ASYNCHRONOUS CELL-DEVS WILDFIRE SPREAD USING GIS DATA

https://github.com/murf85/wildfire

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ABSTRACT

Wildfires are extremely dangerous and destructive. In order to protect populations and infrastructure, government official and firefighter must best decide how to expend their limited resources. Wildfire simulation aids these decision makers by predicting the spread of fire. A wildfire spread model using the Asynchronous Cell-DEVS formalism and simulated with Cadmium is presented. This model incorporates GIS information from publicly available maps to improve the accuracy of the wildfire spread predictions, and allows multiple scenarios to be simulated in timely manner.

1 INTRODUCTION

A combination of climate change and forest management practices have led to a number of damaging forest fires in recent years. On 22 July 2024 in the afternoon a wildfire began in Jasper National Park, at 9:59PM an evacuation order was given for Jasper National Park and the town of Jasper. By 24 July 2024, 20,000 people were evacuated, and over the next three days one-third of the town was destroyed by wildfire (Municipality of Jasper 2024). Thousands of incident management staff from all levels of government were required to support the citizens and first responders. It was not until August 15th that fire perimeter was sufficiently controlled to allow re-entry of citizens. Although the evacuation was successful, in the aftermath of the fire it was reported that "an initial takeaway is that early resourcing and fire prediction and modelling data should be updated." (Fire Fighting in Canada, 2024). In fact, all around the world governments are investing in tools to better predict and track forest fires (Jerusalem Post Staff, 2025)(Royz & Tendler, 2024). The firefighters and government officials responding to wildfires require accurate and timely models to inform their decision-making processes.

The modelling of forest fires is extremely complex; there are many factors which affect the rate of spread - including type of vegetation, volume of vegetation both alive and dead, moisture content, and weather and terrain factors such as humidity, wind, precipitation and elevation change. Forest fire spread models, such as the US Forestry Management Behave model have been effective for over fifty years, and constantly improving due to updated fuel models- fuel being the vegetation composition. These models can only be as accurate as the data that is input, which can be challenging to gather and add to a model, especially over large areas of varying terrain and vegetation. In order to quickly and accurately model active fires, or areas at risk of fire, a technique must be developed to fuse multiple sources of information into a simulation to calculate the fire's spread.

This project models the spread of fire using the Cell-DEVS formalism and BehavePlus fire spread calculations. The model uses terrain and vegetation inputs from publicly available maps published by Natural Resources Canada. Open source mapping software and Python libraries are used to select a simulation area and build individual cells for each area of landmass, including elevation and vegetation types for input into the Cell-DEVS model simulated using Cadmium. The BehavePlus calculations are used to determine the amount of time the fire will take to reach the neighbouring cell, and the results can be viewed in the software. This project builds off of the Capstone Project work of Soulier and Tratnik (Soulier & Tratnik, 2025).

2 BACKGROUND

Cellular Automata (CA) are widely used for modelling of physical systems, their components are known as cells, and they are arranged in a grid pattern and connected to each other in a defined way; each cell is a representation of a physical phenomena. Each cell is influenced by the states and actions of the cells surrounding it, known as its *neighbourhood,* it calculates a change to its own state based on inputs from the neighbourhood. The Cell-Discrete Event System Specification (Cell-DEVS) formalism is well suited to simulate complex CA problems. Cell-DEVS is based on the DEVS formalism, which allows mathematical definition of a system using a hierarchical composition of behavioural and structural models (Wainer, 2009). The cells are represented as behavioural models, known in DEVS as *atomic models*, and they are combined into a large structural model, known in DEVS as a *coupled model*. In Cell-DEVS the explicit time delay and ability to skip periods of inactivity make the simulation of CA problems more efficient. When modelling natural phenomenon it is often not ideal to have a square grid of uniform cells, for this reason an implementation of Cell-DEVS for irregular cell shapes was introduced (Cardenas & Wainer, 2022). Asymmetric Cell-DEVS can be implemented with the Cadmium simulator (Belloli et al, 2019) and can configure scenarios using JavaScript Object Notation (JSON) files.

A Geographical Information System (GIS) is composed of the data, hardware and software used to deal with spatial information on a computer. With a GIS application the user can view digital maps, add spatial information and perform spatial analysis. One popular free and open-source application is called QGIS, originally created in South Africa (QGIS Developmental Team, 2021). QGIS allows users to create custom plug-ins to manipulate map data using a file programmed in Python. Soulier and Tratnik developed a QGIS plug-in that allows users to quickly select a simulation region for a wild fire scenario, the program samples the raster map to find elevation and landcover values at points in a grid, these points represent the center point of cells, their values are output in a JSON format for use in the Cadmium simulator.

The plug-in developed by Soulier and Tratnik used a Von Neumann neighbourhood, which is a square grid with neighbours directly above and below. This is not ideal if the rate of spread is fastest along one of the diagonal directions. The plug-in was modified to represent the grid with a hexagonal topology. Each row of points is offset by half a column width from the one above it, the result resembles a honeycomb with 53-63° spacing from center points of each of the six neighbouring cells. This will better capture all directions of fastest spread.

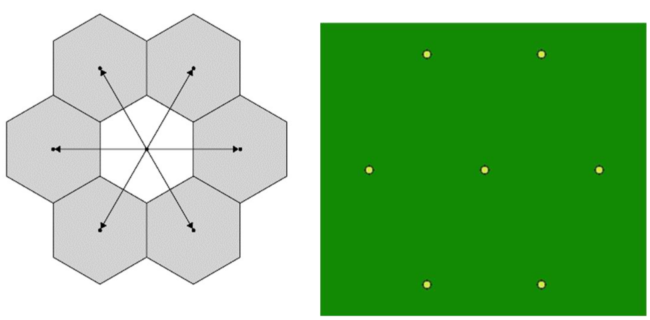

Figure 1: Hexagonal topology and the cell center points in the model

The QGIS software can read many types of maps; there are freely available elevation and landcover raster maps published by the Canadian Department of Natural Resources in the .tif format. In order to create the JSON file with the simulation parameters the user must upload these maps to the software, then the plug-in allows the user to draw polygons over the map layers for the simulation area and the ignition area; cells that are on fire at the beginning of the scenario. The user can select the resolution, the distance between rows and columns of cells, and a wind speed and direction. Figure 2 so shows the landcover layer (left) and elevation layer (right) with yellow and red polygons representing the simulation area and the ignition area.

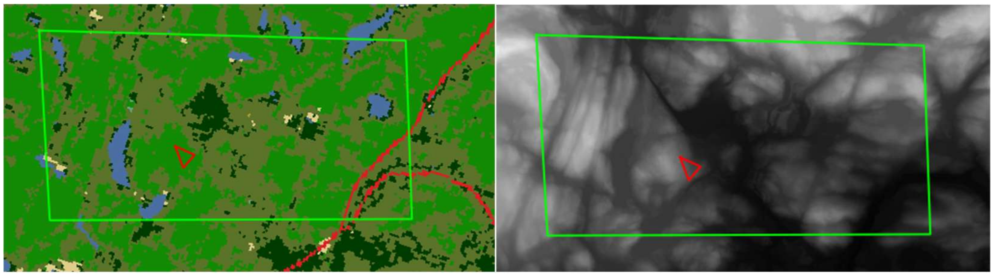

Figure 2 – Polygon simulation areas drawn over landcover and elevation layers in QGIS

The resulting output is a JSON representation for each cell as shown in Figure 3. Cell names are represented as the location on the map in metres referenced to a fixed point defined in the map's parameters, it can be seen that the cells to the left and right of this cell are a distance of 20m away, and the ones offset in the rows above and below are 22.36m away. This cell has a fuel of Type 9 based on the data retrieved from the landcover map and indicated by *fuelModelNumber*, an *elevation* of 362.8m retrieved from the elevation map, and it is not "ignited" as this point was not in the polygon selected for the region initially on fire at the start of the simulation.


```json
        "474240_5104120": {
            "neighborhood": {
                "474240_5104120": 0,
                "474250_5104100": 22.360000000000003,
                "474230_5104100": 22.360000000000003,
                "474250_5104140": 22.360000000000003,
                "474230_5104140": 22.360000000000003,
                "474260_5104120": 20,
                "474220_5104120": 20
            },
            "state": {
                "fuelModelNumber": 9,
                "windDirection": 178,
                "windSpeed": 16,
                "x": 474240.0,
                "y": 5104120.0,
                "elevation": 362.7799987792969,
                "ignited": false
            }
        },
```


Figure 3 - Example of cell output to a JSON file for use in the Cadmium simulator

BehavePlus is software published by the United States Department of Agriculture's Forest Service. The Surface module builds off the widely used Rothermel model (Rothermel 1972) to calculate the surface spread rate of the fire, this model and subsequent improvements are described in (Andrews 2018), including a detailed breakdown of the formulas used and their inputs. The basic mathematical formula for the Rothermel model is shown in Figure 4. This formula remains the base of many fire spread models despite many attempts to improve upon it. Improvements to the fuel models have improved the accuracy of the calculations due to increased accuracy of the individual components of the formula.

$$R = \frac{I_R \xi (1 + \phi_w + \phi_s)}{\rho_b \varepsilon Q_{ig}}$$

Component	Name	Explanation
R	Rate of spread (ft/min)	Flaming front of a surface fire
I_R	Reaction intensity (Btu/ft^2/min)	Energy release rate per unit area of fire front
ξ	Propagating flux ratio	Proportion of the reaction intensity that heats adjacent fuel particles to ignition (no wind)
ϕ_w	Wind factor	Dimensionless multiplier that accounts for the effect of wind in increasing the propagating flux ratio
ϕ_s	Slope factor	Dimensionless multiplier that accounts for the effect of slope in increasing the propagating flux ratio
ρ_b	Bulk density (lb/ft^3)	Amount of oven-dry fuel per cubic foot of fuel bed
ε	Effective heating number	Proportion of a fuel particle that is heated to ignition temperature at the time flaming combustion starts
Q_{ig}	Heat of preignition (Btu/lb)	Amount of heat required to ignite one pound of fuel
$I_R\xi$	No-wind, no-slope propagating flux (Btu/ft^2/min)	Heat release rate from a fire to the fuel ahead of the fire, without wind or slope
$(1 + \phi_w + \phi_s)$		Increase to the no-wind, no-slope propagating flux due to wind and slope
$I_R\xi(1 + \phi_w + \phi_s)$	Heat source (Btu/ft^2/min)	Propagating flux
$\rho_b \varepsilon Q_{ig}$	Heat sink (Btu/ft^3)	Heat required to ignite the fuel
$\frac{I_R\xi}{\rho_b \varepsilon Q_{ia}}$	No-wind, no-slope rate of spread (ft/min)	

Figure 4 - Rothermel's Formula as described in (Andrews 2018)

The slope and wind conditions have a large effect on the rate of spread of the wildfire. The ability of the Asynchronous Cell-DEVS model to accurately model the slope conditions, and run the simulation quickly with multiple wind conditions is a main benefit of this model. Figure 5, as presented in Rothermel's original model, demonstrates the radiation and convection effects of wind and slope when compared to a no-wind and no-slope condition. (Scott, 2021) offers an extremely detailed review of BehavePlus and other fire spread models and the theory behind them.

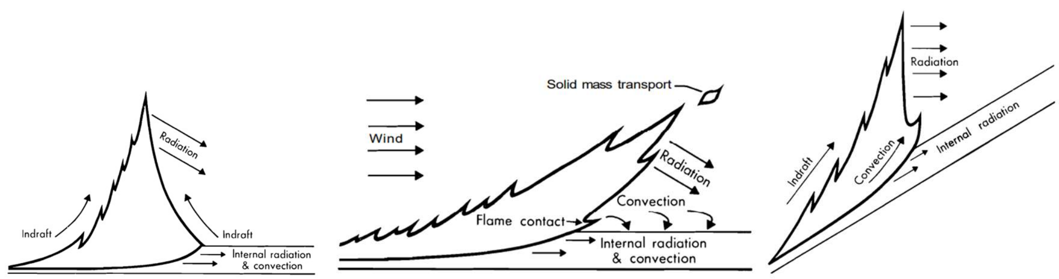

Figure 5 – Effects of wind and slope on fire convection and radiation (Rothermel 1972)

BehavePlus' Surface module is an amalgamation of eighteen different models, with modifications to the original Rothermel model to improve factors such as wind speed, wind affect at various heights, flame and fireline intensity, spread direction, slope corrections, multiple different types of fuel burn rates and behavior, and how to make calculations for combined fuel types (Heinsch & Andrews, 2003). The BehavePlus fire model has been implemented as a C++ library (RMRS Missoula Fire Sciences Lab), the Asynchronous Cell-DEVS model presented in this project calls on the Behave library to calculate fire spread times between cells.

The type of fuel is very important for the rate of fire spread. Unfortunately, the landcover map available does not have very good resolution (30mx30m), and the vegetation types are not very specific. After removing water, snow, barren land and urban areas, there are only eleven different types of fuel specified. The Canadian descriptions of the landcover are mapped to BehavePlus fuel types as shown in Figure 6.

Canadian Landcover Category	BehavePlus Fuel Category
Temperate or sub-polar needleleaf forest	FM10 (10) Timber (Understory)
Sub-polar taiga needleleaf forest	FM13 (13) Medium Logging Slash
Temperate or sub-polar broadleaf deciduous forest	FM9 (9) Hardwood Litter
Forest foliage temperate or subpolar	FM8 (8) Short Needle Litter
Temperate or sub-polar shrubland	SH1 (141) Low shrub fuel load, fuelbed depth about 1 foot; some grass may be present. Spread rate very low; flame length very low.
Temperate or sub-polar grassland	GR1 (101) Grass is short, patchy, and possibly heavily grazed. Spread rate moderate; flame length low.
Sub-polar or polar shrubland-lichen-moss	NB3 (93) Agricultural field, maintained in non-burnable condition.
Sub-polar or polar grassland-lichen-moss	GR3 (103) Very coarse grass, average depth about 2 feet. Spread rate high; flame length moderate.
Sub-polar or polar barren-lichen-moss	NB9 (99) Bare ground
Wetland	NB4 (94) Non-burnable
Cropland	NB3 (93) Agricultural field, maintained in non-burnable condition.
Barren lands	NB9 (99) Bare ground
Urban	NB1 (91) Urban or suburban development; insufficient wildland fuel to carry wildland fire.
Water	NB8 (98) Open water
Snow and ice	NB2 (92) Snow/ice

Figure 6 – mapping of Canadian landcover values to BehavePlus

Soulier and Tratnik were not trained in Cell-DEVS, and as a result there were a number of different issues with their implementation of the models. The QGIS software uses timestamped data to overlay the data on to raster layers, these timestamps were failing to access the current time and instead referencing the sim time starting from the UNIX epoch. The time was update to be able to start at the current time, but can be further refined to allow the user to enter the starting time of the simulation. The Python Rasterio package, (Mitchell, 2025), offers many powerful tools for the manipulation of raster maps, this package takes the polygons created by the user and creates a mask layer, which is then used to greatly reduce the size of the landcover file (which includes all of Canada), and resample it so there is data at the same spacing as the user selected resolution, taking the closest value from the 30mx30m dataset.

Rasterio was also used by Soulier and Tratnik to generate the maximum slope and its direction at each of the point on the raster using the elevation layer, this is not necessarily helpful if that slope is not in the direction of the neighbour cell. The code was modified so that instead of an aspect and slope the cell's state includes its elevation. The change in elevation is then calculated between the points, and the slope aspect is set towards which ever cell is uphill.

3 MODELS DEFINED

The wildfire model follows the Cell-DEVS formal specification <X, Y, S, N, d, , τ, δint, δext, λ, ta>, where there are no inputs or outputs, $X=Y=\emptyset$, the state of the cell includes its x and y coordinates on the map for logging purposes, *ignited* - whether the cell is ignited or not, *willIgnite* – Boolean becomes true when a neighbouring cell is on fire and it is calculated that it will spread to the current cell, *ignitionTime* – the time that the fire will reach the midpoint of the cell based on calculated spread rate, *spreadDir* – the direction that the fire is coming from, *rateOfSpread* – calculated rate of spread from the neighbouring cell. N is the neighborhood, following a hexagonal topology it can be represented by the grid coordinates:

$$(1, 0.5), \quad (1,-0.5),$$
$$(0,1), \quad (0,0), \quad (0,-1),$$
$$(-1,0.5), \quad (-1,-0.5)$$

d is the delay, an inertial delay was selected as it allows the pre-emption of the delay if the fire is going to arrive sooner from a neighbouring cell. The delay is set to the time it takes for the fire to arrive at the cell, and once it has arrived the cell will immediately inform the neighbouring cells that it's on fire. This way the cell doesn't awake its neighbours from a quiescent state until it is on fire. Once ignited the cell informs its neighbours and then the delay is then set to infinity. τ is the cell update rule, this model has a very simple update rule, once a neighbour is on fire it calculates the rate of spread, if it is too low then it will ignore the spread (as occurs with cells over water); typically the rate of spread is high enough and the state will change to *willIgnite* = True, and set the *ignitionTime*, *spreadDirection,* and *rateOfSpread* for logging purposes. δint, δext, λ and ta are set according to the Cell-Devs specification.

4 SIMULATION RESULTS

The logger is setup so that it outputs in a format that can be read by the QGIS software. The software has a *Temporal Controller* that allows the user to move time forward in discrete increments and display GIS data. A custom logger was developed by Soulier and Tratnik so that Cadmium displays the location of the cell's midpoint and the time that it becomes ignited. Modifications were made to the logger so that the user could input the desired start time for the simulation, allowing the modeller to easily compare the results to real fires which occurred in the past or to make predictions for a fire in the future. Figure 6 has an example logger output for a very small simulation region.

time	x	y	ignited	willignite	simtime	ignitionTime	sigma	spreadDir	rateOfSpread
28/04/2025 10:30	470819	5089244	1	0	0	inf	0	0	0
28/04/2025 10:30	470945	5089244	0	1	0	22441.4	22441.4	90	0.00561462
28/04/2025 10:30	470882	5089118	0	1	0	23238.8	23238.8	153	0.00606194
28/04/2025 10:30	470819	5089244	1	0	0	inf	inf	0	0
28/04/2025 16:44	470945	5089244	1	1	22441.4	22441.4	0	90	0.00561462
28/04/2025 16:44	470882	5089118	0	1	22441.4	23238.8	797.402	153	0.00606194
28/04/2025 16:44	470819	5089244	1	0	22441.4	inf	inf	0	0

Figure 7 – Sample logger output

The first four columns of the output are used by the QGIS temporal controller to display the burn pattern, they display the coordinates of the point and the time it becomes ignited. The next four columns, *willIgnite, simtime, ignitionTime* and *sigma* are used to verify the correct functioning of the logic. A problem was identified where many cells were becoming ignited many minutes after they were supposed to, or not at all; it was determined that the JSON file did not include the cell in its own neighbourhood, resulting in delays to the ignition time and output to other cells. *spreadDir* and *rateOfSpread* can be used by the modeller to determine which direction the fire spread came from and at what rate.

The QGIS software allows the user to load the output file as new layer overtop of your polygon simulation regions and map layers. The visualization will step forward at a user selected time step and the show the spread of the fire, each cell having its own dot on the map at the center of the cell. Figure 8 shows the initial conditions at the start of the fire, with the ignition polygon all ignited. Depicted is a wide grid of approximately 2km x 4km, and a large grid spacing of 30m at twelve-hour intervals. The vegetation represented by light green squares has a much quicker spread rate.

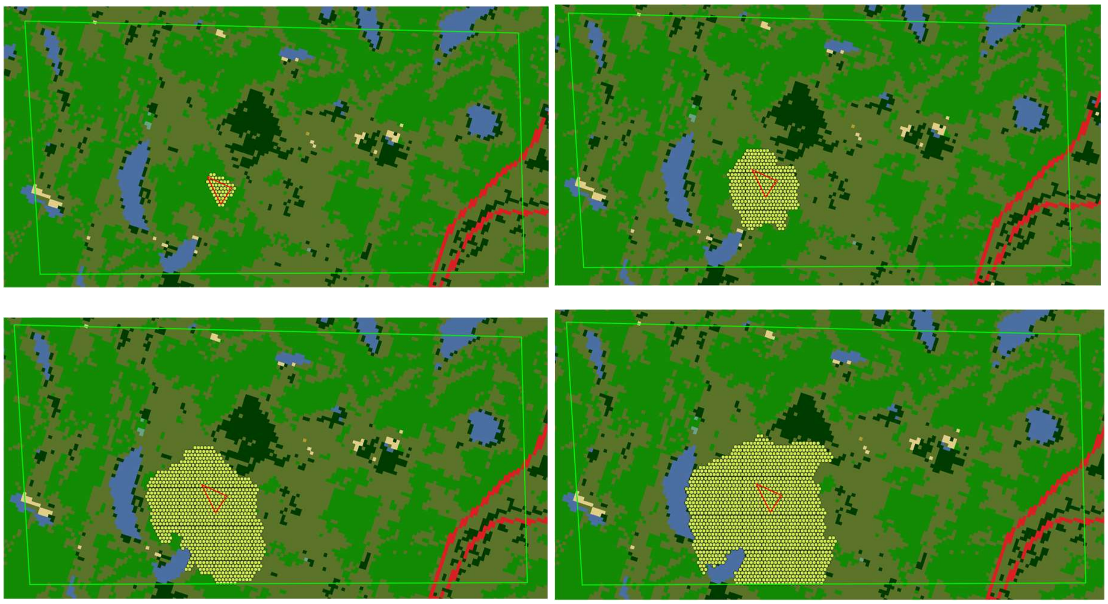

Figure 8 – Example of fire progression in 12 hour increments

The entire grid took almost ten days to burn completely, however it can be seen that within one day the lower boundary had been reached, an important consideration when creating the simulation region. The entire burned simulation can be seen in Figure 9.

Figure 9 – Simulation region at end of simulation

5 DISCUSSION

Preliminary research into the fuel models suggests that there is quite a bit more work required to ensure the correct mapping between Canadian landcover and BehavePlus. The fuel models were not changed from the mapping by Soulier and Tratnik (Figure 6). Much of the land cover in the region north of Ottawa was mapped to the BehavePlus fuel models 8 and 9; it was found that model 9 burns significantly faster than model 8, which seems unlikely given the region mainly consists of a mixture of the two types. Documents describing the fuel models suggest that users should not use the original 13 models; the newer models, introduced in 2005, are more granular options and will provide a better burn rate (Scott & Burgan, 2005). Consultation with experts is recommended to increase the accuracy for Canadian landcover values. The suitability of the moisture numbers was also examined, the current model increased from the values from 1%, selected by Soulier and Tratnik, to 5%, 6% and 7% for 1h, 10h and 100h fuel moisture respectively.

The BehavePlus software is freely available for download and was used to verify a small subset of the calculations performed by the model. The rates found fall in line with the mean rates published by the Government of Canada in Figure 10. Further verification of the proper functioning is demonstrated by the fact that the rivers and lakes don't burn, and the introduction of wind increases the spread of fire in the leeward direction.

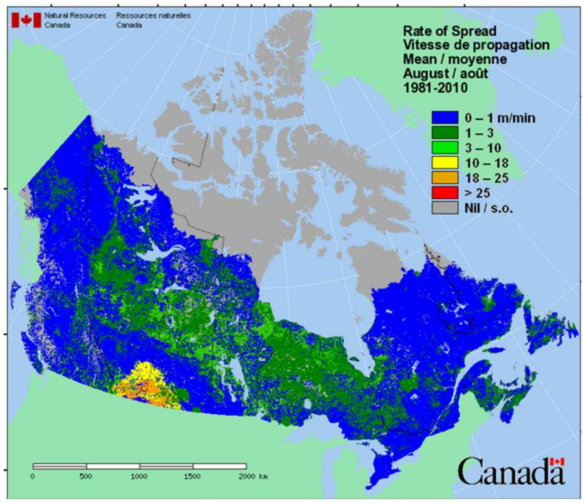

Figure 10 – Mean rate of spread of fires in Canada in August

There is a lot of potential for improvement of the QGIS plugin. It is currently set up to only allow one elevation layer. Many of the elevation layer maps available from the Department of Natural Resources are narrow slices. The plug-in could be modified to include multiple elevation maps in order to draw a larger area. If that is not possible a custom script could be made to combine multiple JSON files. Further modifications to the QGIS plugin could add input ports for separate atomic models representing fire fighting activities such as waterbombing and firebreaks. This would allow decision makers the ability to see the effects of supressing the fire in certain areas.

Increases in satellite technology allow the generation of higher resolution maps, including more granular vegetation data such as canopy height, fuel volume and moisture content. Availability of this data will allow the modeller to obtain more accurate results. The landcover map used by this simulation had 30mx30m resolution, in the event of a fire authorities should provide modellers higher resolution maps. The issue with using such a high-resolution map is shown in Figure 11, where the fire jumps over the river due to an unfortunate placement of a cell on the diagonal of a river. Although it's possible the fire could jump, the river appears to be between 30-60m wide at many points. Satellite imagery has also been used to map the spread of fire, modellers can use this data to refine their models based on past fires, and to better predict the fuel moisture levels in ongoing fires.

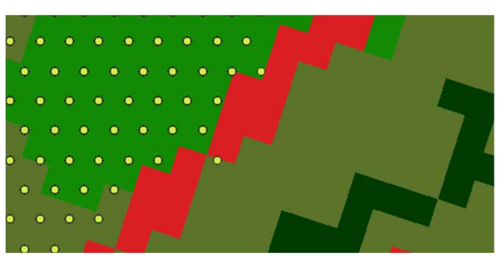
Figure 11 – Fire jumps across the river, likely due to pixel size

Due to the efficiency of the Cadmium Cell-DEVS simulator, it is possible for the modeller to perform multiple runs for varying levels of wind, moisture and vegetation in a timely manner. This would allow the modeller to create a probabilistic outcome for the spread of fire, as in (Freire and DaCamara, 2019). This can also be used to predict best and worst case scenarios, for example by setting moisture levels at lower bounds, and fuel volumes and wind speeds at upper probable bounds.

It should also be noted that Canada has its own programs for monitoring potential fires, known as the Canadian Forest Fire Danger Rating System (CFFDRS). They also have their own fire prediction model called Canadian Fire Behaviour Prediction (FBP) System (Forestry Canada,1992) with sixteen types of fuel. Further investigation in this model would beneficial if working with Canadian authorities.

6 CONCLUSIONS

Recent wildfires in Canada and throughout the world have made it clear that there is a need for more accurate and timely fire spreading models. Modelling wildfires is extremely difficult due to changes in weather and the many fuel factors that must be estimated. Researchers around the world continue to make improvements to fire models and vegetation assessment. The use of cellular automata has proven to be an effective modelling and simulation approach. Asynchronous Cell-DEVS simulated in Cadmium builds on the cellular automata approach, allowing for non-uniformity across cells, complex computations and explicit timing delays; resulting in an efficient computation of the fire spread.

Building on the work of Soulier and Tratnik, this Asynchronous Cell-DEVS model takes inputs from publicly available mapping products to determine the elevation and fuel type of each cell, improving the accuracy of the calculation of fire spread when compared to a uniform cell model. The output of the model is a time lapse of the burn area that can be easily viewed in GIS software. Additional information such as the spread direction and rate are available to researchers. This model can be further modified to add other data such vegetation height, thickness and moisture values, which are increasingly available from satellite imagery. Further work with wildfire experts is recommended to better define the fuel types and moisture content, which will increase the overall accuracy of the model.

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