# Simulation and Modeling - 2D Cellular Automata Ecosystem

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**Abstract:** The main goal of this project is to study and analyse populations in a simple ecosystem given a set of rules. To do this, three actors are used: a top-level predator (wolf), a low-level predator (fox) and a herbivore (bunny). Utilizing a 2D grid, the agents will move semi-randomly while showing interspecies and intraspecies behaviour, that is, either reproducing or hunting/getting hunt. Natural selection will be discussed, a particular ecosystem will be analysed and a stable setting where all 3 actors survive will be found.

## I. THE MODEL

With the intent is to be as loyal to nature as possible and the whole simulation rules are built around that. Its in each species best interest to survive and reproduce, so the way actors move will be determined by the environment, that is, other actors and their position. For this reason, I integrated a semi-random mobility, meaning that preys will run from nearby predators and predators will hunt for preys. If there is nothing within the visibility range, the agent will move randomly (thus the "semi-random" terminology).

Agents can show two different modes; "hunting" mode and "mating" mode. When hunting, the agent will move towards a prey. When mating, the agent will move towards a potential mate. If the actors are close enough, hunting and mating is enabled.

A list of attributes used to characterise the actors is given below:

- Speed: Movement available per timestep. The top-level predator will have the highest velocity and the herbivore, the lowest. However, a natural selection implementation can be switched on and preys can become faster over time.
- Visibility: The higher it is, the more distance the agent can cover when finding a prey/predator/mate.
- Age: It decreases as time goes by. If 0 is reached, the agent dies. This value is typically higher in top-level predators.
- Feeding: Predator attribute. Similar as "Age", it decreases with time as the agent becomes hungry. If 0 is reached, the agent dies. However, it can be refilled when a prey is caught.
  - Feeding threshold: If "Feeding" goes under this threshold, the agent will switch to hunting mode and look for preys. If it is above the threshold, it will stop hunting.
  - Feeding reward: hunger points rewarded for catching a prey, avoiding starvation. Hunting a low-level predator will reward more points than hunting a herbivore.
- Reproduction:
  - Reproduction chance: Each timestep has a chance to trigger "mating mode". 2 agents of the same species must be close and not in "hunting mode" in order for reproduction to happen.
  - Offspring: Number of offspring associated to each successful reproduction. Typically herbivores will have more offspring than predators.

Additionally, the speed of the initial bunny population can be chosen to be random (although between a range of values) so there are faster and slower bunnies. It will be possible to see if the faster bunnies are the ones that reproduce and thus have a fitter offspring. This is done to simulate natural selection.

## II. SIMULATION SETUP

Each actor occupies a cell in a 50x50 2D grid. The world is initialized using, as parameters, the initial number of actors for each species and its attributes. Initial positions are chosen randomly around the grid. Each time step is equivalent to a moving step; t=1 will mean that our actors are done completing their first move, t=10, their first ten moves, and so on. Agents' are conscious about their environment; their sight allow them to move toward potential mates or potential preys depending on their visibility attribute. This will tend to generate same-species clusters, as it happens in nature.

## III. PROBLEM

The main objective is to find a set of parameters that allow stability (survival of the three kinds of actors) in our ecosystem. The method used to do so is nesting, that is, running the simulation for multiple parameters in a loop until stability is found. These parameters are the initial number of participants and some of its attributes. Once the stable ecosystem is found, some observables such as the average population and its standard deviation are measured.

In addition to that, natural selection and population evolution (and its success to be a stable ecosystem) are interesting topics to be discussed.

## IV. RESULTS AND ANALYSIS

### A. Natural Selection

Natural selection for bunnies is implemented in the simulation. A showcase example is displayed in figure (7), which can be found in the appendix section. The three actors are in a low "reproduction chance" environment (thus the straight horizontal lines in the population graphic). In this environment, "hunting mode" is prioritized and thus we can see the effects of natural selection.

The initial sample of rabbits contain slow and fast bunnies, ranging from speed=2 (fastest) to speed=7 (slowest). As it can be seen in figure (), foxes become hungry around time=1000 and rabbits are being hunted down. As a consequence, only the fastest bunnies survive and the average speed of the rabbit population is increased. This is the expected behaviour simulating natural selection, where rabbits that run faster than their predators are likely to prevail.

However, this does not guarantee their survival. Around time=1500, foxes become hungry again and the rabbit population suffers another wave of hunting. It is worth noting that although the number of foxes is approximately the same as in the first wave, the rabbits that get eaten are less. Due to their increased speed, they can run from the predator and they are harder to hunt. Also, there are less rabbits to hunt compared to the ones in the first wave at time=1000, which is another obstacle for the foxes.

One could ask why foxes are able to catch rabbits even though they are faster. Taking a look at the animations, it becomes clear. Rabbits tend to form clusters, and foxes can take advantage of this by cornering and hunting them. As it may be noticed, a significant portion of the rabbit population (approximately 20%) is hunted down at the beginning of the simulation. This is due to the fact that the initial position of the agents is completely random throughout the grid, meaning that rabbits placed near foxes get unavoidably killed. Because there is little time to run from the predator, it does not matter how slow/fast the rabbit is, surviving is a matter of luck. Consequently, natural selection does not intervene and the average speed of bunnies remains the same through this first period.

### B. Population evolution and success rate

It is interesting to analyse the success rate for a stable ecosystem given a set of initial conditions. In our case, stable will mean that all three actors can survive for a long period of time.

For intuitive reasons, the herbivores must be larger in number than the low-level predators, and this in turn larger than the top-level predator. At least in the beginning. Otherwise, preys will get eaten easily and will become extinct. A reasonable approach to reach this kind of ecosystem is to consider the proportion 50:13:3, that is, 50 bunnies, 13 foxes and 3 wolves as our initial participants. This proportion will be used throughout the subsection.

Figure (1) illustrates the idea of success rate. Several simulations (precisely, 100 simulations) are run with the same agents' attributes and parameters. Because of the randomness of the initial position, the participants movement (semi-random walk) and the "reproduction chance", each iteration is different from the other. Some may end in success, others in failure. Each set of iterations belongs to a maximum amount of time. For example, a 100% success rate at t=1000 means that all three actors always survive when 1000 years have passed. The higher the time, the less likely it is for the three agents to survive.

Analysing the results, I can conclude that more iterations are needed. It makes no sense that success rate at t=1625 is higher than the rate at t=1400 since of course, simulations that reach 1600 years will also have reached the 1400 years mark. Each iteration costs, on average, 3 minutes of computation time depending on the number of actors reached (the higher the number, the more actions the processor has to compute). The fact that 100 iterations are not enough sheds some light into how chaotic the system is, being extremely sensitive to slight variations of the initial conditions. It only takes a fox to spawn close to a rabbit cluster to change the game completely. Nonetheless, the general tendency that can be seen in figure (1) is the decreasing of success rate over time, as we could expect.

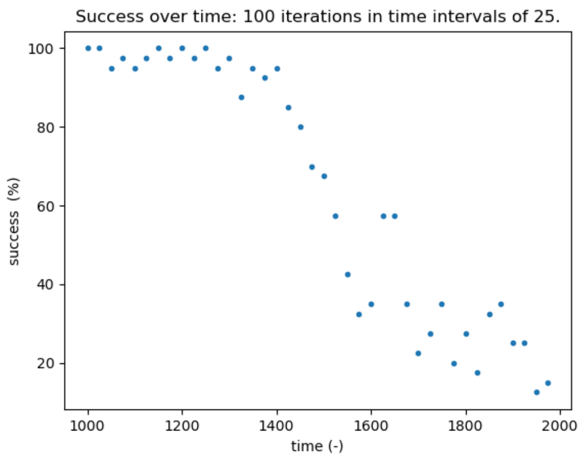



FIG. 1: Success rate (3 actors surviving) for different periods of time. As time is increased, success declines. 100 iterations are done for each particular time, and time intervals are done within a 25 point spacing.

It is possible to see the average reason for the failure of the simulation. In other words, which agent become extinct on average? The ratio between the initial and final population of the agent will be helpful when answering the latter question. Figure (2) shows the case for t=1400. As we can see, the ratio converges to a certain value as we iterate. In this "reproduction study", 100 iterations is a good enough value because of this fast convergence. While bunnies experiment a growth from t=0 to t=1400 (the ratio is greater than 1), foxes have a nearly null ratio. Wolves, on the other hand, remain significantly stable. It can be concluded, therefore, that the average cause of failure is foxes' extinction. They are constantly being hunted by the wolves and bunnies can thrive, having a great ratio. However, it is worth noting that the foxes' ratio is not null, meaning that in some iterations they were not the cause of failure.

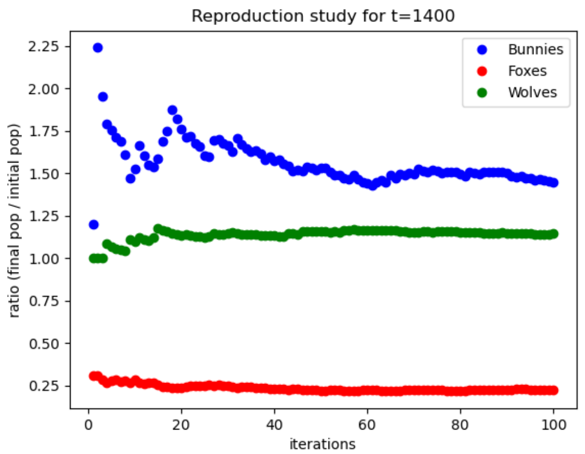



FIG. 2: Reproduction study for the specific time of t=1400. After 100 iterations, the average of the ratio "final population / initial population" converges. Bunnies normally thrive in this environment, wolves maintain their population and foxes tend to become extinct.

### C. Stable Ecosystem

Figure (3) captures the idea of a stable ecosystem, that is, a fluctuating ecosystem (in terms of population) on which all three actors survive. The initial proportions are 173:17:3. Because of its stability, there is statistical interest on both the average population and the corresponding standard deviation for each species. These values are portrayed as dashed and dotted lines respectively.

As it can be seen, a decrease in the rabbit population usually translates into an increase in the fox population. It makes sense for the following reason, after foxes eat the rabbits, they can switch into "mating mode" and reproduce. Particular examples are t=400 and t=2600. However, if the "mating mode" is not activated in the majority of foxes (as it is a matter of chance controlled by the "Reproduction chance" parameter), a bunny population decrease can lead to a fox population

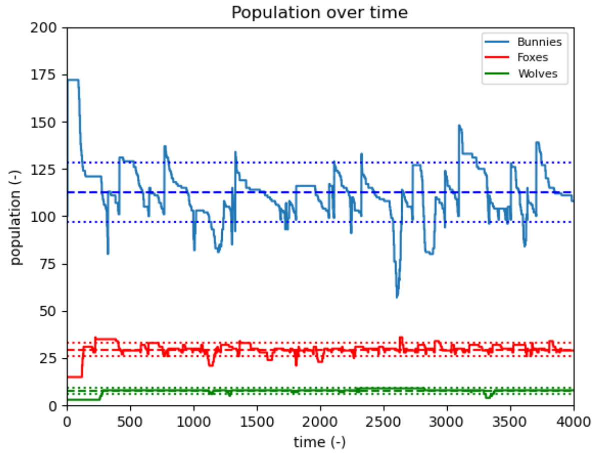



FIG. 3: Stable ecosystem. Initial proportions are 173:17:3. Average and deviation of each population is displayed via dashed and dotted lines respectively.

decrease. An instance would be the decrease for rabbits before t=1000 and the decrease for foxes right after that. Nonetheless, because of the decrease in the fox population, the bunnies are getting hunted less and less (it has a little bit of an snowball effect, since the less bunnies there are, the harder it is to find them) so they can survive and thrive.

The previously done analysis about foxes and rabbits may be correct, but it is necessary to say that there are other factors to take into consideration, such as the number of wolves, clusters, and age. For this particular simulation, wolves do not reproduce so much (low reproduction chance and only one offspring per reproduction) so we can focus on age and clusters:

- **Clusters**

  Aggregations of members belonging to the same species are not unusual, since in every step they consider mating with another agent. Because of the clusters formed, two different things can happen: an increase or a decrease in the population. While the increase would be because agents reproduce when close by, the decrease can happen if a predator finds a cluster of preys.

- **Age**

  Certain spikes on the population graphic are caused because each agent has an "age" associated. To illustrate my point, consider the baby boomer generation (1960s-1970s). If for some mysterious reason, people from that generation died when reaching 50 years old, then the period 2010-2020 would have a high mortality index. This is exactly what happens when a cluster of rabbits is formed, they massively reproduce and after some years,

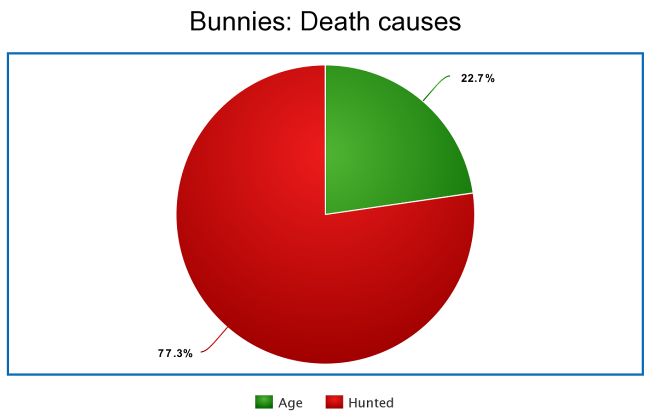
| | Ratio $\frac{2\sigma}{\bar{x}}$ |
|---|---|
| Bunnies | **0.255** |
| Foxes | **0.263** |
| Wolves | **0.348** |

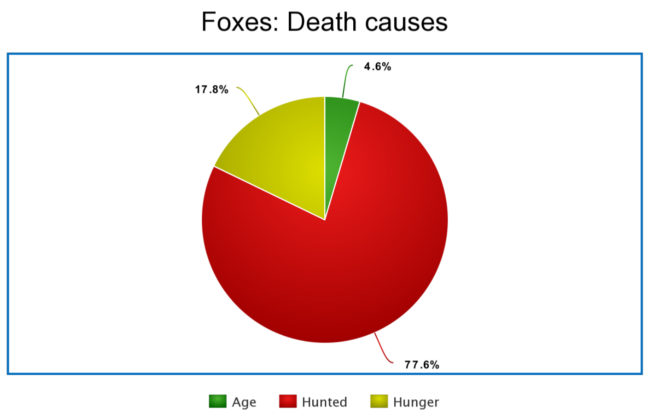
most of the offspring dies because they reach their age limit. There could be a feature on the code adding a "random death when getting old" factor to avoid the boomer effect. However, the code already has lots of parameters and I found to be the case that the more parameters I add, the harder it is to find a stable ecosystem. As a matter of fact, the natural selection feature for bunnies had to be turned off as stability was never reached when turned on.

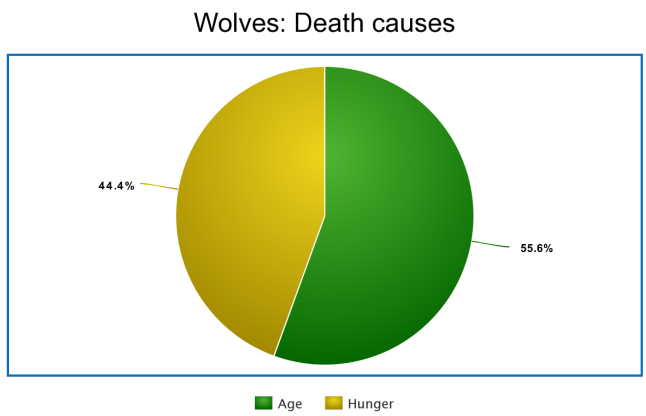
Curiously, the ratio between the standard deviation $\sigma$ and the average population $\bar{x}$ is very similar for the foxes and bunnies. It very well may be a characteristic property of stable ecosystems. If the standard deviation of a particular species is too high, this will be probably lead to its extinction. On the other hand, the same can be said for average populations which are too low. Also, if the said ratio between a prey and a predator differ in a reasonable amount, stability will be harder too reach (for this reason the wolves' and the foxes' ratios are not so different).

There are three possible causes of death: age, hunger and getting hunted. Foxes are the only agents that can die by these three reasons; whereas bunnies cannot die of hunger (since the fourth agent, grass, was not implemented), wolves cannot get hunted. The following figures show the percentages associated to each death cause for the three agents.

We see that bunnies are primarily hunted by foxes. A reasonable fourth of them dies of old age. Foxes are also mainly hunted, but dying from hunger is more common than dying of old age. On the other hand, wolves' death causes are similarly split into dying of age and hunger. It is not surprising that a stable ecosystem's most important death cause is the hunting. If agents die from other reasons they cannot contribute to the trophic chain, and will overall be detrimental for the ecosystem.




## V. CONCLUSIONS

- Natural selection was successfully implemented by generating rabbits with different velocities. When foxes hunted them, the faster rabbits were more likely to live although it did not guarantee their survival. Formation of rabbit clusters lead to foxes cornering and successful hunting.

- Population evolution was studied with the proportions 50:13:3. The success rate of this configuration declined over time, which it was the expected result, but it was concluded that more iterations were needed. With a reproduction study, it was determined that foxes were the principal agent becoming extinct.

- A fluctuating but stable ecosystem was found, and the three actors could coexist in it. The average and deviation of the populations were computed. Factors to take into consideration when analysing the ecosystem are the number of participants in each species but also age limit and cluster forming. The ratio between the average population and the standard deviation was deemed relevant, as it was similar for all three actors. The main death cause for bunnies and foxes in a stable ecosystem is hunting, most likely because its value allows stability between species. If hunting is not the main death cause, predators will inevitably suffer from it.

## VI. APENDIX

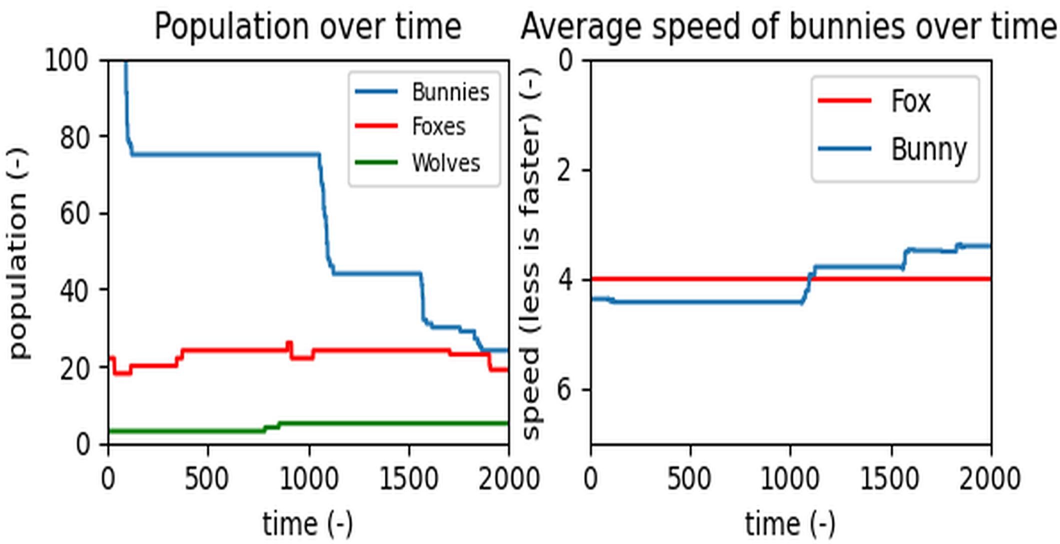



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FIG. 4: On the left, population over time for bunnies, foxes and wolves. On the right, the average speed of bunnies and foxes. As bunnies get hunted, their average speed increase until it surpasses their predators'.