BRNO UNIVERSITY OF TECHNOLOGY
FACULTY OF INFORMATION TECHNOLOGY

Simulation Studies

Root growth
07: Cellular Automaton, area of ecology

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Contents

1 Introduction

This project presents the implementation of a cellular automaton designed for simulating root growth patterns. The inspiration for this work is derived from a research paper [2] that laid the foundation for the cellular automaton model, using formation rules based on the statistical analysis found in ”A New Kind of Science” by Stephen Wolfram and expands them by adding obstacles like stones, for representation of gravel soils.

1.1 Extensions

This implementation extends the findings of the base research paper by incorporating modifications related to soil moisture. The introduction of moisture as a variable introduces a dynamic component to the simulation, reflecting real-world conditions and enhancing the realism of the model. Addition of soil moisture levels, allows the simulation to be applicable to not even gravel soils but for dry or wet soils as well.

2 Topic analysis and technologies used

Root growth constitutes a complex and extensive field of research influenced by various factors such as soil type, moisture, underground water levels, interactions with other plants, macrospores, the ever-changing environment, and plant DNA. While certain aspects may be challenging to simulate or predict accurately [1], this simulation prioritizes the consideration of soil moisture. Moreover, our implementation incorporates stones as obstacles to root growth, as detailed in the referenced research paper [2].

2.1 Implementation technologies

The model is implemented in C++, using object-oriented programming principles. Python 3, along with the matplotlib library was utilized for visualization. Compilation of the source code is accomplished using GNU Make. Formation rules governing the cellular automaton are inspired by rules 1, 2, 3, and 4 found in ”A New Kind of Science” by Stephen Wolfram.

3 Model Concept

In this model, root growth is dictated by a set of rules [2]. These rules determine how the state of each cell, representing the simulated environment, evolves over time. The simulation integrates factors such as moisture levels and potential obstacles to emulate the complex interplay of biological and environmental influences on root growth.

3.1 Root Growth

Root systems exhibit a fractal structure [1]. The growth patterns of roots vary based on factors such as plant type and soil characteristics. Soil structure, including macrospore distribution, water retention, and tillage soil geometry, also demonstrates fractals. To incorporate these factors, the model uses water retention as an input. Cells simulate water, influencing neighboring cells to represent soil parts with better nutrients for root development. Stones are implemented as obstacles, mimicking real-world conditions where roots cannot penetrate through stones.

3.2 Implemented Rules

Each rule consists of four conditions predicting whether the root will grow or not. Conditions compare two cells and determine the state of the cell beneath them. Different rules result in different root patterns. In this representation of rules, white squares represent soil cells and black sqares root cells of the grid. Each rule is derived from [2], in which they found probabilities closely resembling roots.

Rule 1

1. If both cells are roots, the cell (c) remains soil.
2. If the cell (a) is soil and the cell (b) is a root, the cell (c) becomes a root with a 90% probability.
3. If the cell (a) is a root and the cell (b) is soil, the cell (c) becomes a root with a 90% probability.
4. If both cells are soil, the cell (c) remains soil.

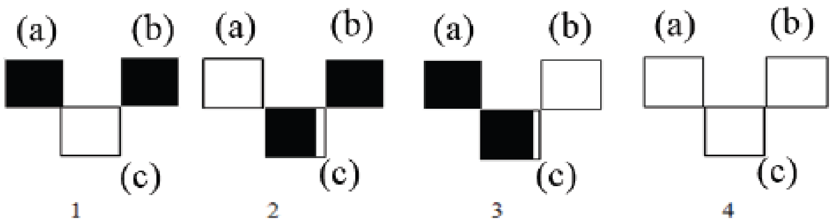


Figure 1: Rule 1 predicting root growth with 4 conditions

Rule 2

1. If both cells are roots, the cell (c) remains soil.
2. If the cell (a) is soil and the cell (b) is a root, the cell (c) becomes a root with a 70% probability.
3. If the cell (a) is a root and the cell (b) is soil, the cell (c) becomes a root with a 70% probability.
4. If both cells are soil, the cell (c) remains soil.

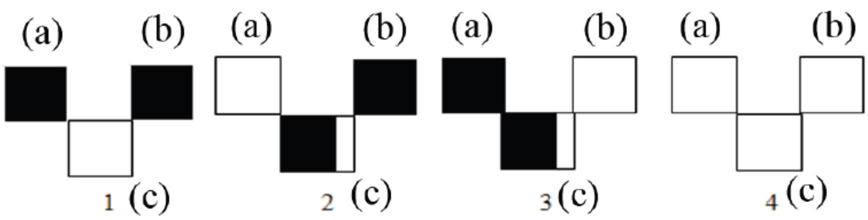


Figure 2: Rule 2 predicting root growth with 4 conditions

Rule 3

1. If both cells are roots, the cell (c) becomes a root with a 70% probability.
2. If the cell (a) is soil and the cell (b) is a root, the cell (c) becomes a root with a 60% probability.
3. If the cell (a) is a root and the cell (b) is soil, the cell (c) becomes a root with a 60% probability.
4. If both cells are soil, the cell (c) remains soil.

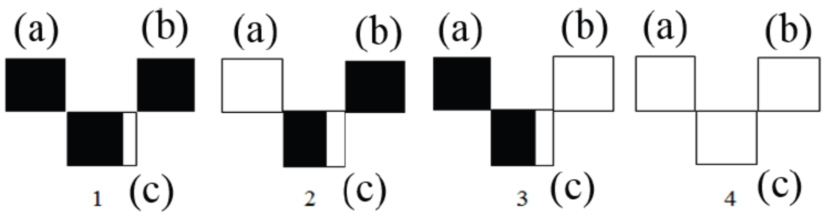


Figure 3: Rule 3 predicting root growth with 4 conditions

Rule 4

1. If both cells are roots, the cell (c) becomes a root.
2. If the cell (a) is soil and the cell (b) is a root, the cell (c) becomes a root with a 60% probability.
3. If the cell (a) is a root and the cell (b) is soil, the cell (c) becomes a root with a 60% probability.
4. If both cells are soil, the cell (c) remains soil.

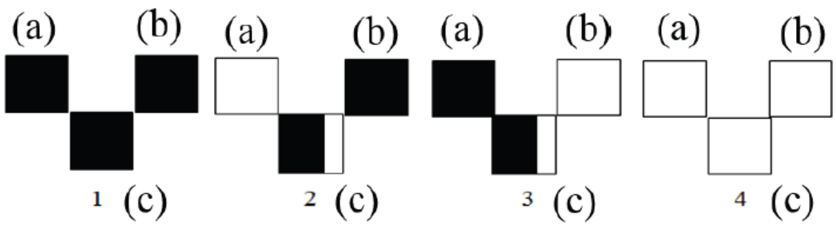


Figure 4: Rule 4 predicting root growth with 4 conditions

4 Model Architecture

4.1 Probability modification

The set of rules, as it stands, effectively mimics the growth of the roots, however the real world has many more factors to look for. Our representation of environment factor is soil moisture. In our representation, each cell of soil starts with a default moisture level of 1.0. Additionally, a user-defined number of cells, representing retained water, are strategically placed within the soil. User can define the moisture level of these cells as well.

The simulation models water spread through the soil in radius figure 5, influencing the moisture level of neighbouring cells. The moisture level is crucial determinant for root growth probability. Higher moisture levels attract roots due to the increased availability of nutrients. This implementation aligns with real-world scenarios where roots exhibit a preference for areas with higher moisture content. [1]

When two or more water cells' areas overlap, they come together, boosting the moisture in that shared region.

1.0	1.0	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7
1.0	1.0	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.6
1.1	1.1	1.1	1.2	1.3	1.4	1.5	1.6	1.5	1.5
1.2	1.2	1.2	1.3	1.4	1.5	1.6	1.5	1.4	1.4
1.3	1.3	1.3	1.4	1.5	1.6	1.5	1.4	1.3	1.3
1.4	1.4	1.4	1.5	1.6	1.5	1.4	1.3	1.2	1.2
1.5	1.5	1.5	1.6	1.5	1.4	1.3	1.2	1.1	1.1
1.6	1.6	1.6	1.5	1.4	1.3	1.2	1.1	1.0	1.0
1.6	1.7	1.6	1.5	1.4	1.3	1.2	1.1	1.0	1.0
1.6	1.6	1.6	1.5	1.4	1.3	1.2	1.1	1.0	1.0

Figure 5: Grid containing 2 water cells with base moisture of 1.7

4.2 Cellular Automaton Implementation

Figure 6 is showcasing the dynamic sequence of the model:

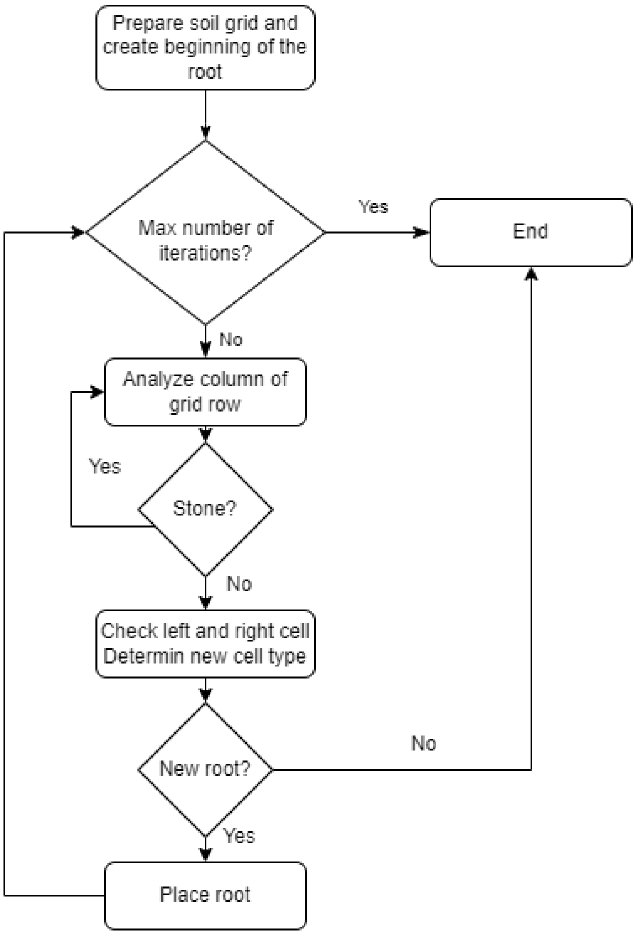


Figure 6: Flowchart of cellular automata model

4.3 Running the simulation

Before the simulation, you have the option to adjust program parameters. The parameters include w/h for the width and height of the grid, -p indicating the number of water cells, -r for the rule number, -m representing the moisture level (default is 1), and -s indicating the percentage for stone spawn The simulation is started with command

```
make run
```

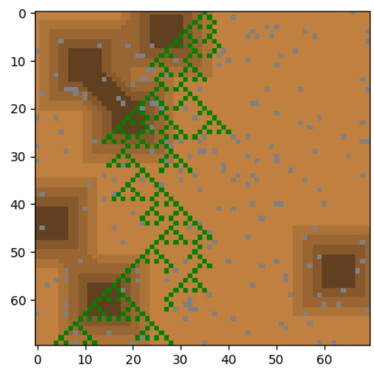
Output will be generated to the data folder as `data.txt`
And the simulation will be visualized. To visualize imported data, run

```
./vis_data.py -f /path/to/file
```

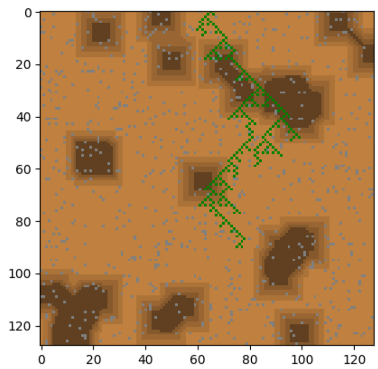
If the simulation is to be executed on a server, it is advisable to include the -Y flag during the SSH connection. This flag enables the server to initiate the graphical interface, ensuring seamless window display.

5 Experiments

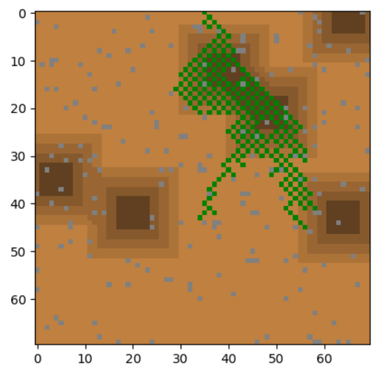
The goal of the experiments was to simulate the impact of each rule on root growth under varying moisture conditions. It's important to note that the simulation incorporates probability as a key factor, and the images presented in this documentation provide representative outcomes of these experiments.



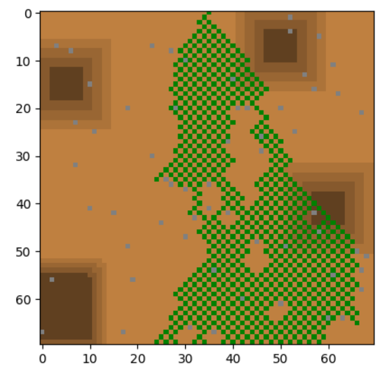
(a) Rule 1, stones, 6 watter cells



(b) Rule 2, stones, 20 watter cells



(c) Rule 3, stones, 6 watter cells



(d) Rule 4, stones, 6 watter cells

Figure 7: Experiments conducted on rule 1(a), rule 2(b), rule 3(c) and rule 4(d)

5.1 Understending visualization

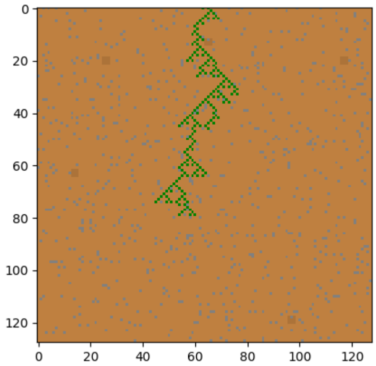
The visual display includes cells with specific colors: green for roots, brown for soil, where darker shades represent increased moisture. Grey cells signify stones in the simulated environment.

5.2 Findings

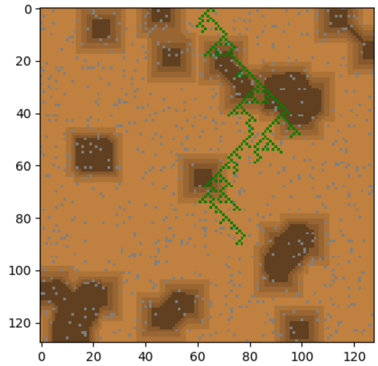
These experiments reveal different root shapes, each influenced by specific rules that mimic various types of roots. Replicating exact root structures in the simulation is challenging due to its inherent complexity. For a more visual understanding of the diverse root forms, refer to the attached GIFs in the `gifs` folder, where each rule is depicted in a dedicated animation.

6 Conclusion

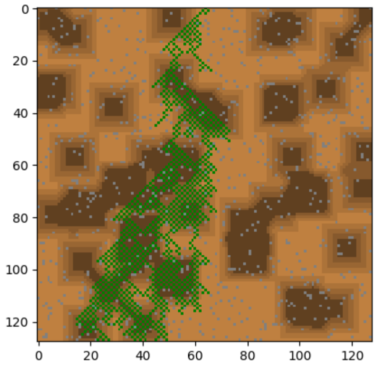
In this project, we successfully implemented a cellular automaton to simulate various root types, their growth patterns, and the hydropatterning mechanism. Our experiments revealed a correlation between root growth rate and soil moisture levels. Roots exhibited accelerated growth in well-moistened soil, mimicking real-world conditions. Furthermore, the simulation accurately replicated the behavior of roots avoiding obstacles, such as stones, aligning with observed phenomena in nature. These findings not only contribute to our understanding of root development but also showcase the potential of cellular automaton models in capturing intricate biological processes. Future enhancements could explore additional factors influencing root growth and refine the model's realism to achieve even closer alignment with natural systems.



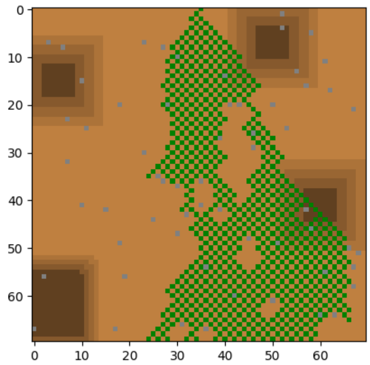
(a) Rule 1, stones, 6 watter cells



(b) Rule 2, stones, 20 watter cells



(c) Rule 3, stones, 6 watter cells



(d) Rule 4, stones, 6 watter cells

Figure 8: Additional interesting patterns

References

[1] Sakae Shibusawa. How to model the branching growth patterns of root system. *IFAC Proceedings Volumes*, 32(2):5611–5616, 1999. 14th IFAC World Congress 1999, Beijing, Chia, 5-9 July.

[2] Nanang Winarno, Eka Cahya Prima, and Ratih Mega Ayu Afifah. Simulation of root forms using cellular automata model. *AIP Conference Proceedings*, 1708(1):070013, 02 2016.