A Cellular Automata Model for Forest Fire Spreading Simulation[1]

Wang Xuehua, Liu Chang, Liu Jiaqi, Qin Xuezhi, Wang Ning
Dalian University of Technology
Faculty of Management and Economics
Dalian, China

Zhou Wenjun
Haslam College of Business
University of Tennessee-Knoxville
Tennessee, America

***Abstract*—In this paper, we analyze a variety of influence factors for the spreading pattern of forest fires. Rules of these crucial factors are expressed with cellular automata (CA), which has powerful simulation capacity. Specifically, we analyze the influence of combustible materials, wind, temperature, and terrain. We implement a CA Forest Fire Forecast System based on the Matlab development platform. Simulation results demonstrate that this model can be used to effectively simulate and forecast the spreading trend of forest fire in various conditions.**

Keywords—natural disaster; spread of forest fire; cellular automata; influence factors; rule expression

I. INTRODUCTION

Forests are invaluable resources for human. They provide food and shelter for human beings and other living things. With the development of human society and economy, more and more forests have been destroyed. Forest fire is one of the most common causes of forest destruction, which causes hazards that have severe and long-term impact on human life. Therefore, there is an urgent need for us to understand the patterns of the forest fire spreading, with which we can effectively prevent forest fires, as well as quickly and accurately respond to a forest fire emergency.

Researchers have developed a number of models to simulate forest fire spreading patterns, including mathematical models, physical models, and semi-physical models. Mathematical models can effectively predict the spreading of forest fire, but they usually rely on ideal assumptions, and do not take environmental factors into account, such as wind, terrain, types of trees and so on. Physical models, such as Rothermel model [1], are based on capacity conservation laws. The Rothermel model aims to construct the kinetic equation to characterize the rate of forest fire spreading with indoor experiments, and a variety of methods have been proposed in the literature. These methods can be mainly divided into two categories: one is the wave propagation model that has a relatively high computing power [2]; the other is the forest fire spreading model [3] based on the grid which has a simple and fast calculation process.

So far, the forest fire spreading model based-on grid has been concerned by some scholars, for it can better predict the behavior of forest fire spreading in a microscopic point of view. It's mainly divided into two categories. One focus on estimating the probability value of grids' influence based on historical data [4], but is limited to poor dynamic description of forest fire spreading. Another is identified in the research point of view on cellular automata (CA) [5] method to solve the above-mentioned research bottlenecks. CA has discrete time, space, state, and strong simulation of complex systems, and soon is used into the simulation of complex dynamic systems [6,7]. Therefore, this paper presents a dynamic simulation model of forest fire spreading in a more microscopic point of view.

II. FACTORS INFLUENCING FIRE SPREADING

Since the study is about the fire spreading process, time t is the indispensable variable. Considering the time t as the key effect parameter of fire spreading, we divide factors influencing fire spreading into two types: dynamic factors and static factors [8,9].

A. Dynamic Factor-Meteorology

Factors related to meteorology are dynamic factors, so the values are changing with time. There are many meteorological factors that influence forest fire spreading, such as wind speed, air temperature, air humidity and so on. Each factor not only affects the fire spreading process alone, but also has interaction and interactive influence. For instance, high speed wind, and high temperature will reduce air humidity. However，this kind of complex interaction relationship is hard to quantify, and as a result, this paper only considers the independent effect of the meteorological factors in the process of fire spreading.

The wind is a very important meteorological factor, and is one of the most direct fire spreading influence factors. The wind can not only accelerate the water evaporation, making combustibles become dry and flammable, but also continuously offer oxygen, increasing the burning conditions and accelerating the burning process. The wind influences fire spreading speed, and changes the area and direction of forest fire. Accordingly, this paper needs to study wind from two dimensions-wind power and wind direction. The vector characteristics of wind will make the influence complicated, so the research on wind is very important for the study of fire spreading.

Air relative humidity is another key factor in meteorology. Research shows that when the air humidity is less than 60%, there is a possibility of forest fire [10]. Relative humidity

1The research is supported by Key Project of Natural Science Foundation Of China: Methodologies for Knowledge Fusion and Services in Big Data Environment with Applications in E-Government (71533001).

changes with seasons and daily time, and what is more important is that it has a certain relationship with temperature and the moisture of combustibles [11].

Air temperature is an important influence factor of a natural forest fire [12]. The air temperature determines the temperature of combustibles. The higher the temperature is, the faster the evaporation of moisture and dry of fuel will be, the greater the chance of fire will be. When air temperature is low, even if there are many combustibles, burning progress will be slow. The temperature works not only on the nature of the combustibles, but also on air relative humidity, moisture content and other fire spreading influence factors.

B. *Static Factor-Terrain*

The factor related to terrain is a static factor. Researches show that the topography and land forms influence fire spreading process remarkably. Terrain can affect the redistribution of ecological factors, making fire environment different, so that it can affect the spread of the heat and fire spreading.

The terrain is varied, such as forms of convex and concave, orientations of southward and northward, windward and back, ridge and valley, etc. The changes of moisture content and the spread of heat will be directly affected by the slope [13].

Therefore, the greater terrain factors that influence the forest fire spreading have six dimensions, including the altitude, mountain trends, length, orientation, slope and the ups and downs.

Obstacles are special factors among the key terrain factors.

C. *Combustibles*

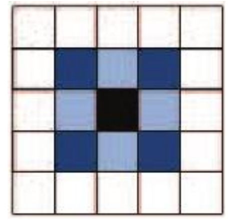
The forest combustibles are the material basis of forest burning. Water content and the effective energy of forest combustibles vary by vegetation composition and growing characteristics. These are the key factors which directly affect the spreading [14] speed of forest fire. There are significant differences in the ignition temperature and spreading speed caused by the difference of the physical and chemical properties and the combustible structure [15]. Forest fire spreading speed and moisture content of combustibles have close relationship. If the water content of combustible is very high, the fire spreading may be restricted.

To sum up, there are many influential factors of forest fire spreading, and all produce some effects on fire behavior. Among these, the wind direction and wind power, terrain and combustible types are the decisive factors affecting the forest fire spreading speed, strength and scale. This paper tries to build a new forest fire spreading model with these key factors in order to predict trend of forest fire spreading in different conditions.

III. RULES OF THE FACTORS

A CA model usually contains four types of elements: unit, state, adjacency range, and transition rule. Unit is the minimum range with uniform properties, and the state is the main attribute of unit.

Fig. 1. Moore Type of Cellular Automata Model



The adjacent arrangement often uses the Moore model, that is to say a cell has 8 neighbors including 4 adjacent neighbors (up, down, left and right) and 4 diagonal adjacent neighbors as shown.

A unit can be transformed from one state to another according to transition rule, which is based on neighboring function to realize [16]. Equation (1) expresses the state transition method.

$$S_{i,j}^{t+1} = f\begin{pmatrix} S_{i-1,j+1}^{t} & S_{i,j+1}^{t} & S_{i+1,j+1}^{t} \\ S_{i-1,j}^{t} & S_{i,j}^{t} & S_{i+,j}^{t} \\ S_{i-1,j-1}^{t} & S_{i,j-1}^{t} & S_{i+1,j-1}^{t} \end{pmatrix} \quad (1)$$

The state of central cell in next time period depends not only on the states of 8 neighboring cells at this time step, but also on the state of itself in this time period. So the definition of rule expression among cells is very important.

A. *Rule Expression of Combustible and Air Temperature Factors*

The happening of forest fire means that combustible is ignited, the combustion intensity and the spreading speed has a close relationship with combustible type. The combustible type determines the quantity of the fuel moisture content, which directly impacts the spreading speed of forest fires. Combustible type is divided into three categories in this paper: coniferous, broadleaf, and coniferous and broadleaved mixed type. The water content of coniferous type is relatively minimal, and its burning speed is relatively fast; the water content of broadleaf type is relatively large, and its burning speed is relatively slow; and coniferous and broadleaved mixed type is in the middle. Here uses F as expression. Fires' arising has different performance with the differences of conditions and environmental factors, which can be depicted by initial spreading speed. If the initial speed of spreading is low, then the fire is difficult to be perceived by surrounding environment, on the contrary, is easy. The initial speed of spreading is considered to measure the spread of combustible in the no wind conditions.

According to the domestic Wang Zhengfei's forest fire spreading model, the initial rate of forest fire spreading (m / min) can be modeled using (2):

$$R_0 = aT + bW - c \quad (2)$$

In this expression, T represents the temperature (◦C); W represents wind level; a, b, and c are the coefficients. In the Northeast region of China, a = 0.053, b = 0.048, c = 0.275. This paper depicts the wind speed, slope, humidity and other factors independently, the initial rate of spreading which is improved, only to reflect the effects of real-time temperature and the type of combustible. The Equation (3) as follows:

$$R_0 = aT + kF - c \qquad (3)$$

The coefficient k of combustible factor F is only seen as the adjustment coefficient of an initial spreading.

In the real situation, almost all of the forests are heterogeneous. The speed in the spreading process is constantly changing, and time step t is the maximum spreading speed of surrounding neighborhood R at that time.

$$t = \frac{L}{R}, R = MAX\{R_{i,j}, 0 < i \le m, 0 < j \le n\} \qquad (4)$$

In this expression, L is the side length of a single cell; m, n are defined as cell numbers in horizontal regions and vertical regions respectively; $R_{i,j}$ is defined as all cell initial speed of spreading.

B. Rule Expression of Wind Factor

Some models only take the wind strength into account, ignoring the impact of wind direction on the spreading of forest fires. To get a perfect forest fire spreading model, both wind power and wind direction and their interaction cannot be ignored. To consider the change of central cell (i, j) after a time period, we need to study the eight neighborhood cells' impact on central cell, which is shown in Fig. 2.

Fig. 2. Influence Direction Schematic of Cellular Neighborhood

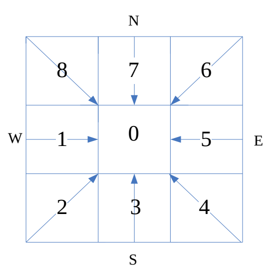
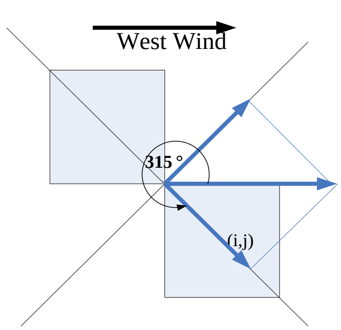


Fig. 3. Wind Vector Decomposition Example



We can confirm the angel and position of eight neighborhood cells that affect the central cell. Using the method of vector decomposition and combining the wind power with wind speed, the vector can be decomposed into the component that affect the central cell and the component that doesn't affect the central cell (the vertical component). When there is west wind, for the 8th cellular, it needs to consider its impact on the 0th cell and to decompose it which is shown in Fig. 3. The decomposition of other neighborhood cells with other wind directions is in the same way.

It is believed that if the direction of cell intervention is vertical compared to wind direction, the value of wind effect coefficient is 1, that is the w_i = 1. Wind power is represented by D, and the decomposition of the wind vector is summarized in Tab.1.

TABLE I. WIND VECTOR DECOMPOSIIONSUMMARY TABLE

Cell ID	**1**	**2**	**3**	**4**
Direction	**0°**	**45°**	**90°**	**135°**
N	1	- Dsin45°	-D	- Dsin45°
S	1	Dsin45°	D	Dsin45°
W	D	Dsin45°	1	- Dsin45°
E	-D	- Dsin45°	1	Dsin45°
WN	Dsin45°	1	- Dsin45°	-D
EN	-Dsin45°	-D	- Dsin45°	1
WS	Dsin45°	D	Dsin45°	1
ES	- Dsin45°	1	Dsin45°	D
Cell ID	**5**	**6**	**7**	**8**
Direction	**180°**	**225°**	**270°**	**315°**
N	1	Dsin45°	D	Dsin45°
S	1	-Dsin45°	-D	- Dsin45°
W	-D	- Dsin45°	1	Dsin45°
E	D	Dsin45°	1	- Dsin45°
WN	- Dsin45°	1	Dsin45°	D
EN	Dsin45°	D	Dsin45°	1
WS	- Dsin45°	-D	- Dsin45°	1
ES	Dsin45°	1	- Dsin45°	-D

TABLE II. WIND VECTOR DECOMPOSIIONSUMMARY TABLE

Cell ID	**1**	**2**	**3**	**4**
Direction	**0°**	**45°**	**90°**	**135°**
N	1	1	1	1
S	1	Dsin45°	D	Dsin45°
W	D	Dsin45°	1	1
E	1	1	1	Dsin45°
WN	Dsin45°	1	1	1
EN	1	1	1	1
WS	Dsin45°	D	Dsin45°	1
ES	1	1	Dsin45°	D
Cell ID	**5**	**6**	**7**	**8**
Direction	**180°**	**225°**	**270°**	**315°**
N	1	Dsin45°	D	Dsin45°
S	1	1	1	1
W	1	1	1	Dsin45°
E	D	Dsin45°	1	1
WN	1	1	Dsin45°	D
EN	Dsin45°	D	Dsin45°	1
WS	1	1	1	1
ES	Dsin45°	1	1	1

This analysis method of wind vector may get some negative values after decomposition that is neighboring cells causing negative effect on, which means the central cell will weaken the burning. However in the real life, no matter how wind blows, it will not weaken the fire, only causing stronger burning or zero impact on fire. So, it needs to revise these decomposed negative components to be 1, and the summary is shown in Tab. 2.

The effect of the change of wind speed and wind direction together on the central cell is expressed as shown in (5).

$$W_{i,j} = \begin{pmatrix} w_8 & w_7 & w_6 \\ w_1 & 1 & w_5 \\ w_2 & w_3 & w_4 \end{pmatrix} \quad (5)$$

When there is no wind, all of the weight is 1.

C. Rule Expression of Terrain Factor

Height difference between cells is regarded as gradient, which is the key to forest fire spreading. If the flame burns along the ascent, the angle between flame and fuel become smaller than that on the ground, which causes burning more sharply; on the contrary, if the flame burns along descent, the angle becomes lager and burning intensity decreases. So we should consider the height difference between central cell and 8 neighboring cells, which is shown in (6).

$$x_k = (h_k - h_0) \quad (6)$$

We use function g(x) to represent the influence of neighboring cells to central cell; it could be a linear or non-linear function, it must meet the following conditions according to actual situations. If $x > 0$, then $g(x) > 1$; if $x = 0$, then $g(x) = 1$; if $x < 0$, then $0 < g(x) < 1$.

It is clear that the speed of fire spreading will be greater if the central cell is higher than neighboring cells; if the height of both is the same, the slope will not cause any influence to the burning; if the central cell is lower than neighboring cells, the burning becomes slower. The coefficient of terrain influence is expressed in (7).

When the topography is absolutely flat where there is no difference of height and gradient, the expression is given as Equation (8).

$$H_{i,j} = \begin{pmatrix} g(x_8) & g(x_7) & g(x_6) \\ g(x_1) & 1 & g(x_5) \\ g(x_2) & g(x_3) & g(x_4) \end{pmatrix} \quad (7)$$

$$H_{i,j} = \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} \quad (8)$$

The obstacles, such as high ground, open space, rivers and so on, which will meet with during the process of forest fire spreading, will cause some effects on the trend and strength of the spreading. These obstacles will not play a role of combustion to the forest, and that representative cells of the obstacles have certain impeditive effect on the around burning cells but not have the function of extinguishing. So when a central cell has a obstacle neighboring cell, we define this coefficient of terrain influence to be negative, that is $g(x_k) < 0$.

IV. Cellular Automation Model of Forest Fire Spread

In the popular K-T model [17], a cellular's initial state is given in (9).

$$S_{i,j}^t = \frac{A_b}{A_t} \quad (9)$$

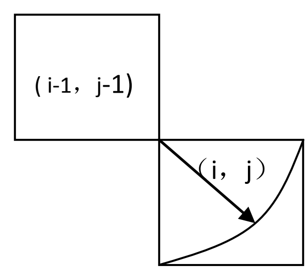
In this expression, $S^t_{i,j}$ represents the state of the cell at time t; A_b and A_t represent the burned and total cell areas, respectively.

Moreover, the CA local rule is given by (10).

$$\begin{aligned} S_{i,j}^{t+1} &= S_{i,j}^t + (nH_{i-1,j}S_{i-1,j}^t + wH_{i,j-1}S_{i,j-1}^t + eH_{i,j+1}S_{i,j+1}^t + nH_{i+1,j}S_{i+1,j}^t) \\ &+ 0.83(nwH_{i-1,j-1}S_{i-1,j-1}^t + neH_{i-1,j+1}S_{i-1,j+1}^t + swH_{i+1,j-1}S_{i+1,j-1}^t + seH_{i+1,j+1}S_{i+1,j+1}^t) \end{aligned} \quad (10)$$

In this model, the CA local rule incorporates both the wind and height differences. Another scholar proposed a more realistic model that the area after burning from diagonal neighbor cell to the main cell is supposed to be a quarter of circular as it is shown in Fig. 4. Then the evolution rule proposed for K-T is given in (11).

Fig. 4. K-T Model Improvement



$$\begin{aligned} S_{i,j}^{t+1} &= S_{i,j}^t + (nH_{i-1,j}S_{i-1,j}^t + wH_{i,j-1}S_{i,j-1}^t + eH_{i,j+1}S_{i,j+1}^t + nH_{i+1,j}S_{i+1,j}^t) \\ &+ 0.785(nwH_{i-1,j-1}S_{i-1,j-1}^t + neH_{i-1,j+1}S_{i-1,j+1}^t + swH_{i+1,j-1}S_{i+1,j-1}^t + seH_{i+1,j+1}S_{i+1,j+1}^t) \end{aligned} \quad (11)$$

Although the model has been recognized by most scholars, its method is too idealistic. The cell state of some traditional cellular automata model is expressed by the comparative discrete values (Such as 0 stands for no forest cover, 1 stands for no burning forest, 2 stands for the burning forest, 3 stands for burned forest), the particle size of cell state definition is larger. Therefore, in order to improve the issue that if the simulation and reality is consistent [18]. Based on this model, this paper uses smaller particle size of cell state which is the ratio of the components to accurately reflect fire spreading.

This paper builds a forest fire spreading model based on Cellular Automata.

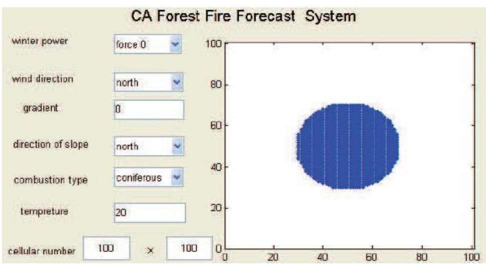
$$S_{i,j}^{t+1} = S_{i,j}^{t} + (W_{i-1,j}H_{i-1,j}S_{i-1,j}^{t} + W_{i,j-1}H_{i,j-1}S_{i,j-1}^{t} + W_{i,j+1}H_{i,j+1}S_{i,j+1}^{t} + W_{i+1,j}H_{i+1,j}S_{i+1,j}^{t}) + 0.785\,(W_{i-1,j-1}H_{i-1,j-1}S_{i-1,j-1}^{t} + W_{i-1,j+1}H_{i-1,j+1}S_{i-1,j+1}^{t} + W_{i+1,j-1}H_{i+1,j-1}S_{i+1,j-1}^{t} + W_{i+1,j+1}H_{i+1,j+1}S_{i+1,j+1}^{t})$$

After a period of combustion, it is possible that the value is greater than 1. In this case, it is taken to be equal to 1 on behalf of this cell in fully burning state.

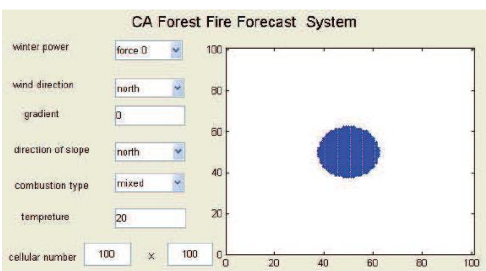
V. Simulation Results

According to the constructed forest fire spreading model, we build a CA Forest Fire Forecast simulation system, use the Matlab development platform to visualize and verify the prediction result of the model. Fig. 5 is the forest fire spreading comparison chart when the case of no wind or the ground, and in the same spread time, the combustion types that are coniferous forest, coniferous and broad leaved mixed forest and broad-leaved.

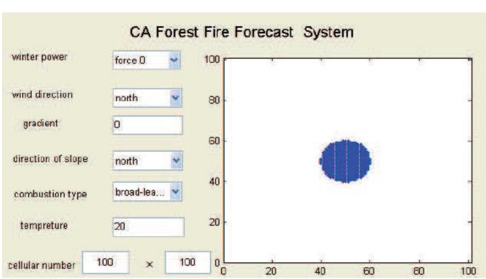
Fig. 5. Different Fuel Burning Result(No Wind, even ground)



(a) Coniferous Forest



(b) Coniferous and Broad-leaved Mixed

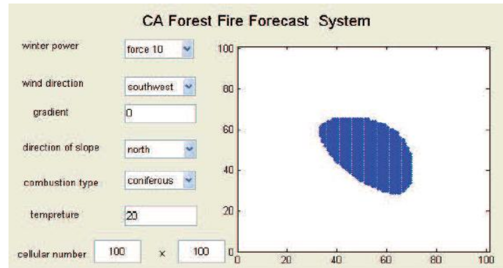


(c) Broad-leaved Forest

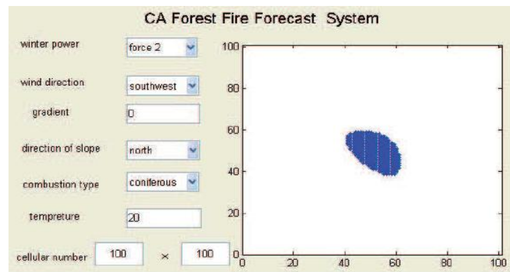
The simulation results prove that: in the same spread time, broad-leaved forest spreads faster than the coniferous forest, and mixed forest rate of spread in between because broad-leaved forest has more water content.

Fig. 6 shows the spread comparison chart when the forest farm is plain, other factors are identical, and in the same spread time, wind power are at the same wind direction but respectively 10 degree and 2 degree. The simulation results prove that wind speed is stronger, providing more sufficient oxygen, and making the fire spread faster.

Fig. 6. Different Wind Power Burning Result

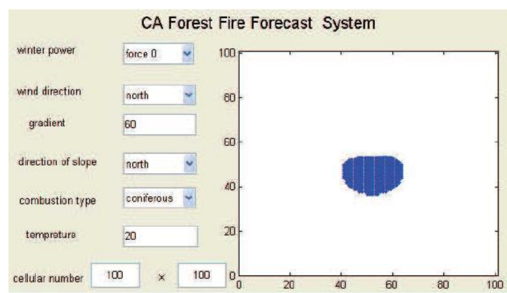


(a) Wind Level=10

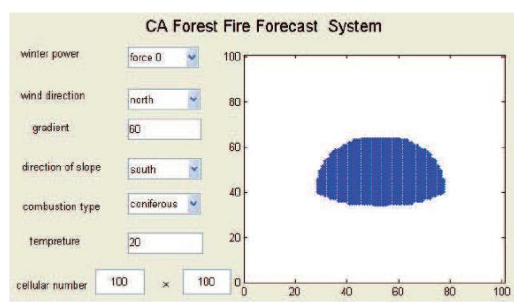


(b) Wind Level=2

Fig. 7. Different Slope Direction Burning Result



(a) Northern Slope



(b) Southern Slope

Fig. 7 shows the combustion comparison chart when slope direction are southern and northern in the same spread time, and the same other factors. The simulation results prove that the combustion area of southern slope is larger than the northern slope area and the spread orientation is in different directions. It fully proves that the southern slope receiving sunlight for a long time, drier fuel, high temperature, low humidity, which is combustible to burn and prone to fire, so forest fire spreads faster in the southern slope than that in the northern slope.

The above simulation results fairly simulate the influence of different wind direction and wind speed, different terrain slopes and different combustible species on forest fire spreading process.

VI. CONCLUSION

According to the characteristics of cellular automata， which is discrete in time, space and states, and the characteristics of forest fire spreading process, this paper makes a detailed analysis and points out the key influence factors of forest fire spreading, and constructs a more micro forest fire spreading model which fits the actual spread process based on the foreign K-T model which uses cellular automata as the frame of building model.

This paper extracts and refines the key influence factors of forest fire spreading process, classifies the fuel according to the characteristics of the species of domestic fuel meanwhile, fully considers the influence of temperature of forest farm on forest fire occurrence, and reasonably analyzes and describes the two key factors of wind and terrain and makes a lot of innovation and exploration in both of their influence rules on the forest fire behavior to ensure the reliability and rationality of the model. Finally this paper develops CA Forest Fire Forecast formulation system adopting Matlab development platform based on the built forest fire spreading model. This system will give a better spread simulation process on the environment of different wind direction and wind speed, different terrain slopes and different combustible species.

Since the complicated process of forest fire burning, there are different degrees of internal relations between influential factors, so these influential relations remain to be further discussed, and it is still required to gather more and more comprehensive forest fire data to improve this model.

REFERNENCE

[1] R. Rothermel, “A mathematical model for predicting fire spread in wildland fuels,” Res. Pap. INT-115, Ogden, UT, US, Dept. of Agric., Forest Service, Intermountain Forest and Range Experiment Station,1972.

[2] G. D. Richards, “A general mathematical framework for modeling two-dimensional wildland fire spread, ”Int. J. Wildland Fire,Vol. 56, 1995 , pp.3–72.

[3] E. Pastor, L. Zarate, E. Planas, J. Arnaldos, Mathematical models and calculation systems for the study of wildland fire behaviour, Prog. Energy Combust. Sci. No.29, 2003, pp.139–153.

[4] H.Huaguo, Z.Xiaoli , W.Lei, “Simulation of forest fire spread based on a 3D-surface Cellular Automata Model.” Journal of Beijing Forestry University, Vol.27, No.3,2005, pp.94-97.

[5] Z. Yongzhong, E. Youhao, H. Tao, Z. Songbing, W. Jihe, “A ca-based information system for surface fire spreading simulation,” in: IEEE ,IGARSS’05 Proceedings, 2005, pp. 3484–3487.

[6] L.Yuewen,Y.Hongye , W.Shuo, Z.Chun , “Design and Implementation of CA-based Forest Fire Spread Model,” Journal of Catastrophology, Vol.24,No.3,2009, pp.98-102.

[7] C.Rong, Y.Liang, H.Yizhu, “Application of Cellular Automata Simulation in Marketing,” Prediction, No.2, 2000, pp.57-60.

[8] W.Haijun, Z.Wenting, C.Yingying , H.Sanwei, “Fire Spreading Model Based on CA Scope, ” Geomatics and Informa tion Science of Wuhan University, Vol.36, No.5,2011, pp.575-578.

[9] Z. Yujian, Z. Shuai, Z. Lei, L. Xuejun, “Simulation of Forest Fire Spreading Based on Geographic Cellular Automata,” Geography and Geo-Information Science, Vol.29, No.2, 2013, pp.121-124.

[10] W. Guangyu, “Meteorological and forest fire, ”Forestry of Gansu ,No.06, 2006.

[11] Z. Shangyin, Z. Canghan, C. Zhenghong,“Research on forest fire meteorological environmental elements and large forest fires,” Journal of Natural Disasters, Vol.19, No.2, 2000, pp.111–117.

[12] L. Liqin, N. Shukui, “Relationship between the climate change and the incidence of forest fires in China,”Journal of Anhui Agricultural Sciences Vol.38, No.22, 2010, pp. 101-106.

[13] Z. Zhanrong, Z. Jianjun, “Study on the model of wildland fire spread, ”Fire Safety Science, Vol.10, No.2, 2001, pp.83–87.

[14] S. Yanlong, S. L. fu, L. Changjiang, “A relation between forest combustible parameters and stand characteristics, ”Journal of Natural Disasters, Vol.13,No.6, 2004 , pp.70–75.

[15] Chandle, “Forest fire behavior and effects, Fire in Forest,”1983, pp.24–28.

[16] L. Xia, Y. Jiaan, “Constrained cellular automata for modelling sustainable urban forms,” Acta Geographica Sinica,Vol.54, No.4,1999, pp289-298.

[17] I. Karafyllidis, A. Thanailakis, “A model for predicting forest fire spreading using cellular automata, ”Ecol. Modell. Vol.99, No.1, 1997, pp.87–97.

[18] C. Zhe, S.Tao, Z. Linghan, Q. Qianqing, “Forest fire spread fast model based on 3D cellular automaton in spatially heterogeneous area,” Journal of Beijing Forestry University, Vol.34, No.1, 2012, pp.86-91.