Simulation Report: Predator-Prey Dynamics and Butterfly Ecosystem

Nguyen Tu Tung

January 10, 2025

Contents

1 Introduction

This report presents a simulation of predator-prey dynamics within a butterfly ecosystem. The model incorporates environmental factors, adaptive behaviors, and visualization tools to analyze population changes, predation effects, and camouflage strategies.

2 Model Overview

The simulation is built using an agent-based approach. The primary components are:

- **Environment Grid:** A discrete grid representing the simulation space.
- **Species:** Includes butterflies, predators, food, and eggs.
- **Agent Behaviors:** Agents exhibit behaviors such as movement, reproduction, predation, and death.

2.1 Key Features

- **Butterflies:** Exhibit camouflage based on color attributes and reproduce to maintain population.
- **Predators:** Hunt butterflies, adapt their behavior based on energy levels, and contribute to ecosystem dynamics.
- **Eggs:** Represent butterfly reproduction and have a probability of successful hatching.
- **Food:** Affects butterfly energy and reproduction rates.

3 Mathematical Formulations

The simulation includes mathematical representations of camouflage effectiveness, predation probability, and environmental feedback mechanisms. These are detailed below.

3.1 Camouflage Effectiveness

The camouflage effectiveness C of a butterfly is modeled as a function of the similarity between its color B_c and the background color E_c. It reduces the probability of successful predation.

$$C = 1 - \frac{|B_c - E_c|}{\max(E_c)}$$

Where:

- B_c is the butterfly's color (normalized between 0 and 1).
- E_c is the environmental patch color (normalized between 0 and 1).
- $\max(E_c)$ is the maximum possible color value in the environment.

Higher values of C correspond to better camouflage.

3.2 Predation Probability

The probability P_h of a predator successfully hunting a butterfly is defined as:

$$P_h = \texttt{predation\_intensity} \cdot (1 - C)$$

Where:

- `predation_intensity` is the predator's hunting efficiency, adjustable in the simulation.
- C is the camouflage effectiveness of the target butterfly.

3.3 Energy Dynamics and Instinct Boost

The predator's energy dynamics are governed by:

$$E_{t+1} = E_t - \texttt{energy\_decay} + \texttt{energy\_gain} \cdot H$$

Where:

- E_t is the predator's energy at time t.
- `energy_decay` is the constant energy loss per cycle.
- `energy_gain` is the energy recovered per successful hunt.

- H is a binary variable indicating the success ($H = 1$) or failure ($H = 0$) of the hunt.

When energy falls below a threshold E_{low}, the predator increases its instinct boost factor:

$$\texttt{instinct\_boost} = \begin{cases} 1 & \text{if } E_t > E_{\text{low}}, \\ 3 & \text{if } E_t \leq E_{\text{low}}. \end{cases}$$

This adaptation increases detection range and hunting success rates.

3.4 Environmental Feedback

The proportion P_e of environmental colors is updated dynamically as butterflies interact with the environment:

$$P_{e,t+1} = P_{e,t} + \frac{\Delta P}{N}$$

Where:

- $P_{e,t}$ is the proportion of a given patch color at time t.
- ΔP is the change in proportion caused by butterfly movements.
- N is the total number of environmental patches.

This equation represents the feedback loop where butterfly activity alters environmental dynamics.

3.5 Population Dynamics

The population N_b of butterflies at time t evolves as:

$$N_{b,t+1} = N_{b,t} + R - D$$

Where:

- R is the reproduction rate determined by egg hatching success:

$$R = H_e \cdot p_h$$

- H_e is the number of eggs laid, and p_h is the hatching probability.
- D is the number of deaths caused by predation and natural causes.

4 Agent Behaviors

4.1 Butterflies

Butterflies are characterized by their color, location, and energy levels. Their behaviors include:

- **Movement:** Randomly move across the grid.
- **Reproduction:** Lay eggs with a probability influenced by energy levels.
- **Camouflage:** Reduce predation risk by blending with the environment.

4.2 Eggs

Eggs hatch into butterflies based on a predefined cycle and a 90% hatching probability. Failed eggs free their occupied grid cell.

4.3 Predators

Predators exhibit adaptive hunting behaviors:

- **Hunting:** Seek and attack butterflies within a detection range.
- **Energy Decay:** Gradually lose energy, leading to death if not replenished.
- **Adaptation:** Increase detection range and hunting probability when energy is low.

5 Extensions

5.1 Extension 1: Predator Instinct and Behavior Adaptation

This extension introduces adaptive predator behaviors to enhance the realism of predator-prey interactions.

5.1.1 Dynamic Instinct Boost

Predators adapt their behavior based on energy levels:

- Increase detection range to locate prey over a larger area.
- Enhance hunting probability to prioritize survival, offsetting camouflage advantages.

5.2 Extension 2: Environmental Dynamics and Feedback

This extension incorporates dynamic environmental changes that influence butterfly populations and predator behaviors.

5.2.1 Environmental Color Dynamics

The environment grid is characterized by patches of different colors (black, white, gray). The distribution of these colors changes over time based on butterfly activity:

- Butterfly movement alters the color proportions of visited patches.
- Color proportions directly influence butterfly camouflage effectiveness.

5.3 Extension 3: Predator Energy and Intensity

This extension enhances predator dynamics by introducing predation intensity and energy-based adaptations.

5.3.1 Predation Intensity

Predators have a `predation_intensity` parameter that influences hunting success:

- Higher intensity increases the likelihood of a successful hunt.
- Intensity adapts within a range based on environmental and population dynamics.

6 Visualization and Outputs

The simulation includes multiple visualization tools to analyze the dynamics:

- **Butterfly Population by Color:** Tracks the population over time for each color.
- **Camouflage Effectiveness:** Monitors the effectiveness of camouflage in reducing predation.
- **Egg Hatching Success:** Displays the proportion of hatched and failed eggs.
- **Hunting Success:** Tracks the number of predation attempts and successes.
- **Predation Bias Analysis:** Analyzes the predation rate based on butterfly colors.
- **Environmental Patch Colors:** Visualizes the proportions of different environmental patch colors over time.

7 Experimental Results

The simulation demonstrates:

- Predators prioritize survival by adapting their hunting strategies.
- Camouflage significantly reduces predation risk.
- Egg hatching success varies based on environmental conditions.
- Predator energy dynamics influence population stability.
- Environmental feedback mechanisms create dynamic camouflage effectiveness.
- Predation intensity directly affects population stability and predator success.

8 Conclusion

This simulation provides insights into the dynamics of predator-prey ecosystems, highlighting the impact of camouflage, predation, and adaptive behaviors on population stability. Future work could include additional environmental variables and more complex predator-prey interactions.

A Output for Visualization

The simulation visualization includes:

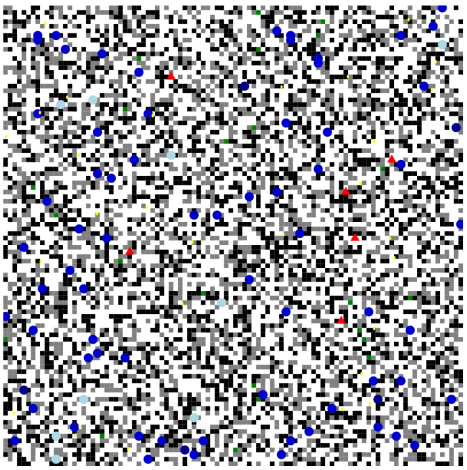

Figure 1: Simulation

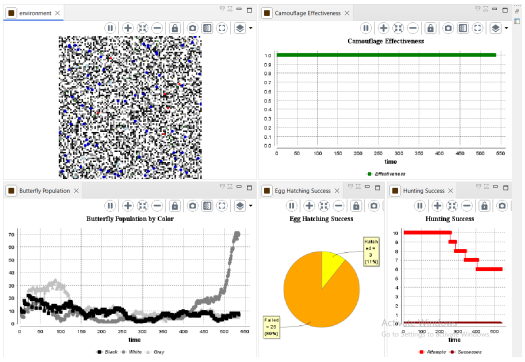

Figure 2: Graph and simulation

A.1 With Extension 1

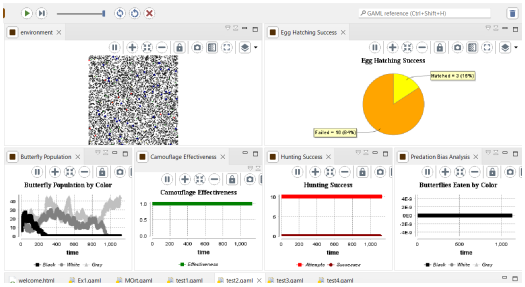

Figure 3: Extension 1 visualization

A.2 With Extension 2

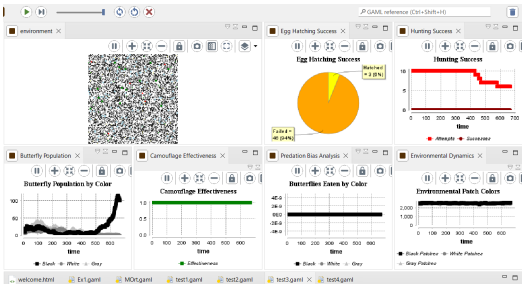

Figure 4: Extension 2 visualization

A.3 With Extension 3

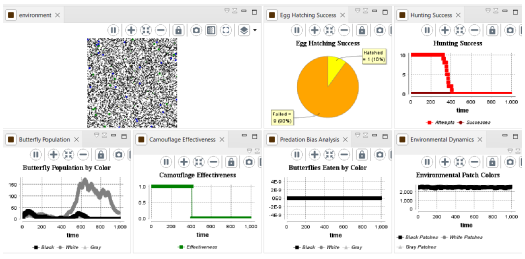

Figure 5: Extension 3 visualization