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Simulating forest fire spread and fire-fighting using cellular automata

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ABSTRACT

In response to the transboundary haze problem in Southeast Asia, a physical model is adopted to simulate the spread and extinguishing of fire. This study is done in the context of Dumai, Indonesia, as it is one of the areas that significantly contribute to the haze problem. This model aims to provide perspectives on the persistence of forest fires despite fire-fighting efforts. While existing models using Huygens' principle of wave propagation allow an understanding of the natural spread of fire, our model applies cellular automata to predict and analyse the effects of fire-fighting intervention strategies, with the spatial and propagation dynamics of fire considered. Cellular automata is an active area of research among physicists, and is widely used by chemists and biologists to model many types of natural phenomena. We note similarities between our model predictions and observations of real-world phenomena. Analyses on the factors that affect the spread of fire are presented, in order to understand which ones are dominant in differing situations. This provides insights on optimum conditions for fire-fighting efforts, and suggests guidelines that may be considered for fire control in future forest fires.

1. Introduction

A forest fire is a large uncontrolled fire in an area of combustible vegetation occurring in a forest or woodland. Fires are a significant source of forest destruction in many countries. Forest fires have devastating results, such as deforestation, air pollution and a loss of animal and human life [1]. This has been a common transboundary issue, even in Europe [2,3] and the Americas [4]. In Indonesia, burnt forests create haze, and cause enormous ecological and economic damage to both Indonesia and nearby countries [5]. Proper fire management regimes must be put in place, and this comes with informed decision-making [6].

Indonesian forest fires are largely determined by climatic conditions—long, dry summers with high temperatures reduce the moisture content of forest litter drastically [7]. Consequently, even a small flame can potentially lead to severe wildfire. Environmental factors such as fire history, vegetation cover, soil type or topography, all affect fire ignition and behavior [8]. In the past several decades, a sharp increase in fire events in Indonesian forests has been observed. These forest fires usually occur due to "slash-

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and-burn" [9] tactics employed to clear vegetation for palm oil, pulp and plantations by small-scale farmers and corporations in Indonesia, as well as in Malaysia [10]. These swidden agriculture methods entail the burning of farming fields to create a nutrient-rich ash layer devoid of weeds, on which crops are then grown, in the process releasing large amounts of airborne pollution. This practice is common in the land of Sumatra, especially the province of Riau, which has been experiencing increasing numbers of human-caused forest fires of various extents and levels of severity.

Despite water bombing and large-scale fire-fighting efforts, these fires are particularly difficult to put out. The resilience of the fires can be attributed to the peat land that the forests [11] lie on, which allows the fire to continue burning underground even with heavy above-ground suppression. The release of combustion heat, and the emission of airborne pollution that contributes to haze, is hence sustained [12]. Furthermore, the conversion of peatlands into plantations necessarily involves the drainage of water from the soil substrate, which causes the land to be sensitive to fire and more readily combustible.

In recent years, transboundary haze has affected many countries in Southeast Asia: Malaysia, Singapore, the south of Thailand, and the Philippines, leading to a significant deterioration in air quality in these [13]. This is reflected by the Pollutant Standard Index (PSI), an indication of air quality that combines metrics such as the concentration of chemical pollutants and airborne particulate matter. Observed PSI levels increase drastically upon occurrence of the haze, and may continue to increase, if the haze situation worsens. For example, on 19 October 2015, estimated PSI in Singapore over the course of 3 hours rose from 96 at 9 pm to 209 at 11 pm, where 96 is categorized as unhealthy, and 209 is categorized as very unhealthy [14]. Apart from reduced visibility, haze presents a variety of negative effects on medical health [15–18]. Short term exposure to high levels of haze can cause irritation of the eyes, nose and throat in healthy individuals; continued exposure can affect the hearts and lungs. Individuals diagnosed with chronic heart or lung diseases are at elevated risk, as the pollutants may clog airways or enter the bloodstream [19]. More severe effects over prolonged exposure include an increased risk of cardiovascular failures, and reduced lung development and chronic respiratory diseases in children [1].

These issues caused by haze can be mitigated by controlling fire spread in areas that employ slash-and-burn tactics. There are currently two types of measures to control the spread of fires [20]. The first type is preventive, and includes burning regulations and anti-fire zones. The second type is operational, and seeks to control and limit the amount of fire spread, through the use of different fire-fighting strategies. However, there are limitations to both measures, as it is difficult to predict the direction of fire spread and the effectiveness of fire-fighting methods. At current, fire-risk evaluation, and in particular, understanding the spatial patterns of forest fires, are growing increasingly essential for Indonesian vegetation management. If the spread of fire can be accurately simulated, then fire-fighting countermeasures can be drawn and evaluated in an effective and timely manner, enabling more robust control with a more optimal use of resources.

A good fire spread model should take into account type of vegetation, density of vegetation, wind direction, humidity and the type of terrain [8]. A number of models that compute fire spread using some or all of these variables have already been presented in literature, with a variety of approaches employed [21–23], such as considering fire spread as wave propagation and employing the Huygens-Fresnel principle to evolve the fire state across time [24]. Such an approach is elegant, and exploits our established understanding of wave behaviour. Another method of simulating fire spread is to employ cellular automata (CA). This involves applying a finite grid at a macroscopic scale, splitting it to a large number of cells [25–27]. Each cell is usually described by several state variables that evolve in discrete time, in accordance to a set of rules and the states of the neighboring cells. CA has been proven to be effective in predicting complex dynamics in interacting physical systems [28]. Due to its grid-based nature, CA is also readily combined with digital data from geographical information systems (GIS) or other sources, to yield models for specific real-world environments [29,30]. These advantages of CA render it a strong choice in comparison to other approaches, and we utilize CA as the basis of our fire spread model in this paper.

This work uses a CA framework adapted from [30] to model forest fire spread. This model is applied to simulate the large-scale forest fire in Dumai, Indonesia from 10 March 2014 to 24 March 2014. Besides optimizing the fire spread model for the conditions in Indonesia, different fire-fighting strategies were also simulated, in order to evaluate their effectiveness in different environmental conditions. Previously, a number of models using CA to examine fire suppression tactics has been presented in literature. These models mainly focused on modeling fire suppression using air tankers [31]; models of fire spread were analyzed to show optimal locations to employ fire fighting strategies, but the fire suppression strategies themselves were not simulated [32]. The effectiveness of these fire fighting strategies in different vegetation conditions were also not discussed in some of these papers. Our paper seeks to cover fire suppression using aircraft (temporary firelines) as well as manual blockages (constructed firelines), and their effectiveness in different vegetation conditions.

The structure of the paper is as follows—the proposed CA and fire-fighting model are detailed in Section 2, simulation results and analyses are presented in Section 3, and lastly, main conclusions from the results, recommendations for fire mitigation strategies, and possible areas for future research are presented in Section 4.

2. Methods

2.1. Cellular automata

The forest area is discretized into a large grid, on which a two-dimensional cellular automata (CA) is supported. The forest cells may be in one of four states at any time—fuel, burning, empty, or burnt. The "fuel" state represents vegetation that can catch fire, the "burning" state represents fuel that is currently combusting in a particular time step, the "empty" state refers to an area of land without fuel or fire (and hence cannot ignite), and the "burnt" state refers to fuel that has stopped burning. Non-vegetated areas are marked as "empty". The evolution of the states of cells across time-steps is governed by a set of rules that model the behaviour of fire propagation. It can be reasoned that, firstly, a burnt cell will remain burnt, as the time-scale of forest fires is typically far too short for vegetation regeneration to occur; secondly, burning cells will become burnt after one time-step, with the physical duration of a time-step appropriately chosen; and thirdly, a fuel cell next to a burning cell may catch fire with a certain probability.

2.2. Fire propagation

We adopt a similar propagation model as used by [30]. The probability of fire spreading from a burning cell to the neighbouring cells can be described as

$$P_{burn} = P_h(1 + P_{den})(1 + P_{veg})P_w, \tag{1}$$

where P_h denotes the (constant) probability that a cell adjacent to a burning cell containing a given type of vegetation and density will catch fire at the next time step under no wind and flat terrain conditions, and P_{den}, P_{veg} and P_w are fire propagation parameters associated with the density of vegetation, the type of vegetation, and the wind speed respectively. These quantities are modelled in the following subsections.

2.3. Wind effects

The fire propagation parameter P_w associated with the wind speed is described by

$$P_w = f_t e^{C_1 V} \tag{2}$$

$$f_t = e^{VC_2(\cos\theta - 1)} \tag{3}$$

where V denotes the wind speed, θ is the angle between the direction of the fire propagation and the direction of the wind, and C_1 and C_2 are wind constants. We adopt parameter values consistent with those used by [30] as shown in Table 1. It is noted that as the angle between the direction of fire spread and the wind direction decreases, the probability of fire spread increases—this is because the wind will increase the spread of the fire in the direction it is blowing in, but will slow the fire spread in directions against the wind.

2.4. Vegetation type and density

The value of P_{veg} is associated with the water content present within the vegetation, and P_{den} is associated with the areal density of vegetation in the cell. The greater these values are, the higher the probability of fire propagation into the cell. Characteristic values are shown in Tables 2 and 3. The effect of these parameters on fire propagation and the effectiveness of fire-fighting methods will later be explored in Section 3.

2.5. Area geography

As the application focus of the study is to investigate the forest fire that had occurred in Dumai, the geography of Dumai, extracted from OpenStreetMap, was utilized as a basis for the construction of the CA grid; in general, however, the grid can be constructed from any topographical basis, and the model is general to the shape and size of the region of interest. Areas that fell outside the borders of Dumai had an "empty" state, while areas that lay within the borders of Dumai were assigned the state of "fuel", consistent with the vegetation-dense environment typical in the region. Such a configuration simulates fire propagation only within the boundaries of Dumai. The type of vegetation and vegetation density were extracted from Global Forest Watch Fires (GFW Fires) [33], based on which parameter values were chosen for the simulation grid. Geographical maps of Dumai and vegetation plots are presented in Fig. 1.

2.6. Fire-fighting strategies and control lines

We incorporate fire-fighting interventions into the simulation, alongside the fire propagation model. Two types of fire intervention strategies are considered—constructed fire lines and temporary holding fire lines. Constructed fire lines are typically created with heavy machinery, and provide a permanent fuel gap to inhibit fire spread. In this simulation, it is taken there is an

Table 1
CA algorithm operational parameters, values consistent with [30].

Parameter	Value	Units
P_h	0.58	$m^{-1}s$
C_1	0.045	$m^{-1}s$
C_2	0.131	$m^{-1}s$
V	8	ms^{-1}

Table 2
Values for P_{den} for different vegetation density categorizations, as adapted from [30].

Parameter	P_{den}
Sparse	–0.4
Normal	0
Dense	0.3

Table 3
Values for P_{veg} depending on the type of vegetation, as adapted from [30].

Parameter	P_{veg}
Agricultural	–0.3
Thickets	0
Hallepo-pine	0.4

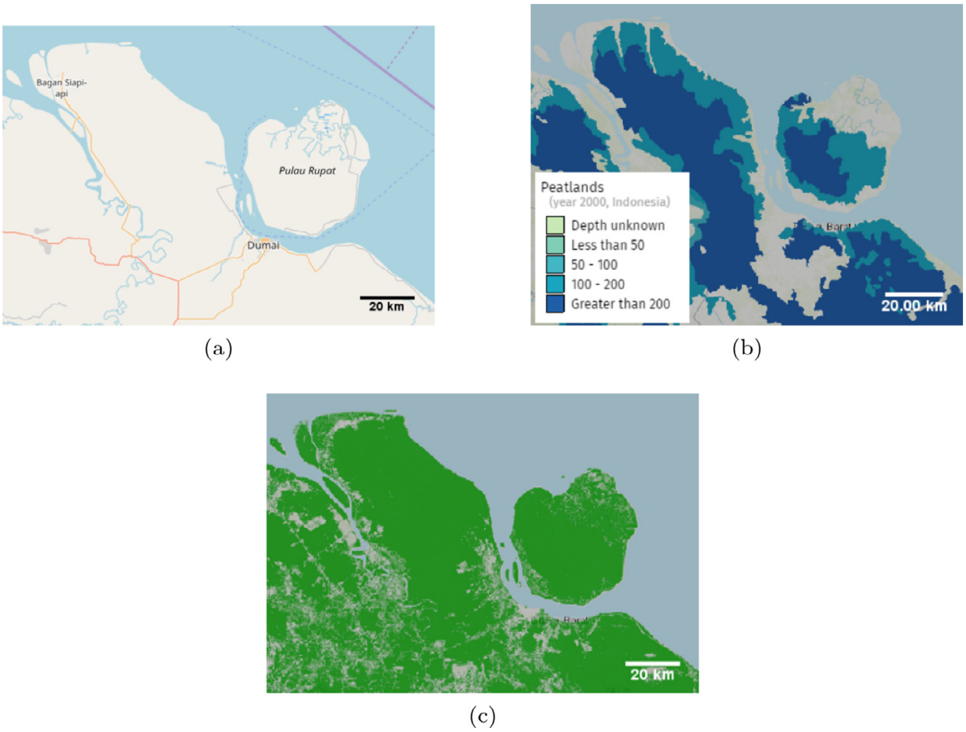
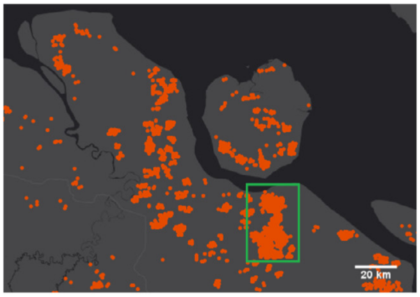


Fig. 1. (a) A picture showing Dumai, Riau, Indonesia. (b) Map of the peatland density and depth in Dumai. (c) Map of the tree cover density in Dumai, computed as all vegetation taller than 5 m in height. Tree cover is the biophysical presence of trees and may take the form of natural forests or plantations existing over a range of canopy densities. This figure was adapted from Global Forest Watch Fires (GFW Fires) [33], an online data platform for monitoring and responding to forest and land fires using near real-time information.

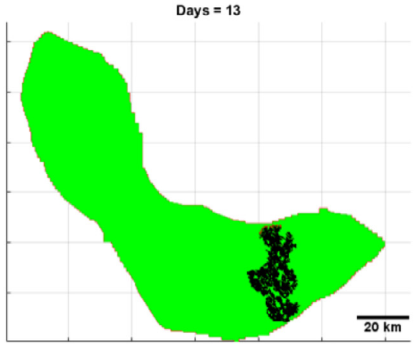
approximately 90% probability that the control lines will be effective. The distance between the control lines and the burning cells can be varied; however, since the setup of these lines requires time and heavy logistics, they can typically only be constructed with a minimum distance of one kilometer away from the fire. On the other hand, temporary holding lines are created by suppressant bombing aircraft, with the resulting effect lasting for a typical of two days [34]. These control lines, which can be placed almost anywhere, do not require any setup time.

3. Results & discussion

The proposed CA-based model for fire propagation can be utilized in Monte Carlo simulations to computationally predict forest fire evolution. We focus on the 2014 Dumai forest fire as an example in this study. A validation that the model is consistent with real-



(a)



(b)

Fig. 2. (a) Actual burnt area of Dumai from 10 March 2014 to 24 March 2014, data adapted from GFW Fires [33]. Red regions denote burnt area; grey regions denote remaining vegetation. The region of interest is highlighted in a green box. (b) Monte-Carlo simulation results of forest fire propagation in Dumai over 14 days, averaged over 100 repetitions. Black regions denote burnt area; red regions denote areas that are still burning; green regions denote remaining vegetation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

world observations of the Dumai forest fire is first presented (Section 3.1); the model is then utilized to investigate fire-fighting strategies and deduce guidelines for their effective usage (Section 3.2). A discussion of model performance and limitations is then presented in Section 3.3.

3.1. Model validation against dumai forest fire

First, we present a verification that the proposed CA-based simulation approach is able to model the Dumai forest fire that had occurred 10 March 2014 – 24 March 2014. The actual fire hotspots observed in Dumai and our simulation results of the fire spread on the same map are shown in Fig. 2. It was assumed that insignificant firefighting efforts were performed, or if any were effected, they were ineffective at controlling the spread of fire. The vegetation type and vegetation density conditions were taken to be “normal”, with the corresponding parameter settings shown in Tables 2 and 3. The vegetation in Dumai consists of a combination of trees, comprising Meranti (Family: *Dipterocarpaceae*) and Jelutung (Family: *Apocynaceae*) woods, and peatlands. The parameters P_{den} and P_{veg} for the CA were chosen to model the vegetation characteristics of Dumai. A close agreement is seen between the real-world observations and the simulation results, suggesting satisfactory accuracy of the model. On average, the simulation results exhibit $\approx$ 81% similarity with the recorded fire spread, based on a cell-by-cell comparison of states.

The remaining differences between the simulation and real-world observations can largely be attributed to the fact that the current model does not accommodate simultaneously propagating fires of distinct causes. For instance, burning splinters or fuel material can occasionally be transported long distances by strong wind, and multiple farming parties may initiate slash-and-burn tactics at different locations, both of which are infeasible to model accurately. Additionally, there is in actuality variations in vegetation type and density throughout Dumai that can skew fire propagation in certain directions, and the homogeneous environment in the model is therefore an approximation. To account for inhomogeneity in environment will require high-resolution terrain and vegetation information across the entire region.

3.2. Fire-fighting strategy analysis

Forest fire-fighting can be performed in a number of ways. As previously discussed, two primary large-scale methods are examined in this study, namely the construction of fire lines through machinery to limit the spread of fire, and the use of temporary holding lines, created through aerial water bombing. In the former, the removal of unburnt vegetation within the fire lines limit the ability of the forest fire to propagate beyond the line boundary, and in the latter, the wetting of large regions of the forest suppresses temperature and reduces the flammability of vegetation. We utilize the simulation model to investigate optimal placements for these control lines in differing scenarios. The optimality condition is where the fire fighting strategy manages to retard fire spread in the quickest possible manner and without allowing for further fire spread at later times, especially relevant when temporary holding lines are used. To simulate these holding lines, we modified the cells in the CA, such that for a fixed number of iteration steps (2 days) they burn with zero probability. This does not mean that the fire cannot spread, as the fire can continue to spread across the holding line after the number of iteration steps, or go around the holding lines.

3.2.1. Optimal placements for temporary holding lines

Holding lines to be placed directly on, or ahead of, the fire propagation front. A water-bombing raid across the width of the Dumai forest fire on Day 5 is simulated, as shown in Figs. 3(a) and 3(b). The suppression effect of the temporary holding line created lasts approximately 2 days, but as it is located behind the fire propagation front, the forest fire is still free to propagate. While there is an

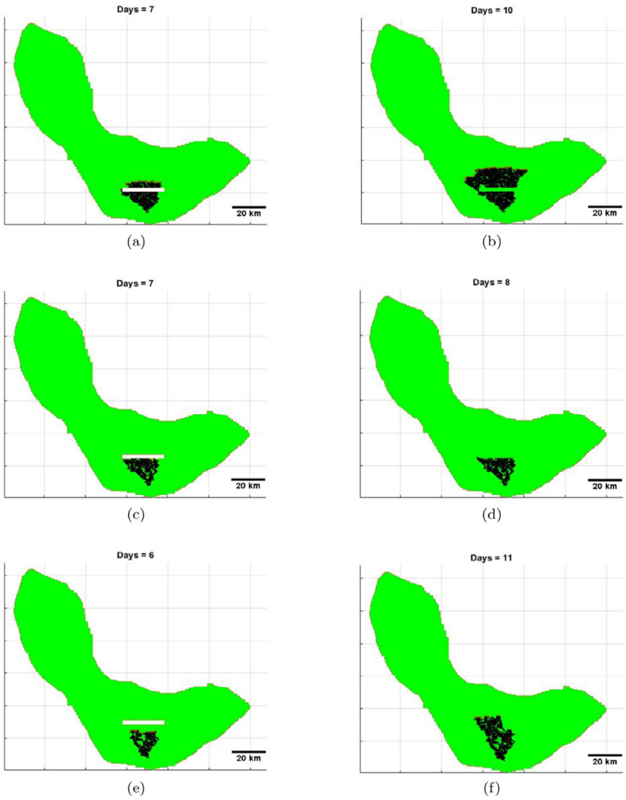


Fig. 3. (a) Temporary holding line placed behind the fire propagation front, and (b) the resulting state of the forest fire more than 2 days later. Fire (red) continues to spread. (c) Temporary holding line placed directly on the fire propagation front, and (d) the resulting state of the forest fire 2 days later. Fire is effectively put out. (e) Temporary holding line placed at a distance ahead of the fire propagation front, and (f) the resulting state of the forest fire more than 2 days later. Fire continues to spread. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

immediate reduction of fire area consequent of the water-bombing, the spread of fire is not effectively halted, and the forest area will eventually recover and surpass its original extent. In order to effectively suppress the forest fire, the temporary holding line needs to be placed almost directly on the fire propagation front. This is shown in Figs. 3(c) and 3(d). The effect of the holding line similarly lasts approximately 2 days, but as the propagation front is extinguished, the fire can no longer spread. The interior of the forest fire then dwindles due to fuel depletion. The result is an effective suppression of the forest fire.

Distance between holding lines and the fire propagation front to be minimized. This is because the effect of temporary holding lines diminishes with time, and they become ineffective after a typical period of 2 days. In Figs. 3(e) and 3(f), the temporary holding line is placed a distance ahead of the fire propagation front, but the fire does not propagate sufficiently quickly to reach the line before it becomes ineffectual. The holding line therefore has little effect on fire propagation. This is in contrast with the scenario in Figs. 3(c) and 3(d), where the holding line was created directly on top of the propagation front. This indicates strongly that the speed of fire propagation ought to be taken into consideration when placing holding lines far from the fire—or, more easily, the water bombing raids can be simply performed in close proximity to the propagation front.

3.2.2. Effects of vegetation density

Increased vegetation density necessitates more aggressive deployment of holding lines. As shown in Figs. 4(a) and 4(b), in sparsely vegetated land, the deployment of a single temporary holding line is able to extinguish the forest fire. This is because the propagation of fire is slow in sparse vegetation, and hotspots at any point in time are likely to be localized and small. The forest fire is hence easily controllable with water-bombing. However, in more densely vegetated land, a single temporary holding line is no longer able to effectively suppress the forest fire. With normal vegetation density, as shown in Figs. 4(c) and 4(d), the forest fire is able to spread to the flank of the holding line and create a smaller fire. The greater speed of fire propagation necessitates the deployment of longer holding lines, or a combination of holding lines to envelope the fire effectively. This problem is even more prominent in densely vegetated lands, as shown in Figs. 4(e) and 4(f), in which the forest fire flanks the holding line completely. It is seen that isolated temporary holding lines are only effective for fire control in sparse vegetation, and more aggressive deployment becomes necessary when vegetation density increases.

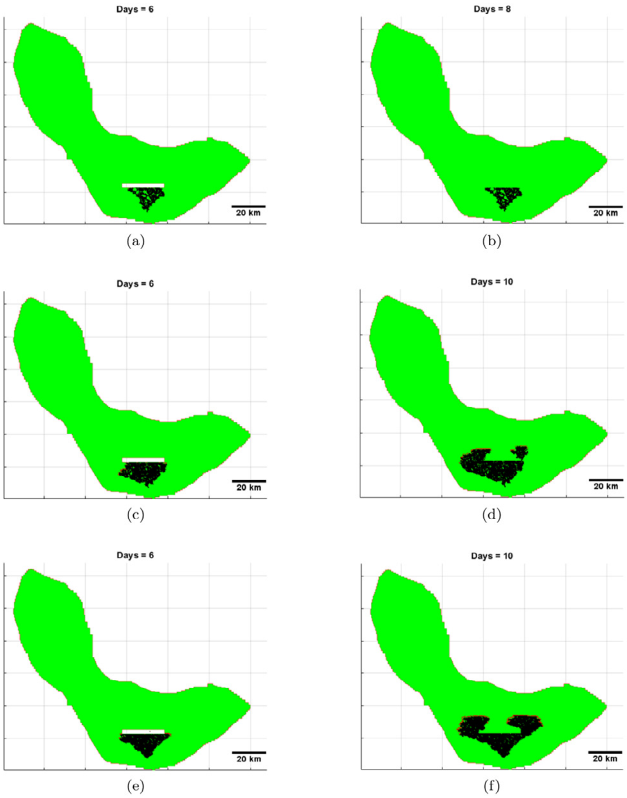


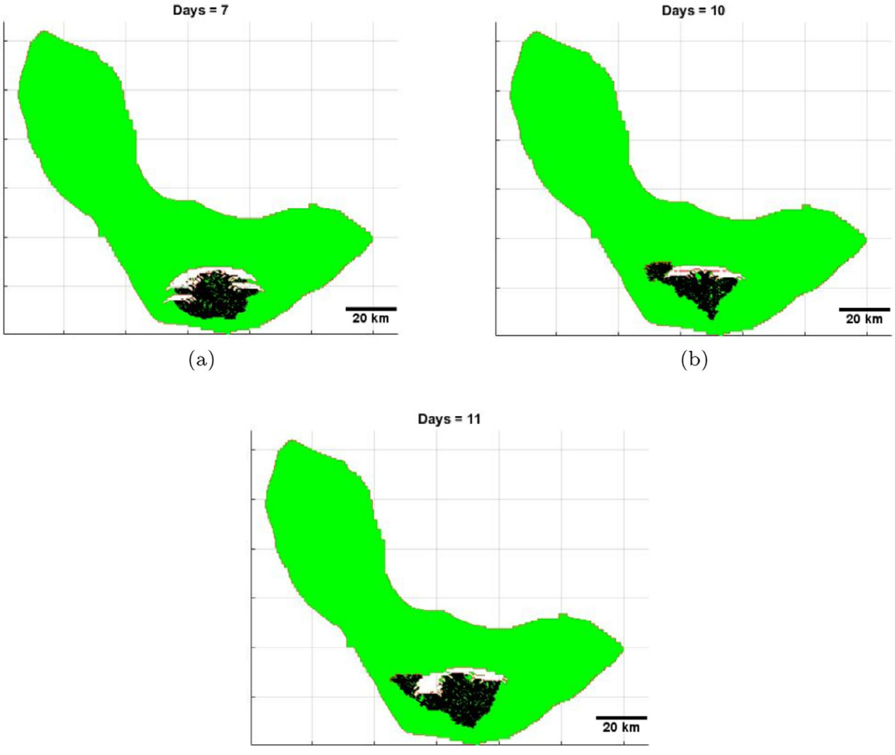
Fig. 4. (a) Temporary holding line placed over a forest fire in a sparsely vegetated land, and (b) the resulting state of the forest fire 2 days later. Fire is put out. (c) Temporary holding line placed over a forest fire with normal vegetation density, and (d) the resulting state of the forest fire more than 2 days later. A smaller fire (red) continues to spread. (e) Temporary holding line placed over a forest fire with dense vegetation, and (f) the resulting state of the forest fire more than 2 days later. A large forest fire continues to propagate. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2.3. Optimal location for constructed firelines

Constructed fire lines to be approximately 1–2 km from fire propagation front. In Fig. 5(a), fire control lines were simulated to have been constructed on Day 6, approximately 1.25 km away from the fire propagation front. The lines were arranged such that they envelope the propagation front, but small gaps are occasionally left between adjacent lines, as it is not always possible to completely join control lines in the real-world (due to topography, such as boulders and cliffs, or limitations in manpower and machinery). The fires were found to have stopped after reaching the control lines, and then eventually extinguished due to fuel depletion. In Fig. 5(b), the control lines were instead constructed 2.5 km away from the fire. As can be observed, the fire largely stopped after reaching the control lines, but a portion continued spreading through the small gaps. In Fig. 5(c), the control lines were constructed farther at 3.75 km from the propagation front, and again penetration past the small gaps between lines can be seen. The deterioration of the effectiveness of fire lines observed here stems from the larger perimeter necessary at larger separation distances—a larger number of fire lines have to be constructed to surround the fire, and therefore a larger number of gaps will inevitably be present. It is hence observed that the distance between constructed fire lines and the fire propagation front should be reduced; but as discussed, due to time and logistical requirements, the minimum viable distance is typically at least 1 km.

3.3. Model performance and limitations

The simulation results indicate that the model is successful in predicting the evolution of the Dumai forest fire, and subsequent analyses have also suggested guidelines for the effective deployment of fire-fighting strategies in various situations. This reflects practical value in the CA-based simulation framework. There are, nonetheless, limitations in the current approach. Firstly, inherent in the current CA approach is an assumption that fire can only propagate from a given cell towards its eight neighbours and not in any intermediate direction, or to non-adjacent cells—this is a reasonable heuristic in typical circumstances, but may not always hold when, for instance, strong winds transport burning material to other sites (as noted in Section 3.1). Secondly, large-scale forest fires can interact with climate systems. For instance, the combustion heat can cause strong updrafts and generate local air circulation cells, and fire activity will also depend on local oxygen density and air humidity. To completely account for such effects, an atmospheric simulation must be coupled to the fire propagation model, yielding increased accuracy but at huge expense of computational cost [35]. The current decoupled approach is computationally cheap in comparison. Lastly, high-resolution data on topographical and



(a) (b) (c)

Fig. 5. Resulting forest fire states after the deployment of constructed fire lines, placed approximately (a) 1.25 km, (b) 2.50 km, and (c) 3.75 km away from the fire on a densely vegetated land.

vegetation features [36] will also enhance simulation robustness. For instance, local streams can be exploited as natural fire lines in fire-fighting maneuvers. The rule-based nature of the current cellular automaton approach enables such types of environmental data to be incorporated easily, for instance as modifiers to the propagation probabilities.

4. Conclusion

We have developed a cellular automaton-based model for fire propagation, taking into account ambient wind, vegetation type, and vegetation density parameters. The model was applied to the March 2014 Dumai forest fire, and was found to be satisfactorily accurate in predicting the evolution of the fire over the 14-day period. Our model was validated by similar observations of real-world phenomena. Analyses on the factors that affect the spread of fire are presented, in order to understand which ones are dominant in differing situations.

Through a series of simulation analyses, we subsequently explored the deployment of large-scale fire-fighting strategies, in particular the creation of temporary holding lines through water-bombing and construction of fire lines, in situations of differing environmental parameters. We found through the simulations that in the later stages of fire propagation, the effectiveness of fire lines deteriorats for fires that span a larger lateral distance. Fire control lines placed too far from the fire source allows the fire to spread laterally; this then allows the fire to penetrate through the control lines. Our simulations suggest that the distance between constructed fire lines and the fire propagation front should be reduced, to typically 1 km up to 2 km. This gives ample time for the logistical requirements for the construction of fire control lines to be in place. The results of this study provide preliminary perspectives in understanding the spread of forest fires, and the effectiveness of firefighting measures. The proposed cellular approach can be used as a basis for the development of future fire spread models, or to aid in enhancing fire-fighting measures in future forest fires. In particular, the ability to computationally predict the propagation of fire given initial data from observations will enable the in-advance optimization of fire-fighting efforts, and can allow more effective suppression of fire activity with available resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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