Seasons of Survival: Investigating Predator-Prey Relationships through Agent-Based Models

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Abstract

The study focuses on understanding the influence of seasonal simulations on the population distribution of a small scale predator-prey model based on foxes and rabbits. Utilizing an agent-based approach, the research scrutinizes the influence of initiating simulations in varying seasons, juxtaposes outcomes from simulations with and without seasonal changes, and investigates the repercussions of altering the duration of seasons. The findings underscore that the existence or non-existence of seasons plays a pivotal role in determining the survival prospects post-settlement.

1 Introduction

1.1 Context

Collective dynamics is a fascinating area of study that focuses on understanding how individuals within a group interact and collectively influence the behaviour and dynamics of the whole system. These interactions often lead to emergent properties and complex patterns that cannot be explained solely by examining the behaviour of individual entities. Agent-based modelling (ABM) has been widely used to simulate these complex systems across many fields, including social sciences and ecology (1). Ecological systems are characterised by the interactions between organisms, their environment, and the feedback mechanisms that shape population dynamics and ecosystems processes. ABM provides a framework for simulating these interactions and capturing the complexity and non linear nature of ecological systems, such as predator-prey dynamics. To make these simulations more realistic, our study not only includes these elements but also takes environmental conditions into account.

Seasonality is one of the crucial environmental elements that controls the dynamics of real-world ecosystems. Seasonal changes have a significant influence on animal behaviours and population variations, and adding these aspects into a predator-prey ABM might offer fresh perspectives on these dynamics (2) . Thus, our study primarily examines how the population dynamics of natural systems that are subject to seasonal environmental variations adapt to these changes.

1.2 Problem Statement

Our study investigates the influence of seasonal variations on predator-prey dynamics, guided by the central question: "How do seasonal simulations affect population distribution in a predator-prey model?" We delve into the impact of the initial season, the presence or absence of seasons, and the duration of seasons on population distribution. These inquiries will shed light on the role of seasonal variations in predator-prey interactions.

2 Methodology

2.1 Agent Design

The agent-based model we develop, utilizing the Violet framework based on Pygame, consists of three distinct agent types: foxes, rabbits, and grass. Each agent type possesses unique characteristics and behaviors that govern their interactions with other agents and the environment. In the model, foxes play the role of predators. They actively hunt rabbits for sustenance, move across the environment, reproduce, and face the risk of starvation if they can not find sufficient food. On the other hand, rabbits assume the role of prey. They organisedly navigate their surroundings, rely on consuming grass for nourishment, engage in reproduction and are susceptible to being hunted by foxes. In our model, grass serves as the crucial environmental component and the primary food source for rabbits. It exhibits cyclic growth over time and is consumed by the rabbits as a means of sustenance.

2.1.1 Movement

In comparison to the stationary grass agent, the two other agent types, foxes and rabbits, exhibit distinct movement rules based on the presence of other agents within their visual range. When no other agents are detected nearby, both foxes and rabbits engage in independent movement patterns driven by a balance between their inertial force and a minor random component.

Rabbits, through the use of a flocking algorithm, demonstrate a tendency to gather with other rabbits when they perceive them within their proximity. This behavior serves to enhance their chances of survival and reproductive success (3). Consequently, rabbits strive to maintain a cohesive group when interacting with conspecifics. Conversely, when rabbits detect the presence of foxes, they exhibit evasive maneuvers in an attempt to distance themselves from potential predation threats.

In contrast, foxes employ a different set of rules in their movement behaviors. When foxes detect rabbits within their radius of vision, they select a target and initiate a chase, aiming to capture and hunt down the chosen rabbit.

This behavior reflects the predator-prey dynamics characteristic of their natural ecological interactions. By simulating these distinct movement and interaction rules into the agent-based model, we aim to simulate realistic predator-prey dynamics. The aggregation behavior of rabbits promotes cooperative survival strategies, while their evasive actions in the presence of foxes highlight their response to predation pressure. In comparison, the hunting behavior exhibited by foxes reflects their predatory nature and their reliance on capturing rabbits as a primary food source. Through the integration of these behaviors, our model aims to capture the intricacies of predator-prey interactions in a dynamic and ecologically meaningful manner.

2.1.2 Reproduction

In our agent-based model, we have incorporated sexual reproductive behaviors for both foxes and rabbits. To simulate realistic reproductive dynamics, we have implemented an age of maturity, beyond which agents become capable of reproduction. Each agent possesses an age parameter, initialized as zero for newborn individuals and increasing with each time step. When two mature individuals of opposite genders encounter each other, and both are in a state of readiness for reproduction, there is a probability assigned to the occurrence of procreation. For foxes, this probability results in the birth of a single offspring, while for rabbits, the number of offspring varies randomly between one and twelve. The variation in the litter size reflects the natural reproductive patterns of these species.

However, it is worth noting that the process of reproduction requires and consumes energy. The energy requirement threshold represents the physiological condition necessary for successful reproduction to occur. The delivery of children results in a subsequent loss of energy for one of the parents, mimicking the energy expenditure associated with motherhood in particular. After reproduction takes place, a certain amount of time must elapse before individuals can engage in reproduction again. This waiting period serves as a mechanism for population control and adds realism to the simulation. By introducing this delay between reproductive events, we account for the limitations and constraints imposed by biological factors on the reproductive capacity of individuals. The integration of age-related maturity, probabilistic reproduction, litter size variations, energy considerations, and reproductive intervals enhances the realism and ecological validity of our model (4).

2.1.3 Nutrition

To maintain a balanced population composition with newborn and deceased individuals, our simulation incorporates the concept of energy for all agents except the Grass agent. Energy serves as a vital resource that depletes for each agent at every time frame, necessitating the acquisition of sustenance.

For rabbits, energy is obtained through grass consumption. When rabbits feed on grass, the energy they gain is determined by a fixed value, further modified by a seasonal factor. However, the grass population is finite and decreases with each consumption event. To ensure sustainability, the grass regrows after a certain period, providing a renewable food resource for the rabbits. On the other hand, foxes in our simulation exhibit a 'specialist' type of predator behavior (**?**), focusing exclusively on hunting rabbits. Foxes engage in hunting and feeding activities when their energy levels are below a set amount. When a fox successfully catches a rabbit, there is a probability associated with consuming the captured prey. If consumption occurs, the rabbit dies, and the fox gains its prey's energy modified by a seasonal factor.

2.2 Seasons Implementation

The base situation, ruled only by agent interaction, is evolved upon through our model's dynamic environment which replicates the shifting weather patterns of a year divided into two distinct seasons: spring and winter. While keeping it simple, we wanted to accurately represent the seasons of the year that have the most effects on animals. Spring is commonly known in ecological studies as a season of birth and growth, when food supplies are at their most plentiful (5), while in winter the lack of food and extreme weather conditions can make it difficult for wildlife to survive (6). To simulate this, during spring the grass will regrow with a quicker rate (every 80 timesteps), the reproduction rate and the energy gained from food will be boosted by an augmenting modifier (between 1 and 1.15) and the energy loss and reproductive timer set off after giving birth will be reduced through a diminishing modifier (0.85 up to 1). On the other hand, for both species, the winter season provides a more difficult environment for survival. Winter causes grass to grow less often (every 120 frames), reproduction rate and energy gained from food to be reduced by the diminishing modifier and energy loss and reproductive timer to be increased by the augmenting modifier. To mimic the unpredictable nature of these large scale weather phenomena, the severity of the seasons is varying at every new beginning, stabilised through a randomization of the augmenting and diminishing modifiers within the described range.

2.3 Randomness and Parameters Choice

Randomness plays a pivotal role in our simulation, adding depth and facilitating a comprehensive understanding of the complex dynamics and emergent patterns within the system (**?**). It is incorporated in various aspects, including the initialization of populations, where each agent is assigned a random age around sexual maturity, a random gender and a random energy level within a species-specific range. Randomness also influences the number of offspring rabbits produce, the component of movement, the probability of reproduction and predation events, and the intensity and impact of seasons. By considering energy dynamics and integrating randomness, our simulation aims to emulate ecological processes such as resource acquisition, predator-prey interactions, and population regulation. This holistic approach enhances the realism and fidelity of the model, facilitating a more insightful exploration of the dynamics and behaviors of the simulated ecosystem.

In our study, we aimed to minimize the number of fixed parameters. For instance, we made the energy gain of a fox, upon consuming a rabbit, equivalent to the rabbit's energy multiplied by the seasonal modifier. Both fox and rabbit populations were initialized to 30, representing a small population. This approach enhanced the efficiency of our simulation in terms of time and resources, enabling us to delve deeper into experimentation and data collection for this specific scenario.

As for the following selected parameters, we initially gathered real-life data, such as the age of sexual maturity, reproductive habits and cycles, and body mass of rabbits and foxes. We then adjusted these values to fit our simulation's framework. Subsequently, these parameters were fine-tuned through a process of trial and error. Our goal was to create a non-deterministic interaction scenario where the dominance of one population over the other, or even a system collapse, would depend on the exact unfolding of each unique scenario.

Animal	Radius	p_reproduce	sex_timer	energy_loss	initial_energy	maturity age
Fox	19	0.7	360	0.0085	(3-5)	720
Rabbit	19	0.8	35	0.004	(1-1.4)	240

3 Experiments

3.1 Data Collection

Collecting population dimension of foxes and rabbits per time step was an insightful and intuitive way to understand what was happening during our simulations, which we used to adjust the parameters, but it would not allow for proper statistical analysis to be applied on it. Therefore, to answer our research question we decided to collect several other metrics, indicators of population dynamics or outcomes. The metrics include:

Parameter	Description
max rabbits	Maximum amount of rabbits alive at some moment in the simulation
min rabbits	Minimum amount of rabbits alive at some moment in the simulation
max foxes	Maximum amount of foxes alive at some moment in the simulation
min foxes	Minimum amount of foxes alive at some moment in the simulation
total rabbits born	Total amount of rabbits born throughout the simulation
total foxes born	Total amount of foxes born throughout the simulation
total rabbits eaten	Total amount of rabbits killed by foxes throughout the simulation
total rabbits starved	Total rabbits dead from energy depletion during simulation
total foxes starved	Total foxes dead from energy depletion during simulation
average energy rabbits	Average non-zero energy of rabbits during simulation
average energy foxes	Average non-zero energy of foxes during simulation
did rabbits take over	1 if only rabbits survived at simulation's end, 0 otherwise
did everybody die	1 if all foxes and rabbits died by simulation end, 0 otherwise

3.2 Statistical Analysis

In our analysis of the model simulation, we employed the Mann-Whitney U test for the statistical examination. This specific test was chosen due to its suitability in comparing a continuous outcome variable with a categorical predictor that consists of two categories, in our case the several couple of scenarios we compared. It makes use of the U statistic, whose magnitude correlates to the difference between the two groups. It was particularly appropriate since the assumptions on the data distribution required for parametric tests were not met, as confirmed by the Anderson-Darling test, and since it also has the advantage of being robust to outliers. It was used to determine if there was any significant difference between the two agent groups.

For the analysis, our null hypothesis was that the population distributions of the two groups were equivalent. Conversely, the alternative hypothesis was set to account for the presence of a significant difference between the two scenarios represented by population data. The metrics employed in this analysis encompassed various factors, previously listed in Data Collection. Most of them, such as peaks and lows of the populations and total amounts of events occurred, stand to represent the population movement and provide a way to measure and analyse it. The energy metric was collected as an extra insight to understand the effect of season distribution on it.

3.3 Experimental Setup

Our research question is segmented into three parts, each addressed by a distinct experiment. While the parameters and rules of the framework remain constant across these experiments, the variables under investigation are the only elements that change in accordance with each hypothesis. Every different type of simulation was run 30 times and all the results collected for the analysis.

Seasons vs No Seasons:

In this experiment, we contrast two scenarios: one where seasons have no impact at all, and another where seasons span 240 frames and exert the previously described effects and influences.

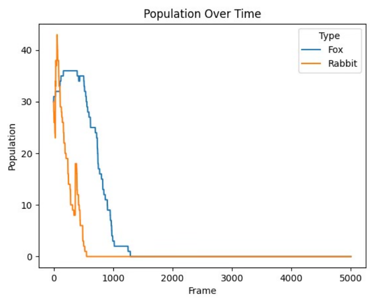

Figure 1: Simulations with seasons

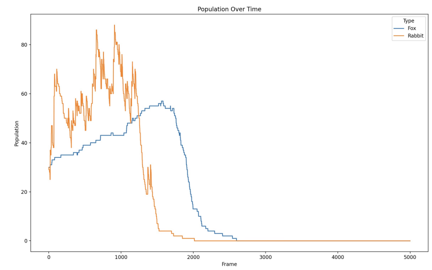

Figure 2: Simulations without seasons

Short vs Long Seasons:

To discern whether the length of a season significantly impacts the outcomes, we compare two frameworks: one with seasons lasting 240 frames, and another with seasons extending to 720 frames. This comparison allows us to understand how the duration of seasons affects the predator-prey dynamics and population fluctuations.

Starting Spring vs Winter:

To evaluate the significance of the initial season when the populations are introduced into the environment, we compare two situations. Both scenarios have a seasonal interval of 240 frames, but one begins with winter, while the other commences with spring. This comparison aims to reveal if the starting season has a substantial effect on the survival and propagation of the populations.

3.4 Results

In the experiment comparing scenarios with and without seasons, several parameters yielded a p-value smaller than 0.05, indicating a significant divergence between the two scenarios. These parameters include max foxes, max rabbits, total rabbits born, total foxes born, total rabbits starved, total foxes starved, total rabbits eaten, average energy rabbits, and min foxes.

In the experiment contrasting the impact of short and long seasons, only two parameters, total foxes starved and total foxes born, showed a significant difference ($p < 0.05$). This suggests that the duration of the seasons significantly influences the reproductive behaviour and starvation rates of foxes.

When comparing scenarios starting with spring versus winter, a significant difference was only observed in the average energy of the rabbits. This could potentially be attributed to the more pronounced impact of seasons on rabbits due to their differing body mass, represented by energy.

Most strikingly, nearly all simulations incorporating seasons resulted in an early collapse of the biological system. This event could be triggered by foxes depleting the rabbit population and subsequently starving, or by the complete extinction of the rabbit population, leading to the starvation of the foxes. The initial season does not significantly influence this outcome, suggesting that the harshness of winter may not be the primary cause of population collapse.

4 Conclusion

4.1 The Impact of Seasons

The presence or absence of seasons plays a pivotal role in the dynamics of our predator-prey model. The significant differences observed in several parameters underscore the profound impact of seasonal variations on both foxes and rabbits.

The length of seasons also emerged as a significant factor, particularly influencing the reproductive behaviour and starvation rates of foxes. This aligns with real-world biological observations, reinforcing the importance of seasonality in shaping animal behaviour and survival strategies.

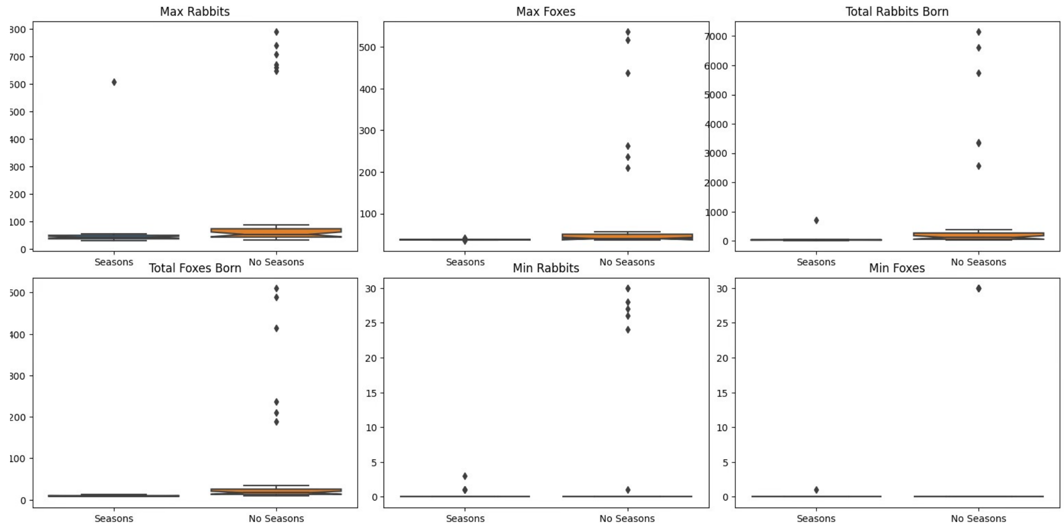

Figure 3: Simulation Parameters Distribution

Interestingly, the initial season—whether spring or winter—did not significantly affect the overall outcomes, except for the average energy levels of rabbits. This suggests that while the timing of seasonal onset may influence certain aspects of prey behaviour, it does not drastically alter the overall dynamics of the predator-prey relationship.

Our findings underscore the critical role of seasons in shaping predator-prey dynamics and survival outcomes. They highlight the complexity of natural systems and the intricate balance that allows for the survival and prosperity of species. The introduction of seasons, an element of major disruptive impact in our predator-prey model, showcases the delicacy and intricacy of cyclical mechanisms in nature with animals and the environment. The presence or absence of seasons was shown to have a fundamental importance, far more significant for unstable small populations in terms of their survival chances than any variation of the seasonal format such as the order or length. These findings illuminate the profound impact of seasons on the survival and interaction of species within an ecosystem.

4.2 Limits and Future Work

The current agent-based model, while effective, has limitations that offer opportunities for future enhancements. Its primary constraints include its focus on small populations and the absence of a stable equilibrium state. To address these, future work should aim to scale up the model to larger populations and improve the stability of predator-prey relationships.

The model could also benefit from the incorporation of additional environmental factors such as habitat types, migration patterns, and disease introduction. This would align the model more closely with real-world ecosystems and enhance its realism. Further refinement of parameters and inclusion of more nuanced behavioral aspects, informed by empirical data and ecological observations, would also improve the model's ability to simulate natural systems.

Statistical analysis could be sharpened by conducting a one-sided test with a stronger hypothesis, providing clearer insights into the effects of seasonal variations on population distribution.

In summary, future work should focus on addressing these limitations, refining the model's parameters, expanding its scope, and integrating additional environmental factors. These enhancements will deepen our understanding of predator-prey dynamics and their responses to ecological changes

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