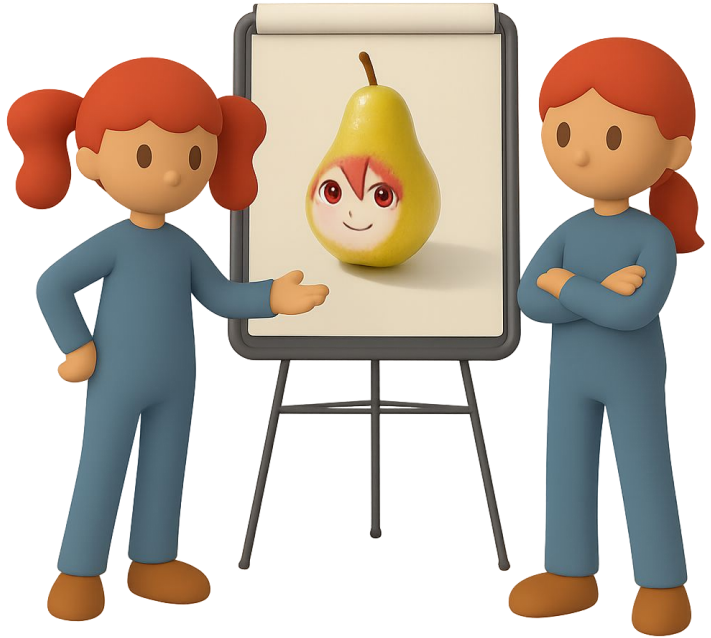
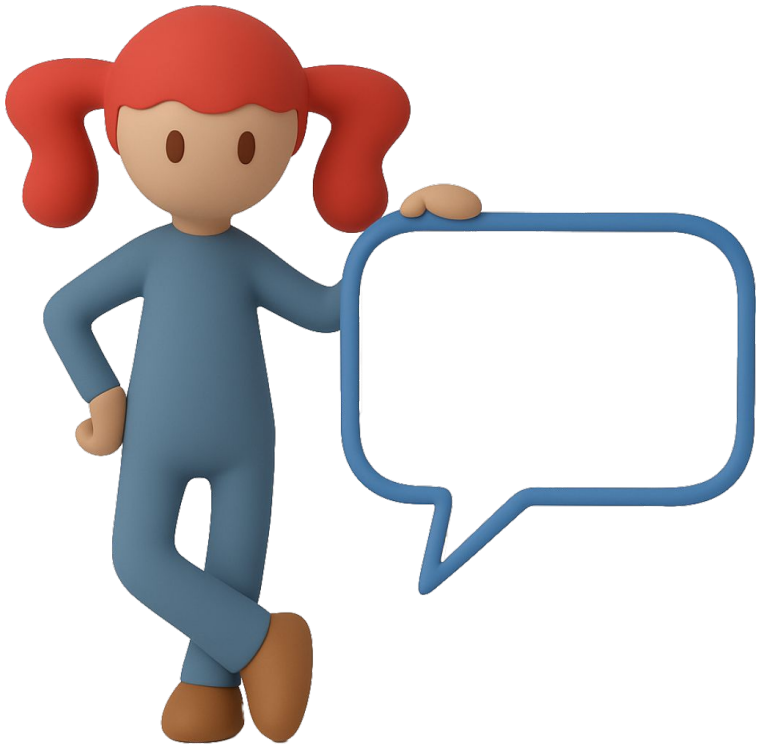
Game-based Understanding of Replication and Trophic cycles

Group Dolores
Timofei Polivanov & Sami Rahali

Table of contents

- Introduction
- Methodology
- Energy mechanism
- Flocking mechanism
- Dynamic traits mechanism
- Aggregation mechanism
- Conclusions
- Future work

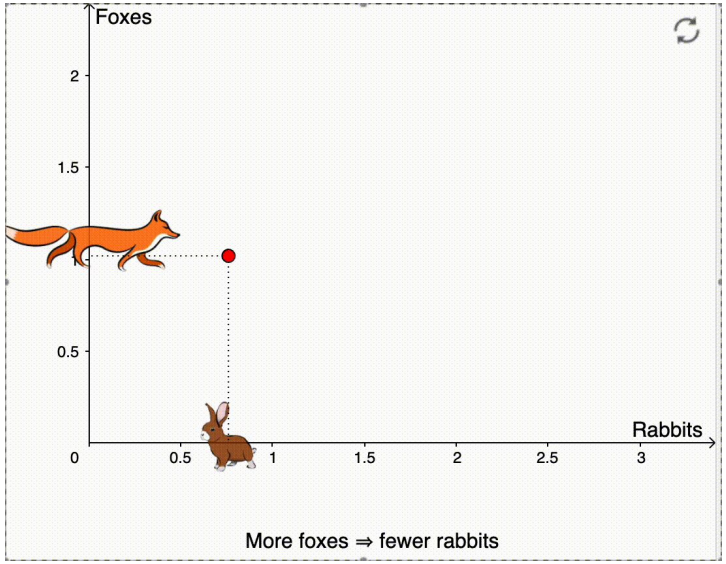


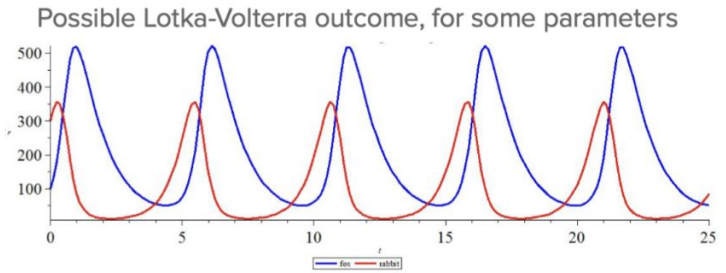


Introduction

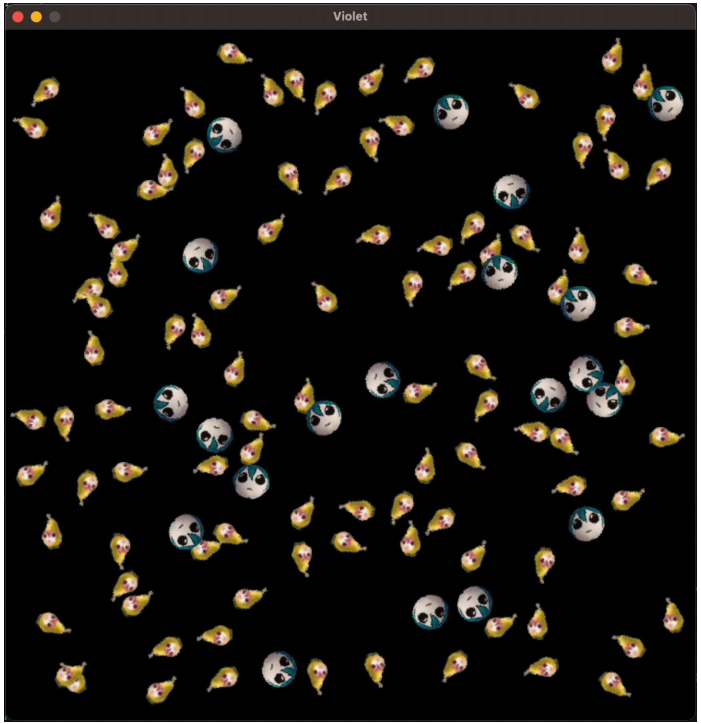
Introduction - Problem description

- Predator-prey interactions are often modeled using Lotka-Volterra equations.
- We simulate these dynamics using an agent-based model with foxes and rabbits.
- Agents act locally: foxes hunt, rabbits reproduce and avoid predation.
- Our baseline is Lotka-Volterra-inspired, extended with additional mechanisms.
- We introduce features like energy use, aggregation, dynamic traits, and flocking.
- The challenge: How do these behavioral mechanisms affect population dynamics?





Introduction - Simulation Explanation



Predator: Miku (fox)

Prey: Pearto (rabbit)

Grass: food (later)

Environment: Agents move within a bounded area edges act as solid boundaries (agents bounce off).

Simulation termination conditions:

- All foxes dead
- All rabbits dead
- Maximum of 2000 ticks reached

Introduction - Purpose of the simulation

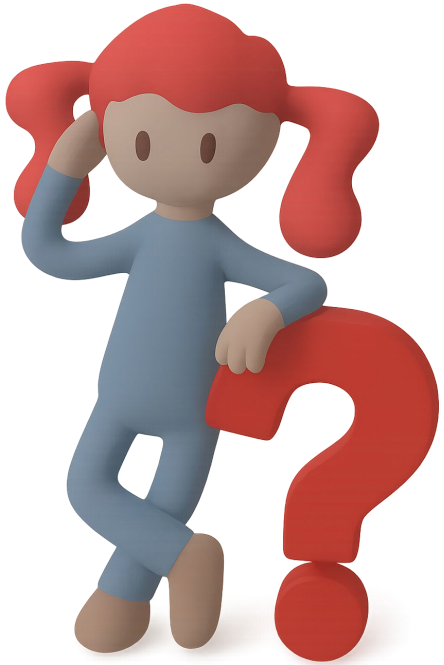
Mechanisms Explored:

- Energy-based survival
- Flocking behavior
- Dynamic traits (e.g. movement speed based on age)
- Aggregation behavior

Goals:

- Analyze population oscillations under different behavioral mechanisms.
- Investigate how different mechanisms affect extinction time, peak population, and population time series.

Introduction - Research Questions



- RQ1: How does introducing energy-based survival affect population time series, extinction time, and peak populations in agent-based predator-prey models?
- RQ2: How does flocking behavior influence population time series, extinction time, and peak populations in agent-based predator-prey models?
- RQ3: How do dynamic traits, such as age-dependent speed and detection radius, impact population time series, extinction time, and peak populations in agent-based predator-prey models?
- RQ4: How does aggregation behavior affect population time series, extinction time, and peak populations in agent-based predator-prey models?

Introduction - Metrics

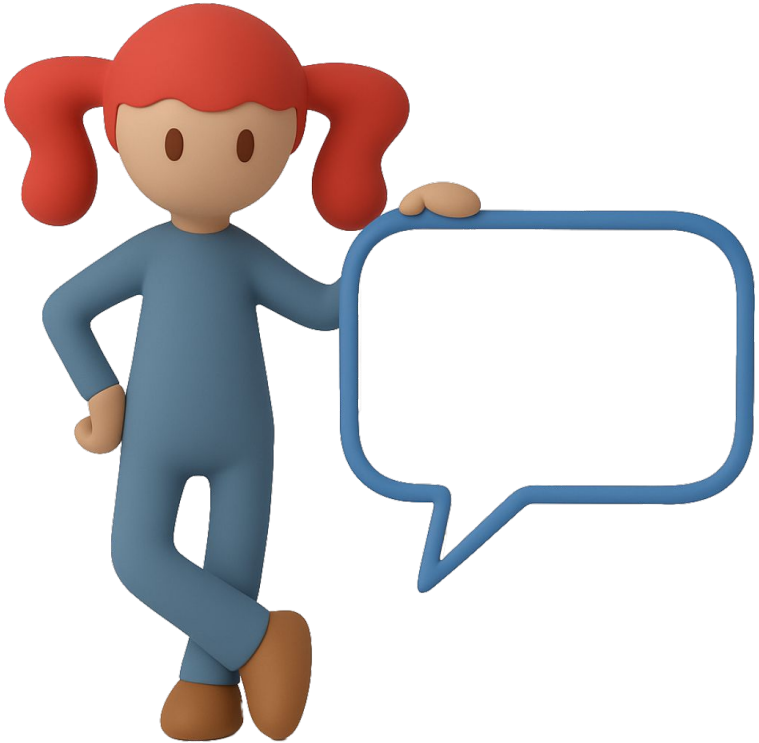
Metrics (per species):

- Population time series: average population over time
- Extinction time: number of ticks until extinction
- Peak population: highest population reached

For each mechanism, we apply the above 6 metrics to both populations.

One hypothesis pair (H_0 / H_1) is formulated per mechanism and metric:

- H_0: The mechanism has no significant effect on the metric.
- H_1: The mechanism has a significant effect on the metric.



Methodology

Methodology - Process per metric per research question

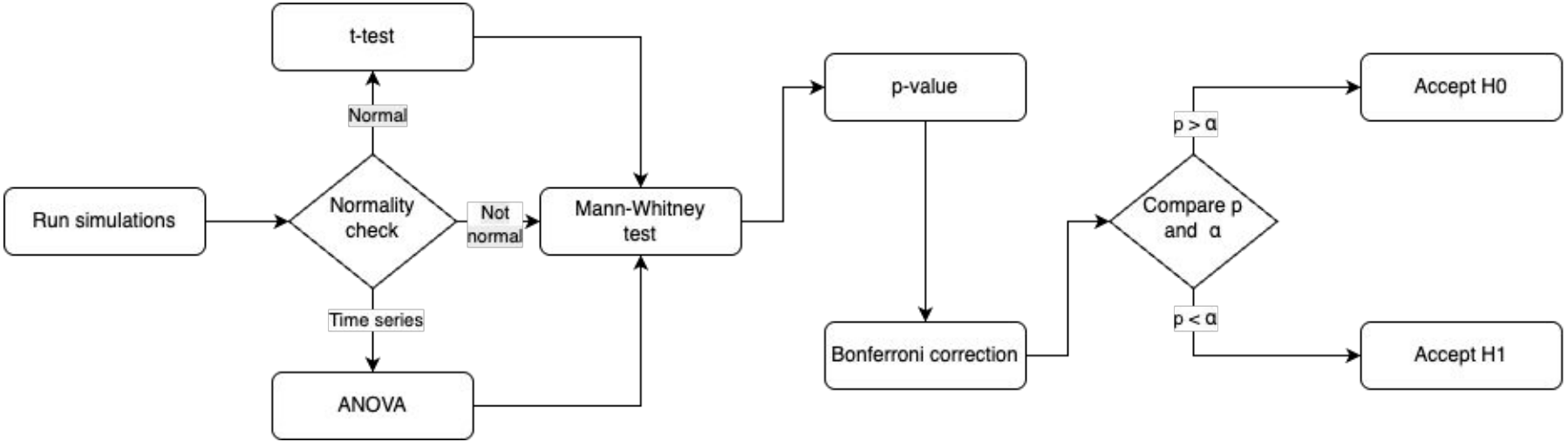
Run simulations:

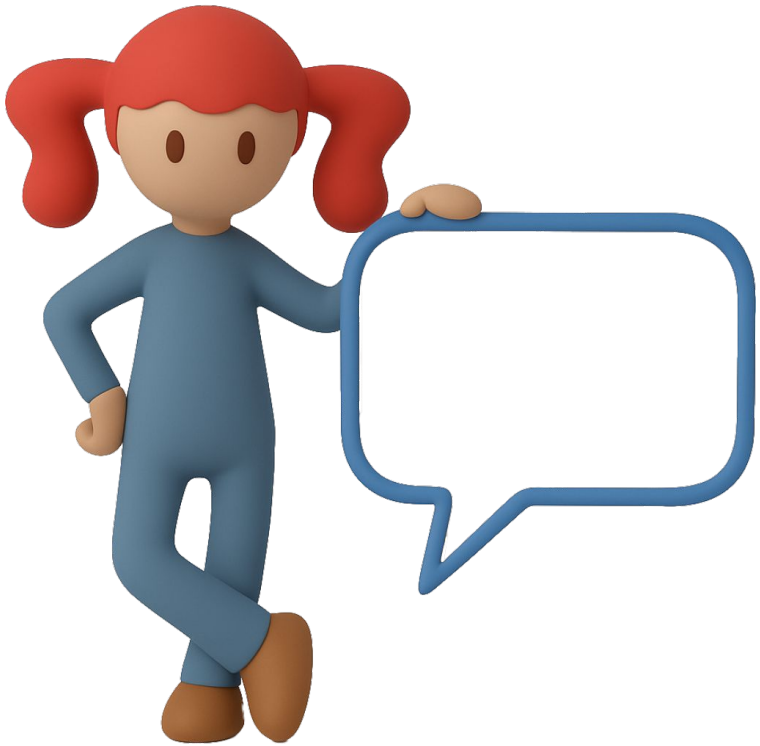
- n^3 times with feature disabled (baseline).
- n^3 times with feature enabled (control).
- n is the number of parameters, 3 values per parameter.
- Grid search on parameter values: other parameters held constant.
- Multiple runs per setup, results averaged for visualization.

Statistical Analysis:

1. Normality Check:
    - Per metric, we apply the Shapiro-Wilk test to check if data is normally distributed.
2. Test Selection:
    - If normal, use Welch's independent two-sample t-test.
    - If not normal, use non-parametric Mann-Whitney U test.
    - For population time series, use Repeated-Measures ANOVA test.
    - This ensures valid conclusions based on distribution properties.
3. Multiple Testing Correction:
    - We apply the Bonferroni correction to adjust the significance threshold (alpha value) and avoid false positives.
4. Hypothesis Testing:
    - For each metric, we determine whether the difference between feature-enabled and feature-disabled scenarios is statistically significant by comparing the p and alpha values.

Methodology - Process flowchart

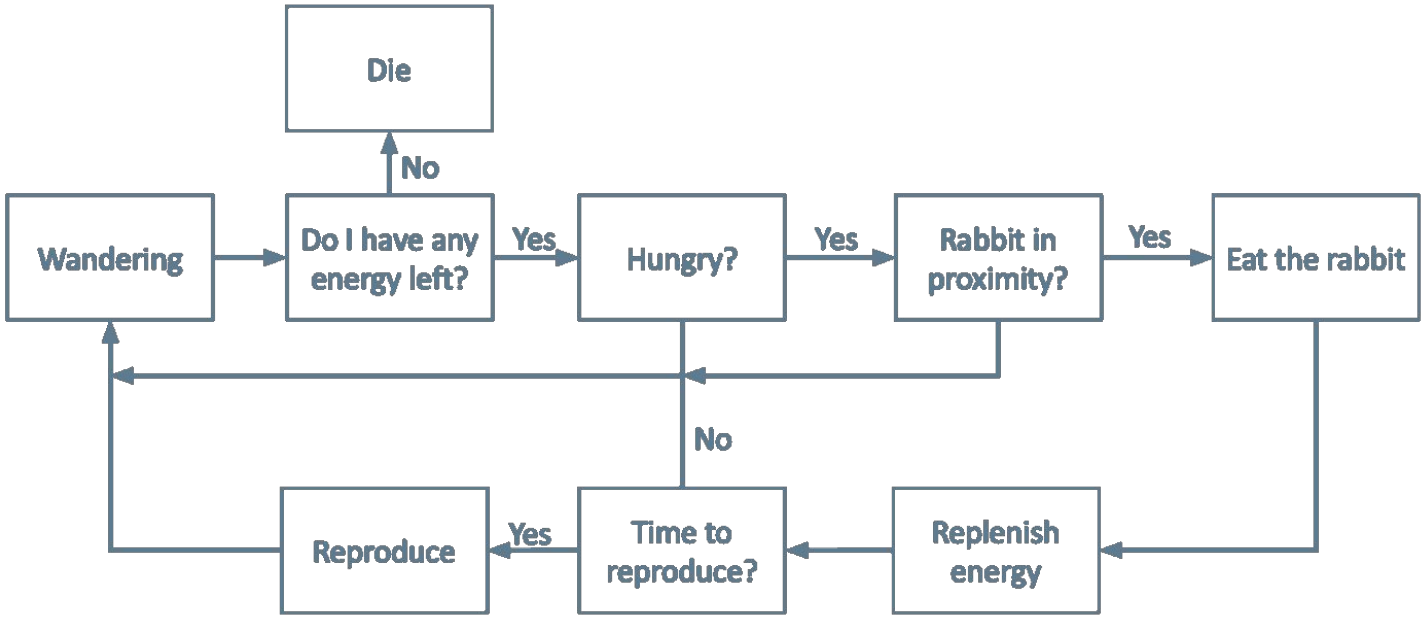




Energy

Mechanism

Flowchart - Energy-based survival mechanism



In Mathematical Terms - Energy-based survival mechanism

Fox Energy Dynamics

The energy of a fox, denoted as EF, changes at each time step t based on energy decay and consumption of rabbits.

1. Energy Decay: At each simulation tick, a fox's energy decreases: $EF(t+1)=EF(t)-DF$.

2. Energy Gain from Rabbit: If a fox successfully eats a rabbit, its energy increases: $EF(t+1)=EF(t)+GF,R$.

3. Energy Cap: A fox's energy cannot exceed twice its initial energy: $EF(t+1)=\min(EF(t+1),2 \cdot EF,initial)$.

4. Starvation Condition: A fox dies if its energy falls to or below a critical threshold: If $EF(t) \leq SF$, then the Fox dies.

Terms used in the formulas:

- ER(t): Energy of a Rabbit at time t.
- EF(t): Energy of a Fox at time t.
- DR: Rabbit energy decay rate (energy lost per tick).
- DF: Fox energy decay rate (energy lost per tick).
- GR,G: Energy gained by a Rabbit when eating Grass.
- GF,R: Energy gained by a Fox when eating a Rabbit.
- SR: Rabbit starvation threshold (minimum energy to survive).
- SF: Fox starvation threshold (minimum energy to survive).
- ER,initial: Initial energy of a Rabbit.
- EF,initial: Initial energy of a Fox.
- t: Current simulation time in ticks.

In Mathematical Terms - Energy-based survival mechanism

Rabbit Energy Dynamics

The energy of a rabbit, denoted as ER, changes at each time step t based on energy decay and consumption of grass.

1. Energy Decay: At each simulation tick, a rabbit's energy decreases: $ER(t+1)=ER(t)-DR$.

2. Energy Gain from Grass: If a rabbit successfully eats a patch of grass, its energy increases: $ER(t+1)=ER(t)+GR,G$.

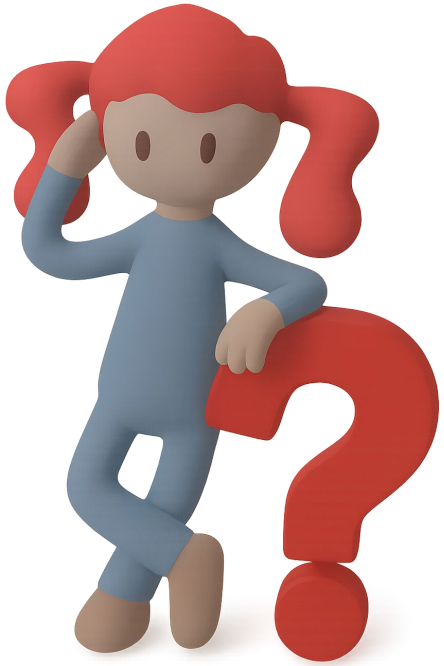
3. Energy Cap: A rabbit's energy cannot exceed twice its initial energy: $ER(t+1)=\min(ER(t+1),2 \cdot ER,initial)$.

4. Starvation Condition: A rabbit dies if its energy falls to or below a critical threshold: If $ER(t) \leq SR$, then the Rabbit dies.

Terms used in the formulas:

- $ER(t)$: Energy of a Rabbit at time t.
- $EF(t)$: Energy of a Fox at time t.
- DR: Rabbit energy decay rate (energy lost per tick).
- DF: Fox energy decay rate (energy lost per tick).
- GR,G: Energy gained by a Rabbit when eating Grass.
- GF,R: Energy gained by a Fox when eating a Rabbit.
- SR: Rabbit starvation threshold (minimum energy to survive).
- SF: Fox starvation threshold (minimum energy to survive).
- $ER,initial$: Initial energy of a Rabbit.
- $EF,initial$: Initial energy of a Fox.
- t: Current simulation time in ticks.

Research Question - Energy-based survival



- How does introducing energy-based survival mechanic affect population time series, extinction time, and peak populations in agent-based predator-prey models?

Parameters - Energy-based survival

Shared Between Both Scenarios:

- rabbit_movement_speed: how fast rabbits move. Values: [1.0, 2.0, 3.0]
- fox_movement_speed: how fast foxes move. Values: [2.0, 3.0, 4.0]
- rabbit_perception_radius: how far rabbits can detect foxes. Values: [30, 50, 70]
- fox_perception_radius: how far foxes can detect rabbits. Values: [50, 70, 90]

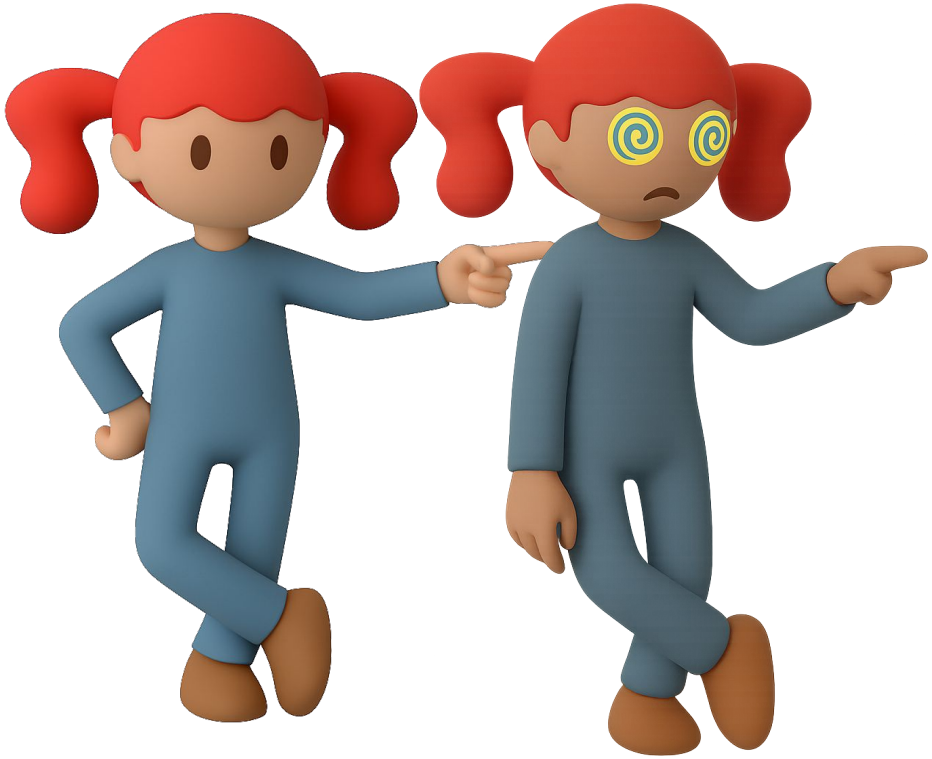
Energy-free Scenario Only:

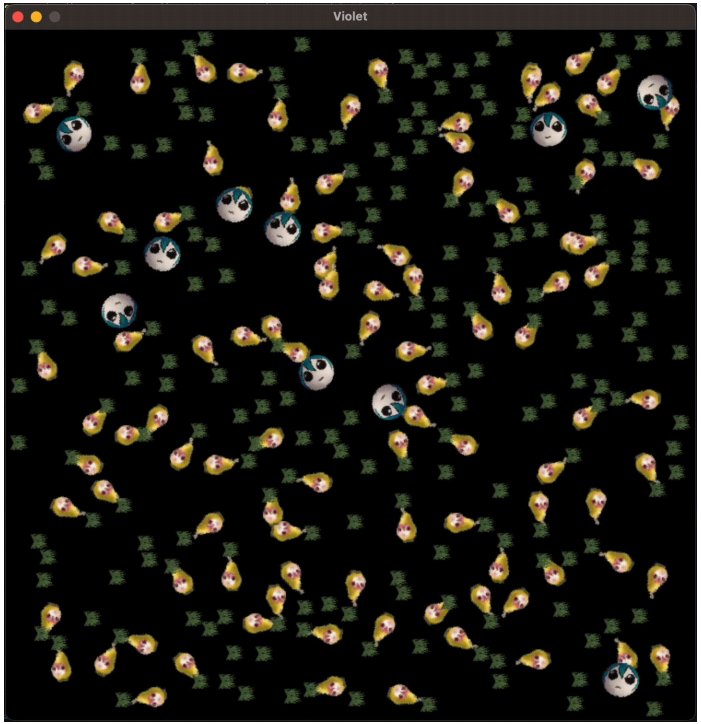
- rabbit_reproduce_chance: chance for rabbits to reproduce. Values: [0.003, 0.005, 0.007]
- fox_spontaneous_death_chance: chance of fox dying spontaneously. Values: [0.002, 0.005, 0.008]

Energy-enabled Scenario Only:

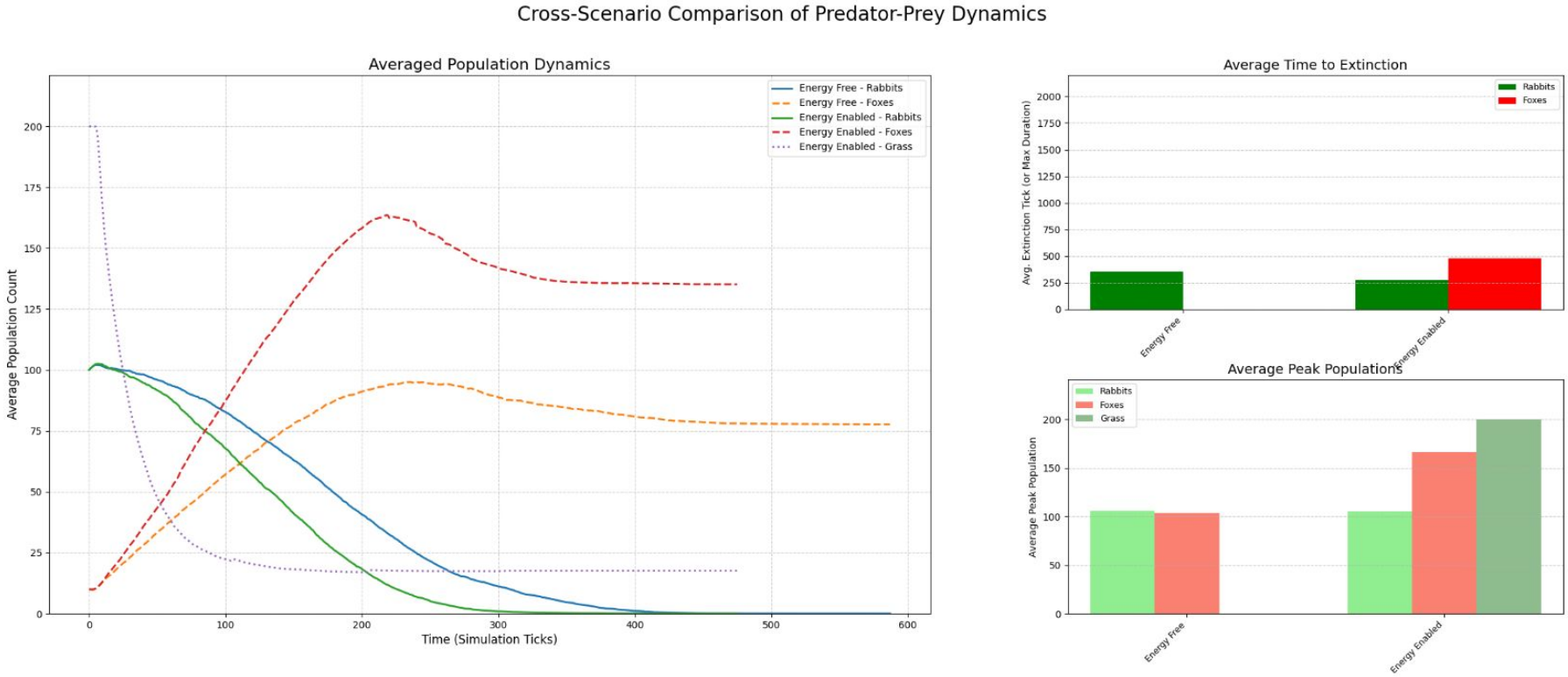
- fox_initial_energy: initial energy level of foxes. Values: [80.0, 100.0, 120.0]
- fox_energy_decay_rate: rate at which foxes lose energy over time. Values: [0.3, 0.5, 0.7]
- rabbit_energy_gain_for_fox: energy gained by foxes after hunting a rabbit. Values: [5.0, 10.0, 15.0]
- fox_starvation_threshold: energy level at which foxes die. Values: [0.0, 10.0]
- rabbit_initial_energy: initial energy level of rabbits. Values: [30.0, 50.0, 70.0]
- rabbit_energy_decay_rate: rate at which rabbits lose energy over time. Values: [0.1, 0.2, 0.3]
- grass_energy_gain_for_rabbit: energy rabbits gain from eating grass. Values: [3.0, 5.0, 7.0]
- rabbit_starvation_threshold: energy level at which rabbits die. Values: [0.0, 5.0]
- grass_regrowth_time: time it takes for grass to regrow. Values: [80, 100, 120
- grass_perception_radius: how far rabbits can detect grass. Values: [20, 30, 40]

Simulation - Energy-based survival

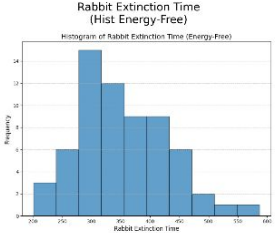


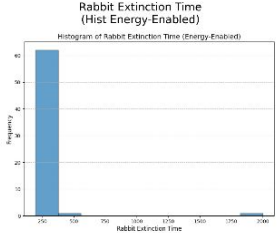


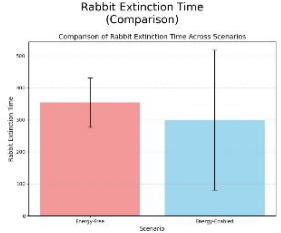
Results - Energy-based survival

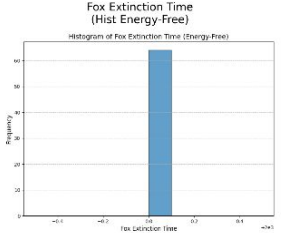


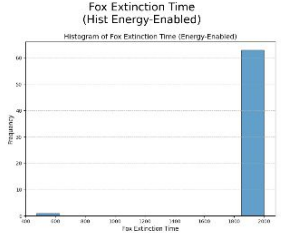
Results - Energy-based survival

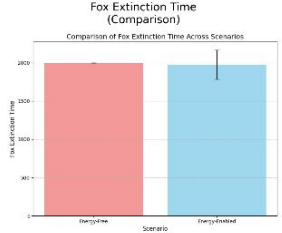


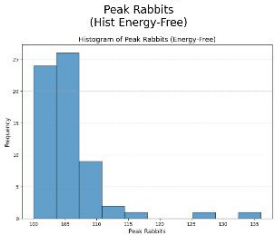


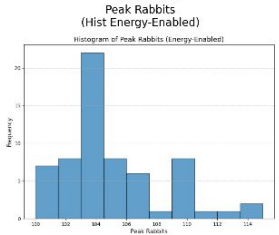


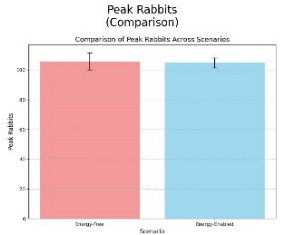


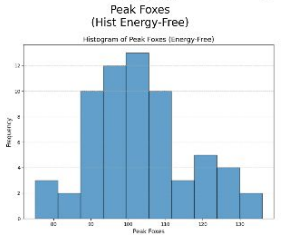


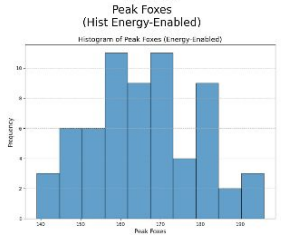


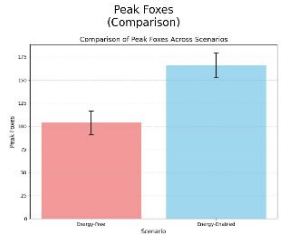


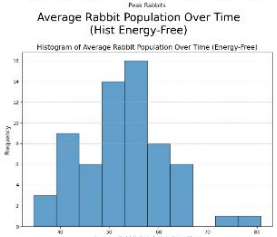


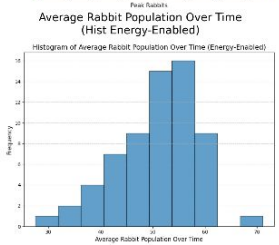


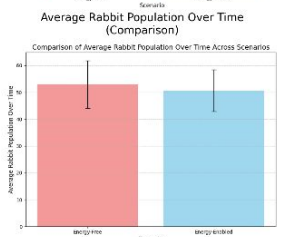


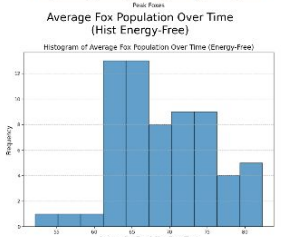


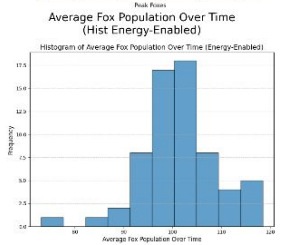


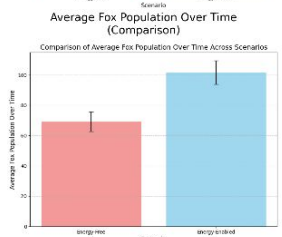






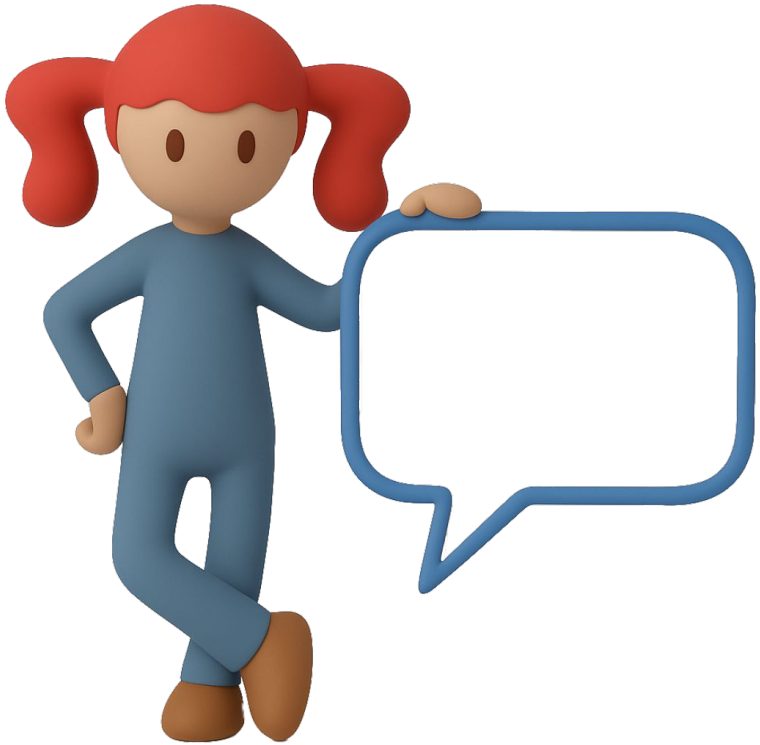






Results - Energy-based survival

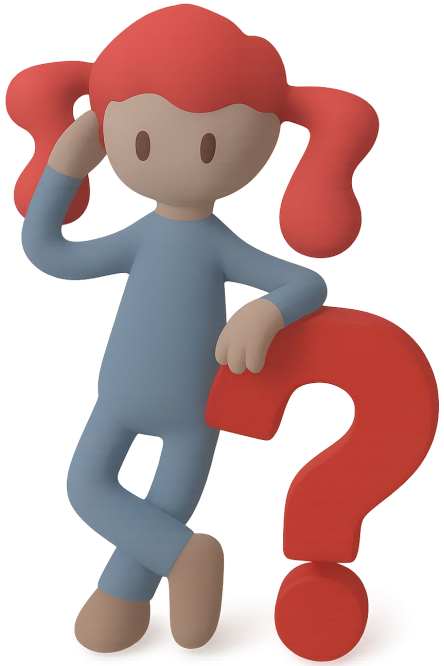
```
=========================================================
📊 Statistical Test Results Summary 📊
=========================================================
Metric                          | P-value | Corrected Alpha (Energy-Free vs Energy-Enabled) | Accepted Hypothesis
---------------------------------------------------------------------------------------------------------------------
Rabbit Extinction Time          | 0.0000  | 0.0083                                         | H1 Accepted ✅
Fox Extinction Time             | 0.3249  | 0.0083                                         | H0 Accepted ❌
Peak Rabbits                    | 0.6031  | 0.0083                                         | H0 Accepted ❌
Peak Foxes                      | 0.0000  | 0.0083                                         | H1 Accepted ✅
Average Rabbit Population Over Time | 0.1271  | 0.0083                                         | H0 Accepted ❌
Average Fox Population Over Time    | 0.0000  | 0.0083                                         | H1 Accepted ✅
=========================================================
```



Flocking

Mechanism

Research Question - Flocking



- How does flocking behavior influence population time series, extinction time, and peak populations in agent-based predator-prey models?

Parameters - Flocking

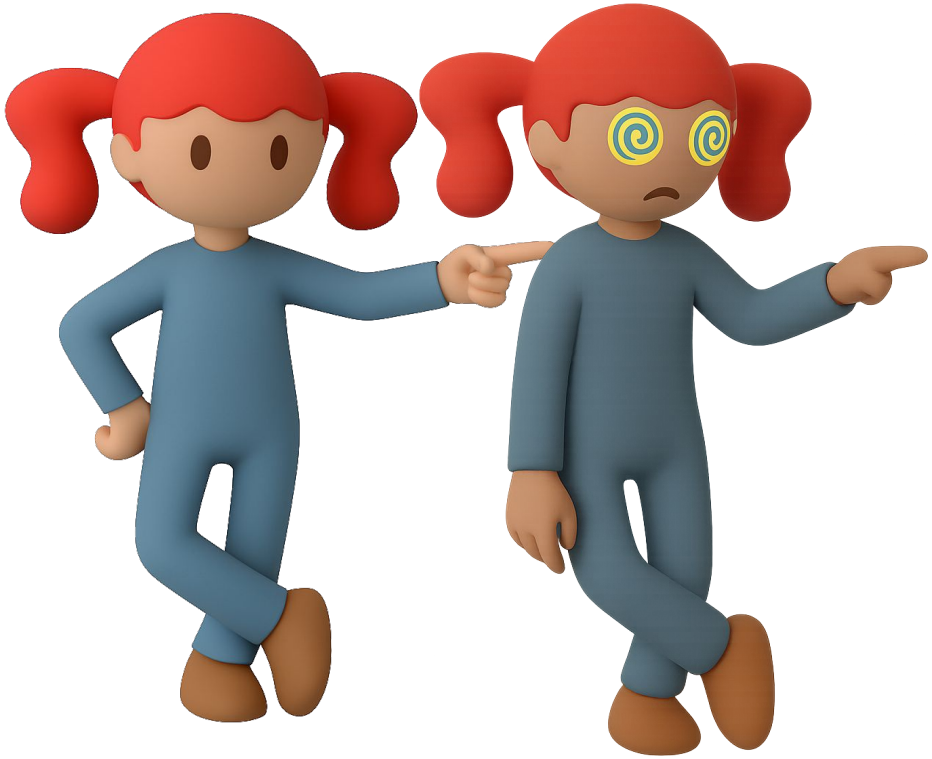
No Flocking Scenario:

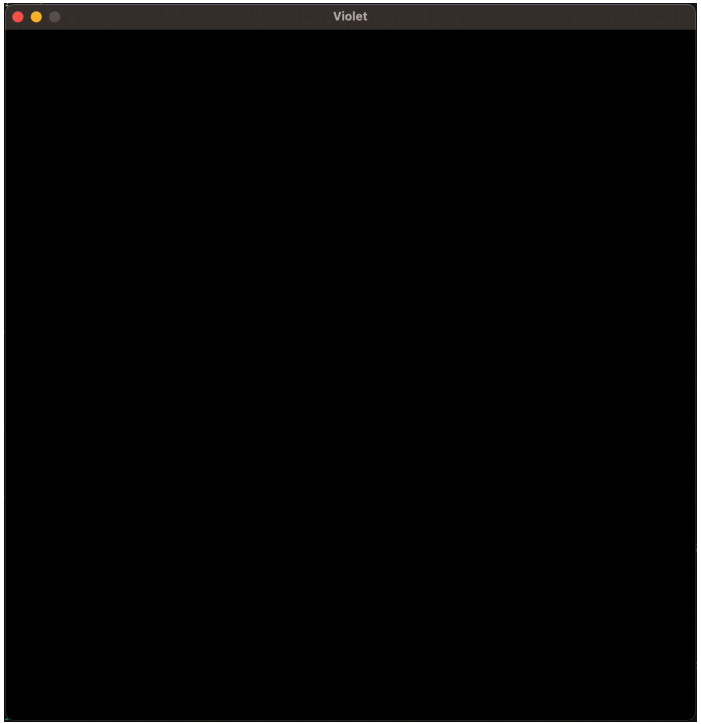
- rabbit_movement_speed: how fast rabbits move. Values: [1.0, 2.0, 3.0]
- fox_movement_speed: how fast foxes move. Values: [2.0, 3.0, 4.0]
- rabbit_perception_radius: how far rabbits can detect foxes. Values: [40, 50, 60]
- fox_perception_radius: how far foxes can detect rabbits. Values: [60, 70, 80]
- rabbit_reproduce_chance: chance for rabbits to reproduce. Values: [0.004, 0.005, 0.006]
- fox_spontaneous_death_chance: chance of fox dying spontaneously. Values: [0.004, 0.005, 0.006]

Flocking Scenario:

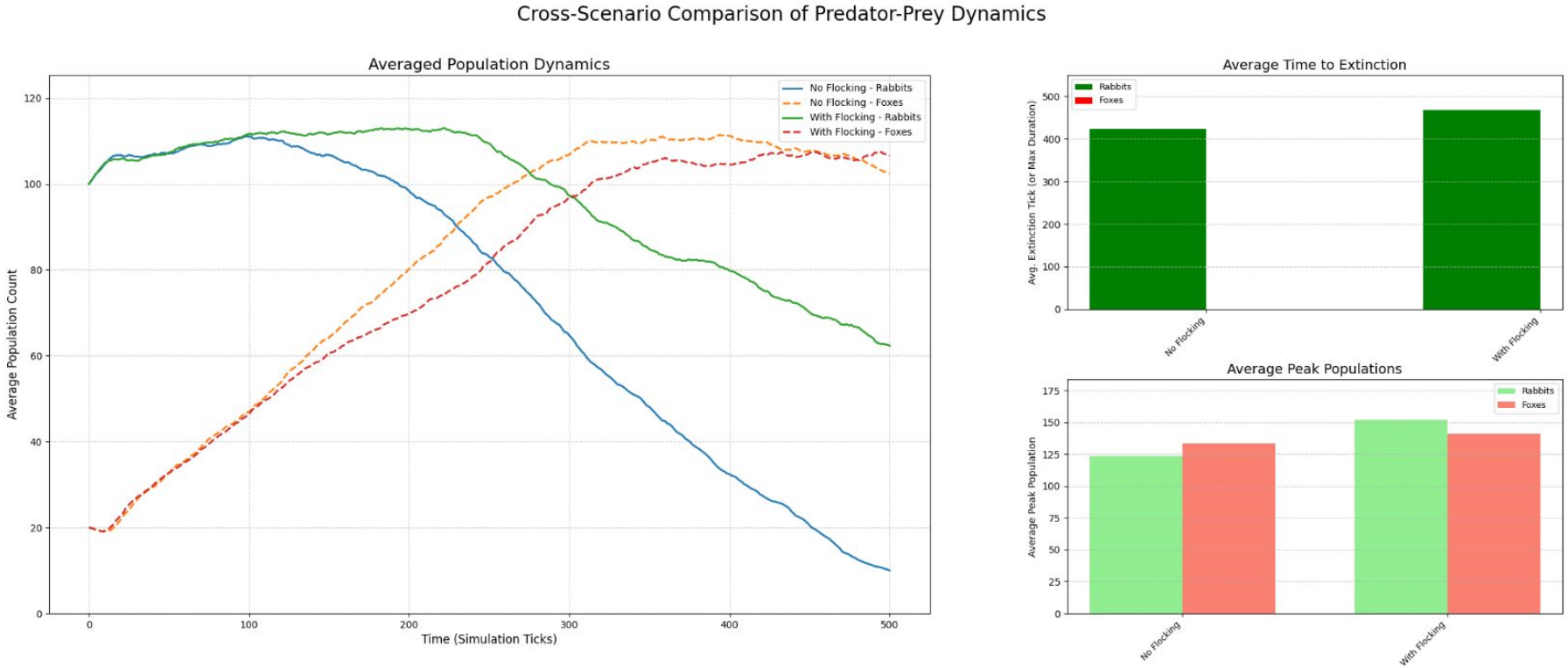
- alignment_weight: influence of neighbors' direction. Values: [0.5, 1.0, 1.5]
- cohesion_weight: influence of group centering. Values: [0.5, 1.0, 1.5]
- separation_weight: influence of avoiding crowding. Values: [0.5, 1.0, 1.5]

Simulation - Flocking



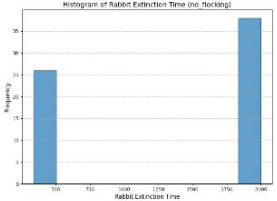


Results - Flocking

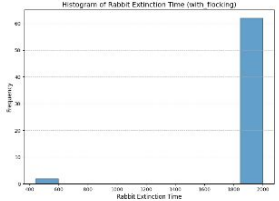


Results - Flocking

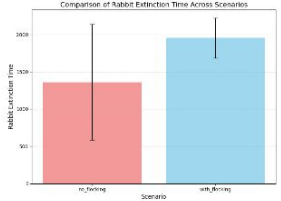
Rabbit Extinction Time
(Hist No Flocking)



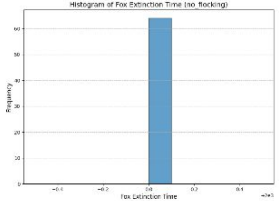
Rabbit Extinction Time
(Hist With Flocking)



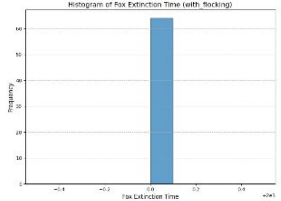
Rabbit Extinction Time
(Comparison)



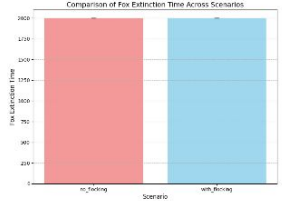
Fox Extinction Time
(Hist No Flocking)



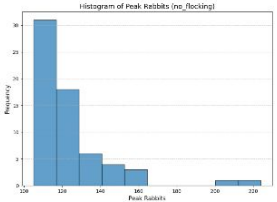
Fox Extinction Time
(Hist With Flocking)



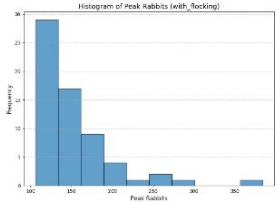
Fox Extinction Time
(Comparison)



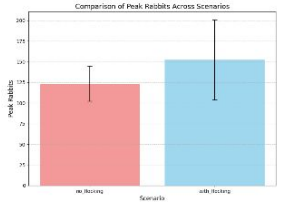
Peak Rabbits
(Hist No Flocking)



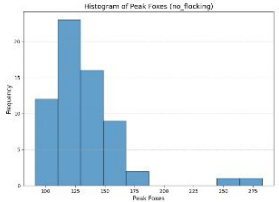
Peak Rabbits
(Hist With Flocking)



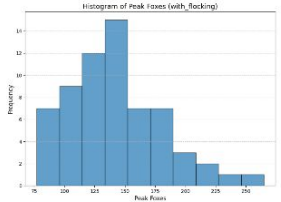
Peak Rabbits
(Comparison)



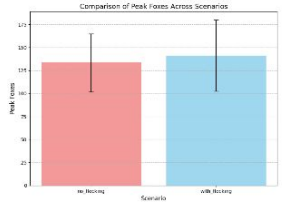
Peak Foxes
(Hist No Flocking)



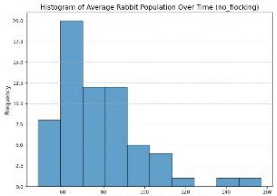
Peak Foxes
(Hist With Flocking)



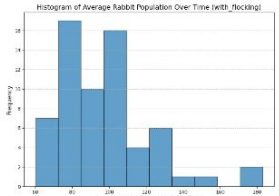
Peak Foxes
(Comparison)



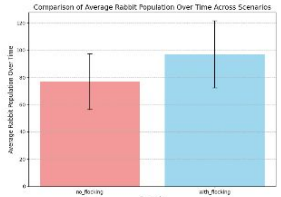
Average Rabbit Population Over Time
(Hist No Flocking)



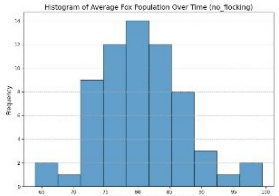
Average Rabbit Population Over Time
(Hist With Flocking)



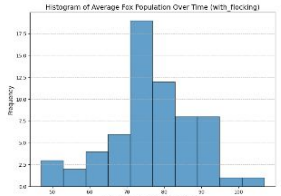
Average Rabbit Population Over Time
(Comparison)



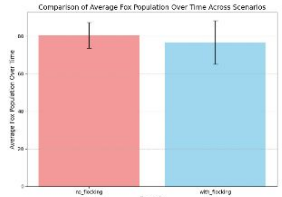
Average Fox Population Over Time
(Hist No Flocking)



Average Fox Population Over Time
(Hist With Flocking)

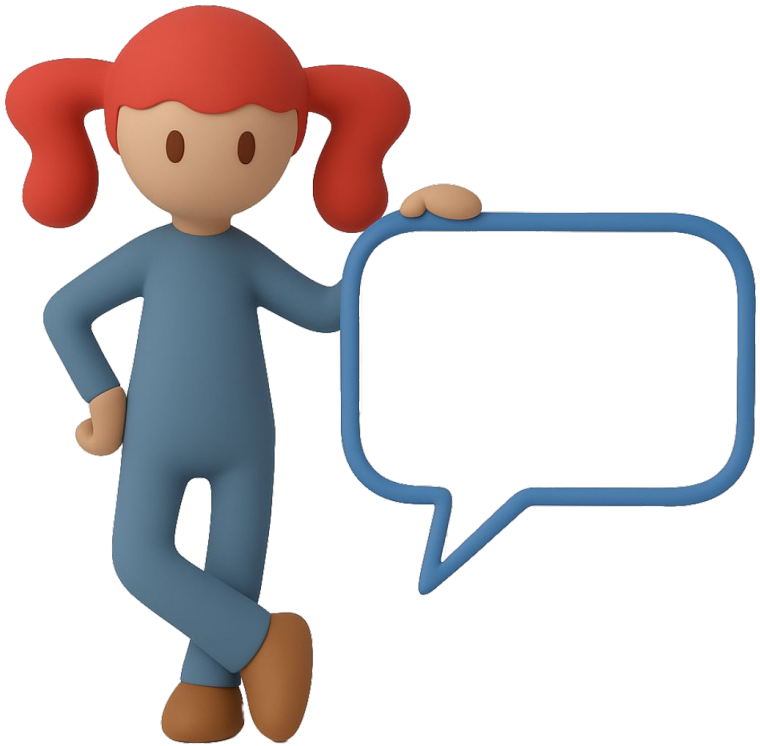


Average Fox Population Over Time
(Comparison)



Results - Flocking

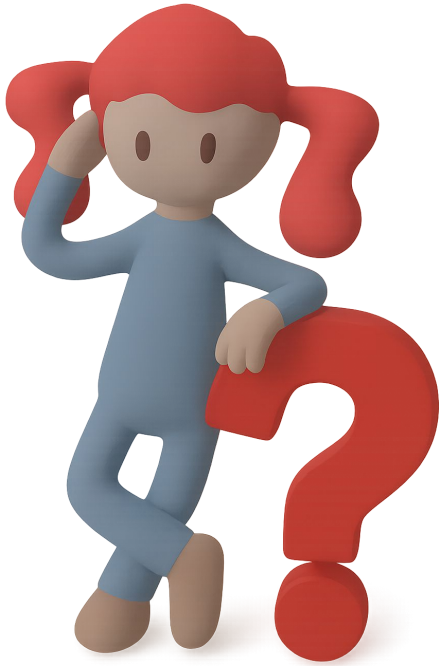
```
=========================================================
📊 Statistical Test Results Summary 📊
=========================================================
Metric                          | P-value | Corrected Alpha (no_flocking vs with_flocking) | Accepted Hypothesis
---------------------------------------------------------------------------------------------------------------------
Rabbit Extinction Time          | 0.0000  | 0.0083                                         | H1 Accepted ✅
Fox Extinction Time             | nan     | 0.0083                                         | H0 Accepted ❌
Peak Rabbits                    | 0.0000  | 0.0083                                         | H1 Accepted ✅
Peak Foxes                      | 0.1555  | 0.0083                                         | H0 Accepted ❌
Average Rabbit Population Over Time | 0.0000  | 0.0083                                         | H1 Accepted ✅
Average Fox Population Over Time    | 0.0256  | 0.0083                                         | H0 Accepted ❌
=========================================================
```



Dynamic traits

Mechanism

Research Question - Dynamic traits



- How do dynamic traits, such as age-dependent speed and detection radius, impact population time series, extinction time, and peak populations in agent-based predator-prey models?

Parameters - Dynamic traits

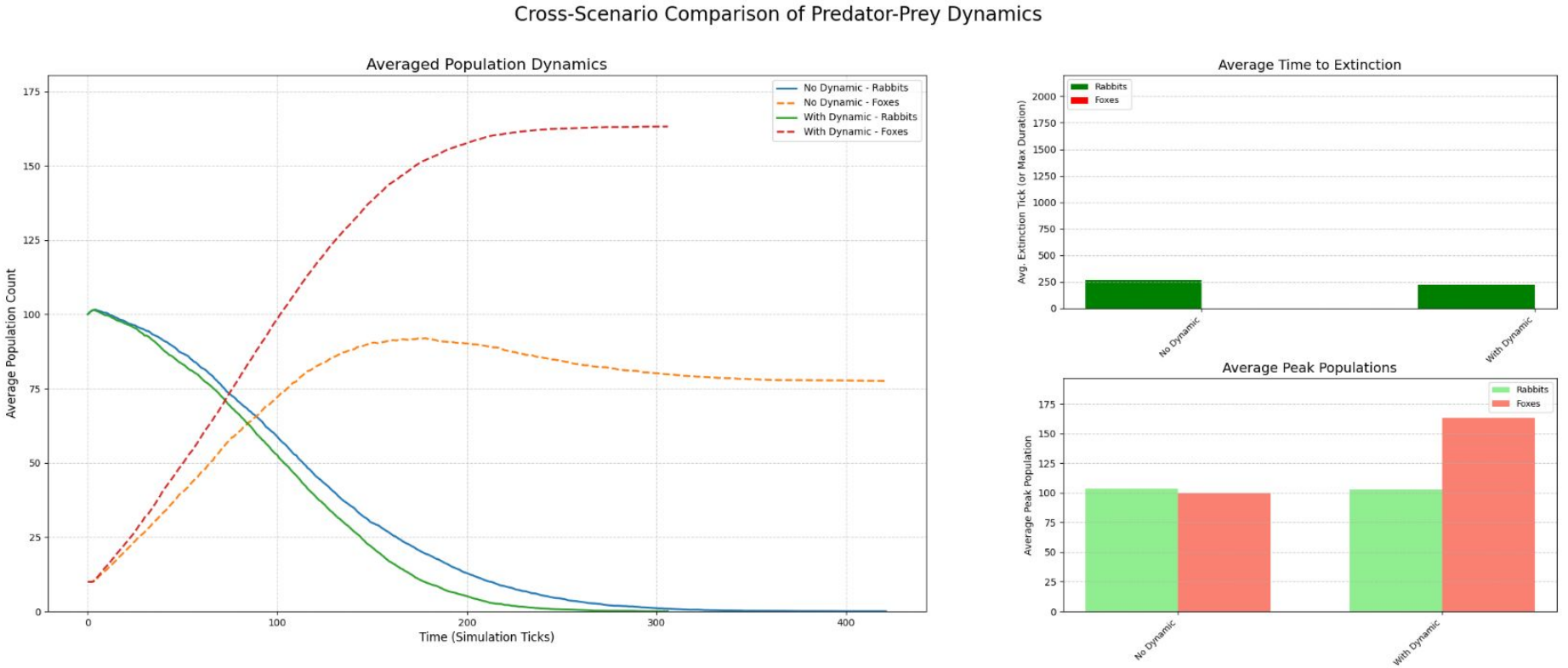
No Dynamic Traits Scenario:

- rabbit_movement_speed: how fast rabbits move. Values: [2.0, 3.0, 4.0]
- fox_movement_speed: how fast foxes move. Values: [3.0, 4.0, 5.0]
- rabbit_perception_radius: how far rabbits can detect foxes. Values: [40, 50, 60]
- fox_perception_radius: how far foxes can detect rabbits. Values: [60, 70, 80]
- rabbit_reproduce_chance: chance for rabbits to reproduce. Values: [0.004, 0.005, 0.006]
- fox_spontaneous_death_chance: chance of fox dying spontaneously. Values: [0.004, 0.005, 0.006]

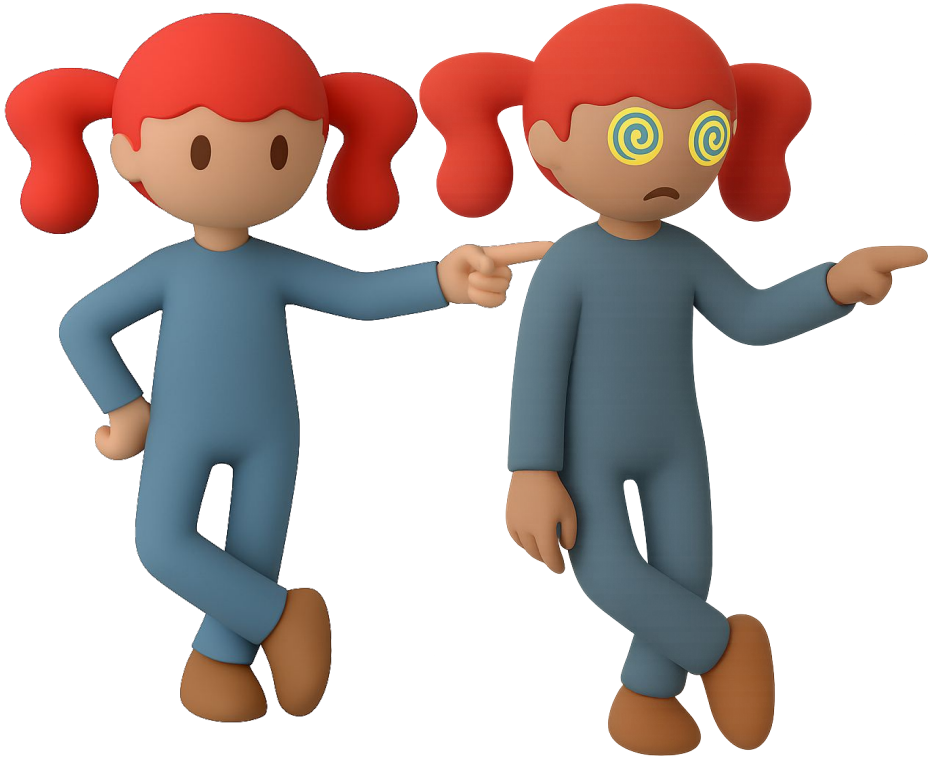
Dynamic Traits Scenario:

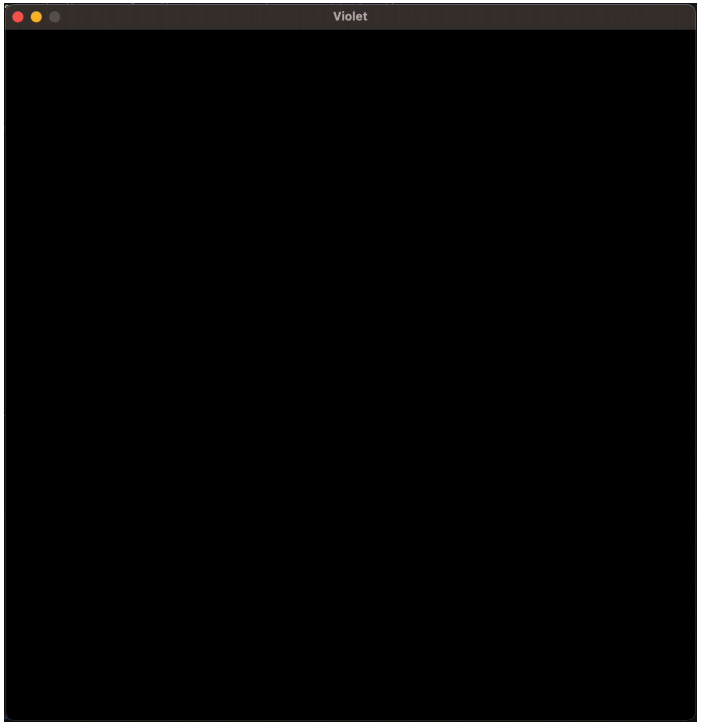
- rabbit_aging_rate_speed: how quickly rabbit speed declines with age. Values: [0.0005, 0.001, 0.0015]
- rabbit_aging_rate_perception: how quickly rabbit vision declines with age. Values: [0.03, 0.05, 0.07]
- fox_aging_rate_speed: how quickly fox speed declines with age. Values: [0.001, 0.002, 0.003]
- fox_aging_rate_perception: how quickly fox vision declines with age. Values: [0.08, 0.1, 0.12]

Results - Dynamic traits

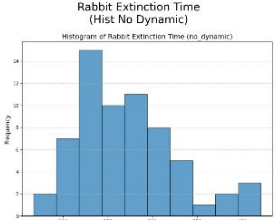


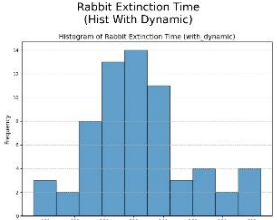
Simulation - Dynamic traits

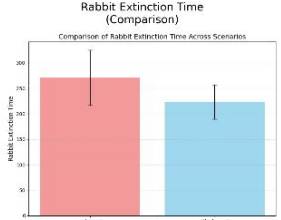


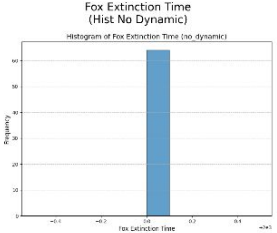


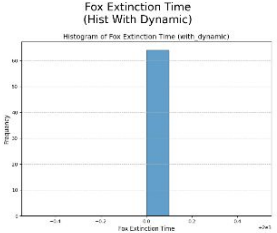
Results - Dynamic traits

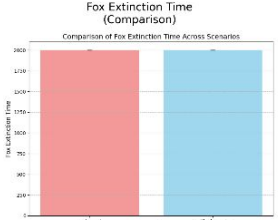


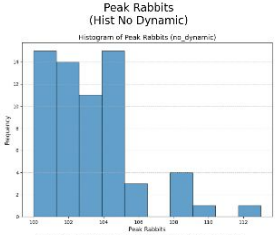


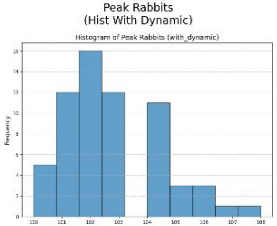


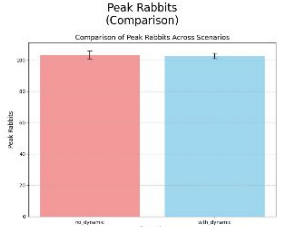


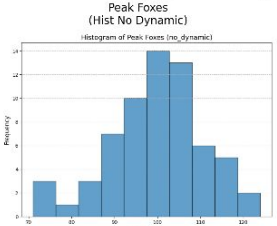


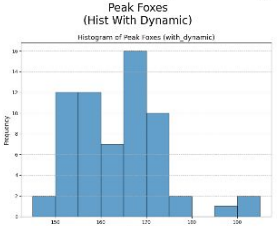


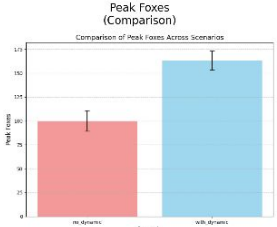


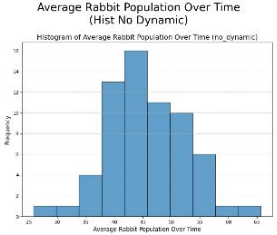


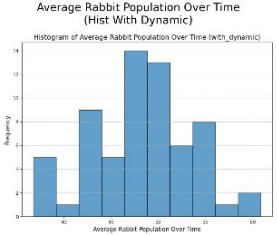


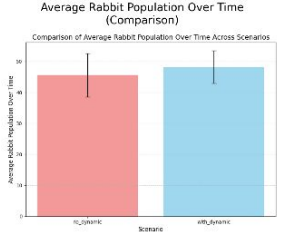


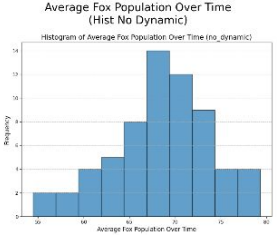


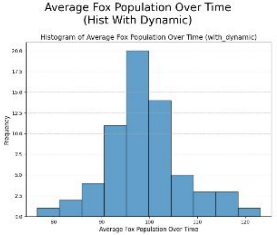


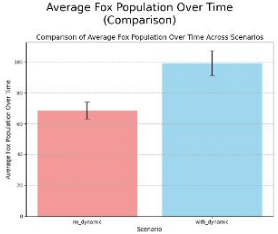






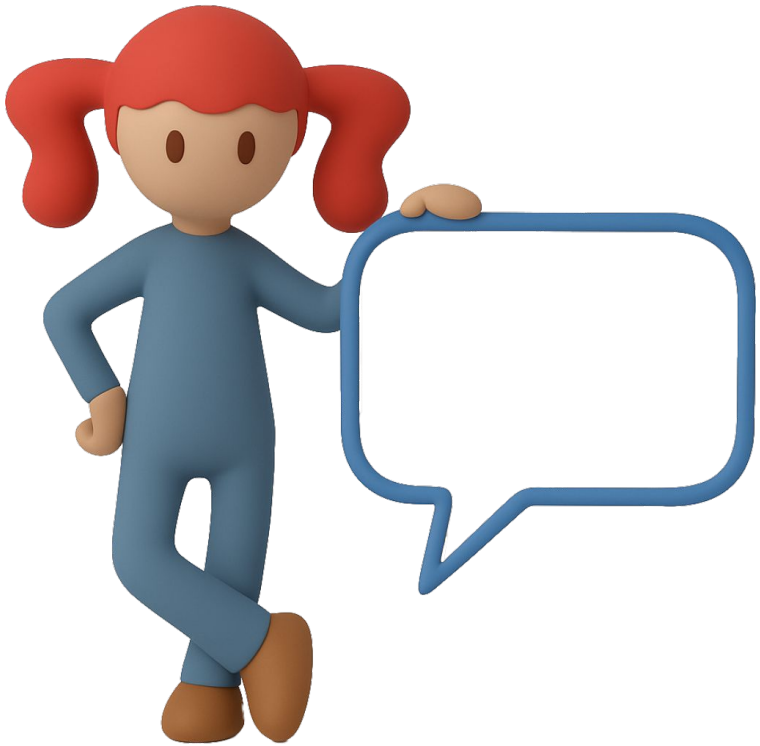






Results - Dynamic traits

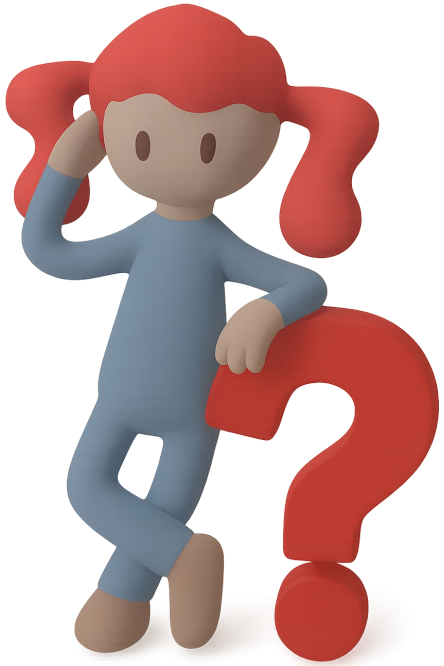
```
============================================================
📊 Statistical Test Results Summary 📊
============================================================
Metric                          | P-value | Corrected Alpha (no_dynamic vs with_dynamic) | Accepted Hypothesis
------------------------------------------------------------------------------------------------------------------------
Rabbit Extinction Time          | 0.0000  | 0.0083                                       | H1 Accepted ✅
Fox Extinction Time             | nan     | 0.0083                                       | H0 Accepted ❌
Peak Rabbits                    | 0.2789  | 0.0083                                       | H0 Accepted ❌
Peak Foxes                      | 0.0000  | 0.0083                                       | H1 Accepted ✅
Average Rabbit Population Over Time | 0.0199  | 0.0083                                       | H0 Accepted ❌
Average Fox Population Over Time    | 0.0000  | 0.0083                                       | H1 Accepted ✅
============================================================
```



Aggregation

Mechanism

Research Question - Aggregation



- How do dynamic traits, such as age-dependent speed, impact population time series, extinction time, and peak populations in agent-based predator-prey models?

Parameters - Aggregation

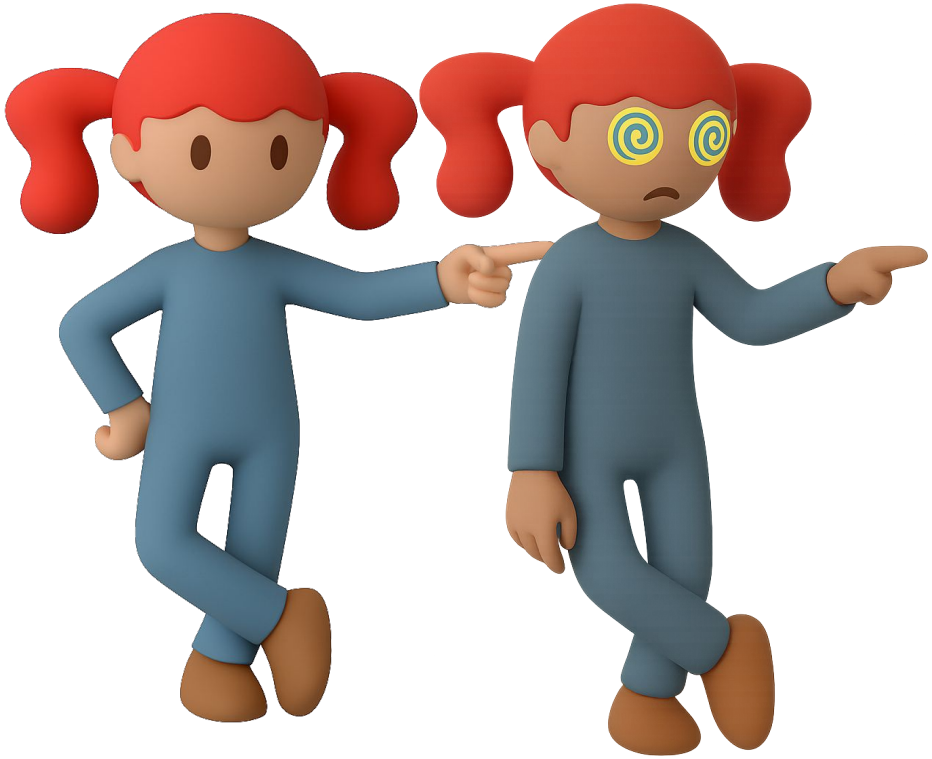
No Aggregation Scenario:

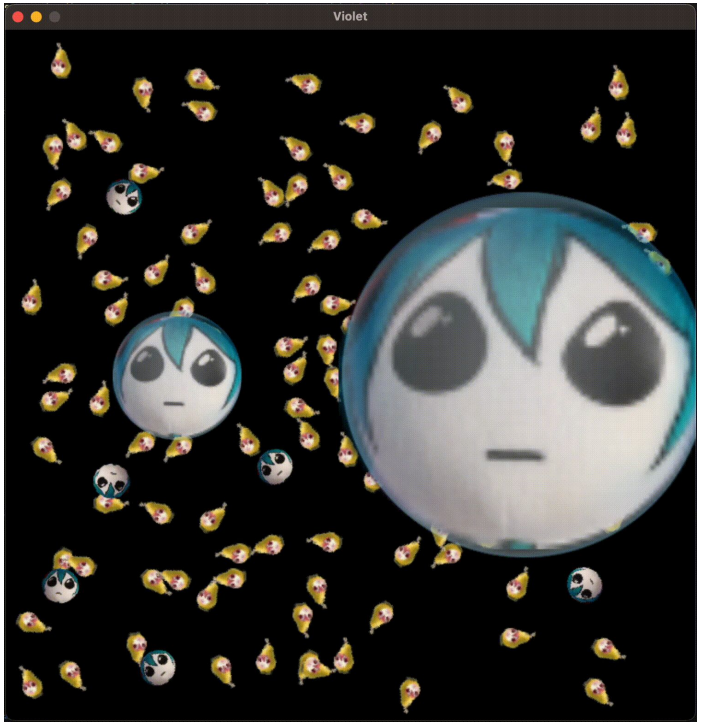
- rabbit_movement_speed: how fast rabbits move. Values: [1.5, 2.0, 2.5]
- fox_movement_speed: how fast foxes move. Values: [2.5, 3.0, 3.5]
- rabbit_perception_radius: how far rabbits can detect foxes. Values: [40, 50, 60]
- fox_perception_radius: how far foxes can detect rabbits. Values: [60, 70, 80]
- rabbit_reproduce_chance: chance for rabbits to reproduce. Values: [0.004, 0.005, 0.006]
- fox_spontaneous_death_chance: chance of fox dying spontaneously. Values: [0.004, 0.005, 0.006]

Aggregation Scenario:

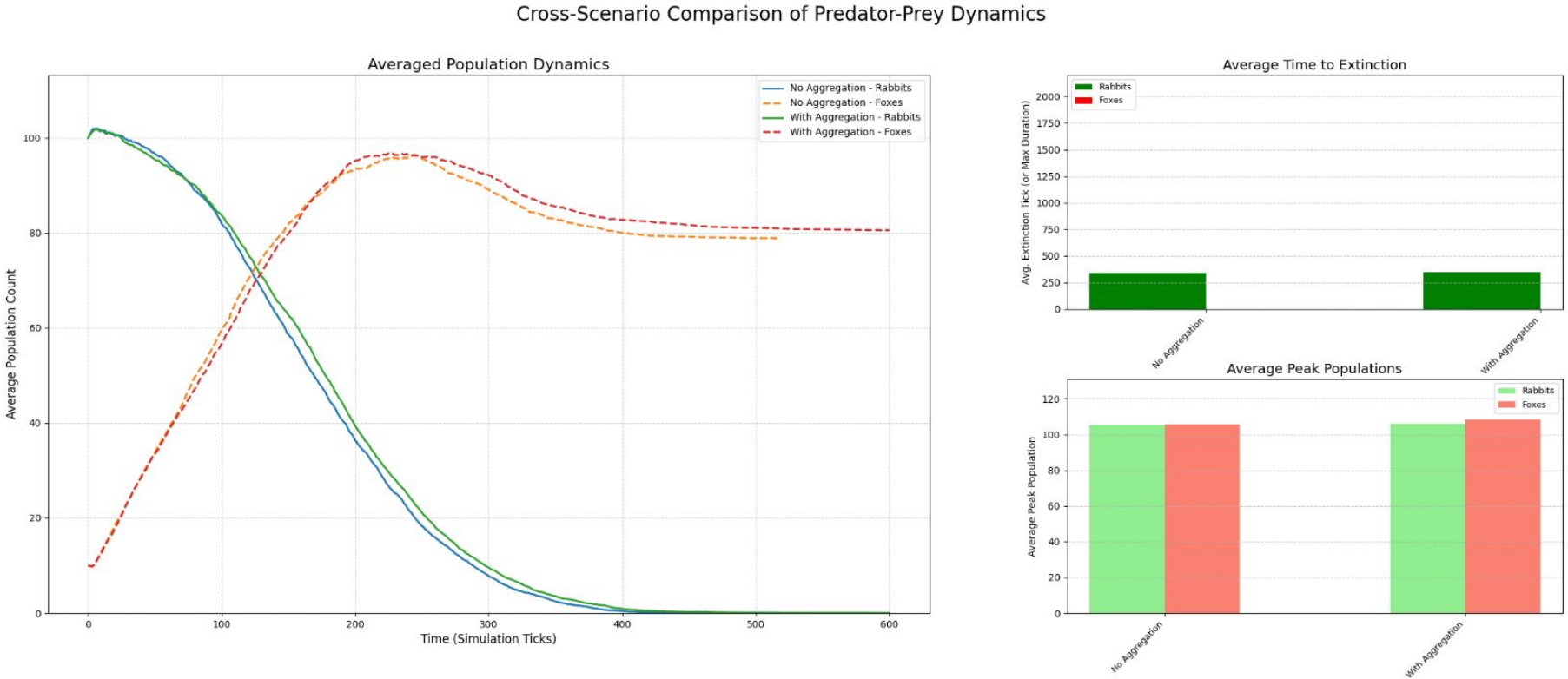
- p_join_factor: likelihood of rabbits joining an aggregation site. Values: [5.0, 10.0, 15.0]
- p_leave_factor: likelihood of rabbits leaving an aggregation site. Values: [40.0, 50.0, 60.0]
- t_join_min: minimum ticks before joining a site. Values: [5, 10, 15]
- t_join_max: maximum ticks before joining a site. Values: [15, 20, 25]
- t_leave_min: minimum ticks before leaving a site. Values: [160, 180, 200]
- t_leave_max: maximum ticks before leaving a site. Values: [340, 360, 380]
- d_check_frequency: how often aggregation decisions are evaluated. Values: [20, 30, 40]
- num_aggregation_sites: number of available aggregation sites. Values: [1, 2, 3]

Simulation - Aggregation

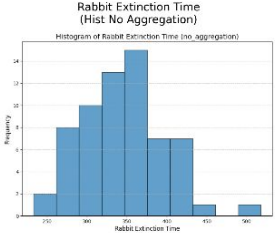


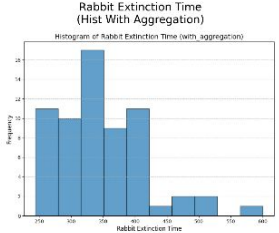


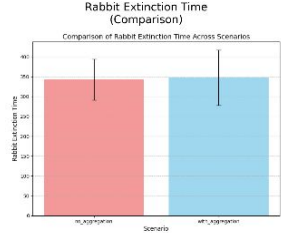
Results - Aggregation

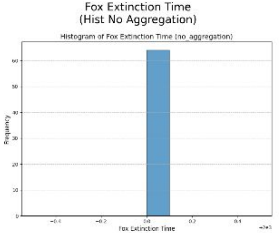


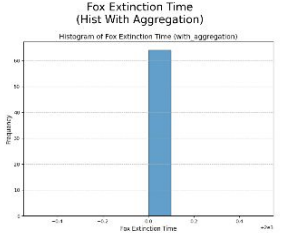
Results - Aggregation

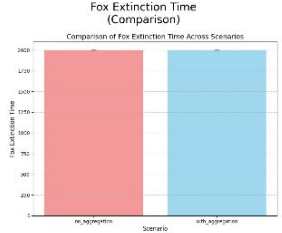


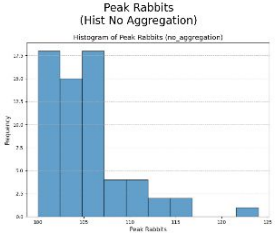


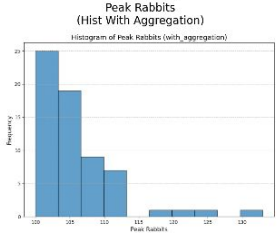


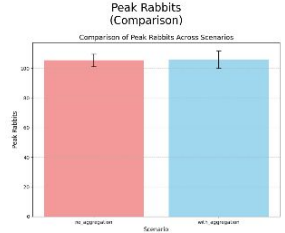


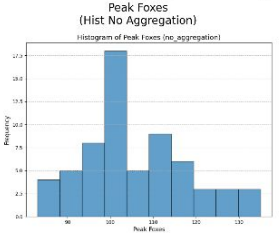


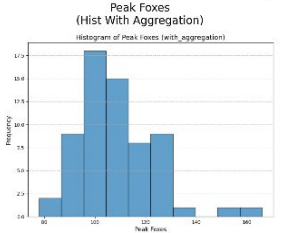


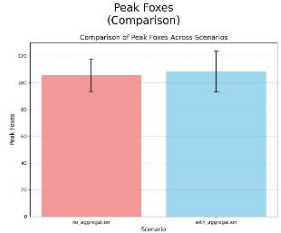


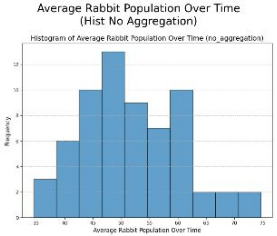


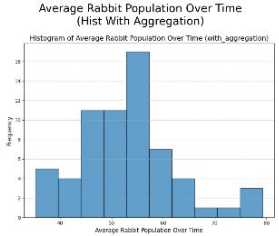


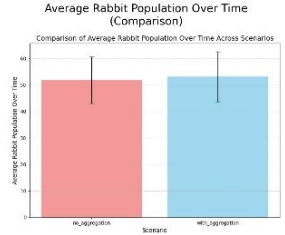


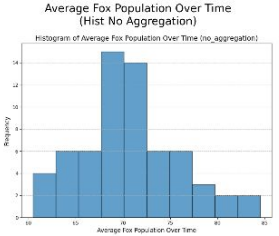


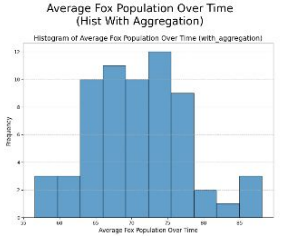


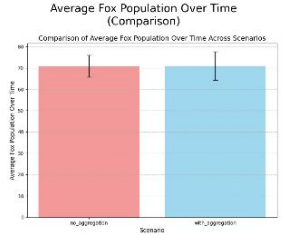








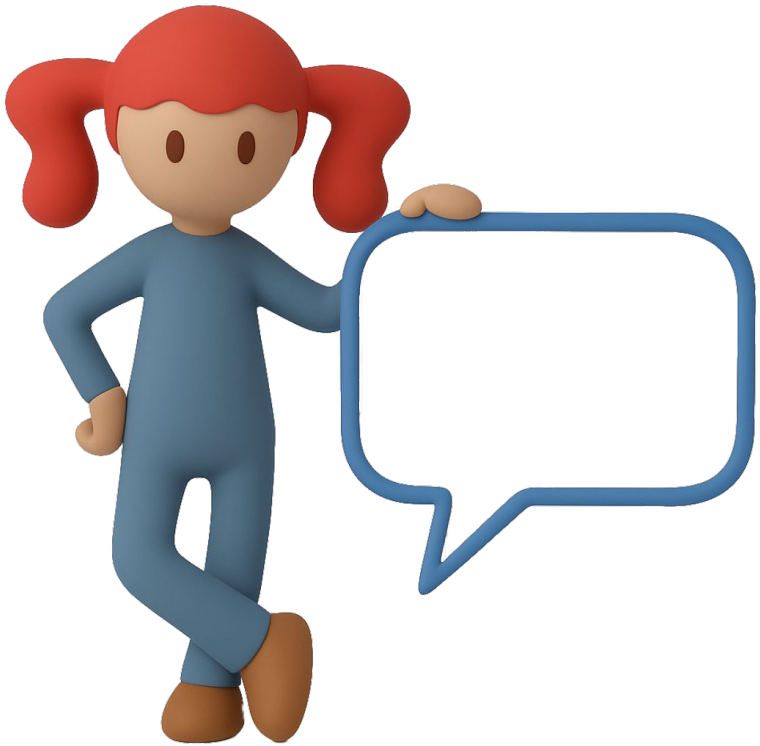




Results - Aggregation

📊 Statistical Test Results Summary 📊

Metric	P-value	Corrected Alpha (no_aggregation vs with_aggregation)	Accepted Hypothesis
Rabbit Extinction Time	0.9487	0.0083	H0 Accepted ❌
Fox Extinction Time	nan	0.0083	H0 Accepted ❌
Peak Rabbits	0.9828	0.0083	H0 Accepted ❌
Peak Foxes	0.3260	0.0083	H0 Accepted ❌
Average Rabbit Population Over Time	0.5466	0.0083	H0 Accepted ❌
Average Fox Population Over Time	0.9325	0.0083	H0 Accepted ❌



Conclusions

Conclusions

Statistical tests revealed the following effects of each mechanism:

Energy mechanism:
- Rabbit extinction time: significantly reduced.
- Fox peak population: significantly increased.
- Average fox population over time: significantly increased.

Flocking behavior:
- Rabbit extinction time: significantly increased.
- Rabbit peak population: significantly increased.
- Average rabbit population over time: significantly increased.

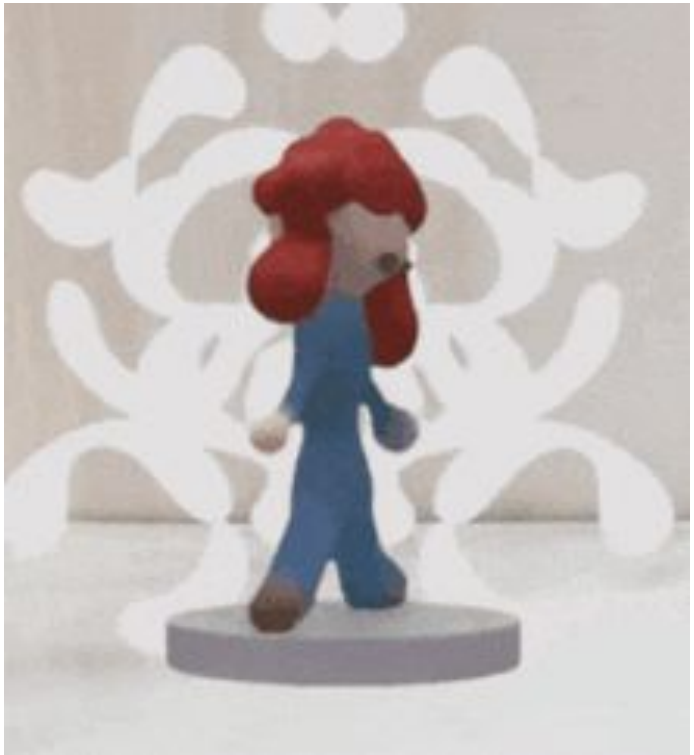
Dynamic traits:
- Rabbit extinction time: significantly reduced.
- Fox peak population: significantly increased.
- Average fox population over time: significantly increased.

Aggregation behavior:
- No significant effects observed.

Future work

Extra features that can be added in future:

- Different FOVs for predators and prey.
- Two agent reproduction.
- Different space zones, such as grass fields.
- Additional experiments with aggregation mechanic.



Thank you

For paying attention