Cellular Automaton Model of Pine Savanna Dynamics in Response to Fire and Hurricanes

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Introduction

I have chosen a cellular automata [1] simulation project. This demonstration [2] investigates the range of savanna vegetation patterns that can be achieved using a simple set of ecological rules embedded in a cellular automaton model. Pine savanna communities contain pine trees within a grassland matrix. The savanna is gradually invaded by hardwood trees in the absence of disturbance, eventually becoming a closed hardwood forest. Frequent disturbance can bound the system in an open grassland or pine savanna state. Savanna dynamics are modeled using a two-dimensional cellular automaton that incorporates intrinsic processes of dispersal, growth, and succession as well as extrinsic fire and hurricane disturbances. Ecosystem dynamics are explored in response to hurricanes, fire, and interactions between fire and vegetation.

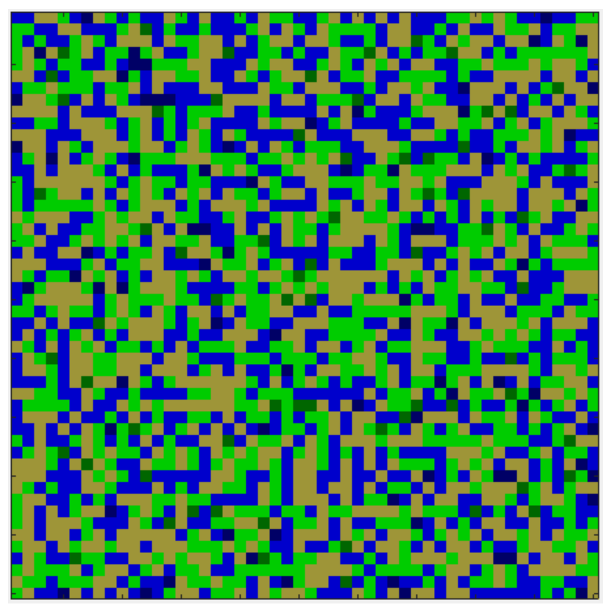

Figure 1: Initial savanna layout. Grass cells are brown, young pines are blue, adult pines are dark blue, young hardwoods are green and adult hardwoods are dark green.

An example initial layout is shown in Figure 1. In the project specification not all the dynamics were explained in detail, so I needed to find out some correlations, which I will unfold later.

Simulation details

Cells and landscape

Each cell can be in a grass, pine, or hardwood tree state. Pine and hardwoods could be either in a juvenile ('young') or mature ('adult') state: survivorship in hurricanes and fires varies across these age classes. A juvenile plant becomes adult after 5 years. This information was not included in the original description of the project, so I made the age as an alterable parameter and I found that I could reproduce similar results to the original simulation with the value of five.

A landscape of 50x50 cells is simulated for 115 years from an initial landscape state, where the amount of the three plants are approximately equal: grass (0.34), pine (0.32), and hardwoods (0.34) cells randomly assigned to the landscape. The ages of the pine and hardwood cells forms a discrete uniform distribution. Final landscape state is simulated in response to lightning intensity, hurricane frequency, and grass-pine interactions on fire probability. Parameters that describe cell transitions are described in the following. See Figure 1 for the initial landscape.

Model parameters

Plant growth

Annual probability of cell transition (without disturbance) from grass to pine is 0.03, from grass to hardwoods is 0.01, and from pine to hardwoods is 0.02. Since only this three transition were defined in the original project, I assumed that the annual probability of cell transition from hardwood to pine, from hardwood to grass and from pine to grass is zero. After that assumption, the following transition probability table can be calculated easily.

Annual transition probability		*From*		
		grass	pine	hardwood
To	grass	0.96	0	0
	pine	0.03	0.98	0
	hardwood	0.01	0.02	1

Dispersal distance for grass is 1 cell, for pine is 4 cells, and for hardwoods is 1 cell.

Hurricane

Annual probability of a hurricane can be alternated between {0, 0.05, 0.1, 0.2, 1}, which corresponds to a return period of {∞, 20, 10, 5, 1} years. Survival probability in hurricane for grass is 1, for young pine is 1, for adult pine is 0.2, for young hardwoods is 1, and for adult hardwoods is 0.2. I assumed here, that if a pine or hardwood does not survives the hurricane it became grass (independently if it has adjacent grass cells or not).

Lightning

The number of lightning strikes on the landscape is distributed as a Poisson random variable [3] with lambda parameter equal to lightning strike intensity multiplied by the number of cells in the landscape. Lightning strike intensity can be alternated across the set {0, 0.0004, 0.004, 0.04, 0.4}, which corresponds to an expectation of {0, 1, 10, 100, 1000} lightning strikes in a 50x50 cell landscape. The lightning strikes distributed in the landscape uniformly. The cell of the lightning strike will burn with probability 1, and can spread the fire to the adjacent cells.

Burning

Burn probability for grass is 0.4, for young pine is 0.1, for adult pine is 0.1, for young hardwoods is 0.05, and for adult hardwoods is 0.05. The simulation did not mention this, but I assumed that only lightning strikes can create fire, and after that, the fire will spread with the above probability.

Survival probability in fire for grass is 1, for young pine is 0.2, for adult pine is 0.8, for young hardwoods is 0.05, and for adult hardwoods is 0.1. I assumed here also, that if a cell does not survives fire it becomes grass, which was not mentioned explicitly.

The grass-pine interaction term originally varies over {1, 100, 1 000, 10 000, 100 000}, which should corresponds to a maximum odds ratio [4] of the cell burning of {1, 100, 1 000, 10 000, 100 000} when the neighborhood of adjacent cells includes four cells of grass and pine. Unfortunately from this few information I was not able to reproduce this calculation of the burning intensity. The odds ratio quantifies how strongly the presence or absence of a property is associated with the presence or absence of an another property in a given population. So in my case I would need to use for the first property the composition of the neighborhood and for the other property the burning of the cell, but the description does not mention the probability of a given neighborhood, so I was not able to calculate this ratio.

Instead I defined an own variable for the flame up probability, which varies over {0.1, 1, 1.2, 1.5, 2}. In my algorithm I go through the cells for 6 iterations (from top to down and from left two right alternately with from down to up and from right to left), and calculate for each cell which contains fire in its neighborhood if it will flame up or not. A cell will flame up with the probability of it's original burn probability multiplied with the flame up probability. Since the original description does not explains in detail how the spread of the fire is calculated, I found this method, which can produce similar results to the originally described one.

I also introduced a chart, where I represent the distribution of the population by time. This contains a lot of useful information about the patterns in the process. Another little change is that I run my simulations for 115 years instead of 100. Whit this little more time the result of the simulation becomes more clear with my parameters.

I visualize the different disturbances on the simulation layout. The cells which are destroyed by hurricane become gray, the cells where are lighning strike become white and the cells which are burning become red. See on Figure 2.

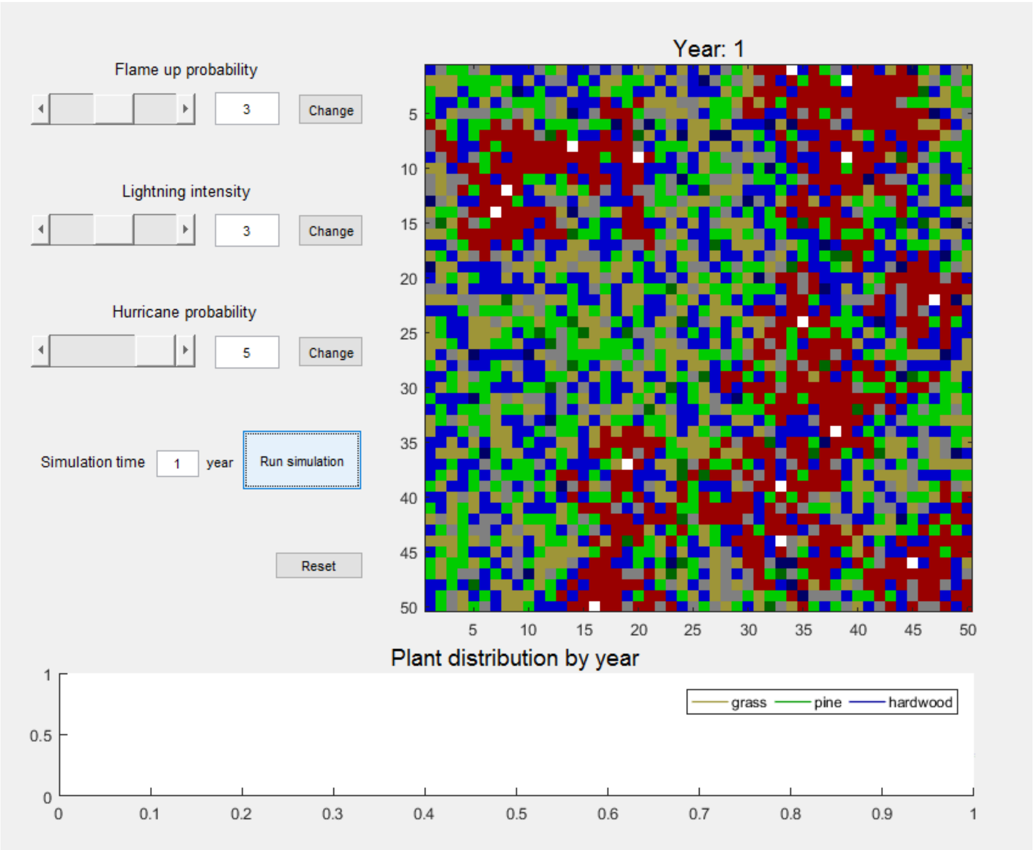

Figure 2. My simulation UI. Notice the newly introduced chart on the bottom and the visualization of the disturbances. Hurricane is grey, lightning is white and fire is red.

Comparing the results

A simple set of ecological rules can recreate the complex patterns and dynamics observed in savanna vegetation of the southeastern U.S. This can be observed in the original simulations and in mine also. In the first case I set the flame up and hurricane probability to minimal, which shows that without disturbance the savanna becomes a hardwood forest (Figure 3). This is mostly because the hardwood expanding to the detriment of the pine trees.

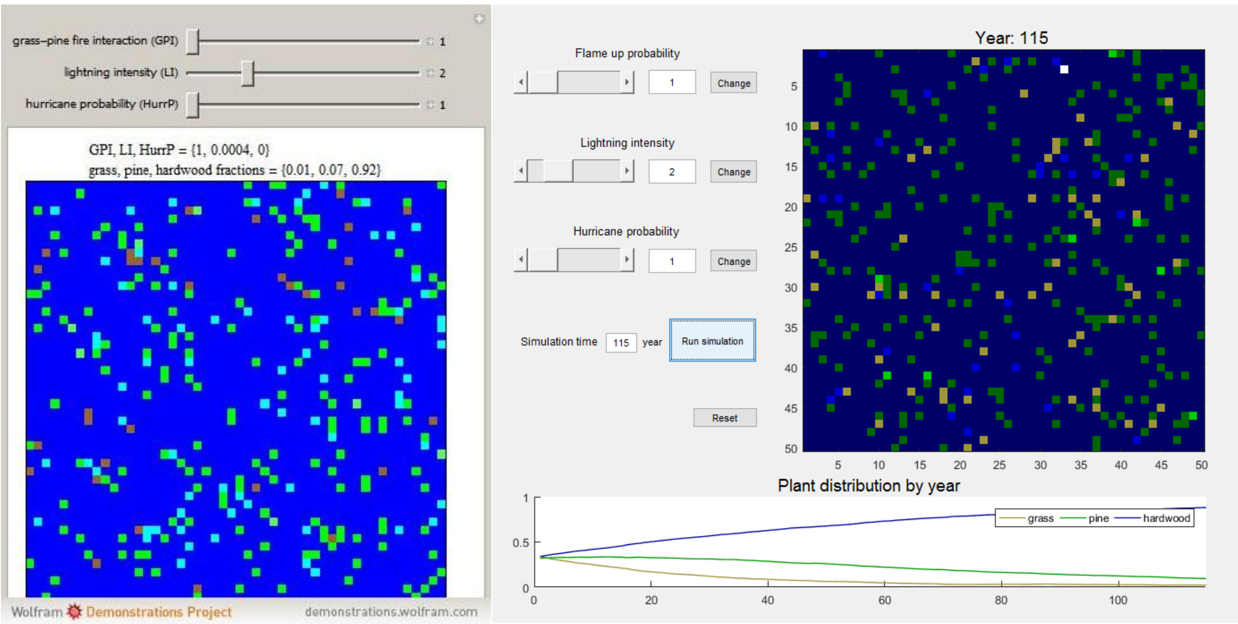

Figure 3. The original simulation on the left and mine on the right. When the flame up probability is set to 0.1, the lightning intensity is one and the hurricane probability is zero, the result is hardwood forest.

In the second simulation I set the hurricane probability to 0.05, which corresponds to a return period of 20 years. The result of this simulation can be seen in Figure 4. This setting results the retreat of hardwood trees from the landscape, which gives the possibility for the pine trees to spread. It can also be observed, that the hardwood is more sensible to the hurricane, because it is not able to spread as fast as the pine trees.

In the third simulation I increased the flame up probability to 1, so all the disturbance factors are “turned on”. In this case the hardwood trees are almost totally died out from the landscape. This shows that the pine trees are more immune to disturbances than the hardwood trees. See Figure 5 for the details.

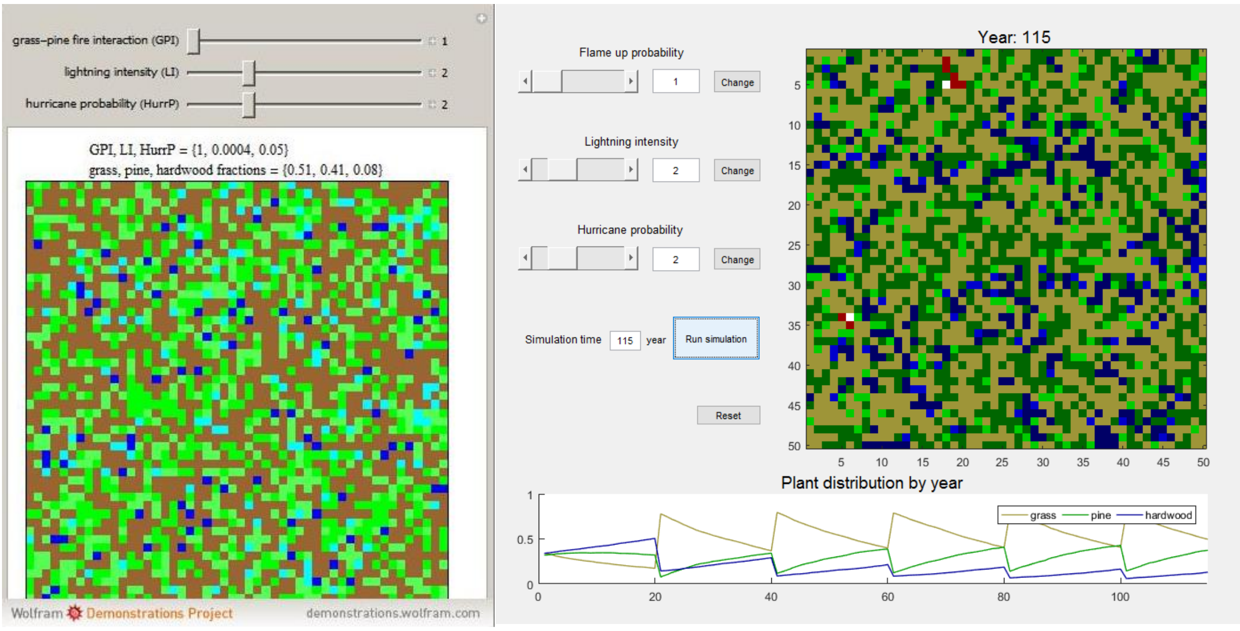

Figure 4. The original simulation on the left and mine on the right. The flame up probability is 0.1 the lightning intensity is 1 and the hurricane probability is set to 0.05, the result is mixed pine savanna.

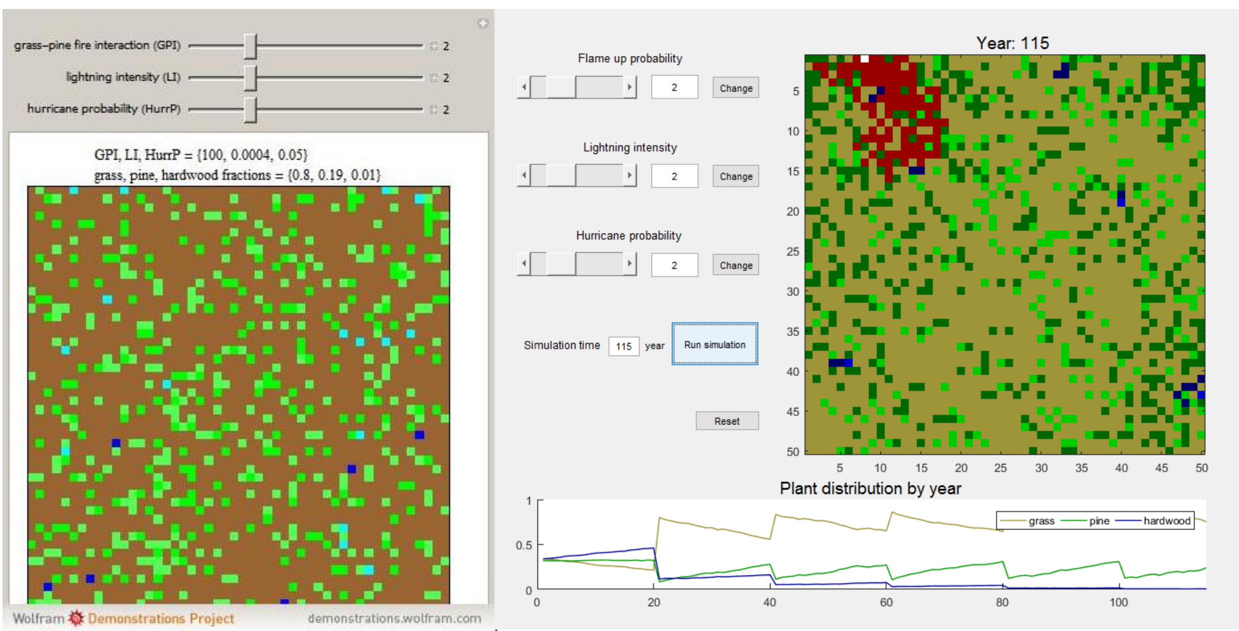

Figure 5. The original simulation on the left and mine on the right. The flame up probability is 1, the lightning intensity is 1 and the hurricane probability is 0.05, the result is open pine savanna forest.

Summary

A set of simple ecological rules can reproduce the patterns observed in pine savannas of the southeastern U.S. The model illustrates the potential importance of fire and hurricane disturbance in bounding these communities away from a closed forest in either a savanna or grassland state. An interaction between fire and grass-pine vegetation can facilitate the maintenance of savannas, while also leading to the spatial overdispersion characteristic of pine trees in southeastern savannas.

Sadly I was not able to copy all the original formulas but I was able to reproduce all the simulation results with my own work environment and have also added some more features to the simulation, like setting the length of the simulation, visualize the disturbances and the distribution of the species by time.

References

[1] W. D. Project, "Cellular Automation," Wolfram mathematica, [Online]. Available: http://mathworld.wolfram.com/CellularAutomaton.html. [Accessed 05 12 2017].

[2] W. D. Project, "Cellular Automaton Model of Pine Savanna Dynamics in Response to Fire and Hurricanes," Wolfram Mathematica, [Online]. Available: http://demonstrations.wolfram.com/CellularAutomatonModelOfPineSavannaDynamicsInResponseToFireA/. [Accessed 05 12 2017].

[3] Wikipedia, "Poisson distribution," [Online]. Available: https://en.wikipedia.org/wiki/Poisson_distribution. [Accessed 05 12 2017].

[4] Wikipedia, "Odds ratio," [Online]. Available: https://en.wikipedia.org/wiki/Odds_ratio. [Accessed 05 12 2017].