Patterned Growth in Extreme Environments

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Abstract

In this paper, cellular automata are used to model patterned growth of organisms in extreme environments. A brief introduction to cellular automaton modeling is given to assist the reader. Patterned growth of soil surface cyanobacteria and biovermiculation microbial mats in sulfuric acid caves are modeled and simulations conducted. Simulations are compared with actual systems, and future directions are discussed.

1 Introduction

In resource limited environments, organisms grow in patterns that are self-enforcing and exhibit hysteresis [1, 14, 17]. Among the techniques that have been used to model these patterns are evolutionarily stable strategies in game theory and differential equations [6, 10, 14, 16, 17]. While good results have been generated using differential equations, they require tuning of the parameters and experience in mathematical and numerical techniques to obtain valid results.

In this work we developed cellular automata that produce similar predictions to the differential equation models, while preserving the rapid modeling and hypothesis testing of cellular automata. Similar models can also be applicable to group animal behavior [7, 11, 13, 15]. While cellular automata have been used to show patterning due to slope considerations [9], our method for deriving rules for cellular automata from observed data in organism growth patterns accounts for soil nutrients, water, root growth patterns, and geology allowing scientists to easily examine the effects of modifying conditions without damaging the environment. We apply this model to identify factors affecting patterning with respect to growth, die-out, and stabilization in extreme environments. We compare the results of our model with biovermiculation microbial mats growth in acid caves, and cyanobacteria growth in Zzyzx, CA.

2 Cellular Automata

A cellular automaton (CA) is a computational model that is discrete in both space and time. Essentially we divide space into boxes called cells, and only calculate their values at discrete time (you could consider this as dividing space-time into boxes if you like). CA use a set of fixed rules to transition from one state to another.

A state could represent anything, and in our case it represents the amount of water, nutrients and the biomass. The rules describe how the organism grows or dies in the presence of the water, nutrients and competition from other organisms. CA rules are not usually expressed as formulas, rather they are visual, such as drawing pictures of the neighboring cells and then labeling the next state. To avoid tedium, we

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group similar cell patterns using heuristics discerned from discussions with biologists and born out in practice.

Typically CA are deterministic, do not use the current value of the state in the calculation of the next state, and use only one state variable. We consider a generalization of this in which these constraints are relaxed. For this paper, we only relax the determinism constraint, as this allows for more realistic looking results.

Consider the following simple transition rule.

> If 3 or 4 of the cells in a neighborhood (±1 row and/or column) of a cell are 1 then the next state for the cell is 1.

This is illustrated by the transition of cell S:

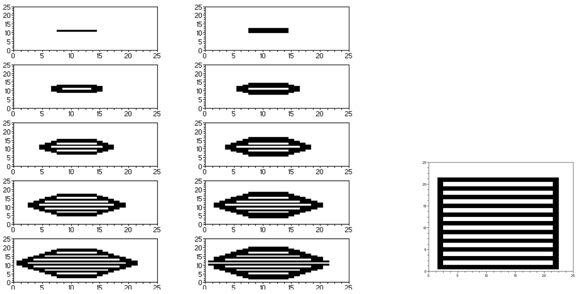
$$\begin{array}{c} \text{Time } t_0 \\ \begin{array}{|c|c|c|} \hline 0 & 1 & 1 \\ \hline 1 & \text{S} & 0 \\ \hline 0 & 0 & 0 \\ \hline \end{array} \end{array} \Rightarrow \begin{array}{c} \text{Time } t_1 \\ \begin{array}{|c|c|c|} \hline 0 & 1 & 1 \\ \hline 1 & 1 & 0 \\ \hline 0 & 0 & 0 \\ \hline \end{array} \end{array}$$

Thus we only need to specify the necessary value for biomass to enable organism growth, which value of the sum allows organism survival, and which value will result in organism death.

Such rules are deceptively simple, but can lead to very complicated results. We allowed the neighborhood to vary to simulate plant root systems and other nutrient effects. We also allowed the value of the sum to be specified as a list of numbers or a single interval.

To show how this can relate to a case of crowding, consider the following simple rules. An organism is in a hostile environment. It can live if it has no more than 6 neighbors. Above that number, resource competition is too high. A new organism will grow if 2 or 3 of the neighboring squares have organisms (it takes at least 2 to generate a new organism, but the new one needs room- i.e. few neighbors). Start with a row of five organisms and an interesting thing happens, as you can see in Figure 1. The ten small figures show the first 10 time periods, the last one is the area after 40 time periods, when it is stable. If you allow life to be supported then the lines continue to fill the region. None can grow in the "dead zones" once they are established, and placing a living organism there will cause them to die (it will have too many neighbors). This self-enforcing nature of the pattern is the basis of the maze-like growth of plants in extreme environments. More complicated rules that fit more realistic situations generate patterns that imitate the striking structures found in nature. This paper presents first steps toward a general model.

Figure 1: Graphic (a) shows the first ten time periods for the rules: if neighbors=2 or 3 then grow, if neighbors > 6 then die, else stay same. Graphic (b) shows the final pattern for these rules.



(a) (b)

3 Cyanobacteria Growth

Cyanobacteria are aquatic, photosynthetic bacteria and are notable for many reasons, including being the oldest fossils, the original producers of atmospheric oxygen, the source of much of our oil, and an ability to grow in extreme environments (including Antarctica). The cyanobacteria in Zzyzx are fossils, but preserve the structured growth we are considering.

Figure 2 shows a typical cyanobacteria fossil. These patterns were fairly dense, so we used a neighborhood with a range of 1 square (1 square in all directions for a total of 8 neighbors). Cyanobacteria often grow in blooms, so we modeled this using growth on having 3 neighbors only. We also allowed random death with probability of 10%. The resulting simulation is shown in Figure 3, and shows much of the same structure as is seen in the actual fossil in Figure 2.

Figure 2: Cyanobacteria fossils from Zzyzx, CA.

Figure 3: Simulated cyanobacteria at $t = 5$, $t = 40$.

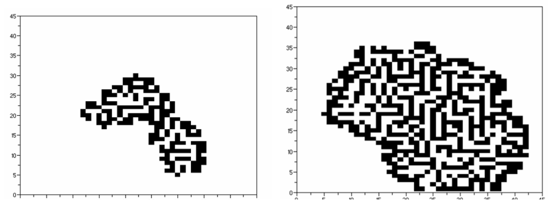


Figure 4: Biovermiculation with discontinuities.

4 Biovermiculation Growth

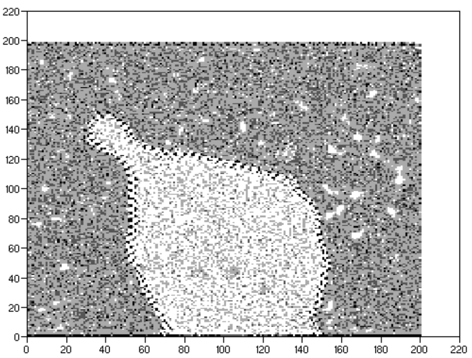
Biovermiculations are microbial mats composed of bacteria, extracellular polysaccharide slime, embedded clay and other particles, in situ precipitated minerals (e.g. sulfur and gypsum), and even some small invertebrates like mites and nematodes.

Investigators have identified them from sulfuric acid caves [12]. More recently, observers have begun to see them in a wide variety of chemical and physical subsurface settings including mines, carbonate caves, lavatubes, and even Mayan ruins [3].

These structures are interesting because of their intrinsically intriguing biology and geochemistry, the distinctive growth patterns that they exhibit, and also because they may be a highly distinctive biosignature that could be interpretable in extraterrestrial settings based on gross morphology [5]. Interest in the biovermiculations has grown as better methods of studying such structures has become available. They also provide a model system of a biomat that might occur on the interiors of various cave types on Mars. Lavatubes have been identified on Mars [2] and more recently confirmed in a more elaborate study [8]. Mechanisms to create solutional caves in evaporite mineral deposits on Mars have also been proposed [4]. Such potential subsurface habitats could conceivably house or have housed microbial populations on Mars and left traces similar to those found in geomicrobiological communities in Earth's subsurface.

The patterning of biovermiculation growth is still a mystery. To understand it will require simulations that test different sets of rules enabling us to arrive at a good pattern match for the microbial mat growth that we are observing in nature. Such simulations will then be correlated with actual pattern examples from cave walls and other occurrences. Figure 4 shows an area that has biovermiculations so thick that they become the solid mat, but there are weird uninhabited areas that follow the rock curvatures. These are not simple water pathways that have prevented growth, so their origin is unknown. In figure 5, no nutrient or water differentiation was induced, only crowding rules, and an ability to pull nutrients from surrounding cells. The result was the depleted region in the middle. Note the shape has many indents, like the actual system in Figure 4.

Figure 5: Simulated biovermiculation growth



5 Conclusions

Cellular automata show great potential for simulation of patterned organism growth in extreme environments. In this paper an introduction to the method was provided. Further we examined the use of cellular automata to model patterned growth of cyanobacteria and biovermiculations. Early results are quite promising, and further work is going on to systematize the rule generation, and to connect differential models with cellular automaton models.

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