Introduction

Agent-Based Modeling (ABM) is an incredibly powerful tool in a GIS analyst’s toolbox. It is a spatial modeling method that can account for the dynamics and complexities of real world systems. This is accomplished by modeling entities as individual actors, or agents, with different characteristics and seeing how they interact with other actors and their environment, given a set of rules and behaviors. The rules and behaviors are developed through a combination of quantitative and qualitative data alongside theory to provide an abstraction of reality. The agents play out their roles in a virtual environment, represented by a series of patches containing data such as land classification, akin to pixels on a screen. Simulating these systems can reveal emergent phenomena, such as species segregation or social inequality, which could inform decision makers or stakeholders (Lindkvist et al). Though ABM is most often known as an ecological tool, the applications are numerous and growing. For this study, a simple fire model in the NetLogo ABM software was modified to display more complex fire behaviors. A GIS extension within NetLogo allows for the import of both raster and vector data, allowing for real world environments to be simulated.

These complex fire behaviors were simulated on a portion of land in Central Washington State in the Northwestern United States. Central Washington is much different than the typical idea of the rainy Pacific Northwest as the region sits in the rain shadow of the Cascades Mountain Range. Simply put, due to the height of the mountain range, rain clouds are prevented from moving further east, trapping the rain near the coast and allowing only a small portion to travel over the mountains. It is in this region where most of the state’s wildfires occurred in 2020 and 2021. With the onset of climate change, conditions have exacerbated and the already arid region continues to dry. With less rain, more fuel is available, radically increasing wildfire risk and intensity for Central Washington. By August of 2021, Washington had already experienced over 800 wildfires, with over 60% being caused by humans (King 5).

The model developed for this study aims to simulate the spread of wildfires as they encounter different classifications of land. For example, fire cannot typically spread over bodies of water and thus water would be a barrier to movement. Conversely, dry vegetation would be optimal to propagate fire. Additionally, the model acknowledges the human causes of these fires and thus only ignites fuel directly adjacent to developed areas. Finally, the model incorporates a form of precipitation to vary the amount of fuel available to burn. A long term goal of this model development would be building a more complex wildfire model to anticipate spread and support distribution of emergency services.

Spatial Data

This study only used a single dataset, the 2019 National Land Cover Database from the Multi-Resolution Land Cover Consortium (MRLC). The dataset contains the land cover data for the Continental United States, classifying each portion of land into one of 16 categories. It is at the 30m resolution.

As described in the previous section, the study area is in Central Washington. More specifically, the area of interest sits on the eastern edge of the farming community of Royal City (map study area). It is an approximately three square mile area that contains farmland and a portion of the Columbia National Wildlife Refuge conservation area. Thus, the study area contains one form of the wildland urban interface, where human development intersects with natural habitats.

Study area

Methods

The workflow for this study can be considered in three phases: data preparation in ArcGIS, data importation and model modification in NetLogo and finally model improvement.

The land cover data were obtained from the MRLC website and were first clipped to the boundary of Washington State to reduce extraneous data and free memory on the computer system. The data were further clipped to the study area. Originally, a 75 square mile area was planned, but due to limitations within NetLogo, the area had to be reduced to three square miles.

Once clipped to the area of interest, the data were reclassified into one of four categories, Dry Fuel, Wet Fuel, Developed and Water. The 16 land classifications were reduced to four to allow greater ease in the transfer of files between software in addition to simplifying the process of coding. Table 1 shows the land classifications contained within the new categories. The relationships between these categories are as follows: fires will start in Dry Fuel patches adjacent to Developed patches, Wet Fuel patches will have a lower chance to burn and will never be ignition points and Water patches will act as barriers to inhibit the movement of fire.

| **Category** | **NLCD Classification** | **Assigned Netlogo Color** | **Patch Variable** |
| --- | --- | --- | --- |
| Dry Fuel | Barren Land, Deciduous Forest, Evergreen Forest, Mixed Forest, Shrub/Scrub, Herbaceous, Hay/Pasture, Cultivated Crops | Yellow | is-dry, is-IgP |
| Wet Fuel | Woody Wetlands, Emergent/Herbaceous Wetlands | Green | is-wet |
| Developed | Developed (Open Space, Low Intensity, Medium Intensity, High Intensity) | Gray | is-dev |
| Water | Open Water, Perennial Snow/Ice | Cyan | is-wtr |

Table caption

With the data reclassified, it was copied three times to create four identical layers. These layers would represent one category each, with the other categorical data being deleted. By doing this, each land category could be kept as a separate dataset in NetLogo and be assigned different behaviors and qualities. Particular care was given in ensuring extraneous data were excluded such that when the layers were viewed together, they would compose a single image with no overlapping cells. Finally, the raster layers were exported into separate .asc files using the Raster to ASCII tool. There were also .prj and .xml files for each that contained projection information and other data for NetLogo to read and interpret.

With NetLogo initialized, the Fire Model was loaded from the sample models section of the built-in model library (Uri Wilensky). The original model demonstrates the spread of fire through a user generated forest. The user may designate the density of the forest and thus the model shows the relationship between the density of fuel and the spread of fire in a nondescript forest. For the model, the agents are individual fires, which constantly seek adjacent tree patches to burn until no fuel is immediately available.

The world environment size for the wildfire ABM was changed to 244x265 from the default 150x150. These proportions were taken from the above .asc files in order to ensure the environment exactly fit the dimensions of the raster data. The patch size was set to 2, as larger sizes exceeded the memory of the computer the software was running on, causing the software to crash and making the project file of the model inaccessible.

The *gis:load-dataset* command was used to import the data, following the instructions listed by Brown (2021). Unfortunately, there were many issues at this stage of the workflow. Initially, an error message was returned when attempting to start the model, noting incompatibility with the projected coordinate system (PCS) of the data, Web Mercator. Davies (2014) noted that projection error messages could be addressed by updating the listed projection in the .prj file with the Well Known Text (WKT) format of the WGS1985 geographic coordinate system (GCS) (figure WKT).

| GEOGCS[“GCS\_WGS\_1984”,DATUM[“D\_WGS\_1984”,SPHEROID[“WGS\_1984”,6378137,298.257223563]],PRIMEM[“Greenwich”,0],UNIT[“Degree”,0.017453292519943295]] |
| --- |

Figure WKT

This solution was unsuccessful, only importing the Dry Fuel dataset, which necessitated the nuclear option of deleting all project files and restarting with fresh land cover data. In preparing the data again, similar steps to above were maintained with the addition of setting the project environment to WGS1984 and using the Project Raster tool to ensure the data were solely in the WGS1984 GCS. The nuclear option was used three additional times due to the same incompatibility issues and suspicion of file corruption. Finally, three of the four datasets were successfully imported: Wet Fuel, Developed and Water. Rather than attempt to load the Dry Fuel data, a solution was devised where the patches not included in the three datasets were simply recolored, creating a pseudo dataset based on that color rather than by land classification. Functionally, this pseudo dataset would act identically to the raster data. This was justified because the nature of the patches for this model were binary, whether they were or were not something and were not quantitative, such as elevation. At this stage of model development, there was a basic map of the study area where all features burned, regardless of land category.

To build the basic behaviors, each dataset was first assigned a color using the *gis:apply-raster* command (table1). The datasets were also assigned patch variables (is-dry, is-wet, is-dev, is-wtr) to allow ease of identification with the code. Dry fuel patches were also assigned the is-IgP patch variable, designating them as potential ignition points.

The first agent behavior sought was to ignite fires next to developed patches. All developed patches were asked to look at neighbors and seek any with the IgP patch variable. *Random-float 20000 < 3* was used to randomly select a number of those identified patches to start fires. This true/false command works by generating a random nonzero number, in this case 20,000, and comparing it to the second number, in this case 3. If the comparison is true, then the overall command, igniting fires at selected patches, is executed (GIS Documentation). For this command block, there would be a 0.0001% independent chance that a Dry Fuel patch next to developed land would be selected as an ignition point.

The next basic behavior developed was incorporating a probability of spread when encountering different land categories. The idea was that not every portion of land will burn evenly and some may even survive following a fire, adding variability to each run of the ABM. Using the *random-float* command with the *if*, *or* and *and* logical operators, Dry Fuel was given a 100% probability of burning when encountered, Wet Fuel 30%, Developed 10% and Water 0% (Figure behaviors).

To add complexity to the model, a form of precipitation was incorporated, code represented in figure Precipitation. How this command block functions is that after NetLogo assigns the patches their colors and variables, it randomly converts a number of Dry Fuel patches to Wet Fuel based on the amount of rainfall. On an annual basis, Central Washington receives 5 to 10 inches of rain (WA Dept of commerce). Thus, a slider was added to the interface to allow users to designate between 0 and 10 inches of precipitation, giving a dry fuel patch an up to 0.009% probability of being converted. 0-5 inches of rainfall was included to allow for the possibility of reduced or nonexistent rain.

| ask fires  [ ask neighbors [  if ((pcolor = yellow) or ((pcolor = green) and (random-float 100 < 31)) or ((is-dev = 1)  and (random-float 100 < 11)))[ignite]]  set breed embers ]  fade-embers  tick |
| --- |

Figure behaviors

| ask patches [  if ((pcolor = yellow) and (random-float 1000 < rainfall))  [set pcolor green]] |
| --- |

Figure precipitation

Results

For this study, a simple fire ABM was modified to display complex wildfire behaviors within a portion of land in Central Washington. These fires would be ignited on sections of dry land adjacent to Developed land, such as roads, due to the human origin of most wildfires. As the fire propagates through the study area, different land types would have different chances of burning. To add variability, precipitation was incorporated to vary the ability for fire to consume the landscape.

When initializing the ABM, it was observed that 0-7 fires would be ignited in any given run (Figure abm start). In the case of zero, no fires would begin, requiring the ABM be set up again until a nonzero number of ignition points was selected. These fires mostly began in the northern half of the study area, adjacent to roads, though some developed patches in the southeast corner allowed for fires to begin there.

As the fire(s) moved across the landscape, all the Dry Fuel would be consumed. Additionally, much of the developed patches and the majority of Wet Fuel would be burned as well, fragmenting their groups of patches (Figure ABM in prog). With added precipitation, wet fuel patches occurred sporadically across the entire study area. These Wet Fuel patches did not appear to slow the spread of fire, though a number would survive at the end of each run of the model. Water provided a much stronger inhibitor to movement, never having been affected by the fire. This resulted in the southwest corner of the study area almost always being the last to burn as the water body extended approximately ⅔ the length of the study area from the western edge. Finally, once the first extinguished itself, it was observed that 96-97% of the study area burned, varying based on the survival of the wet fuel and developed patches (Figure abm burned). This ranged occurred regardless of precipitation.

Figure abm start

Figure abm in prog

Figure abm burned

Discussion

Though the model is very simplistic in nature, there are a few implications in the model that would carry more weight if the ABM is improved upon. The first is the fragmentation of the landscape. This model could help indicate higher or lower risk areas in addition to infrastructure that may be damaged. For example, perhaps homes next to wetlands may be assigned lower evacuation priority than those next to dry fields. Or this model may inform responders the probability a road may be damaged and to what degree.

The model also demonstrates the importance of diverse native landscapes. Within the bounds of this study, all human development was destroyed. But as mentioned in the previous section, the southwest corner of the study area was often protected by the water body and would burn last. This feeds into the concept that more native landscapes can manage wildfires to some degree on their own. Of course while this does not stop the fires, human induced climate change has ensured we are far past that, it could inform conservation efforts restoring the landscape just outside human settlements to give residents more time to escape during a fire. Additionally, human developments could be redesigned to resemble the natural landscape more, such as by having a wide stream carve through farmland to inhibit fire spread and protect crops and livestock.

Looking ahead, there are many potential improvements to this model. First and foremost would be the addition of more land classifications to model more complex interactions. For example, there are four classifications for developed land in the NLCD and they all likely have different fire ignition risks and ability to resist fire. It would be interesting to explore these classifications further to build a more robust model. An issue with this wildfire model is that the fires often had straight line leading edges, which is not necessarily realistic. By including different land classifications with different fire resistances, a more erratic, realistic edge could be displayed.

Another improvement would be the ability to point to specific patches to set fire to. As mentioned in the introduction, 61% of Washington fires were human in origin, leaving 39% to be naturally occurring. Thus this model ignores over a third of fire scenarios for the region. Pointing at patches to set fire to would not only make up for this shortfall, but allow for the planning of specific fire scenarios. For example, if there is a known industrial manufacturer or farmer with more fire-prone practices, fires could be modeled from those points of origin to inform preemptive efforts or direct emergency services following an ignition.

Finally, this model is not simply limited to modeling wildfires. Wildfires are high energy systems and thus this model has the potential to be applied to other similar systems. One such are mass landslides. Once a landslide is initiated, the earth moves downward and outward, running across different landscape features. By incorporating the landslide features with the ability of portions of land to slow or resist the movement, the effects of mass movement events could be modeled.

Lindkvist et al

<https://www.king5.com/article/news/local/wildfire/washington-wildfires-human-caused-2021-climate-heat/281-c499e0ab-0fbc-43d1-b0c1-d3ab1522e131>

Wilensky, U. (1997). NetLogo Fire model.<http://ccl.northwestern.edu/netlogo/models/Fire>. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.

Brown (2021) - <https://www.youtube.com/watch?v=_qR9lZy6xjE>

Davies - turtles in space

GIS documentation

Wa dept of commerce