A Comprehensive Study of Forest Fire Behavior as Cellular Automata Model

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In this paper, we present a comprehensive study in which a 2D cellular automata model is created which is evolved using a genetic algorithm. Cellular automata (CAs) are spatially-extended discrete dynamical systems which has many desirable features for large class of computation [?]. Our CA model is tailored to mimic the famous forest fire behavior in presence of lightening strike. Some other properties like multiple species of trees and presence of firefighters are introduced in our model. We analyzed our simulation results in detailed manner with and without these properties and observed many interesting behavioral patterns in the forest fire model. The resultant behavior of the model is used to explain relationships among evolving forest growth, forest biomass, longevity and fire-fighters' role on the overall model.

General Terms: Complex, Adaptive, Genetic, Algorithm, Cellular Automata, Forest-fire model

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AUTHOR CONTRIBUTIONS

Author1 - wrote the code for effect of firefighter in the forest, ran the simulations and generated all the graphs; in the paper, wrote the introduction and related work sections.

Author2 - wrote the skeleton of the code, implemented all the codes for CA and effect of multiple species; in the paper, wrote methods section.

Pair work - Both the authors took part in implementation of the GA, visualization of the model, bug fixing of the code and analyzing the simulation results; in the paper, both the authors wrote abstract, results and conclusion together; took part in formatting and proof reading.

1 INTRODUCTION

Cellular Automata (CAs) are examples of mathematical systems constructed from many identical components,each simple, but together capable of complex behavior [?]. As cellular automata is a complex pattern itself, it is able to analyze dynamical and information processing systems and widely used in parallel computations. In 1940, Cellular Automata was invented by John von Neumann and described in [?] as equivalent to universal turing machine [?]. CAs are used in performing complex computation in different sectors of science. In this paper, we emphasize on using Genetic Algorithms (GA) to evolve a 2D Cellular Automata that behaves like a famous dynamical model called Forest-Fire Model. In this model, each cell is either empty or occupied with a tree which represent the whole 2D lattice as a forest with presence of lighting that causes fire. In this paper we will observe the evolution of forest growth under different parameters.

The paper demonstrates the behavior of the forest growth with the presence of lighting strike probability that burns the trees. The genetic algorithm is used to achieve the evolving growth rate of the forest. The parameters such as multiple tree species and presence of fire-fighters effect the forest growth which is analyzed in section 4. The paper also shows computations that are performed to calculate relationship among factors such as: forest biomass, forest longevity, evolved growth rate and the amount of fire suppressions. These factors are described in a detailed manner in section 3.

2 RELATED WORK

In this section, we will review some previous works related to Cellular automata, use of genetic algorithms to evolve CAs to perform calculations and the famous forest-fire model.

Although John von Neumann invented CA, however, his rule was somehow complicated [?]. In 1970, British Mathematician John Conway invented his famous model *Game of Life* [?] where he used two-state cellular automataa which evolved a with set of rules and initial conditions. It was capable of universal computation [?].

In the early 1980s, Stephen Wolfram started working with CA and its pattern and discussed some universal features and general properties of the pattern of CA [?]. He showed that for different initial conditions any CA can yield into one of four classes. All the patterns of CAs fall in these four classes. Wolfram and gis colleagues also developed a programming language called Mathematica to simulate cellular automata [?].

In 1989, Meyer et al. developed a genetic algorithm to build a cellular automaton that may be used for forecasting or for regenerating global spatial patterns [?]. Since then scientists have worked on several methods to design rules of cellular automata using genetic algorithms. Genetic algorithms are a search method that can be used for both solving problems and modeling evolutionary systems. [?]. In 1994, Mitchell et al. published a detailed result from experiments where genetic algorithm was used to evolve computationally useful CAs and described mechanism by which GAs can create complex global behavior in a system consisting of many simple parts [?].

Forest-fire model can be considered as a 2D cellular automata with a set of predefined rules and initial conditions. Forest-fire model was used to demonstrate critical scaling behavior in a turbulent non-equilibrium system in [?]. Many people have worked on the modeling of forest-fire using cellular automata and also genetic algorithm [?], [?], [?]. It has many applications like parallel processing and decision support system [?]. We can find the basic

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implementation and simulation of the forest-fire model in almost all of the programing languages[1].

3 METHODS

In this section, the methods of the implementation of the 2D cellular automata in respect of Forest fire model is discussed. The approaches of how the model of forest growth evolved using different parameters of Genetic algorithm as well as the process of introducing multiple tree species and concept of fire-fighters are described in detailed manner.

3.1 Forest Fire model

The model consists of 2 dimensional cellular automata that is a spatial lattice of 250 by 250 (in total 62500) cells. At each time step, each of these cells is in one of 3 states: fire, tree, empty. For the growth of the trees there is a probability p. Using the growth rate there is probability to grow tree in an empty cell. The fire occurs in the forest by an independent probability f which is referred as a lightening strike that hits the cell. When a cell with a tree is hit by the lightening, it catches on fire. The fire spreads to adjacent cells in every time step according to the law of Moore Neighborhood [2]. Trees effected with fire are converted to empty cell in the next time step. In this CA, each cell follows these set of rules for updating its status in every time step. Therefore, the state of each cell at time step $t+1$ depends on its own state and the state of eight neighboring cells at time t [**?**].

The growth rate of the forest is evolved using a simple genetic algorithm. For the GA, we are considering the growth rate probability as the genome and creating a population of 20 genes. The first set of population is generated randomly from the range of 0.0 to 1.0. Two fitness functions were considered for the GA; Longevity and Biomass. Longevity [3] is defined to be the time till all cells are empty. Biomass[4] is the percentage of cells that are occupied by trees. Average biomass is calculated over the CA lifetime. For the evolution of the population we used Random selection and mutation operator in our GA. Selection methods are used in GA to choose an optimal set of parents to produce the next generation based on their fitness score. In the random selection, the population of growth rates are sorted according to their fitness score. The population selected to create the next generation was chosen by replacing the lower half of the population with randomly selected warriors from the top half. For the mutation operator, we used 0.5% mutation rate for the diversity in population. In mutation, we randomly changed the growth rate of a gene and computed the fitness. Here two individuals with highest fitness function values are remained unchanged for maintaining elitism in GA. Every gene in the population is iterated for 5000 time steps for the fitness evaluations.

3.2 Fire-fighters

In our model, we have introduced the concept of fire-fighters who work on stopping the fire to spread in the trees. The fire-fighters extinguish the cells in fire and transform them to cells with trees in the next time step. In the presence of n fire-fighters we are creating a random list of n cells with fire state and turning them into tree state. 0 to 1000 fire-fighters are used in our model with increment of 50. Once the population is evolved then we are using the fire-fighters on the model. By using fire-fighters, the spread of fire decreases, so we can find its effect in the fitness of population in Section 4.

3.3 Multiple Species

To observe the forest behavior with multiple species, we introduced another species of trees in our forest model. This species of trees have different growth rates and they are evolved independently according to their own growth rate. We generate a random probability for each of the species. An empty cell turns into a tree cell when at-least one of the random probabilities falls under its growth rate. We also analyze the effect of using two species on the fitness of forest model in section 4.

3.4 Visualization

The visualization of the CA enables us to visually observe the behavior and changes in the forest. To visualize the forest, we created graphical window which represents the forest where each block of 2 by 2 pixels represents a cell in the forest. There is no border between two consecutive cells. We used color 'black' to represent an empty cell and 'green' for cell with trees. When a cell has a burning tree, the color is 'orange' and when a cell has a tree just rescued by any fire fighter, the cell color is 'blue'. By default, there is a time gap of 750 milliseconds between two consecutive iterations.

3.5 Border Condition

We assume that, there is empty space outside our 250 by 250 arena and no tree can grow in that space. Therefore a lightning strike can not hit outside our arena; fire can not spread outside of the arena from inside and vice versa. At any time step, we update all the rows of the forest.

4 RESULTS

In this section, we present the results and corresponding figures from the simulation of our cellular automata model. The results are obtained using the methods discussed in section 3. For the simulations we used a population of 20 genes and created 10 generations. We are using the lighting strike probability $f = 0.001$.

4.1 Relationship between Longevity and Biomass

When we are running the GA to evolve the growth rate of the forest, we are calculating the longevity and biomass of the forest as fitness function. We can see the relationship of both longevity and biomass in figure 1.

From figure 1, we can say that the longevity is constant at 5000 which is the total iteration time step. We can interpret from this that our forest model is not evolved to any growth rate for which the forest is completely depleted. We think it is because of low lighting strike probability, the chance of catching trees on fire is lower than the chance of growing trees. Therefore, longevity is not an interesting fitness function for our model as it fails to explain the

[1] http://rosettacode.org/wiki/Forest_fire
[2] http://mathworld.wolfram.com/MooreNeighborhood.html
[3] http://cs.unm.edu/ mfricke/CS523_2017spring/Projects/Project3/Assignment.pdf
[4] http://cs.unm.edu/ mfricke/CS523_2017spring/Projects/Project3/Assignment.pdf

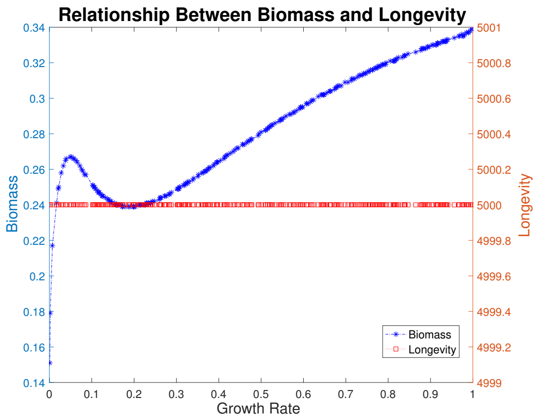

Fig. 1. The plot shows the fitness landscape of growth rate vs longevity and growth rate vs biomass. Longevity remains unchanged over the growth rate. Biomass increases over growth rate and converges to the value 0.34.

behavior of the growth. We will focus on the other fitness function biomass.

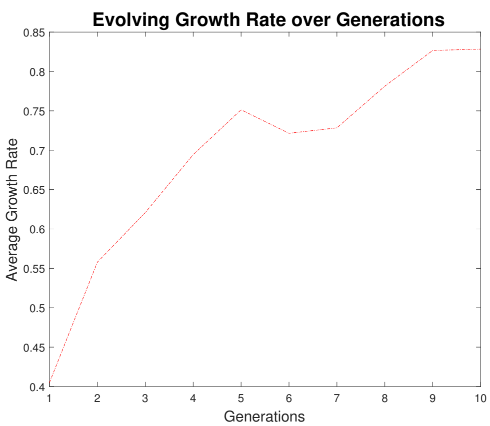

Fig. 2. The plot shows relationship between evolving growth rate over 10 generations. For each generation average growth rate is presented. The growth rate is increasing with almost every generation. The evolution of the growth rate depend on the design of GA.

Biomass is fraction of trees in CA lifetime. We can say from figure 1 that the biomass in increasing with increasing growth rate probability. However we observe in our model that the biomass converges to 0.34 and do not increase any further even if the growth rate is increased. By running our GA multiple times for 10 generations we have identified that growth rate 0.997 maximizes value of biomass to 0.34 in our model.

In figure 1 we can observe that in lower growth rates from 0.1 to 0.3 there is a decrease in the biomass. Then from 0.3, the biomass keeps increasing. Here we can see a phase transition from where biomass does not decrease anymore and keep on increasing.

Again we have tried to observe how the growth rate is evolved in our genetic algorithm with generations. From figure 2, we observe that GA is evolving an increased growth rate probability with each generation. It also explains why we are not observing any change in longevity. With constant lightening strike probability and increasing growth rate it is very unlikely to evolve to a state with completely barren state.

4.2 Effect of Multiple Species

After introducing another species of tree in the forest we can observe some changes in biomass. Figure 3 is showing the average biomass for both of the species over 10 generations. From this graph, we can observe that, after introducing multiple species in our model we get constant higher biomass than single species over the generations. Therefore, the multiple growth rate of trees can be explained to cooperate with each other and cause overall increase in the biomass of the forest. We can see a positive influence of the multiple species on each other more clearly in figure 4.

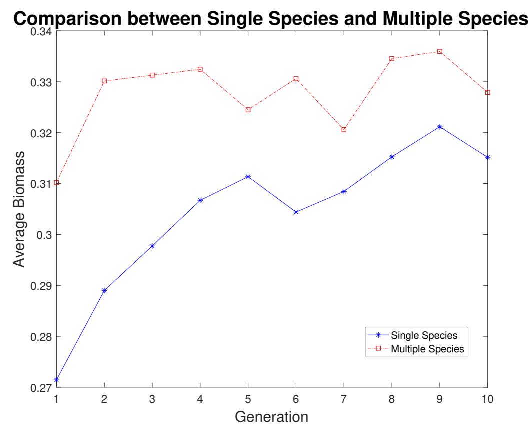

Fig. 3. The plot shows the effect of introducing multiple species on the model. In comparison to the single species, the biomass of multiple species is constantly high which results as a positive on the model. The growth rate of the multiple species work together to increase overall fitness.

In figure 4, we are showing the average growth rate of the forest for both single species ans multiple species over the generations. Here in some cases, we observe that single species growth rate is higher than both of the growth rates in multiple species. However, still the biomass for the multiple species is higher than sin species. From this fact. it can be inferred that multiple species growth rates are co-operating each other and despite of having lower growth rates are managing to show higher biomass.

4.3 Effect of Fire-Fighters

We are introducing fire fighters in our model with the growth rate that maximizes biomass which is 0.997. We can see the results in figure 5. We are increasing the biomass in increments of 50. We can see that for 0 and 50 firefighters the biomass is almost close as before. However, when 100 fire fighters are working there is a rapid change in biomass increase. This fact prevails with fire fighters more than 100 till 1000. The result correlates with the design of our model. As we are keeping our lightening strike probability at constant rate

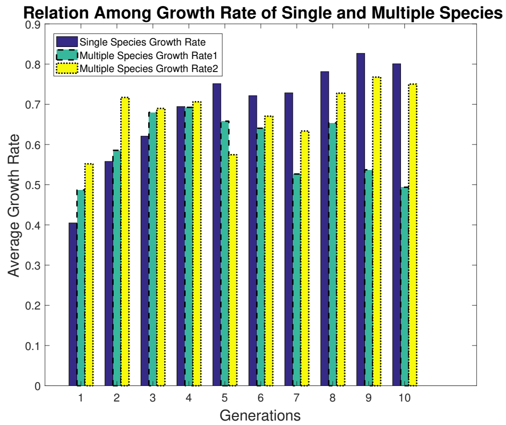

Fig. 4. The bar chart shows the relationship among growth rate of single species and multiple specie. The average growth of both cases are presented over 10 generations. In some generations single species growth rate is higher than multiple species. However, still the biomass remains low for single species. This is because the two growth rate of multiple species influence each other positively.

of 0.001, in every iteration there is highest chance of 62 cells to be struck by fire. Therefore,when the fire fighters are less than 62 there is probability for fire spreading and obtaining low biomass. As soon as the number of fire fighters cross 62 i.e from 100 there is no chance of fire spreading as firefighters are able to extinguish every tree that catches fire. With our growth rate probability, the forest then only grows and has constant biomass of the value 0.999.

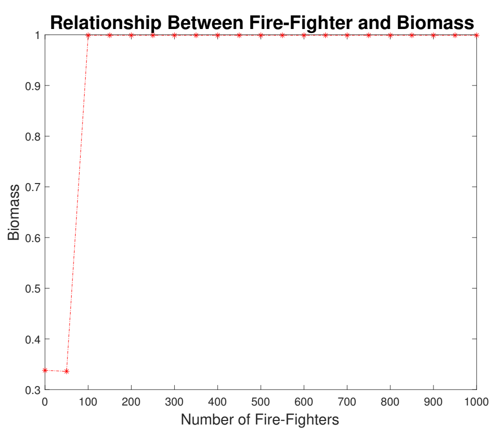

Fig. 5. The plot shows effect of introducing fire-fighter in the model. The number of fire-fighters are incremented in 50. The biomass is comparatively low until 50 firefighters. After 100 fire-fighters the biomass changes rapidly to 0.999 which remains constant till 1000 firefighters.

We can conclude that as soon as introducing 100 fire fighters we are observing a constant change in biomass. It cannot be considered as a prominent phase transition, however, it is prominent change in the our model that is effecting the whole forest.

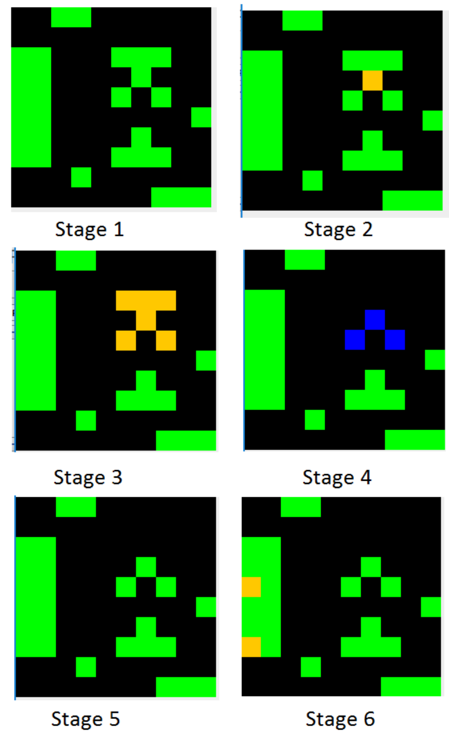

Fig. 6. Some continuous zoom-in screen shots of forest model. Stage 1: combination of some tree (green) cells and some empty (black) cells. Stage 2: one cell is burning (orange) due to lightning strike. Stage 3: fire spreads to adjacent tree cells. Stage 4: fire fighters rescue (blue) three of the burning cells. Stage 5: Rescued tree cells become green again. Stage 6: two more tree cells catch fire due to lightning strike.

4.4 Visualization

From the figure 6, we can observe the microstate changes of the sub-forest with presence of fire fighter. In stage 1, there are some already grown trees indicated by green cells. The orange cell in stage 2 shows that the cell is burning due to lightning strike. Fire spreads to others tree cells according to Moore neighborhood law which is shown in stage 3. In stage 4, fire fighters come into action and randomly pick 3 burning cells. Therefore , the burning cells are rescued (blue) and the remaining burning cells become empty cells. The rescued cells are actually tree cells and shown in green color from stage 5 onwards. In stage 6, lightning strikes two more tree cells and they become orange. The process continues in this way. These changes in the microstates eventually cause change in the macrostate behavior of the overall forest model such as average biomass.

5 CONCLUSIONS

In this paper, we implemented a 2D cellular automata model to simulate the behavior of forest fire. We evolved the tree growth rate using our genetic algorithm. We observed that, the growth rate converges to achieve the maximum biomass value. However, the longevity value always remains 5000 throughout our GA. It is clear that, the probability of lightning strike (0.001) in the GA is very low. It was our intuition that, with the lightning strike probability 0.001, it is not possible to get a longevity less than 5000. Therefore we changed this probability and experimented with different values. It seemed that,if we keep the lightning strike probability over 0.85, we may get longevity value less than 5000.

Afterwards we introduced another species of tree in our forest model. We noticed that, the two species cooperated each other while evolving. From prisoner's dilemma [**?**], we know that two parties can cooperate or compete each other. In our case, we observe the supporting influence on each other.

We also introduced fire fighters in our model. We have seen that, after a certain number of fire fighter, the biomass almost touches the highest point and stays there. As discussed in the results section, it is very obvious that with the given low lightning strike rate, fire can not spread across the forest with 100 or more fire fighters.

We also observed the influence of changing microstate behavior in macrostate behavior. Little changes in the states has shown significant changes in the overall behavior. Further tests may be performed to get diverse outcome. Changes in GAs, lightning strike probability, different range in fire fighter number and concept of more than two species may show other interesting outcomes.