On the Nature of the Honeybee

Simulating Colony Collapse Disorder due to environmental stressors in Honeybee Colonies through Agent-Based Modeling using NetLogo

Abstract

Colony Collapse Disorder threatens honeybee populations crucial for pollination. This paper utilizes an agent-based model in NetLogo, enhancing the BeeSmart Hive Finding model by incorporating pesticide pollution and pathogen-infected hives. Extensive simulations reveal that pathogen strength significantly elevates bee mortality and increases the likelihood of colony collapse more than pollution levels. Feedback loops from stress accumulation accelerate bee deaths, while collective intelligence aids in locating optimal hives. However, bees' inability to detect pathogens and pollution intensifies colony decline. This research highlights the importance of feedback mechanisms and self-organization in complex systems, providing insights into the dynamics of CCD.

Introduction

Honeybees are integral to global ecosystems as primary pollinators for a vast array of plant species, including many crops essential for human consumption [1]. In recent years, the alarming phenomenon known as Colony Collapse Disorder (CCD) has threatened bee populations worldwide, leading to significant ecological and economic concerns [2]. CCD is characterized by the sudden disappearance of worker bees from a hive, leaving behind the queen, immature bees, and ample food supplies [3]. Despite extensive research, the exact causes of CCD remain elusive, with factors such as pesticides, pathogens, habitat loss, and environmental stressors being implicated [4].

Understanding the complex interplay of factors contributing to CCD requires a systems thinking approach that considers the behaviors and interactions of individual bees within their environment. Agent-based modeling provides a powerful tool for simulating such complex systems, allowing for the exploration of emergent phenomena resulting from simple rules at the individual level. By modeling bees as autonomous agents interacting with each other and their environment, we can gain insights into how local interactions can lead to global patterns, such as the collapse of a colony.

This project aims to investigate the dynamics of CCD through an agent-based model built in NetLogo [5], adapted from the BeeSmart Hive Finding model [6]. The original model demonstrates how scout bees collectively decide on a new hive location through self-organizing behaviors and waggle dances. By extending this model to include environmental stressors like pollution and infected hives, we can simulate the impact of these factors on bee behavior and colony health. This adaptation allows us to explore how individual stress accumulation and mortality can lead to feedback loops that contribute to the collapse of the entire colony.

The adapted model incorporates key concepts discussed in the course, such as feedback loops and self-organization. It demonstrates how local interactions and simple behavioral rules can lead to complex system-level outcomes. By simulating the effects of environmental stress on bee populations, the model provides a computational framework to investigate potential mechanisms behind CCD, contributing to our understanding of this critical ecological issue.

Model

The agent-based model developed for this project simulates CCD in honeybee colonies by extending the original BeeSmart Hive Finding model using NetLogo. This adaptation incorporates environmental stressors, namely pesticide pollution and pathogen-infected hive locations to explore their effects on bee behavior and colony stability.

The environment is represented by a two-dimensional grid containing two types of agents: Hive sites (patches) and scouts (turtles). Sites are potential new hive locations, each assigned a quality score and an infection status. Polluted areas are introduced as clusters of red patches outside a designated safe radius around the central swarm, simulating environmental contaminants. Scout bees are individual agents tasked with exploring the environment, discovering hive sites, and communicating findings through waggle dances.

Upon initialization, the setup procedure clears the environment and configures hive sites and polluted areas. A specified number of hives are randomly placed around the swarm, with some designated as infected based on user-defined parameters. Polluted clusters are created outside the safe radius to represent areas affected by pesticides or other pollutants.

A population of 100 scout bees is then created near the center. Each bee is assigned attributes such as home location, stress level, and task-related variables. A subset of these scouts are designated as initial scouts, responsible for exploring new hive sites after a randomized delay. Bees operate as state machines, transitioning through tasks like discover, inspect-hive, go-home, dance, re-visit, pipe, and take-off.

During exploration (discover), scouts search for nearby hive sites. Upon finding a site, bees inspect its quality and infection status. Inspecting infected hives or moving through polluted areas increases a bee's stress-level (**Figure 1a**). If a bee's stress exceeds a predefined max-stress threshold, it is removed from simulation. This might be due to the bee getting disoriented and flying in the wrong direction, or dying from a parasite infection that was present in the hive location the bee was inspecting.

After inspection, scouts return to the swarm to communicate their findings through waggle dances. The duration and enthusiasm of these dances are proportional to the hive's quality, influencing the likelihood of other scouts following the dance and inspecting the advertised site. If a quorum of scouts supports a particular hive, the colony decides to relocate, initiating the pipe and take-off states.

To prevent premature colony collapse due to insufficient exploration, the model ensures a minimum number of active scouts (minimum-active-bees) by activating idle bees when necessary. The simulation progresses through discrete time steps managed by the go procedure, which updates bee tasks, adjusts stress levels, and monitors colony health. The model can terminate in two ways (**figure 1b**): First, if the scout population drops to 50% of the original size, the colony can no longer sustain itself and it collapses. Second, since bees lose interest in hives that were already investigated with each visit, after a time it is possible that no suitable hive was found and there are no more hives to be visited. This means the hive was not able to find a new location to migrate to and it collapses.

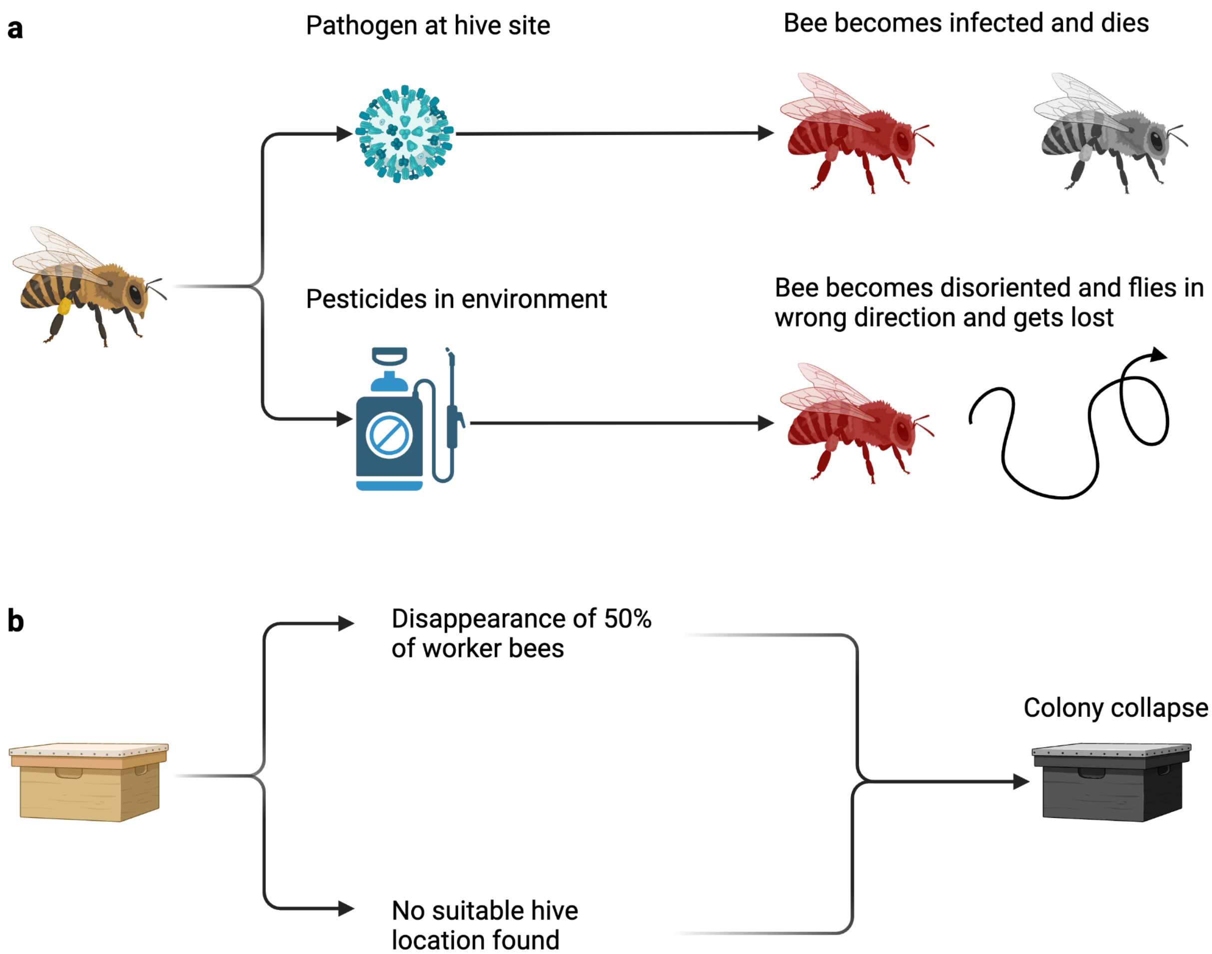

Figure 1: Illustration mechanisms affecting CCD in the simulation. **a**, Bees accumulate stress in two ways: By pathogens at hive sites and pesticides in the environment. This can lead to them dying from the pathogen or getting disoriented and flying off in the wrong direction. **b**, Likewise, a colony can collapse in two ways: It can die due to the sudden disappearance of at least 50% of its worker bees, or it can die due to failure to find a new suitable hive location to migrate to. Created with biorender.com.

Key parameters such as pollution-strength, infection-strength, max-stress, and others are adjustable via NetLogo's interface (**Figure 2**), allowing users to investigate various scenarios. Visualization tools, including plots for committed bees, on-site bees, and mortality rates, provide insights into the colony's dynamics over time.

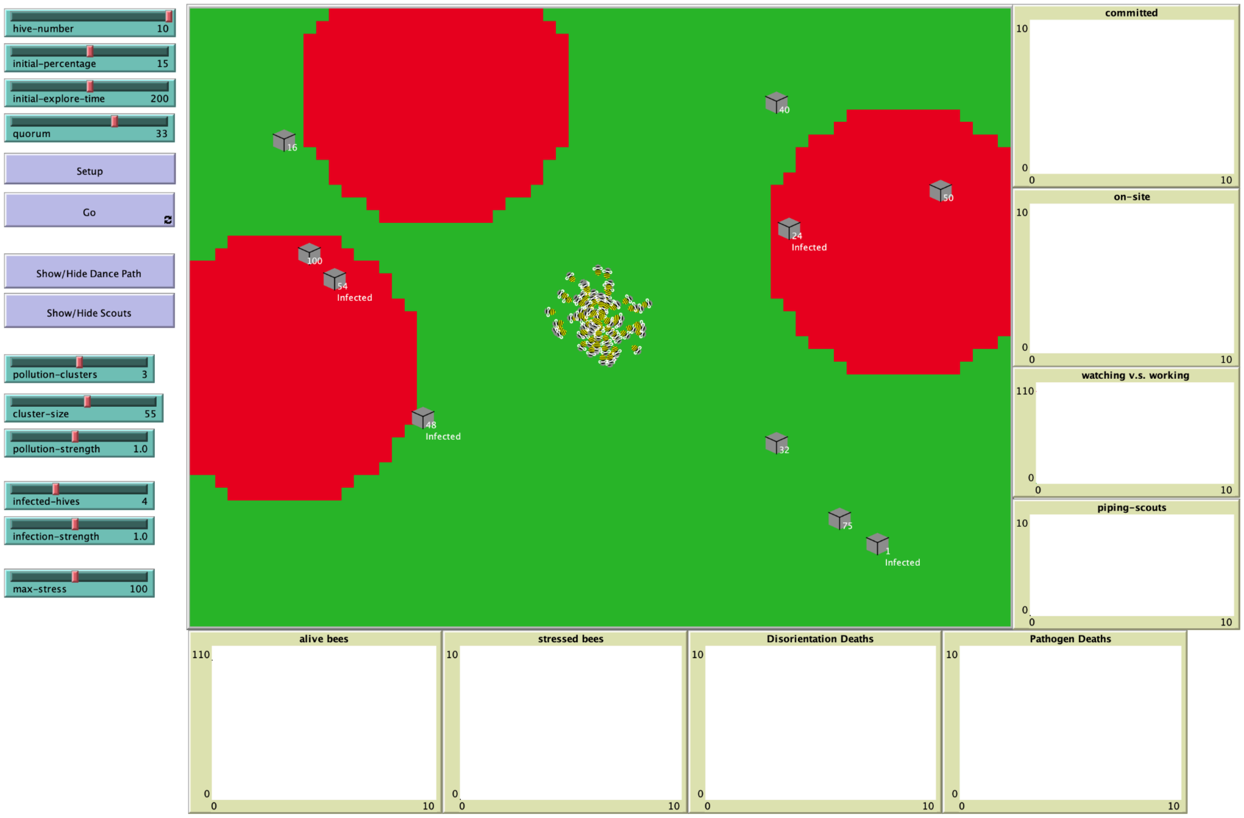

Figure 2: NetLogo interface with default parameter values prior to simulation.

In summary, this model effectively captures the interactions between individual bee behaviors and environmental factors, demonstrating how local stress accumulation and feedback loops can lead to the emergent phenomenon of Colony Collapse Disorder. By incorporating elements of pollution and hive infections, the simulation offers a framework to study the potential mechanisms driving CCD within complex systems.

Results

Default parameter values represent significant risk for the colony

To determine the likelihood of the colony to survive when parameters are set to default values, I ran 100 simulations, using NetLogo's BehaviourSpace tool, to account for stochastic variations, such as random placement of pollution zones and hive locations. Out of the 100 runs, the majority resulted in a "Success", meaning the colony was able to survive without collapsing, with 72 successful outcomes (**Figure 3a**). However, in the rest, the colony collapsed due to either "No hive visits", where the bees were unable to find a suitable hive, or due to "Population collapse", which occurred when the population dropped below 50% of its initial size. The distribution of steps until either collapse or success varied, with most runs completing in around 1000 steps, while some extended to as many as 6000 steps (**Figure 3b**).

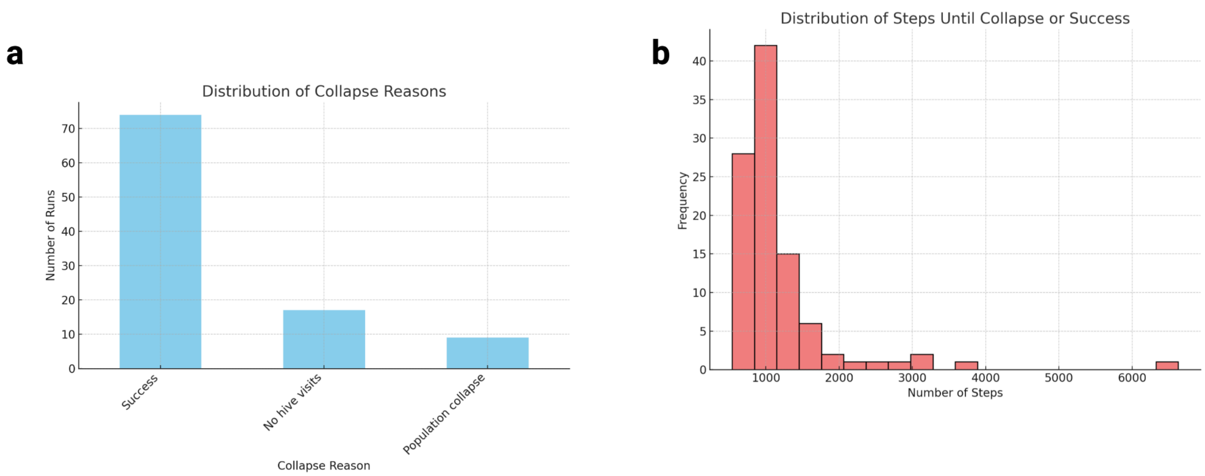

Figure 3: Distribution of outcomes using default parameter values. **a**, Distribution of hive outcomes in terms of survival rates. **b**, Distribution of step counts until model completion.

Large scale simulation with varying parameter values displays sensitivity to initial conditions

Next I investigated how the survival rates depend on initial conditions (**Figure 4).** Using NetLogo's BehaviourSpace tool I ran a total of 2025 simulations with varying initial conditions. Each combination was run 25 times to account for stochastic variability. Other parameters than pollution and infection strength were varied as well, but not displayed here for space reasons.

The hive demonstrates significant variations in survival rates, depending on conditions. However, it is interesting to note that even in severe conditions the hive still displays a 50% likelihood of adapting and surviving. Furthermore, we can observe that the hive's survival chances appear more sensitive to infection strength than to pollution strength.

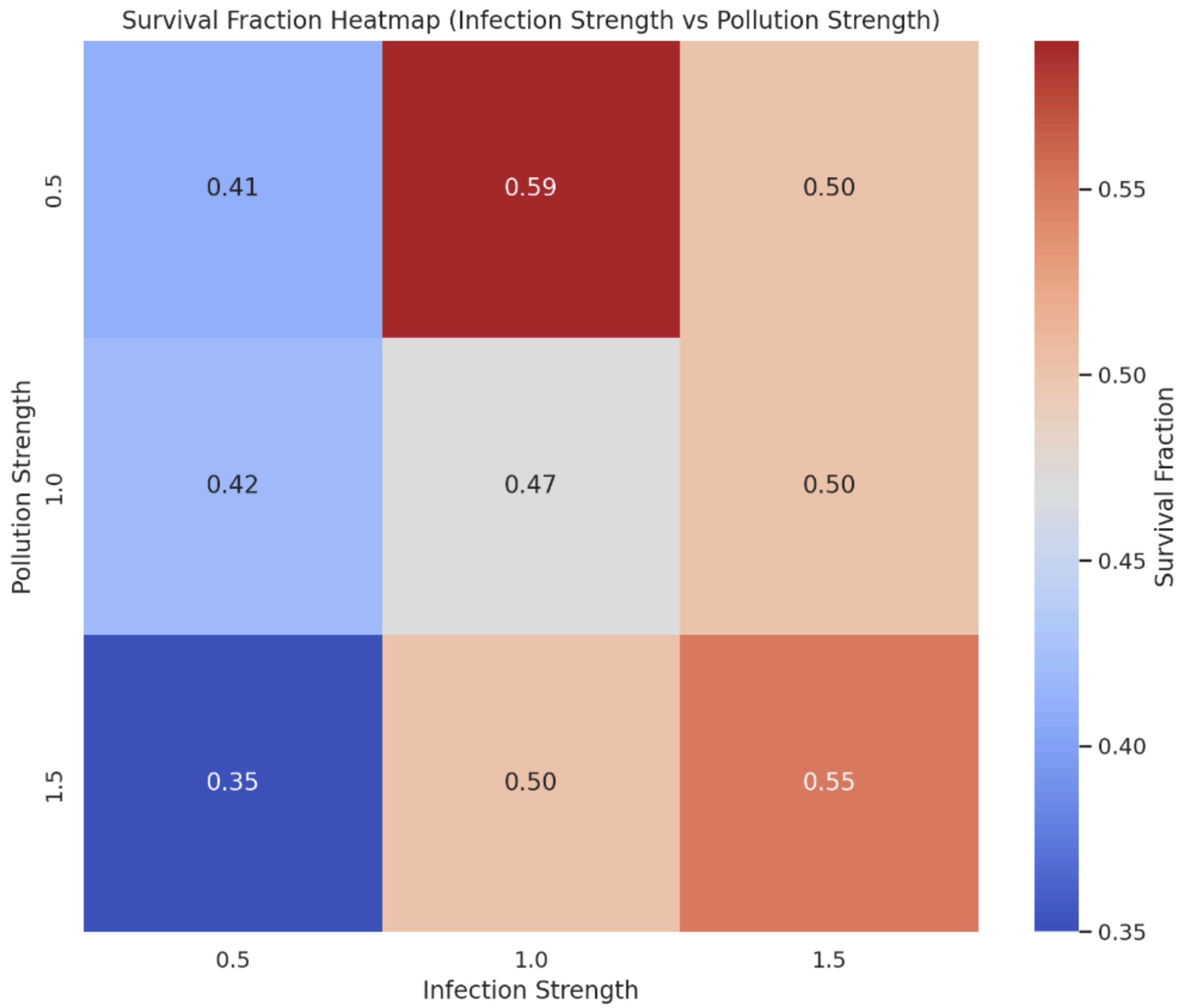

Figure 4: Heatmap showing the hive survival rate with varying levels of infection and pollution strengths.

Bees are unable to sense pathogen and pollution levels thus causing a feedback loop leading to colony collapse

Figure 5 shows how the bee population declines when leading to a colony collapse due to disappearance of worker bees. This is a common pattern visible in many scenarios, which is why it was chosen as an example here. In this case, pathogen deaths were clearly the driving factor causing the death of worker bees, with it being responsible for around 4 times as many deaths as disorientation deaths.

Furthermore, we can observe that the decline in the population, and rise in the amount of stressed bees (a bee gets classified as stressed when its stress level surpasses 50% of the stress level that causes death), accelerates over time. This is due to bees not being aware of the presence of the pathogen (which real bees in nature cannot sense, they look for location, food availability, and so forth, but not pathogens), and directing more and more bees to the otherwise promising looking hive location. Not being aware that this causes the infection of many more bees causing a feedback loop, the decline accelerates.

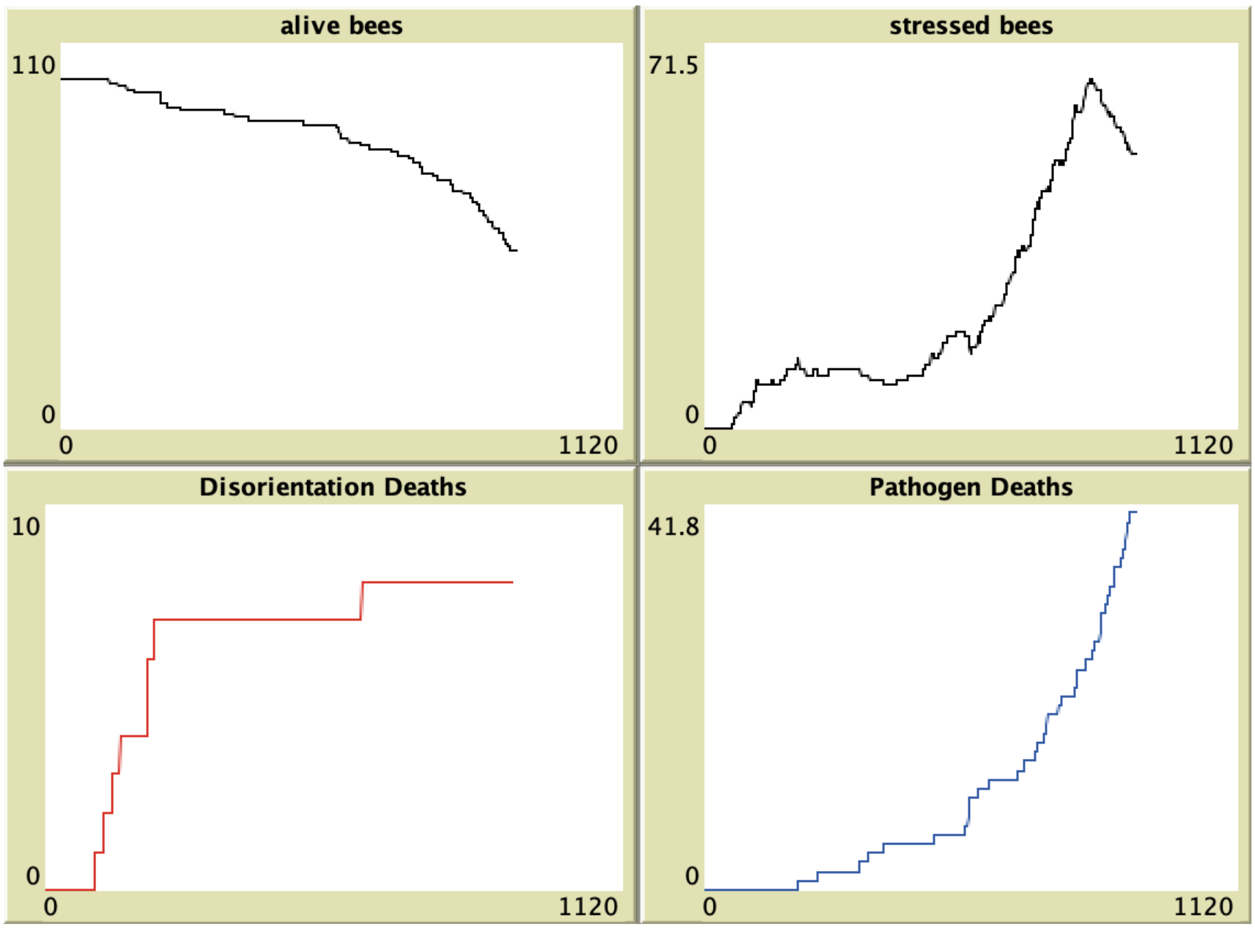

Figure 5: Typical evolution of plotted metrics when colony collapses due to disappearance of worker bees.

Bee swarm exhibits collective intelligence by finding the best non-infected hive outside of pollution zones

Remarkably, the bee swarm, in many cases, still is able to navigate around these dangers and find good, albeit suboptimal, solutions. **Figure 6** demonstrates such a case, where the best hive (quality = 100) is infected, and the next best hive (quality = 75) is in a polluted zone. Expectedly, the hive does take some losses in population size, as can be seen from the graphs, but the swarm manages to find the best hive location that is not in a polluted zone or infected (quality = 54, in this case).

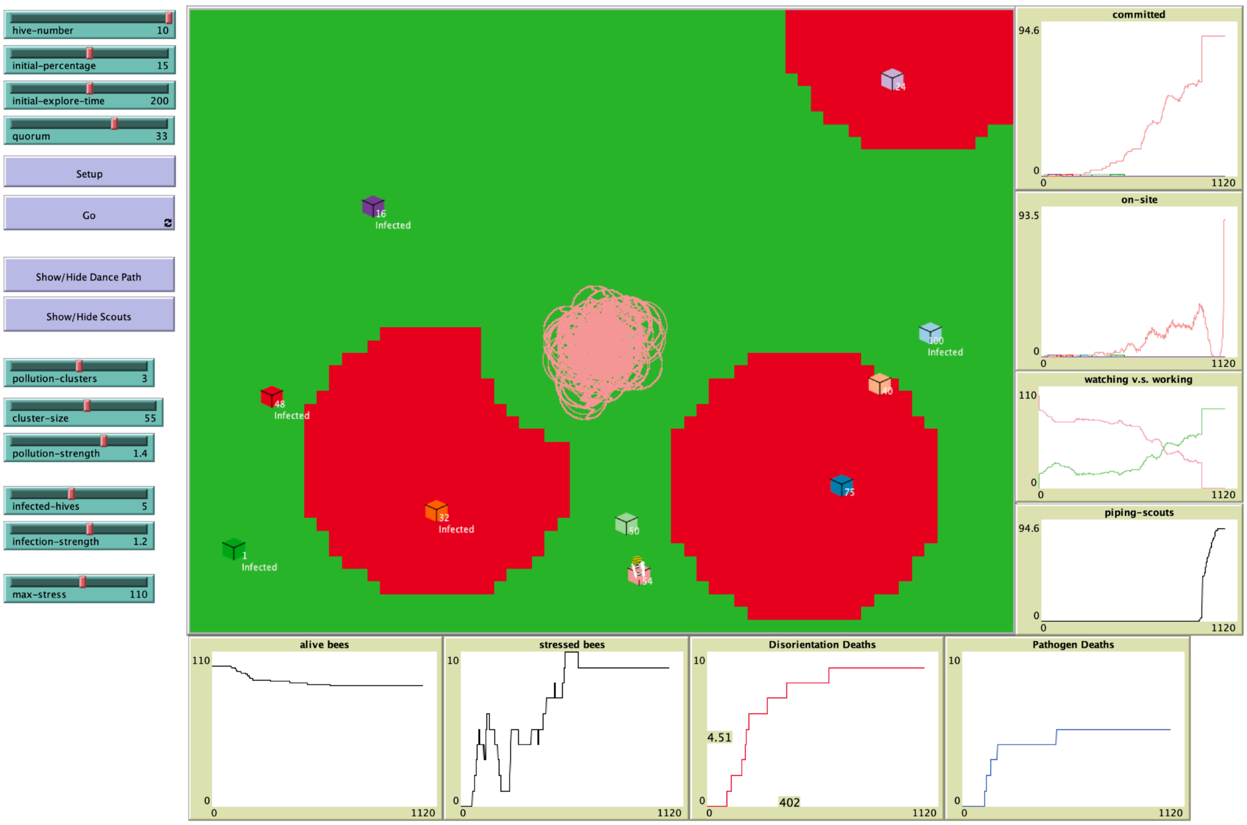

Figure 6: Scenario where hive successfully identifies the highest quality hive that is not infected or in a polluted area.

Discussion

The simulation results highlight the dynamics of CCD through the framework of complex systems and agent-based modeling. By integrating environmental stressors like pollution and infected hives into the BeeSmart Hive Finding model, this paper demonstrates how individual bee behaviors and stress accumulation can lead to emergent colony-wide collapse.

A significant observation is the greater sensitivity of colony survival to infection strength compared to pollution levels. This highlights the role of negative feedback loops, where increased pathogen-induced stress accelerates bee mortality, thereby reducing the colony's ability to sustain essential functions. Such feedback mechanisms exemplify how local interactions and stressors can amplify vulnerabilities, leading to systemic failure within the bee population.

The use of BehaviorSpace for extensive simulations shows the utility of agent-based models in capturing emergent phenomena. By systematically varying parameters, the model reveals critical thresholds that influence colony outcomes, showcasing how simple rules at the individual level can result in complex, large-scale behaviors. Additionally, the ability of the bee swarm to self-organize and adapt to find optimal hive sites illustrates the principles of self-organization and emergence, fundamental concepts in complex systems.

However, the model also highlights limitations of the collective hive intelligence, such as the bees' inability to detect pathogens and pollution, which creates detrimental feedback loops leading to accelerated colony decline. Furthermore, incorporating more nuanced behaviors and additional environmental factors in future iterations could provide a more comprehensive understanding of CCD.

Overall, this paper shows how agent-based modeling and the exploration of feedback loops can offer valuable insights into complex ecological issues like Colony Collapse Disorder, reinforcing the importance of systems thinking in addressing multifaceted environmental challenges.

References

1. Klein, A.-M. *et al.* Importance of pollinators in changing landscapes for world crops. *Proc. R. Soc. B Biol. Sci.* **274**, 303–313 (2007).
2. Evans, J. D. & Chen, Y. (Judy). Colony Collapse Disorder and Honey Bee Health. in *Honey Bee Medicine for the Veterinary Practitioner* 229–234 (John Wiley & Sons, Ltd, 2021). doi:10.1002/9781119583417.ch19.
3. vanEngelsdorp, D. *et al.* Colony Collapse Disorder: A Descriptive Study. *PLOS ONE* **4**, e6481 (2009).
4. Brown, M. J. F. & Paxton, R. J. The conservation of bees: a global perspective. *Apidologie* **40**, 410–416 (2009).
5. Tisue, S. & Wilensky, U. NetLogo: A Simple Environment for Modeling Complexity.
6. NetLogo Models Library: BeeSmart Hive Finding. https://ccl.northwestern.edu/netlogo/models/BeeSmartHiveFinding.