Presenting SPECIES: Simulating Populations Evolving Complex Interactions in Ecological Systems

Agent-Based Simulation of a Prey-Predator Ecological System

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15th December, 2025

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Project Overview

Objective:

- Simulate natural selection in a closed environment.
- Analyze the survival strategies of prey and predator.
- Observe emergent behavior (evolution, population cycles).

Key Components:

- **Environment:** Toroidal Grid with regrowing plant resources.
- **Agents:**
  - Herbivores.
  - Carnivores.
- **Genetics:** Mutable traits passed to offspring.

Tech Stack & Architecture

- **Language:** Python 3.13
- **Simulation Core:** Custom Object-Oriented Engine (‘World‘, ‘Cell‘, ‘Animal‘ classes).
- **Frontend:** Streamlit (Web-based dashboard).
- **Visualization:** Matplotlib (Grid rendering) & Streamlit Native Charts.
- **Data Collection:** Automated CSV logging for statistical analysis.

The World

- **Grid System:** A toroidal $N \times N$ grid of cells.
- The toroidal shape removes "corner effects" where predators can easily trap prey.
- **Resources (Plants):**
  - Grow based on logistic probability.
  - Probability of regrowing increases if neighbor cells have plants.

The Cycle

Plan $\rightarrow$ Movement $\rightarrow$ Action $\rightarrow$ Cleanup $\rightarrow$ Regrowth.

The Prey: Herbivores

Herbivores are the prey in the environment. They gain energy by eating plants and they try to survive the relentless hunt of the Carnivores. They reproduce with a higher rate than Carnivores.

Gene	**Function**
Speed	Movement range for each simulation tick.
Vision	Range of cells visible to an individual.
Sociability	Affinity for other members of the species.
Armor	How well an individual can resist to a carnivore's hunt attempt.
w_plant	Weight for the presence of plants in planning.
w_threat	Weight for the presence of predators in planning.

The Predator: Carnivores

Carnivores are the predators in the environment. They gain energy by hunting Herbivores, so they are pressured to be more efficient at hunting. They reproduce at a lower rate compared to Herbivores.

Gene	Function
Speed	Movement range for each simulation tick.
Vision	Range of cells visible to an individual.
Sociability	Affinity for other members of the species.
Strength	How efficient the predator's hunt attempts are.
w_prey	Weight for the presence of prey in planning.
w_threat	Weight for the presence of other predators in planning.

Simulation Logic and Formulae

Energy is the key for survival. Energy allows agents to be more effective at hunting or defending, and to reproduce.

- Income: eating plants (Herbivores), eating prey (Carnivores).
- Expenditure: metabolism, movement (-distance $\times$ cost), reproduction (-50%).

Hunting provides both energy income to Carnivores and Herbivore population managing.

- `success_chance = 0.5 + 0.5 * ((advantage - defense) / (advantage + defense))`

Crossover and Mutation

- **Crossover**: Reproduction is asexual. When an individual has enough energy to reproduce, it gives half to the offspring and its genome is duplicated.
- **Mutation**: After reproduction each gene has a fixed probability of mutating. When a gene is selected for mutation, it has the same probability of increasing or decreasing by one unit.
- The idea is that individuals fit for survival have a higher probability of reaching the energy threshold for reproduction, so that their genome can spread. Mutation introduces variability and forces the exploration of the search space.

Simulation Interface

The interface allows:

- Real-time grid visualization.
- Live population graphs.
- Detailed statistics (Mean/Max gene values).
- Start/Stop/Reset controls.

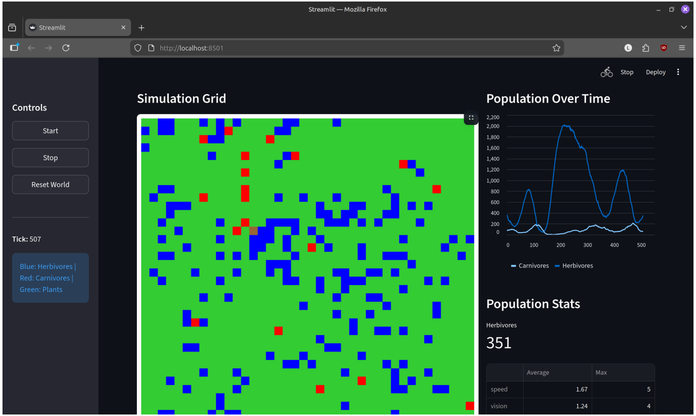


Figure: Streamlit Dashboard

Simulation Configuration

To ensure reproducibility, the following parameters were fixed across all experiments (Baseline, 2 Herbivores, 2 Carnivores).

Environment & Population

- **Grid Size:** 40×40 (Toroidal)
- **Initial Herbivores:** 400
- **Initial Carnivores:** 80
- **Lifespan:** 50–90 steps (Random)
- **Mutation Rate:** 10% per gene

Energy Economics

- **Initial Energy:** 50 (Max 150)
- **Metabolic Cost (Idle):** 2 / step
- **Movement Cost:** $1 \times$ Distance
- **Food Gain:** $+20$ (Plant), $+30$ (Prey)
- **Reproduction Threshold:** 80

Key Constraint

Movement is expensive (cost $= 1 \times$ distance). High speed requires high energy intake, creating a natural trade-off between mobility and starvation.

Observed Dynamics

In the baseline experiment a single population of Herbivores and a single population of Carnivores are observed competing in the environment.

1. **Lotka-Volterra Cycles:** Classic predator-prey population oscillation.
2. **Arms Race:**
   - Predators evolve higher *Strength*.
   - Armored Herbivores evolve higher *Armor*.
3. **Extinction Events:** If Carnivores become too efficient, they wipe out the Herbivores and then starve. Otherwise, if Herbivores become too resilient, Carnivores cannot keep up and starve.

Population Dynamics Analysis

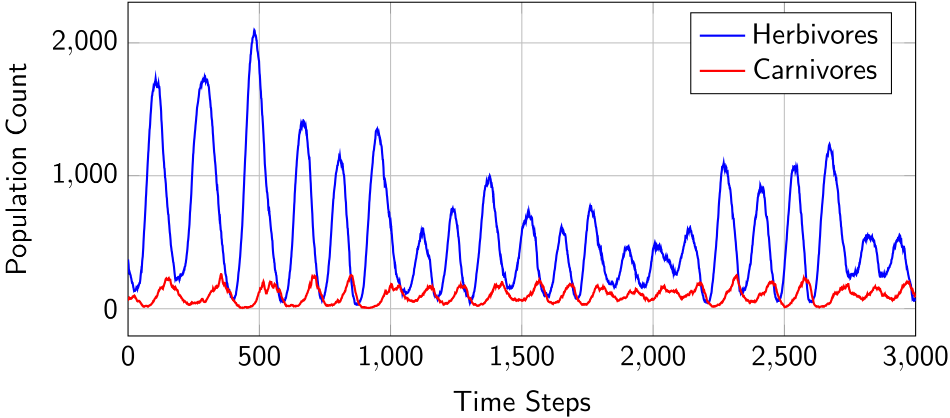
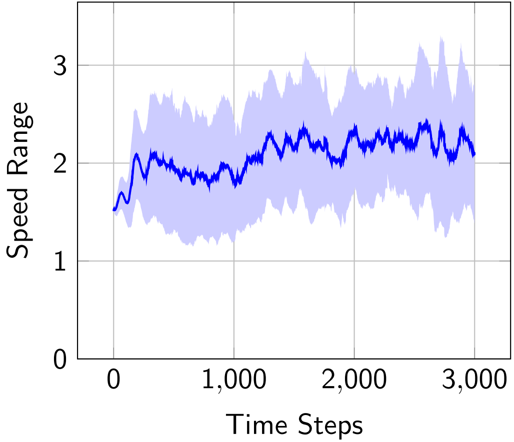
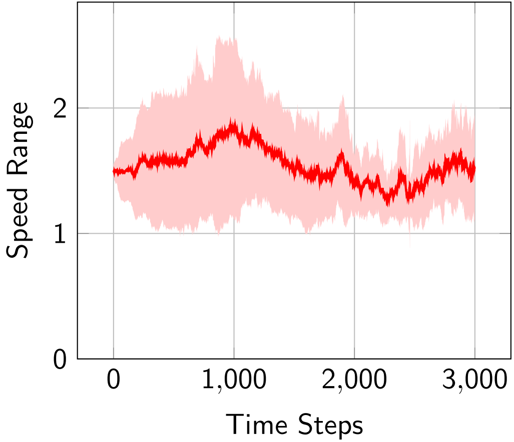


Figure: Population count over time for a single simulation run.

Speed Evolution



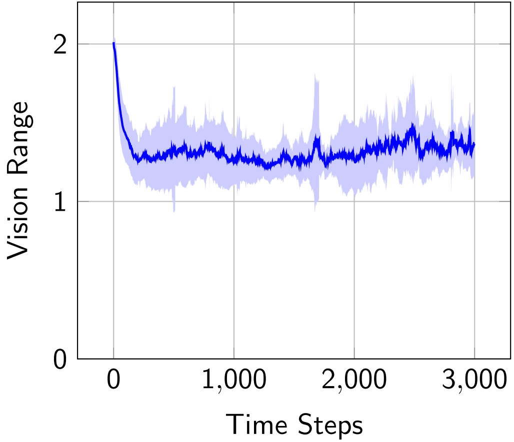
(a) Herbivore Speed



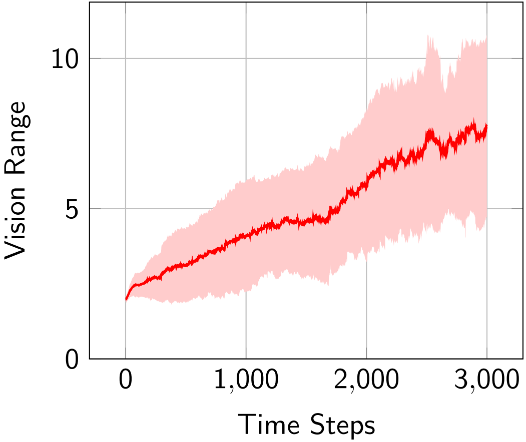
(b) Carnivore Speed

Figure: Evolutionary trends of speed averaged over all simulations.

Vision Evolution



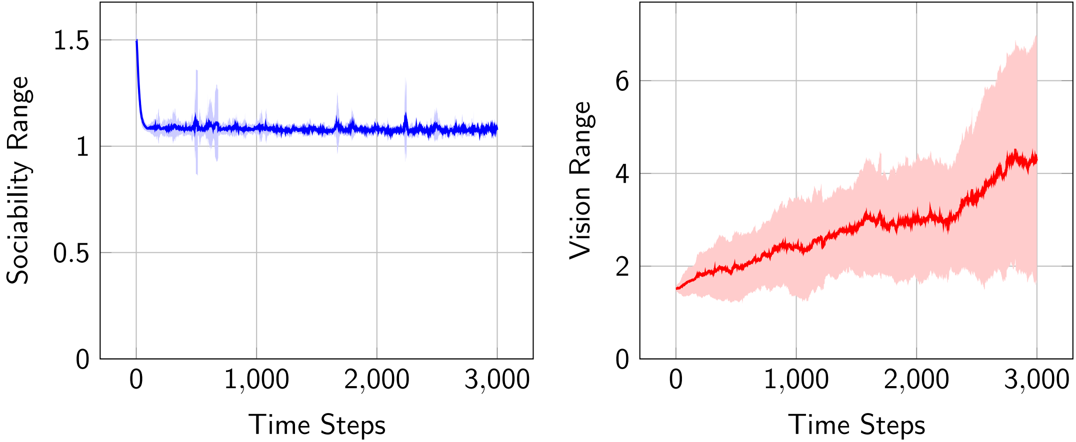
(a) Herbivore Vision



(b) Carnivore Vision

Figure: Evolutionary trends of vision averaged over all simulations.

Sociability Evolution



(a) Herbivore Vision

(b) Carnivore Vision

Figure: Evolutionary trends of sociability averaged over all simulations.

Armor/Strength Evolution

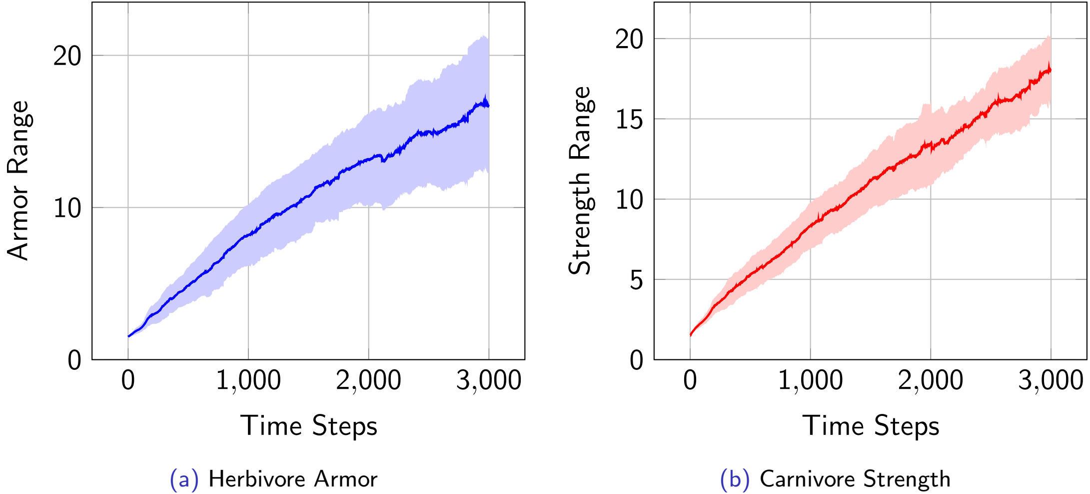
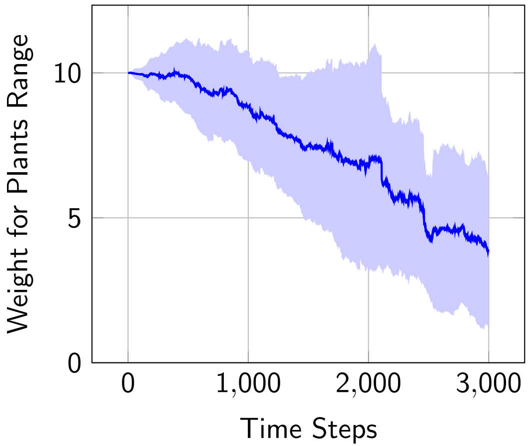
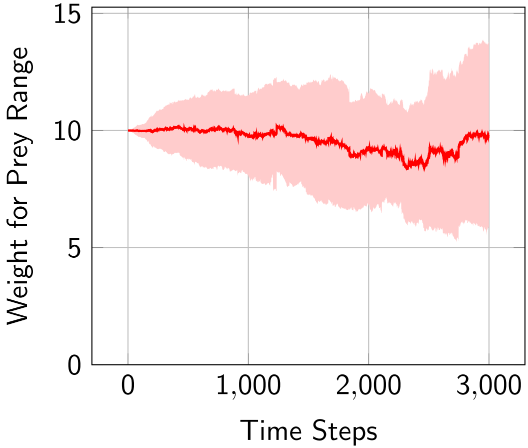


Figure: Evolutionary trends of armor/strength averaged over all simulations.

Food Weights Evolution



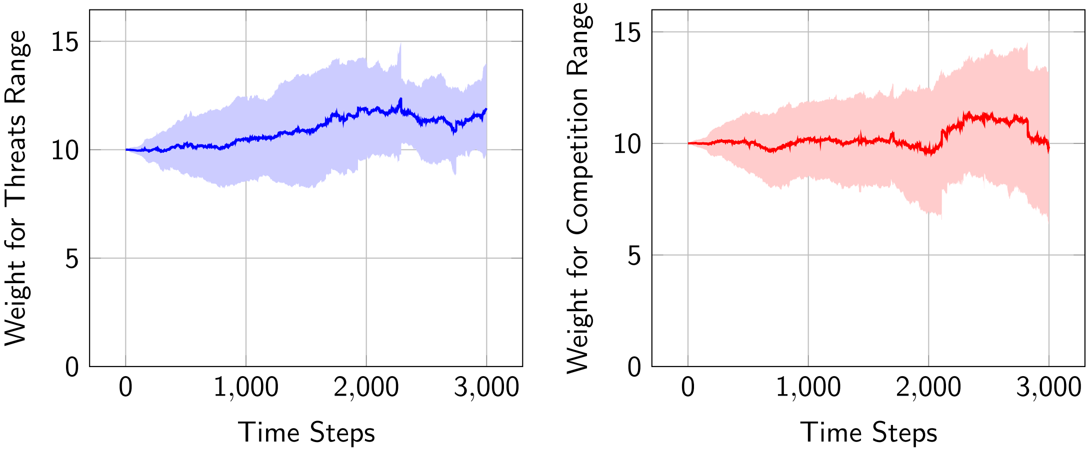
(a) Herbivore Weight for Plants



(b) Carnivore Weight for Prey

Figure: Evolutionary trends of weights for food averaged over all simulations.

Threat/Competition Weights Evolution



(a) Herbivore Weight for Threats

(b) Carnivore Weight for Competition

Figure: Evolutionary trends of weights for threat/competition averaged over all simulations.

2 Herbivores Experiment: Overview

- To verify whether other ecological niches are possible within the framework, a second experiment has been conducted. This time two distinct Herbivore populations, one with armor and one without, have been set to compete against the same predator as the previous experiment.
- The idea is that the unarmored Herbivores may evolve other strategies to survive, like faster movement to stay out of range from predators, other than maximising their armor.
- However, the unarmored Herbivores never survive for long, fading while the other two species continue their fight for survival.
- This is not a surprise, since the previous experiment highlighted a very strong evolutionary drive towards tougher Herbivores.

Population Dynamics Analysis

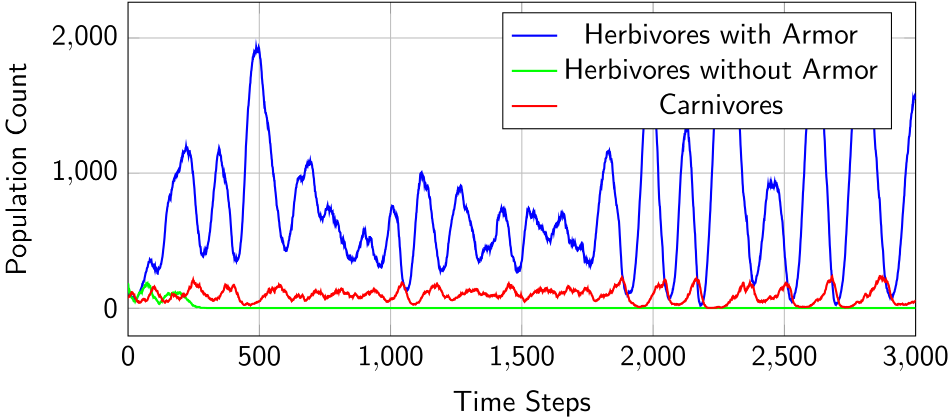


Figure: Population count over time for a single simulation run.

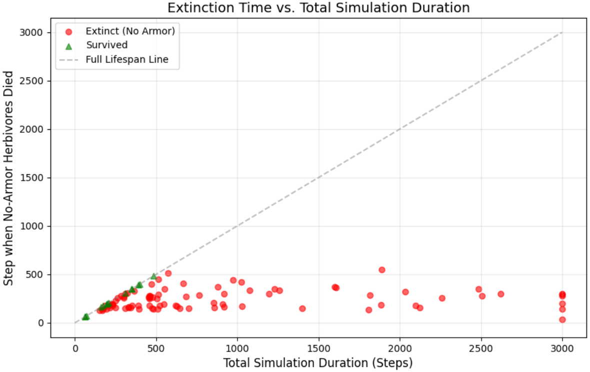
Extinction Analysis

Observation: The unarmored Herbivore variant faces significant selective pressure.

Statistics:

- **Extinction Rate:** 86%
- **Average Time to Extinction:** 242 Steps
- **Fastest Extinction:** Step 35

Without armor, speed alone is often insufficient against evolving predators.



2 Herbivores 2 Carnivores Experiment: Overview

- To expand even more the investigation of different population configurations, an experiment using 2 populations for each agent has been conducted. This time, for each agent, one population is the same as the first experiment, while the second has higher base vision and speed but has an upper bounded armor/strength.
- The idea is still the same, that is, observing whether populations with different characteristics give rise to different survival strategies, but with less restrictions than the previous experiment.
- This time, the "light" Herbivores disappear almost immediately as before, while the "light" Carnivores are not as competitive as the standard population, but they are able to survive sometimes.

Population Dynamics Analysis

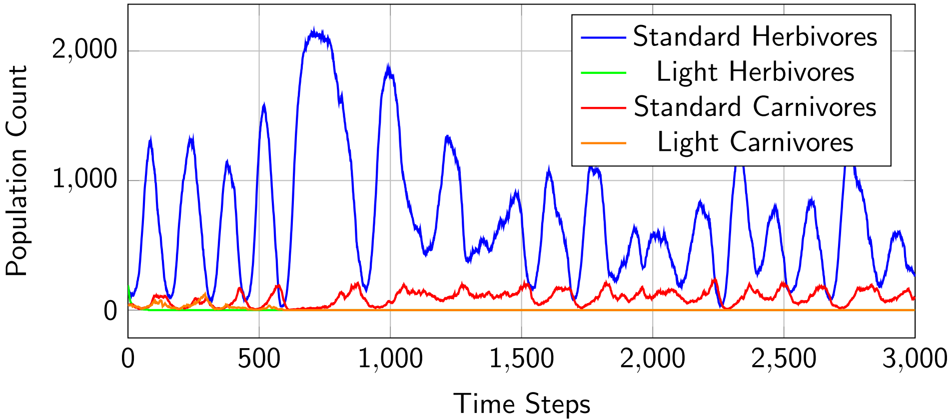


Figure: Population count over time for a single simulation run.

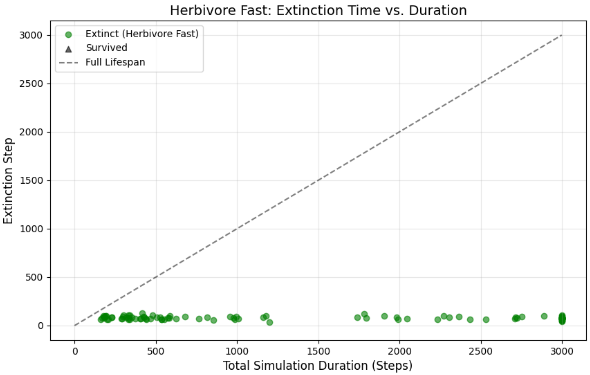
Extinction Analysis

Observation: The "light" Herbivore variant is never able to survive and reproduce.

Statistics:

- **Extinction Rate:** 100%
- **Average Time to Extinction:** 80 Steps

The increased metabolic cost from the higher speed and the lower armor dictate the complete extinction of the population.



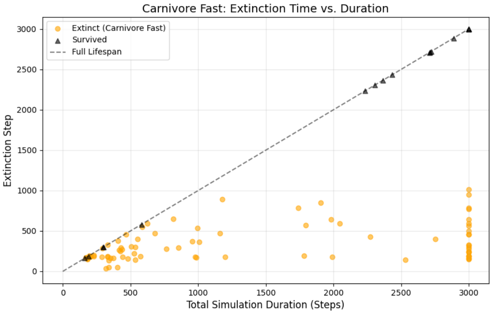
Extinction Analysis

Observation: The "light" Carnivore variant are able to carve a small niche and sometimes to survive. However, they are clearly less fit to survive than the standard Carnivore population.

Statistics:

- **Extinction Rate:** 82%
- **Average Time to Extinction:** 340 Steps

The higher speed means more chances at hunting. Although they have a lower success probability, in the right conditions they are able to survive.



Future Developments

- **Sexual Reproduction:** Introduce crossover of genes instead of asexual cloning.
- **Terrain Complexity:** Add obstacles (water, rocks) affecting movement cost.
- **Neural Networks:** Replace heuristic weighted logic with small neural nets for behavior.
- **Speciation Analysis:** automatic procedure to differentiate populations and identify ecological niches.

Thank You!

Questions?