Lab 8 Forest Fire Modeling

Part One: Literature Study

Read article: Alexandridis, et al. (2008) A cellular automata model for forest fire spread prediction: The case of the wildfire that swept through Spetses Island in 1990, *Applied Mathematics and Computation*. 204:191-201.

1. Which factor is **not** taken into account in this model? – (   )
   a. type of vegetation
   b. density of vegetation
   c. wind speed
   d. direction
   e. slope
   f. spotting phenomenon
   g. none above

2. Match the following concepts with appropriate statements:
   1) Spotting – (   )
   2) Cellular automata – (   )
   3) Hexagonal cells – (   )

   a. can describe more accurately the spatial behavior of the fire, however this comes at the cost of significantly increasing the computational complexity of the resulting model.

   b. a cell-based model in which each cell is described by several variables whose states, being usually discrete, evolve in discrete time, according to a set of rules and the states of the neighboring cells.

   c. a phenomenon where burning material is transferred by the wind or other reasons such as the fling of flaming pinecones to areas that are not adjacent to the fire front.

3. In this research, each cell is characterized by a finite number of states which evolve in discrete time. The possible states are the following:
   1) State = 1: (   )
   2) State = 2: (   )
   3) State = 3: (   )
   4) State = 4: (   )

   a. The cell contains forest fuel that has not ignited
   b. The cell contains forest fuel that is burning
   c. The cell contained forest fuel that has been burned down
   d. The cell contains no forest fuel and cannot burn

4. The CA model rules: (match rules with explanations)
    1) Rule 1: IF state (i, j, t) = 1 THEN state (i, j, t + 1) = 1. – ( )
    2) Rule 2: IF state (i, j, t) = 3 THEN state (i, j, t + 1) = 4. – ( )
    3) Rule 3: IF state (i, j, t) = 4 THEN state (i, j, t + 1) = 4. – ( )
    4) Rule 4: IF state (i, j, t) = 3 THEN state (i ± 1, j ± 1, t + 1) = 3 with a probability P_{burn}. – ( )
    5) Rule 5: IF state (i, j, t) = 3 THEN state (i ± ic, j ± jc, t + 1) = 3. – ( )

    a) This rule implies that if a cell is on fire, each neighboring cell will be ignited in the next stage with a probability
    b) This rule implies that a burning cell at the current time step will be burned down at the next time step.
    c) This rule implies that if a cell is on fire, it may ignite a distance cell
    d) This rule implies that the state of an empty cell that has been burned down in the previous step stays the same.
    e) This rule implies that the state of a cell with no forest fuel (empty cell) remains the same and thus it cannot catch fire.

5. The probability for a cell to be ignited is calculated by

$$P_{burn} = P_h(1 + P_{veg})(1 + P_{den})P_wP_s$$

Where

P_h = ( )

P_{veg} = ( )

P_{den} = ( )

P_w = ( )

P_s = ( )

a) probability based on the density of vegetation,
b) a constant probability (0.58)
c) probability based on slope
d) probability based on wind speed
e) fire propagation probability based on the type of vegetation

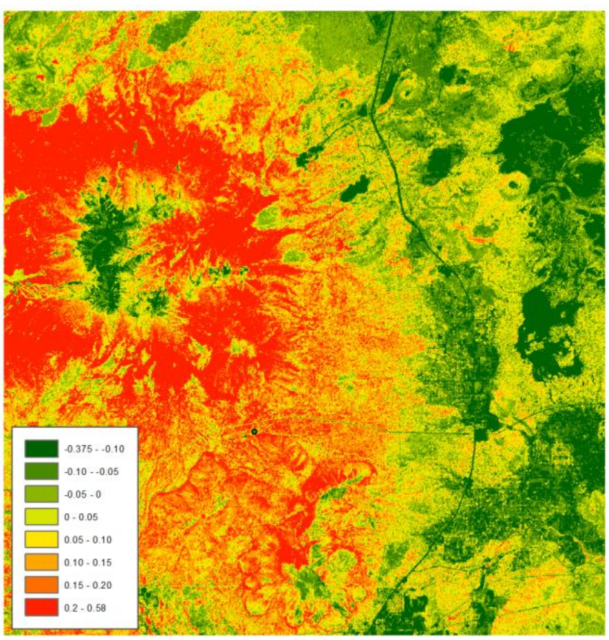
Part Two: Modeling the Schultz Pass fire

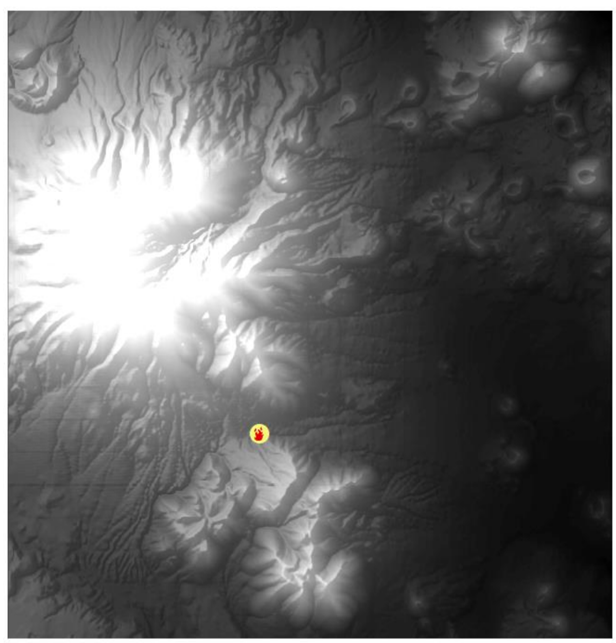
The Schultz Fire is a wild fire that began at 11:09 A.M. on June 20, 2010 near the Schultz Pass north of Flagstaff. Due to high winds, it grew rapidly and burned over 15,000 acres (6,100 ha) of the Coconino National Forest, which mainly consists of ponderosa pine trees, in the subsequent ten days. Watch this video clip to see simulated spread of the Shultz Pass fire (http://oak.ucc.nau.edu/rh83/Fire_Model).

How It Works

The spreading of forest fires is affected by a number of factors including the amount of fuel which can be measured by vegetation density, wind direction and speed, topography, etc. When a vegetated location is approached by a fire, it will be ignited subsequently. Moreover, winds can cause a fire to spread in the downstream direction much faster than in the upstream direction. In other words, winds can cause fire spread probability to increase in downstream direction but to decrease in upstream direction. Furthermore, topography can affect the speed of fire spread. Fires tend to spread faster upslope than downslope. Therefore, a location upslope a fire has a greater chance to be ignited than a location downslope the fire. In addition, burning pine cones, assisted by strong winds, can shoot into the sky like popcorn and fly over a distance to sparkle a location not immediately adjacent to the fire front. This is called fire spotting.

This model uses Cellular Automata (CA) technology to simulate fire spread by computing cell ignition probabilities based on the factors mentioned above. The amount of fuel is indicated by the Normalized Difference Vegetation Index (NDVI) derived from the ASTER satellite images acquired prior to the fire (Lab 7). Wind data was obtained from wind simulation results of the National Renewable Energy Laboratory (NREL) and interpolated to create raster layers. A Digital Elevation Model (DEM) was downloaded from the USGS National Map online data source. The spatial resolution of both ASTER and DEM datasets are 15 meters and so are the interpolated daily wind speed and direction fields.





This CA model adopts a 15 x 15 meters spatial resolution. A raster layer is created to maintain initial states, in which state 0 represents not flammable, state 10 represents flammable but not ignited, states 20 to 29 represent burning, and state 30 represents burned.

10	10	10	10	10
10	10	10	10	10
21	20	10	10	10
30	21	20	10	0
30	30	21	10	0

Cell states:

0 = no fuel, not flammable;

10 = Flammable, unignited;

20 to 29 = Burning. 20: ignited; 29: nearly burned

30 = Burned

Rules:

Rule 1: $S_{i,j,t} = 0 \Rightarrow S_{i,j,t+1} = 0$; $S_{i,j,t} = 30 \Rightarrow S_{i,j,t+1} = 30$. This rules means that if the state of a cell is 0 or 30 at time t, its state will stay unchanged in the subsequent simulation step (time t+1).

Rule 2: $S_{i,j,t} = 10 \Rightarrow S_{i,j,t+1} = 20$ if $S_{i\pm1,j\pm1} \in \{20 \ldots 29\}$ with probability $P_{spreading} = Spreading(x, n, \vartheta, v, s)$. This rule means that if an unignited flammable cell is next to a burning cell at time *t*, it will be ignited in the subsequent step (t+1) with a spreading probability derived from the burning state (x), ndvi (*n*), wind angle (ϑ) and speed (*v*), as well as slope (*s*).

Rule 3: $S_{i,j,t} = 10 \Rightarrow S_{i,j,t+1} = 20$ if $S_{i\pm2,j\pm2} \in \{21, 22\}$ with probability $P_{spotting} = Spotting(n, \vartheta, v, s)$. This rule means that a burning cell of state 20 has a probability to spot a cell apart from it in the next step based on ndvi, wind angel, wind speed, and slope.

Rule 4: $S_{i,j,t} \in \{20 \ldots 28\} \Rightarrow S_{i,j,t+1} = S_{i,j,t} + 1$. This means that the state of a burning cell will update state in the next step (t+1)

Rule 5: $S_{i,j,t} = 29 \Rightarrow S_{i,j,t+1} = 30$. This rule means that a burning cell of state 29 will become a burned cell in the next step.

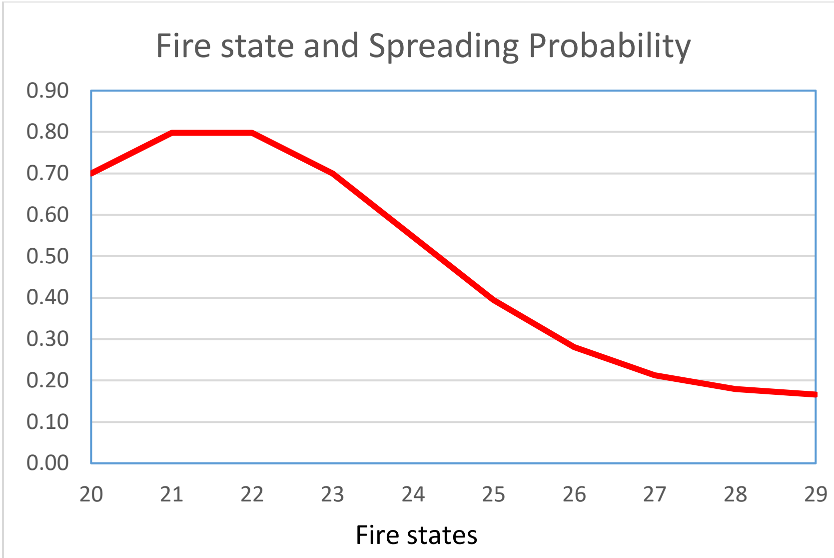
Fire spreading probability

Given $S_{u,v} \in \{20 \ldots 29\}$, where $u = i\pm1$ and $v = j\pm1$, the probability of fire to spread from a neighboring cell (u, v) to the current cell (i, j) is computed as the following.

1) Probability contributed by the burning stage factor (x)

$$P_{x(u,v)} = a_1 + b_1 \frac{1}{\sqrt{2\pi\sigma^2}} e^{-(x-\mu)^2/2\sigma^2} \quad \ldots\ldots (1)$$

Where μ, σ^2, a_1, b_1 are parameters.



2) Probability contributed by the ndvi variable

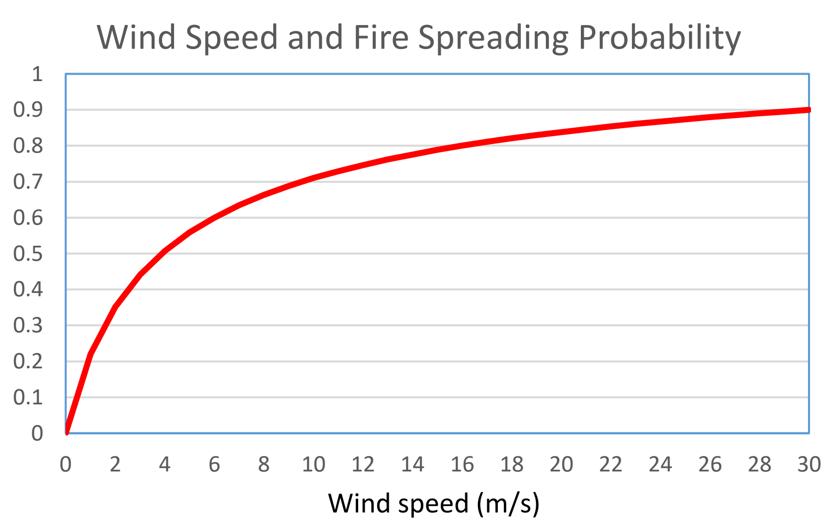
$$\bar{n} = \frac{n_1+n_2}{2} \quad \text{......} \quad (2)$$

$$P_{n(u,v)} = a_2 - \frac{b_2}{(c_1\bar{n}+1)^2} \quad \text{......} \quad (3)$$

Where n_1 and n_2 are ndvi of the source and target cells, and a_2, b_2, and c_1 are constants.

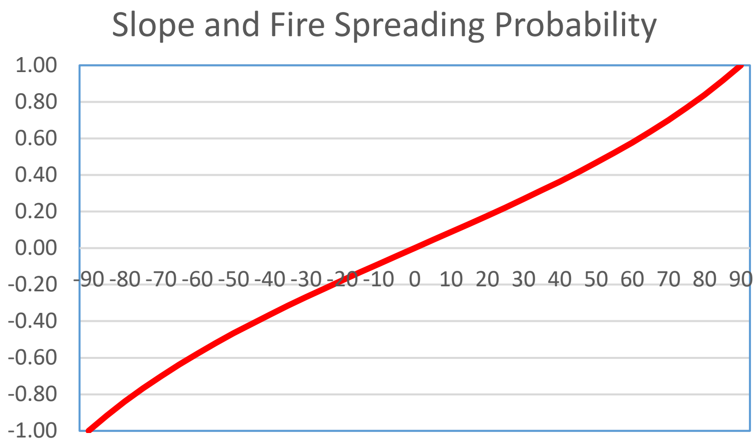
3) Probability contributed by the wind speed and direction variables is derived from the following equation where *v* represents wind speed, ϑ represents the angle between wind direction and fire spreading direction, and c_2 is a constant.

$$P_{w(u,v)} = c_2\left(1.0 - \frac{1}{\sqrt{\frac{v}{2}+1}}\right)\cos(\theta) \quad \text{......} \quad (4)$$



4) Probability contributed by the topography (slope) factor

$$P_{s(u,v)} = \tan(\frac{s}{2}) \quad (5)$$



Fire spreading probability from a neighboring cell (u, v) to the current cell (i, j) is computed as

$$P_{u,v} = 1 - (1 - P_{x(u,v)})\big(1 - P_{\eta(u,v)}\big)\big(1 - P_{w(u,v)}\big)(1 - P_{s(u,v)}) \quad (6)$$

Finally, the overall probability of fire spreading to cell (i, j) from its neighbors is

$$P_{spreading} = 1 - \prod_{u,v}\big(1 - P_{u,v}\big) \quad (7)$$

Fire spotting probability

Given $S_{u,v}$ = 20, where $u = i\pm2$ and $v = j\pm2$, the probability of fire to jump from cell (u, v) to the current cell (i, j) is computed by the following:

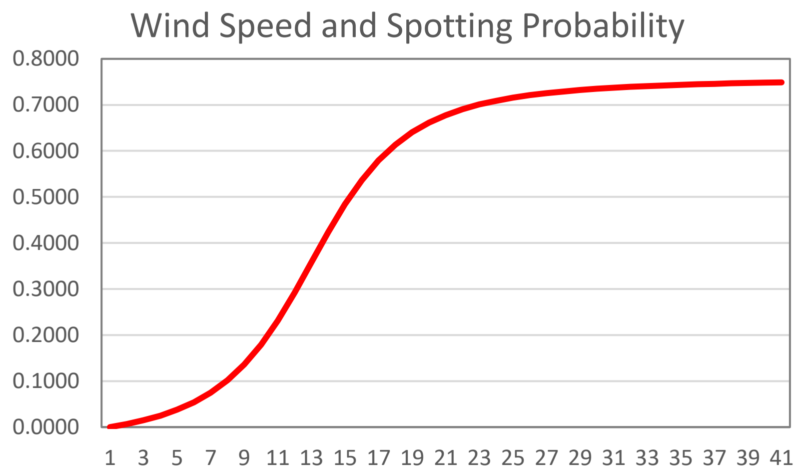
1) Probability contributed by the ndvi is derived from the ndvi of the source cell.

$$P_{n(u,v)} = a_2 + b_2\log(n+1) \quad (8)$$

2) Probability contributed by the wind variable

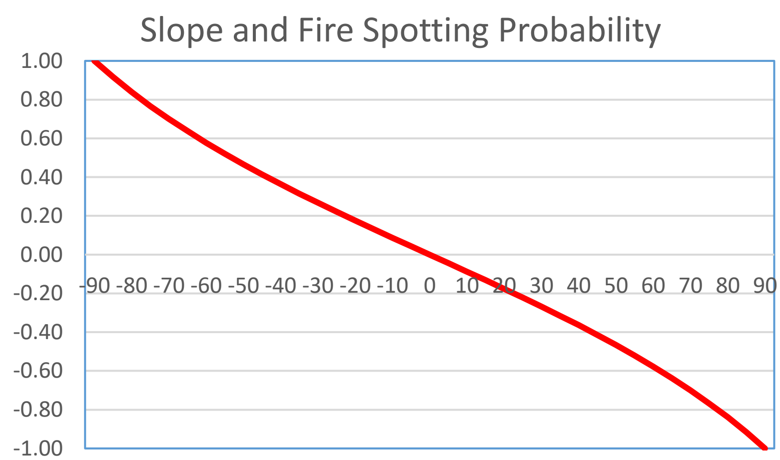
$$P_{w(u,v)} = \frac{2c}{d}\left(a_3 + b_3\frac{\frac{v}{6}-2}{\sqrt{1+\left(\frac{v}{6}-2\right)^2}}\right)\cos(\theta) \quad (9)$$

Where c represents cell size, d represents distance between the centroids of cell(u, v) and cell(i, j), θ is the wind angle, and a_3 and b_3 are parameters.



3) Probability contributed by the topography (slope) factor

$$P_{s(u,v)} = -\tan(\frac{s}{2}) \quad (10)$$



Fire spotting probability from cell (u, v) to the current cell (i, j) is computed as

$$P_{u,v} = 1 - \left(1 - P_{n(u,v)}\right)\left(1 - P_{w(u,v)}\right)\left(1 - P_{s(u,v)}\right) \quad (11)$$

For the entire processing window,

$$P_{spotting} = 1 - \prod_{u,v}\left(1 - P_{u,v}\right) \quad (12)$$

Finally, the overall ignition probability is

$$P_{ignition} = 1 - \left(1 - P_{spreading}\right)\left(1 - P_{spotting}\right) + \varepsilon \quad (13)$$

Fire Model in Python

These formulas are implemented by a fire model kernel function in Python. Please download file "fire_model.zip" from Bblearn and unzip the file to your computer.

This zip archive contains two Python scripts: "kernel.py" and "kernel_test.py". The first one contains a function named "ignitionprob()" that computes an ignition probability for the central cell of a 5 x 5 cell processing window. This function takes several inputs (arguments):

1) a 5 x 5 matrix of current fire states
2) a 5 x 5 matrix of NDVI values
3) a 5 x 5 matrix of wind direction values
4) a 5 x 5 matrix of wind speed values
5) a 5 x 5 matrix of elevation values
6) a cell size value

When this function is called with appropriate inputs, it returns an ignition probability value of the central cell of the processing window, and prints a spreading probability and a spotting probability.

You can open the "kernel.py" script in IDLE (or Pythonwin if you installed it) by right clicking on the file in Windows Explorer and select "Edit with IDLE" to take a look at the code and close it. But do not make changes to the code and do not run the script.

Script "kernel_test.py" is used to test the kernel function. Please open the file in IDLE to look at the code. The script first defines five 5 x 5 cell matrices for five arguments (states, ndvi, wind direction, wind speed, and elevation) and a cell size (value 15), then it calls the ignitionprob() function in the kernel module and use variable *prob* to hold the resulting probability. The last line prints the final result.

Please note that in Python text headed by a pound sign (#) are comments. A comment explains the code but itself is not part of the effective code and it is not interpreted or executed by the computer.

To run the script ("kernel_test.py") in IDLE, click menu Run >> Run Module F5. You can also use the shortcut key F5 to run the script. Results are printed in the IDLE command window (a separate window).

<u>Question 1</u>: Run the script, what are the probabilities (spreading, spotting, and final) for the central cell to be ignited? You may not get 1.0 for the final probability at beginning, try to run the script a few times. You will find the final probability varies because there is a stochastic component in fire spread.

Look at the arguments and answer the following questions:

<u>Question 2</u>: How many cells are burning? What are the row and column numbers of the burning cell(s)?

<u>Question 3</u>: What are the NDVI values of the burning cell(s)?

<u>Question 4</u>: what are the wind direction and wind speed at the burning cell(s)?

Modify the arguments and run the script.

Question 5: Change the state of row 2 and column 4 to 20. What are the resulting probabilities? Note that this cell is downstream the central cell in terms of wind. After the test, change the cell back to 10.

Question 6: Change the state of lower-left corner cell to 21. What are the resulting probabilities? Note that this cell is upstream the central cell in terms of wind.

Question 7: Change the state of row 3 and column 2 to 20, what are the resulting probabilities? Change the state of the cell back to 10 after the test.

Question 8: Change the wind speed of row 4 and column 2 to 0.624751 (delete integer 13) what are the resulting probabilities? Change the value back to its original after the test.

You may perform more tests by adjusting cell states, ndvi, wind speed and direction, and elevation and observe how they affect fire propagation probabilities.

This kernel function can be implemented in a wildfire model with real data including a current states raster, an NDVI raster, a wind direction raster, a wind speed raster, and an elevation raster. The kernel function is called to calculate an ignition probability for each cell in a state raster that covers the study area for a time instant. To compute the ignition probability for cell (i, j) in the state raster, you must extract a 5 x 5 cell matrix of values from each input dataset with cell (i, j) positioned at the center of the matrix. If the resulting ignition probability of cell (i, j) is 1.0, the state of the cell is changed to a burning state. When all cells of the current states raster are processed, a new states raster is created. The video clip you watched early was created from results of 724 simulation steps (at 20-minute interval). The computation took about 53 continuous hours to complete on a desktop PC with 8 cores and 16 GB of memory.

Finally, **create a poster presentation** (50 points) on Cellular Automata (CA) modeling for wildfire spread. You do not have to use equations, but need to explain the methodology (how it works) including an overall procedure, rules of the CA model, data requirements, expected results, etc. You may discuss how different factors, such as wind speed, wind direction, ndvi, and topography, affect fire propagation. You are encouraged to use diagrams to illustrate the CA model rules as well as various components of the model.