# Population dynamics of agent-based predator-prey system in a changing arena

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With the recent interest in increased land exploitation of northern Scandinavia, concerns have been raised about the effects on the traditional reindeer husbandry conducted in the region. In light of this, methods for analyzing the impact of area exploitation on reindeer husbandry are required. In this report, an agent-based predator-prey system interacting in a dynamic arena was implemented, simulating the effect on reindeer and its predators after parts of the grazing land was made unavailable. When a semicircle with varying radius was removed from the arena after half of the total simulation time, and the population dynamics were averaged over 100 independent runs, a decrease in both reindeer population and the amount of culling of reindeer was increasingly visible for larger radii. With an intrusion radius of 60 the culling decreased by approximately 15%, with a corresponding area decrease of approximately 20%. When the re-growth rate of the pasture was reduced to mimic the effects of climate change on the quality and quantity of the grazing lands, the effects of the added intrusion were consistently larger for different radii, indicating a higher sensitivity to intrusions.

## I. INTRODUCTION

The demand for renewable energy is increasing rapidly all over the world [1], and in order to meet this demand several wind farm projects are planned in northern Sweden [2]. Meanwhile, there is also an increase in exploration for mines in Sweden [3], and Europe's largest deposit of rare earth metals, needed for the production of wind energy and electric vehicles [4], was recently found in Kiruna, Sweden [5]. Combined, this has produced an increased demand for exploitation of land in northern Scandinavia. However, this increased exploitation has raised concerns for the traditional reindeer husbandry industry [6], since previously opened mines have had a large impact [7] and wind farms have been shown to disturb reindeer in areas larger than the footprint of the wind farm itself [8]. In addition to the human exploitation of the land, northern Europe is experiencing environmental changes driven by climate change, where warmer winters, altered snow cover patterns, and thawing of permafrost are impacting the availability and quality of grazing grounds for reindeer [9].

Moreover, predation on reindeer can also put the industry at risk. Sametinget, the representative body of the Sámi people in Sweden, estimates that a predation level above 22% severely increases the risk of a collapse, where the population of the herd gradually dies out [10]. They also estimate that the average predation among all herding areas already are at a level of 24%, while some reaching losses up to 30–40%. As a response to the growing concern regarding the sustainability of the industry from the active herders, the Swedish parliament (Riksdag), adopted a proposition in 2013 to only allow a maximum predation level of 10% [11] – a goal which in practice has not yet been achieved.

In light of this, methods for investigating how reindeer husbandry is affected by changes in its environment and what can be done to ensure a sustainable population are needed. Properly developed, this method could be used as guidance on where to place new mines or wind farms. Mathematical models, like the Lotka-Volterra model [12], have been extensively used to study ecosystems on a large scale, but generally do not incorporate any information about the potential dynamics of the ecosystems' landscape. Therefore, despite their enhanced analytical researchability and generalizability, they might not be the best fit for systems where local interactions and emergent behaviors can come into play. Agent-based simulations (ABS), remedy this by allowing the modeling of individual agents with unique behaviors, interactions, and decision-making processes, which is especially useful for simulating complex systems like predator-prey dynamics in a changing environment[13].

Therefore an ABS model was developed, modeling a herd-grazing animal together with a predator animal interacting on a customizable landscape. This model aims to capture the complex interplay between environmental changes and population dynamics, providing qualitative insights into how such changes may affect the survival and distribution of both species. By focusing on customizable landscapes, this approach facilitates the exploration of scenarios that are directly relevant to land-use planning in northern Scandinavia. Ultimately, the insights derived from this study could inform decision-making processes, ensuring a balance between economic development and the preservation of traditional reindeer husbandry. Specifically, this model can provide a better understanding of how changes in land use and environmental dynamics influence reindeer populations and their ecosystems. Furthermore, the model has the potential to extend beyond reindeer husbandry, serving as a template for analyzing the impacts of environmental change on other herd-grazing or ecologically sensitive species.

## II. MODEL DESCRIPTION

The model consisted of two types of agents: herd-grazing animals and predators, which interacted within an arena. An overview of the model dynamics, represented in a flowchart, and the complete source code for the project are both provided in Appendix A.

### A. Prey agents

The herd-grazing animals, inspired by reindeer, moved according to a scheme directly based on the Boid model [14], which is designed to promote clustering behavior, similar to that observed in reindeer. In this model, the animals' herd-like movements were determined by the sum of three key forces derived from the Boid model: a separation force to maintain individual space, an alignment force to match the direction of nearby agents, and a cohesion force to draw individuals towards the center of the group. Furthermore, an additional attractive pasture force was implemented, where the reindeer would tend to move in the direction of the richest pasture area. This force was also increased by 100% whenever the energy fell below a certain threshold.

To replicate reproduction, energy and age thresholds were also introduced. The energy of each reindeer was set to be linearly dependent on the amount of grazing and decreased at a constant rate and with a fixed amount immediately after reproduction. Whenever an individual's energy declined to zero or below, it would die of starvation. At each reproduction cycle (a set number of time steps), the reindeer would reproduce with a certain fertility probability, provided it had reached a mature age and had enough energy to procreate.

To mimic the reindeer's instinct to distance themselves from predators, a fifth repulsive force was also introduced. If a predator entered their visual range, the prey increased their speed and moved in the opposite direction.

A portion of the herd (12%) was culled at each reproduction cycle, unless the total population dropped below 100 individuals, in which case the culling temporarily stopped. Additionally, if an upper limit of 300 reindeer was reached, the culling amount increased to limit further growth of the herd. This was introduced to replicate the culling done by reindeer herders to ensure a stable and economically sustainable herd[15].

### B. Predator agents

The predators, mainly inspired by lynx, used an energy parameter to determine their actions. Predators with low energy hunted for the nearest prey at a high speed, while predators with high energy walked around at a slower speed. If the predator was far away from any prey, a tracking mechanism was implemented such that the predator moved to the median of the prey population in order to emulate how a predator would track a herd in a real environment. If a predator caught a prey, i.e. came within a certain distance, its energy was replenished. Energy diminished at a fixed rate, and predators with less than zero energy died of starvation.

The predators also had a reproduction method similar to that of the prey. Predators with adequate energy and age could, with some probability, produce a new predator next to them and lose some energy in the process. In the rare case that the predator population went extinct, a reintroduction function was called, that ensured that there was always at least one predator present in the arena. As the main predators of reindeer (lynx, wolverine, eagles) are solitary hunters [16], no interacting forces were implemented between the predators.

### C. Arena characteristics

The model consisted of a customizable arena. The shape of the arena was set to be a rectangle with a 300 by 100 size, roughly mimicking the shape of a normal reindeer grazing region [17]. The arena was implemented as a continuous space where the animals could move, with food growing in a grid-like space with square cells of size 1 by 1. Each cell contained a number between 0 and 1 indicating the amount of food available in that region. Initially, all grid cells were set to random values of available food and regenerated with the difference function

$$F(t+1) = F(t) + r \cdot (1 - F(t))$$

where $F$ denotes the food grid, $t$ is the time step and $r$ is the growth rate. During simulations, certain parts of the food grid could be made unavailable, simulating, for example, a mine or a wind farm where the prey are either greatly disturbed or not allowed to be. This was implemented by introducing a semicircle centered on the lower boundary of the arena. All the agents inside were pushed to the borders of the intrusion radially, and around the removed area, reflective boundaries were implemented.

### D. Simulation parameters

Using the model described above with the parameters listed in Table I in Appendix B, 150 prey agents and 5 predator agents were initialized on the 300 by 100 grid with a random initial distribution of food. The agents were placed randomly in the arena. The system was allowed to run for a total of 10000 time steps, corresponding to approximately 250 years, with an intrusion of varying size included during the latter half of the simulation. When comparing different parameters the simulations were done with the same random seeds. A visualization of the simulation after the intrusion is seen in Figure 1.

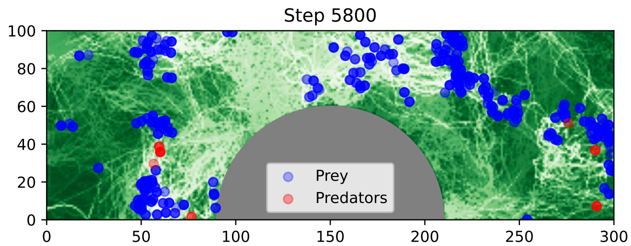


FIG. 1. Visualization of the simulation. Blue dots represent the grazing prey and red dots the hunting predators. The added circular intrusion is seen in grey. Regions with darker green indicate richer pasture areas, while lighter green areas indicate lower food availability. Older agents are depicted with increasingly lower opacity.

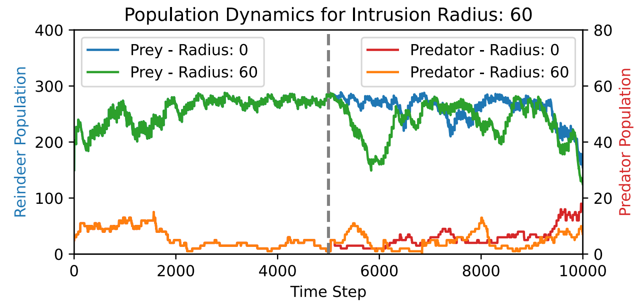


FIG. 2. Population dynamics of a single simulation pair with and without an added intrusion at the half-time step, starting from the same random seed.

### III. RESULTS

The simulations were performed using a set of fixed parameters, along with a few tunable parameters of interest, such as pasture re-growth rate and intrusion radius. For a full list of parameters used, see Appendix B.

The intrusion radius was first set to 60, representing 60% of the total height of the arena but only around 19% of the total area, which was chosen to resemble a moderate disturbance of the grazing land. Later, both smaller and larger intrusion radii were also studied with 100 different independent runs for each radius to see the effects the size of the intrusion has on the model, e.g. representing smaller wind farms or more extensive mining operations [7].

#### A. Prey and predator dynamics

Initially, before the intrusion, the prey moved as expected, forming clusters, moving to richer pasture areas, and avoiding predators. This led to relatively stable dynamics, where the population level of the prey steadily increased until it reached the culling threshold of 300 reindeer, where it remained with only some sporadic fluctuations caused by the inherited random dynamics of the model. This matches real herd dynamics where the predation levels are not significant enough to cause frequent population disruptions. This was partially achieved by fine-tuning the parameters until semi-stable dynamics emerged without venturing beyond unrealistic bounds.

After the intrusion with radius 60 was introduced, the probability of unstable population dynamics generally increased, where the chance of sharp population declines noticeably increased. The effect of the intrusion can be seen in Figure 2, where a single representative run of the population dynamics is shown.

Figure 3 further highlights this effect through an ensemble average of 100 independent simulations. The results indicate that, on average, populations subjected to the intrusion indeed do exhibit more significant declines compared to those without it.

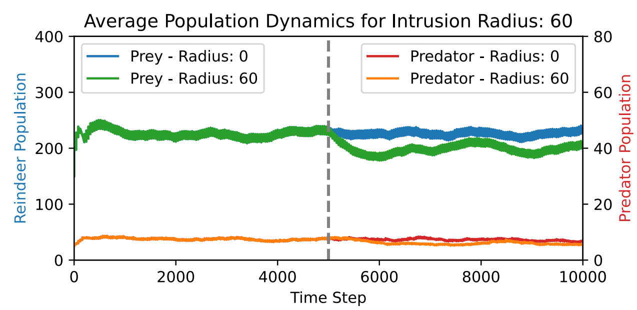


FIG. 3. Ensemble average of 100 independent simulation runs per case, comparing no intrusion with an intrusion of radius 60.

This corroborates the idea that the populations of prey experience an intrusion transition to more unstable dynamics, as reported by the active reindeer community in northern Sweden.

At a larger radius of 90, the effects were amplified (see Figure 4), where all runs consistently led to smaller average population sizes. Conversely, smaller radii had no discernible impact on the population dynamics before and after the intrusion.

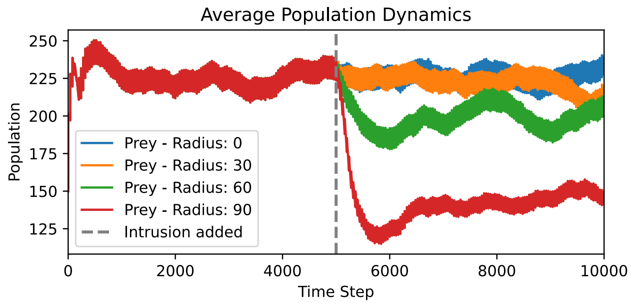


FIG. 4. Population dynamics of a series of ensemble averages with varying intrusion radii. 100 simulations were performed for each case. No intrusion is depicted in blue.

The predator parameters were, similarly to the prey, tuned to produce stable dynamics before the intrusion. Likewise, a decrease in average population after the introduction of the intrusion can be seen.

### B. Intrusion effect on culling

Similar to the population dynamics, for smaller intrusion radii ($\leq 40$), there were no conclusive effects on culling from the collected data; see Figure 5. At an intrusion of radius 50 and above, a noticeable decrease in the amount of culling can be seen, which gradually increases with the intrusion size.

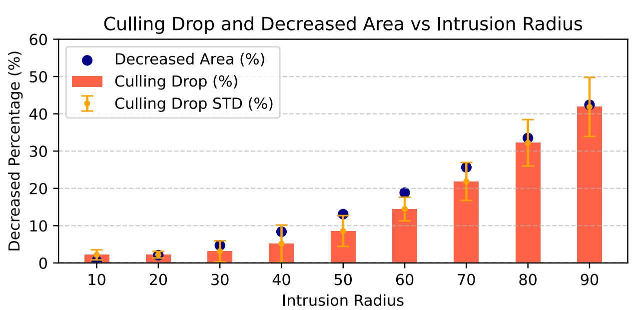


FIG. 5. Different intrusion radii effect on culling.

As seen from the figure, the percentage drop in culling closely follows the percentage decrease of available grazing land, indicating a near linear relationship between the two.

To further investigate how the dynamics changed for increasing intrusion radii the cause of death for the prey were collected and is shown in Figure 6.

We can see a slight increase in starvation correlating with an increasing radius, but it never becomes a large cause of the total amount of deaths, staying below 20% on average regardless of radius.

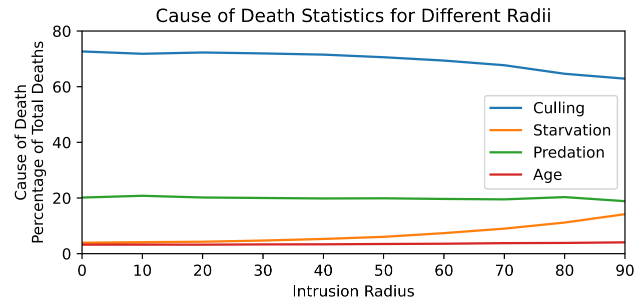


FIG. 6. Average percentage cause of death for the prey for different intrusion radius.

### C. Reducing the availability of food

The model has so far assumed a relatively high pasture re-growth, which makes it unlikely for the prey population to ever suffer extensively from food shortage. This remains realistic for lands rich in pasture where the environment is relatively stable. However, as the effects of climate change begin to have an increasingly negative impact on the quality and quantity of available grazing lands, this can not always be assumed to be true. To simulate this, the re-growth rate was reduced from 0.0035 to 0.0025. See Figure 7 for the results.

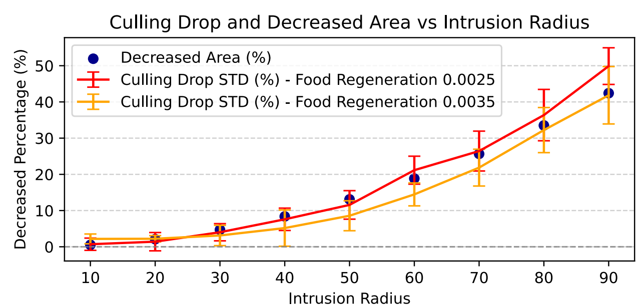


FIG. 7. Different intrusion radii effect on culling with an approximately 30% food regrowth rate of 0.0025, compared to rate of 0.0035 used in Figure 5. The data showed averages of over 100 independent runs for each radius.

The graph indicates a consistently larger effect on culling in a more food-scarce environment. This not only highlights the potential effects of reduced food availability for herd animals, but also the model's sensitivity to the chosen parameters.

### D. An unconstrained system

The settings of the simulation featured some population control, with an increased culling of the population when it reached above 300 individuals, and no culling below 100 individuals. This is in an effort to avoid extreme fluctuations in population size. In Figure 8, a simulation run with the culling rate lowered from 12% to 6% and no increased culling with a population size above 300 is shown.

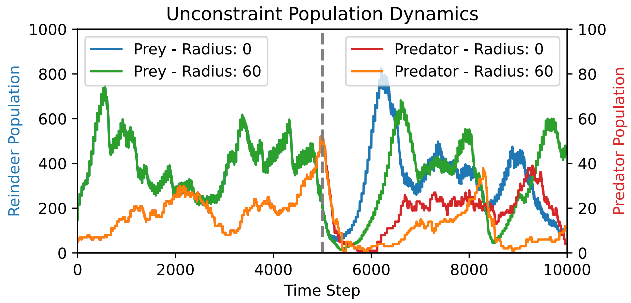


FIG. 8. Example of simulation with a lower culling rate and no upper or lower limits for when the culling sets in/stops or increases/decreases.

The population dynamics exhibit more extreme fluctuations with a much larger difference between high and low points. This further showcases how the parameters of the system greatly can affect the outcomes, and results may differ depending on various parameters.

## IV. DISCUSSION

A pattern that was seen in the population dynamics of the predators was that the predators begin to thrive when the prey population is high. The higher the prey population, the greater the rate at which the predator population increases. However, this appears to lead to a significant and quick decline in the prey population, which in turn leads to a decline in the predator population due to starvation. Consequently, the prey population increases, and the cycle continues. Such cycles of growth and decline are also seen in mathematical predator-prey models, such as the Lotka-Volterra model.

It is interesting to note that, in Figure 5, the percentage drop of culling corresponds very well to the percentage drop in grazing area. One possible conclusion from this would be that the area change does not impact the system in any complex way; a decrease in grazing land yields a corresponding decrease in the reindeer population. This is not the case, as can be seen when comparing Figure 4 and Figure 5 we can see that the effect on culling is larger than the effect on population. For example, in the 60-radius case, the population decreased by around 10 percent, but the culling decreased by 15 percent. We could also see that the amount of available food is sufficient to sustain larger reindeer populations, as seen in Figure 8. This is still the case after the intrusion was added, and we did not see a significant increase in starvation until very large intrusion radii as seen in Figure 6, indicating that the area decrease affects the system in a more complex way.

Moreover, we can see in Figure 7 that a slower food regeneration consistently leads to a larger drop in culling for a radius of 30 or larger. This indicates that an ecosystem with more food scarcity will be more severely affected by intrusions in the landscape, and the effects can be more pronounced for lower intrusion sizes. It can also be noted that the results may differ depending on the choice of function used for food regeneration, and an area of improvement for the model could be to further develop food regeneration to more realistically imitate reality.

It can also be noted that the population dynamics of the prey population appear more volatile after the intrusion is added for all intrusion radii equal to or larger than 60% of the total height of the arena. If this result holds for real reindeer husbandry, it would mean more uncertainty for the reindeer herders, thereby reducing its viability as a livelihood.

### A. Model limitations

The real interaction between the reindeer and its environment is much more complex than the dynamics simulated in this report. An important difference between the above model and the real-world system is that the areas where reindeer graze are greatly impacted by both the reindeer's memory as well as the reindeer herders' choice of where to allow the reindeer to graze, e.g. in regards to their seasonal grazing areas [18]. Since the area where the reindeer graze is only determined by the proximity to the herd in this model, it is plausible that some effects of the intrusion placement are not captured. This conclusion is further supported by the fact that the impact of an intrusion in the real world has been seen to depend on the local conditions in the herding district [6], something that the model fails to capture.

Another significant simplification in the model is the scale of the movement compared to the reproductive cycle. We chose to try and simulate both scattering effects caused by predators as well as large-scale population dynamics over a long timescale in a single model and have thus compromised how realistic it is. While the model could be changed to correspond to real life in both spatial and temporal terms it would require significantly more computational time to gather sufficient data.

Furthermore, the behavior of the system as a whole depends quite sensitively on the parameters used. The parameters, e.g. reproduction rate, walking speed, herd size for the prey and walking speed, visual radius, and energy gain for the predators, were chosen to replicate the behavior of reindeer and lynx respectively as closely as possible. However, there is still a lot of room for tweaking the parameters, and some parameters are difficult to get a reasonable estimate of in the real world. This can be seen as a weakness of the model, and further research could be done in order to either reduce the amount of parameters or get better estimates of the parameters.

Since one of the questions we want to answer with this paper is the effect on culling, it is natural to wonder how different culling parameters affect the simulations and maybe try and optimize for maximized culling. If we reduce the culling rate and increase the upper threshold for culling, we get a much larger population to cull from, but with the negative consequence of a significantly more volatile system, where both the prey and predator populations swing dramatically. Consequently, even if the area can support more prey it leads to more unstable unwanted dynamics.

## V. CONCLUSION

Using the model, it is clear that area removal impacts the population dynamics of a predator-prey system in a complex way, resulting in decreased prey population sizes as well as decreased culling, with substantial effects for intrusions with a radius larger than or equal to 60. The model thus gives some insight into how area removal affects a predator-prey system with clustering prey. However, in order to draw more general conclusions about how reindeer husbandry is affected by land area changes, further refinement of the model is needed. This could, for example, be done by implementing some kind of memory in the prey or fitting the parameters closer to realistic values.

## VI. CONTRIBUTIONS

Everyone worked on different parts but contributed equally to the whole project. P. Gradin, A. Khandait, J. Lindgren and W. Tangwanidgoon focused more on the implementation of the simulation and data gathering, while G. Forsberg and A. Udén worked more on the written report and the poster layout. Individual substantial contributions across the different focus areas were also done.


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### Appendix A: Additional Resources

The source code for this project is available on GitHub at: `https://ongkrab.github.io/SCS-G13/`

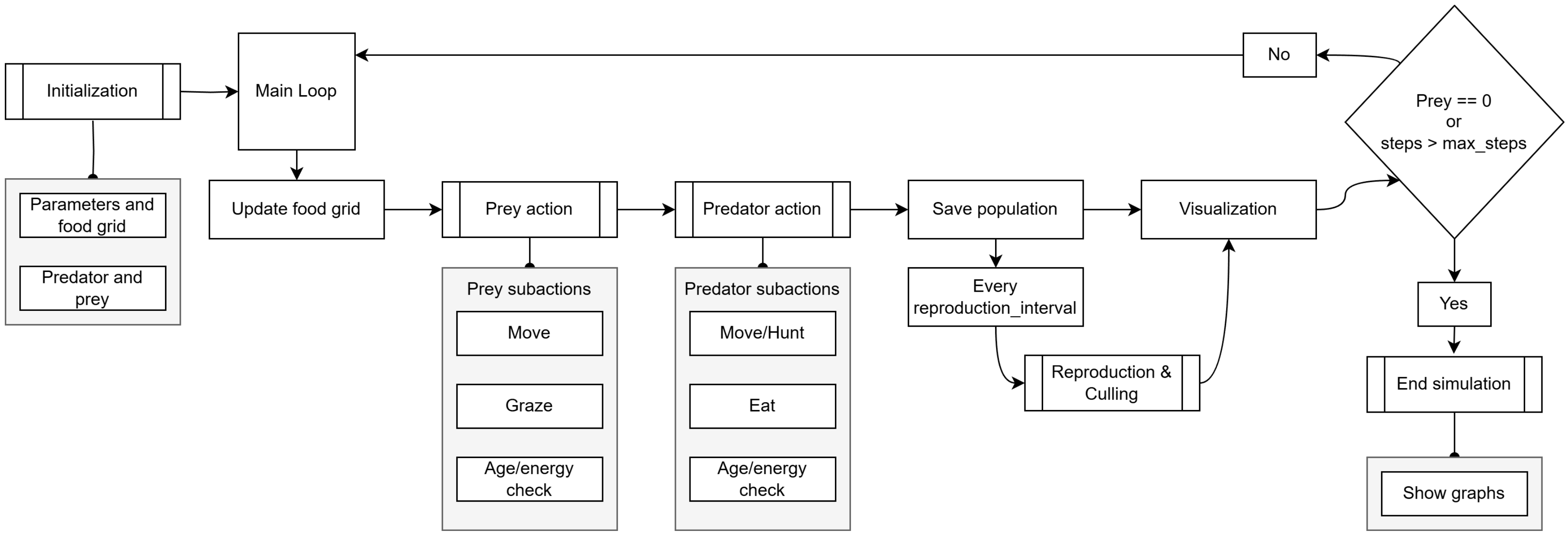


FIG. 9. Flowchart visualization of the simulation dynamics. After initialization, the main simulation loop runs until either the maximum number of time steps (10000) is reached or the prey population completely dies out. At every time step, the actions of the prey and predators are updated based on their visual input, energy level, and in the case of the prey, the amount of available food.

### Appendix B: Model parameters

In Table I, the most important parameters used during the simulations are presented.

**Simulation**

| Parameter | Value |
|---|---|
| Grid size | 100x300 |
| Max time steps | 10000 |
| Food regeneration rate* | 0.0035 |
| Intrusion radius* | - |

**Prey**

| Parameter | Value |
|---|---|
| Initial population size | 150 |
| Soft population limit | 300 |
| Age | 0–15 |
| Energy | 0–1 |
| Energy decay rate | 0.02 |
| Reproductive age | 5 |
| Reproduction rate | 0.7 |
| Reproduction interval | 40 |
| Reproduction energy threshold | 0.7 |
| Offspring energy | 0.5 |
| Grazing speed | 0 |
| Visual range | 10 |
| Culling population threshold | 100 |
| Culling rate* | 0.12 |
| Culling interval | 40 |

**Predators**

| Parameter | Value |
|---|---|
| Initial population size | 5 |
| Age | 0–12 |
| Energy | 0–1 |
| Energy decay rate | 0.015 |
| Reproductive age | 3 |
| Reproduction rate | 0.175 |
| Reproduction interval | 40 |
| Reproduction energy threshold | 0.4 |
| Offspring energy | 0.5 |
| Walking speed | 0.4 |
| Hunting speed | 1.5 |
| Visual range | 40 |
| Hunting range | 1 |
| Energy gain from kill | 0.4 |

TABLE I. Main model parameters used to produce the result presented in this report. Parameters that were tuned to study their effects were marked with (*). The complete source code with additional information on how the parameters interact can be found in Appendix A.