Modeling Succession

Project Module Associated with
2nd Edition, Introduction to Computational Science: Modeling and Simulation by

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Prerequisite: One of Module 10.3 on "Spreading of Fire," Module 10.4 on "Movement of Ants–Taking the Right Steps," or Module 10.5 on "Biofilms: United They Stand, Divided They Colonize"

Introduction

If you had been on Luzon, the largest of the Philippine Islands, on June 15, 1991, you would probably have feared for your life. A typhoon, known locally as Diding, passed through, coinciding with a massive eruption of Mt. Pinatubo. This eruption turned out to be the second largest eruption of the twentieth century, and Pinatubo had only recently been classified as inactive. It had only been a year since a 7.8 magnitude earthquake had shaken the region (USGS 2015).

The eruption of Pinatubo sent an ash cloud more than 20 miles into the air, much of it blown in many directions, some falling in the Indian Ocean. The ash cloud was followed around the world by satellites. Volcanic ash and pumice covered an area of 1500 square miles. Avalanches of hot ash, gas, and pyroclastic flows (high-density mixtures of hot, dry rock fragments, and hot gases that move away from the vent that erupted them at high speeds (USGS 2014)) moved rapidly, destroying everything in their course (NOAA 2012). The rain from the typhoon combined with the ash, generated a concrete-like sludge, capable of collapsing roofs miles from the eruption (Pappas 2011). Some valleys surrounding Pinatubo were filled with deposits in excess of 600 feet deep (USGS 2015). Once Pinatubo's magma chamber emptied, the roof collapsed, producing a huge caldera (crater) and reducing the height of Mt. Pinatubo by 260 meters (Jol).

Besides the physical changes made to the island of Luzon, scientists calculate that the Pinatubo eruption infused about 20 million tons of sulfur dioxide into the stratosphere. This cloud of gas spread around the globe and lowered the earth's temperature by 1°F for over a year (USGS 2005).

What was left in the areas of Luzon impacted by the outpouring of the volcano was essentially bereft of living organisms. However, over the years following the eruption, these barren areas have been colonized and changed by some hardy organisms. The initial organisms, mostly plants and microbes, which were able to survive under such harsh conditions, formed **pioneer** communities. Biological communities may be defined as groups of interacting populations of different species of microbes, plants, and animals. As these early inhabitants become established and grow, they also change the habitat by breaking down the inorganic surfaces and adding organic matter. Soon, a shallow soil forms, which makes the habitat more amenable to other organisms. The new organisms start another community, which also commences to alter the living environment, making it possible for yet another community of plants and animals to become established. This progressive series of community changes, over relatively large periods of time, is called **ecological succession**. Ecological succession is defined by scientists as a progressive and directional set of changes over time in the structure and composition of biological communities, interconnected with changes in the abiotic components of the habitat. When succession begins on a bare, sterile areas, the process is referred to as **primary succession**. If succession begins in an area where there was already established vegetation and soil, such as in abandoned farm land, the succession is termed **secondary**. In either case, the sequence of communities that develop usually lead to a self-perpetuating community, termed the **climax community**.

Thomas Marler, an ecologist from the University of Guam, realized that the devastating eruption of Pinatubo provided an excellent opportunity to study the succession of communities from the barren surfaces. He began to conduct botanical surveys in 2006, collaborating with a University of Washington ecologist, Roger del Moral. The results of their work, published in 2011, contributes significantly to our understanding of the recovery of areas affected by natural disasters (Science Daly; Marler & del Moral 2011).

Project

1. Employing cellular automaton modeling, Beckage and Ellingwood (2008) examined the dynamics of succession in southeastern United States pine savannas, which are subject to fires and hurricanes. Using a 50 × 50 grid, each cell represents a 10 m × 10 m area and can have one of five states: grass, juvenile pine, adult pine, juvenile hardwood, and adult hardwood. The basic simulation time step is one year, and it takes 10 years for a juvenile pine or hardwood to become an adult capable of reproducing.

Based on data, the simulation employs the following transition probabilities: If an adult pine is within 4 cells of a grass site, there is probability of 0.03 that at the next time step the site will have the state of juvenile pine instead of grass. Similarly, if an adult hardwood is within 1 cell of the grass site, the next time step, the site has a 0.01 probability of becoming juvenile hardwood. Should a site contain juvenile or adult pine with an adult hardwood neighbor, with a probability of 0.02, the site could have the state of juvenile hardwood at the next time step.

When fire occurs, grass, juvenile pine, adult pine, juvenile hardwood, and adult hardwood have probabilities of 0.4, 0.1, 0.1, 0.05, and 0.05, respectively, of burning. Should fire occur in a cell, the probabilities of vegetation survival are 1.0, 0.3, 0.8, 0.1, and 0.2, respectively.

In this project, we will develop a similar model and examine the results of various simulations. So that simulations, particularly with fire, do not take as long, we will employ smaller grids and fewer time steps than those of Beckage and Ellingwood (2008).

a. Create an initialization function, *init*, with parameters for the length of one side of the grid (*n*) and the desired fraction of each state. Return an initial grid (*savanna*) of states and a corresponding grid (*age*) of vegetation ages. Because only juvenile ages are significant for the simulation, generate random values between 0 and 9 for each *age* element corresponding to a juvenile pine or juvenile hardwood and assign 0 to other *age* elements.

b. Develop a script, *testSuccession*, to test your simulation. Have the script call *init* to return a grassland area of mainly grass but some other vegetation. Display the percent of each of type of vegetation, grass, pine, and hardwood. Have the script also generate a mixed environment with the three types of vegetation and a hardwood forest of mainly juvenile and adult hardwoods.

c. Develop a procedure, *succession*, to drive the simulation and other functions as needed. Initially, consider vegetative succession without the chance of fire or hurricane.[1]

d. Create a procedure to visualize the simulation. Using a 10×10 grid ($n = 10$), run the simulation several times for 300 time steps (years) for each of the three major landscapes, grassland, mixed, and hardwood. Describe and discuss the results.

e. Without visualization, run the simulation for 300 time steps (years) several times for each of the three major landscapes and average the final percentages for each type of vegetation. Describe and discuss the results.

f. Refining *succession* and developing other functions as necessary, consider the impact of fire caused by lightning strikes in the simulation. At each time step, the simulation should perform vegetative succession and then consider fire initiation (lightning strikes) and spread. One technique of handing such fires is to generate another grid initialized with random lightning strikes. Because each major time step of the simulation represents one year, have the fire(s) spread and burn out before continuing. To do so, you might want to incorporate an *EMPTY* state, indicating burned vegetation in a cell. Then, after all fires have dissipated in a time step, change the *EMPTY* states to *GRASS*, because grass succeeds all burned vegetation. Be sure to take into account burn and survival probabilities as indicated in the opening paragraphs of the project. In *succession*, have a parameter for the probability of a lightning strike in a cell. Appropriate values for this parameter are in the range 0.000 to 0.020.

g. Using several positive probabilities of lightning strike, repeat Part d, comparing the results to Part d. Probabilities of lightning strike for grassland might be 0.0002, 0.0004, and 0.0006; for mixed, 0.002, 0.004, and 0.006; and for hardwood forest, 0.005, 0.010, and 0.015. Discuss the nature of transitions between forested and grassland landscapes.

h. Using several positive probabilities of lightning strike, repeat Part e, comparing the results to Part e. Discuss the predominant nature of terminal landscapes as the probability of lightning strike increases and as the

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[1] One possible simplification, which unfortunately does not agree as well with the data, is to consider the dispersal distance of pines to be 1 instead of 4. In this case, if a cell with adult pine(s) is a neighbor of a grass site, there is probability of 0.03 that at the next time step the site will have the state of juvenile pine instead of grass.

probability decreases. Discuss the impact, if any, of the initial landscape on the final results.

i. Refining *succession* and developing other functions as necessary, consider the impact of hurricanes in the simulation. In *succession*, have a parameter for the probability of a hurricane occurring in a time step. At each time step (year), the simulation updates the landscape in response to the three processes of "vegetative succession, fire initiation and spread, and hurricane disturbance."

j. Using several positive probabilities of a hurricane in a year and with zero probability of lightning strike, repeat Part d, comparing the results to Part d. Probabilities of hurricane in a year might be 0.1, 0.2, and 0.3. Discuss the predominant nature of terminal landscapes as the probability of hurricane increases and as the probability decreases. Discuss the impact, if any, of the initial landscape on the final results.

k. Using several positive probabilities of a hurricane in a year and with zero probability of lightning strike, repeat Part e, comparing the results to Part e. Probabilities of hurricane might be 0.1, 0.2, and 0.3.

l. Considering the impact of fire and hurricane, repeat Part d. Compare the results of this and Parts d, f, and j.

m. Considering the impact of fire and hurricane, repeat Part e. Compare the results of this and Parts e, g, and k. Do periodic hurricanes along with fires affect the final landscape? If so, why do you think there is such an impact? With higher probabilities of hurricanes and lightning strikes, is it harder or easier to maintain intermediate savanna environments? With climate change, the number and intensities of hurricanes are increasing. El Niños, which result in fewer fires in the southeastern United States, are also anticipated to increase. Based on your simulations, can you predict the impact that a greater number of hurricanes and a fewer number of fires might have on landscapes in the southeastern United States?

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