Prediction of Fire Spread Based on Geographical Cellular Automata

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Abstract. China is a country with frequent forest fires. Forest fires not only damage the forest ecosystem, cause the loss of forest resources, but also threaten the safety of people's lives and property. If the spread trend of forest fire can be predicted quickly and accurately after the fire, it will be of great significance and role to put out the fire and reduce the loss and casualties. In this study, based on the in-depth comparison of domestic and foreign commonly used forest fire spread models and related algorithms, the geographic cellular automata is selected as the diffusion algorithm, combined with the revised Wang Zhengfei fire spread model, and the host development method is adopted to achieve the forest fire spread prediction. Through the comparative analysis of the prediction results in the actual cases, the error is within the acceptable range, achieving the expected effect, meeting the requirements of real-time and efficient simulation of forest fire spread, and providing reliable decision support for the management.

1. Introduction

Forest is an important natural resource, which is closely related to human beings. Its contribution to human beings is diverse. It not only provides all kinds of wood and economic plants, but also is the source of many foods. But the forest is being destroyed continuously now, and still faces many threats, among which forest fire is a big threat. The Australian forest fire, which burned for several months in 2019, destroyed the "heart of the earth" and brought great losses to the world. In April 2020 alone, there have at least five major fires. Such as Xichang, Linzhi and Panzhihua in Sichuan, Lijiang and Yiliang in Yunnan. To reduce the loss caused by the fire, on the one hand, monitoring must be strengthened, on the other hand, it is necessary to put out the fire in time.

Using computer technology to simulate the spread trend of fire can effectively improve the efficiency of fire fighting and reduce the loss and casualties caused by fire.

2. Selection of Prediction Model of Forest Fire Spread

For different countries and regions, the importance of many factors inducing the occurrence and spread of forest fires is not the same, which directly leads to the difficulty of using a unified model to express the occurrence and spread of forest fires. It is a great challenge to choose a correct forest fire spread model to simulate an actual forest fire accurately.

2.1 Rothermel Model of the United States:
The model is a semi empirical model, which requires more parameters to be input, some parameters need to be obtained by experiments, and parameters need to be updated in time according to different
conditions such as time and place. In most areas of China, there is no condition to provide these parameters.

2.2 Canada National Forest Fire Spread Model:
Canada forest fire spread model belongs to statistical model, it does not consider the physical nature of fire behavior, but through the collection, measurement and analysis of actual fire and simulation experiment data, establishes the model and formula. Its advantage is that it can easily and vividly understand the fire process and the whole fire process, can successfully predict the fire behavior under the condition similar to the test fire parameters, and can fully reveal the action law of the complex phenomenon of forest fire. Its disadvantage is that this kind of model does not consider any heat transfer mechanism. Due to the lack of physical basis, when the actual fire conditions are inconsistent with the test conditions, the accuracy of the statistical model will be reduced [4].

2.3 McArthur Model in Australia:
McArthur model can not only predict the dangerous weather, but also quantitatively predict some important fire behavior parameters. It is an indispensable tool for fire fighting. But this kind of statistical model does not consider any heat conduction mechanism, it is only a statistical description of the test flame, when the field fire is similar to the test fire, it can predict the useful results. Its application background is the winter wildfire forecast of New South Wales grassland in Australia, so its applicable combustible types are relatively single, mainly grassland and eucalyptus forest, which has certain reference value for forest fire prevention in South China [8].

2.4 Wang Zhengfei Model
The empirical model of forest fire spread put forward by Wang Zhengfei is mainly based on the data of more than 100 fire tests in Xing'an Mountains and Xiaoxing'an Mountains, and the initial spread speed is deduced:

$$R_0 = aT + bW - c$$

(1)

Where: $T$ is the temperature (°C); $W$ is the wind force (grade); $a = 0.053$, $B = 0.048$, $C = 0.275$. The model is suitable for the case of slope less than 60° and downwind uphill. The statistics is more accurate, and the spread parameters are easy to obtain, which is convenient and practical. However, the actual situation of fire is very complex. Mao Xianmin uses the exponential relationship to fit the relationship between the wind correction coefficient, the wind speed and the ground slope correction coefficient, and corrects the Wang Zhengfei model. The modified spread speed is:

$$R = R_0 K_s \exp (0.1783 V \cos \theta) \exp ((-1)^{3.533 \tan \phi})$$

(2)

Where: $R_0$ is the initial spreading speed, $K_s$ is the combustible correction coefficient, $V$ is the wind speed in the main wind direction, $\theta$ is the included angle of the main wind direction rotating clockwise to the specified direction, $\phi$ is the slope angle. When the terrain is uphill, $a = 0$; when the terrain is downhill, $a = 1$.

It can be seen that in Wang Zhengfei model after parameter modification, only the number of combustible configuration pattern, wind speed, wind direction, slope direction and temperature obtained by extraction and processing are needed to get the prediction results, which are more flexible than the original model. The $K_s$ check table is shown in table 1.

| Vegetation type | Water system bare land | Cultivated land | broad-leaved forest | Mixed forest | bushes | grassland | coniferous forest |
|-----------------|------------------------|-----------------|--------------------|-------------|--------|-----------|-----------------|
| $K_s$           | 0                      | 1.0             | 1.3                | 0.5         | 1.0    | 1.5       | 1.8             |

*Table 1.* $K_s$ lookup table of different vegetation types.
2.5 Prediction Model Selection.
Although the above researches have made some progress and achievements, but they are slightly inadequate in considering the impact of natural environment factors on neighborhood cells and sub neighborhood cells in the forest fire spread, and the simulation accuracy needs to be improved. Therefore, according to the characteristics of forest fire spread in China, based on forest fire spread models of Zhengfei Wang and Xianmin Mao combined with the principle of cellular automata, this paper studies the prediction of forest fire spread, fully considering the terrain factors such as slope, slope direction, wind speed, wind direction, temperature and other meteorological factors, as well as the vegetation factors such as combustible type and combustible bearing density, and calculates the situation of forest fire spread, including forest fire range, spreading speed, etc.

3. Application of the Algorithm of Geographical Cellular Automata
Cellular automata (CA) is a kind of grid dynamic model with discrete time, space and state, local space interaction and time causality. The model can simulate all kinds of extremely complex forms in the way of "bottom-up" self-organization evolution according to very simple state transition rules, reflecting the complexity scientific thought of "complexity comes from simplicity".

3.1 Neighborhood and State of Cell
Each cell uses 8 neighboring cells as its neighbor cells (NW,N,NE,E,SE,S,SW,W), as shown in Figure 1. The state of central cell will affect the state of 8 neighboring cells, as shown in Figure 2.

According to the change of time, the combustion states of neighboring cells can be divided into five categories: unburned = 0, just ignited = 1, violent burning = 2, start to extinguish = 3, and burnt = 4.

![Figure 1. Moore Neighborhood](image)

![Figure 2. Heat transfer from center cell to neighbors](image)

3.2 Cell Transformation Rules
In cellular automata, rules are defined locally in space. At the time of $t+1$, the state of cell is determined by its state at time $t$ and the spreading speed of eight neighborhood cells in a specific time step. The formula is:

$$S_{ij}^{t+1} = f(S_{i,j}^t, R_{i-1,j}^t, R_{i-1,j-1}^t, R_{i-1,j+1}^t, R_{i,j-1}^t, R_{i,j+1}^t, R_{i+1,j-1}^t, R_{i+1,j+1}^t)$$  \hspace{1cm} (3)

Where: $S_{ij}^{t+1}$ is the state function of the cell at $t+1$ time, and $R$ is the spreading speed of forest fire from the eight neighborhood $t$ time of the cell to the central cell. The cell spread rate of unburned and burned cells in the neighborhood is 0. If the square cell grid be a * a, and the time for the central cell to be ignited by the burned cells in the eight neighborhoods is as follows:

$$t_a = a/R_{ij} \quad \text{and} \quad t_d = \sqrt{2}t_a$$  \hspace{1cm} (4)

Stephen[3] deduced that 17% of the heat needed to ignite cells $(i,j)$ is released by cells on the diagonal, and the remaining 83% is released by two cells directly adjacent to each other. Therefore, according to the energy accumulation of neighborhood cell to central cell, the area of neighborhood cell spreading to central cell is calculated, and the state transition function of CA is defined as:

$$S_{ij}^{t+1} = S_{ij}^t + \left[ \frac{1}{4a} (R_{i-1,j}^t + R_{i,j-1}^t + R_{i,j+1}^t + R_{i+1,j}^t) \right] \Delta t + 0.17 \left[ \frac{1}{\sqrt{2a}} (R_{i-1,j-1}^t + R_{i-1,j+1}^t + R_{i-1,j-1}^t + R_{i+1,j+1}^t) \right] \Delta t$$  \hspace{1cm} (5)
If the time for a neighborhood cell to ignite a central cell is \( T_a \), the time for a diagonal neighborhood cell to ignite a central cell is \( t_d = \sqrt{2} T_a \). At \( t+1 \) time, if \( S_{ij}^{t+1} < 1 \), the cell \((i,j)\) does not burn; if \( S_{ij}^{t+1} < 1 \) and \( t < t_s + t_a \) (\( t_s \) is the time when the cell starts to burn), the cell \((i,j)\) burns and spreads to the neighboring cell; if \( (t+\Delta t) \geq (t_s + t_d) \) (\( \Delta t \) is an iteration time), the combustion cell goes out.

4. Experimental Data and Process of Forest Fire Spread Prediction

4.1 Experimental Data
This study takes Laoshan fire area on April 5, 2014 as the research scope. The highest temperature on the day of Laoshan fire was 30°C and the lowest relative humidity was 23%. The wind speed at the time of fire was about 9m/s and the wind direction was northeast by East. The location of the fire point is E120°36'52.452" N 36°12'22.901". The original data of the study area includes DEM elevation data of Laoshan Mountain, text data of wind observation points, vegetation distribution map, vector data of roads and water systems, satellite image of fire point and one hour fire spread in Laoshan area. As shown in Figure 3, Figure 4, Figure 5, Figure 6, Figure 7 and Figure 8.

4.2 Experiment Process
Firstly, according to the needs of the model, the collected data of the research area will be processed, including extracting slope factor and slope direction factor according to DEM data, importing the data of wind speed observation points into ArcGIS to calculate wind speed factor, wind direction factor and vegetation type factor, importing vector data of roads and rivers, and classifying the factors that affect the spread speed, using C++ programming language in the VS2012 platform, the cellular automata algorithm is implemented, the coordinates of the fire and the relevant control parameters are input, and the simulation of the fire spread in the study area is completed. According to the simulation results, the actual fire spread trend and the range of the fire spread are compared, and the conclusion is drawn. The experimental flow is shown in Figure 9.

Figure 3. Satellite image of Laoshan Forest Fire Point.

Figure 4. One hour satellite image of Laoshan Forest Fire.

Figure 5. Vegetation classification.

Figure 6. Slope direction.
4.3 Experimental Results:
In this experiment, the fire spread range of one hour and four hours after the fire is predicted respectively, as shown in Figure 10 and Figure 11; the comparison of the satellite images of one hour after the fire with Laoshan is shown in Figure 12. In practice, the range of fire spread in different time can be obtained by inputting relevant parameters according to different needs.
5. Conclusion

The prediction model of forest fire spread discussed in this paper fully considers the factors such as slope, slope direction, vegetation distribution, wind direction and wind field that affect forest fire combustion, uses the corrected Wang Zhengfei model and cellular automata algorithm to simulate the complex phenomenon of forest fire spread, and improves the simulation accuracy of forest fire spread. Compared with the actual situation of fire spread, it is found that the predicted results are close to the actual situation of fire spread, with small error and high reliability. After the combustion is blocked by the non combustible area (water system and road), it is consistent with the actual situation, which can meet the actual fire extinguishing needs, and has strong practical value. However, the spread of forest fire is a complex physical phenomenon, with uncertainty, especially the wind direction in mountainous areas is affected by the heat complex changes, in the early stage of the simulation and the actual fire has a good fit, the error is controlled within 6%. However, with the passage of time, the simulation error is large, especially under the action of wind, when multiple ignition points are caused by flying fire, the simulation error of fire spread becomes larger. In practical application, it is also necessary to timely adjust the ignition point and relevant wind direction, wind transformation data, etc. in combination with satellite image or aerial image results.

6. Reference

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