

Modeling

Cellular Automaton Model

SLIM NAU -CHINA 2020

Cellular Automaton Model

Q&A

1. What can Cellular Automaton do?

As the carrier of engineered bacteria (*Bacillus Subtilis*), earthworm can move freely and enrich the lead in the soil by eating during the movement. In this way, the range of movement is roughly equivalent to the range of soil purification by earthworms. By setting a series of model rules, Cellular Automaton can automatically simulate material diffusion with certain probability. We hope to use Cellular Automaton to simulate the movement of earthworms in soil and record the location of them. The range of soil purification by earthworms can be easily obtained after the movement track of earthworms is obtained.

2. What makes earthworms move?

The movement of earthworms is easily affected by the environment. We assessed the attraction of different locations according to the factors such as humidity, organic matter content, geographical features and the real-time number of earthworms. Among them, the real-time number of earthworms had the opposite effect on attraction. In this way, attraction will be the key to the earthworm's movement, and earthworm's trajectory could be predicted.

3. What is the connection between earthworm releasing and soil lead purification?

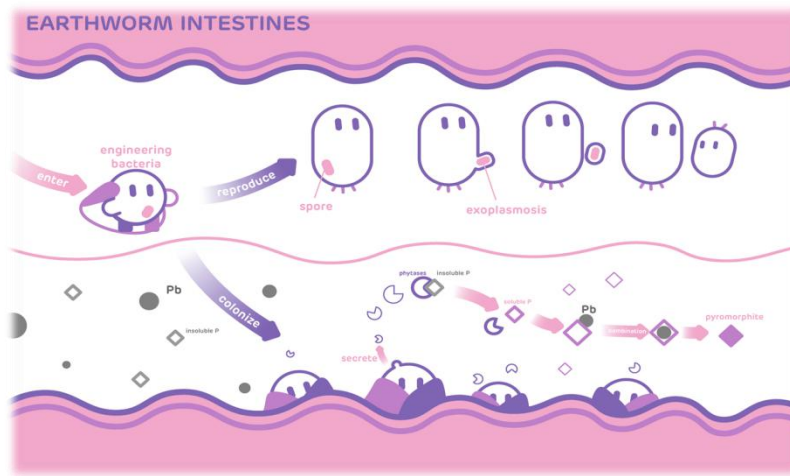
The engineered bacteria that earthworms carry enable them to deal with lead in the soil. Before the simulation, we'd like to quantify the ability of processing lead, such as the efficiency of soil lead purification by a single earthworm. Earthworms would use this ability to address soil lead pollution every time they feed.

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1 Abstract

Our project is to address soil lead pollution by releasing earthworms carrying the redesigned *Bacillus subtilis*. To simulate earthworm release effect and provide reference for earthworm release strategies, we constructed Cellular Automaton Model to obtain the effects of different strategies. Based on its mechanism, the model could be used to deal with lead pollution of cultivated land in different regions around the world. The model quantitatively analyzed different release strategies and gave a reasonable release strategy.



2 Model Hypothesis

- ◆ Due to different terrains and other factors, we set different attractions for different regions.
- ◆ The soil within each cell is homogeneous.
- ◆ Dispersive feeding is obviously better than centralized feeding, and our model only simulate the interval earthworm releasing strategies.
- ◆ Since earthworms feed little food in one day, we assumed that earthworms can process all the lead in food in one day.
- ◆ Earthworm reproduction was not considered as engineered bacteria will not be repeatedly subcultured.

3 Symbol Description

List of Variables

Symbol	Explanation	Unit
$p(i,j)$	Percentage of earthworms entering the target cell in the original cell	—
$attract(i,j)$	The attraction of the cell	—
sum_{ew}	The total number of earthworms in the hive	—
$now_{ew}(i,j)$	Real-time earthworm number in a cell	—
$now_{pb}(i,j)$	Real-time lead content in one cell	mg
$\Delta Pb(i,j)$	The amount of lead in the cell decreased with each update	mg
α	Probability coefficient of migration in and out	—
β	Coefficient of relation between food intake and earthworm weight	—

List of Constants

Symbol	Explanation	Value	Unit
h	Percentage of earthworms entering the target cell in the original cell	10^*	cm
ρ_{soil}	Soil density	1.5	g/cm^3
ρ_{pb_0}	The amount of lead in the soil at the initial time	300 ± 20 [1]	mg/kg
m_{ew}	Weight of mature earthworm	1.2	g
m_{soil}	Weight of soil to be treated within each cell	3750	kg

* The data are estimated based on reasonable assumptions.

4 Modeling

4.1 Introduction to Cellular Automaton

By setting a series of evolution rules, the Cellular Automaton^[2] can automatically simulate the diffusion of substances with a certain probability. In dynamic systems, Cellular Automaton can be divided into three types: uniform, periodic and chaotic structure. With a view to the complexity of earthworm movement and boundary conditions, the Cellular Automaton with periodic structure is obviously superior. In terms of algorithm complexity and accuracy, the Cellular Automaton also performs better than the partial differential equation.

4.2 Building An Environmental Map

Take the range of earthworm activities and topographic features into consideration, we set the size of the hive at **500 m×500 m**. In addition, considering the effective range, we set the number of cells to **100×100**. So, the entire environmental map represents a square area covering **2,500 m²**.

Since it is difficult to obtain accurate topographic maps, we use random maps generated according to the topographic features of Jiangsu Nanjing Baima National Agricultural Science and Technology Zone. We use matrix to simplify topographic map and classify the map according to topographic characteristics and soil conditions. The map is then reduced to a 100 by 100 matrix with different attraction, where 80 represents the highest attractive region and 0 represents the lowest attractive region. The matrix is shown in **Figure 4.2.1**.

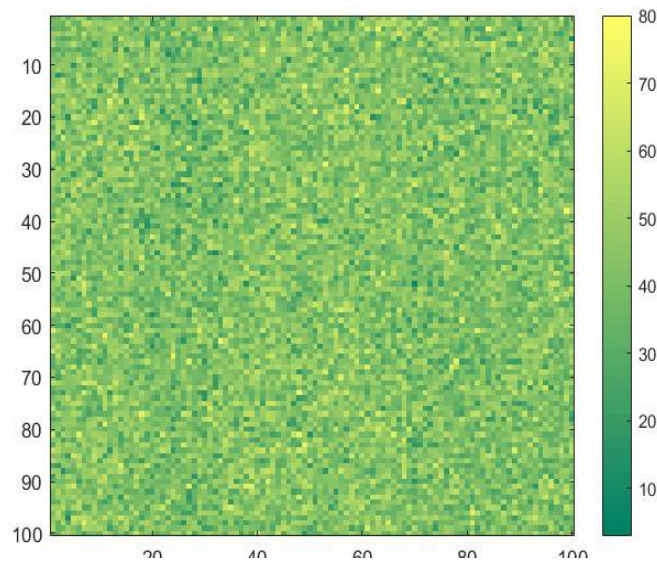


Fig.4.2.1. Initial Attraction

4.3 The Earthworms in Cells

1. To simulate the distribution of earthworms in the real life, we abstracted the area into a two-dimensional figure. We first simulated the situation when the distance between earthworms was 50 meters and the number of earthworms in each pile was 10000. The initial distribution of earthworms is shown in **Figure 4.3.1**.

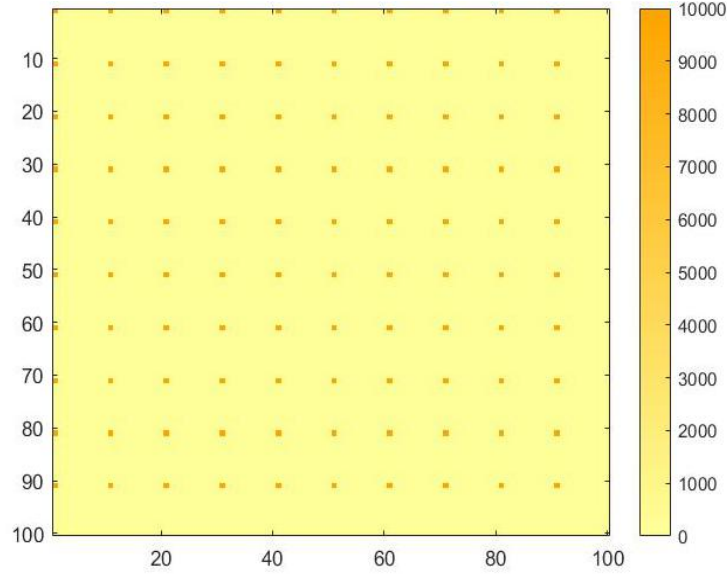


Fig.4.3.1. Initial Distribution of Earthworms

2. We set some rules:

a. Earthworm Movement

In the cellular, the movement of earthworms was expressed as the migration between different cells. We stipulated that the probability of migration in and out is proportional to the attraction of cell and inversely correlated with the number of earthworms in the target location. Here, in order to increase the applicability of the formula, we introduced the migration in and out cell probability coefficient α . The probability of earthworm movement to (i,j) was as follows:

$$p(i, j) = \alpha \times attract(i, j) \times \frac{1}{\frac{now_{ew}(i, j)}{sum_{ew}} + 1}$$

b. Lead Purification

The change of soil lead concentration was mainly related to the food intake of earthworms, which was affected by their weight. Here, β , the coefficient of relation between food intake and earthworm weight, was introduced. The change in lead concentration was represented by the following formula:

$$\Delta Pb(i, j) = m_{eat} \times \rho_{Pb}(i, j) \times now_{ew}(i, j)$$

$$m_{eat} = \beta \times m_{ew}$$

$$\rho_{Pb}(i, j) = \frac{now_{Pb}(i, j)}{m_{soil}}$$

c. Earthworm Mortality

Earthworms live for three months, but it was difficult to obtain earthworm mortality directly. Earthworm population was rounded down each cellular regeneration, which was used to replace the earthworm death.

3. All earthworms in the cell have a certain probability to migrate to the nearby cells. They are more likely to migrate toward the "highly attractive" cells and stay away from the "less attractive" cells. Therefore, after **3 months** of cellular automaton evolution, the distribution of earthworms is shown in **Figure 4.3.2**.

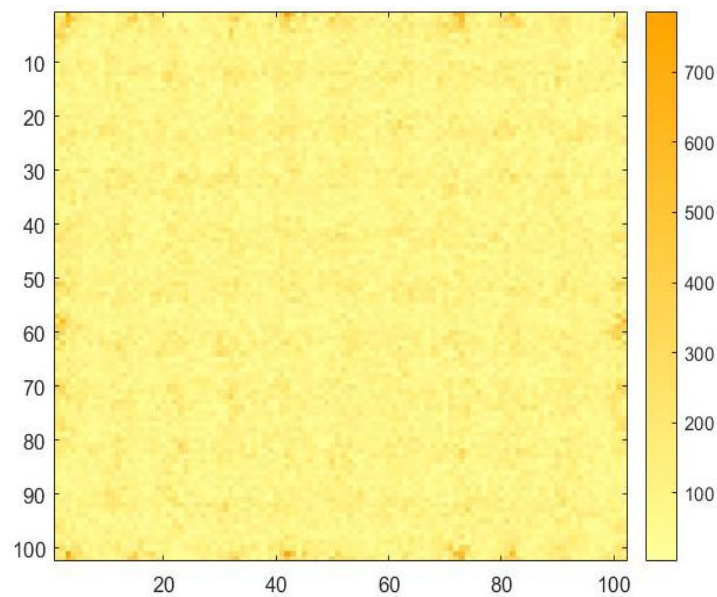


Fig.4.3.2. Distribution of Earthworms after 3 Months

5 Results & Analysis

Based on the above model setting, when 10,000 earthworms were put into each pile at an interval of 25 m after three months, the lead residue of the target land was shown in **Figure 5.1** and **Figure 5.2**.

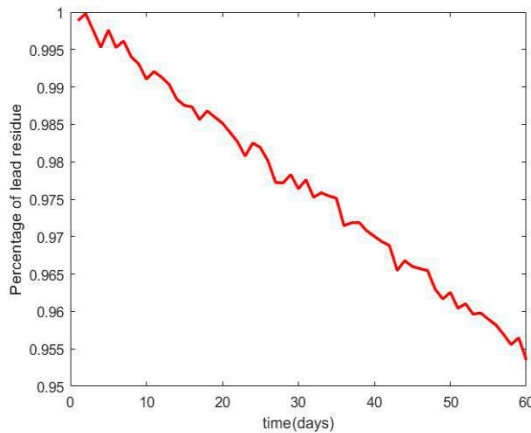


Fig.5.1. The Ratio of Pb within 3 Months

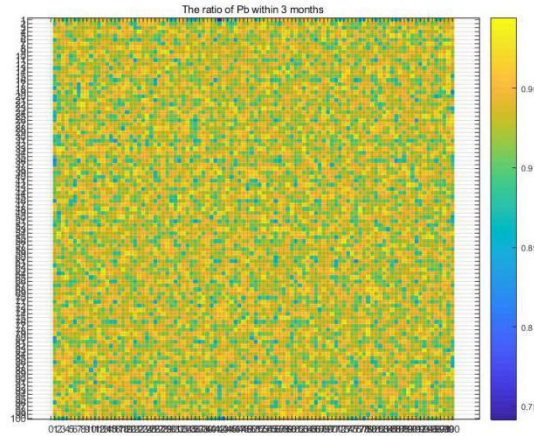


Fig.5.2. Treatment Effect within 3 Months

The results suggested that after three months of treatment, the lead concentration in the soil had decreased by about **5%** on average, and the earthworms had spread in a small area. Based on these, we decided to adjust the strategy to seek more superior treatment effect.

After that, we carried out simulation analysis on other earthworm feeding strategies. The range of earthworm releasing interval is 5 m to 500 m, and the range of earthworm quantity per pile is 500 to 10,000. The treatment effect of different combinations within three months was obtained as shown in the **left of Figure 5.3**. Through the results, we found that when the releasing interval ranged from 1 m to 20 m, the effect would change greatly, so we focused on this part of the combination, as shown in the **right of Figure 5.3**.

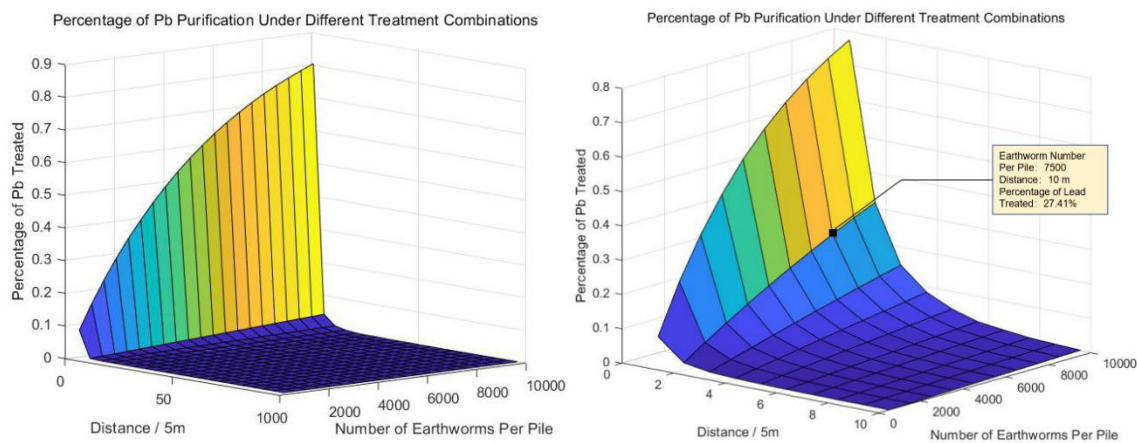


Fig.5.3. Effect of Different Treatment Combinations

The results showed that:

1. When 10,000 earthworms were put into each pile at an interval of 1 meter, the lead in soil could be reduced by 60% within three months, reaching the risk screening value level;
2. When the releasing interval ranged from 5 m to 20 m, the effect did not change significantly.

Considering the life span of earthworms, environmental bearing capacity and the above results, we suggested that the release strategy is as follows:

Put 7500 earthworms into each pile at an interval of 10 meters, and run it twice, each time for three months.

Under this strategy, the treatment effect of lead in three months was shown in **Figure 5.4**. The soil lead concentration can reduce by **27.41%** once and by about **60%** after the second releasing, reaching the risk screening value level, that soil lead concentration should be less than 100 mg/kg.

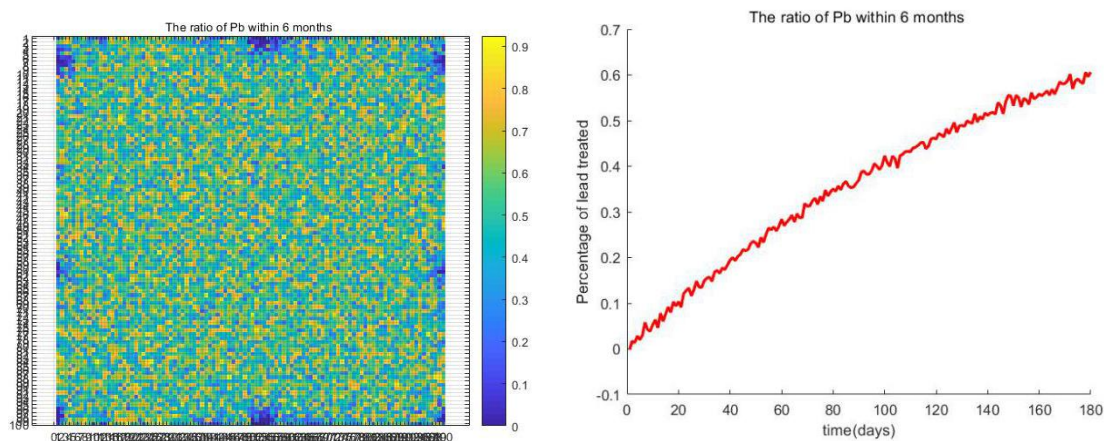


Fig.5.4. 7500 Earthworms in Each Pile at an Interval of 10 Meters

6 Sensitivity Analysis

Sensitivity Analysis could calculate the change range of the ultimate index caused by the change of one or more uncertain factors, and analyze the impact of each factor on the realization of the expected goal. Therefore, it helps to provide an important advice for project decision.

♦ Probability Coefficient of Migration in and out

Since it is difficult to determine the probability of earthworm migration in and out of cell, we calculated the parameters by function at the beginning of the model, and introduced the probability coefficients of migration in and out.

Here, we conduct sensitivity analysis on the coefficients, as shown in **Figure 6.1**

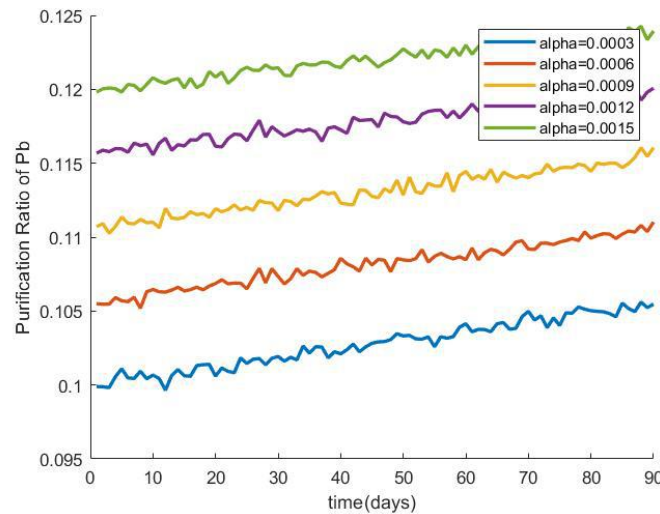


Fig.6.1. Sensitivity Analysis of the Probability Coefficient of Migration in and out

The results showed that:

Within a certain range, probability coefficient of migration in and out has little influence on the degree of lead residue in soil. The probability coefficient fluctuation range of the model is about -0.011~0.009.

◆ **Coefficient of Relation Between Food Intake and Earthworm Weight**

The food intake of earthworms determines the lead enriched by earthworms, and the food intake is obviously related to the weight of earthworms. In the model, we added the coefficient of relation between food intake and the weight of earthworms, namely β , to describe the relationship.

Now, we carried out sensitivity analysis on the coefficient, as shown in **Figure 6.2**

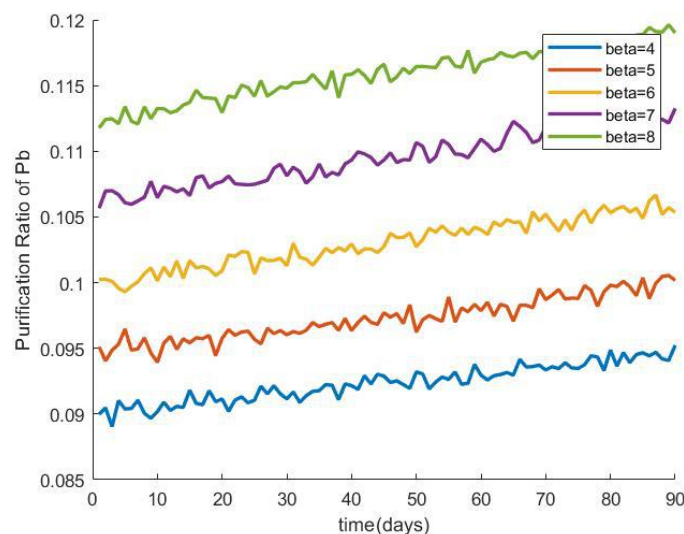


Fig. 6.2. Sensitivity Analysis of the Coefficient of Relation Between Food Intake and Earthworm Weight

The results showed that:

The coefficient of relation between food intake and earthworm weight has little influence on the degree of soil lead residue. The allowable fluctuation range is -0.009~0.012.

Reference

- [1] Huang Daoyou, Huang Xin, Liu Shoulong, et al. Current status of cadmium, lead and other heavy metal pollution in Hunan Province and control measures[C]. Meeting of the Standing Council and Youth Academic Committee of Hunan Agricultural System Engineering Society.
- [2] Ceccherini-Silberstein T, Coornaert M. Cellular Automata and Groups[M]. 2010.