

Study On Forest Fire Spreading Model Based On Remote Sensing And GIS

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Abstract. Based on remote sensing and meteorological data of fire occurrence area, a forest fire spread model is established by means of such algorithms as combustible information extraction, calculation of forest fire spread velocity and elliptic model. The input data include vegetation type, forest water content, forest slope and slope direction, forest combustible materials, wind speed, wind direction and other data. Through the analysis of fire spread, duration and fire intensity, this model can quickly judge the impact range, development trend and damage loss of forest fire in real time, so as to provide decision basis for fire fighting and rescue command. Taking the Oroqen Autonomous Banner of Greater Khingan Mountains as the research area, this model was used to predict and verify the fire spread range and trend.

1. Introduction

Forest fire is a sudden, strong and harmful natural disaster. It not only endangers forest resources, but also seriously threatens people's life and property security, as well as ecological environment health. In order to prevent forest fire and put out forest fire in time, we need to study the time and space evolution of forest fire and provide scientific basis for controlling the spread of forest fire [1]. For nearly a century, human beings have been trying to explore the evoked factors and effective observation methods of forest fire, study the mechanism of burning and spreading, so as to achieve the ultimate goal of controlling fire. Forest fire spread is the main form of forest fire behavior, and its quantitative analysis and modeling is the research direction of many institutions. The appearance of computer, remote sensing and GIS technology makes it possible to develop the computer solution of forest fire spread model.

In the 1980s, with the development of 3S technology, the research on forest fire behavior simulation gradually turned to the quantitative simulation of spatial range. With the support of geographical information system and remote sensing technology, substantial progress has been made in theoretical and empirical simulation of fire field expansion and forest fire behavior prediction, which is gradually becoming practical [2-3].

It has been seen that the use of GIS and remote sensing technology plays an important role in forest fire prediction and prediction. At the same time, their extensive application in the international community and their role in social and economic development have proved that the combination of GIS and forest fire management will surely create enormous economic and social benefits [4].



Countries and regions such as Canada, Australia and the European Community have led the world in the development and application of forest fire prediction and forecasting systems. In addition to the application of some advanced communications, remote sensing and other equipment, another common feature of forest fire prevention system is the introduction of GIS concept [5]. For example, the FIRE management Information System (FMIS) used in Ontario of Canada is based on the ARCVIEW developed by ESRI. SALTUS system developed by the European Community has its own GIS expression system and has good 3D display and analysis functions.

In this study, meteorological and remote sensing data such as vegetation type, forest moisture content, forest slope map, slope direction, forest combustible material, wind speed and wind direction were used as input data. Based on RS and GIS technologies, flammable material information extraction, forest fire spreading speed calculation and elliptical model algorithm are adopted to analyze the fire spreading range and route, as well as the duration and intensity of the fire. It realizes the judgment of forest fire's influence range, development trend and various disaster losses in real time and quickly, and makes computer visualization. The model can provide an assistant decision-making means for forest fire prevention system, and thus provide a scientific basis for disaster prevention, mitigation and assessment of post-disaster losses.

2. Methods

According to the fire spread model, the characteristic quantities of fire spread and fire state can be calculated accurately. Then, the disaster information in the fire field is simulated with dynamic visualization method. The following are the main functions of the simulation of forest fire spread: 1) predict the trend of forest fire spread at a given fire site; 2) the model can manually set the initial ignition area according to the images of the fire field obtained by aviation and satellite, and predict the spread trend of forest fire on this basis; 3) support fire departments to establish forest fire isolation zones and predict the trend of forest fire spread on this basis. Accordingly, the fire department can establish a reasonable isolation zone to control the fire within the acceptable range. In order to realize the above functions, the model needs to include information extraction method of combustible materials, forest fire spreading velocity model and fire spreading prediction method.

2.1 Calculation of basic information data

2.1.1 Fuel information extraction

The combustible parameters involve nine physical quantities: load of dry combustible (W_0), density of drying particles (ρ_p), surface area to volume ratio (σ), water content of combustible (M_f), extinguishing water content of combustible (M_s), bed depth of combustible (δ), low heat content of combustible (h), total mineral content (S_T), effective mineral content (S_E).

2.1.2 Weather information extraction

In the algorithm, u_m is the average wind speed at the half-flame height and u_{10} is the average wind speed 10 meters above the ground. Then u_m can be calculated from the following formula:

$$u_m = u_{10} \times 2.3 \quad (1)$$

Where, u_m and u_{10} are in m/min.

2.1.3 Terrain information extraction

Topographic information data include slope (θ_s) and slope (θ_a) in radians, which are obtained by processing remote sensing data.

2.2 Forest fire spread rate model

The calculation of forest fire spread rate is based on Rothermel model [6]. In this model, the forest surface is regarded as a continuous distribution of porous fuel bed, and the spread of fire can be

regarded as the process that the flame ignites the unburned area from the burned area during the energy transfer process of heat conduction, heat convection and heat radiation. According to Rothermel model, the spread rate of forest fire is related to combustible information, meteorological information and terrain information.

2.2.1 Calculation of fire spreading speed in the absence of wind and slope

When there is no wind or slope, the spread speed of fire is only related to fuel, that is, the combustion speed R_0 is a function of several combustible parameters, which can be calculated by the following formula:

$$R_0 = \frac{I_{p0}}{\rho_b \cdot \varepsilon \cdot Q_{ig}} = \frac{I_R \cdot \zeta}{\rho_b \cdot \varepsilon \cdot Q_{ig}} \quad (2)$$

Where, ε is the effective heating coefficient of fuel, and the solving series of equations are shown in table 1.

Under the condition of no wind and no slope, the spread speed of forest fire is generally slow, usually several meters to ten meters per minute. However, in the actual fire field, due to the combined effect of slope and wind, the forest fire speed will increase sharply and the fire spread scope will expand sharply. In serious forest fires, most of them are caused by high wind speed and steep terrain, so that forest fires spread at a high speed. Due to the impact of terrain, it is inconvenient to rescue people, and sometimes it will cause heavy casualties of firefighters. Therefore, studying the fire spread under certain gradient and wind speed can calculate the fire spread more accurately.

Table 1. Equations to solve the fire spreading speed in the absence of wind and slope.

Name	Solve
Bed depth of combustible	$\rho_b = \frac{W_0}{\delta}$
Compression ratio	$\beta = \frac{\rho_b}{\rho_p}$
Optimum compression ratio	$\beta_{op} = 0.20395 \cdot \sigma^{-0.8189}$
Optimal rate coefficient	$A = \frac{1}{4.774\sigma - 7.27}$
Net fuel load	$W_n = \frac{W_0}{1 + S_T}$
Humidity damping coefficient	$\eta_M = 1 - 2.59 \frac{M_f}{M_s} + 5.11 \left(\frac{M_f}{M_s} \right)^2 - 3.52 \left(\frac{M_f}{M_s} \right)^3$
Mineral damping coefficient	$\eta_s = 0.174 S_E^{-0.19}$
Spread rate	$\zeta = (192 + 7.905\sigma)^{-1} \cdot e^{(0.792 + 3.7597\sigma^{0.5})(\beta + 0.1)}$
Precombustion heat	$Q_{ig} = 581 + 2594M_f$
Effective heat coefficient	$\varepsilon = e^{\frac{-4.528}{\sigma}}$
Maximum reaction rate	$\Gamma_{max} = (0.0591 + 2.926 \cdot \sigma^{-1.5})^{-1}$
Optimal reaction rate	$\Gamma = \Gamma_{max} \cdot \left(\frac{\beta}{\beta_{op}} \right)^A \cdot e^{A(1 - \frac{\beta}{\beta_{op}})}$
Response intensity	$I_R = \Gamma \cdot W_n \cdot h \cdot \eta_M \cdot \eta_s$
Spread	$R_0 = \frac{I_R \cdot \zeta}{\rho_b \cdot \varepsilon \cdot Q_{ig}}$

2.2.2 Correction coefficient of wind speed

In the case of wind, the Rothermel model regards the shape of fire field as an ellipse, which is consistent with the direction of the long axis of the ellipse along the direction of wind direction. In this direction, the fire spread speed is the maximum, and the maximum fire spread speed is expressed as:

$$R = R_0 (1 + \Phi_w) \quad (3)$$

Φ_w can fit the empirical formula from the experimental results:

$$\Phi_w = C(3.284 \cdot u_m)^B \cdot \left(\frac{\beta}{\beta_{op}} \right)^{-E} \quad (4)$$

$$B = 0.15988 \cdot \sigma^{0.54} \quad (5)$$

$$C = 7.47 \cdot e^{-0.8711 \cdot \sigma^{0.55}} \quad (6)$$

$$E = 0.715 \cdot e^{-0.01094 \cdot \sigma} \quad (7)$$

Where, u_m is the wind speed at the half-flame height; β is fuel compactness; β_{op} is the optimal fuel compactness; C, B and E are coefficients, which are determined by experimental fitting.

2.2.3 Correction factor for slope

In the case of slope, the shape of the fire field is ellipse, and the long axis of the ellipse is consistent with the slope. In this direction, the fire spread speed is the maximum, and the maximum flame spread speed is:

$$R_{max} = R_0 (1 + \Phi_s) \quad (8)$$

In addition, the slope correction coefficient is:

$$\Phi_s = 5.275 \cdot \beta^{-0.3} \cdot (\tan \theta_s)^2 \quad (9)$$

Where, β is the fuel compression ratio and θ_s is the slope.

2.2.4 Influence factor of wind force and slope

Although the Rothermel model gives the correction coefficient of wind speed and the correction coefficient of slope, it does not consider the influence of the Angle between wind direction and slope on the fire spread. Therefore, a geometric method is adopted for correction. The influence factor value under the combined action of wind force and slope is:

$$\Phi_{sw} = (\Phi_w^2 + 2\Phi_s\Phi_w \cos(\theta_a - \theta_w) + \Phi_s^2)^{\frac{1}{2}} \quad (10)$$

Under the combined action of wind speed (direction is θ_w) and slope (direction is θ_a), the forward direction of the fire head is the combined vector direction of Φ_s and Φ_w , the size is Φ_{sw} , the Angle is θ_{sw} , and the diagram of resultant effect is shown in figure 1. The maximum flame spread speed in the direction of wind force and slope vector force is:

$$R_{max} = R_0 (1 + \Phi_{sw}) \quad (11)$$

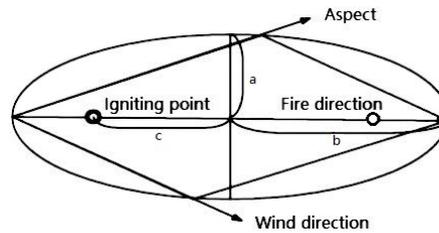


Figure 1. Vector superposition diagram of wind force and slope.

2.2.5 The rate of fire spread in any direction

The maximum spreading velocity under the combined action of wind speed and slope is determined by the correction coefficient of wind speed, wind direction Angle, slope correction coefficient and slope direction Angle. The propagation velocity R in any direction θ can be obtained by the characteristic parameters of the ellipse. The solving process is as follows.

First, the equivalent wind speed in the direction of maximum spreading velocity is calculated:

$$u_{me} = 0.3045 \left[\frac{\Phi_{sw}}{C} \cdot \left(\frac{\beta}{\beta_{op}} \right)^E \right]^{1/B} \quad (12)$$

Secondly, the ratio of long circumference to short circumference and the eccentricity are calculated:

$$LW = 1 + 0.0093226u_{me} \quad (13)$$

$$ee = (1 - LW^{-2})^{0.5} \quad (14)$$

Finally, the spread velocity in any direction is calculated:

$$R_{\theta} = \frac{(1 - ee)R_{max}}{1 - ee \cdot \cos(\theta - \theta_{sw})} \quad (15)$$

2.3 Fire spread prediction algorithm

The spread algorithm of forest fire is based on grid calculation. The main principle is to divide the simulated area into small units which are adjacent to each other. And the continuous spread of fire in a region is regarded as a discrete point-to-point spread between adjacent units.

2.3.1 32 neighborhood lattice patterns

Forest fire spread is simulated based on the principle of cellular matrix, which is applied to various complex geographical process simulation and has made great progress in the research fields of land use change, landscape simulation and urban expansion [7]. In this method, the ignition point is located at the center O of the cellular matrix, and the diffusion process of the central cellular to other 32 cellular neighborhood is studied (figure 2). In the diffusion simulation of cellular automata, only the boundary of cellular automata needs to be calculated. The boundary of cellular automata refers to that the cellular is in the state of "combustion", and there is the neighborhood of "non-combustion" state in the neighborhood of cellular units.

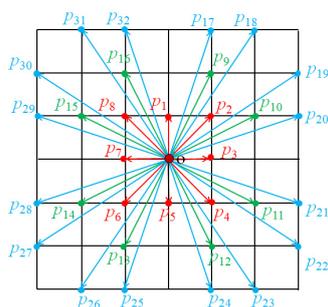


Figure 2. The position of any lattice point O and 32 neighborhood lattice points.

2.3.2 Raster-based fire prediction algorithm

The grid state is divided into five categories: non-combustible, combustible but not yet burnt, initial combustion zone, combustible and about to burn, and combustion zone.

The forest fire propagation simulation based on cellular automata can be divided into the following three stages: (1) in the initial stage, geographically separated cells are "non-combustible", while all other cells are "non-combustible"; (2) in case of fire, set the cell of fire to be in the state of "combustion" and begin to spread to its neighborhood; (3) in the process of diffusion of cellular in the "combustion" state to its neighborhood, only the boundary of cellular automata is calculated, while cellular in the internal "combustion" state is not calculated. In the diffusion simulation of cellular, a cellular in an "unburned" state may be affected by multiple cellular diffusion at the same time. The model selects the shortest time needed for the boundary of cellular automaton to diffuse to that cellular, and then changes the cellular state to a "burning" state. When the "burning" state cell lasts for a period of time, the state of the cell is changed to "extinguishing" state.

3. Model application

3.1 Study area

Daxing'anling forest region is the northernmost and largest forest area in China. It is an important timber production base and one of the few original forest areas in China. It is located in northwest of Heilongjiang province, northeast of the Inner Mongolia autonomous region and the northeast slope of the Greater Khingan Mountains. It across $50^{\circ} 08'$ to $53^{\circ} 34'N$, and $121^{\circ} 11'$ to $127^{\circ} 02'E$, north from Heilongjiang River, south to the upper valley of Xar Moron River. As a natural barrier of Songnen Plain and Hulun Buir Grassland, its ecological and social benefits are remarkable.

The Greater Khingan Mountains have a cold temperate continental monsoon climate, with obvious mountain climate characteristics, as well as rare precipitation in winter. This area belongs to the coniferous forest region in the Chinese vegetation regionalization. The main vegetation composition is the Hingan larch. Historically, the Greater Khingan Mountains have been a frequent area of fire, and the burning traces of living wood in the past 100 years can be seen everywhere, as well as the burnt black interlayer in the soil peat layer. The dry and cold weather conditions and high winds in the northern part of Greater Khingan Mountains make forest fires frequently occur in this forest area. The long-term accumulation of dead leaves in the forest leads to an increase in the amount of combustible materials, among which tall and dry wood is the main cause of lightning fire.

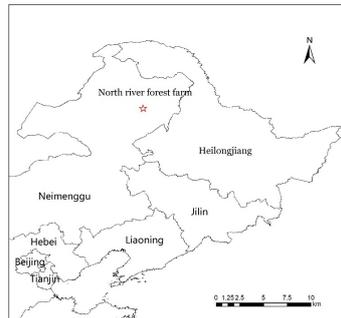


Figure 3. The location of the research area in Greater Khingan Mountains.

3.2 Data acquisition and processing

3.2.1 Topographic data

The topographic data required in this study are slope and aspect data, which are processed and obtained by ASTER GDEM data of 30m resolution.

3.2.2 Basic data

The basic data include administrative division data from China's basic geographic information vector atlas, as well as population, watershed area, roads, transmission lines and residential areas.

Through the projection transformation and cutting of the basic data, the position of the ignition point and fire area is confirmed, and the non-burning area is identified, so as to analyze the area affected by forest fire and make the disaster impact assessment and prediction.

3.2.3 Meteorological data

The meteorological data required by the model include wind speed and wind direction data. These data are obtained by solving the horizontal momentum equation and the non-pressure continuous equation by applying the principles of meteorological model and non-static non-pressure equation.

3.2.4 Vegetation data

The vegetation data used in the model include vegetation fuel parameters and vegetation type data. The vegetation fuel parameters involve nine physical quantities: load of dry combustible, density of drying particles, surface area to volume ratio, water content of combustible, extinguishing water content of combustible, bed depth of combustible, low heat content of combustible, total mineral content, effective mineral content. Among them, forest dry combustible content load was obtained based on Landsat8 remote sensing data and forest survey data, and was estimated using support vector regression method. Vegetation water content is obtained by using the near-infrared and short-infrared band of Landsat8 to obtain the ratio coefficient, which is then obtained according to the empirical coefficient. The remaining parameters can be obtained from the forest management department in the disaster area. Based on the multiperiod Landsat data, the vegetation types in the study area were divided by the supervised classification method and the support vector machine method.

3.3 Simulation of forest fire spread process

Based on the investigation of the recent forest fire incident, this study adopted the data of a forest fire in North River forest farm in the Oroqen Autonomous Banner of Greater Khingan Mountains, 2017, for the simulation of the model. The zonal vegetation in this area is mostly cold coniferous forest and medium temperature broadleaf forest, both of which are flammable tree species. These species are more likely to catch fire and spread quickly once they catch fire. In order to test the influence of topography and wind on the fire spread, the fire simulation was carried out in several cases of no wind, wind, steep slope and gentle slope.

First, the simulated starting point is located on the north slope of the east-west mountain. In the absence of wind, the burning area of the fire field after 1h is 30hm², and the fire field boundary length is about 3700m. In the case of wind, the burning area of the fire field after 1h is about 160hm², and the boundary length of the fire field is about 15000m, which indicates that the wind speed has great influence on the spread of forest fire.

In the fire environment is basically the same, the location of the fire point also plays an important role in the fire spread. When the fire was set on a steep slope, the fire area under the condition of no wind was 45hm², and the peripheral length of the fire site was about 6300m. The fire area under the wind was 249hm², and the boundary length was about 17000m. After several simulated ignition experiments, it can be seen that for the spread of fire on steep slopes, the expansion range of the fire field is relatively larger whether in the absence of wind or in the presence of wind. And whether the fire point is on a steep slope or a slow point, the wind speed has a great impact on the spread speed and range.

4. Conclusions

This study constructed a forest fire spread model based on remote sensing and meteorological data. It can make use of abundant ground object information of remote sensing image and combine with meteorological data to study the spreading range, spreading route, duration and intensity of fire, etc., so as to simulate and predict the occurrence, development and spreading process of forest fire.

Remote sensing image has rich ground object information, cellular automata has the ability to simulate the spatio-temporal evolution process of complex system, GIS has powerful spatial data management, spatial analysis and visualization ability, and the combination of the three can effectively realize the simulation of forest fire spread. However, the acquisition of satellite remote sensing data in this region is restricted by cloudy and rainy weather, and the quality of data preprocessing is directly related to the analysis accuracy of remote sensing images. It is necessary to consider the three-dimensional spreading model of forest fire and visualize the spreading results of underground fire and flying fire. In addition, forest fire spread is a complex process, so it is necessary to fully study various factors affecting forest fire spread and establish a more accurate forest fire spread model. Therefore, more accurate forest fire spread model and three-dimensional simulation are the future research direction of forest fire spatio-temporal evolution.

Acknowledgments

The authors appreciate the Project 2017YFC0803301 National Key R&D Program of China, and the Project 71673163 support by NSFC.

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