Final Project SI1336 - Predator/Prey Simulation

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Introduction

Predator and Prey

In nature, out on the steppes of large landscapes, several species wander, doing what they can to survive the harsh circumstances. Depending on species, different strategies and behaviors have developed throughout evolution. Hence, the ecosystem has developed to be in somewhat a brutal environment for many beings. The most common issue to be depicted is that of the hunter and the hunted - *the Predator and the Prey.* This project aims to simulate the events of that nature. What parameters are crucial for the population of a species? How well can a suitable simulation method depict the real ongoing events on the steppe? Can theoretical generalization apply to the nature of the Predator and the Prey to a satisfactory degree?

Physics & Model

Animals undergoing the process described in the previous subsection, have various categorizations: vertebrates, invertebrates, mammals, amphibians, birds, insects, spiders etc.. Regardless of the specific animal class, this project makes a generalization, categorising the studied animals in to three different types - predators, omnivores and herbivores.[1] From this, one can easily conclude that the level of hunting instinct and aggression declines in order from predator, to omnivore, and last, to herbivore. Also, it is likely that an omnivore will hunt and kill a herbivore an arbitrary number of times during its life cycle. However, these are only a few examples in behavioral differences amongst the species, that all give both assets and setbacks for each being.[2] Only because the hunter possesses the capability to kill, doesn't mean it will succeed at all opportunities. Sometimes, it fails because of different circumstances being of more advantage to that of the hunted. Sometimes, the predator dies and the prey lives on.

With this in mind, several properties for each species must be taken on to consideration. An abstract model, formulating each set of properties in a clear and vivid way is to be constructed.

[1] Here, *predators* and *carnivores* is considered to be the same thing.

[2] Also, *species* will be equivalent to *types* in this article.

The Predator
The predator is a very aggressive and dangerous creature, that needs a continuous meat consumption to survive. For this, a constant hunger and hunting instinct is present in its mind, resulting in a relatively inadequate capability of always being in the mood of mating and reproducing with a partner. Rather than being in herds or packs, the predators initially socialize in smaller groups at most. If no nutrition satisfies its survival needs, it will lose stamina and energy, and eventually die of starvation. It eats *both* the omnivores and the herbivores, when succeeding its hunt.

The Omnivore
Off course, a subtle thing about this species is that it can vary its diet. When no eatable preys are present, the omnivore simply satisfies with eating grass on the steppe, biding its time and socialising with the others in the pack. Even though not being able to hunt, kill and eat a predator by its own, the omnivores can group together and harm the predator when being confronted by it, even though it is a fatal outcome for them.

The Herbivore
These creatures are incapable of fighting of or hunting any other species of any kind, and can do nothing but flee, hoping the predator will exhaust and starve, or that they will be many enough to reproduce and carry on their survival as a species. Speaking of which, they tend to surround themselves with many of their own, creating large herds where it is likely they will find a partner and mate, whilst easily providing themselves nutrition from the steppe grass and the surrounding vegetation.

The above model must now be put in to play. I.e, some description ϕ must quantify the state for each animal given its species belonging and *surrounding environment* at any given time.

Method

Simulation & Approximations - Cellular Automata

For the simulation, the steppe in which the model was applied, was discretized in to a grid of cells, where one living animal occupied one cell. The mentioned ϕ, quantifying the state of an animal, was produced using *Cellular Automata*. From its definition, it quantifies the state of an arbitrary cell at some time t in (in this case) a two-dimensional grid, to develop as a function of its present state and the state of its surrounding neighbors, in the nearby future. Thus, time was also discretized in order to distinguish the present from this nearby future, and hence, the state quantification was as follows:

$$a_{i,j}^{t+1} = \phi[a_{i,j}^t, a_{i-1,j-1}^t, a_{i,j-1}^t, a_{i+1,j-1}^t, a_{i-1,j}^t, a_{i+1,j}^t, a_{i-1,j+1}^t, a_{i,j+1}^t, a_{i+1,j+1}^t],$$

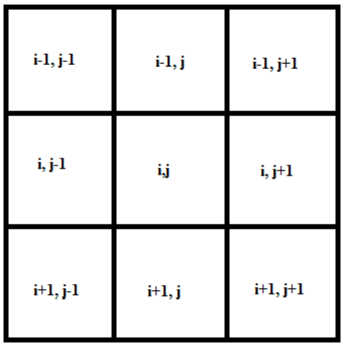
marking (i, j) the position of row i and column j in the grid, and some time t. The so called *Moore Neighbourhood* was used, including the cornering neighbors. The indexing and color coding of each species can be shown in Figure 1. The present state at any current cell was living or dead for all species. Besides its state, every individual being was given assets for reproductions, i.e *fertility* or probability of reproduction, depending on what species it was. For the predator, also, an energy bar with a discrete number of energy points was applied, to approximate its stamina and nutrition state, described in the model. These approximations now put demands on ϕ, that had to be set with different rules, depending on the state and species of each cell in the grid.

Periodic Boundary Conditions

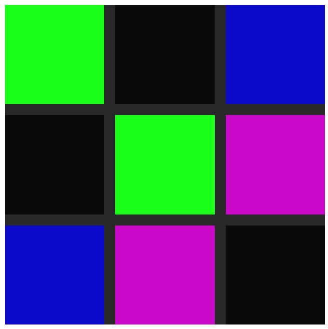
The grid displaying the steppe in which the events occur, is assumed to be a *typical* environment. Hence, if any of the boundary cells are concerned during a timestep in the simulation, grid *mirroring* the other side of the grid as a current (partial) neighbor surrounding will be made. This because the typical environment means that it describes a periodic behaviour on a larger scale. For a grid of nxm cells, the indexing of cells , $(row = i, column = j)$, oblige the following conditions:

$$i = \begin{cases} n-1 & , if \;\; i = -1, \\ 0 & , if \;\; i = n. \end{cases} \; and \;\; j = \begin{cases} m-1 & , if \;\; j = -1, \\ 0 & if \;\; j = m. \end{cases}$$

Note: The indexing is dragging with 1 here, because that is how the Python Numpy Arrays work. That is, the nxm grid means that $i \in [0, n-1]$ and $j \in [0, m-1]$



Indexing in Moore Neighborhood



Green is a herbivore, purple is an omnivore, blue is a predator and black is an empty/dead cell

Figure 1

Rules

A Living Cell

Living cell is a predator:

- The predator energy at time t, decreases with m energy points in the next time step, for some integer m. That is: $E_p(t+1) = E_p(t) - m$

- If its surrounding neighbors are *at least* m_o omnivores, they will hurt the predator, decreasing its energy with n points in the next time step, where m_o and n are integers. So, $\sum neighbors \geq m_o \cdot omnivores \Rightarrow E_p(t+1) = E_p(t) - n$

- If the predator successfully hunts and eats a surrounding neighbor, its energy will increase with an integer s. $E_p(t+1) = E_p(t) + s$, if the predator eats a neighbor. The predator can not eat one of its own, but can eat both omnivores and herbivores.

- The predator fertility rate is defined as a reproduction probability P_p, where $0 \leq P_p \leq 1$. , where r is a random float number initiated in the simulation. More of this will be further specified below.

Living cell is am omnivore:
- The omnivore dies if at least $m_{p,o}$ neighbor cells are predators. $\sum neighbors \geq m_{p,o} \cdot predator \Rightarrow$ omnivore dies.

Living cell is a herbivore:
- The herbivore dies if at least $m_{p,h}$ neighbor is a predator. $\sum neighbors \geq m_{p,h} \cdot predator \Rightarrow$ herbivore dies.

- The herbivore dies if at least $m_{o,h}$ neighbors are omnivores. $\sum neighbors \geq m_{o,h} \cdot omnivore \Rightarrow$ herbivore dies.

- Similarly, the omnivore has its own fertility, or in this simulation, reproduction probability P_o, initiated in the same way as for the predator.

A dead cell / Cell with no living species on it

- If an empty cell has at *exactly* n_p predator neighbors, a birth of a predator will occur at that cell in the next timestep, with a probability of P_p. That is, $\sum neighbors = n_p \cdot predator \Rightarrow$ if $r < P_p \Rightarrow reproduction$, $r \in random(0, 1)$, else; no birth.

- If an empty cell has *exactly* n_o omnivore neighbors, an omnivore wirth be born in that cell in the next timestep with propability P_o. This means: $\sum neighbors = n_o \cdot omnivore \Rightarrow$ if $r < P_o \rightarrow reproduction$, $r \in random(0, 1)$, else; no birth.

- For a herbivore birth, similarly, the following holds: $\sum neighbors = n_h \cdot herbivore \Rightarrow$ if $r < P_h \rightarrow reproduction$, $r \in random(0, 1)$, else; no birth.

Choices of Parameter Magnitudes

Now that the rules have been set from the cellular automata approximation, the conditions and behaviours for each species are determined with the magnitude of each parameter.

Social Structure and Family Behaviour
The reproduction probability quantifies the fertility. Even though a high fertility is crucial from a biological perspective, there are also demands that rely on social structure for a species to survive. E.g, a predator can be very fertile but seldom interact with other of the same species. Vice versa, a herbivore could interact with several of its species frequently over time, but have low reproduction probability when studying each individual case. These scenarios demonstrate the behavior of the different species described in the model, given different living conditions. They can be quantified in the simulation by varying P_i and n_i, where $i \in \{p, o, h\}$.

Aggression and Hunting Capability of Predators and Omnivores
The rules are set, and no species is said to be harmful to one of their own. However, if the energy of a predator is at level n, and is faced against m_o neighbor omnivores, the omnivores will kill the predator! Depending on the value of $m_{p,o}$, the omnivores will either die or continue to live or by doing so. Thus, the choices of n, m_o and mp, o, will determine the stamina/hunger resistance of the predator, the aggression of the omnivores and the aggression of the predators, respectively.

Herbivore fleeing skill and Predator/Herbivore Hunting Skill
Depending on how easy prey the herbivores are, their skill of avoiding being killed by meat-eating species are determined by $m_{p,h}$ and $m_{o,h}$, defined as the number of predators or omnivores, respectively, required to successfully hunt and kill a herbivore. It is assumed to be natural that hunting species always will hunt eatable meat, so rather than aggression, these parameters describe the skill possessed by each species in close predator-prey interaction.

Choice of Species Distribution
The PyGame module was used to simulate the cellular automata in Python. Initially, the mouse event buttons *Left click, Right click* and *Middle click (scroll button)* was used to *place* a *predator, herbivore* and *omnivore* respectively. For a variety of parameter setups, three manual distributions where initialized:

Realistic distribution
The herbivores are over-represented in the initial state, standing in herds. The omnivores are in packs, and predators in groups or alone.

Unrealistic Distributions
1: Now, instead, the omnivores are the ones in a herd, whilst the herbivores and predators arbitrarly stand in packs or groups.
2: The predators are the ones in a herd, over-populating the grid initially, as the packs and groups consists of omnivores and herbivores.

The unrealistic distributions do *not* fit the description given in the model. In the results section, the distributions at different parameter settings will be observed.

Results and Analysis

Each cell always hade a size of $10x10$ pixels. The PyGame grid was set to $100x100$ grid cells (i.e ,$1000x1000$ pixels). The animations of the Relistic Distributions in Simulation 1 and 3 can be displayed in the attached zip-file on the Canvas hand-in.

Simulation 1

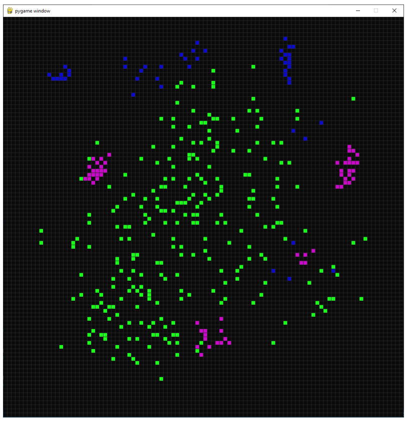
Reproduction Parameters

P_p	P_o	P_h	n_p	n_o	n_h
0.4	0.4	0.6	3	2	3

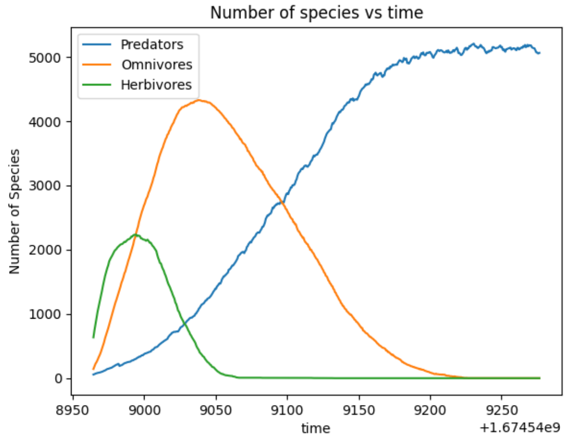
Aggression-/Survival Parameters

m	n	m_o	s	$m_{p,o}$	$m_{p,h}$	$m_{o,h}$	E_p
1	3	2	1	1	1	2	25

With the chosen parameter setting as above, the result of simulating the*Realistic Distribution* is shown in Figure 2.



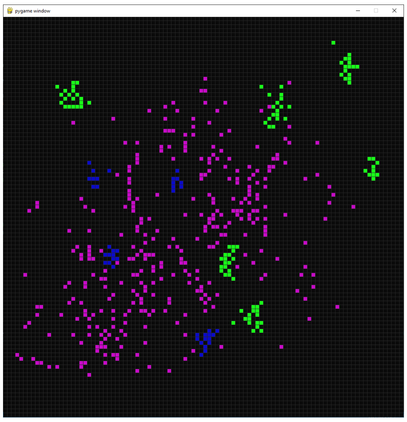
Realistic Distribution



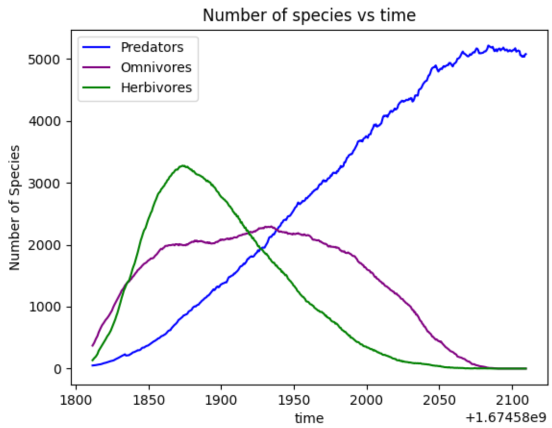
Simulation 1

Figure 2: The predators are the superior ones, eventually killing and eating all other species and living on after the others are gone.

Moving on to the *Unrealistic Distribution 1* in Figure 3



Unrealistic Distribution 1



Simulation 1

Figure 3: The same result as for the Realistic Distribution was obtained, although a slight difference in the early development, due to the initial state of the system.

As shown above, part from the early development of the herbivores and omnivores, the Realistic Distribution and the Unrealistic Distribution 1 similarly ended up with

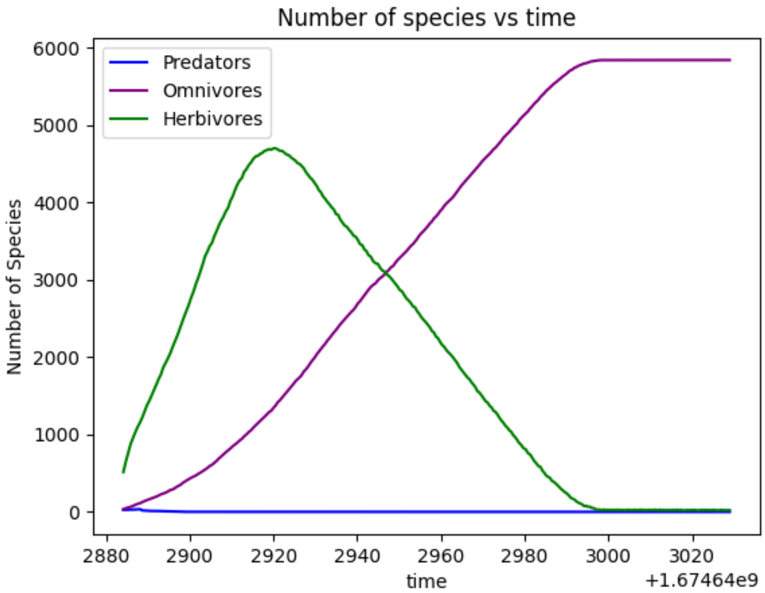


Figure 4: Simuulation 2 - Realistic Distribution

predators thriving in a way that abandons the model described in the introduction - the predators must eat to survive! The same happened for Unrealistic Distribution 2, with the difference that the herbivores and omnivores were wiped out even earlier in the simulation (trivially, since the herd consisted of predator with unnaturally good parameters).

Simulation 2

Since the previous simulation showed that the a $E_p = 25$ energy was too favorable for the survival of the predator, the parameters was now modified. In this simulation, an environment was set that was tough for the predator. Its initial energy level and fertility was decreased, and also, it took more energy for the predator to survive at each timestep. The defence mechanism for omnivores against predators was improved, so that they could do greater harm to predators (still dying when doing so). Also, the herbivores was modified to be more fertile and socially developed. This resulted in the following parameters:

Reproduction Parameters

P_p	P_o	P_h	n_p	n_o	n_h
0.2	0.4	0.8	3	2	2

Aggression-/Survival Parameters

m	n	m_o	s	$m_{p,o}$	$m_{p,h}$	$m_{o,h}$	E_p
2	4	2	1	1	1	2	15

The three initial distributions are shown in Figure 4, 5 and 6

As shown here, the predators die out very quickly and the omnivores thrive in an environment that enables them to be more aggressive and that is exhausting for the predators. The herbivores are mainly being wiped out by the omnivores that easily

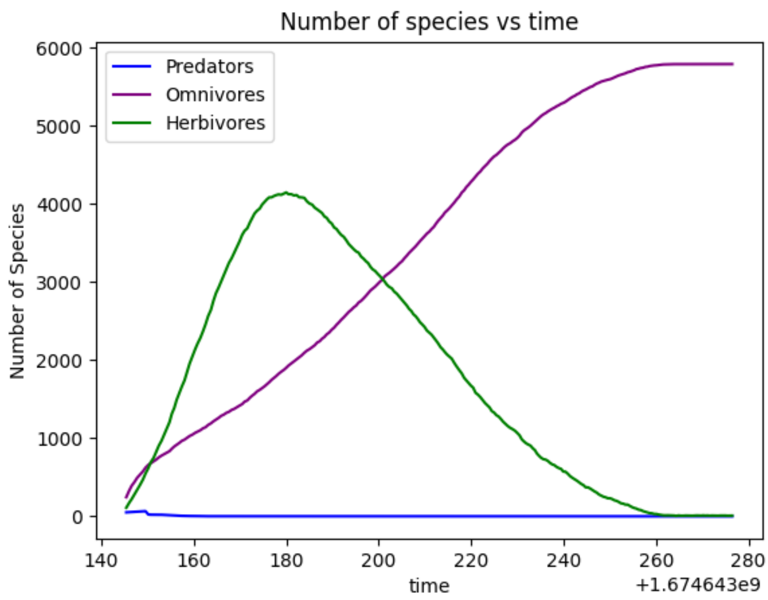


Figure 5: Simulation 2 - Unrealistic Distribution 1

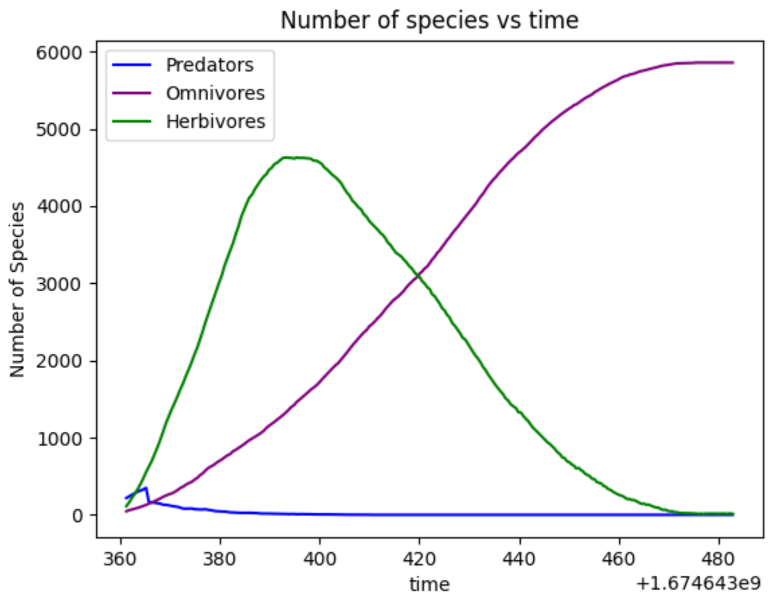


Figure 6: Simulation 2 - Unrealistic Distribution 2

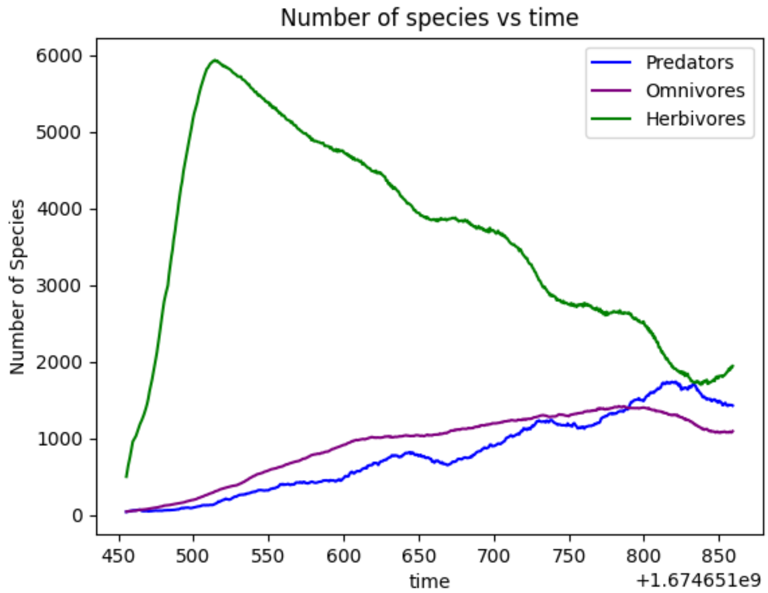


Figure 7: Realistic Distribution - Simulation 3. The animation of this simulation can be found in the zip-file

kills them and reproduces not too much slower than them.

As it was concluded that the species behaviors of Simulation 1 disobeys the model, Simulation 2 however, does not! The predators go extinct and eventually also the herbivores, but the remaining omnivores have followed the principal of being able to survive by eating grass in the absence of prey. The issue remaing with Simulation 2 from Simulation 1, however, is that it becomes **independent of the initial conditions**. The omnivores thrive no matter if the initial distribution is realistic or not.

Simulation 3

The predators were given a further decreased initial energy, making them more vulnerable to areas with no prey. However, the surrounding environment was now instead of favor for the them along with the herbivores, as the omnivore aggression, fertility and social capability was decreased.

Reproduction Parameters

P_p	P_o	P_h	n_p	n_o	n_h
0.25	0.3	0.9	3	3	2

Aggression-/Survival Parameters

m	n	m_o	s	$m_{p,o}$	$m_{p,h}$	$m_{o,h}$	E_p
1	1	3	1	1	1	2	8

The results are displayed in Figure 7, 8 and 9.

Now, during Simulation 3, the species both follow the model properly, *and* react to an initial population distribution differently. The predators die in the regions that lack

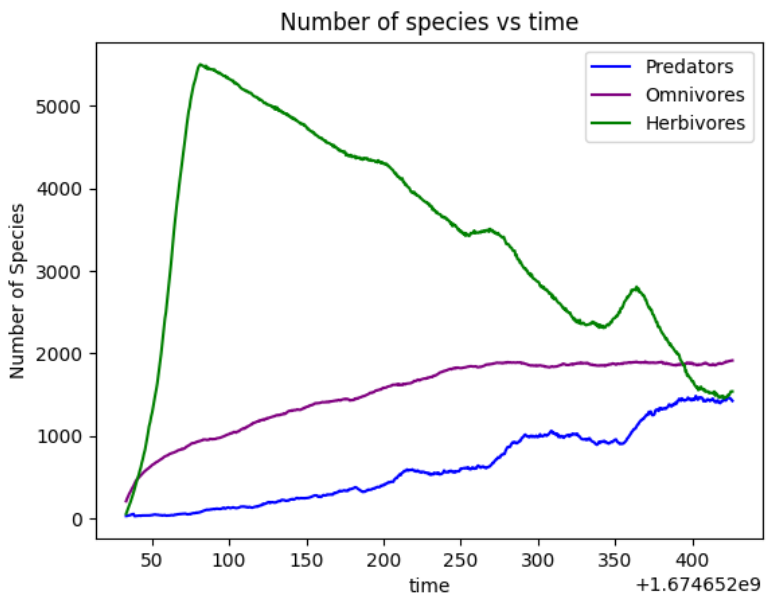


Figure 8: Unrealistic Distribution 1 - Simulation 3

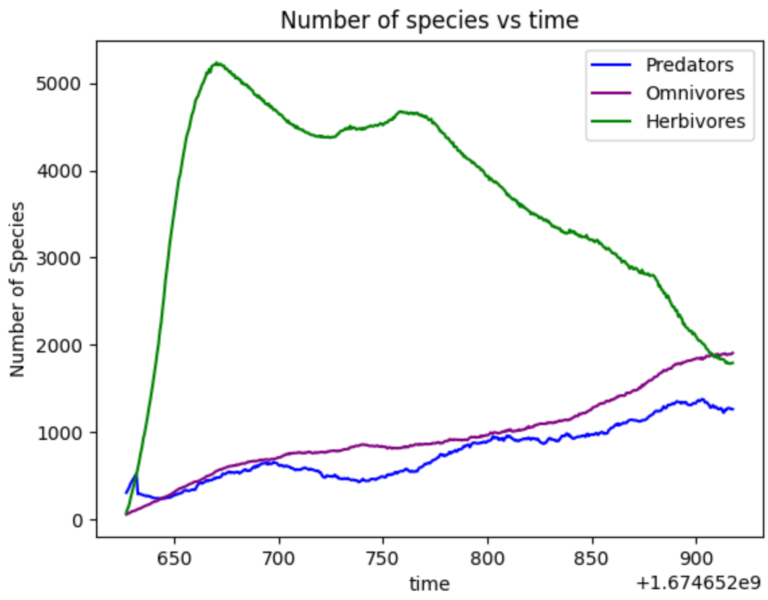


Figure 9: Unrealistic Distribution 2 - Simulation 3

prey, their reproduction rate is not keeping up with the misery they are going through there. Only when the herbivores - that reproduces much better than the others - or omnivores starts showing up, do the predators gain in strength and quantity.

Last but not least, shown in the figures, what stands out about Simulation 3 in comparison to the other simulations is; **the population development is different for various initial conditions - i.e it is sensitive for initial conditions**.

Discussions & Conclusions

As concluded from the analysis of the results, only Simulation 3 was satisfactory to the demands of a proper simulation of the model, using a 2D Cellular Automaton. This can be explained, by dividing into different aspects, that will give answer to the questions asked in the introduction.

Quantifying Realistic Assets of Species

When using parameters to quantify the assets of each species in the simulation, the results showed that adjusting these had a large impact on the result. Simulation 1 & 2, that gave results unsatisfactory to the model, had a parameter setup that gave one species unnatural benefits.

In Simulation 1, predators did have a constant hunger and hunting instinct, and did not need continuous meat consumption to survive. This was due to the fact that its reproduction capability and stamina/hunger resistance deviated from that of the model, since E_p and P_p was too high.

Simulation 2 was not living up to the model, because after the equilibration, it showed that in all initial states, no fatal outcome occurred for the omnivores a a group when getting confronted by predators, not even in the *Unrealistic Distribution 2*, where the predators definitely should have decreased the reproduction rate of the omnivores. The reason for this being an unrealistic set of parameters, where the predators were too vulnerable to the environment and omnivore aggression.

It was not until Simulation 3 when the parameters initialized showed consistency with the model. E_p was furthermore reduced and the fertility of the omnivores and predators were set to be more similar, whilst the herbivores was superior in that regard. Also, the aggression of the omnivores where reduced. All-in-all, the result was that all meat-eating actors on the steppe more vulnerable in general.

From this, the most *crucial parameters* found in the simulations were E_p, P_p, n and P_o

Chaotic Motion

The accuracy of the simulation could be measured by the sensitivity of the initial species distribution. Since the model was set to have herbivores wandering in large herds whilst meat-eaters in general go about in smaller packs or groups, the suggestion that one could not be able to predict the outcome of an "unsuitable" would apply to the accuracy of this simulation, since the evolution is said to be a chaotic system.[3] When decent parameters were chosen in Simulation 3, the first signs of *chaotic motion* occurred, indicating that the 2D Cellular Automaton is not predictable up to a suitable set of parameters. I.e, if the environment changed so that another species would be one living in herds, it would be impossible to predict the development on nature in that region. Hence, the accuracy of the simulation was measured in that sense.

2D Cellular Automaton - perks and disadvantages

The Cellular Automaton along with the Moore Neighborhood was applicable to the model, in the sense that it could take a lot of different aspects of of the neighbors and decide what do to next. A lot of rules could be quantified with different parameters, which made the simulation setup very dynamic. Hence, the theory behind 2D Cellular Automata was satisfactory to the Predator and Prey model.

[3] Chevin L.M, Débarre F., Rego-Costa A.. Chaos and the (un)predictability of evolution in a changing environment. Natural Library of Medicine, 1/10-2018. `https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5958977/`