A Computational Model for Wildfire Propagation: The Case of Vale Natural Reserve

Sergio Viademonte[1], Mariana Senna[2], Nikolas Carneiro[1], Caio Bastos[1], André Quadros[1] Rodolfo Almeida[3]

[1]Instituto Tecnológico Vale
66055-090 – R. Boaventura da Silva n° 955 – Belém – PA – Brazil

[2]Vale Natural Reserve
Rodovia BR 101, KM 122 – Linhares – ES – Brazil

[3]Universidade Federal do Oeste do Para (UFOPA)
68040-255 – Rua Vera Paz, s/nº , Santarém -– PA – Brasil

{sergio.viademonte,nikolas.carneiro}@itv.org,

mariana.senna@vale.com, {caio.bastos,andre.quadros}@pq.itv.org,

rodolfo.almeida@ufopa.edu.br

Abstract. *This document describes a research project about the development and application of a wildfire propagation computational model, which simulates the occurrence and spread of wildfires in order to understand and predict their behaviour. The aim is to assist in the prevention, fighting and management of wildfires. It has been applied at Vale Natural Reserve (RNV) and Sooretama Biological Reserve (REBIO), in the State of Espírito Santo, southeast of Brazil. These reserves are a constant target for forest wildfires, and they represent approximately 13% of the remaining Atlantic Forest in the State of Espírito Santo. Initial results were obtained comparing three cases of observed wildfires with predicted area, which shows a satisfactory level of area agreement.*

1. Introduction

Fire is a complex phenomenon and when occurs in forests it can have a huge impact in the loss of biodiversity, human life's and properties. According to the Brazilian National Institute for Space Research [INPE 2024] in 2023 alone an area of more then 370 km² was burned throughout Brazil. One of Brazil's largest biomes is the Atlantic forest, which today represents a small area, close to the 150 million hectares originally covered by this biome [Ribeiro et al. 2009].

Vale SA, a mining organization, privately owns the RNV, and is also encharged to protect Sooretama Biological Reserve (REBIO), a national forest reserve. Together, both reserves have an area of approximately 50,000 hectares, making up 11% of the remaining Atlantic forest in the state of Espirito Santo in the southeast of Brazil. Bordering four municipalities and several farms, the area of the two reserves is a constant source of forest fires, mainly caused by poor fire management in agricultural and domestic activities. Vale has invested in the research and development of technologies for wildfire management and decision support as part of its duties in protecting its natural area's as well as its environment policies.

The computational model developed in this research project aims to simulate the advance of the fire front over the vegetation in order to support firefighting and fire prevention efforts. The usefulness of this type of model is both predictive, with the simulation of fire propagation scenarios, and diagnostic, with the simulation of a developing fire in order to know where it will develop. Those capabilities give support for forest fire management and mitigation of its impact. This research project applied the mathematical formalism of cellular automata to model the front of fire and its behaviour. Several recent papers describe the development and application of mathematical models through *raster* (*a vectorized data structure representing a shapefile*) techniques based on technologies such as the cellular automata formalism [Wu et al. 2022, Alessandri et al. 2021, Tonini et al. 2020, Maduro 2012] and operational research [Fujioka 2002].

The fire propagation model represents the behavior of the perimeter advance of the fire front during a forest fire as a function that depends on three main factors, which are: *vegetation*, *atmospheric conditions* and *topography* [Columbia 2023, Wu et al. 2022]. Vegetation provides the source of energy or fuel that feeds the fire, and can be characterized into classes of vegetation with different distributions, arrangements, compositions and physical characteristics. The topography directly influences the direction of fire propagation, as it spreads faster on surfaces with slopes than on flat surfaces. Atmospheric conditions primarily include variables such as *air temperature*, *relative humidity*, and *wind speed and direction*. The air temperature and the relative humidity of the air influence the conditions of humidity or vigor of the vegetation. The drier the vegetation is, the more favorable the conditions for fire to spread quickly. The wind, expressed in terms of its speed and direction, is the factor with the most relative importance in the propagation of fires, as it induces a tendency in the direction of propagation. Fire spreads faster in the direction of the wind and slower in opposite or adjacent directions.

This study describes a fire propagation computational model developed to give support for firefighting at Vale Natural Reserve (RNV). It is divided in five sections. First section introduces this research project, second section introduces the specification of the model, including a brief description of the applied mathematical formalism. Third section describes the model adjustment procedures to simulate the onset of forest wildfires. Fourth section presents preliminary evaluation results comparing simulated and observed fire occurrences, and the fifth section presents a discussion about the proposed model and the future directions of this research project.

2. A Fire Propagation Model

The fire propagation model proposed in this paper applies the cellular automata formalism to model the behaviour of front of fire and its spread [Clarke et al. 2014, Batty 2000, Maduro 2012]. Space, time, and state variables are all discrete. The spatial domain corresponds to the Earth's surface and is represented by a two-dimensional grid, a cellular space. Each element of this grid is a cell and represents a geographical area. Each cell has a finite set of states that can change over time. Cells have neighborhood relationships with adjacent cells. At any point in time, a cell has a state, and this state depends on the state at the previous point in time and the state of the adjacent cells. Time is defined in discrete steps called iterations. A time interval Δt defines the elapsed time between two successive iterations. In the iteration $(n = 0)$, we have $(t_0 = 0)$. In the other iterations

$(n > 0)$, the instant of time is defined by $t_n = n * \Delta t$ [Weisstein 2023, Maduro 2012].

The state of a cell can change over iterations. The concept of automata is used to represent these changes, with the definition of a transition function, which consists of a set of rules for changing cell states, depending on the current state of the cell and neighboring cells [Encinas et al. 2007]. At each iteration, the state transition function of each cell is evaluated. The dynamic behavior of the model over the iterations starts from a given initial configuration of the states of all cells in the cell space.

The surface is represented by a two-dimensional, square and regular grid of *N* rows and *M* columns, for a total of *N* * *M* cells. The neighborhood of each cell includes both corner and adjacent cells, called the Moore neighborhood [Weisstein 2023]. Each cell can assume one of four states, namely: empty or inert cell (**E**), overgrown cell (**V**), burning cell (**F**), and burned cell (**O**). The transition function, which determines the state change of a cell depending on its state and the states of the neighboring cells, is evaluated for each cell at each iteration. An inert cell never changes its state over iterations. This cell represents regions that are not flammable. In a given iteration, a cell with vegetation can become a burning cell, corresponding to a change of state **V** → **F**. In a given iteration, a burning cell can become a burned cell, corresponding to a change of state **F** → **O**.

The rules that define state changes are described as follows. A cell with vegetation can start to burn, moving from state V to F. This state change can only occur if at least one neighboring cell is burning. Given a cell with vegetation, for each neighbor that is burning, there is a probability *I*, called the *ignition probability*, that the fire will advance to that cell and change its state from V to F. If the cell with vegetation does not ignite, its state remains unchanged. Given a burning cell, there is a probability *B*, called the *extinction probability*, that the fire will extinguish in the same cell, and its state will change from F to O. If the fire does not extinguish in the burning cell, its state remains unchanged. Burned cells remain in that state. An empty or inert cell represents an area that cannot catch fire and its state does not change over time. Cell states are represented by colors. Cells with vegetation are represented in green, burning cells in red, burned cells in black, and empty cells in white. Figure 1 illustrates these state transitions mechanism.

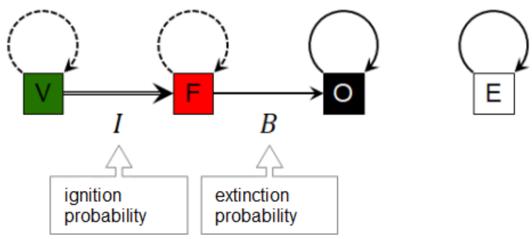

Figure 1. Illustration of the state transition

An initial configuration of cell states is defined including, in addition to cells with vegetation and inert cells, cells that are burning at the beginning of the simulation (the fire ignition points). The fire propagates from the burning cells to vegetation cells according to the rules of the state transition function shown in Figure 1. The simulation ends when the desired number of iterations is reached, or until a cellular automaton step where there are no more burning cells.

Another important result that can be obtained from the model simulation is the fire front propagation time. The propagation time of the fire front is the time at which the cell started to burn. Throughout the simulation, the time t at which a cell caught fire is stored. Once the simulation is completed, this time is visualized on a color scale and can summarize the fire propagation in a single result, providing important information about areas that are potentially affected by fire after a given time. It is important not to confuse fire *spread time* with fire *duration time*. Fire *duration time* is the time it takes for the last burning cell to become a burned cell.

2.1. Setting the propagation model parameters

Setting the propagation model parameters includes the following activities:

- Defining the spatial and temporal resolutions of the model
- Selecting the environmental variables that influence fire behavior
- Specifying the explicit relationship between the model parameters and the selected environmental variables

Geographic areas are represented by a two-dimensional grid, where each cell is represented by a square. The spatial resolution of the model corresponds to the edge size of each cell, denoted here by Δl. The temporal resolution of the model is the time interval Δt corresponding to one iteration of the model. Fixed values for the spatial and temporal resolution are assumed.

The fire behavior is conditioned by the probability of ignition I and probability of extinction B. Those probabilities are conditioned by the effects of the following environmental variables: *vegetation fuel type (physiognomies)*, *air humidity*, *wind speed* and *direction*, and *topography*.

Depending on the values of B and I, an ignited fire can be extinguished quickly, propagate with difficulty in a dendritic pattern, or propagate freely. The probability I is associated with the ignition or spread potential. Since the vegetation is exposed to the heat of the fire front during the fire, the probability I determines how easily (or how difficult) the vegetation can ignite. The higher the value of I, the easier it is for the fire to spread. Conversely, the smaller the value of I, more difficult it is for the fire to spread from one cell to another. Once the vegetation in the cell has been ignited, the probability that the vegetation fuel will be completely burned and the fire will not be able to spread is represented by the probability B. The larger the value of B, the greater the chance that the fire in the cell will be extinguished. Conversely, the smaller the value of B, the greater the chance that the fire will remain in the cell and persist for more iterations. If the fire remains in the cell for more iterations, the greater the chance that this cell will ignite neighboring cells, if they represent a flammable vegetation class.

It is assumed that there are elementary propagation and extinction probabilities, I_0 and B_0, respectively. These elementary probabilities are important when modeling fire spread in areas with different classes of physiognomies. The values of I_0 and B_0 can be subjectively chosen for each class. This equivalence is based on the comparison in terms of fire support capacity, more specifically in terms of the characteristics of the plant fuel class.

For each physiognomies (fuel) class there are specific probabilities of fire ignition and extinction. When fire spreads over a class of physiognomies under the influence of these variables, the factors that quantify this influence are considered. We use λ_M, to represent humidity influence factor, λ_S, for the topography influence factor, and λ_W, for the wind influence factor [Maduro 2012, Alessandri et al. 2021]. The humidity of the plant fuel is the main environmental variable affecting the probability *B* of fire extinction, and it is directly related to the relative humidity of the air. The plant fuel gains or loses humidity as it interacts with the atmosphere. The wetter the fuel, the lower its calorific value and the more heat it requires to ignite. Therefore, the higher the relative humidity of the air, the higher the probability that the fire in the cell will be extinguished because the vegetation in the cell will be more humid.

Studies show that the relationship between fuel humidity and relative humidity is exponential [McArthur 1966, Noble et al. 1980, Cheney and Sullivan 2008, Sullivan 2009]. This relationship is represented by the factor multiplicative of the humidity of the plant fuel, as shown in equation 1:

$$\lambda_M = \exp(-b_1 * M) \tag{1}$$

where *M* is the relative humidity, which varies from 0% to 100%, and b_1 is an empirical constant ($0 \leq b_1 \leq 1$). The higher the humidity value, the lower the value of λ_M.

In establishing the relation of λ_M to the probability *B*, the inverse relation $\frac{1}{\lambda_M}$ is used as a factor, and Equation 2 is adopted to represent the relation of the humidity of the fuel to the effective probability of extinguishing the fire.

$$B = B_0 * (\frac{1}{\lambda_M})^{b_2} \tag{2}$$

In Equation 2, B_0 is the elementary probability of extinction of the plant fuel fire, λ_M is the humidity effect factor, and b_2 is an empirical constant ($0 \leq b_2 \leq 1$). The larger the relative humidity value, the smaller the value of λ_M, and its inverse $1/\lambda_M$ will be a larger value. The empirical constant b_2 serves to model the dependence on the inverse of λ_M.

The effective probability of fire spread depends on the probability element I_0 and factors such as the effects of wind, topography, and humidity on the plant fuel. This dependence is given by the Equation 3.

$$I = I_0 * \lambda_M * \lambda_S * \lambda_W \tag{3}$$

In Equation 3, I_0 is the elementary probability of plant fuel ignition, λ_M is the humidity effect factor, λ_S is the topography effect factor, and λ_W is the wind effect factor.

The relationship between vegetation humidity and the probability of fire spread is inverse. That is, the greater the humidity in the plant fuel, the lower the probability of fire spread. Therefore, the relationship between the effective probability of spread and the coefficient of influence of the fuel humidity is direct, and its representation is shown in the equation 1.

When fire spreads on elevated surfaces, the distance between the flames and the vegetation at the front of the fire shortens [Pyne et al. 1996]. In these conditions, the heat is transferred more intensely and the plant fuel is ignited more rapidly. To represent this behavior we use the relationship between topography and ignition proposed by McArthur [McArthur 1966]. That relation is represented by the Equation 4.

$$\lambda_S = \exp(\alpha * \theta_S) \tag{4}$$

In Equation 4, θ_S is the angle of inclination of the surface, in degrees, between the cell (*i,j*) and its neighboring cell (*i*,j**), and α is an empirical constant. The steeper the surface, the higher the value of θ, and therefore the higher the value of λ_S. The surface slope θ_S is calculated from the digital elevation model. Readers interested in more detail about the equations to calculate the surface slope should refer to specific literature [Alessandri et al. 2021, Maduro 2012].

Equation 5 shows how the wind effect factor is calculated.

$$\lambda_W = 1 + c_1 * f(\omega) * U^{C_2} \tag{5}$$

In this equation U is the wind speed in m/s, $f(\omega)$ is a function representing the spatial effect of wind direction on fire propagation, c_1 and c_2 are empirical constants. The function $f(\omega)$ weights the effect of wind on fire propagation along the eight possible propagation directions defined by the Moore neighborhood and is calculated using the expression in Equation 6.

$$f(\omega) = \exp(c_3 * U * (cos(\omega) - 1) \tag{6}$$

In this equation, again, U is the wind speed in m/s, ω is the angle between the propagation direction and and the direction the wind is blowing. The propagation direction takes eight possible values. The wind direction takes continuous values. Both use azimuthal coordinates to represent their values, and true north is the origin reference.

The maximum value of the function occurs when the fire propagation direction coincides with the wind direction ($\omega = 0$). As the difference between the directions increases (or decreases), the value of $f(\omega)$ tends to zero. In other words, the function of $f(\omega)$ is to weight the effect of the wind along the possible fire propagation directions. The parameter c_3 increases (or decreases) this effect. The effect of c_1 and c_2 relates the intensity of the wind direction to the wind effect factor. The higher the wind value, the greater the effect on fire propagation. The c_2 parameter indicates whether this relationship is sub-linear or super-linear.

3. Fire Propagation Model Adjustment

Model adjustment consists of selecting the values of probabilities and empirical constants so that the model can simulate fires in a given area. The adjustments are: definition of an area of interest to apply the model; identification of classes of physiognomies fuels in the area; equalization of physiognomies with respect to their specific fire support capacity; and selection of values of empirical constants and elementary probabilities for each class of physiognomies fuels. Physiognomies fuels are the vegetation fuel classes, both terms are used interchangeably in this document.

3.1. Definition of an area of interest and identification of physiognomies

The area of interest for the application of the model includes the Vale Natural Reserve (RNV) and Sooretama Biological Reserve (REBIO), with a three kilometers buffer zone. The total area is 112,820 hectares, of which approximately 24% (27.860 hectares) is occupied by the REBIO and approximately 20% (22.400 hectares) by the RNV. There is an interest in the region to define strategies to combat and prevent the occurrence of forest fires that could reach ecological reserves. These fires occur systematically around ecological reserves and are mostly caused by human activity.

Approximately 49% of the area is occupied by the *Native Forest class*, which is mainly concentrated within ecological reserves. The second largest class is *Permanent Agricultural Cultivation*, which occupies about 17% of the area.

The model calibration procedure begins with the identification of the vegetation fuel classes, that are used to refer to all types of potentially flammable biomass that accumulates on the surface and contributes to the spread of fire. The predominant type of physiognomies on the surface varies with the type of land use and cover. Depending on the characteristics of the physiognomies, i.e., size, shape, horizontal distribution, fuel load (tons/hectare), moisture content, etc., we have different fire support capacities. Because of these characteristics, some vegetation fuels have a greater tendency to resist fire spread than others. Matching vegetation fuel classes with respect to fire support capacity is a very important step in understanding the dynamics of fire in a given region. Once every fuel class fire support capacity is well calibrated the model can do simulations in any area inside the it's area of interest, given that the information on atmospheric conditions and elevation is provided. Details of this calibration activity in the region of interest are described below.

3.2. Equalization of vegetation fuel classes in relation to fire resistance capacity

This section describes the vegetation fuel classes identified for the area of interest, their respective descriptions, and the associated fire support capacity. Areas with very low fuel capacity are identified as *Non-flammable*, and their fire support capability is assigned to 0. Types of *non-flammable* areas are *edification's*, *roadways*, *sand and oil areas*, *water bodies* and *exposed soils*.

Areas of *native forest* were assumed to have the lowest fuel capacity (capacity equal to 1). These are areas with closed vegetation and a continuous canopy, with little fuel accumulated on the surface (dry leaves/shrubs). *Planted forest* areas have a capacity equal to 2, followed by forest areas with *rubber tree* plantations (capacity equal to 3) and *eucalyptus* plantations (capacity equal to 4). Areas of native forest in the *regeneration* stage are assumed to have a capacity equal to 5, being areas that have been modified in the past and that are in the forest succession stage of secondary vegetation.

Areas of *permanent agricultural* cultivation are assumed to have a capacity equal to 6, being open areas for the production of coffee, coconut and papaya, and there may be some accumulation of plant fuel on the surface. *Temporary agricultural* areas are assumed to have a capacity equal to 7, as they are areas used for large-scale agriculture, where the crop is removed after harvesting, and may be prone to the development of undergrowth that can support the spread of fire.

The *swamp* areas, which are areas of native vegetation in rugged topography with a predominance of shrub and sparse tree species, are assumed to have a capacity equal to 8. The *muçununga* areas, which are areas of native vegetation with a predominance of shrub-herbaceous species and low density of trees, located on sandy soils and mostly humid, were assumed to have a capacity equal to 9. *Native fields*, which are areas with a predominance of grasses, were assumed with a capacity equal to 10. *Pasture* areas, which are areas with a predominance of grasses and vegetation used to feed ruminants, were assumed to have a capacity of 11. The *macega* areas, where a high concentration of grasses and shrubs predominate, were assumed with a capacity of 12. It is important to note that the assignment of values of fire support capacity for each vegetation fuel class is an empirical activity, as it relies in the specific characteristic of the areas of interest. There is no a defined standard which globally specify a value of support capacity. A physiognomy may have different values, for different geographical areas, also, this varies according to human judgments and interpretation [Tonini et al. 2020], [Silva et al. 2022]. Table 1, presents some of the vegetation fuel classes discussed.

Table 1. Examples of vegetation fuel classes identified in the area of interest and their corresponding fire carrying capacity

Class	Fire support capability	Description
Non-flammable	0	Not flammable. Area without tendency to the spread of fire, taking into account its type of land use and cover.
Native forest	1	Forest region with predominance of native species.
Planted forest	2	Reforested region.
Muçununga	9	Region with native vegetation of herbaceous-shrub predominance and thin tree.
Native fields	10	A region of native vegetation with a predominance of grasses.
Pasture	11	Anthropized region with predominance of grass/pasture on the surface.
Macega	12	Region of native vegetation or initial stage of forest succession predominance (high concentration) of grasses.

3.3. Configuration values for vegetation fuel classes

The next activity is to choose values for the probabilities B_0 and I_0 for each class of vegetation fuel. The (elementary) probabilities are values ranging from 0 to 1. The values of B_0 and I_0 chosen for each vegetation fuel class depend on its characteristics and fire carrying capacity. In addition, values of the empirical constants also need to be determined. Each of the empirical constants presents a range of possible values that can be assumed, obtained from scientific publications of mathematical models of fire behavior in forest wildfires occurrences.

The values of the elementary probabilities are adjusted manually, using a history of documented fires for the region of interest, and human expertise in the area.

To proceed with the configuration, first a value is chosen for the elementary probabilities. If a plant fuel is consumed by fire faster than another, the latter will have a higher B_0 value. This combustibility is related to the moisture content of the plant fuel. If fire spreads faster in one class of plant fuel than another, it will have a higher I_0 probability. The ease of fire spread is related to the horizontal distribution of the plant fuel. Equalization helps in this initial subjective choice of probability values.

To evaluate the selected probability values, and to proceed with the eventual adjustment if necessary, it is essential to use documented fire data. To proceed with the evaluation and adjustment, first, for each documented fire, you must identify the classes of plant fuel reached by the fire. If the values for the probabilities B_0 and I_0 of one or more of these classes have already been chosen in a previous adjustment, these should no longer be changed, and only the remaining values not yet evaluated can be adjusted.

The validation and adjustment of the model is performed by comparing the shapes of the area of the simulated fire with the observed fire. The optimal values for the elementary probabilities are those whose simulated fire most closely resembles the observed fire in both area and duration. If the values do not meet the criteria, new values are selected and the simulation is repeated. The comparison between the fires in terms of area reached and duration time is performed visually [Filippi et al. 2014][Finney 2000].

For the calibration of the model, data from mapped fires occurring between 2019 and 2021 were used. In total there were 13 mapped fires, with 4 occurring in 2021, 6 occurring in 2020, 2 occurring in 2019, and one with no recorded date. The land use and land cover types affected by the fires are shown in Figure 2. The calibration refers to the classes of plant fuel, and respective probabilities of fire ignition and extinction.

Other information of wild fires, including the place of ignition, date and time of ignition were obtained in reports of occurrence of fires made available by the administration of the RNV. Environmental data of wind speed and direction, and relative humidity, recorded by the meteorological station of the National Institute of Meteorology (INMET) located in the municipality of Linhares-ES, were also obtained. Figure 2 illustrates the observed fire occurrences.

4. Results obtained applying the propagation model

The validation of the proposed computational model was done through the visual comparison between the shapes of observed and simulated occurrences of wildfires. Visual comparison has traditionally been the main means of comparing observed and simulated fire patterns [Filippi et al. 2014]. Among the observed fires shown in Figure 2, three were selected for validation.

The Figure 3 shows a wildfire occurrence, on September 28, 2020, starting at 12:45 and extinguished at 17:30. The class of vegetation fuel affected was eucalyptus forestry. The coordinates where the fire started are: 40°05'34 "S 19°06'38 "W. The

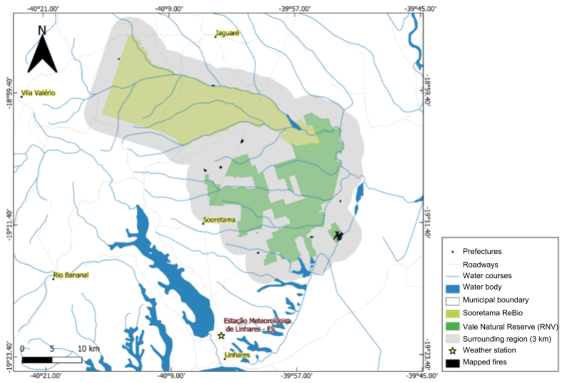

Figure 2. Observed fires in the area of interest

atmospheric conditions measured at the Linhares weather station were: 49.83% relative humidity; the wind direction was 230.5°; and the wind speed was 5.37 m/s.

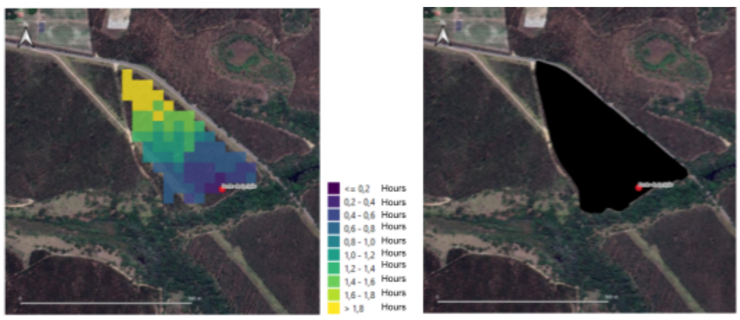

Figure 3. Observed and simulated shape results for a wildfire. The red dot in the image represents the fire ignition point

The Figure 4 shows a second fire occurrence, on March 21, 2021, starting at 17:30 and extinguished at 18:00. The classes of vegetation fuel affected were eucalyptus forestry and *macega*. The coordinates where the fire started are: 40°04'52"S 18°58'50"W. The atmospheric conditions measured at the Linhares weather station were: 37.50% relative humidity; the wind direction was 234.5°; and the wind speed was 3.6 m/s.

The vegetation fuel classes with the adjusted probability values were native forest, forestry area (eucalyptus), *macega*. The validation shows a satisfactory level of agreement, between the observed and simulated shapes. The simulated burned shape of areas closely match the observed shapes, as well as the time of spread of the fires.

5. Final Remarks

This paper describes a computational model for simulating wildfires propagation. It uses the mathematical formalism of cellular automata to represent the behaviour of a fire front. We use a two-dimensional matrix to represent a geographic area, and each cell of this matrix is mapped as a unit, also called cell, in the cellular automata. The state transition function of the automata represents the behaviour of the front of fire. This work has been applied in the region of RNV and the Sooretama Biological Reserve with a buffer zone of three kilometres, in the southeast of Brazil.

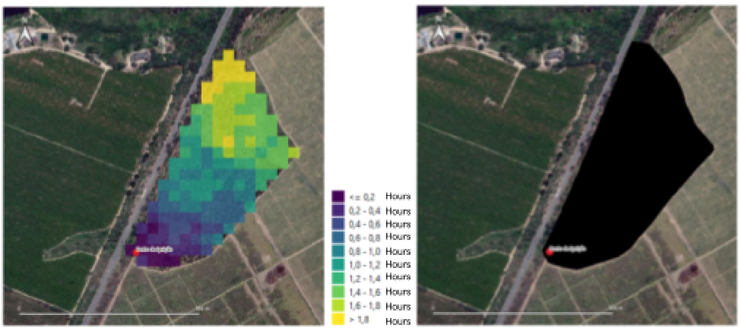

Figure 4. Observed and simulated shape results for fire 02.The red dot in the image represents the fire ignition point

The results obtained indicate that the proposed model can significantly assist in fire planning and management in the regions covered by this study. This is an ongoing research and development project, and in the next phase of this project, a computational prototype will be developed, and interfaced with a mobile weather station to allow the provision of meteorological data at the onset of fire ignition. It is also important to note that the proposed technology can be extended to other regions, as long as the fire dynamics and vegetation fuel classes (physiognomies) are known and information on past fire occurrences is available.

Despite of the small amount of data available, the results indicated a satisfactory level of agreement in representing the areas and duration times of fire occurrences used in the model validation. To further improve the accuracy of the model, it would be necessary to have access to more wildfire events with a reasonable representation of all the different vegetation fuel classes (physiognomies).

Future work will include the development of image analysis capabilities to provide detailed mapping of the area of interest, including roads and highways around fields and farms, which is essential information to identify barriers to fire spread. Also, the developing of a methodology to more accuretaly assess the performa

References

Alessandri, A., Bagnerini, P., Gaggero, M., and Mantelli, L. (2021). Parameter estimation of fire propagation models using level set methods. *Applied Mathematical Modelling*, 92:731–747.

Batty, M. (2000). Geocomputation using cellular automata. In *Geocomputation*, pages 95–126. New York: Taylor & Francis.

Cheney, P. and Sullivan, A. (2008). *Grassfires: fuel, weather and fire behaviour*. Csiro Publishing.

Clarke, K., Fischer, M., and Nijkamp, P. (2014). Cellular automata and agent-based models. *Handbook of Regional Science.*

Columbia, B. (2023). All about wildfire. https://www2.gov.bc.ca/gov/content/safety/wildfire-status/wildfire-response/about-wildfire. Last accessed: 30 June 2023.

Encinas, A. H., Encinas, L. H., White, S. H., del Rey, A. M., and Sánchez, G. R. (2007). Simulation of forest fire fronts using cellular automata. *Advances in Engineering Software*, 38(6):372–378.

Filippi, J., Mallet, V., and Nader, B. (2014). Representation and evaluation of wildfire propagation simulations. *International Journal of Wildland Fire*, 23:46–57.

Finney, A. (2000). Efforts at comparing simulated and observed fire growth patterns. *USDA Forest Service, Rocky Mountain Research Station, Fire Science Laboratory. Final Report INT-95066-RJV*.

Fujioka, F. M. (2002). A new method for the analysis of fire spread modeling errors. *International Journal of Wildland Fire*, 11:193–203.

INPE (2024). Área queimada 1km. https://terrabrasilis.dpi.inpe.br/queimadas/aq1km/. Last accessed: 12 June 2024.

Maduro, R. (2012). Modelagem da propagação do fogo como ferramenta de auxílio a tomada de decisao no combate e prevenção de incendios no parque nacional das emas, go. tese de doutorado do curso de pós-graduação em computação aplicada. instituto nacional de pesquisas espaciais – INPE.

McArthur, A. G. (1966). Weather and grassland fire behaviour. *Leaflet. Forestry Timber Bureau Australia*.

Noble, I., Gill, A., and Bary, G. (1980). Mcarthur's fire-danger meters expressed as equations. *Australian journal of ecology*, 5(2):201–203.

Pyne, S. J., Andrews, P. L., and Laven, R. D. (1996). *Introduction to wildland fire*. John Wiley and Sons.

Ribeiro, M. C., Metzger, J. P., Martensen, A. C., Ponzoni, F. J., and Hirota, M. M. (2009). The brazilian atlantic forest: How much is left, and how is the remaining forest distributed? implications for conservation. *Biological conservation*, 142(6):1141–1153.

Silva, J., Marques, J., Gonçalves, I., Brito, R., Teixeira, S., Teixeira, J., and Alvelos, F. (2022). A systematic review and bibliometric analysis of wildland fire behavior modeling. *Fluids*, 7(12):374.

Sullivan, A. L. (2009). Wildland surface fire spread modelling, 1990–2007. 2: Empirical and quasi-empirical models. *International Journal of Wildland Fire*, 18(4):369–386.

Tonini, M., D'Andrea, M., Biondi, G., Degli Esposti, S., Trucchia, A., and Fiorucci, P. (2020). A machine learning-based approach for wildfire susceptibility mapping. the case study of the liguria region in italy. *Geosciences*, 10(3):105.

Weisstein, E. W. (2023). "cellular automaton". mathworld. https://mathworld.wolfram.com/2002. Last accessed: 18 May 2023.

Wu, Z., Wang, B., Li, M., Tian, Y., Quan, Y., and Liu, J. (2022). Simulation of forest fire spread based on artificial intelligence. *Ecological Indicators*, 136:108653.