Beehive Simulation

A Multiagent System for Modeling Bee Foraging Behavior
Group 20

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ABSTRACT

This project proposal details the creation of a multiagent system to simulate the behavior of bee colonies in a foraging environment. It aims to explore the interactions between bee colonies, food sources, and their environment with the goal of understanding collective foraging behaviors, interactions and survival. Employing a decentralized approach, individual bee agents will make decisions based on local information and simple rules. The project seeks to offer insights into emergent behaviors in complex systems and to empirically validate design choices by analyzing the survival rates across simulations.

1. INTRODUCTION

Bee foraging behavior is a fundamental aspect of ecosystem stability and agricultural productivity, making bees central pollination agents, essential for ecosystem health and crop management.

We propose a multiagent system modeling of a simplified ecosystem, where bees are the protagonists, in order to predict what could happen to the ecosystem when certain variables (*e.g.*, abundance of flowers, coexistent colonies) are tweaked. We expect to capture collective foraging behaviors, interactions, and survival strategies, providing insights into emergent behaviors in complex adaptive systems.

Similar to existing software such as Beehave (Jaffe et al., 2010), the proposed system aims to simulate realistic bee foraging behavior. However, it emphasizes a decentralized approach, focusing on local interactions and emergent behaviors. By exploring these aspects, the system seeks to validate its design choices and provide a deeper understanding of these dynamics.

2. APPROACH

The proposed environment consists of bees as agents (that may be assigned to colonies, but still act individually), wasps as common enemies, food sources (flowers) and a beehive for each colony. Bees will move based on biologically inspired behaviors. The environment will be represented as a two-dimensional space, where bees can detect nearby food sources.

Each bee will be modeled as an autonomous agent with the objective to return to their beehive to deposit resources while not getting lost from the colony (the further the bee travels, higher likelihood to be unable to return to the beehive). Flowers will have a finite amount of food, which depletes as bees collect from them, as well as periodically generation of new food sources. The hive will have a food stock, gradually consumed by the bees for them to survive. Food surplus will lead to the appearance of new bees. The queen bee has to leverage how many bees it wants inside the beehive. If its resources reach a quantity below a set threshold, it will send more bees to forage, but if for a minimum of timesteps they don't have the required number of bees to ensure safety from wasps, it's probably a good idea to keep them inside until stable.

The wasps act as common enemies to all bees, attacking beehives and can only be defeated by agent cooperation.

The design choices for the system architecture are motivated by the need to capture key aspects of bee foraging behavior while maintaining computational efficiency. By simplifying individual bee behavior and focusing on emergent collective behavior, negotiation and cooperation between intra-colony agents, we aim to create a scalable model that can simulate large-scale pollination dynamics.

3. PROBLEM

Environment

The BeeColonyEnv represents a meticulously designed simulation environment crafted to model the complex dynamics between various bee species, queen bees, and wasps within a predefined grid space. This environment, implemented on top of the PettingZoo library, functions as a parallel environment where multiple agents operate simultaneously, capturing real-world ecological interactions.

Central to the environment are the agents: queen bees, bees, and wasps, each with their unique roles and capabilities. The queen bees manage the colonies, bees forage and defend the colony, and wasps act as predators. The grid has a specified shape and size, within which flowers are generated given a density, number of clusters and their spread, providing food resources for the bees.

Each time step in the environment sees agents performing actions based on their perceptual inputs, which include everything within the vision range (flowers, other bees, wasps, …). Agents are able to keep a small state between actions.

Special attention is given to the creation of flowers and the strategic placement of beehives and wasps, ensuring that each species' starting locations and movements are fair and adhere to realistic ecological patterns. This setup not only challenges the agents in resource acquisition and survival but also integrates critical aspects such as vision multipliers and attack ranges, enhancing the simulation's depth and realism.

The BeeColonyEnv, with its robust configuration options for things like seed setting for reproducibility, the number of agents, and their behaviors, serves as a versatile platform for studying and visualizing the adaptive behaviors and survival strategies of bee colonies under various environmental pressures and threats.

Agents

In the bee colony simulation project, a variety of agents interact within a complex ecosystem, each playing a crucial role in the dynamics of their environment. These agents are categorized into bees, queen bees, and wasps, each with different behaviors and strategic implications for the simulation.

Bee

Each bee's action space is defined by staying in place, moving in different directions, attacking, collecting pollen from a flower, and entering the beehive while dropping the pollen for its colony bee's benefit.

But they have to comply with certain rules, namely, they may not leave the beehive unless ordered by the queen bee, and they may not re-enter the beehive without pollen. Each alive bee consumes a food source (portion of pollen unit) from the beehive per time step. Bees may attack wasps only when the wasp is attacking their beehive. They have an attacking power, but it is a suicide mission, *i.e.*, once they attack a wasp, they are no longer alive for the next time steps.

In the bee colony simulation project, three types of bee agents: Greedy, Respectful, and Social, exhibit distinct behaviors affecting the colony's dynamics:

- **Greedy Bee**: These bees follow a greedy-like algorithm, always aiming to the nearest flower with available pollen to gather. They do not take into account the observable bees.
- **Social Bee**: Social Bees enhance collective efficiency through coordinated foraging, using a shared map to avoid overlapping efforts. Once a bee has targeted an available flower, it communicates to the nearby bees that the said flower is already a target of a bee. The next ones may only target a flower that is not yet a target of any bee. The communication is implemented with a dynamic set for each section of the grid for each colony, holding the currently targeted flowers.
- **Respectful Bee**: Taking a role-based decision approach, Respectful Bees take into account every visible bee and only target a flower if it is the closest bee to the targeted flower. There is no communication in this algorithm.

Queen Bee

Each Queen Bee action space follows a Multi Binary structure, *i.e.*, each queen bee decides for each bee that is inside the colony if it leaves or not.

Queen Bees have to keep track of a health function. If the health is good, they reproduce another Bee to their beehive. If the health is bad, they need to sacrifice a Bee for their beehive. The health function is the ratio between food quantity and number of bees. If the food runs out completely, both the queen and all the bees from that colony will be immediately killed.

In the bee colony simulation project, the Queen Bee is central to the dynamics of the hive, integrating strategies from various agent types to manage the colony effectively:

- **Greedy Queen Bee**: This queen adopts an aggressive expansion strategy, maximizing resource intake and rapid population growth. However, the lack of cautious resource management can lead to potential vulnerability to external threats like wasp attacks.
- **Conservative Queen Bee**: With a focus on defense and stability, this queen moderates the release of bees based on the colony's health and external threats, ensuring sustainable growth and resource management by keeping more bees within the hive when threats are detected or health is compromised.
- **Considerate Queen Bee**: This queen balances between resource acquisition and colony safety, adjusting the number of active foragers based on the current health status of the colony. Its approach minimizes risk by adapting bee activity levels to both

internal and external environmental conditions, promoting long-term stability.

Wasp

Wasps in the simulation act as formidable adversaries to the bee colonies. The Greedy Wasp variant exemplifies an aggressive predator, strategically identifying and targeting the nearest active beehive. This aggressive behavior introduces a dynamic element of conflict and challenge, pushing bee colonies to evolve defensive strategies and manage resources effectively to ensure survival.

Wasps attack by stealing food from the beehive.

4. **EVALUATION**

Metrics

In this study, several metrics are employed to evaluate the impact of different bee types on the dynamics and health of a bee colony under the governance of a single queen bee. Each metric offers unique insights into the colony's functioning and sustainability:

- Alive: This metric records the count of bees that remain alive over time, providing a direct measure of the survival rates of various bee types when exposed to identical environmental conditions. It is critical for assessing the resilience and adaptability of bee types in the colony.
- Dead Count: By tallying the number of bees that have died, this metric highlights potential issues within the colony's capacity to sustain its population. A higher death rate could indicate inefficiencies in resource gathering, poor colony defense, or health management, which are essential for the colony's survival and productivity.
- Food: This quantifies the total food reserves within the colony, reflecting the efficiency of bees in resource accumulation and management. Differences in this metric across scenarios with various bee types can reveal disparities in foraging effectiveness or resource conservation strategies, which are vital for colony endurance through adverse conditions.
- Health: Derived from the food quantity and the number of living bees, the health score of the colony offers insights into its overall robustness and vitality. It encapsulates how well bees are performing in sustaining adequate nourishment levels and supporting each other, which are crucial for the colony's thriving.
- Presence in Beehive: Monitoring the count of bees present in the hive at any given time, this metric sheds light on behavioral patterns such as foraging frequency. It also provides insights into how bees respond to external environmental pressures, such as the presence of a wasp, which could affect their survival and efficiency.

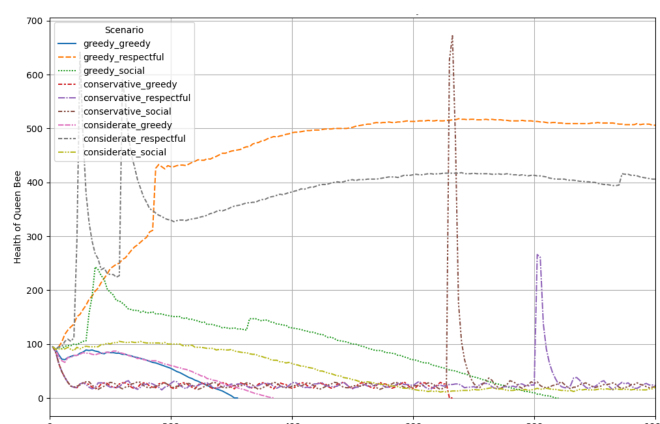
These metrics collectively form a comprehensive framework to systematically analyze and compare the performance and behavior of different bee types within the same colony environment. By understanding these dynamics, the study aims to derive actionable insights that could inform beekeeping practices and strategies for enhancing colony health and productivity.

Default Parameters

The default parameters can be found and tweaked to explain different scenarios in the *config* folder by adapting the *base.json* script to the user's scenario.

5. RESULTS

The first testing round consisted of creating all combinations of bee and queen bee types and comparing their behaviors in exactly the same environment. Firstly, with the hive placed inside a cluster of flowers and, secondly, with a uniform random distribution of flowers across the grid. With this, our aim was to filter the best and worst approaches to select for further exploration.

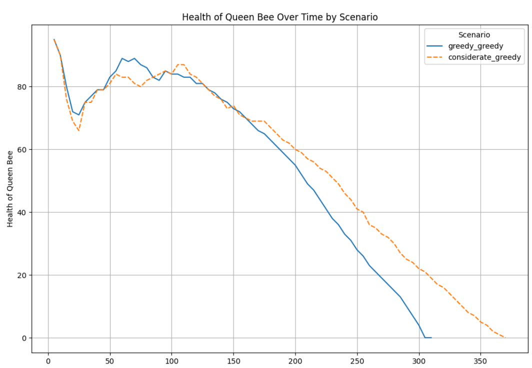


Evaluating both testing rounds, successful strategies such as Greedy_Respectful and Considerate_Respectful show the best balance of growth and sustainability, making them ideal for exploring variations in resource availability and competitive scenarios, although the second is less stable. On the other hand, Conservative strategies consistently perform poorly, likely due to their restrictive nature, suggesting a need for adjusted parameters or hybrid strategies. Social variants like Greedy_Social and Considerate_Social exhibit significant fluctuations and instability, indicating problematic social dynamics and poor adaptability to non-greedy queen policies.

In uniform distribution studies, problematic strategies remain ineffective, while successful strategies continue to perform well. However, two switches are notable: Greedy_Social adapts and thrives in this environment, while Conservative_Social fails early. The Greedy_Greedy approach needs further study, as a computational issue may be causing early failure.

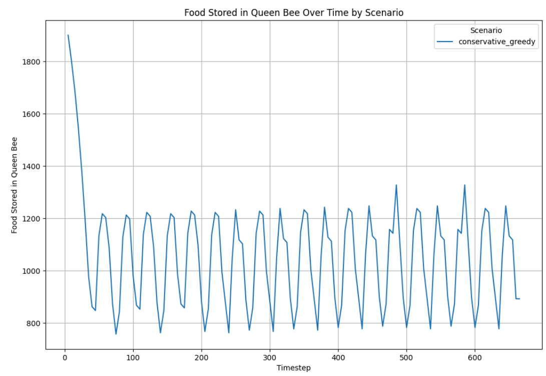
Greedy_Greedy and Considerate_Greedy

Both display a high initial amount of food quantity, that will cause the bees to reproduce and consequently, a rise in health as we can see in Figure 1. This leads to a shortage of food and a sudden decline in population. Population growth is high but shows fluctuations, indicating instability in the environment, bad resource management and exploration resulting in death of the population. The fact that the bees are greedy means that they take too long to in the foraging process and the hive can't survive.



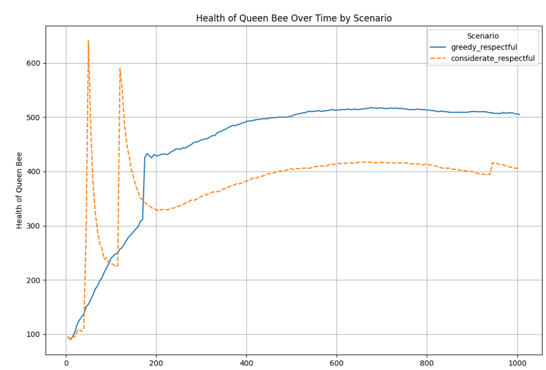
Conservative_Greedy

Shows a more stable and sustainable than previous approach, but not enough growth to survive the wasp attack around timestep 700. There is not enough foraging so the food quantity and population remains low with no significant growth observed, indicating a strategy that is too restrictive. With the wasp attack, this number is not enough to protect the hive and it can’t survive. The plot in Figure 2 also shows a typical behavior of a Conservative queen bee because it only demands food when its quantity is below a certain threshold.



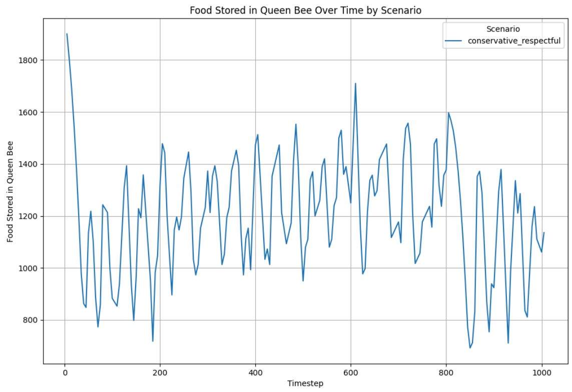
Greedy_Respectful and Considerate _Respectful

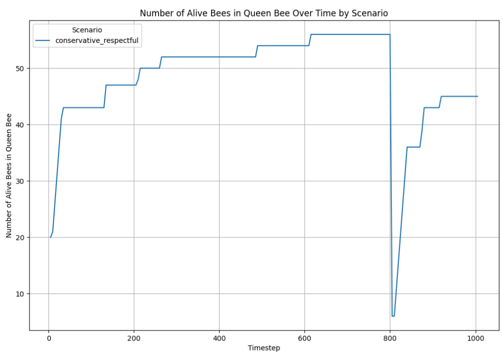
Best found approaches for the environment nearly achieving health stability (Figure 3) while sustaining increasing growth. Both approaches are effective, although greedy_respectful obtains stability while considerate is unstable, but shows good environment adaptability. They guarantee the sustainability of the hive for the rest of the execution, without being disturbed in the slightest by external events, such as a wasp attack.



Conservative_Respectful

Health initially declines before reaching an equilibrium state with slight resource fluctuations indicating a low reproductive behavior, but more stable and strong enough to survive a wasp attack. When the wasp attacks, the superior number of bees is able to withstand the damage caused by the wasp and eventually kill it, which leads to a sharp drop in the number of bees (Figure 4) but a subsequent rise due to the fact that the "Food quantity" has remained unchanged (Figure 5).





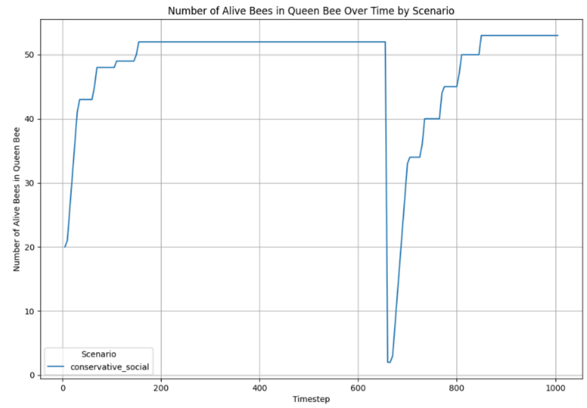
Respectful bees tend to reach an equilibrium state, but the approach difference infers high reproduction or just sustainability.

Greedy_Social

This approach shows no adaptability to the environment and the research strategy unable to sustain this colony. Greedy Queen and social bees aren't a compatible match, as social dynamics affect effective resource allocation. Both queen health and population numbers are unstable, suggesting a problematic interaction within the environment. Additionally, the interaction of social bees with a greedy queen bee demonstrates the vulnerability of the colony to external threats, such as wasp attacks.

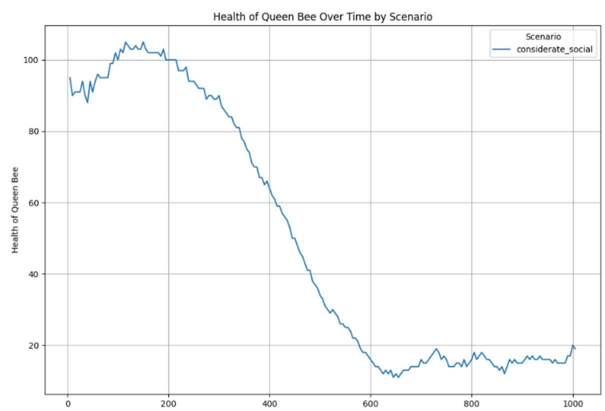
Conservative_Social

Social bees match with the conservative Queen behavior, effectively allocating resources for the equilibrium state the queen searches. After the wasp attack, they quickly recover back to their previous numbers. Like in the Conservative_Respectful the colony can withstand the attack of the wasp losing some bees, but recovering them afterwards due to the high amount of food available as we can see in Figure 6.



Considerate_Social

For this strategy, it shows initial health growth but then fluctuates and declines constantly (Figure 7) and although it survives the maximum number of steps, continuing the simulation the predicted result is slow colony extinction similar behavior tendencies to "Greedy_Social" bees, but a bit more stable and sustainable.

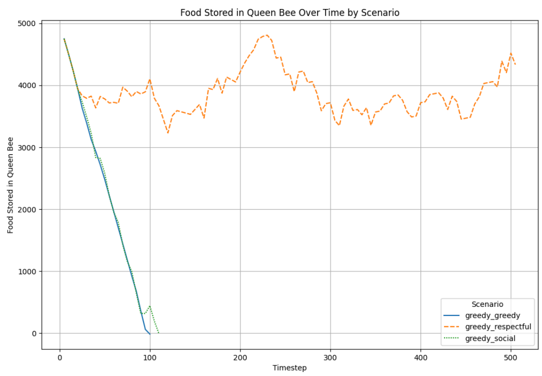


6. Further Exploration

Resource Scarcity and Abundance:

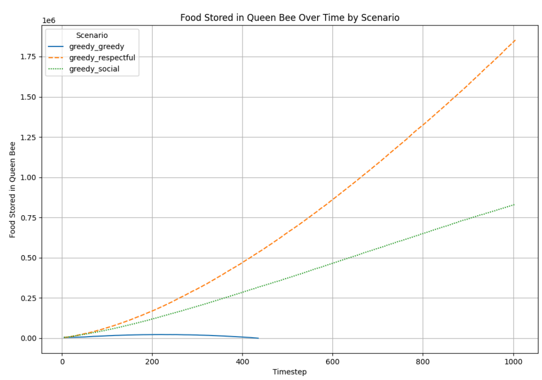
To explore the effects that environment variables may have on a single population of bees, (without wasps and other colonies interfering), we modeled:

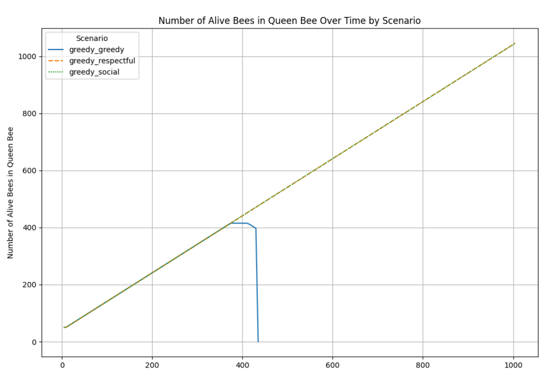
Resource Scarcity: by reducing the flower density in the grid by a significant amount. Now, it is expected that the bee species that has the best coordination, would turn out to be the best performant. These were the results:



As we may observe, only the Respectful Bee species could survive and keep a balance of pollen gathering rate in this hostile environment. The others were similarly bad at coordinating in a poor environment.

Resource Abundance: by simply increasing the flower density. It is expected that every bee will survive, since there are no blockers to gathering the desired pollen quantity. These were the results:





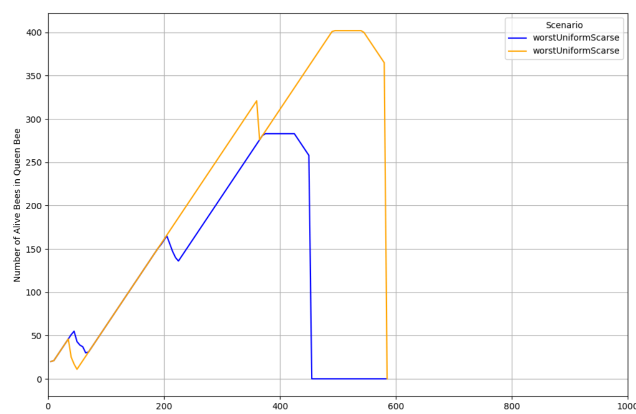
Surprisingly, greedy bees could not survive, even when food is plentiful. This is an evident effect of overpopulation. If we take a look at the population growth, we can see that the Greedy Bees became unsustainable and reached a point of no-return. It was impossible for them to find a balance without a better coordination algorithm.

Obligatory: since there are no wasps in these environment variations, there is no reason to keep any bee in the beehive. This is why the GreedyQueenBee is relatively better. To keep the information as clean as possible, we will omit the other variants of Queen Bee species.

Environmental Variability:

To investigate the least effective strategies in terms of stability and environmental adaptability, namely Greedy_Greedy and Considerate_Greedy, we experimented with various parameters to identify a sustainable environment for these combinations. Despite these adjustments, both strategies consistently exhibited problematic behavior.

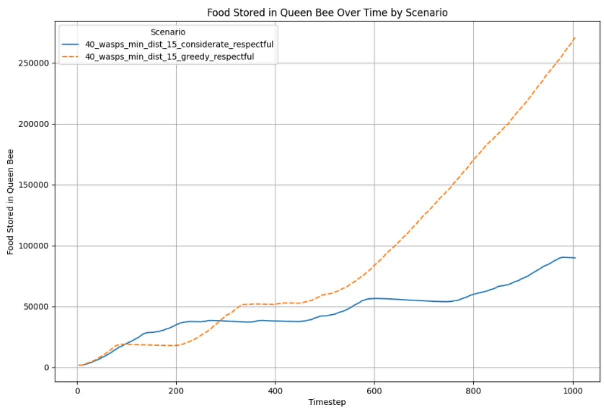
In the absence of communication or collaborative (hierarchical) strategies, these approaches failed to sustain the attended growth, proving unable to adapt to their environment and ultimately reaching collapse, even in the absence of Enemy Agents (wasps). The best outcomes were observed under conditions of uniform and scarce resource distribution, which naturally limited resource gathering, yet these results still fell short of achieving long-term sustainability.



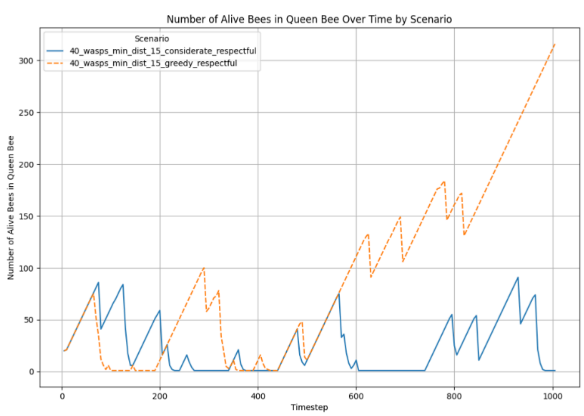
Impact of Predation:

This study examines the resilience of bee colonies under increased wasp threats by analyzing how two optimal bee-queen bee combinations, Greedy_Respectful and Conservative_Respectful, cope with a high number of closely spawned wasps at the simulation's start. The study focuses on the colonies' defensive responses, resource management, and health recovery post-predation, providing insights into which strategies most effectively mitigate intensified predation pressures and facilitate recovery and adaptation.

As we can see in the following figure, greedy queen bees are more likely to survive in such scenarios because their main focus is on obtaining food.



In the case of the conservative bees, we can see that they were on the verge of death several times, and all it took was a more coordinated attack by the wasps to destroy the hive.



The greedy approach contrasts with the conservative one, which, while potentially providing stability under normal conditions, seems less adaptable to sudden increases in predation.

7. FUTURE WORK

Hybrid Strategies:

For future project testing and development, hybrid strategies that combine different bee types or queen bees with mixed approaches should be explored to identify new effective strategies that leverage the strengths of various methods.

One potential hybrid strategy could involve combining Considerate_Social with Conservative_Social. This approach would aim to merge the expansion tendencies of the Considerate_Social strategy with the resource preservation characteristics of the Conservative_Social strategy, potentially resulting in a controlled, stable, and efficient approach.

8. CONCLUSION

Our study successfully utilized a multiagent system to simulate the complex interactions within bee colonies. We discovered that certain foraging strategies, particularly those that balanced resource gathering and colony defense, significantly enhanced colony sustainability and resilience. Strategies that overly prioritized aggressive resource exploitation often led to instability and collapse. These findings underline the importance of strategic resource management in maintaining colony health and highlight the potential of adaptive, hybrid strategies for future exploration.

9. NOTES

The demo video is available in the source files for our project and also [here](https://youtu.be/QQ6ufTtMS0k) (https://youtu.be/QQ6ufTtMS0k)

The source files for our project also include the original plot images (and many omitted plots), if you are having trouble viewing them in this document.