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Modeling of communication within termite-like population using agent-based model: pheromone evaporation effects

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Abstract. In this study, we evaluate the communication of a termite-like population using agent-based modeling (ABM) with a specific focus on pheromone-based communication. While termites can also communicate through tactile and vibration signals, our model only considers pheromone communication in the context of foraging. The study examines the effect of trail-following pheromones by computing the mean free path of the termites and how pheromone evaporation impacts foraging efficiency. Three basic rules govern the ABM model: (i) agents wander randomly in search of food, but only mature agents can harvest it, (ii) agents sense and track pheromone trails that direct them to food, and (iii) reproduction occurs once sufficient food supplies are stored, while starvation due to aging results in death. Simulation experiments with various scenarios of pheromone concentration show that low evaporation rates enhance self-organization and foraging efficiency. Future research will include statistical verification to measure these effects.

1 Introduction

Evaporation is a natural phenomenon and a fundamental process in various physical and ecological systems. It plays a crucial role in the water cycle, which directly influences soil moisture distribution and the stability of living organisms [1]. One organism closely linked to soil moisture is the subterranean termite (Macrotermes sp.). Termites are social insects that contribute significantly to soil fertility and ecosystem stability. They enhance soil aeration, improve water absorption and storage, decompose organic matter, enrich the soil with humus, and fertilize the soil during their feeding and nesting activities [2]. However, despite their positive contributions, termites pose a threat to the environment.

Termites are also a worrying threat to the environment. They are known as destructive pests because they can consume cellulose-containing materials such as wood, paper, and textiles. This ability to manage lignocellulose makes termites a major contributor to methane, or greenhouse gases, in the atmosphere [3]. Termites also cause structural damage to artificial buildings, resulting in significant financial losses and safety risks to occupants [4].

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The duality of termite roles has prompted researchers to devise effective termite management strategies. However, the complexity of the evaporation phenomenon within termite colony ecosystems, including temperature and humidity variables, makes it challenging to control experiments, thus making simulation an alternative solution. Termites heavily depend on chemical communication, particularly TFP, to coordinate their foraging activities. Pheromones are chemical compounds released by living organisms, especially insects, to communicate with others of the same species. Pheromones associated with the TFP phenomenon are secreted from the sternal gland located at the base of the termite's body, known as the sternum, and are then released onto the ground surface or onto objects they encounter.

TFP occurs when termites gather food from a source and leave a pheromone trail back to the nest. This pheromone prompts other termites to follow the trail from the nest to the food source. The TFP phenomenon is crucial for the foraging process of termite colonies. Previous studies, such as those by Hedayatzadeh *et al.* (2010) [5] and Ahmad *et al.* (2018) [6], have demonstrated that pheromones improve collective foraging performance. However, our study specifically examines the impact of pheromone evaporation rates on colony dynamics using the agent-based modeling (ABM) approach. Therefore, it is essential to investigate the evaporation rate of the TFP phenomenon, as indicated in the research by Oudenhove et al. (2011) [7], which found that temperature significantly influences the evaporation rate of the TFP phenomenon. Nonetheless, research on how temperature affects the evaporation rate of termite pheromones is still incomplete.

Therefore, an alternative solution to this complex challenge is simulation. One of the simulation systems that can be used is an agent-based modeling system, also known as an agent-based model (ABM). While ABM has received significant attention in simulating insect behavior, previous models specifically focused on termite behavior have not adequately accounted for the role of pheromone evaporation in food procurement efficiency. Although research by [8], [9] has examined the emergent patterns of termite swarms, pheromone degradation effects have not been exhaustively explored. ABM allows each agent to interact with the environment [10], facilitating an understanding of behavioral patterns that are difficult to measure experimentally. For instance, regarding the distribution of environmental humidity and temperature in termites, ABM will provide a more straightforward approach to modeling this complex phenomenon. Thus, this study aims to analyze previous research by simulating the impact of various evaporation rates on the viability and functional efficacy of termite colonies and the round-trip ratio of agents in search of food.

2 Theoretical Background

2.1 Trail-following Pheromone

Communication among individual social insects, like termites, is crucial for the colony's functioning. Termites use several mechanisms to communicate, with chemical communication being the most common form [11]. This form of chemical communication during foraging is also referred to as the TFP phenomenon. The pheromone communication of termites is well documented, involving over 68 species. One chemical molecule responsible for establishing pheromone trails is (Z, Z, E)-3,6,8-dodecatrien-1-ol, found in 12 species of Rhinotermitidae and 24 species of Termitidae [12]. For termites, foraging is a collective activity involving hundreds to thousands of individuals, coordinated through pheromones. Worker termites that locate food leave a trail by releasing pheromones on their return to the nest. Research by Hedayatzadeh et al. (2010) [5] supports this, as they discovered an algorithm for optimizing food search paths (Termite Colony Optimization) in termite colonies influenced by pheromones. Additionally, Ahmad et al. (2018) [6] found that pheromones released by termites can draw other individuals to follow the same path, thereby enhancing food search efficiency.

2.2 Agent-Based Modeling

ABM is a computational modeling technique that employs a complex systems modeling approach to simulate the interactions of agents with their environment, aiming to understand the behavior of the overall system [13]. The interactions among agents, governed by simple rules, result in changes to system dynamics. The focus of ABM is on the diversity of agents within the population, distinguishing it from other modeling techniques such as discrete event simulation and system dynamics [14]. To effectively implement ABM-based modeling, three key elements must be present: first, a collection of agents with defined attributes and behaviors; second, the relationships and methods of interaction among the agents; and third, the environment in which the agents operate [10]. These components are essential for understanding how agents can interact with one another, as the fundamental principle of ABM simulation is based on connectivity or relationships between agents. ABM is an effective approach for simulating complex biological interactions, allowing for individualized agent behavior while capturing emergent population dynamics. Our model incorporates agent interactions, movement rules, and environmental influences, with these rules reflecting the phenomena present in the system. These rules result in a collection of interactions among agents that promote diversity among them. Consequently, the observed phenomena later demonstrate the interactions between agents due to their evident connectivity [8the figure is as close as possible after the point where it is first referenced in the text. If there is a large number of figures and tables, it might be necessary to place some before their text citation.

3 ABM Simulation

The simulation operates according to simple rules based on natural events. Agents possess characteristics such as age, hunger, and the capacity to release pheromones. The rules for this simulation are as follows: (i) agents randomly wander in search of food, but only mature agents can harvest it, (ii) agents sense and track pheromone trails that guide them to food, and (iii) reproduction occurs after adequate food reserves are stored, while the starvation of aging agents leads to death. Simulations were conducted using a two-dimensional agent-based model in the NetLogo environment to incorporate spatial constraints and allow a thorough exploration of pheromone dynamics. The models are systematically organized as a two-dimensional grid of $X \times Y$ cells, where each cell represents a unique location in the environmental setup. Each unique location connects to eight neighboring cells, both cardinal and diagonal, thus defining a setup often referred to as a Moore neighborhood. Each site can include:

1. A single attribute that indicates the presence of nutritional resources and nest (breeding sites). Nutritional resource availability decreases cumulatively as termites feed on them.
2. Termites exist as individual units with specific foraging habits. In the model structure, the entire termite population is denoted by n, where each termite goes through a behavioral cycle of food exploration, pheromone marking, and then returning to the nest.
3. Pheromone concentrations, like trail pheromones used for navigation, and chemical markers that are critical for colony organization.

The simulation is run for a fixed number of discrete time steps (tmax). At each time step, the model adjusts the spatial coordinates and behavior of individual termites, recalibrates pheromone levels, and evaluates overall colony performance. Food sources are randomly assigned across the grid. Worker termites are initially positioned near the nest site and begin foraging.

Every pheromone variant in the model is expressed by a continuous scalar field that is distributed evenly over all spatial positions. The pheromone concentrations undergo dynamic changes by diffusion and evaporation processes, performed at every five time steps. Diffusion occurs between cardinal neighbors and is represented by a temperature-dependent evaporation function, derived from the Clausius-Clapeyron equations:

$$f(T) = \frac{1}{1+\beta\times e^{\left(-\alpha\left[\frac{\Delta H\times 1000}{R}\left(\frac{1}{T_{ref}}-\frac{1}{T_{now}}\right)\right]\right)}} \tag{1}$$

$f(T)$ is the pheromone concentration at time step t, ΔH is the enthalpy of vaporization, which in this simulation ΔH is 20.47 [15], R is the gas constant, $Tref$ is the reference temperature, and $Tnow$ is the current temperature. This system regulates pheromone evaporation based on temperature, demonstrating that pheromone trails degrade more quickly at higher temperatures and persist longer at lower temperatures. Worker termites deposit trail pheromones when they return to the nest after locating a food source.

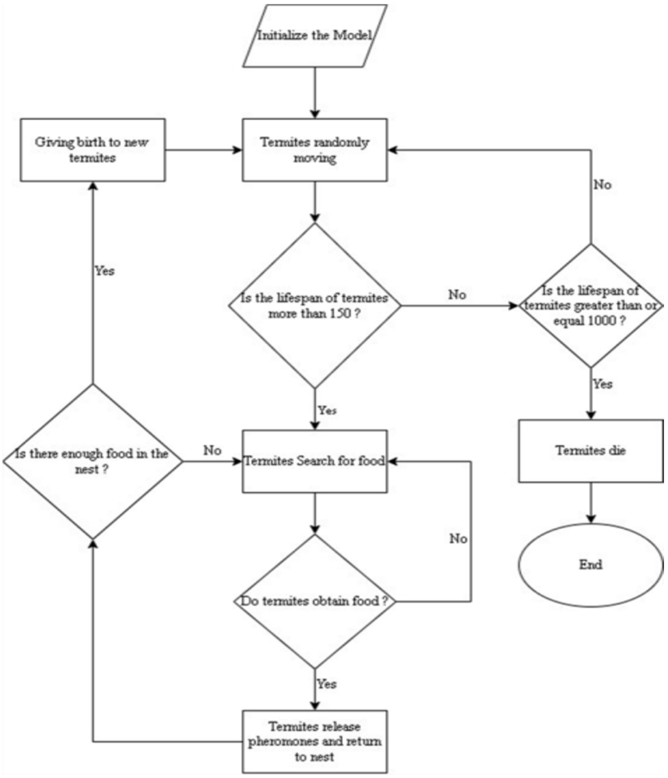


Fig. 1. Flowchart of the trail-following pheromone algorithm

There are six steps to establishing communication among termite populations. First, the initial conditions are established, including environmental factors such as pheromone concentration, food availability, and termite nests. Second, termites search for food; when they locate food, they check their age; if they are old enough, they collect the food and return to the nest. Otherwise, they continue to wander randomly. Third, termites lay down pheromone trails that gather food and head back to the nest, while pheromone evaporation occurs gradually. Fourth, termites near the pheromones follow the scent to the food source, collect food, and return to the nest. Fifth, the nest will produce new termites if there is enough food. Sixth, termites that deplete their energy will die. The algorithm of the termite communication model is illustrated in Figure 1.

4 Result and Discussion

Simulations were conducted using an agent-based modelling (ABM) approach. This approach demonstrates that the pattern of termite interactions with their environment, including the effect of pheromone evaporation, significantly influences population dynamics and foraging efficiency. The simulation effectively represents the TFP phenomenon through the release and evaporation of pheromones by termites, which has been shown to impact the behavior of other agents in following the trail and retrieving food.

In this study, we investigated the effect of three levels of evaporation on termite colony populations. In the low evaporation scenario, specifically at 0%, the pheromone released by the termites remains entirely stable without evaporating. This significantly impacts the interaction patterns among agents and the dynamics of the colony, leading to emergent phenomena such as self-organization. Conversely, at high evaporation rates, pheromone traces dissipate more quickly, resulting in more random movement behavior among the agents and reduced foraging efficiency, as demonstrated in Figure 2. The path marked in red shows that stable chemical signals facilitate communication between termite colonies. It is clear that at low evaporation levels, termite colonies take fewer steps in their food search due to the strong influence of pheromones. This is in contrast to the 5% and 10% evaporation levels, where movement becomes more random yet still allows for the emergence of self-organization phenomena.

Additionally, pheromones that do not readily evaporate lead termite colonies to gather in specific locations. This gathering happens because termites are continually drawn to the pheromone trails they detect. Furthermore, the low evaporation rate also enhances the efficiency of food searching. In this simulation, a colony is found to collect more food in the nest, accumulating nine units, whereas another nest collects only one unit. This disparity indicates a reliance on the strategic location of the food source for the colony's survival. This is also why, at low evaporation concentrations, the ability of termite colonies to thrive diminishes, causing the population to dwindle gradually over time (Figure 3a).

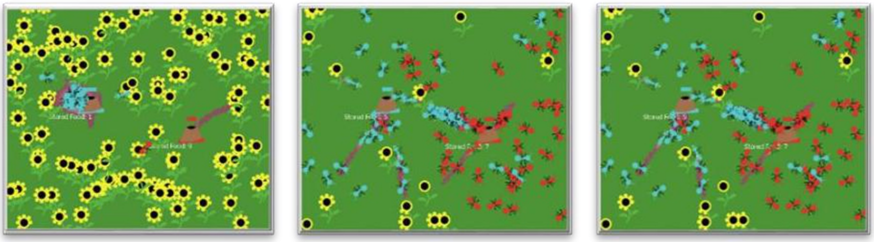
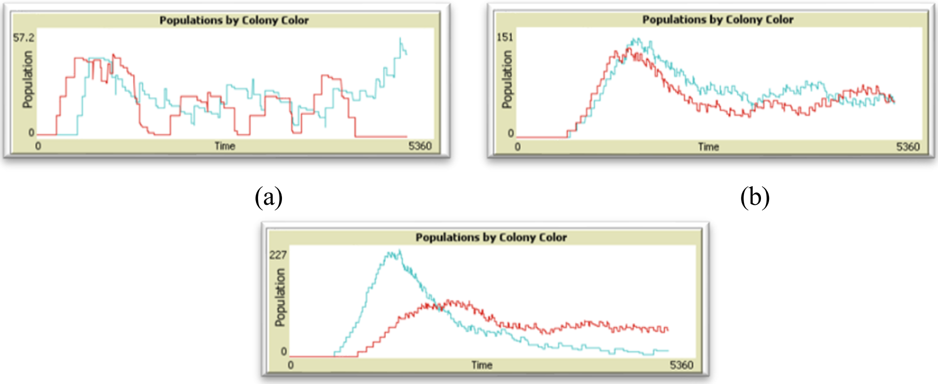

(a) (b) (c)

Fig. 2. Trail-following pheromone Phenomenon with Different Evaporation Rates: (a) 5%, (b), 5%, (c) 10%

When the evaporation rate was increased to 5%, termite colonies showed a significant population increase. Slightly faster evaporation keeps the pheromone trail accessible long enough for termites to follow it without clustering in one spot for an extended period. This leads to a more stable population and prolonged survival of the termite colony (Figure 3b).

Conversely, if the evaporation rate is significantly elevated to 10% (Figure 3c), there is a sharp rise in the population. This happens because the pheromone evaporates quickly enough for termites to reach it directly, preventing prolonged accumulation while still enabling termites to experience the pheromone phenomenon associated with trail-following. Although the results suggest differences between evaporation rates, no statistical tests have been performed in this study. Future research should incorporate statistical analyses such as ANOVA to quantitatively evaluate the significance of these differences.

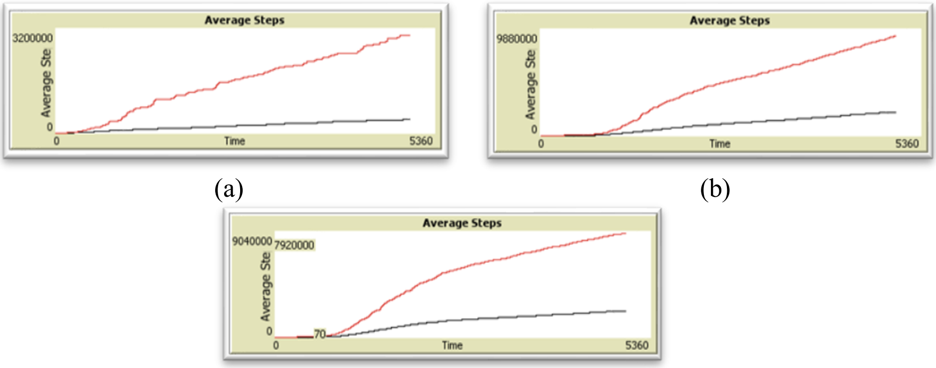


(a) (b)

(c)

Fig. 3. The effect of Evaporation Rates on Termite colony Population for: (a) 0%, (b), 5%, (c)10 %

This study also examined the average number of steps influenced by the evaporation rate of the trail-following pheromone (Figure 4). The red line represents the average number of steps required for termites to return to their nest, while the black line indicates the average number of steps needed to find food. At low evaporation rates, the number of steps tends to increase linearly (Figure 4a), suggesting that pheromones remaining in the environment longer help termites find paths more efficiently. However, as the evaporation rate increases (Figures 4b and 4c), a linear rise in steps back to the nest is observed. This phenomenon shows that the pheromone trail dissipates more quickly, requiring termites to take additional time and steps to return to the nest.



(a) (b)

(c)

Fig. 4. The effect of Evaporation Rates on Average Steps: (a) 0%, (b) 5%, (c)10 %

5 Conclusion

This study concludes that evaporation rates significantly affect termite foraging efficiency. Further research can explore how optimal evaporation rates influence the sustainability of termite colony populations. Based on our results, we suspect that pheromone regulation plays a crucial role in optimizing termite foraging strategies, but more observational studies supported by statistical analysis are needed to confirm this hypothesis. By refining quantitative measures and incorporating additional behavioral mechanisms, this model can serve as a valuable tool for understanding the complex dynamics of termite foraging and potentially informing pest management strategies. To broaden understanding, agent-based modeling (ABM) can be enhanced by introducing new rules, such as competitive traits among termite colonies or other environmental factors. This could lead to a more realistic interpretation of the complex interactions within termite ecosystems, allowing for more effective colony management solutions.

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