Study on Forest Fire Diffusion Method Based on Cellular Automata

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***Abstract*—As one of the serious natural disasters, forest fire has the characteristics of strong suddenness, hard to detect, wide range of disaster, difficult to extinguish and heavy losses. Frequent forest fires put forward an urgent need for dynamic monitoring of forest fire diffusion and prediction of forest fire behavior. This paper constructs a forest fire diffusion model based on cellular automata, and outputs the visualization results of forest fire diffusion by inputting environmental factors such as terrain data, meteorological data and vegetation type data and the location of the fire point. Finally, the model is used to simulate the forest fire diffusion process in Xichang City, Sichuan Province, and the validity of the model is verified by remote sensing images. The results show that the over-fire area obtained by the simulation experiment is similar to the spatial distribution of the over-fire area extracted by Sentinel-2 satellite, which proves that the cellular automata model constructed in this paper has high accuracy.**

Keywords—Forest fire spread; Cellular automata; Forest fire model; Computer simulation

I. INTRODUCTION

As the first of the three major natural disasters that destroy forests in the world, forest fire has the characteristics of great destruction, strong suddenness, great difficulty in fighting and high cost. In order to timely, accurately and effectively grasp the size of the fire and the scope of the affected area, and provide decision support for emergency response and rescue coordination and collaborative work, the key is to quickly and effectively obtain the technology and methods of relevant information about the fire area. Therefore, accurately grasp the development trend and spread law of the fire, which can greatly improve the monitoring and control of forest fire, to provide more effective auxiliary decision-making support for forest fire disaster prevention and mitigation. China has incorporated forest fire prevention into the key content of the construction of the national public emergency system.

So far, scholars in China and abroad have conducted a lot of scientific research on the diffusion process of forest fire and put forward many scientific and effective models. In China, Wang Zhengfei[1-2] and Mao Xianmin[3-4] have made great contributions to the construction of forest fire models. But Wang Zhengfei's model only considers the situation of uphill and downhill, and when the wind direction and slope are not consistent, the applicability of the model is low; Mao Xianmin improved the Wang Zhengfei model and conducted further research on the slope, which is more in line with the actual situation; Li Xingdong[5] et al. proposed the LFS model by combining genetic algorithm with Wang Zhengfei's velocity model to optimize the parameters of the formula; Huang Ran[6] and other people used the Rothermel model and Huygens principle to simulate the forest fire spread in real time for the fire in Yunnan Province. This model, starting from the main mechanism of forest fire spread, has good simulation results, and many future models have referred to this model; Zhang Feifei[7] proposed a new forest fire spread model based on the principle of cellular automata; Zhang Quanwen[8] et al. used cellular automata to conduct three-dimensional visual simulation of forest fire spread on the plateau. In foreign countries, Australia's McArthur et al. established a forest fire spread model suitable for Australia based on Australia's grassland fire experiment, which means that it has relatively few applicable situations, and only grasslands or eucalyptus forests can be used for this model; Canada has established a national forest fire spread model based on a large number of fire experiments; Alexandridis[9] and others used cellular automata model to predict forest fire spread.

This paper combines cellular automata with Wang Zhengfei - Mao Xianmin forest fire diffusion model, designs forest fire diffusion model algorithm, simulates the forest fire diffusion in Xichang City, Sichuan Province, and verifies the accuracy and effectiveness of the model by comparing with remote sensing images, thus providing more abundant and dynamic fire site information for forest fire emergency management.

II. Forest Fire Diffusion Model Based on Cellular Automata

A. Principle of cellular automata

Cellular automata is defined as a dynamic system that is staged in discrete time according to certain local rules in a cellular space composed of discrete and finite cells. Because its grid characteristics are highly consistent with geographic data such as DEM, the principle of cellular automata can better simulate the dynamic diffusion of forest fire. In the cellular automata of forest fire diffusion simulation, it is composed of four basic elements: cell, state, neighborhood and rule.

B. Diffusion velocity formula of forest fire based on cellular automata

Cellular automata is a network dynamics model with discrete time, space and state, and local spatial interaction and temporal causality, while forest fire spread is a spatiotemporal dynamic process, and forest fire behavior occurs in geographical space. Because of the high compatibility between cellular automata model and geographical space, the analysis of forest fire spread using cellular automata is a hot topic in the neighborhood of forest fire spread model.

Based on the modified model of Wang Zhengfei and Mao Xianmin, this paper constructs a forest fire diffusion model based on cellular automata to calculate the actual diffusion speed of forest fire under different factors.

The factors affecting the spreading speed of forest fire are mainly divided into three categories: fuel factors, terrain factors and meteorological factors. This paper mainly considers the impact of combustible type, slope, wind speed and surface building type on forest fire spread.

1) Calculate the initial forest fire spreading speed R_0. The initial forest fire spreading speed is related to wind power grade, temperature and humidity, and the specific formula is:

$$\mathrm{R}_0 = 0.03\mathrm{T} + 0.05W + 0.01H - 0.3 \tag{1}$$

Among them, the constant coefficients are obtained through experiments, T is the daily maximum temperature （℃）; W is the average wind level at noon; H is the daily minimum humidity （RH%）. The comparison between wind speed class W and wind speed V is shown in Table I:

TABLE I. COMPARISON TABLE OF WIND POWER GRADE AND WIND SPEED.

Wind power level	Wind speed (m/s)
0	0~0.2
1	0.3~1.5
2	1.6~3.3
3	3.4~5.4
4	5.5~7.9
5	8.0~10.7
6	10.8~13.8
7	13.9~17.1
8	17.2~20.7
9	20.8~24.4
10	24.5~28.4

2) Obtain the combustible correction factor K_S. Combustible type refers to the complex with obvious representative plant species, combustible species, shape, size, composition and other similar or identical characteristics that affect the spread and control of forest fire. K_S represents the impact of different vegetation types on the diffusion rate of forest fire. The combustible correction factors summarized by Wang Zhengfei are shown in Table II.

TABLE II. COMBUSTIBLE CORRECTION FACTOR K_S

Vegetation type	K_S
Pine needle	0.8
Forest lands such as Korean pine, Huashan pine and Yunnan pine	1.0
Dead branches and fallen leaves	1.2
Thatch weed	1.6
Cyperus dwarf birch	1.8
Pasture grassland	2.0

3) Calculate the terrain slope correction factor K_Φ. The slope and aspect in the terrain are another important factor affecting the spread of forest fire. Generally, the fire spread on the uphill is fast, and the fire spread on the downhill is slow. The size of the slope will affect the rate of water loss, thus affecting the drying degree of the fuel, indirectly affecting the spread of forest fire, and different slope directions will also affect the humidity of the fuel. There is sunlight on the sunny slope, the humidity of the fuel is low, and the spread of forest fire is fast; On the contrary, the humidity of combustible materials is high, and the spread of forest fire is slow. K_Φ represents the influence of terrain slope on the spreading speed of forest fire. Combining with cellular automata, Mao Xianmin's model is improved, and the calculation formulas of adjacent cells and sub-adjacent cells are obtained as follows:

$$K_\Phi = e^{3.533(-1)^G(\tan\Phi)^{1.2}} = e^{3.533(-1)^G\left|\frac{h_{m,n}-h_{i,j}}{L}\right|^{1.2}} \tag{2}$$

$$K_\Phi = e^{3.533(-1)^G(\tan\Phi)^{1.2}} = e^{3.533(-1)^G\left|\frac{h_{m,n}-h_{i,j}}{\sqrt{2}L}\right|^{1.2}} \tag{3}$$

Where L represents the side length of the cell, $\sqrt{2}\mathrm{L}$ represents the diagonal length of the cell, $\mathrm{h}_{\mathrm{i,j}}$ is the elevation value of the neighboring cell (i,j), $\mathrm{h}_{\mathrm{m,n}}$ is the elevation value of the central cell (m,n), and is the height of the central point of the cell. When going uphill, i.e. $\mathrm{h}_{\mathrm{i,j}} > \mathrm{h}_{\mathrm{m,n}}$, the diffusion speed of forest fire increases, $G=0$; When going downhill, that is, $\mathrm{h}_{\mathrm{i,j}} < \mathrm{h}_{\mathrm{m,n}}$, the forest fire diffusion speed decreases, $G=1$.

4) Calculate the wind correction factor K_w. The wind factor is divided into wind speed and wind direction. The wind speed affects the spreading speed of forest fire, while the wind direction affects the spreading direction of forest fire. It is well known that the higher the wind speed, the greater the spreading speed of forest fire in the wind direction, and the larger the wind correction coefficient K_w. K_w represents the influence of wind on forest fire spread. The wind correction coefficient in Mao Xianmin's model is related to wind speed and direction, and its formula is as follows:

$$K_w = e^{0.1783V\cos\alpha} \tag{4}$$

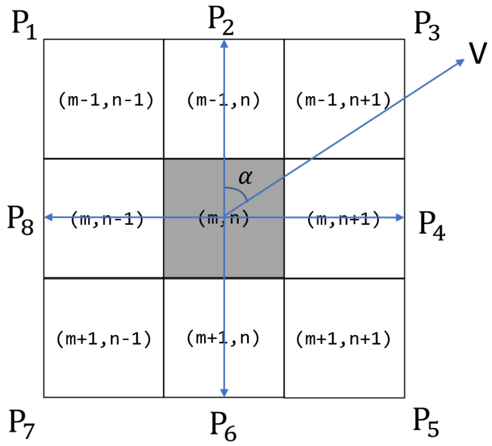

Figure 1. Cell neighborhood direction and wind direction assumption

According to the spreading direction of fire from the central cell to the neighboring cells, it is divided into due north, northeast, east, southeast, south, southwest, west and northwest directions. The neighboring cells in the north, east, south and west directions of the central cell are regarded as the neighboring cells, and the neighboring cells in the northeast, southeast, southwest and northwest directions are regarded as the secondary neighboring cells. In the cellular automata model in this paper, the wind direction is projected onto the eight neighborhood directions of the cell, and the cosine value of the included angle and the wind correction coefficient in the direction of the adjacent cell are obtained as shown in Table III.

TABLE III. WIND DIRECTION AND WIND CORRECTION COEFFICIENT OF CELL NEIGHBORHOOD

Cell type	Diffusion direction	Included angle cosine value	K_w
Adjacent cell	$\overrightarrow{OP_2}$	$\cos\alpha$	$e^{0.1783V\cos\alpha}$
	$\overrightarrow{OP_6}$	$\cos(180°-\alpha)$	$e^{0.1783V\cos(180°-\alpha)}$
	$\overrightarrow{OP_8}$	$\cos(\alpha+90°)$	$e^{0.1783V\cos(90°+\alpha)}$
	$\overrightarrow{OP_4}$	$\cos(\alpha-90°)$	$e^{0.1783V\cos(90°-\alpha)}$
Secondary cell	$\overrightarrow{OP_1}$	$\cos(315°-\alpha)$	$e^{0.1783V\cos(315°-\alpha)}$
	$\overrightarrow{OP_3}$	$\cos(\alpha-45°)$	$e^{0.1783V\cos(\alpha-45°)}$
	$\overrightarrow{OP_7}$	$\cos(225°-\alpha)$	$e^{0.1783V\cos(225°-\alpha)}$
	$\overrightarrow{OP_5}$	$\cos(\alpha-135°)$	$e^{0.1783V\cos(\alpha-135°)}$

5) Obtain the DSM surface building correction factor K_d. DSM, the digital surface model, refers to the ground elevation model that includes the height of surface buildings, bridges and trees. Compared with the DEM model used in the traditional forest fire spread model, DEM only contains the elevation information of the terrain, and does not contain other surface information. The surface buildings covered in DSM will affect the wind speed, wind direction and other factors, thus affecting the spread of forest fire. K_d represents the impact of different types of surface buildings on the diffusion rate of forest fire. Some DSM surface building correction factors are shown in Table IV.

TABLE IV. DSM SURFACE BUILDING CORRECTION FACTOR K_d

Surface building type	K_d
Water tower	0.2
Ancient city wall	0.3
High tower and communication base station	0.5
Bridge	0.9
Wooden house	1.4
Gas stations and other flammable and explosive places	2.0

6) Calculate the forest fire diffusion rate R. The initial spreading speed of forest fire is modified according to the four correction parameters obtained above, and the formula is:

$$R = R_0 * K_w * K_\Phi * K_S * K_d \tag{5}$$

C. State and update rules of cellular automata

According to the rules of forest fire spread, the burning state of each cell changes continuously with the advance of discrete time, but the state change of each cell is only related to the state of its neighbor cell and the current state of the current cell. The state transition rule is the core of driving the operation of the entire cellular automaton. In the forest fire diffusion model based on cellular automata, the cell state value represents the burning state of forest fire. According to the forest fire diffusion speed model, the cell state will be automatically updated in each round. In this model, cell state division is shown in Table V.

TABLE V. FOREST FIRE CELL COMBUSTION STATE

Forest fire cell state	Status Description
SV0	Unburned
SV1	Start to burn without spreading around
SV2	Completely burnt and can spread around
SV3	Off

The burning state of the central cell (m,n) at time t+Δt is determined by its burning state at time t and the diffusion rate of the eight adjacent cells to the central cell. The state transition function of the central cell (m,n) is as follows:

$$S_{m,n}^{t+\Delta t} = S_{m,n}^{t} + \frac{(R_{m-1,n-1}^{t} + R_{m+1,n-1}^{t} + R_{m-1,n+1}^{t} + R_{m+1,n+1}^{t})\Delta t}{\sqrt{2}L} + \frac{(R_{m,n-1}^{t} + R_{m-1,n}^{t} + R_{m+1,n}^{t} + R_{m,n+1}^{t})\Delta t}{L} \tag{6}$$

$$\Delta t = k\frac{L}{R_{\max}}(k<1) \tag{7}$$

Where L is the side length of the cell, Δt is the time step, and k is the step coefficient.

Based on the actual situation, the updated rules of forest fire cell combustion state designed by this model are shown in Table VI.

TABLE VI. UPDATE RULES OF FOREST FIRE CELL COMBUSTION STATE

State transition	Conversion rules
$SV0 \rightarrow SV1$	The cell (m,n) is unburned, and there are fully burned cells in the neighborhood. At the next moment, $t+\Delta t$, $SV0 \rightarrow SV1$
$SV1 \rightarrow SV2$	The cell (m,n) starts to burn, and the cell state is calculated according to Equation (6). When $S_{m,n}^{t+\Delta t} \geq 1$, $SV1 \rightarrow SV2$
$SV2 \rightarrow SV3$	When the cell (m,n) is completely burned and all other cells in the field are $SV2$ or non-combustible, the next moment $t+\Delta t$, $SV2 \rightarrow SV3$

III. SIMULATION EXPERIMENT OF FOREST FIRE DIFFUSION

A. Overview of the study area

The study area of this paper is Xichang City, Liangshan Prefecture, Sichuan Province (100°15′E—103°53′E, 26°03′N—29°27′N), bordering the Jinsha River in the south, Dadu River in the north, Sichuan Basin in the east, and Hengduan Mountains in the west. The terrain is complex and the landform is rich and diverse. The region has a subtropical climate, with high temperature and rainfall in summer, mild and little rain in winter, and sufficient annual sunshine, so the forest resource coverage rate is high. According to the survey of the Meteorological Research Center, the temperature in the study area is high in February to April, and the continuous rainfall is less, so it is the frequent season of forest fire. This paper takes the forest fire in Xichang City, Liangshan Yi Autonomous Prefecture, Sichuan Province on March 30, 2020 as the experimental background, and uses its real data to conduct the dynamic simulation of forest fire spread.

B. Experimental data

The terrain data used in this experiment is the 30-meter resolution digital elevation data of ASTER GDEM from the geospatial data cloud (https://www.gscloud.cn/); The DSM data is from the 30-meter resolution digital terrain model data of ALOS AW3D30; The remote sensing image data comes from the satellite remote sensing image of Xichang City, Sichuan Province downloaded by Bigemap software; According to the statistical results of the China Meteorological Data Network, the parameter value of the daily maximum temperature T of the forest fire diffusion model in the experiment is set to 31, the parameter value of the daily minimum relative humidity H is set to 5%, the parameter value of the wind speed V is set to 5.8, the parameter value of the wind speed class is set to 4, and the wind direction angle θ is set to 45°; According to the vegetation cover type of Xichang City, Liangshan Prefecture, Sichuan Province, the parameter value of combustible correction coefficient K_S is set as 1.0; According to the DSM database of Xichang City, Liangshan Prefecture, Sichuan Province, the parameter value of the DSM surface building correction coefficient K_d is set to 1.0.

C. Experimental simulation

The cellular space of forest fire diffusion based on cellular automata, namely 137*164 grid space, is constructed, where the cell side length is 30m, and each cell contains the state value of forest fire combustion. Input DEM data, temperature, humidity, wind speed, wind direction and other meteorological data, vegetation type and fire point cell location, and use the model built in this paper to calculate through Python programming language to generate the simulation diagram of the diffusion range of forest fire in Xichang in 1h, 2h, 3h.

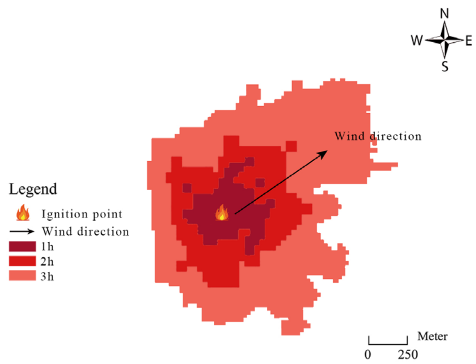

Figure 2. Range of forest fire spread in Xichang within 3 hours

The fire spreads from the ignition point to the surrounding direction. The closer it is to the ignition point, the easier it is to burn, and the darker its color is on the map. On the contrary, the farther it is from the ignition point, the harder it is to burn. Incomplete burning cells are distributed around the completely burning cells. Only when the incompletely burning cells are converted to complete combustion, can they diffuse to the surrounding cells. The cells are not uniformly diffused, but are different in all directions, indicating that different combustibles, terrain, wind speed and surface building types have influence on fire behavior.

D. Result analysis

From the simulation results, it can be seen that the forest fire was ignited by the fire point of Ma'anshan and spread to the northeast, which is consistent with the actual situation. Calculate and count the over-fire area at different times of the forest fire diffusion simulation experiment in Xichang. The experimental over-fire area is shown in Table VII:

TABLE VII. OVERFIRE AREA OF FOREST FIRE DIFFUSION EXPERIMENT IN XICHANG

Simulation time (hour)	Overfire area (hectare)
1	0.09
2	9.27
3	49.59
4	135.99
5	246.24
6	388.89
7	561.15
8	764.28

According to the investigation report of forest fire events in Xichang issued by the Sichuan Provincial Emergency Department, the actual total forest fire area of the fire is 791.6 hectares. In this simulation experiment, the experimental over-fire area when the fire spread for 8 hours was 764.28 hectares. Using the Equation (8), the error ratio between the experimental results and the actual fire area is 3.45%. It can be seen that the model is effective to some extent, but there are still errors, mainly because the model simplifies the continuous process of forest fire diffusion into the diffusion of discrete grids, and the time and spatial resolution are limited.

$$Ratio = \frac{|S_{actual} - S_{experimental}|}{S_{actual}} \tag{8}$$

E. Sentinel-2 remote sensing image to verify the accuracy of forest fire diffusion experiment

Using remote sensing images to identify the forest fire area and comparing it with the fire field range simulated by the forest fire diffusion model built in this paper can effectively verify the accuracy of the model in terms of spatial distribution. Sentinel-2 satellite is the second constellation satellite of the Copernicus plan, including two satellites 2A and 2B. Its revisit period is 10 days, and the replay period of the two satellites operating simultaneously can reach 5 days. It can cover 13 narrow spectral bands at the same time, which can better distinguish the subtle differences between different objects, and is very effective in monitoring plant conditions, The normalized burning rate index (NBR) is particularly sensitive to the changes of vegetation, moisture content and some soil conditions in the near infrared band (NIR) and the section infrared band (SWIR) that may occur after a fire. Therefore, this paper selects the Sentinel-2 satellite image to identify and extract the fire area, and uses the normalized burning rate index constructed in the near infrared band and the short wave infrared band of the remote sensing image as the identification index of the fire site, Calculate the normalized combustion index on March 30 and April 9 respectively.

$$NBR = \frac{(NIR - SWIR)}{(NIR + SWIR)} \tag{9}$$

The theoretical value range of NBR is $[-1,1]$, and its size is negatively correlated with the degree of forest fire combustion, that is, the more intense the forest fire combustion, the smaller the corresponding NRB value.

The normalized combustion index of the two periods before and after the fire is subtracted, and the difference dNBR represents the fire severity, and then threshold segmentation is performed to extract the fire area. The calculation formula of dNBR is as follows:

$$dNBR = NBR_{Before\ fire} - NBR_{After\ \mathrm{fire}} \tag{10}$$

The method used in this paper is the threshold extraction method, that is, by setting the size of the threshold to distinguish whether a certain area has been extracted, and the size of the threshold will affect the accuracy of the extraction. After setting the appropriate threshold, the over-fire area extracted from Sentinel-2 image and the forest fire diffusion model in this paper conduct the forest fire diffusion simulation experiment to obtain the over-fire range as shown in the following figure:

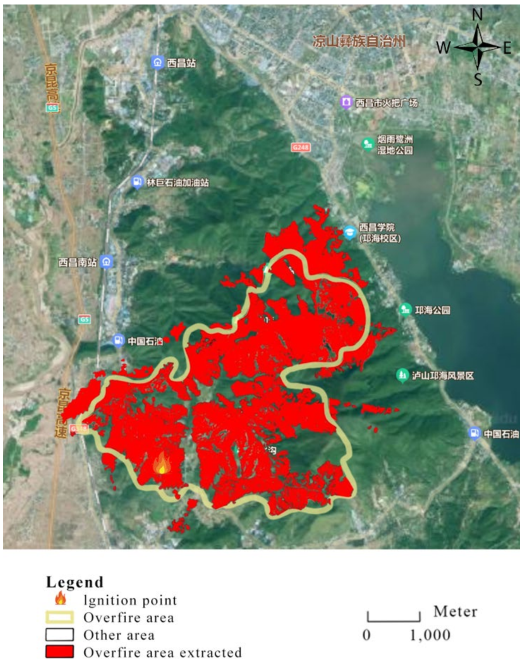

Figure 3. Comparison between the fire area extracted by Xichang Forest Fire Satellite and the experimental fire area

The yellow line in Figure 3 is the result of the simulation of forest fire diffusion in Xichang City, Sichuan Province by using the combination of cellular automata and Wang Zhengfei - Mao Xianmin forest fire diffusion model, while the red area is the actual fire spread area in the report on forest fire investigation in Xichang City issued by the Sichuan Provincial Emergency Department, which can be clearly seen, The range of forest fire diffusion in Xichang is similar to the spatial distribution of the area of forest fire extracted by Sentinel-2 satellite, which can prove the accuracy and effectiveness of the forest fire diffusion model based on cellular automata constructed in this paper.

IV. SUMMARY AND PROSPECT

This paper establishes a forest fire diffusion model based on cellular automata, fully considers the influence of combustible factors, terrain factors, wind factors and surface building factors on forest fire diffusion, and uses Python programming language to simulate and visualize the forest fire diffusion process. At the same time, the forest fire in Xichang City, Sichuan Province on March 30, 2020 was selected for the experiment, and the fuel data, meteorological data and DSM data at the time of the fire were input to carry out the simulation experiment of fire diffusion. Through the verification, it was found that the forest fire diffusion model constructed in this paper has good fitting in practical application, which is conducive to the prevention, monitoring and control of forest fire.

But this experiment also has some shortcomings, the current model cannot fully conform to the complex diffusion process of forest fire in reality, such as the continuous change of wind speed and direction, the three-dimensional rather than planar wind field, the different vegetation types and surface building types in different grid positions, etc. It is necessary to consider these complex situations and the interaction between factors; At the same time, the forest fire spreading method based on cellular automata used in this paper divides the burning state of the cell into three states: unburned, incipient combustion and complete combustion. Only three states are used to represent the burning state of the cell. The span is a little large, so the forest fire spreading state cannot be accurately displayed, and the error is large. In the future, the intermediate state between states can be considered again, and the burning state of the cell can be fully considered; In addition, the cellular automata assumes a certain time interval to update the cellular state, discretizing the continuous process of forest fire, but also losing some accuracy. In the future, it needs to enrich the cellular state values and design the cellular state transition rules that are similar to the actual situation.

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REFERENCES

[1] Wang Z F, “Calculation method of initial spreading speed of mountain fire”, *Mountain Research*, vol.1983(02), 1983, pp.42-51.

[2] Wang Z F, “General forest fire risk level system”, *Journal of Natural Disasters*, vol.1992(03), 1992, pp.39-44.

[3] Mao X M, “Effects of wind and terrain on the spreading speed of forest fire”, *Journal of Applied Meteorology*, vol.1993(01), 1993, pp.100-104.

[4] Mao X M, Xu W Q, “Study on Calculation Method of Forest Fire Spread Speed”, *Liaoning Meteorology*, vol.1991(01), 1991, pp.9-13.

[5] Li X D, Li X, Li X K, et al. “A Model of Forest Fire Spread Based on Cellular Automata”, *Forestry Machinery & Woodworking Equipment*, vol.47(06), 2019, pp.48-55.

[6] Huang R, Ma Y, Zhou F R, et al. “Research on visualization of forest fire spread in power grid based on ArcGIS”, *Yunnan electric power*, vol.49(03), 2021, pp.65-68.

[7] Zhang F F, Xie X L, “An Improved Forest Fire Spread Model and Its Implementation”, *Mapping and Spatial Geographic Information*, vol.35(02), 2012, pp.50-53.

[8] Zhang Q W, Yang Y C, Wang T, Ma J, “Three-dimensional visual simulation of forest fire spread in plateau based on cellular automata”, *Science Technology and Engineering*, vol.21(04), 2021, pp.1295-1299.

[9] Alexandridis A, Vakalis D, Siettos C I, Bafas G V, “A cellular automata model for forest fire spread prediction: The case of the wildfire that swept through Spetses Island in 1990”, *Applied Mathematics & Computation*, vol.204(1), 2008, pp.191-201.

[10] Andrews P L, “Current status and future needs of the BehavePlus Fire Modeling System”, *International Journal of Wildland Fire*, 23(1), 2014, pp.21.

[11] Li Z, Wang F, Zheng X, Jiang W, et al. “GIS Based Dynamic Modeling of Fire Spread with Heterogeneous Cellular Automation Model and Standardized Emergency Management Protocol”, *ACM Sigspatial Workshop on Emergency Management Using*, vol.2017, 2017, pp.1-7.

[12] Balbi J H, Morandini F, Silvani X, Filippi J B, Rinieri F, “A physical model for wildland fires”, *Combustion & Flame*, vol.156(12), 2009, pp.2217-2230.

[13] Yang F L, “Three-dimensional simulation of forest fire spread based on cellular automata”, Beijing Forestry University,2016.