Research Article
doi: 10.1590/01047760202127012932
vol(27), 2021

CERNE

Study on Forest Fire spread Model of Multi-dimensional Cellular Automata based on Rothermel Speed Formula

Shiyu Zhang[1iD], Jiuqing Liu[1], Hewei Gao[1], Xiandong Chen[1], Xingdong Li[1✤iD] and Jun Hua[1]

[1] Northeast Forestry University, Habin, P.R. China

FOREST MANAGEMENT

ABSTRACT

Background: The spread of forest fire is a complex natural phenomenon. The cellular automata(CA) is a common model of forest fire spread, which fails to combine the unique combustion properties of forest fire spreading, resulting in inaccurate simulation results. In order to improve the accuracy of forest fire spread simulation, the Rothermel forest fire rate formula is simplified and combined with CA to form a multi-dimensional cellular automata(MD-CA) model of forest fire spread with different combustion properties in each cell. The formulas of the spread rate of forest fire in eight directions are obtained through the training datasets, and the testing datasets are used to compare the simulation results of CA model, MD-CA model and the actual fire spread.

Results: It is concluded that the simulated areas and perimeters of the MD-CA are closer to the actual forest fire spread, the area error rate is 9.42% - 15.63%, and the perimeter error is 4.21% - 8.99%, The errors are less than CA model.

Conclusion: The MD-CA model based on Rothermel has the strong ability to simulate the spread of fire in the laboratory, however, how to eliminate the errors over time is the task of the next stage.

Keywords: Rothermel, cellular automata, forest fire spread, fire contour area and perimeter, error rate

HIGHLIGHTS

The complex Rothermel formula is simplified to better adapt to cellular automata.
The forest fire spread model of multi-dimensional cellular automata combines slope, moisture content, wind speed and other factors.
Multi-dimensional cellular automata has a better effect of spreading simulation.
It provides a new method for the development of forest fire spread model.

ZHANG, S.; LIU, J.; GAO, H.; CHEN, X.; LI, X.; HUA, J. Study on Forest Fire spread Model of Multi-dimensional Cellular Automata based on Rothermel Speed Formula. CERNE, v. 27, e-102932, doi: 10.1590/01047760202127012932

✤Corresponding author e-mail: lixd@nefu.edu.cn
Received: 23/04/2021 Accepted: 23/07/2021

CERNE
ISSN 0104-7760
UNIVERSIDADE FEDERAL DE LAVRAS

INTRODUCTION

Forest fire is a very serious natural disaster, which not only destroys human living environment, but also endangers human life and health. In order to reduce unnecessary loss of life and property, scholars all over the world are trying their best to study the mechanism of forest fire spread, combining artificial intelligence to build forest fire spread model and forest fire prediction model, so as to grasp the trend of forest fire in time. These can provide forest firefighters with the necessary technical support, reduce the loss of life and property, and respond to the slogan of intelligent forestry. Therefore, it is necessary to study the forest fire spread model to solve the thorny problem of low prediction accuracy of the existing models.

The self-organization of cellular automata is similar to the spread of forest fire (Wang et al. 2013; Zhang et al. 2012), researchers have proposed a variety of improved models based on cellular automata to study the spread of forest fire. The standard CA consists of cellular space, cellular state, and cellular local transition rules (Ntinas et al. 2017; Alexandridis et al. 2011). The CA is a dynamic model that evolves on the discrete time dimension according to certain local transition rules, which is usually defined in the cellular space composed of discrete and finite state cells, and simulates the global evolution through the evolution of local transition rules (Collin et al. 2011; Sun et al. 2013; Russo et al. 2014). Therefore, the CA is suitable for the transmission of forest fire spread. In the standard CA forest fire spread model, the cell only contains the combustion properties of simple combustible factors such as fuel moisture content, excluding the influence factors of wind speed and slope, so the simulation effect is not good (Mandel et al. 2014; Filippi et al. 2014). Zhou et al. (2018) proposed a CA forest fire spread algorithm model based on multi-agent. Based on the local transition rules of CA, combined with the self-learning habit of multi-agent algorithm, this algorithm improves the prediction accuracy of the model. The simulation results show that the actual forest fire spread process is similar to the spread process of the multi-agent cellular automata model proposed in this paper. Zhou et al. (2017) proposed a CA forest fire spread model combined with multi-objective genetic algorithm in another article, the simulation results show that the spread process of the model is similar to the actual forest fire spread. Ghisu T. (2015) reduces the problem of fire shape distortion by redefining the propagation velocity of fire and modifies the parameters in the vector equation of fire propagation velocity by numerical optimization. The results compared with the two CA simulators in other literatures show that the proposed method provides better results in terms of accuracy. Zheng et al. (2017) aims at the complex local transition rules in the simulation of fire spread by traditional cellular automata, a new algorithm using extreme learning machine instead of CA is proposed. The results show that the extreme learning machine has a good ability to predict the ignition probability of each cell, and the simulation data show that this method can effectively describe the influence of wind speed on the law of fire spread. However, only the spreading effect of flat slope is considered in this paper. Tiziano (2015) combined Rothermel and ellipse aspect ratio to calculate the spread speed in any direction, based on this speed and CA, the spread contour and area are obtained. The simulation experiments show that the algorithm proposed in this paper has good performance in computing time and accuracy, however the paper can not evaluate the performance of this algorithm in actual fire.

In summary, the speed of fire spread in various directions at the process of forest fire spread is different. The models of scholars can predict the spread process of forest fire under the influence of different wind speed. However, there are more factors need considering, for example, the slope and combustible factors also take into account the influence of fire speed in various directions. Therefore, this paper creates a fire spread model based on the actual fire spread data, compares the fire spread process under the influence of multiple factors with the simulation results to verify the prediction ability of the model.

MATERIAL AND METHODS

As shown in Fig. 1, each layer contains M*N cells, and each layer is the influence factor of forest fire spread, such as the fuel factor, the wind direction wind speed factor and the combustion bed inclination factor. The cells of multiple dimensions on the same vertical plane belong to the same cell, and these factors are the input of Rothermel forest fire speed formula. The state between the cells can be realized by the local transition rules, the field of cellular automata is divided into Moore and Neimann according to the shape (Lautenberger et al. 2013), the Moore studies the influence of the upper and lower left and right fields on the central domain, so it can better realize the spread of forest fire. The next state of a cell is determined by the spread speed of adjacent cells and the state at this time. The speed can be calculated by simplified Rothermel fire spread formula. Next, the forest fire spread mode of MD-CA will be described from three parts: the state of the MD-CA, the local transition rules of MD-CA, the simplified Rotherme speed formula and the data and pre-processing.

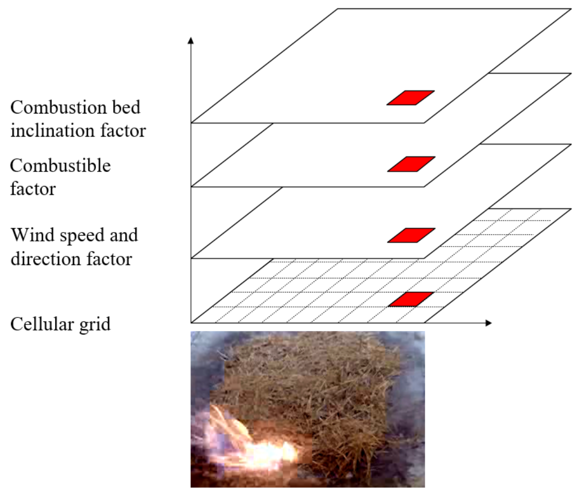

Fig. 1 Forest fire spread model of multi-dimensional CA.

The state of MD-CA

As shown in the Formula (1), The state value can be determined according to the ratio of the burning area to the cell area, and the state value can be divided into three types: state 1(A_{ij}^t=0) is combustible, but has not been ignited, state 2(0<A_{ij}^t<1) is burning and not fully burned, and state 3(A_{ij}^t $ 1) is that the fuel has been burned, which can't be ignited and burned. If the state of the cell is 1, the next time is state 2. If the state of the cell is 2, the state of the cell at the next moment is 3, which means that the existing fuel has been burnt out and can no longer be ignited and burned. The state of a cell at t time is defined as:

$$A_{ij}^t = \frac{S_{Burning\,area}}{S_{Cell\,area}} \quad [1]$$

The local transition rules of MD-CA

As shown in Fig. 2 and Formula (2), the burning state of the central cell at the t+Δt is determined by the state of the domain cell at the time t and the spreading speed of the domain cell, where R is the forest fire spread speed, and its value is the Rothermel forest fire speed formula, which will be discussed in the section of "The simplified Rotherme".

$$A_{ij}^{t+\Delta t} = A_{ij}^t + f(R_{1\to5}^t, R_{2\to5}^t, R_{3\to5}^t, R_{4\to5}^t, R_{6\to5}^t, R_{7\to5}^t, R_{8\to5}^t, R_{9\to5}^t) \quad [2]$$

The state of the central cell at the time t+Δt can be calculated by the formula (3). As shown in Fig. 3 and Formula(3), the eight cells around the central cell are divided into 2, 4, 6, 8 domain cells and 1, 3, 7, 9 sub-domain cells. Due to the position of domain cells and sub-domain cells relative to the central cell, they are not the same, so the local transition rules are different and need to be discussed separately. Firstly, for the 2,4,6,8 domain cells, take the cell 2(i−1,j) as an example, the speed of cell 2(i−1,j) spreading to cell 5(i,j) is $R_{(2\to5)}$, the time is Δt, the side length of the

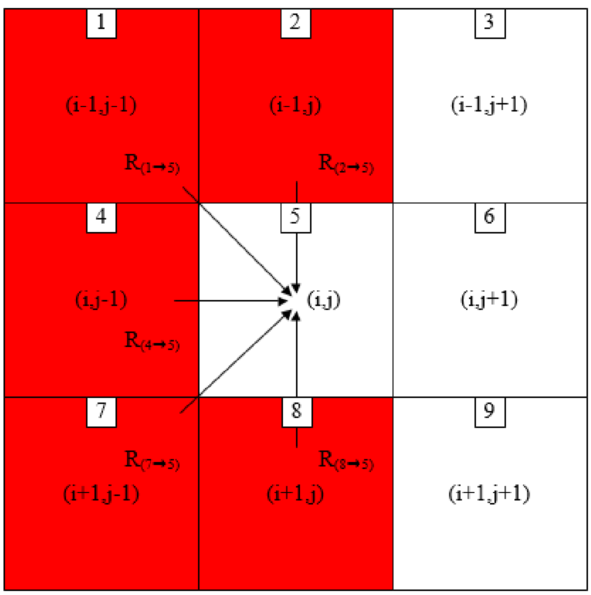

Fig. 2 The relationship between central cell and domain cell.

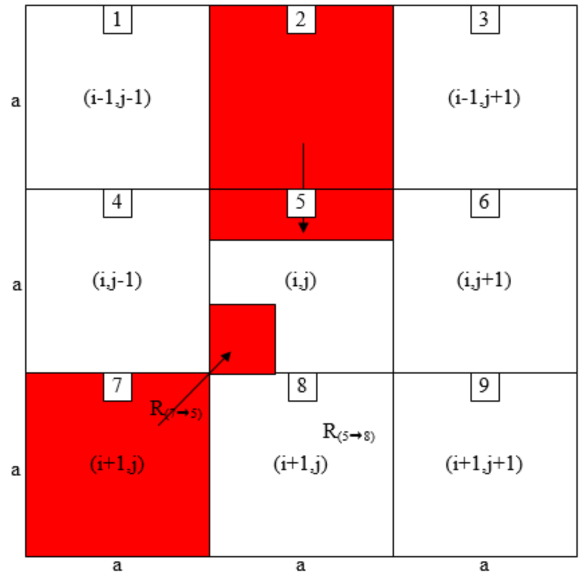

Fig. 3 The influence of domain cell and sub-domain cell on the central cell

cell is "a", the burning area of the cell S= $R_{(2\to5)}$Δta can be calculated, and then the burning area ratio is $\frac{R_{(2\to5)}\Delta t}{a}$. Similarly, the burning area and burning area ratio of the cells in the other three domains 4,6,8 can be obtained. Secondly, for the 1,3,7,9 sub-domain cells, take the cell 7(i−1,j−1) as an example, the speed of cell 7(i-1,j-1) spreading to cell 5(i,j) is $R_{(7\to5)}$, the time is Δt, the side length of the cell is "a", the burning area of the cell $S = \frac{(R_{(7\to5)}\Delta t)^2}{2}$ can be calculated, and then the burning area ratio is $\frac{(R_{(7\to5)}\Delta t)^2}{2a^2}$. Similarly, the burning area and burning area ratio of the cells in the other three sun-domains 1,3,9 can be obtained.

It is concluded that the local transition rules of domain cell 1(i-1,j-1)、3(i-1,j+1)、7(i+1,j)、9(i+1,j+1)、2(i-1,j)、4(i,j-1)、6(i,j+1)、8(i+1,j) around central cell 5 (i, j) are obtained, where is the cellular state of the cell at the t time. Only when the state value of the cell is greater than or equal to 1, the cell is completely burned, and the cell has the ability to spread to the surrounding eight cells, otherwise the cell does not have the ability to spread. Where Δt is 1 second, the "a" is the side length of a single cell, according to the total numbers of the cells and the total areas of the combustion bed, it is concluded that the side length of "a" single treasure is 0.02m, and R is the speed of eight directions forest fire spread, which will be discussed in next section.

$$A_{i,j}^{t+\Delta t} = A_{i,j}^t + \frac{(R_{2\to5}^t, R_{4\to5}^t, R_{6\to5}^t, R_{8\to5}^t)\,\Delta t}{a} + \frac{[(R_{1\to5}^t)^2, (R_{3\to5}^t)^2, (R_{7\to5}^t)^2, (R_{9\to5}^t)^2]\Delta t}{\sqrt{2}\,a^2} \quad [3]$$

The simplified Rotherme speed formula

At present, common forest fire spread models include Rothermel spread model, Wang Zhengfei spread model and McArthur spread model (Brun et al. 2014). Rothermel forest fire spread is known by researchers as a semi-empirical forest fire spread model (Denham et al. 2012; Plucinski et al. 2013), such as formulas (4)-(11) are Rothermel speed formula, where I_R is the reaction intensity, ξ is the spread rate, Φ_w is the wind speed correction coefficient, Φ_s is the slope correction coefficient, P_b is the drying particle density, ε is the effective heat coefficient, and Q_{ig} is the pre-combustion heat. The Rothermel speed formula is a semi-empirical model, some parameters in the model can only be obtained by experiments. Moreover, the model needs to input 11 parameters, and there is a nesting relationship between the parameters, from which we can see the complexity of the model. Therefore, the Rothermel forest fire speed formula needs to be simplified. Bring formula (5)-(11) into formula 4, the expansion of Rothermel speed formula can be obtained (12-13).

$$R = \frac{I_R \xi (1 + U_w + U_s)}{P_b \varepsilon Q_{ig}} \qquad [4]$$

$$I_R = (0.0591 + 2.926\sigma^{-1.5})^{-1} (\beta/\beta_{op})^{8.9033\sigma^{-0.7913}} \exp\left[8.9033\sigma^{-0.7913}(1-\beta/\beta_{op})\right][W_0(1-S_T)] \; h\left[1 - 2.59\frac{Mf}{Mx} + 5.11\left(\frac{Mf}{Mx}\right)^2 - 3.52\left(\frac{Mf}{Mx}\right)^3\right](0.174 S_E^{-0.19}) \qquad [5]$$

$$\zeta = (192 + 7.9095\sigma)^{-1} \exp\left[(0.792 + 3.7597\sigma^{0.5})(\beta + 0.1)\right] \qquad [6]$$

$$\Phi_w = 7.47 exp(-0.8711\sigma^{0.55})(3.281U)^{0.15988\sigma^{0.55}} \left(\frac{\beta}{\beta_{op}}\right)^{-0.751 exp(-0.01094\sigma)} \qquad [7]$$

$$U_s = 5.275 b^{-0.3} (\tan U)^2 \qquad [8]$$

$$P_b = W_0/d \qquad [9]$$

$$f = exp(-0.5428/v) \qquad [10]$$

$$Q_{ig} = 581 + 2594 M_f \qquad [11]$$

$$R = \frac{(0.0591 + 2.926\sigma^{-1.5})^{-1} (\frac{\beta}{\beta_{op}})^{8.9033\sigma^{-0.7913}} \exp[8.9033\sigma^{-0.7913}(1 - \frac{\beta}{\beta_{op}})] W_0 (1 - S_T) h \, [1 - 2.59(\frac{Mf}{Mx}) + 5.11(\frac{Mf}{Mx})2 - 3.52(\frac{Mf}{Mx})](0.174 S_E^{-0.19})(192 + 7.9095\sigma)^{-1} \exp[(0.792 + 3.7597\sigma^{0.5})(\beta + 0.1)] \, [1 + 7.47\exp(-0.8711\sigma^{0.55})](3.281U)^{0.1598\sigma^{0.55}} (\frac{\beta}{\beta_{op}})^{-0.751\exp(-0.01.94\sigma)} + 5.275\beta^{-0.3}(\tan\phi)^2]}{\frac{W_0}{\delta}\exp(-0.5428/\sigma)(581 + 2594Mf)} \qquad [12]$$

$$R = h \cdot (1 - S_T)\delta(0.174 S_E^{-0.19})[(0.0591 + 2.926\sigma^{-1.5})^{-1} \cdot (192 + 7.9095\sigma)^{-1} (\frac{\beta}{\beta_{op}})^{8.9033\sigma^{-0.7913}}] \exp[8.9033\sigma^{-0.7913} \cdot (1 - \frac{\beta}{\beta_{op}}) + (0.792 + 3.7597\sigma^{0.5})(\beta + 0.1) + \frac{0.5428}{\sigma}] \, [1 + 1.747\exp(-0.8711\sigma^{0.55})(3.281U)^{0.1598\sigma^{0.55}} (\frac{\beta}{\beta op})^{-0.751\exp(-0.01094\sigma)} + 5.275\beta^{-0.3}(\tan\phi)^2] \, [\frac{1 - 2.59\frac{Mf}{Mx} + 5.11(\frac{Mf}{Mx})^2 - 3.52(\frac{Mf}{Mx})^3}{581 + 2954Mf}] \qquad [13]$$

For combustibles of the same material, surface area to volume ratio , low heat content h, total mineral content S_T, effective mineral content S_E are all fixed values. compression ratio $\beta = \frac{P_b}{P_p} = \frac{W_0}{\delta P_p}$, The density of dried particles P_b is also constant for the same kind of combustibles, and $\beta_{op} = 0.20395\sigma^{-0.8189}$, The formula (13) can still be simplified to (14).

$$R = B\bar{\sigma}\left(K\frac{W_0}{\sigma}\right)^C \exp\left[C \cdot \left(1 - \frac{W_0}{\sigma}\right) + E\left(K\frac{W_0}{\sigma} + 0.1\right) f(m)\right] \cdot \left[1 + GU^H\left(K\frac{W_0}{\sigma}\right) I + J\left(\frac{W_0}{\sigma}\right)^{-0.3} (\tan\Phi)^2\right] \qquad [14]$$

$$B = h \cdot (1 - S_T)(0.174 S_E^{-0.19})[(0.0591 + 2.926\sigma^{-1.5})^{-1} \cdot (192 + 7.9095\sigma)^{-1}] \qquad [15]$$

$$C = 8.9033 v^{-0.7913} \qquad [16]$$

$$E = 0.792 + 3.7597 v^{0.5} \qquad [17]$$

$$f(m) = \frac{1 - 2.59\frac{Mf}{Mx} + 5.11(\frac{Mf}{Mx})^2 - 3.52(\frac{Mf}{Mx})^3}{581 + 2954Mf} \qquad [18]$$

$$G = 1.747 exp(-0.8711 v^{0.55}) \# (3.281^{0.1598 v^{0.55}}) \qquad [19]$$

$$H = 0.1598 v^{0.55} \qquad [20]$$

$$I = -0.751 exp(-0.01094 v) \qquad [21]$$

$$J = 5.275 P_b^{-0.3} \qquad [22]$$

$$K = \frac{1}{P_b(0.20359 v^{-0.8198})} \qquad [23]$$

In the simplified Rothermel forest fire speed formula, R is the speed of forest fire spread, B, C, E, G, H, I, J and K are the parameters to be estimated respectively. The combustible bed thickness δ, drying combustible load W_0, middle flame wind speed U, slope Φ, combustible moisture content Mf, combustible extinguishing moisture content Mx, f (m) are functions containing Mf and Mx, which are all independent variables (Pérez et al. 2011). Therefore, the model includes combustible factors such as combustible bed thickness, fuel load, fuel moisture content, combustion bed slope factor, wind direction factor that affect the trend of fire spread. The multi-dimensional and multi-factor framework makes the empirical equation and cellular automata skillfully combine to form a forest fire spread model. This multi-dimensional framework makes Rothermel empirical equations and cellular automata better integrated, making the abstract spreading model concrete, thereby improving the understanding of fire behavior.

Data and pre-processing

In the MD-CA model, the changes of combustible factor, slope factor, wind speed factor and fire spread speed with fire spread need to be measured, so the experiment is carried out, and the local transition rules of MD-CA are obtained by the data.

In this experiment, we set up a forest fire spreading bed in the laboratory (Maoershan Forest Fire Laboratory of Northeast Forestry University, Harbin, Heilongjiang Province, N45 °20'~ 45 °25 °, E127 °30 °127 °34') to explore the relationship between independent variables such as wind speed, moisture content, slope, fuel load, combustible bed thickness and fire spread wind speed. The experiment was conducted from October 23 to November 20, 2019. The combustion bed is 1.0 to 1.5m. The moisture content of combustibles is the difference of mass between fresh combustible and dry combustible divided by fresh combustible, in which dry combustible is drying in the oven for 30 hours, and the fresh combustible is naturally regained. The wind speed in the middle of the flame is measured by the hand-held anemometer to follow the flame spread, the wind speed is measured by anemometer and the wind direction is changed by the angle between the fan and the combustion bed. The thickness of the bed is determined by measuring the average thickness of the combustible bed in many places. The bed inclination of the combustion bed is measured by the level meter. The type of combustible is Pinus sylvestris var. mongolica, the inclination angle of the combustion bed is 8 °, and the bed thickness is set between 0.04 m and 0.08 m. According to the grid shape and local transition rules of CA, the angle between the direction of wind and the direction of fire spread is divided into five cases, that is, the direction of wind and spread are 0 °, 45 °, 90 °, 135 °and 180 °respectively.

We did 17 spot burning tests, recorded the data, and divided the data into 90% of the training datasets and 10% of the testing dataset. The training datasets are used to obtain the values of the parameters (B, C, E, G, H, I, J, K), as a result, the model of multi-dimensional cellular automata is obtained. The testing datasets are used to verify the accuracy of the multi-dimensional cellular automata model. The training datasets are shown in the Tab. 1, the testing

Tab. 1 The training datesets.

Num	Mass (kg)	Area (m^2)	Load capacity ($kg.m^{-2}$)	Bed thickness (m)	Slope direction/ inclination	Moisture content	Angle between wind direction and spread direction
1	0.69	0.8*0.6	1.44	0.05	Up/8°	5.24%	0°
2	0.62	0.8*0.6	1.29	0.04	Up /8°	6.14%	45°
3	0.83	0.8*0.6	1.73	0.07	Up /8°	7.00%	90°
4	0.91	0.8*0.6	1.90	0.07	Up /8°	8.37%	135°
5	0.63	0.8*0.6	1.31	0.06	Up /8°	8.37%	180°
6	0.93	0.8*0.6	1.93	0.07	Down/8°	8.92%	0°
7	0.53	0.8*0.6	1.10	0.05	Down/8°	8.92%	45°
8	0.55	0.8*0.6	1.14	0.05	Down/8°	8.81%	90°
9	1.09	0.8*0.6	2.26	0.08	Down/8°	6.49%	135°
10	0.73	0.8*0.6	1.52	0.05	Down/8°	8.81%	180°
11	1.01	0.8*0.6	2.10	0.08	Flat/0°	5.24%	0°
12	0.79	0.8*0.6	1.65	0.04	Flat /0°	6.14%	45°
13	0.92	0.8*0.6	1.92	0.07	Flat /0°	6.45%	90°
14	0.80	0.8*0.6	1.67	0.05	Flat /0°	5.10%	135°
15	0.98	0.8*0.6	2.05	0.07	Flat /0°	5.10%	180°

datasets are shown in the Tab. 2. In the process of fire spread, there will be changes in uphill and downhill, as well as downwind and headwind changes, so these factors are added to a fire spread test. The combustible bed is divided into two stages, in the testing dataset 1, the first stage is flat slope, the second stage is uphill, the wind direction is downwind, and the slope is 8 °, in the testing dataset 2, the first stage is uphill, the second stage is downhill, the wind direction is headwind, and the slope is 8 °.

The indoor burning experiments are carried out respectively, the infrared camera and visible light camera are used in the laboratory to monitor the fire, the position of the fire line is extracted by using the principle of perspective transformation, and the spread speed of the fire line is calculated. The Levenberg-Marquardt (LM) algorithm is used to solve the nonlinear equation, and the values of the parameters to be estimated are shown in Tab. 3. With the determination of the above parameters, the spread speed of the cells in eight directions at a certain time are known, and calculate the burning area ratio of the cell through each time step, so as to the state of the cell is judged and then the spread state of the fire is simulated.

RESULTS AND DISCUSSION

In this paper, by comparing the simulation result of CA, MD-CA and actual fire spread, the accuracy of the model is obtained from the contour area, perimeter and error rate. Fig. 4 and 5 are obtained by testing dataset 1, and Fig. 6 and 7 are obtained by testing dataset 2.

Tab. 2 The tesing datesets.

Num	Slope direction/ inclination	Wind direction	Surface area of the first stage (m^2)	Surface area of the second stage(m^2)	Load capacity ($kg.m^{-2}$)	Bed thickness (m)	Moisture content
1	Flat-Up/8°	Downwind	0.8*0.5	0.8*0.5	2.28	0.05	7.68%
2	Up-Down/8°	Headwind	0.8*0.5	0.8*0.5	1.82	0.05	5.38%

Tab. 3 The parameters to be estimated in different directions.

Slope direction/inclination	Angle between wind direction and spread direction	B	C	E	G	H	I	J	K
Up/8°	0°	34.06	8.20	-21.18	7207	0.192	6520	434656	0.01
Up /8°	45°	32.14	8.67	-20.08	7020	0.215	6014	424532	0.01
Up /8°	90°	36.34	8.90	-28.77	7819	0.216	6732	420410	0.01
Up /8°	135°	33.11	8.61	-20.84	7863	0.205	6240	474322	0.01
Up /8°	180°	31.75	8.23	-24.19	7014	0.230	6241	417772	0.02
Down/8°	0°	32.89	8.65	-29.77	7426	0.238	6127	415210	0.03
Down/8°	45°	31.17	8.64	-25.12	7262	0.258	6002	414984	0.04
Down/8°	90°	36.74	8.78	-23.99	7102	0.212	6011	431741	0.03
Down/8°	135°	31.03	8.87	-23.45	7017	0.210	6280	435599	0.03
Down/8°	180°	34.99	8.86	-23.92	7105	0.282	6072	420795	0.01
Flat/0°	0°	30.41	8.17	-24.76	7001	0.247	6046	-	0.01
Flat/0°	45°	34.14	8.56	-24.63	7124	0.222	6009	-	0.02
Flat/0°	90°	30.06	8.17	-20.54	7418	0.200	6291	-	0.02
Flat/0°	135°	34.84	8.46	-21.89	7012	0.209	6031	-	0.01
Flat/0°	180°	37.54	8.85	-21.68	7004	0.237	6008	-	0.01

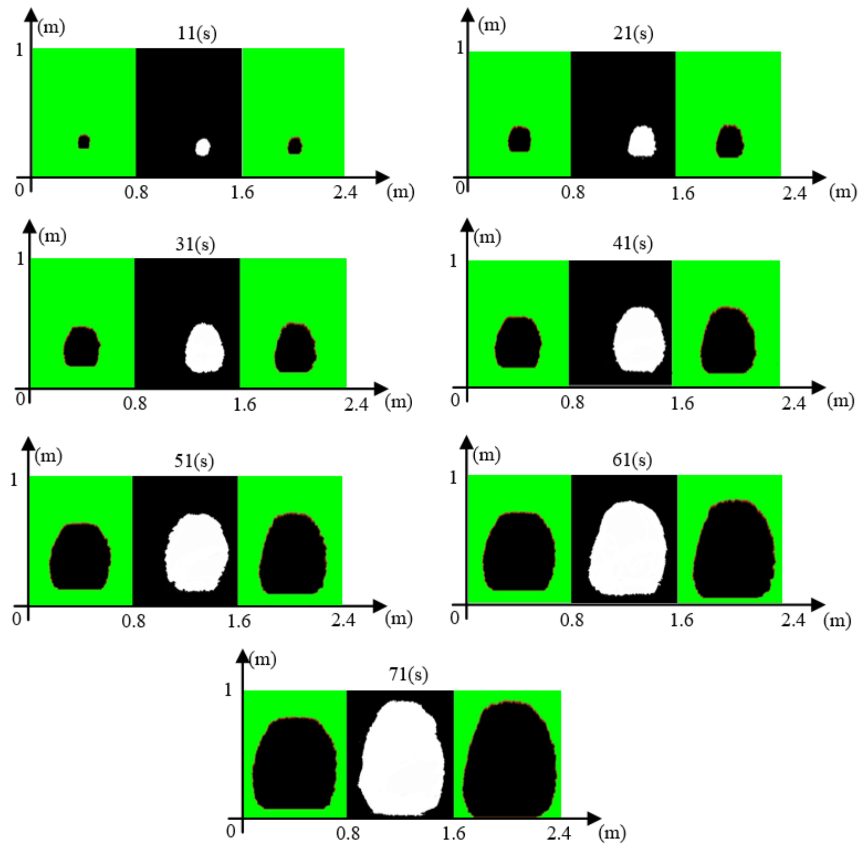

Fig. 4 The comparison between simulate restult of cellular automata, actual fire spread and simulate restult of Multi-dimensional Cellular Automata with time in tesing dateset 1.

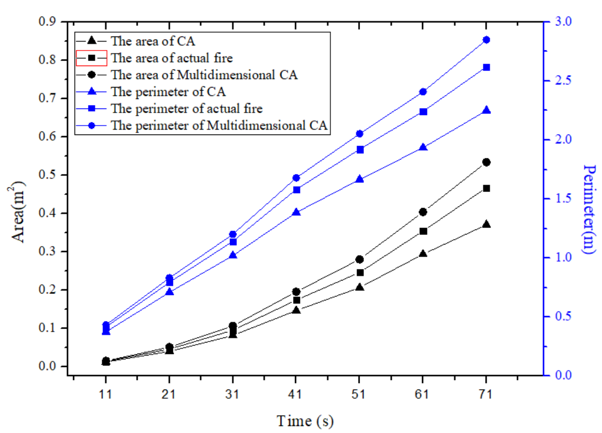

Fig. 5 The comparison between simulate restult of cellular automata, actual fire spread and simulate restult of Multi-dimensional Cellular Automata with time in tesing dateset 1.

As shown in Fig. 4 and 6, in each group, the left side is the simulation result of CA, the middle is the actual fire spread, the right side is the simulation result of MD-CA. the ordinate is 1m for the length of the combustion bed, and the abscissa 0.8m is for the width of the combustion bed. As shown in the Fig. 5 and Fig. 7, the area and perimeter of the CA spreading simulation, actual fire spreading and MD-CA spreading simulation are broken line graphs with time, the time of testing dataset 1 is 71 s, and the testing dataset 2 is 81 s. It can be seen from the figures that MD-CA has better simulation effect. However, the MD-CA is larger than the actual data, because the combustible mixture of the real fire is mixed with a certain amount of sand and soil particles that hinder the spread of the fire, and the combustibles in the model simulation are absolutely pure combustibles, so the spread data will be larger than the real data.

As shown in Tab. 4, it is the error rate of CA and MD-CA. In testing dataset 1, the maximum area error rate of cellular automata simulation is 20.64%, the minimum error rate is 11.18%, and the average error is 15.37%. The maximum perimeter error of the CA simulation is 14.14%, the minimum error is 9.99%, and the average error is 12.09%. The maximum area error rate of the MD-CA simulation is 14.33%, the minimum error rate is 9.42%, the average error is 12.55%, the maximum perimeter error of the simulation is 8.47%, the minimum error is 4.21%, and the average error is 6.20%. In testing dataset 2, the maximum area error rate of cellular automata simulation is 21.17%, the minimum error rate is 11.36%, the average error is 15.80%, the maximum perimeter error of simulation is 15.20%, the minimum error is 10.59%, and the average error is 13.01%. The maximum area error rate of the MD-CA simulation is 15.63%, the minimum error rate is 10.27%, the average error is 13.12%, the maximum perimeter error of the MD-CA simulation is 8.99%, the minimum error is 5.14%, and the average error is 4.15%.

CONCLUSION

In this paper, it is found that the CA can not describe the important influence factors such as the slope, the wind

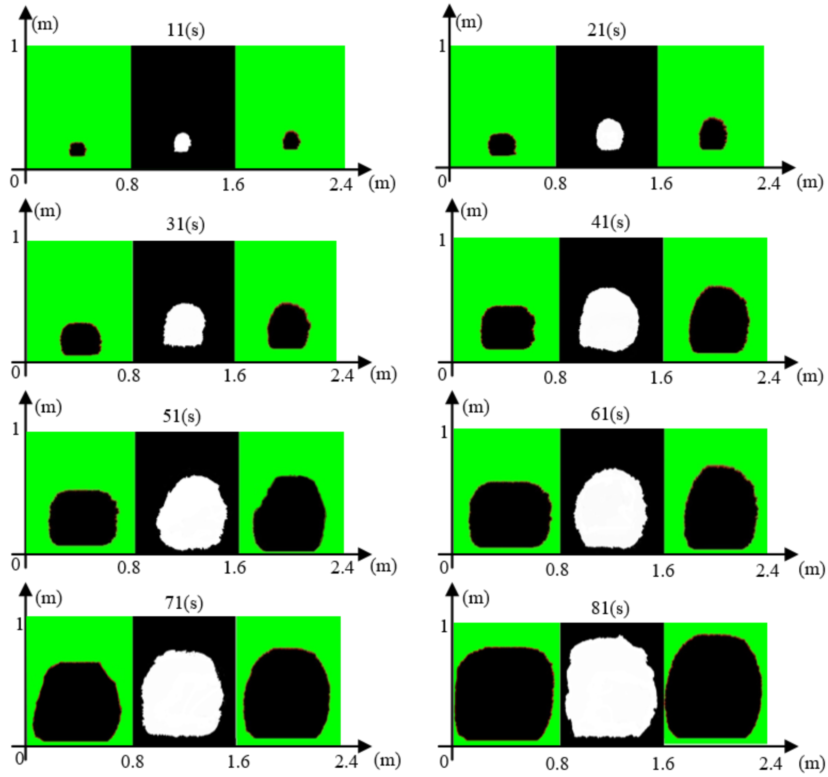

Fig. 6 The comparison between simulate restult of cellular automata, actual fire spread and simulate restult of Multi-dimensional Cellular Automata with time in tesing dateset 2.

Tab. 4 The error analysis of area and perimeter in the tesing dateset 1 and 2

Time	Tesing dataset 1				Tesing dataset 2			
	CA		Multi-dimensional CA		CA		Multi-dimensional CA	
	Area	Perimeter	Area	Perimeter	Area	Perimeter	Area	Perimeter
11	11.18%	9.99%	9.42%	4.21%	11.36%	10.59%	10.27%	5.14%
21	12.69%	10.54%	11.64%	4.74%	12.24%	11.07%	11.85%	5.98%
31	14.12%	10.65%	12.04%	5.22%	13.73%	12.29%	12.07%	6.49%
41	15.80%	12.36%	12.41%	6.22%	14.83%	12.76%	12.21%	6.94%
51	16.05%	13.29%	13.97%	6.81%	16.09%	13.23%	13.42%	7.35%
61	17.08%	13.68%	14.06%	7.44%	17.80%	14.19%	14.33%	8.09%
71	20.64%	14.14%	14.33%	8.74%	19.21%	14.80%	15.16%	8.25%
81	—	—	—	—	21.17%	15.20%	15.63%	8.99%
Average	15.37%	12.09%	12.55%	6.20%	15.80%	13.01%	13.12%	7.15%

speed and the middle of the flame in the fire spread, which leads to the inaccuracy of the simulation results. Therefore, the MD-CA forest fire model is established by combining the CA with Rothermel forest fire speed formula, and the important factors affecting fire spread, such as the slope, fuel load, combustible bed thickness, wind speed in the middle of flame and fuel moisture content are integrated into the CA, so that there are different sets of combustion properties in each cell. Experiments are designed to record the slope, fuel load, combustible bed thickness, fuel moisture content, time-varying wind speed in the middle of the flame, and the spread process of fire. The parameters to be estimated in the simplified Rothermel are obtained by LM algorithm. The local transition rules of MD-CA are defined by combining the spread speed formula of eight directions with the local transition rules of CA to realize the simulation of fire spread. By comparing the actual fire spread process of testing datasets with the simulation of CA and MD-CA, it is found that, introducing the MD-CA, the contour is closer to real fire spread, the area error was simulated in the range of 9.42% - 15.64%, and the perimeter error in the range of 4.21% - 9.88%. The MD-CA forest fire spreading model solves the problem of different spreading speeds in different directions during the fire spreading process, and realizes the accurate prediction of the forest fire spreading contour and burning area, which provides reference value for the ignition experiment in the laboratory.

Although, the experimental results show that MD-CA can simulate well the spread of fire in the laboratory, there are some errors, and the simulated value is larger than the real value. First, the error comes from the change of the fire extinguishing moisture content in the Rothermel speed formula, while the fire extinguishing moisture content in this paper is calculated by a fixed value. Secondly, in the process of actual fire spread, combustibles are mixed with sand and soil particles to prevent the spread of fire, the model can

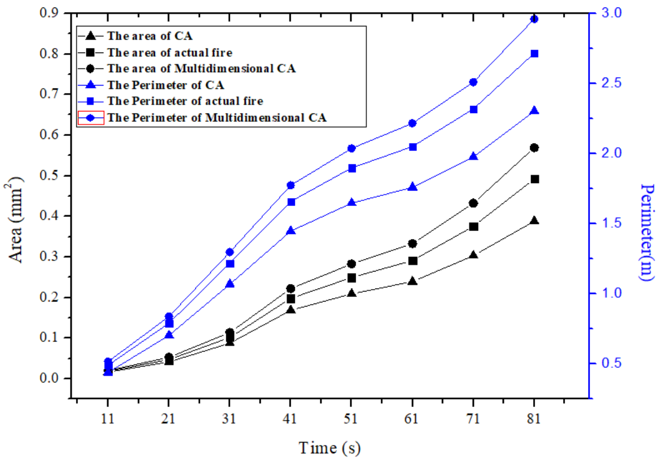

Fig. 7 The area and perimeter of the cellular automata spreading simulation, actual fire spreading and multi-dimensional cellular automata spreading simulation with time in tesing dateset 2.

not increase such a blocking effect, so attention should be paid to avoid similar problems in future research. In addition, it can be seen from the experimental results that the error of the model simulation will increase with time, so how to reduce the superposition of errors will be the focus of the next research.

ACKNOWLEDGEMENTS

This work was supported by " Natural Science Foundation of Heilongjiang Province of China (Grant No.TD2020C001)"; "Fundamental Research Funds for the Central Universities (Grant No.2572019CP20) ".

AUTHORSHIP CONTRIBUTION

Project Idea: SYZ

Funding: JQL, XDL

Database: HWG

Processing: XDC

Analysis: SYZ, HWG, XDC, JQL, JH

Writing: SYZ
Review: JH

REFERENCES

ALEXANDRIDIS, A., RUSSO, L., VAKALIS, D., BAFAS G. V., SIETTOS, C. I. Wildland fire spread modelling using cellular automata: evolution in large-scale spatially heterogeneous environments under fire suppression tactics. International Journal of Wildland Fire, v.20, n.5, p. 633-647, 2011.

BRUN, C.; MARGALEF, T.; CORTÉS, A., SIKORA, A. Enhancing multi-model forest fire spread prediction by exploiting multi-core parallelism. The Journal of Supercomputing, v.70, n.2, p. 721–732, 2014.

COLLIN, A.; BERNARDIN, D.; SÉRO-GUILLAUME, O. A Physical-Based Cellular Automaton Model for Forest-Fire Propagation. Combustion Science and Technology, v.183, n.4, p. 347–369. 2011.

DENHAM, M.; WENDT, K.; BIANCHINI, G.; CORTÉS, A.; MARGALEF, T. Dynamic Data-Driven Genetic Algorithm for forest fire spread prediction. Journal of Computational Science, v.3, n.5, p.398–404, 2012.

FILIPPI, B.; MALLET, V.; NADER, B.; Evaluation of forest fire models on a large observation database. Natural Hazards and Earth System Sciences, v.14, n.11, p.3077–3091, 2014.

FINNEY, M.; COHEN, D.; MCALLISTER, S.; JOLLY M. On the need for a theory of wildland fire spread. International Journal of Wildland Fire, v.22, n.1, p.25–36, 2013.

GHISU, T., ARCA, B., PELLIZZARO, G. An optimal Cellular Automata algorithm for simulating wildfire spread. Environmental Modelling & Software, v.71, p.1–14, 2015.

SAN, H.; XIAOPING, R.; YAO, L. An Improved Forest Fire Spread Simulation Algorithm Coupled with Cellular Automata. Geomatics and information Scicnce of Wuhan University, v.41, n.10, p.1326–1332. 2016.

LAUTENBERGER, C. Wildland fire modeling with an Eulerian level set method and automated calibration. Fire Safety Journal, v.62, p.289–298, 2013

MANDEL, J.; AMRAM, S.; BEEZLEY, D.; KELMAN, G.; KOCHANSKI, K.; KONDRATENKO, Y.; LYNN, H.; REGEV, B.; VEJMELKA M. Recent advances and applications of WRF-SFIRE. Natural Hazards and Earth System Sciences, v.14, n.10, p. 2829–2845, 2014.

NTINAS, V. G.; MOUTAFIS, B. E.; TRUNFIO, G. A.; SIRAKOULIS, G. C. Parallel fuzzy cellular automata for data-driven simulation of wildfire spreading. Journal of Computational Science, v.21, p.469–485, 2017.

PÉREZ, Y.; PASTOR, E.; PLANAS, E.; PLUCINSKI, M.; GOULD, J. Computing forest fires aerial suppression effectiveness by IR monitoring. Fire Safety Journal, v.46, n.1, p. 2–8, 2011.

PLUCINSKI, M.; PASTOR, E. Criteria and methodology for evaluating aerial wildfire suppression. International Journal of Wildland Fire, v.22, n.8, p. 1144–1154, 2013.

RIOS, O.; PASTOR, E.; VALERO, M. M. Short-term fire front spread prediction using inverse modelling and airborne infrared images. International Journal of Wildland Fire. v.25, n.10, p. 1033-1047, 2016.

RUSSO, L.; RUSSO, P.; VAKALIS, D., SIETTOS, C. Detecting weak points of wildland fire spread: a cellular automata model risk assessment simulation approach. Chemical Engineering Transactions, v.36, p. 253-258, 2014.

SUN, T.; ZHANG, L.; CHEN, W. Mountains forest fire spread simulator based on geo-cellular automaton combined with wang zhengfei velocity model. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, v.6, n.4, p. 1971-1987, 2013.

TIZIANO, G.; BACHISIO, A.; GRAZIA, P.; PIERPAOLO, D. An optimal Cellular Automata algorithm for simulating wildfire spread. Environmental Modelling & Software, v.71, p. 1-14, 2015.

WANG X. H.; ZHANG J.; JIN S. Research progress of forest fire spreading simulation. Journal of Central South University of Forestry & Technology, v.35, n.2, p. 50-53, 2013.

ZHANG, F.; XIE, X. An Improved Forest Fire Spread Model and Its Realization. GEOMATICS & SPATIAL INFORMATION TECHNOLOGY, v.35, n.02, p. 50-53, 2012.

ZHENG, Z.; HUANG, W.; LI, S. Forest fire spread simulating model using cellular automaton with extreme learning machine. Ecological Modelling, v.348, p.33–43. 2017.

ZHOU, G.; WU, Q.; CHEN, A. Forestry Fire Spatial Diffusion Model Based on Multi-Agent Algorithm with Cellular Automata. Journal of System Simulation, v.30, n.3, p. 824-831, 2018.

ZHOU, G.; WU, Q.; CHEN, A. Research of cellular automata model for forest fire spreading simulation. Chinese Journal of Scientific Instrument, v.38, n.02, p. 288-294, 2017.