Agent-Based Competition Modeling with Disease Factor

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Abstract

Predator-prey relations form the basis of many ecosystems; one factor that can influence these relations is disease, which can cause population crashes in both wild and domestic populations, and has far-reaching effects on ecosystems. For example, the outbreak of a disease like avian influenza can devastate a population of birds [1], which in turn has ripple effects on the animals that depend on them for food [2]. In this report, the effects of three diseases are simulated and observed on a predator-prey relation consisting of one predator population and one prey population. Each disease is tested with either one of the populations or both populations being initially affected. The results of the simulations are compared with a base case simulation, which demonstrates predator-prey relationships with no disease interference.

1 Introduction

Population dynamics is a field of research that involves studying the change in the number of individuals in a population, such as members of a species under certain conditions. In addition to having significant applications in biology, this discipline also has applications in other subjects such as robotics and demographics. Differential equations are used within population dynamics for the study of multiple phenomena [3]. There are many of these models; the Lotka-Volterra predator-prey model is a very common model to illustrate the relation between two species in which both demonstrate population spikes. The populations can also demonstrate collective behaviors, wherein the agents' behavior is affected by those of the surrounding agents. Examples of collective behavior include aggregation, flocking, and task allocation.

The SIR model is a simple epidemiological model that describes the transmission of a disease in a population. The model consists of three compartments: susceptible (S), infectious (I), and recovered (R). The susceptible compartment represents individuals who are susceptible to the disease but have not yet been infected [4]. The infectious compartment represents individuals who are infected and can transmit the disease to susceptible individuals. The recovered compartment represents individuals who have recovered from the disease and can no longer transmit the disease. A simplified model is the SI model, where individuals are born with no immunity, and once an individual is infected, they remain infected, with no treatment nor quarantine of the compromised individuals. This general model is used within the simulation.

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The spread of infectious diseases is a complex phenomenon. The spread of infectious diseases is determined by the interaction between the disease and the population, which can be unpredictable and volatile. This has been studied with numerous conclusions. Driessche and Zeeman conclude that disease can either “lead to stable or oscillatory coexistence of both species” if in the absence of disease, there is instability in the populations, or if there is stability in the absence of disease, the prosperity of the populations is determined by reproduction [5]. Furthermore, Holt and Pickering determine that the infection rates parallels the competition coefficient [6]. The literature demonstrates that there has been research into this topic, however, the unpredictable nature of disease leads to room for further investigation.

In order to investigate the effects of disease, the following question is posed: What is the impact of non-lethal disease on predator-prey relationships for diseases which have either single-species or cross-species transmission? This question thus represents the research question of this report. To observe the effects, a base case simulation that is disease free is created. To this simulation disease is then introduced and the fluctuation in the population sizes are recorded. The effects that disease has on the population sizes of two species is analyzed, with the goal of determining if there is an impact of non-lethal disease on predator-prey relationships.

2 Hypothesis

- Null Hypothesis: There is no difference with the impact of non-lethal disease on predator-prey relationships.
- Alternative Hypothesis: There is a difference with the impact of non-lethal disease on predator-prey relationships.

3 Methodology

The observation of predator-prey interactions is difficult to study, thus, agent-based modeling allows for the exploration of this interaction. To emulate predator-prey relations, an environment consisting of fox and rabbit agents was generated in which the agents can interact with each other. The fox agents can only interact with rabbit agents, meanwhile the rabbit agents can interact with both fox agents and other rabbits agents through flocking. Fox agents are the predators in the simulation and can be in one of three states: wander, eat, or reproduce. Fox agents will wander and if they encounter a rabbit and their energy level is not at the maximum level, they will eat the rabbit, causing the rabbit to die. After eating, the fox agent has a probability of asexual reproduction and ultimately returns to the wandering state. They have a finite energy level that incrementally decreases every frame, by eating a rabbit they replenish some of this energy making them dependent on rabbits for survival. The rate at which energy depletes and the energy gained from eating a rabbit is proportional to the total energy level the fox agent possesses. Different proportions were tested, but other proportions caused fox agents to become extinct very quickly or survive indefinitely. Indefinite survival or quick extinction were regarded as undesirable for the interaction between fox agents and rabbit agents. Therefore, the final proportions chosen were a 2% energy depletion of the total energy every frame and a 10% energy gain of the total energy when a fox eats rabbits. Lastly, if the energy level becomes zero then the fox agent will die.

Rabbit agents are the prey in the simulation and can be in one of two states: wander or reproduce. From the wandering state, a rabbit has a probability of reproducing asexually. Unlike the fox agents, they do not have an energy level; their only cause of death is when a fox agent eats them. Additionally, rabbit agents exhibit a particular spatial behavior: flocking. While agents are not assigned genders, but to copy the clustering behavior in rabbits, flocking of rabbit agents was implemented [7; 8]. Flocking is the self-organized formation of individuals to form clusters with neighboring individuals, flocking consists of three individual behaviors: cohesion, separation, and alignment. The three behaviors can be modeled through mathematical formulas that can be implemented to simulate the behavior. To implement disease into the simulation, the effect and the spread of disease needed to be established. There is a chance that the disease can spread from a diseased individual to a neighboring agent (of the same species). There are, however, very limited overlap states that both the fox and rabbit agents share. To view the effect of a disease on both populations, the disease should be able to induce the same effect on both populations. The only states both types of agents have in common are wandering and reproduction, thus the effect of the disease will target these states. The three types of disease types chosen:

- Halving the reproduction probability when the agent has the disease
- Inhibit reproduction when the agent has the disease
- Freeze movement when the agent has the disease

These disease types can alter behavioral elements of both fox and rabbit agents, thus allowing for the observation if the disease alters the fluctuating population size that normally occurs and comparing if the disease has a different effect on the two populations.

4 Experiments

The experimental setup consisted of two parts. The first of which was the tuning of parameters for the basic simulation. For this the aim was to find the longest self-sustaining simulation configuration where the agent populations were constantly maxed out, i.e. there should be some fluctuation in the rabbit and fox agent population size over the duration of the simulation, the populations are set to spawn with 50 rabbit agents and 25 fox agents. This type of simulation was considered desirable due to two considerations; the simulation ends when one of the two populations dies out, therefore a long self-sustaining simulation will continuously contain data on both species. Furthermore, the simulation running for a long duration on its own ensures that when a disease is introduced and the simulation cuts short, the cause of this is due to disease and not the basic simulation parameters.

The second aim was to not have the populations be at their max capacity for the entire run. To keep the simulation running without utilizing too much computational power, max population size values were implemented for the agents which were 250 for fox agents and 500 for rabbit agents, consistent with their initial population ratio of 1 to 2. Changes in the population size for both species should be observed, a simulation where both are constantly at max capacity will not allow any conclusions on the interaction between the agents. These two requirements had to be balanced via the parameter selection [9]. This balance was necessary since a long running simulation favors the populations to be at their max capacity. In contrast, a change in population sizes often comes with early extinction events.

The tested parameters and respective test ranges were 100 to 1000 for the fox energy and 0.01 to 0.99 for the reproduction probabilities for each species separately. The testing of the parameters was done systematically. For each parameter, they were separately set to their lowest value, this was then increased in consistent step sizes, the step sizes were dependent on the currently tested parameter. For the initial fox energy the step size was n = 100, for the reproduction values the step size was n = 0.01. The reason for selecting these step sizes was, for the fox agents, that the frame rate of Violet is approximately 60 frames per second, therefore anything below 100 would mean that the fox agents died out in under one second. This also then determined the step size. For the reproduction values they were modeled according to probabilities, therefore their range is limited from 0 to 1, however, 0 and 1 were excluded since that would set reproduction to be always false or true respectively.

When testing the fox energy level, it was observed that a low energy of 100 caused the foxes to die out very quickly, in contrast, an energy level above 300 led the fox agents to survive for a long time thus either depleting the rabbit population or reaching their max capacity constantly. Therefore, the fox energy level was set to 200.

The reproduction values were tested concurrently; due to their dependence, this was done by first increasing the fox reproduction and then testing the simulation followed by an increase in the rabbit reproduction if necessary. This led to the observation that a reproduction value above 0.05 for either population led to maxed out population capacity or the extinction of one species for every test run, therefore testing above this value was stopped. Reproduction values that were too low caused similar issues. A balance of parameters was found at 0.035 for the fox agents and 0.02 for the rabbit agents. The authors acknowledge that there are potentially other parameter combinations that could also fulfill the set goals, however, testing all possible combinations was not feasible.

The final parameters chosen for the base case were: Initial fox agent energy = 200, reproduction probability fox agent = 0.035, reproduction probability rabbit agent = 0.02. When the parameter values which suit the above mentioned criteria were found, the simulation was run 60 times to acquire a sufficient sample. For the experiment, the objective was to investigate disease in one population, either rabbit agents or fox agents, and disease in both populations where cross-species transmission was possible from rabbit agent to fox agent. For the different possibilities of disease, different effects of the disease were also investigated which included halving reproduction probability, inhibiting reproduction, and freezing movement.

For single-species transmission the agents have a 1 in 10 chance of getting sick if they are in proximity to a diseased agent of their species. Higher transmission rates were tested, but led to total domination of the disease too quickly. Inter-species transmission works when a fox agent eats a diseased rabbit, in this case the fox agent will get sick. This was selected to model nature, i.e. consuming food that carries a disease that the consumer is susceptible to leads to disease [5]. To include disease in the simulation 10 % of either the fox or the rabbit agents spawned diseased for single-species transmission, which means 3 out of 25 foxes and 5 out of 50 rabbits. For inter-species transmission 10% of the rabbits spawned sick. Higher rates were tested, but led to disease domination. There are three disease types, half reproduction, no reproduction, and freeze movement, for when an agent contracts the disease. For each disease type and situation, 30 trials were run, resulting in 270 trials in total. For each trial the population size over the duration of the simulation was recorded.

5 Results

For each run of the experiment, the 30 simulations were compared and classified according to the similarity of their behavior. From this, the most often occurring behavior group was selected. For this, a representative graph was chosen for this report. It was not possible to apply statistical methods to these results, since as mentioned in the lecture by Dr. Ferrante, these simulations are not static measurements but represent cycles. Therefore, the application of statistical methods was not feasible. The agents began at a set population size and were able to move around the environment freely,

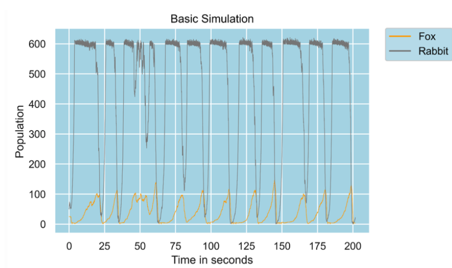
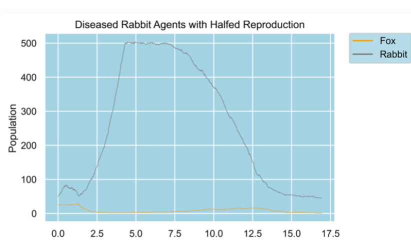
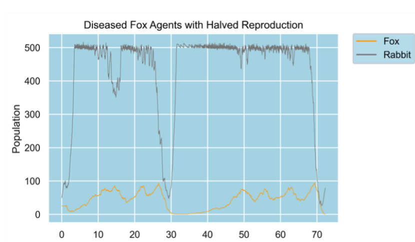


Figure 1: Base case simulation

with the rabbits being subject to flocking. The simulation shown in Figure 1 is used as the base case which is compared with the various disease simulations. The base case simulation displays a fluctuating pattern between both the rabbit and fox agents throughout the simulation; it can be considered self-sustaining. Whenever the rabbit agents reach a maximum population, the fox agents population also begins to rise leading to a massive drop in the rabbit agent population, which in return leads to a drop in the fox agent population and that is when the rabbit agent population starts to grow again. This pattern can be observed throughout the simulation.



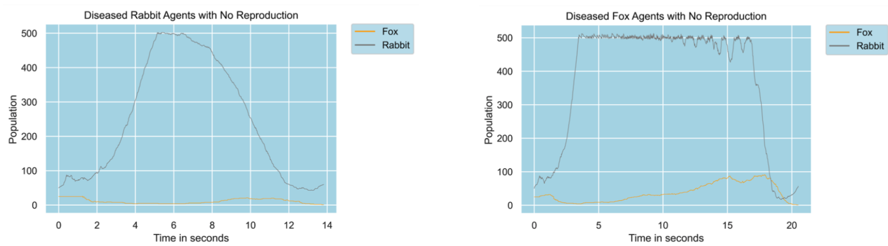
(a) Disease affects rabbit



(b) Disease affects fox

Figure 2: Disease halves the reproduction

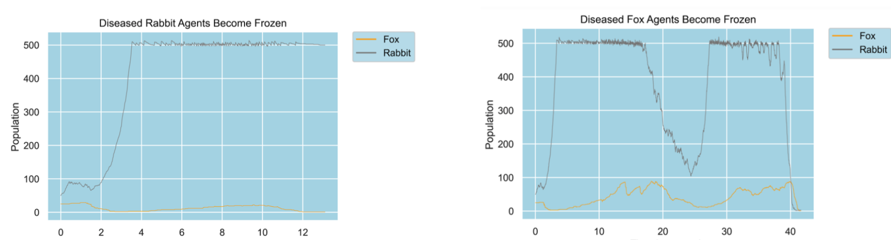
The first experiment which was executed was one population being infected by a disease which halved their reproduction. The graph in Figure 2a displays the result in which only the rabbit agent population has the disease. The results initially show decreased rabbit agent reproduction, which leads to a decline in the fox population. The rabbit population manages to still reach its max capacity, though at a slower rate compared to the base case. The fox population never fully recovers from the initial lack of rabbits. The graph in Figure 2b displays the result in which only the fox agent population has the disease. The rabbit agent's population thrives at their max capacity with a few signs of fluctuations, and the same is not visible in the fox population. Instead, the fox agents only slowly grow in number and die out after consuming the rabbit population, since they are unable to reproduce sufficiently.



(a) Disease affects rabbit (b) Disease affects fox

Figure 3: Disease halts the reproduction

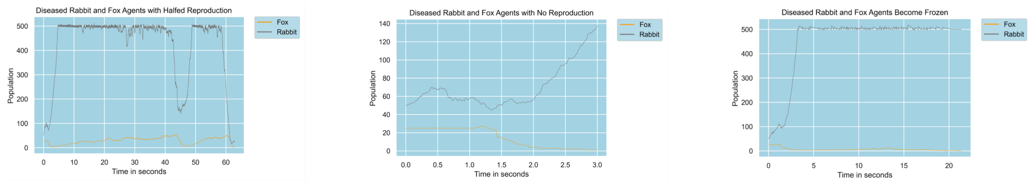
The following experiment involves one diseased population which halts the reproduction if infected. In Figure 3a, only the rabbit agent population has the disease. The rabbit agents reach the maximum population for a short amount of time before gradually declining, and the fox population eventually starves and dies out. In Figure 3b, only the fox agent population has the disease; the rabbit population thrives at the maximum population with minimal fluctuations and the first sign of dip in the rabbit agent population, the fox agent population dies out.



(a) Disease affects rabbit (b) Disease affects fox

Figure 4: Disease freeze movement

The subsequent experiment is where one diseased population freezes in place. In Figure 4a, only the rabbit agent population has the disease and the results display an increase in the rabbit agent population where it remains at its maximum population without any fluctuations. The fox agent population shows minimal signs of increase, and eventually dies out. In Figure 4b, only the fox agent population has the disease and the results display an increase in the rabbit agent population where it remains at maximum population for a while before fluctuating and rising again. The fox agent population also shows some signs of fluctuation; however, when the rabbit agent population dips too much and too fast, the fox agent population dies out quickly.



(a) Half reproduction (b) Halt reproduction (c) Freeze movement

Figure 5: Cross-species transmission of disease

In the next set of results, both populations are affected by the disease. In the following experiment both the fox and rabbit agent population have halved reproduction as a result of being infected. The results observed in the graph in Figure 5a display a rise in the rabbit agent population with infrequent fluctuations, while the fox agent population shows minimal growth in population and no fluctuations. Eventually, the fox agent population dies out when the rabbit agent population has a sudden dip in population size. The next experiment is when both the fox and rabbit agent population are now affected by the disease where they are unable to reproduce. Figure 5b displays a very short run where the fox agents almost immediately die out before having a chance to eat any rabbit agents. The rabbit agents show signs of increase in population size. In the final experiment, both the rabbit and fox populations are affected by the disease that makes them freeze in place. The graph in Figure 5c displays a sharp increase in the population of rabbit agents to a maximum amount with almost no fluctuations; however, the fox population shows a gradual dip and minimal signs of increase in their population before completely dying out.

6 Conclusion

From the obtained results, it can be concluded that the presence of a disease in one or both populations has a detrimental effect on survival, specifically for the fox population. The null hypothesis of there being no difference compared to the base case simulation despite the presence of disease, can therefore be rejected. When disease was present, the fox population died out faster compared to the base case simulation, whilst the rabbit population would usually thrive despite disease. This effect was observed in all disease types, and is most likely caused by the dependence of the fox population on the rabbit population, e.g. when there are fewer rabbits to eat, the foxes have a higher chance of going extinct due to hunger. In contrast, the rabbit agents have a higher survival chance since they are not dependent on eating to reproduce. The rabbits thrive if fewer foxes are present in the environment, causing less fluctuates in their population size. Even in simulations where the rabbits were the diseased species and were affected by lessened or no reproduction, the foxes would still die out before the rabbits. This is also observable in the simulation where either species froze, if the rabbits froze they would still form small clusters due to flocking and simply continue their reproduction. It was therefore harder for the foxes to find rabbits to eat since they had to come upon such a cluster. For the same reason, if the fox froze they were fully dependent on a large rabbit population so that sufficient rabbits would wander into their proximity. Therefore, the state and size of the rabbit population has considerable influence on the survival of the fox population, i.e. if the rabbits are sick, the foxes will go extinct. This is true for both single-species and inter-species transmission.

It can be concluded that even if the disease is only present in one of the species, both will still be subject to its effects. This circumstance is heightened when there is inter-species transmission. These simulations followed the observed trends for the single-species transmission. The predator-prey relationship exists in a balance; too many or too few of either species will cause one to dominate and the other to die out. This pattern is disrupted by the disease, and can also be observed in nature, as if the prey species suffers reduced numbers, then its predator will consequently be affected. Though unlike the simulation a predator in nature has the option of chasing different prey to sustain itself. This presents one of the limitations of this simulation: with only two species being modeled for observability, the predator is limited to one prey. The simulation also does not include a species that preys on the predator. These limitations omit the complexity of food chains found in nature, but were necessary to ensure that results could be obtained. These limitations do present ideas for future work, i.e. how disease affects an entire interdependent food chain. Other potential research could include introducing mortality to the rabbit population or introducing cannibalism for the fox population.

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