Stochastic Model for Wildfire Simulation based on the characteristics of the Brazilian Cerrado*

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Abstract. As a result of an upsurge in the number of wildfires, several studies are underway to discover methods to mitigate the side effects of the flames on the ecosystem and in marginalised settlements. This work proposes an improvement to a stochastic model based on cellular automata that simulates wildfires. The main objective is to increment the model's representation based on the characteristics of the Brazilian Cerrado, enabling a better understanding of the dynamics of these wildfires, aiming to increase the speed and assertiveness in the decision-making of firefighting forces. We propose some improvements to the model, including the incorporation of additional states to represent the different phytophysiognomies of the mentioned biome, a novel approach to representing wind currents that redirect the flames, and a function that considers the air humidity of the region being analysed to influence the fire spread probability. Based on the experimental results, it was possible to conclude that the model achieves the expected objectives, effectively simulating the phenomenon under analysis.

Keywords: Cellular automata · Stochastic rules · Wildfire simulation · Cerrado Biome · Complex phenomena · Firefighting efficiency

1 Introduction

In recent decades, the occurrence of wildfires has exponentially increased, mainly due to the indiscriminate exploitation and extraction of natural resources, which results in the intensification of the greenhouse effect and climate changes. In some biomes, such as the Brazilian Cerrado, wildfires are a natural part of their life cycle [12]. However, these biomes are not able to withstand this unnatural growth of wildfires, and, in most cases, end up collapsing. Other aspects to consider are the immeasurable loss of fauna and flora, and the potential for these wildfires to advance into areas of human occupation [9], especially those of marginalised populations (e.g., indigenous tribes, *quilombolas*, *favelas* and riverside dwellers), which lack ideal physical infrastructures.

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Research studies are being carried out in order to identify effective solutions to address the problem at hand. In the work by Jazebi et al. [8], a review of wildfire management techniques is presented considering monitoring, surveillance, detection, suppression, and prevention. Simulation is another important technique as a mean to understanding the behaviour and effects of wildfires. By comprehending the evolution of the flames, proactive countermeasures can be implemented, thereby enhancing the ability to prevent and suppress fires and safeguarding human lives, natural habitats, and property.

Due to its simplicity and capability to predict a wide range of complex phenomena, including wildfires, the Cellular Automata (CA) [4] stands out as a simulation technique: pedestrian dynamics [2], coordination of swarm of robots [15], epidemiological analysis [11], among others. Define as a machine of transitions, discrete in both time and space, composed of lattices of identical regular cells, at each time-step, each cell evolves considering its local neighbourhood and according to a finite set of states and transition rules.

Accordingly, this work proposes an improvement to the wildfire simulation model proposed by Tinoco et al. [14], aiming to reproduce the characteristics of the Cerrado biome. Given the importance of this biome to the Brazilian biodiversity and the fact that it has been frequently affected by the increase in wildfires, a specific study considering its main characteristics becomes of great importance. Implementing the native flora of the Cerrado, the model maintains as its basis a CA with stochastic rules for fire propagation. Moreover, it takes into account not only the burning time, but other crucial characteristics during a wildfire, such as fire intensity, air humidity, the state of the vegetation before the fire, the presence of wind currents, and obstacles. Furthermore, this work contributes from an experimental standpoint by conducting a comprehensive set of experiments to analyse different parameters on the evolution of wildfires.

2 Related Literature

A brief literature review that includes some important works related to the application of CA in wildfires simulation is presented. Table 1 compares key characteristics of these models with our proposed model.

One of the seminal studies proposing a CA model to simulate fire spreading is the work of Chopard [5]. The model employs three states and stochastic transition rules to recover burnt cells and provide spontaneous combustion.

In the work of Yongzhong et al. [18] it was proposed the application of hexagonal tessellation spaces in the CA. Experiments allowed to conclude that the model can be useful in managing wildfires with heterogeneous characteristics.

Exploring solutions for Geographic Information Systems (GIS), in the work of Yassemi et al. [17], the authors proposed the integration of CA and GIS for the simulation of forest fires. The system presents different options for terrain, vegetation and weather. According to the authors, the model can be adapted to other CA-based spatio-temporal modelling applications.

Table 1: Detailed comparison between CA-based wildfire simulation models

Authors	Year	CA States				Prblty.	Wind	Topog.	Veg. recover
		Veg.	Fire	Obst.	Total				
Chopard et al. [5]	1998	1	2	0	3	Yes	No	2D	Linear
Yongzhong et al. [18]	2004	1	2	0	3	No	Yes	3D	No
Yassemi et al. [17]	2008	1	[0.0...1.0]	0	~	Yes	Yes	3D	No
Alexandridis et al. [1]	2008	1	2	1	4	Yes	Yes	3D	No
Ghisu et al. [7]	2015	1	2	0	3	No	Yes	3D	No
Xuehuaet al. [16]	2016	1	2	1	4	No	Yes	3D	No
Sun et al. [13]	2021	1	4	0	5	No	Yes	3D	No
Previous Model [14]	**2022**	**1**	**4**	**1**	**6**	**Yes**	**Yes**	**2D**	**Non-linear**
Proposed Model	**2023**	**3**	**4**	**1**	**8**	**Yes**	**Yes**	**2D**	**Non-linear**

Bringing the models closer to reality, a case study related to a forest fire (Spetses Island, 1990) was carried out in the work of Alexandridis et al. [1]. The authors proposed a simulation model using a non-linear optimisation approach to approximate its behaviour to that of the analysed event. The simulation results were promising in terms of the predictive capacity of the model.

More current works still present CA as an important tool for fire simulation models. In the work of Ghisu et al. [7], the authors proposed a model for the simulation of forest fires based on CA that applies a numerical optimisation approach to find values that correlate the model parameters. Simulations showed promising results, bringing the proposal closer to the classical methods.

In the work by Xuehua et al. [16], the authors evaluated a set of factors that influence the spread of flames in forest fires. Among the analysed factors, the authors highlight combustible materials, wind, temperature, and terrain. Implemented through CA rules, the model demonstrates to be able to satisfactorily simulate the flame spread trends under different conditions.

Finally, in the work of Sun et al. [13], a model based on CA was proposed for simulating wildfires. The main objective was to improve the accuracy in relation to the spread speed of the flames. According to the results, the model demonstrated a good accuracy to simulate and predict fire spread.

3 The Cerrado Biome

The Cerrado biome is located on the central plateau of Brazil and it is the second largest biome in the country. In terms of size, it covers an area of ≈ 2 million km^2 (≈ 204 million hectares), which represents almost a quarter of the entire territorial extension [10]. Moreover, it is considered a “global hotspot of biodiversity” due to its flora, which contains around 12,385 different types of plants, and its fauna, with 320,000 animal species catalogued to date.

Concerning the phytophysiognomy of the Cerrado, i.e., the characteristics of its vegetation (as illustrated in Figure 1), it can be divided into three major formations [10]: forest, meadow and savannah. Forest formations are characterised

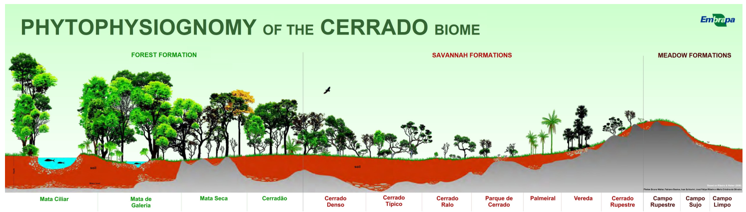


Fig. 1: Phytophysiognomies of the Brazilian Cerrado, with three main formations: meadow, savannah and forest [Adapted from [10]].

by a continuous vegetative canopy, having a predominance of trees, with a small amount of shrubs and undergrowth. It occurs near bodies of water or in places with a high density of nutrients. Due to its dense vegetation and water bodies, there is a greater presence of moisture compared to the other two formations. In contrast, savannah formations are characterised by a random distribution of trees, without the formation of a continuous vegetative canopy. It still contains shrubs, but with a larger volume of vegetation than the meadow formation. Finally, meadow formations have the least amount of vegetation in volume. It is characterised by the predominance of bushes and a rocky substrate.

4 Model Description

This work proposes an improvement to the wildfire simulation model proposed by Tinoco et al. [14]. The fundamental aspects of the previous model, including stochastic evolution, a non-linear recovery function based on an exponential probability, and the composition of a combustion matrix with wind currents, are preserved. In addition, this improved model incorporates heterogeneous vegetation states based on the phytophysiognomy of the Brazilian Cerrado biome and the influence of relative humidity on the fire dynamics.

Figure 2 shows the possible states for each CA cell. The states "initial-fire", "stable-fire" and "ember" (orange, red and dark-red, respectively) representing the fire states, the state "ash" (grey) and the state "water" (blue) have been defined in our previous model [14]. The states "meadow", "savannah" and "forest" (in green), represent cells with different types of vegetation of the Cerrado biome. These vegetation states do not influence each other, but can be influenced by the fire states, i.e., they are susceptible to combustion. Besides, each type of vegetation has a different amount of combustible material, with meadow having the lowest, forest intermediate, and savannah the highest amount.

To determine the probability of fire spread, it is important to consider not only the type of vegetation but also the air humidity. It has an inversely proportional influence on the probability of burning, i.e., the higher the humidity, the lower the probability that a cell to ignite. The effect of air humidity is captured by a factor ω determined by predefined thresholds, and it is incorporated into the ignition probability calculation, where: $\omega = 1.5 \;\; if \; \big((\gamma > 0\%) \; and \; (\gamma \leq 25\%)\big)$;

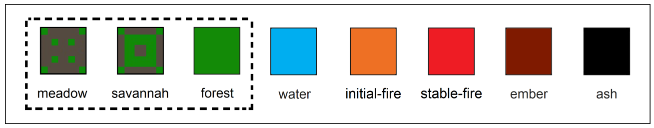


Fig. 2: States for the CA cells described by different colours.

$\omega = 1.0 \ if \ \big((\gamma > 25\%) \ and \ (\gamma \leq 50\%)\big); \omega = 0.8 \ if \ \big((\gamma > 50\%) \ and \ (\gamma \leq 75\%)\big)$; and, $\omega = 0.6 \ \ if \ \big((\gamma > 75\%) \ and \ (\gamma \leq 100\%)\big)$.

Air humidity also affects the duration of fire states. Specifically, in conditions where the air humidity is less than 30% ($\gamma \leq 0.3$), the transition time from state "stable-fire" to state "ember" increases by a factor of 5, whereas the transition time from state "ember" to state "ash" decreases by a factor of 3. This effect is due to the increase in flame intensity, which leads to faster consumption of flammable materials. On the other hand, if air humidity is greater than 30% ($\gamma > 0.3$), cells at state "initial-fire" change to state "stable-fire" after two time-steps. Cell stays at state "stable-fire" for four time-steps and change to state "ember", in which it stays for 10 time-steps before transitioning to state "ash", representing the absence of flammable material.

Each cell in the neighbourhood of the central cell has a probability of propagating the fire based on the formula of Equation 1.

$$\phi_{i,j} = \beta - (\delta * r) \tag{1}$$

where: (i) $\phi_{i,j}$ is the probability P of the fire on the (i, j) position spread to the central cell; (ii) β is the base intensity of the flames; (iii) δ is the decay of the base intensity, the greater the decay, the more directional is the wind, if $\delta = 0$ there is no wind, creating a circular pattern; and (iv) r is the direction factor, representing the orientation $(\{cardinal\} \cup \{collateral\})$ of the wind current.

Cells change state according to transition rules, here defined as fire propagation rules. These rules employ a combustion probability matrix [14], which quantifies the probability of a given cell igniting through the propagation of fire from its closest cells (considering the Moore's Neighbourhood).

In addition to the transitions between fire states, the previous model implemented a transition from the "ash" state to a vegetation state, representing the capability of burnt cells to recover. Vegetation recovery is an essential process to consider, especially in biomes like the Cerrado, which are highly resilient to wildfires. Equation 2 [14] describes the recovery probability P_r of a cell x_{ij} on the 2D lattice. If a period of idleness is defined, then the probability is zero. Otherwise, the probability is equal to the square of the time steps counted since the cell x_{ij} turned to ash (ts_r) over 10 to the a^{th} power. This exponential represents the longitudinal extent of a probability distribution.

$$P_r(x_{ij}) = \begin{cases} 0.0, & \text{if } idle \\ {}^{(ts_r)^2}/_{10^a}, & \text{otherwise, such that } ts_r \geq 1 \ and \ a \geq 1 \end{cases} \tag{2}$$

CA Rules: Considering the characteristics presented, the fire propagation rules can be described as follows. *If the central cell is in the state:*

- *"vegetation"* and there are no cells in a fire state in its neighbourhood $\rightarrow$ maintain the same state;
- *"vegetation"* and a cell *'cl'* in its neighbourhood is in a fire state $\rightarrow$ there is a probability to change to the state *"initial_fire"*;
  $\{P(\text{"}initial\_fire\text{"}) = combustion\text{-}matrix(cl) \times local\text{-}fire\text{-}intensity \times (\lambda)\}$
- *"initial_fire"* (it is not influenced by other cells) $\rightarrow$ maintains this state for 3 time-steps and switches to the state '*'stable_fire"*;
- *"stable_fire"* (it is not influenced by other cells) $\rightarrow$ maintains this state for 3 time-steps and switches to the state *"ember"*;
- *"ember"* (it is not influenced by other cells) $\rightarrow$ maintains this state for 10 time-steps and switches to the state *"ash"*;
- *"ash"* (it is not influenced by other cells) $\rightarrow$ it can change to the state *"vegetation"* according to the recovery function (Eq. 2);
- *"water"* $\rightarrow$ there is no interaction with others states.

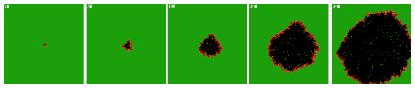
Model Parameters (values obtained by preliminary experiments): fire spread probability ($\phi = P(c_{ij} \rightarrow c_{central})$, given Equation 1); local fire intensity (*"initial_fire"* = 0.6; *"stable_fire"* = 1.0; *"ember"* = 0.2); dwell time of states with active fire (*"initial_fire"* = $2ts$; *"stable_fire"* = $4ts$; *"ember"* = $10ts$); recovery time-step ($ts_r = \{1..\} \parallel ts_r \in \mathbb{N}^*$); and, the exponent ($a = 6$).

5 Simulations and Analyses

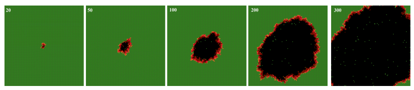
The proposed model was implemented in the GameMaker Studio [6] and in the C programming language, in which the former was used for visualisation and the latter for mass processing. All simulations have run for 300 time-steps, while the mass experiments consist of 100 executions to ensure statistical significance, and different seeds to avoid outliers. Screenshots are composed of a CA lattice (128×128) in the same time-step intervals $ts = \{20, 50, 100, 200, 300\}$.

As the first simulation, a visual assessment of fire behaviour was carried out in the three types of implemented vegetation: forest, savannah and meadow. The objective of this assessment is to observe the differences in the proportion and speed of the fire spreading when the type of combustible material is changed. For this, the same variables were used in these three scenarios, and a spark was placed in the same spot (centre of the lattice) to start the fire. It is noteworthy that, the intensity of the fire in each vegetation type was defined based on an approximation of the natural characteristics of the Cerrado biome.

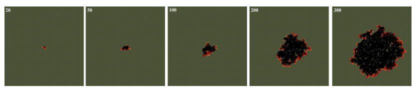
Figure 3 depicts the simulation of wildfires in different vegetation formations, where Figure 3a represents forest, Figure 3b savannah, and Figure 3c meadow formations. The scarcity of combustible material in meadow formations leads to a slower rate of fire propagation compared to savannah and forest formations (see Sec. 3). As a result, upon reaching 300 time-steps, the extent of the burned area in the meadow formation (Fig. 3c) approaches the burning areas in the savannah



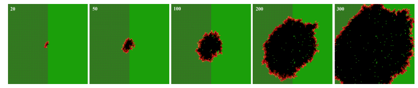
(a) S1: forest formation.



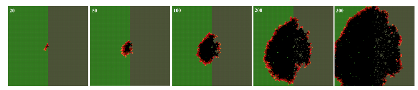
(b) S2: savannah formation.



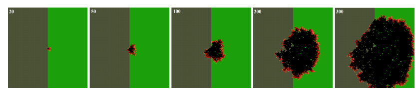
(c) S3: meadow formation.



(d) S4: {savannah + forest}



(e) S5: {savannah + meadow}



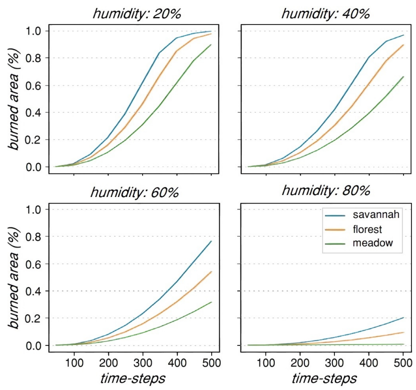
(f) S6: {meadow + forest}

Fig. 3: Wildfire simulations with the three major groups of the Cerrado phyto-physiognomy (forest, savannah and meadow) - disjoined (a-c) and merged (d-f).

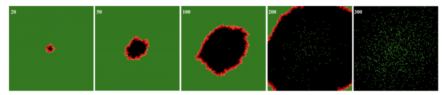
and forest formations with 100 and 200 time-steps, respectively. In turn, given the higher concentration of moisture in forest formations, it is expected that the burning rate would be lower. This behaviour can be observed where, after 300 time-steps, the burned area of the forest formation (Fig. 3a) has not yet encompassed the entire analysed area, unlike the simulation in the savannah formation (Fig. 3b), approaching the real characteristics of the biome.

It is important to analyse scenarios that include more than one type of vegetation. Figure 3 illustrates wildfire simulations in areas that have two different vegetation formations: Figure 3d combines savannah and forest formations, Figure 3e savannah and meadow, and Figure 3f meadow and forest. According to the simulations, one can observe that the behaviour of flames in savannah and forest formations (Fig. 3d) are more similar. This similarity is a result of a large amount of combustible material present in both formations. However, forest formations have a higher humidity rate, which contributes to a slower spread of fire. On the other hand, when meadow formations are present (Fig. 3e and Fig. 3f), there is a distinct difference in the propagation of flames. This can be attributed to the undergrowth nature of meadow formations and their low amount of combustible material. For instance, with 300 time-steps (Fig 3e), almost the entire savanna region was consumed by the flames, while in the meadow formation, only around 50% of the region was consumed.

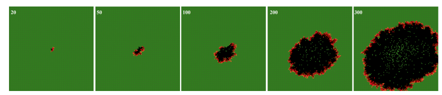
Humidity varies among different types of vegetation. Forest formations, for example, exhibit higher levels of humidity and moisture compared to savannah and meadow formations. Thus, it is important to assess wildfires under such conditions. Figure 4 illustrates experiments conducted to examine the impact of the humidity level on wildfires: a quantitative analysis (percentage of burned area (Fig. 4a)) and simulations in forest formations (scenario S1 with 20% humidity (Fig.4b) and S2 with 80% (Fig. 4c)). According to the charts, one can observe the influence of humidity on the proportion of burned area and the burning



(a) Burning evol. with diff. humidity.



(b) Scenario S1: 20% of humidity.



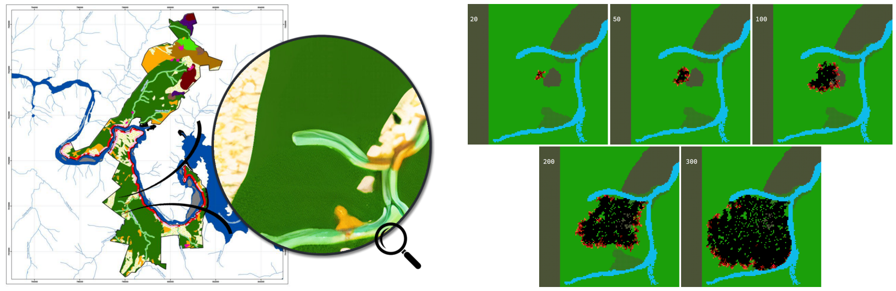
(c) Scenario S3: 80% of humidity.

Fig. 4: Wildfire simulations varying the humidity coefficient.

behaviour in different types of vegetation. Furthermore, simulations in scenario S1 (Fig. 4b), where the humidity is lower, nearly the entire environment was burned after 200 time-steps, in scenario S2 (Fig.4c), where the humidity is higher, only about 50% of the cells were burned.

Another important analysis is the evaluation of burning edges (cells in fire states) and the proportion of unburnt cells. It is expected that the model can accurately mimic fire propagation resistance under high humidity conditions. This characteristic can be observed by comparing the burning edges of each simulation. In scenario S1 (Fig. 4b), in which humidity is low, the burning edges demonstrate a higher homogeneity. In turn, with a high humidity rate in scenario S2 (Fig. 4c), the burning edge becomes entirely irregular, and it is possible to observe areas where the flames have even been extinguished. Moreover, with high humidity rates, some cells within the burnt area did not ignite (in scenario S2 with 100 time-steps, several cells within the burnt area remained in a vegetation state), which is a striking feature of humid environments.

One of the main objectives of this work is to comprehend the behaviour of wildfires in the Cerrado biome, aiming to prevent and minimise the adverse impacts of wildfires. Hence, it is important to analyse real-world data. Figure 5 presents a simulation of a wildfire in the Pau-Furado State Park, a conservation unit located in the state of Minas Gerais, Brazil. Figure 5a shows an area of interest within the park where simulations were conducted. Figure 5b illustrates the time sequence of the wildfire simulation in this region. Simulations show the fire starting in the centre of the area and spreading radially, with the speed and intensity of scattering varying according to the vegetation formations. As forest formations are predominant in this region, the humidity rate strongly affects the intensity of the flames. An important characteristic to be highlighted is the capability of watercourses to function as fire barriers in this scenario.



(a) Pau-Furado Park [Adapted from [3]]. (b) Simulation in the highlighted area.

Fig. 5: Wildfire simulation of an approximate reproduction of the highlighted area of the Pau-Furado State Park (Protected Cerrado area in Brazil).

6 Conclusion and Future Work

This study proposed an enhanced wildfire simulation model based on Cellular Automata to more accurately represent the unique features of the Brazilian Cerrado biome. The improvements include the following: (i) incorporating different vegetation states based on the phytophysiognomy of the Cerrado, allowing for the simulation of various fire spread scenarios; (ii) application of different humidity coefficients for the assessment of the intensity of the flames; and (iii) reproduction of a real Cerrado-dominated environment for simulating forest fires.

Based on preliminary analyses, it can be concluded that the proposed improvement to the wildfire simulation model produced the expected outcomes. The model satisfactorily simulated fire behaviour under different vegetation states and humidity coefficients. The representation of environments with various types of vegetation and their respective particularities, represents a significant improvement over the previous model, which only accounted for a single type of vegetation. Furthermore, the results showed the expected correlation between the spread of flames and low air humidity, whereas an inverse correlation was observed with increasing air humidity.

In terms of future work, we intend (i) to update the recovery function to take into account different characteristics of each area; (ii) to incorporate the influence of terrain relief, accounting for how the topography can impact the spread of wildfires; and (iii) to apply evolutionary computation in the optimisation of the model's parameters, taking into account real wildfire data.

References

1. Alexandridis, A., Vakalis, D., Siettos, C., Bafas, G.: 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**(1), 191–201 (2008), `https://doi.org/10.1016/j.amc.2008.06.046`

2. Bandini, S., Crociani, L., Vizzari, G.: An approach for managing heterogeneous speed profiles in cellular automata pedestrian models. J. Cell. Autom. **12**(5) (2017), https://doi.org/10.17815/CD.2020.85
3. Bevilaqua, A.C.: Plano de manejo parque estadual do pau furado (2011), http://biblioteca.meioambiente.mg.gov.br/index.asp?codigo_sophia=13597
4. Bhattacharjee, K., Naskar, N., Roy, S., et al.: A survey of cellular automata: types, dynamics, non-uniformity and applications. Natural Computing **19**(2), 433–461 (2020), https://doi.org/10.1007/s11047-018-9696-8
5. Chopard, B., Droz, M.: Cellular Automata Modeling of Physical Systems. Cambridge Univ. Press (1998), https://doi.org/10.1007/978-0-387-30440-3_57
6. Games, Y.: Gamemaker: Studio (2014), https://www.yoyogames.com/gamemaker
7. Ghisu, T., Arca, B., Pellizzaro, G., Duce, P.: An improved cellular automata for wildfire spread. Procedia Computer Science **51**, 2287–2296 (2015), https://doi.org/10.1016/j.procs.2015.05.388
8. Jazebi, S., De Leon, F., Nelson, A.: Review of wildfire management techniques—part i: Causes, prevention, detection, suppression, and data analytics. IEEE Transactions on Power Delivery **35**(1), 430–439 (2019), https://doi.org/10.1109/TPWRD.2019.2930055
9. Lozano, O.M., Salis, M., Ager, A.A., et al.: Assessing climate change impacts on wildfire exposure in mediterranean areas. Risk Analysis **37**(10), 1898–1916 (2017), https://doi.org/10.1111/risa.12739
10. Ribeiro, J.F., Walter, B.M.T.: As principais fitofisionomias do bioma cerrado. Cerrado: ecologia e flora **1**, 151–212 (2008)
11. Schimit, P.H.T.: A model based on cellular automata to estimate the social isolation impact on COVID-19 spreading in Brazil. Comput. Methods and Programs in Biomed. **200**, 105832 (2021), https://doi.org/10.1016/j.cmpb.2020.105832
12. Schmidt, I.B., Eloy, L.: Fire regime in the Brazilian Savanna: Recent changes, policy and management. Flora **268**, 1–5 (2020), https://doi.org/10.1016/j.flora.2020.151613
13. Sun, L., Xu, C., et al.: Adaptive forest fire spread simulation algorithm based on cellular automata. Forests **12**, 1431 (2021), https://doi.org/10.3390/f12111431
14. Tinoco, C.R., Ferreira, H.F., Martins, L.G.A., Oliveira, G.M.B.: Wildfire simulation model based on cellular automata and stochastic rules. In: Int. Conf. on Cellular Automata for Research and Industry (ACRI). pp. 246–256. Springer (2022), https://doi.org/10.1007/978-3-031-14926-9_22
15. Tinoco, C.R., Oliveira, G.M.B.: Heterogeneous teams of robots using a coordinating model for surveillance task based on cellular automata and repulsive pheromone. In: IEEE Congress on Evolutionary Computation (CEC). pp. 747–754. IEEE (2019), https://doi.org/10.1109/CEC.2019.8790266
16. Xuehua, W., Chang, L., Jiaqi, L., et al.: A cellular automata model for forest fire spreading simulation. In: IEEE Symp. Series on Computational Intelligence. pp. 1–6 (2016), https://doi.org/10.1109/SSCI.2016.7849971
17. Yassemi, S., Dragićević, S., Schmidt, M.: Design and implementation of an integrated gis-based cellular automata model to characterize forest fire behaviour. Ecological Modelling **210**(1-2), 71–84 (2008), https://doi.org/10.1016/j.ecolmodel.2007.07.020
18. Yongzhong, Z., Feng, Z.D., Tao, H., et al.: Simulating wildfire spreading processes in a spatially heterogeneous landscapes using an improved cellular automaton model. In: IEEE Int. Geoscience and Remote Sensing Symp. vol. 5, pp. 3371–3374 (2004), https://doi.org/10.1109/IGARSS.2004.1370427