
Variable Names	Plant	Pest	Omnivore
Chance of Reproducing	P_p = 0.08	P_h = 0.09	P_o = 0.3
Energy needed for reproduction	Rep_needed_p = 0	Rep_needed_h = 8	Rep_needed_o = 10
Energy cost of reproduction	Rep_cost_p = 0	Rep_cost_h = 5	Rep_cost_o = 9
Energy attributed upon birth	Birth_energy_p = 1000	Birth_energy_h = 4	Birth_energy_o = 2
Energy gained by consuming		Eat_plant_h = 3.5	Eat_plant_o = 2 Eat_pest_o = 10
Consumtion Rules		One pest can directly eat one plant	One omnivore can eat one plant. Two omnivores can eat one pest



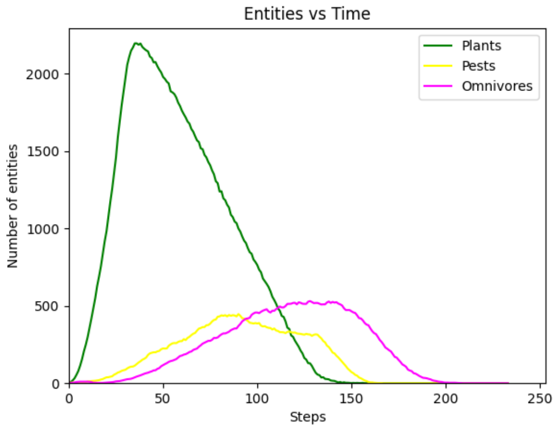
A dynamic equilibrium is reached



Increasing the probability of pests to reproduce causes them to die out faster $P_h = 0.2$



Decreasing the plant's reproduction probability to $P_p = 0.1$



Increasing energy upon birth for animals

Figure 1: The four different types of equilibriums visualized as number of entities versus number of steps

The three-agents dynamic equilibrium showed is near what is desired however the pest and omnivore population appears too large. For a realistically stable predator-pray equilibrium, there needs to be more food than predators. In the following parameter variation this will be sought after. Visible in the same image is the cascading effects of the random variables. Around step 2000 a substantial increase in plants fed the omnivores causing them to increase rapidly, consuming many herbs and plants.

1.3 Starting Configuration

The starting configuration makes a large difference on the early behaviour of the system. The longer the system survives the more dampened the effect of the starting configuration becomes. In this way it is transient. For our inquiry on the effectiveness of pesticides the toxin will be introduced late in the simulation thence the starting configuration lacks importance. Therefore, it will be kept constant as in the following image. This configuration is picked to simply allow all species to be able to grow undisturbed initially.

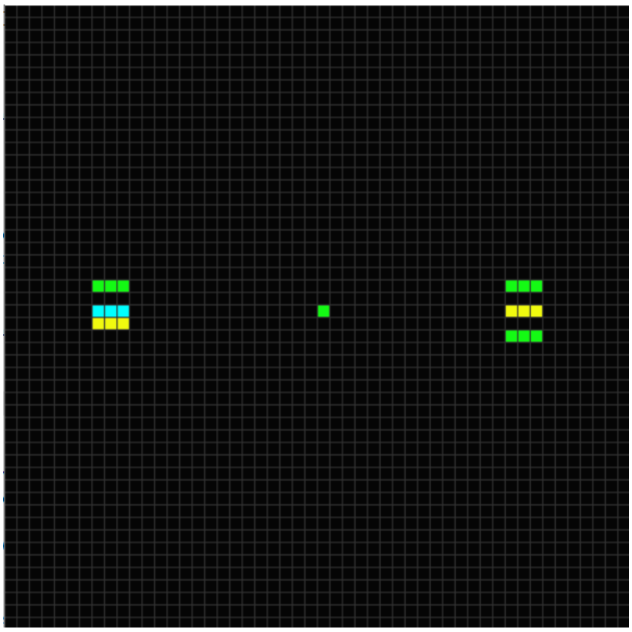


Figure 2: In the grid a green tile represents a tile dense with plants, yellow represents pests, and teal represents omnivores

1.4 Parameter variation

To restrict random errors and large cascading effect caused by the probabilistic reproduction, each simulation is ran 5 times and the number of every entity at each time step is averaged before plotted. Judging from Figure 1 the equilibrium is reached around step 500. Hence to ensure equilibrium has been reached, 2000 steps is taken in each simulation. It is very likely there are very slow patterns emerging due to the randomness, these will be eradicated by the pesticide control.

1.4.1 Varying reproduction probabilities

Realistically plants reproduce further and more widely than animals. However, omnivores reproducing slower than herbivores is so far an assumption. In this subsection the omnivore and plant reproduction rate is fixed to $P\_o = 0.08$ and $P\_p = 0.3$ respectively while and $P\_h \in (0.3, 0.08)$.

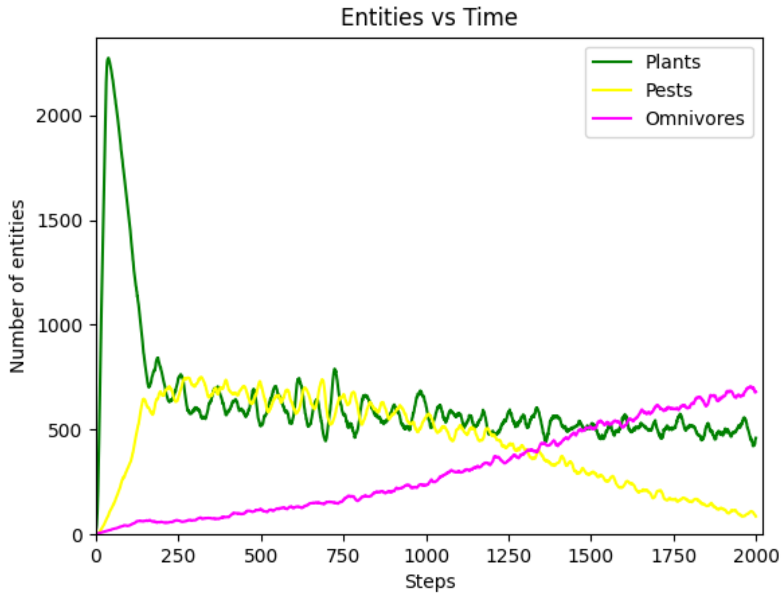


Figure 3: Increased probability of pest' reproduction cause them to die out faster P_h = 0.3. The x-axis is cut before this as they died slowly

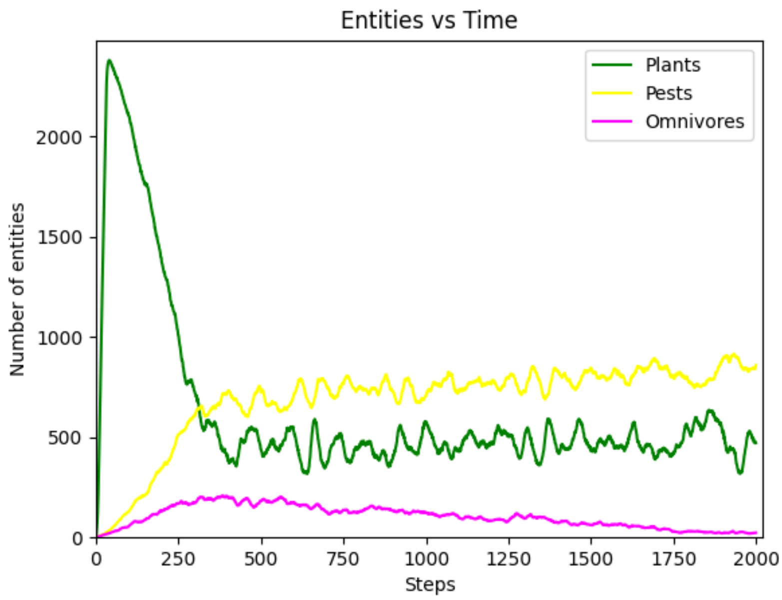


Figure 4: Too low of a reproductive rate for pests cause the omnivores to die out slowly P_h = 0.08

Around P_h = 0.09 an interesting change occurs. Due to the large energy increase gained for omnivores by eating pests, the omnivores benefit from the increased pests resulting in the pests' extinction despite their faster reproduction rate. At lower values of P_h = 0.09 the omnivores suffer from lack of food. P_h = 0.09 appears perfect for remaining in an equilibrium with all species.

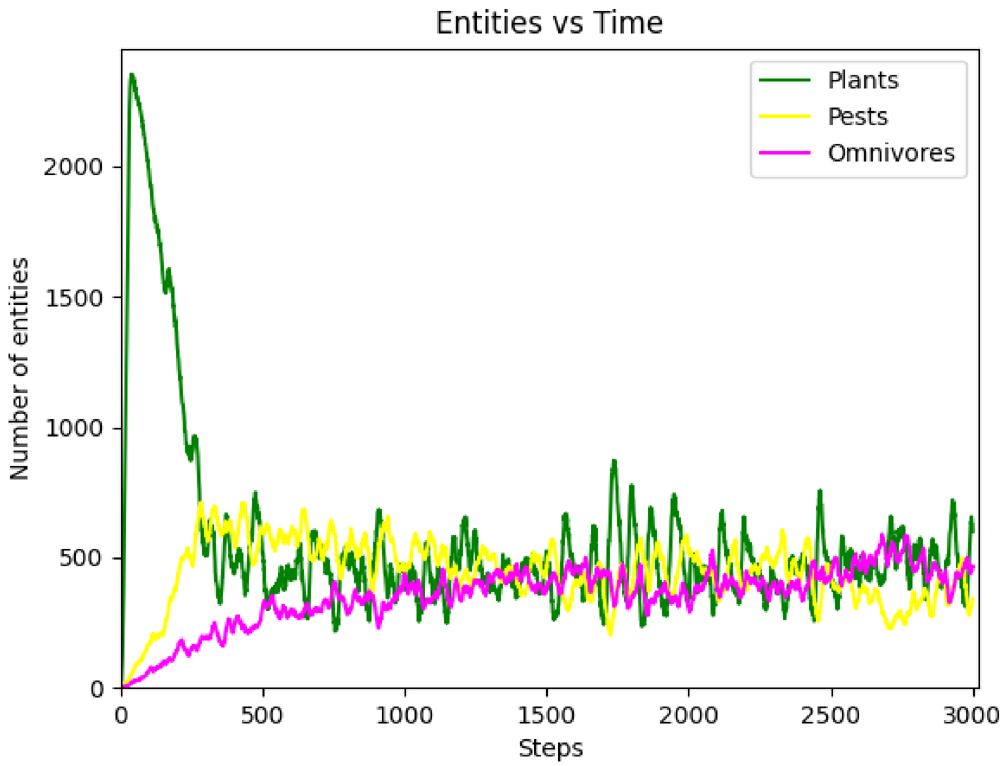


Figure 5: Quantities of all three species survive with P_h = 0.09

However, observing the figure above, it is not realistic to have predator populations greater than their food supply. A slow shift between pests and omnivores is also evident, that will be corrected for.

1.4.2 Varying reproduction energies

Firstly, lets make it harder for omnivores to gain in quantity. Rep_needed_o is changed from 10 to 12 step by step and Rep_cost_o from 9 to 10.

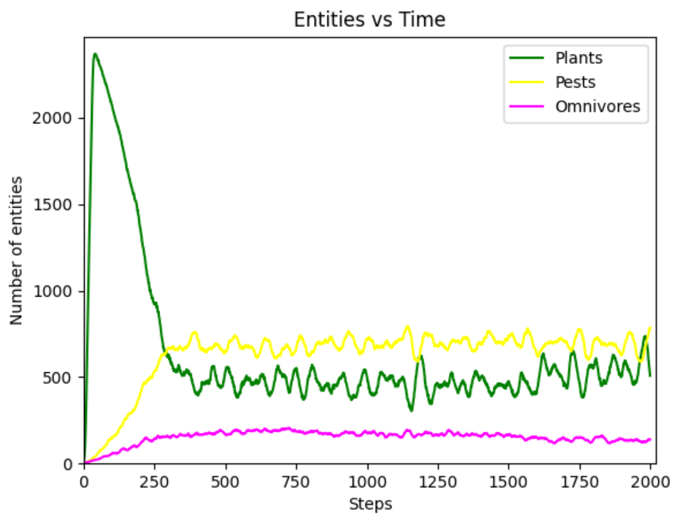


Figure 6: These changes make it harder for for omnivores to reproduce

Making it harder for omnivores was beneficial for reaching an realistic amount of animals given the food. However now there are slightly too many pests. To decrease them one can increase omnivores again, decrease the pests' food gain, or decrease their life span. However, we saw in section 1.4.1 that reducing the pests' ability to reproduce decreased the amount of omnivores. This is evident again for any changes making it more energy costly for herbivores to reproduce, for example in Figure 7.

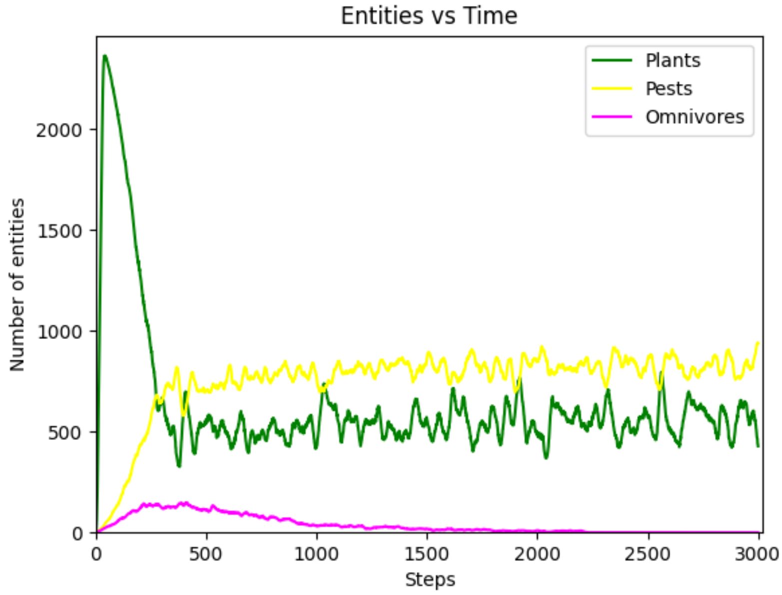


Figure 7: Changing the Rep_needed_h from 8 to 10 and Rep_cost_h from 6 to 8 makes it harder for the pest to reproduce. This does not affect the pest but instead causes the omnivores to go extinct.

As can be seen there is no apparent decrease in the pest population by making it harder for them to reproduce as this first kills the omnivores, and then lets the pest reproduce without natural predators. The parameters are returned to 8 respectively 6 since this change did not help and instead consumption energies will be varied.

1.4.3 Varying consumption energies, longevity and consumption rules

In order to decrease the number of pests more omnivores need to consume them. One manner of increasing the amount of omnivores is increasing their attributed birth energy. This would ensure they occupy tiles on the board for longer even if their food has dwindled, ensuring that herbivores cannot spread as easily without being eaten. However, this will also cause a greater omnivore population, to counteract this their minimum energy for reproduction is also increased. Iteratively it is tested birth_energy_o $\in (2, 5)$ and rep_needed_o $\in (12, 14)$.

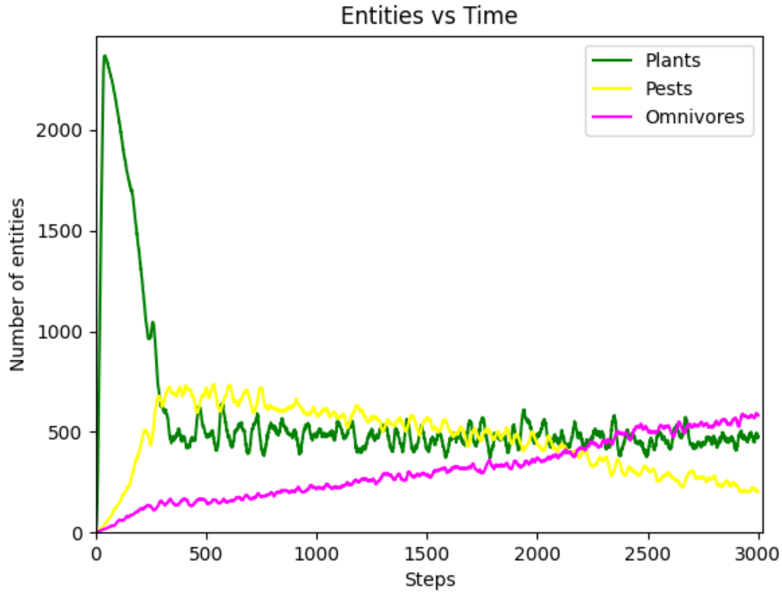
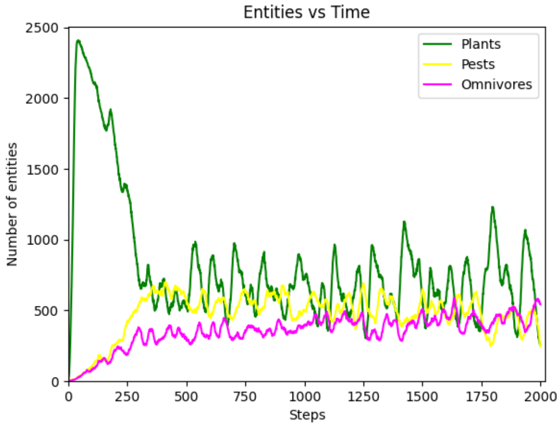


Figure 8: Attempting to decrease the number of pests by increasing the number of omnivores shows this correlation

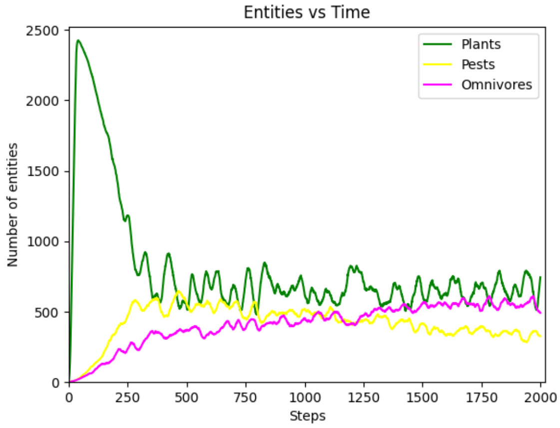
All of these changes cause the omnivore population to increase proportionally to the decrease of pests. This change appears almost linear. The same pattern occurs for many parameter variations that impact on how the pests and omnivores interact. This implies that changing quantities of one directly correlates to an increase in the other. Therefore, to make the plants survive longer the manner the animals consume must be changed.

Currently two omnivores is needed to consume a herbivore and singular animals can eat plants. Arguing that in order for a population to completely wipe out another there needs to be many arriving, the total amount of each species to consume a plant tile is increased to two and the number of omnivores needed to consume pests is increased to 3 accordingly. It is expected that greater migratory patterns appear and more distinct oscillations on the population graph arses as entire groups should appear and disappear together. The following figure shows the effect on changing the consumption rules.
The graph showing the average of many simulations have a more dampened oscillatory pattern. It also shows a more long-term behaviour taking place. However, it looks as if the pests are decaying in favor of the omnivores as intended. Nonetheless, having changed the consumption rules greatly improved the similarity to reality.

Iterative fine-tuning the parameters from what has been learnt: Decrease the gain for omnivores consuming herbivores and decrease birth rate of omnivores. Then to avoid an increase of pests decrease the energy gain for pests consuming plants. Adjusting this combinations within what is realistic until a qualitatively adequate result appears yields the following parameters and figure averaged over five simulations.



A single simulation which looks promising. Clearer oscillations and more natural proportions of entities



This images shows the average of five simulations with these settings

Variable Names	Plant	Pest	Omnivore
Chance of Reproducing	P_p = 0.08	P_h = 0.09	P_o = 0.3
Energy needed for reproduction	Rep_needed_p = 0	Rep_needed_h = 8	Rep_needed_o = 10
Energy cost of reproduction	Rep_cost_p = 0	Rep_cost_h = 4	Rep_cost_o = 7
Energy attributed upon birth	Birth_energy_p = 1000	Birth_energy_h = 3	Birth_energy_o = 2
Energy gained by consuming		Eat_plant_h = 3	Eat_plant_o = 3 Eat_pest_o = 7.2
Consumtion Rules		Two pests are needed to consume a plant-tile	Three omnivores consumes a pest-tile. Two omnivores can eat a plant-tile.

This result is adequate and all parameters have been thoroughly tested. The board is shown in Figure 9. Green represents high plant density, yellow for pests, teal for omnivores, and red for dying tiles. After a few hundred steps one can see how the newly introduced animals rapidly consume the abundant plants. After nearly 2000 steps the omnivores group's spread-out migration is visible while large chunks of pests are distributed over the board.

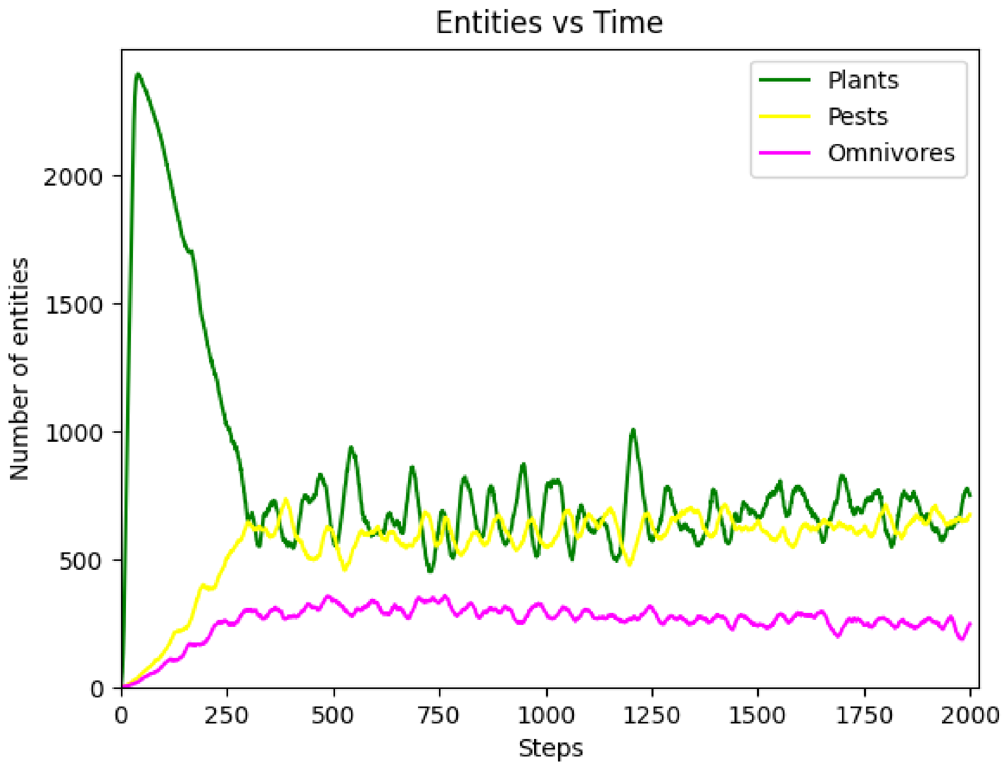
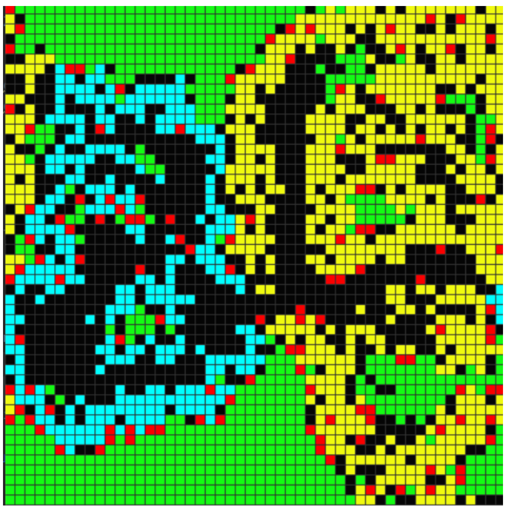
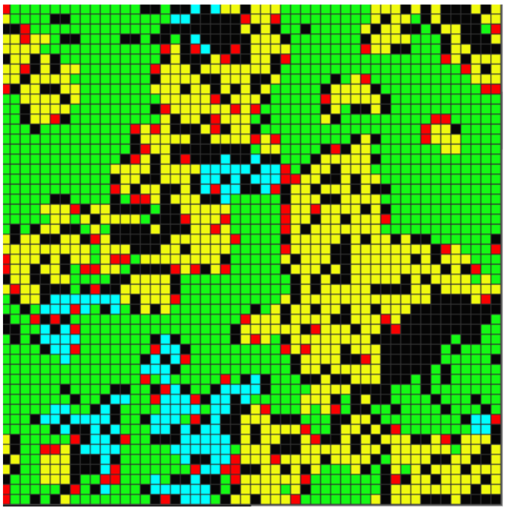


Figure 9



The board after a couple of hundred steps

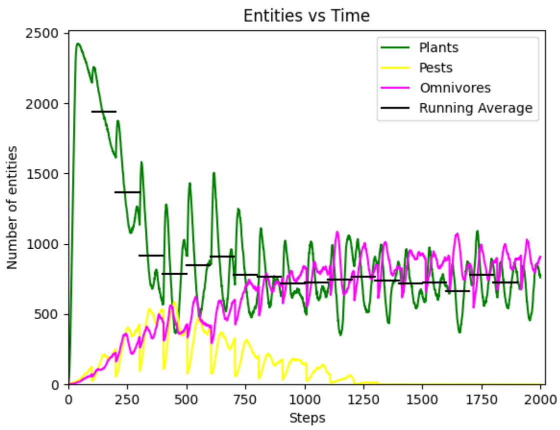


The board after almost 2000 steps

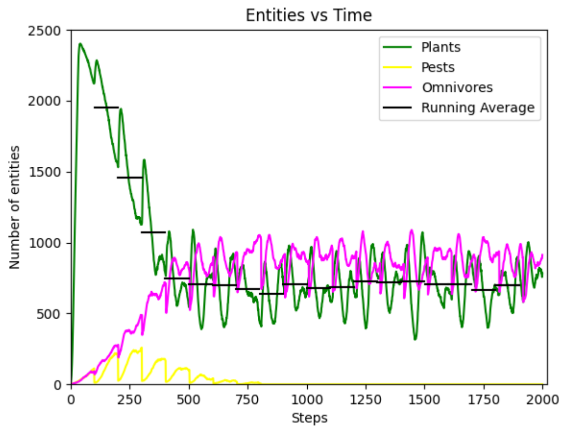
2 Introducing Pesticides

Upon noticing that the pest spread across the island the inhabitants decides to employ pesticides to favor their plants. Pesticides are specialized for specific species, however, a pesticide-rich environment is unhealthy for all entities. In a modern environment a pesticide kills essentially all of the targeted species it touches, yet, some will survive due to being covered, underground, or genetically favoured. There are two ways of implementing this, either the pesticide cause energy reduction or they directly remove entities. Given that the inhabitants intentionally tries to kill a specific species modern specialized pesticides will undoubtedly kill its target upon touch. However, other species will not be killed as pesticides due to the same specialization. Therefore, the pesticide is modelled to exterminate a pest with P_kill per cent probability and thereafter with the same probability reduce an omnivore's energy with 6. The inhabitants employ the pesticide periodically in modulo t_kill = 100.

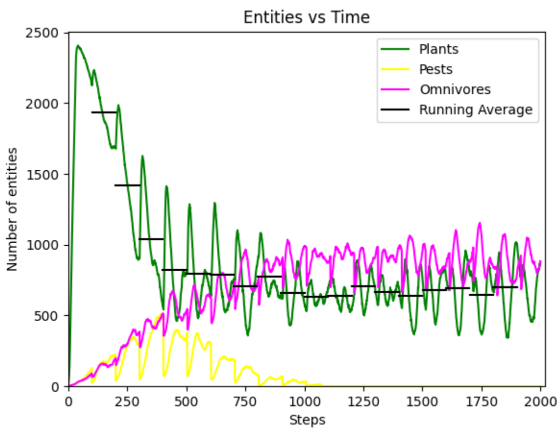
The intention of the pesticide is to increase the amount of plants on the island. To show this graphically, the average amount of plants between each pesticide treatment is shown on the graph and the total average number of plants after the first pesticide treatment is written in the caption. In the three agent system, a stronger pesticide can have an adverse effect on the number of plants as omnivores manage to spread much more. This is tested for P_kill $\in$ [0.7, 0.95] and some highlighting graphs are shown below.



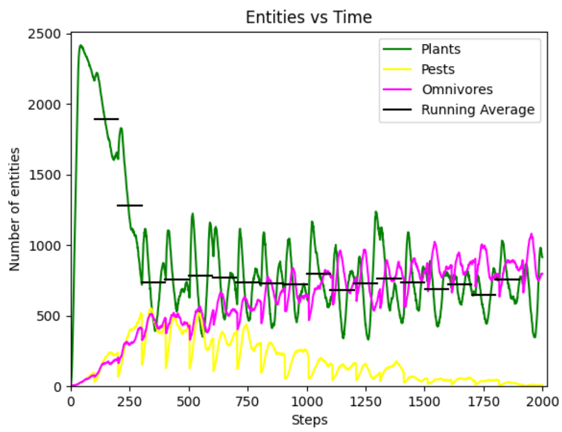
80 per cent is killed in each implementation. The average number of plants became 857



90 per cent killed. Average dropped to 827



85 per cent killed. Average is 822



85 per cent killed. Average is 820

Figure 10

No matter which strength of pesticide is implemented, the same final equilibrium is approached where all pests die out.A weaker pesticide only takes longer to arrive at that point. A slight increase in the average appeared around P_k = 0.8 .

Instead, if no pesticide is introduced the population graph and averages become:

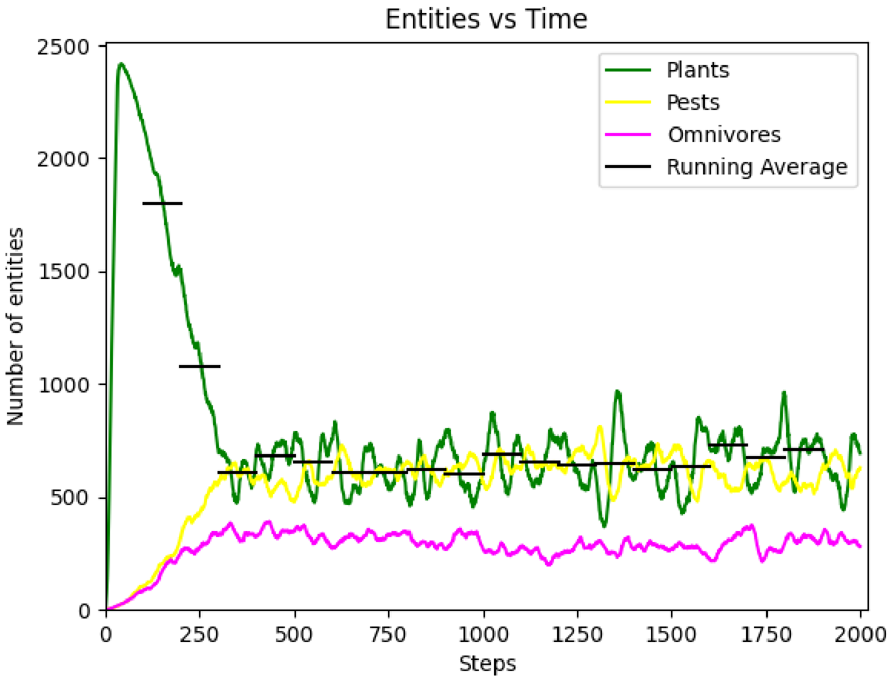


Figure 11: Average 725. It can be seen that the running averages are about 50 to 100 lower towards the end compared to when pesticides were introduced. Hence pesticides increase the number of plants in general!

3 Results and Analysis

3.1 Parameters and their effects

There is a direct and almost linear relationship between changes in omnivores and pest. Improving the longevity of pests results in their extinction as they become too great as food. Improving the longevity of omnivores also cause the extinction of pests as they become overpowered. Decreasing the plants ability to spread exterminates omnivores as their most prevalent food decreases, and decreasing this further causes extinction for all species.

3.2 Statistical Accuracy

The number of simulations needed to achieve accurate results appears to be the largest contributor to errors. Currently the simulation takes around two minutes to run 2000 steps. Therefore due to time, it was reasonable during the project to only average over five simulations at most. The true standard deviation as you increase the number of simulations should be somewhat constant. However, because some simulations will deviate greatly while all deviate somewhat the graph of the standard deviation should be choppy unless it is run for a very long time. In order to calculate the standard error and standard deviation the computer is left to work for more than an hour. The most accurate standard deviation is near the end of the following figure.

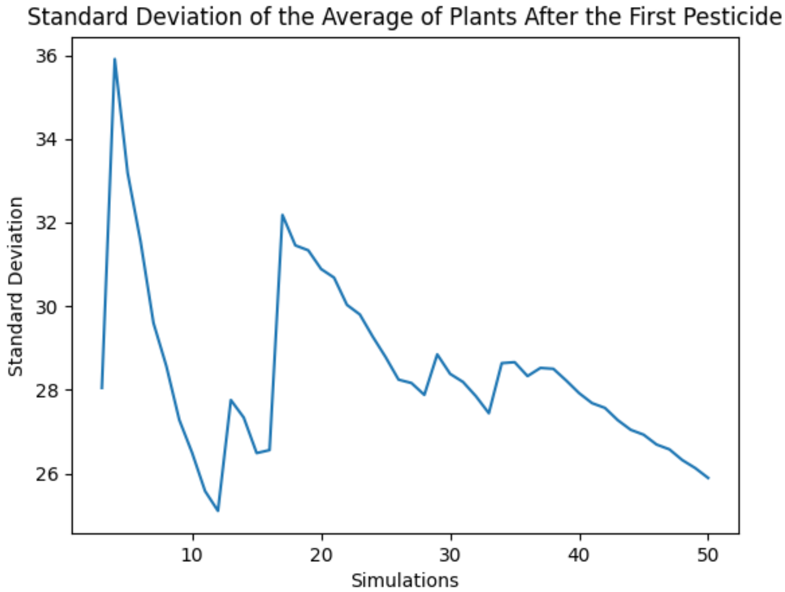


Figure 12

The large spikes in the deviation is attributed to very large abnormalities in the average for a specific simulation. These are caused by the randomness within the simulation. Truthfully, the exact standard deviation takes too long to calculate. Nonetheless, it is approximately 28 given the figure. This implies that the decision for which value to take for P_kill to optimize plant-survival was dignified within one standard deviation compared to the other outcomes in Figure 10.

More interestingly, the standard error should decrease as factor of one over square root of the number of simulations as the true standard deviation is about constant while the number of simulations increases.

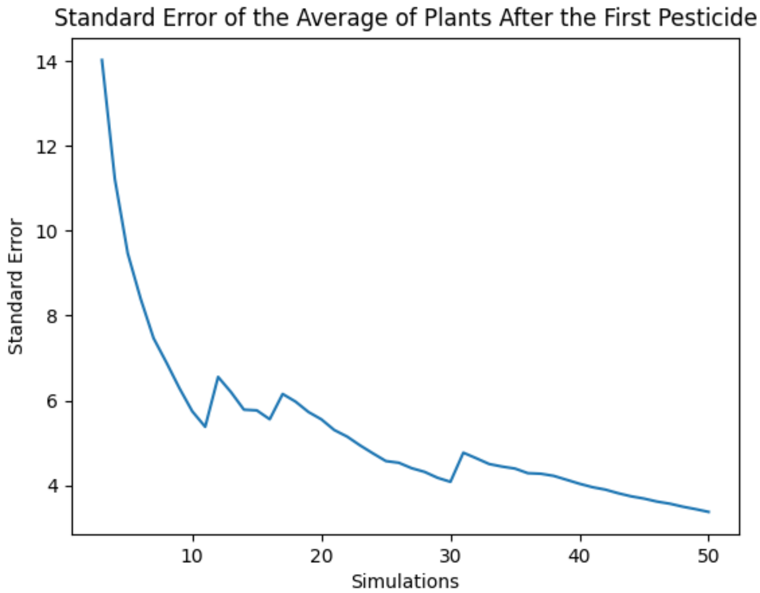


Figure 13

With five simulations the standard error of the average is around 10, hence the indicative result of the optimal strength of pesticide is at least two standard errors away from the other results shown in Figure 10. This indicates weakly that P_kill = 80 was the optimal choice. Furthermore, as the average number of plants with and without pesticides was 857 respectively 725, the obtained results for the same number of simulations with the standard errors are:

Average number of plants without pesticides: 730 ± 10
Average number of plants with pesticides: 860 ± 10

Using the average of plants achieved by executing the simulation for one hour with pesticides the latter number is more precisely estimated to be 840 ± 10

The running averages were visibly higher after putting in pesticides (Figure 10 and 11), with a quantifiable difference of 80 This standard error follow the same correlation as the total average but is lesser in magnitude after the initial explosion of plants has calmed, as including that increases the standard deviation. Hence both the running averages and the total average of plants benefit from pesticides confidently. The most modest estimate of the increase in the total average is as above:

$$850 - 740 = 110$$

Using the same standard error, which is an overestimate for the running averages, the running averages increased with approximately 60 tiles of plants after the initial plant-population explosion has calmed.

For future inquiries, given the shape of the standard error curve, the simulation's accuracy benefits greatly from running around 25 more simulations before averaging. This would reduce the errors to around half of their current values.

4 Conclusion and Discussion

4.1 Pesticides impact on population dynamics

Periodic use of pesticides causes the populations in an ecosystem to oscillate more than naturally. In a three-agent system with a plant, a pest, and an omnivore, the use of pesticides is beneficial for the omnivores and plants, allowing them to reproduce more. In total, this results in both a higher moving average and a higher total average of plants. In this simulation, the increase was at least 110 tiles more of plants for the total average. Equivalent to an increase of approximately 14 per cent. Combined with a 60 tiles increase of plants on the moving average counted in the intervals between pesticide use. With a qualitative observation, the forced oscillatory movement caused y the periodic pesticides made the populations have a more predictable pattern.

4.2 Simulation Versus Reality

The results are applicable in a controlled environment with only three species. The result can be generalized to more types of entities as long as their relations remain as they are in the simulation. However, as was noted in the impact of changing consumption rules, small changes in the characteristics of animals have great impacts on their population. For example, if the omnivore was a ladybug it would simply fly away during the introduction of pesticides and return much later. This would look very different in the population patterns as the omnivores would disappear as well, allowing many more plants to blossom, and then migrate in from the sides. Clearly, the simulation assumes very simple organisms.

Additionally, on an island, this simulation could be realistic as they are somewhat isolated. However, on a larger land mass, there will be a carnivore stabilizing the omnivore population. That the simulation was optimized for three species simultaneously is evident when the pesticides make the pests go extinct as there are too many omnivores on the graph for the given food supply. It became impossible adjusting parameters for both types of equilibrium to be realistic. In reality, a carnivore would appear and stabilize the omnivore population and as such improving this simulation requires introducing an additional agent.

Lastly, on a large timescale species would evolve to adjust the equilibrium which is why this project only focused on short timescales. However, even on a short timescale the real world introduces disease to maintain populations at reasonable amounts. Before generalizing any results, the spread of disease in overpopulated areas should be taken into account. In this project such exterior factors were assumed dismissible.

4.3 Conclusion

Within the uncertainties it is clear that introducing pesticides will shift upwards the running average of plants by a visible amount and benefit the total average with an increase from around 750 plants to 850 plants. The introduction of pesticides eradicate the pests resulting in a new dynamic equilibrium between plants and omnivores. The optimal strength of the pesticide is weakly indicated to be at an 80 percent kill rate. Lastly, it is clear that for this three agent system, it benefits the plants to reduce it to a two agent system without the pest. For future inquiries, the estimates' errors would half from running around 25 more simulations before averaging. In order to induce more general results, a carnivore and some adjustment contrary overpopulation, such as disease, should be introduced.