Social Insects

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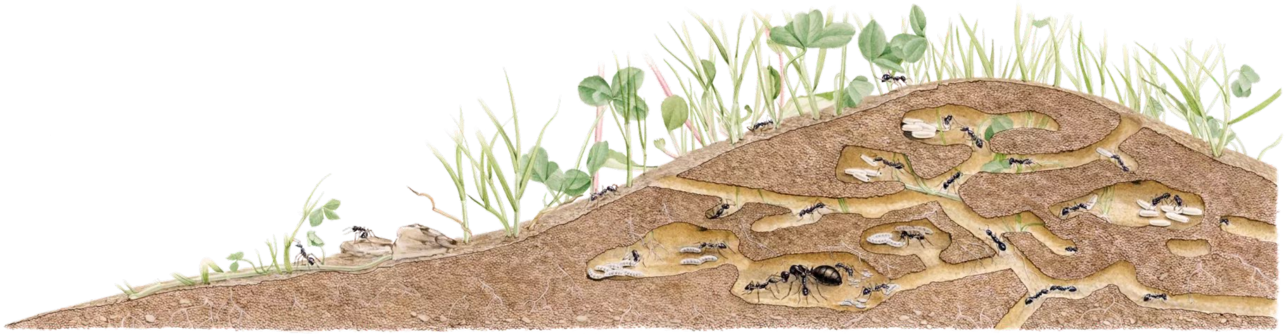
Ant Background

Ants form complex physical structures called **nests**, the structure of which can vary between species depending on their needs. Specifics of nest architecture may play a role in mediating the manner and speed with which information diffuses through the nest. Therefore, nest structure can provide insight into both biological and social aspects of the species in question. The rich social structure of ant colonies provides a number interesting avenues for research.



Ant Background

Information can transfer in a number of ways in ants; pheromones, antennation, and trophallaxis. In the first, ants leave different chemicals as they walk for either themselves or other ants to follow later. In both antennation and trophallaxis, physical contact is needed to pass information. The latter is usually used to pass messages related to food and the former is for everything else.

An example of antennation

An example of trophallaxis

Network Science

A **network** (or graph) is thought of as a set of nodes with a directed set of edges between them. A **time-aggregated network** is a collection of directed interactions which occur over some time window.

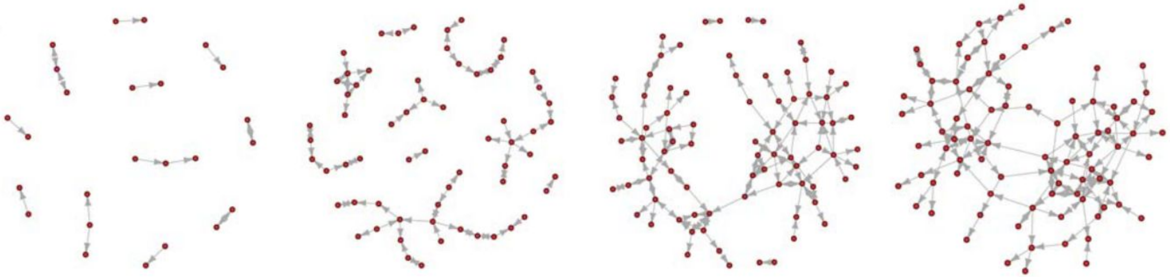


Image from ‘Information Processing in Social Insect Networks’ (Waters and Fewell)

Our Project

Our Question: How does nest structure affect the interaction rate and time-aggregated interaction networks of a colony?

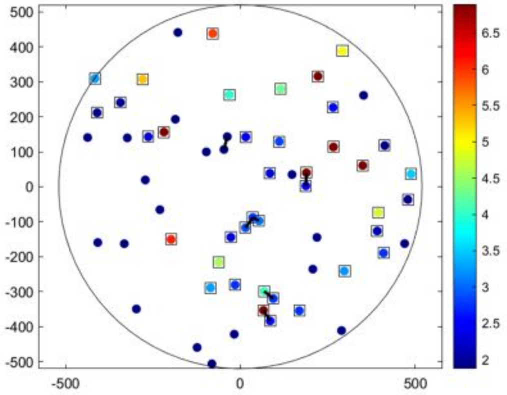
How we will answer this question:

- We will modify an existing model to better address our research question:
    - Replicate the physical reality of an ant nest by adding tunnels and walls
    - Add an adjacency matrix to track directed interactions

- We will compare different metrics for interaction rates and network topologies as nest shape, density, and spatial fidelity are varied. This will be done for a variety of preselected shapes which are each meant to study specific features of larger nest structures.

Previous Models

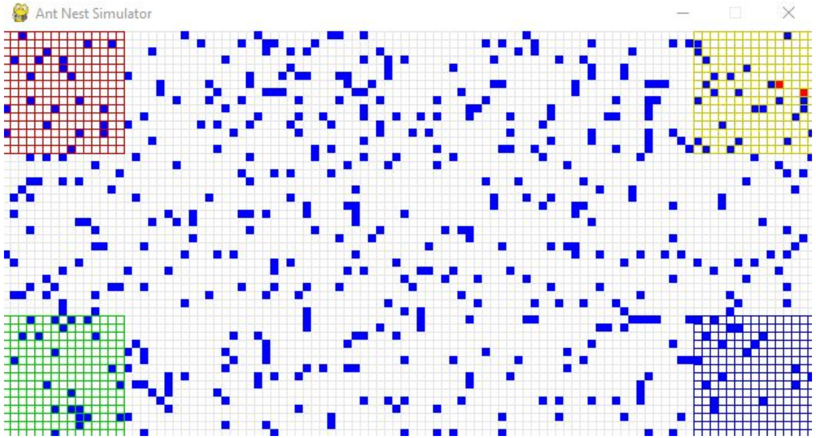
Existing models will either place agents on a rectangular grid or in a circle. In these models, ants are given a number of parameters to control speed, direction, information status, etc. The model then evolves in time with ants moving based on their surroundings and current state and interacting in a directed manner when entering some neighborhood of another ant.



Model from ‘Mechanistic modeling of alarm signaling in social ant colonies’
(Lin, Guo, Fewell, Milner)

Previous Models

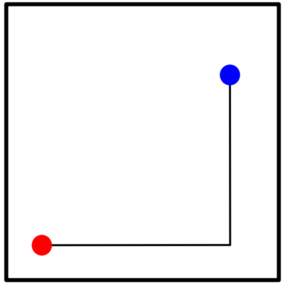
Another model was made to understand the effect of distinct **spatial fidelity zones**, which are areas associated with a particular task, on the distribution of ants over time and the rate of information flow between them.



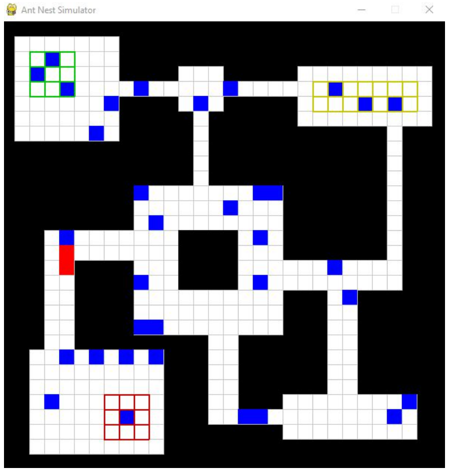
Model from ‘Dynamics of task allocation in social insect colonies: scaling effects of colony size versus work activities’ (Feng, Charbonneau, Qiu, Kang)

Previous Models

We decided to build a model based on the grid model since defining the more complex boundaries of a nest would be easier to do in a grid than a continuous space. However, simply using the same algorithm as the previous grid model would not be enough. In this model, ants calculate their distance from a task zone using the L1 distance from its center. Since this ignores obstacles between the ant and the spatial fidelity zone, some unrealistic behaviours arise if this is used on more complex boundaries.



L1-distance between two points in R2

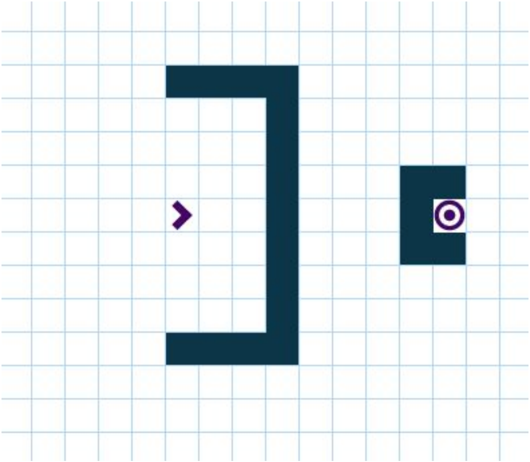


An example of the previous grid model with a more complex boundary

Notice that ants get stuck in corners as they try to walk directly through the wall to their task zone

A* Pathfinding

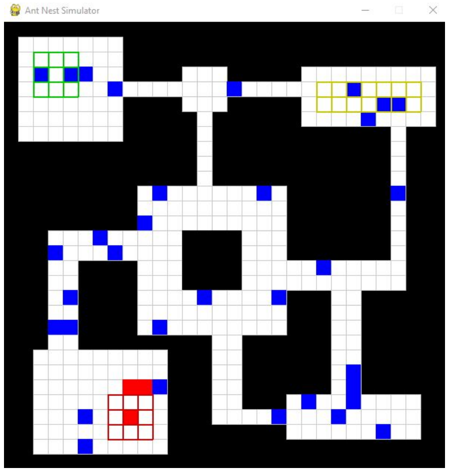
If we want ants to navigate obstacles, we need to endow them with some sort of path finding ability. The A* algorithm guarantees the shortest path between two points on a grid but can be computationally slow in many cases.



Animation from
https://clementmihailescu.github.io/Pathfinding-Visualizer/#

Our Model

By giving ants the ability to pathfind, they are able to more realistically move through the nest. Adding this relies on the assumption that the nest is saturated with enough pheromones for ants to be able to follow to their task zone.



An example of the our grid model with a more complex boundary and path finding

Ant Attributes

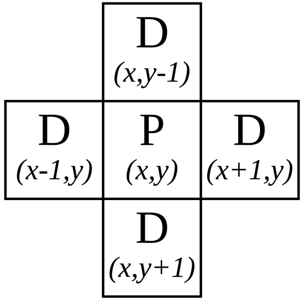
An ant A is described by a set of primary attributes which depend on time:

Differences between our model and the previous model are in red

- l(A, t), the location of the ant in the grid
- p(A, t), the task of the ant (between 1 and P)
- w(A, t), the walking style of the ant (either Random or Drifted)
  - Random: Ant randomly selects an open neighboring cell to move to with uniform probability
  - Drifted: Ant moves to next cell in path if open, if not, it moves to the open cell nearest to its task zone (in l1)
- f(A, t), the information status of the ant (either 0 or 1)
- path(A, t), the current route an ant is following (the optimal sequence of adjacent grid cells to get to S(p))

One assumption of the model is that task and walking style do not vary with time (since we are simulating the ants on a small time scale), ie. p(A, t) = p(A, 0) and w(A, t) = w(A, 0). Ants also have:

- NC(A, t), the set of grid cells which neighbor A (von Neumann neighborhood)
- N(A, t), the set of ants which neighbor A
- Beta(A), the probability an ant will respond to an interaction from another ant



Another assumption is that all ants have Beta(A) ~ Uni(0.3, 0.7).

Colony Attributes

A colony has a number of associated values:

- X, a set of integer coordinates considered to be in the nest
- Area, the size of the nest
- N, the number of ants
- P, the number of task zones
- S(p), the **spatial fidelity zone** associated with task p
- SF(p), the **spatial fidelity** of a task p which is the proportion of workers with task p which have drifted walking style
- SHD, the **spatial heterogeneity degree** which is a measure of the variance of worker distribution at some time t

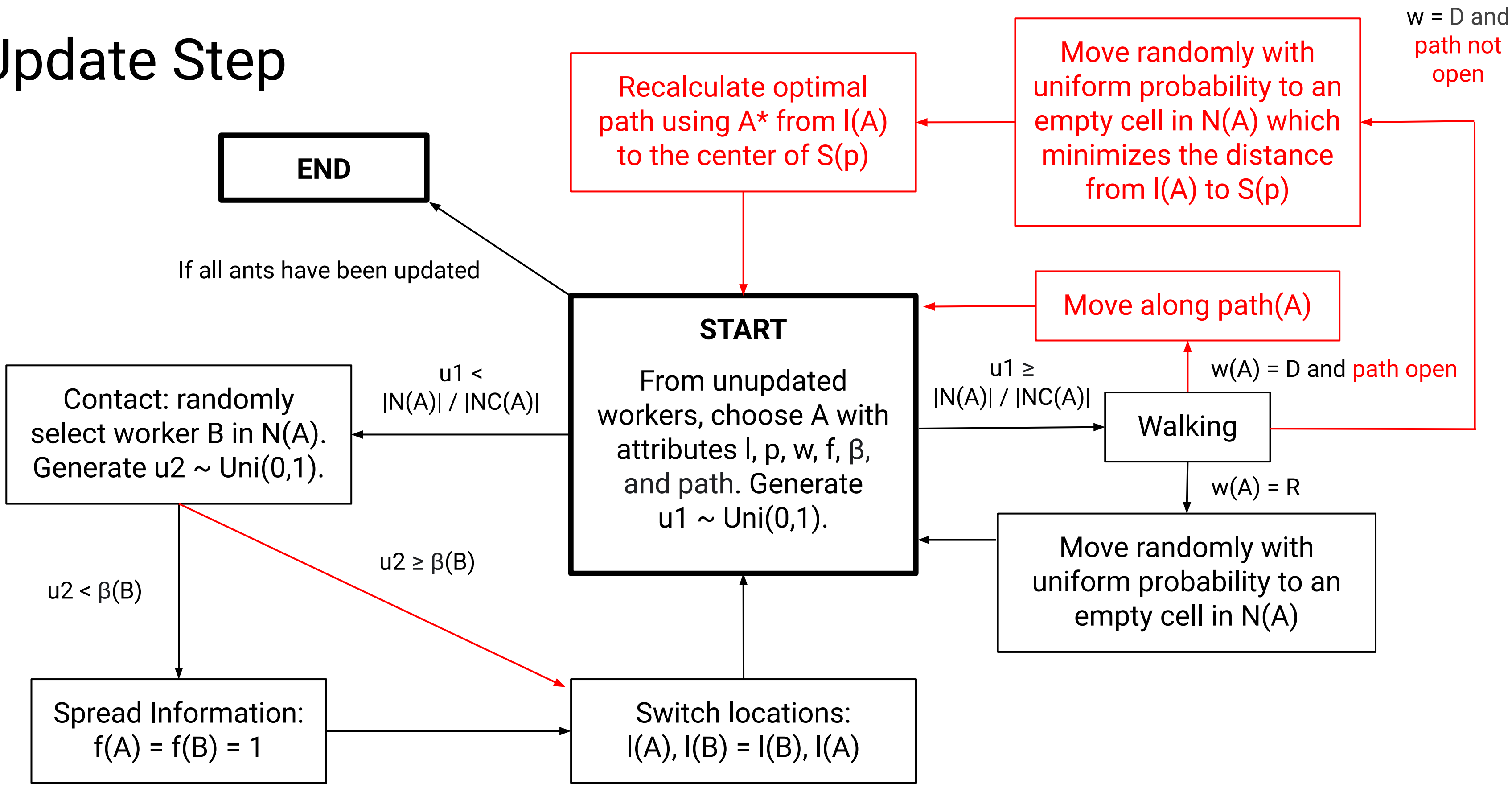
$$SF(p) = \frac{|\{A : p(A,t) = p, w(A,t) = D\}|}{|\{A : p(A,t) = p\}|}$$

$$SHD(t) = \frac{\sum_{x \in X} (P_x(t) - \frac{N}{A})^2}{A}$$

Higher spatial fidelity means less randomness in overall ant movement in the nest.

Higher spatial heterogeneity degree means more clustering among the ants.

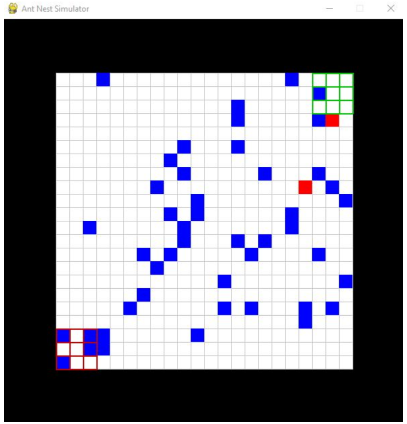
Update Step



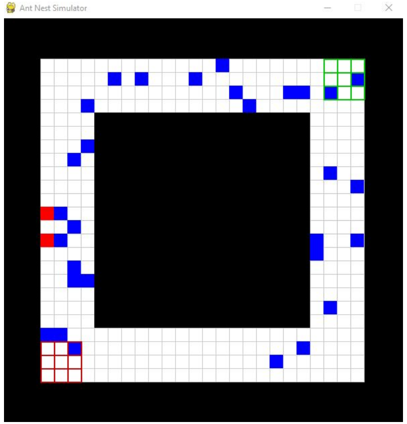
END
If all ants have been updated
Recalculate optimal path using A* from l(A) to the center of S(p)
Move randomly with uniform probability to an empty cell in N(A) which minimizes the distance from l(A) to S(p)
w = D and path not open
Move along path(A)
START
From unupdated workers, choose A with attributes l, p, w, f, β, and path. Generate u1 ~ Uni(0,1).
u1 < |N(A)| / |NC(A)|
u1 ≥ |N(A)| / |NC(A)|
w(A) = D and path open
Walking
w(A) = R
Contact: randomly select worker B in N(A). Generate u2 ~ Uni(0,1).
u2 ≥ β(B)
u2 < β(B)
Move randomly with uniform probability to an empty cell in N(A)
Spread Information: f(A) = f(B) = 1
Switch locations: l(A), l(B) = l(B), l(A)

Nest Features

Our goal was to test four different nest features, each representing some feature seen in real ant nests.

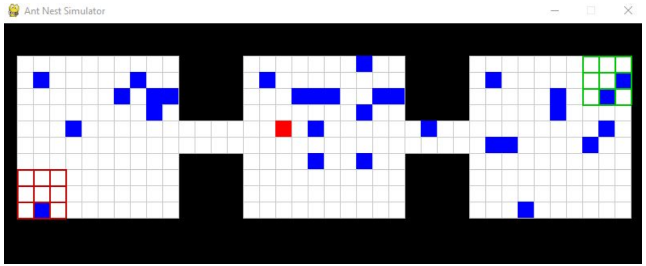


Squares model above-ground interactions since they are a large open area. With these, we vary side length.

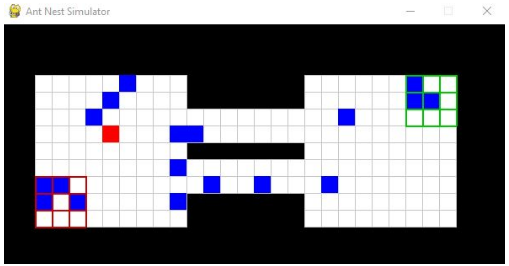


Donuts model the presence of loops within a nest. With these, we vary hole size.

Nest Features



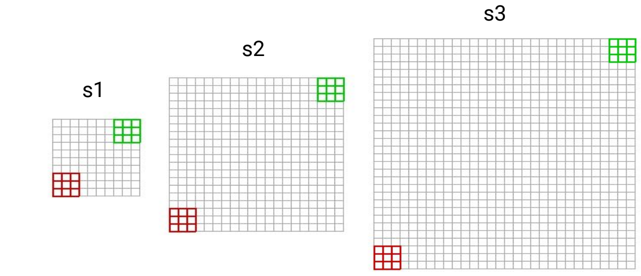
Chains model connection depth similar to the long vertical stems seen in ant nests. With these, we vary number of chambers.

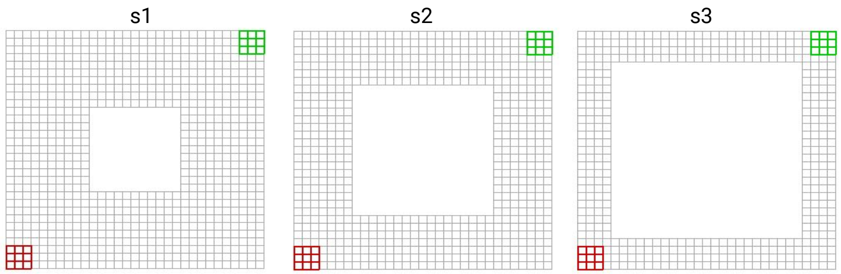


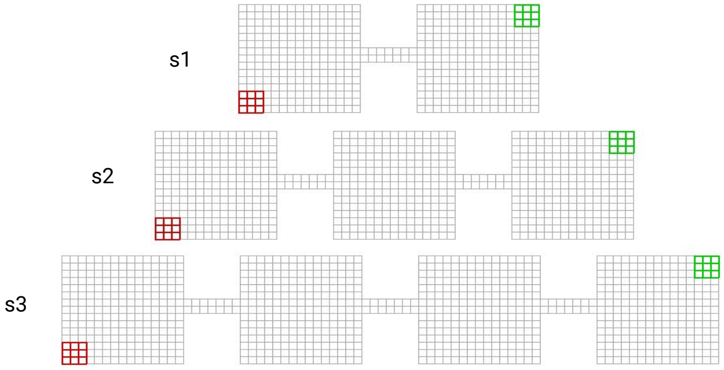
Tunnels model connection degree. With these, we vary the number of tunnels between a pair of chambers.

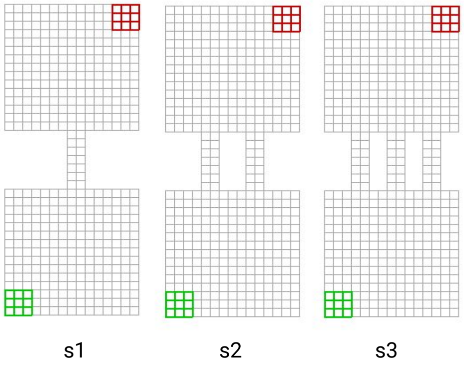
Shape Variations

For each feature we designed three variations to test more extreme versions.



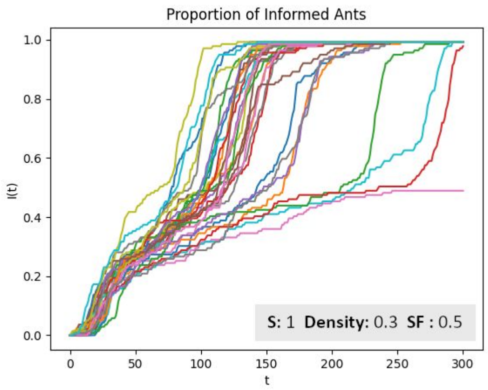


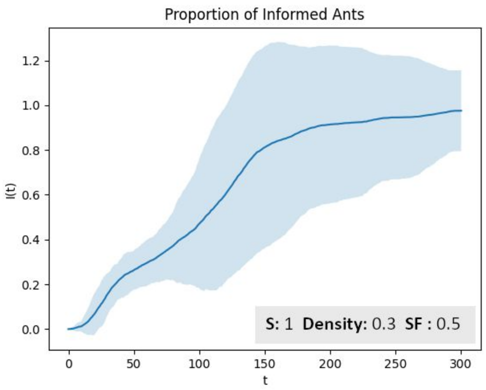




Running the Model

We ran each of the three variations of the nest features in each combination of densities 0.1, 0.2, 0.3 and spatial fidelities 0.2, 0.5, 0.8. For each, we ran 30 simulations to average and kept track of 6 different figures. These included proportion of informed ants, average proportion of informed ants, final motif counts, contact rates within and between groups, and SHD over time.

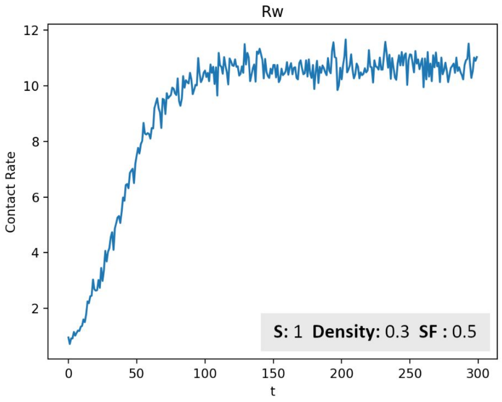


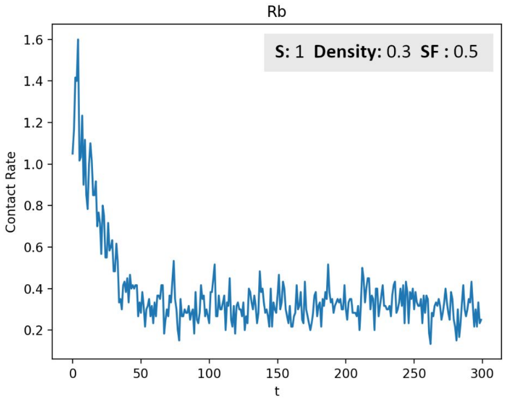


Proportion of informed ants can be displayed in two ways: plotting each simulation within the nest feature separately or with an average and two standard deviations.

Running the Model

There are two contact rates we tracked, rates within the task groups and rates between the task groups. These let us break down not only how often interactions are happening but what types they are. In the figures, we display these contact rates as an average across all 30 simulations. With high spatial fidelities, we expect Rw to increase and Rb to decrease over time.



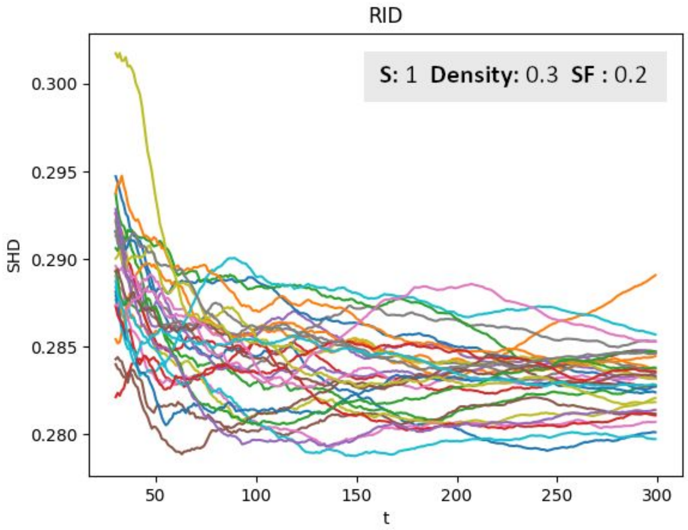


$$R_w(t) = \frac{dC_w}{dt} \approx \frac{C_w(t) - C_w(t - \Delta t)}{\Delta t}$$

$$R_b(t) = \frac{dC_b}{dt} \approx \frac{C_b(t) - C_b(t - \Delta t)}{\Delta t}$$

Running the Model

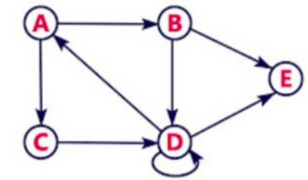
Spatial Heterogeneity Degree tracks the amount of clustering in the nest over time. With high spatial fidelities, we expect this clustering to increase over time as ants reach their task zones.



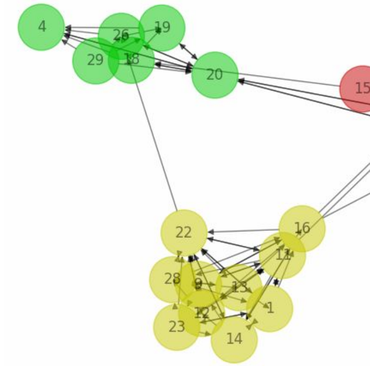
$$SHD(t) = \frac{\sum_{x \in X} (P_x(t) - \frac{N}{A})^2}{A}$$

Running the Model

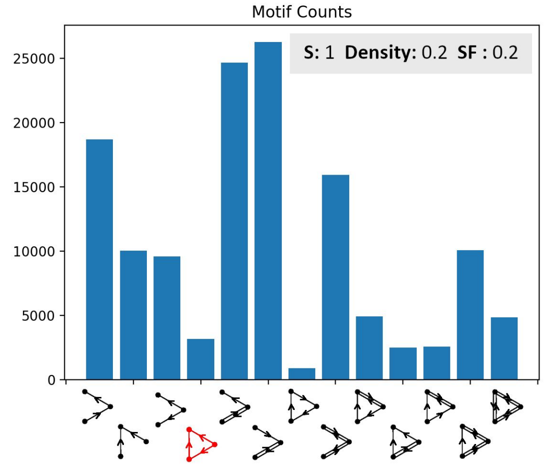
Motifs are directed triads that are subgraphs of a larger network. High numbers of certain motifs can suggest certain network functionalities. One motif commonly seen in empirical ant networks is the **feed-forward loop** (seen below in red). We were expecting to see a higher proportion of these than a random network would have. The directed network of interactions is tracked with an adjacency matrix which we later use to quickly count the motifs.



	A	B	C	D	E
A	0	1	1	0	0
B	0	0	0	1	1
C	0	0	0	1	0
D	1	0	0	1	1
E	0	0	0	0	0



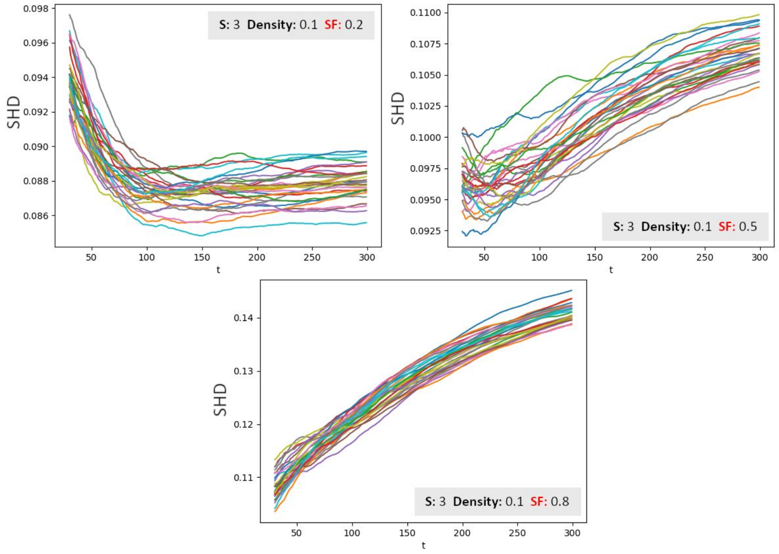
Simulated in-nest time-aggregated network where color represents task



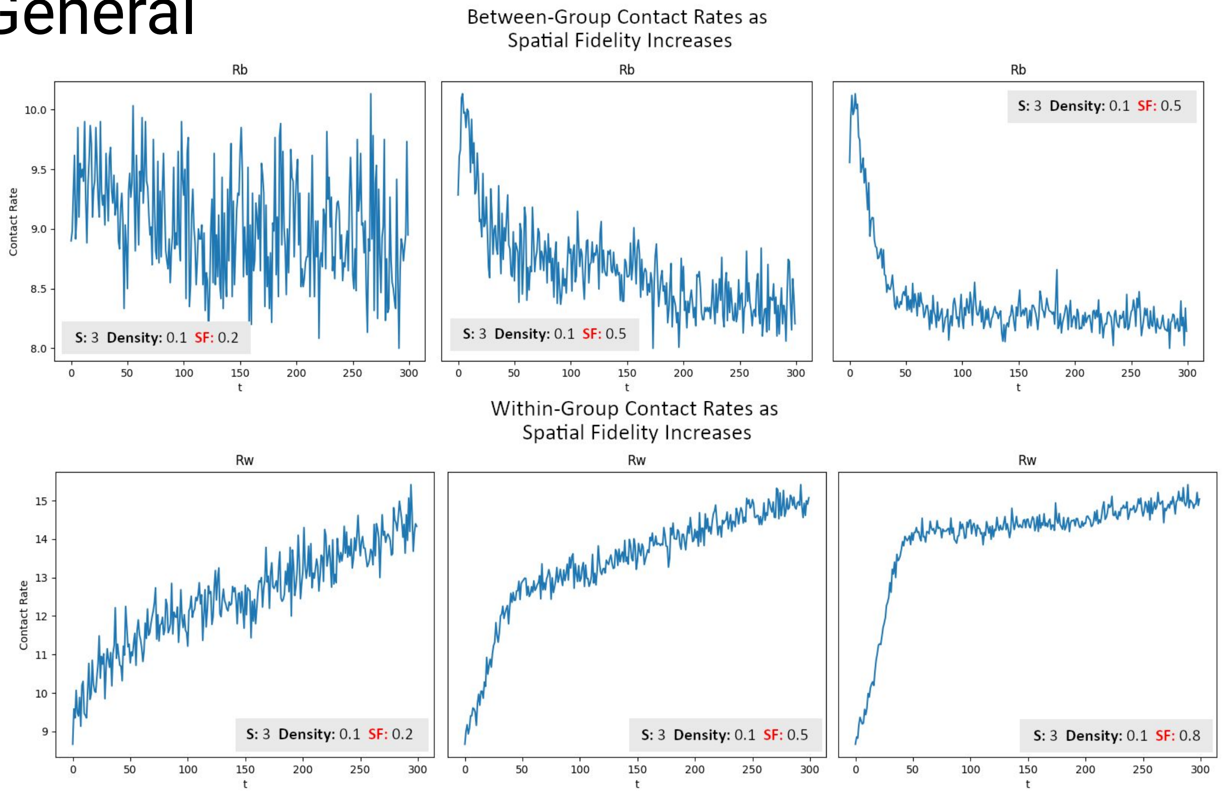
Results: General

After running all of these simulations, we found a number of trends we were expecting, and some others that we weren't expecting. To begin with the expected results, contact rates and SHD didn't seem to change across nest feature, shape variation, or density. The only factor that seemed to matter was the spatial fidelity of the colony, which makes sense because these track the amount of clustering and contact among groups and higher spatial fidelity forces groups together faster.

Spatial Heterogeneity Degree as
Spatial Fidelity Increases



Results: General

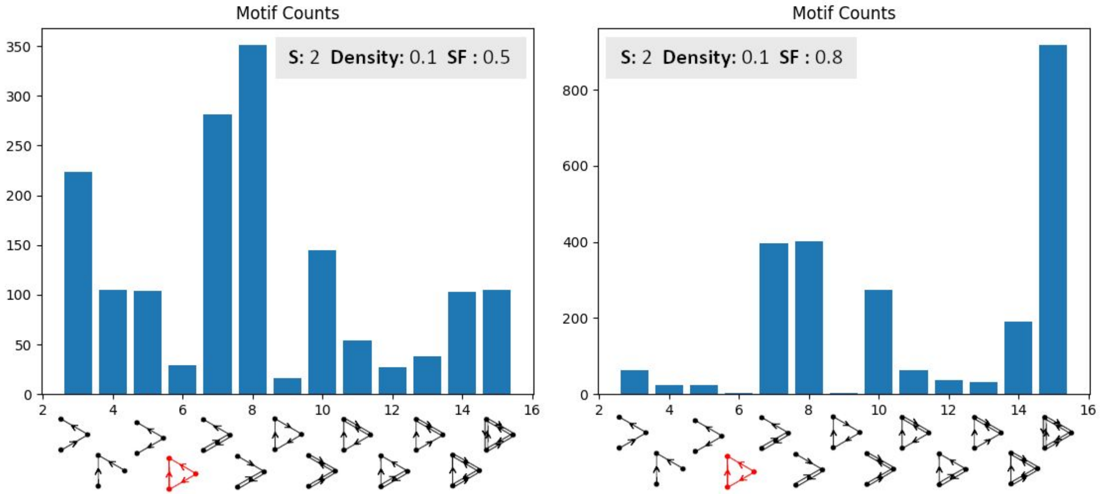


Contact rates as spatial fidelity varies for 4-chains

Results: General

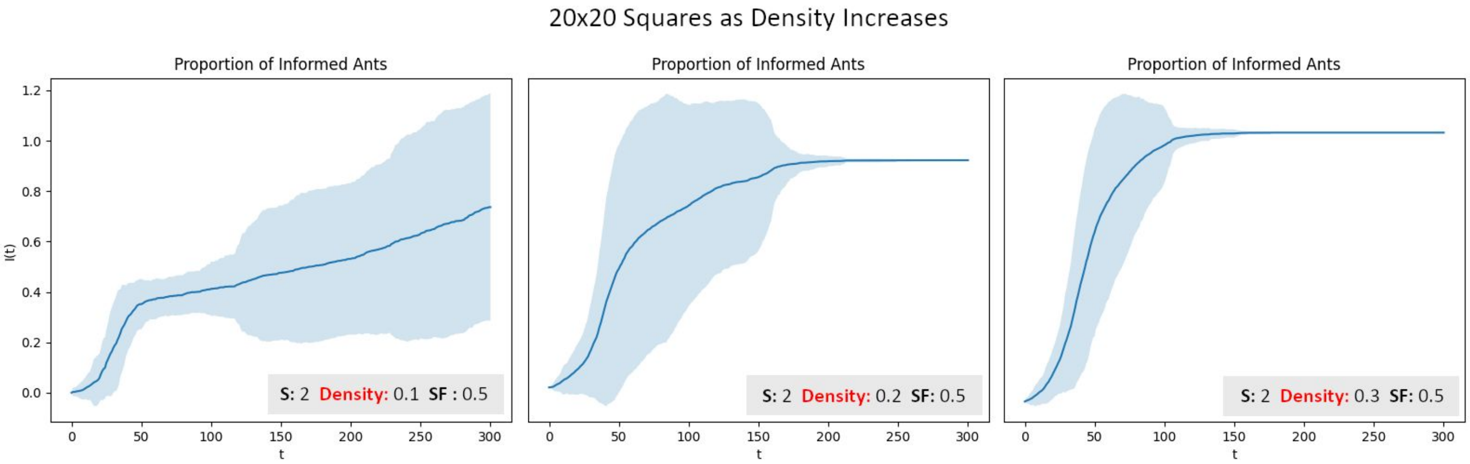
Motif counts also didn’t vary much but they weren’t what we expected. There were low counts of the feed-forward loop but high counts of motifs 7, 8, 10, and 15. Large numbers of motif 15 are likely because of too long of a time window which causes subgraphs associated with the various task groups to become highly connected. We interpret the high prevalence of motifs 7 and 8 as a representation of an exchange of two different types of information between ants, such as one ant informing another ant with a food signal, and then receiving an alarm signal from this ant. We also recognize that this could be due to the asynchronous update step our model uses.

Final Motif Counts for Tunnels (s2)



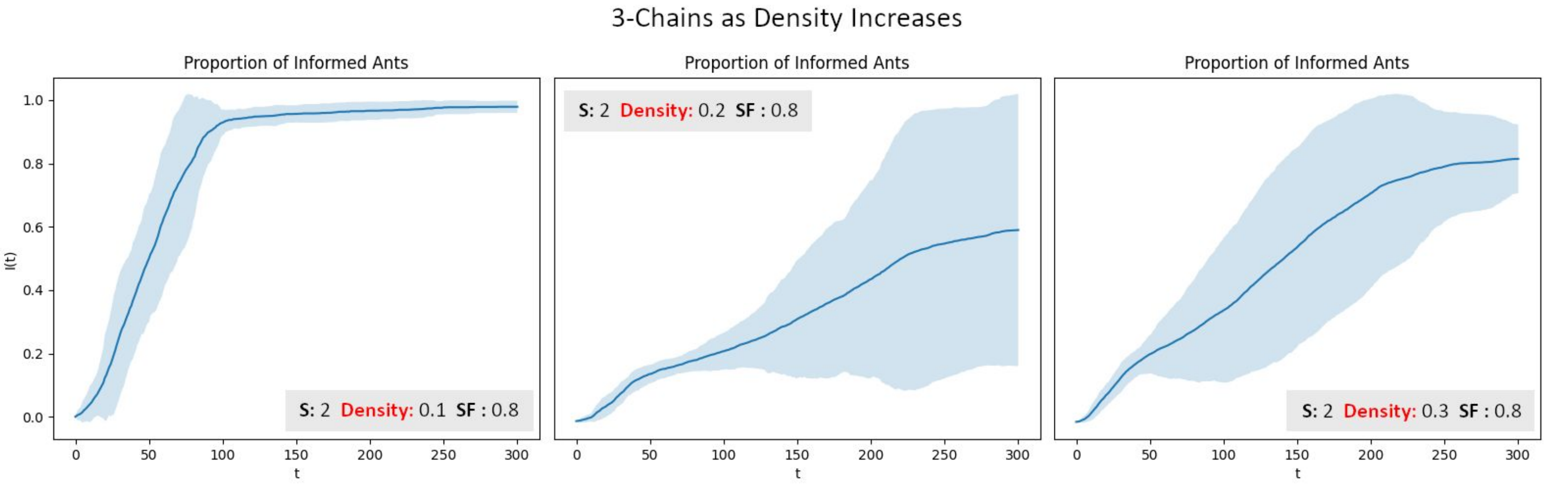
Results: Squares

In the square model simulations, we expected that an increase in density would result in a higher proportion of informed ants across all time steps. Upon further analysis it became clear that there was practically no discernible difference between proportions of informed ants in the first 50 time steps regardless of density. We discovered that this was caused by the drifted walking style of the ants. After all ants in fidelity zones are informed, density affects proportion of informed ants as we predicted, as high density nests have proportions of informed ants in all time steps between 50 and 300.



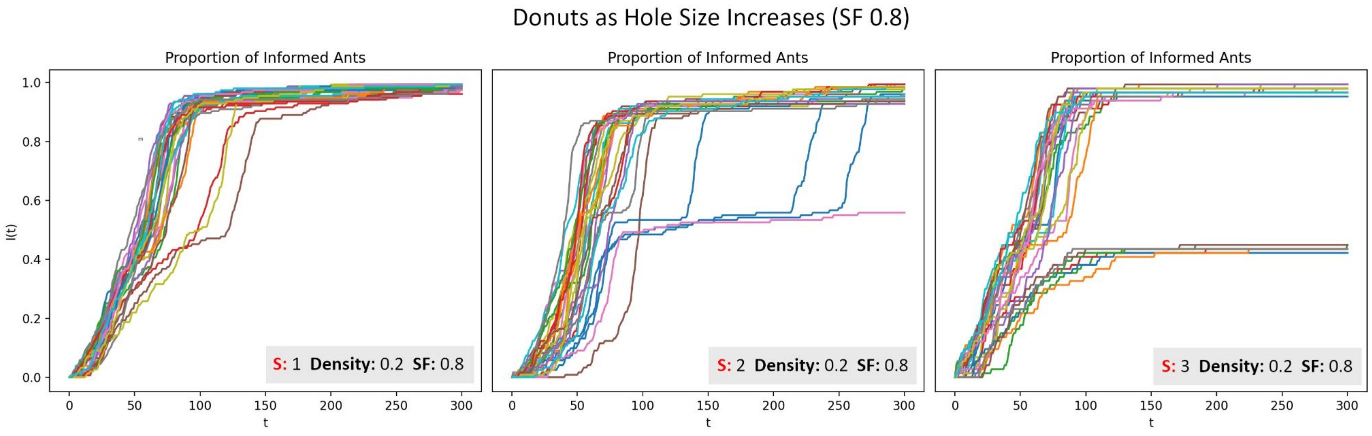
Results: Chains

For the chain shapes, we predicted that an increase in density would provide less of a benefit to the proportion of informed ants at each time step than it did for the squares. As we predicted, our data shows that increasing the density of chain colony shapes does not generally result in an increase in the proportion of informed ants. In fact, this increase sometimes even caused a decrease in information spread through the colony, as seen in figure below.



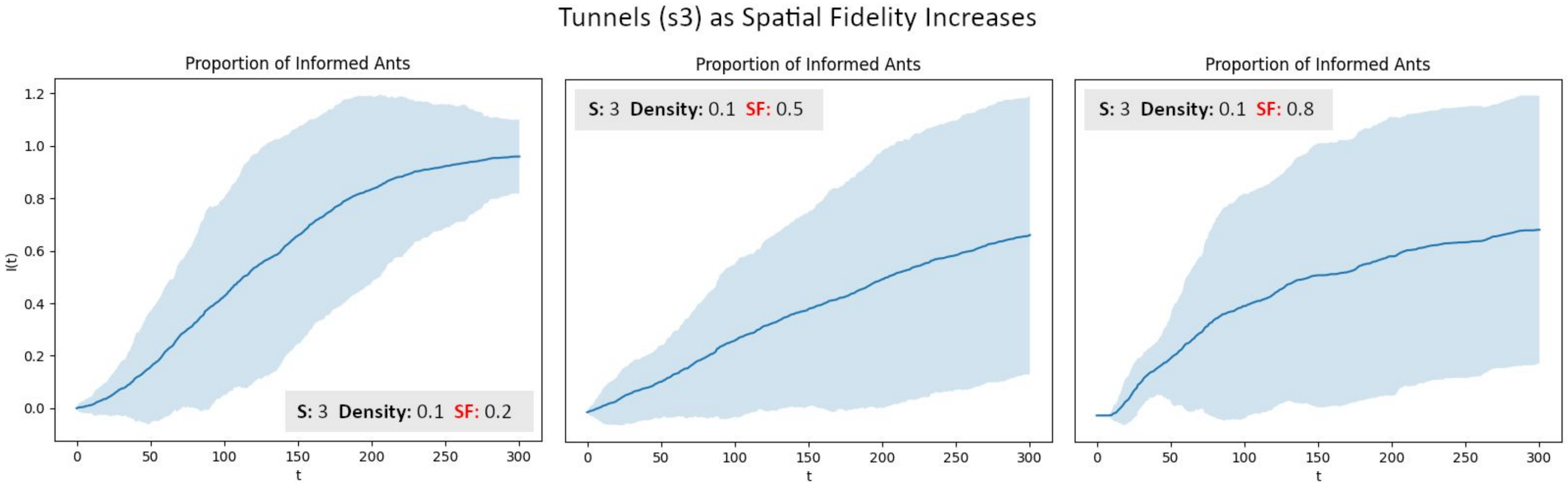
Results: Donuts

An interesting result we saw was with a high spatial fidelity, there were more simulations which reached a steady state other than a fully saturated ant population. We suspect this is because the donut edges serve as two large alternative routes for ants to travel along towards their spatial fidelity zone. Because of this, increased spatial fidelity causes ants to reach their zones along one of these paths faster, potentially without passing information to ants of the other task. There is no bottleneck that all ants necessarily need to pass through to get this information so we get many graphs such as those in the figure below. We note that it was useful to have both mean ant proportion graphs and ant proportion graphs of all the individual colonies since on the mean graph, these lower steady states just look like higher variation.



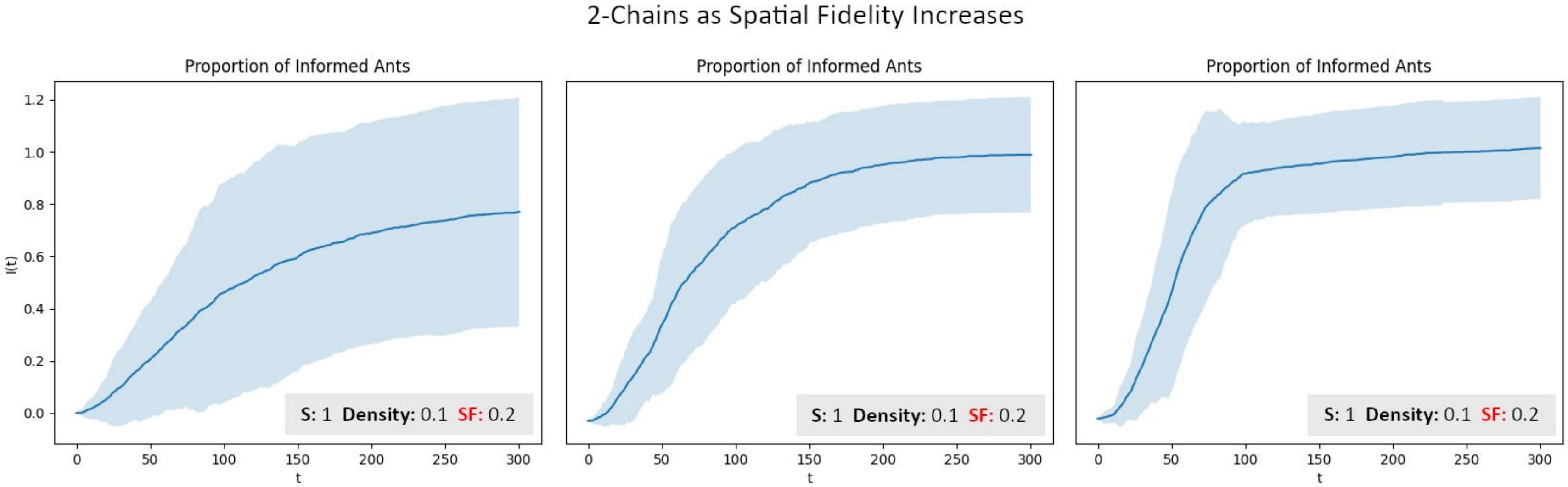
Results: Tunnels

When density is low increased spatial fidelity almost always results in decreased speed of information diffusion for a fixed connectivity. This is likely because with few individuals around increased spatial fidelity encourages worker to congregate at task zones, which enhances within zone contact rates at the expense of global contact rates. It's worth noting in this scenario that increased connectivity tends to have little noticeable effect.



Conclusion

Each nest shape had very different optimal conditions. For example, in 2-chains we observed that an increase in spatial fidelity resulted in more efficient information flow, but this trend did not appear elsewhere. We concluded that there were no general nest conditions for density, spatial fidelity, or shape that increased information flow in all colonies. To pinpoint optimal nest shapes in particular, future work would include studying interaction proportions and contact rates across combinations of these nest features. Other enhancements to our model could include incorporation of additional task zones and more realistic ant movement.



Thank you!

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