A COMPUTER SYSTEM FOR PREDICTING GROUND FIRE BEHAVIORS IN FOREST

Jiping Zhu*, Haihui Wang*, Junhua Zhang*, Qingan Wang*,
Wei Jiang+, and Baishui Zhu+

(* State Key Lab. of Fire Science, U.S.T.C, Hefei, P.R. China 230026)
(+ Fire Prevention Office of Anhui Province, Hefei, P.R. China 230001)

ABSTRACT

Based on the understanding of the nature of fire spread over surface fuels, in this paper a mathematical model has been developed for estimating surface fire behaviors under the conditions of complicated fuel types, changing terrain and weather. By means of modern software compiling techniques, a computer system has been successfully established, which can rapidly predict characteristic parameters of fire behaviors under different stages of fire spread.

Key words: ground fires, characteristic parameters of fire behaviors, prediction, computer system

1. INTRODUCTION

Forest fires include ground fires, crown fires, and underground fires. Among them, ground fires occur most frequently. It takes more than 90% in total of forest fires. Behaviour prediction of fire spread over ground fuels in forest is an important technique in fire prevention and extinguishment, and is the necessary foundation for the fire management.

Some excellent work on this area was done by USDA forest Service. Based on a number of experiments, a series of models to estimate the parameters of fire behaviors were developed, and a program -- BEHAVE (1986) -- to predict fire behaviors was made[1-2]. It can predict characteristic parameters of fire behaviors after inputting distribution parameters of surface fuels, condition of weather (such as speed and direction of wind) and terrain (slope). However, parts of the model are crude. For example, in the program, upon the ellipse assumption all probable fire fields were assumed as elliptic shapes. In complicated fire conditions, the predicted results are irrational.

Based on the understanding of the nature of fire spread over surface fuels, in this paper a mathematical model has been developed for estimating surface fire behaviors. By means of modern software compiling techniques, a computer system has been successfully established, which can rapidly predict characteristic parameters of fire behaviors under the conditions of complicated fuel types, changing terrain and weather

2. FORMULAS FOR FIRE BEHAVIORS CALCULATION

Characteristic parameters of fire behaviors are divided into characteristic parameters of fire spread including rate and direction of spread, and characteristic parameters of fire field including fire boundaries, areas of fire fields, and perimeter of fire boundaries.

2.1 Characteristic Parameters of Fire Spread

The ground fire spread can be actually regarded as a series of proceeding that the fire successively ignites the unburnt fuels contiguous to the flame front. The spreading velocity for no-wind and no-slope fires is

$$R_0=\frac{I_r\xi}{\rho_b\varepsilon Q_{ig}} \tag{1}$$

where I_r is the reaction intensity; ξ is the propagating heat flux ratio; ρ_b is fuel bulk density; ϵ is the effective heating number; Q_{ig} is the heat required to bring a unit weight of fuel to ignition.
Maximum fire spread velocity R for both wind and slope fires is

$$R=R_0(1+\psi_{sw}) \tag{2}$$

where ψ_{sw} is an overall rectifying coefficient, described as follows:

$$\psi_{sw}=\begin{cases} 0 & \text{(no-wind and no-slope)} \\ \psi_w & \text{(only wind)} \\ \psi_s & \text{(only slope)} \\ (\psi_s^2+2\psi_s\psi_w\cos\alpha+\psi_w^2)^{1/2} & \text{(both wind and slope)} \end{cases} \tag{3}$$

here ψ_w,ψ_s are the wind speed and slope rectifying coefficients, respectively, determined by empirical formulas. α is the angle between the wind direction and upslope direction clockwise.

The angle of the direction of maximum spread in the coordinate system, θ, is determined by

$$\theta=\arcsin\frac{\psi_w\sin\alpha}{\psi_{sw}} \tag{4}$$

2.2 Characteristic Parameters of Fire Fields

Among the parameters of fire fields, the fire field distribution at a certain moment and the corresponding fire boundary are the most important circles for the evaluation of fire field. If fire boundary has been calculated, it is easy to get other parameters of fire fields.

Considering a fire boundary line being composed of a great deal of ignition sources, the fire boundary extension to unburnt areas is performed by every ignition sources igniting unburnt fuels nearby separately, and new fire boundary is linked by all the newly ignited parts.

Therefore, to determine the extending fire boundary can be fulfilled by the following two steps: 1) To a certain ignition source from fire boundary line, fire spread within a short time interval is in the shape of ellipse by the assumption of ellipse, and the ignition source is at a focal point of the ellipse; 2) All the ignition sources from the fire boundary, spreading with the elliptical shapes respectively, make a series of ellipses, and the envelope of ellipse groups is considered as the new boundary.

Assuming that combustible materials are unitary distributed and on a same slope, the point fire spreads with the shape of ellipse. The direction of maximum fire spread is just on the direction of major axis of ellipse, and the point source is situated on one focus point of ellipse. The shape factor k which is defined as the ratio of semi-major axis to semi-minor axis in an ellipse is[4]

$$k=1+\lambda\left[\frac{\psi_{sw}(\beta/\beta_0)^{E_w}}{C_w}\right]^{\frac{1}{B_w}} \tag{5}$$

where λ is a coefficient; β is fuel packing ratio; β_0 is fuel optimum packing ratio; E_w, C_w and B_w are all the factors determined by experiment.

The maximum fire spread velocity R can be calculated by Eq.2 and burning time t is known, thus the ellipse is prescribed. The boundary of point fire spread is predicted.

As shown in Fig.1, at t moment fire boundary sits on the curve of $y'=f(x',t)$ in o'x'y' coordinate system which is set up in the ground surface around point C. After dt time interval the new boundary will situate on the curve of $y'=f(x', t+dt)$. Every points on the old boundary are new fire sources in dt time interval, and the new boundary of the fire is the envelope of all boundaries of point fire spread. The envelope has a tangent point with each boundary of point fire spread, and the tangent point C' can be regarded as the new location for point C propagating from the old boundary. As a result, the new boundary is constructed by each point on the old boundary propagating to the new location.

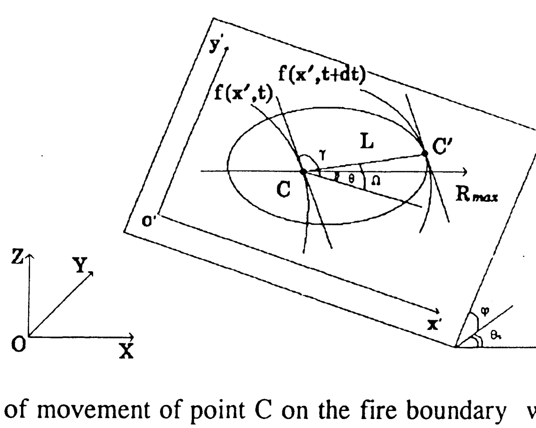


Fig.1 Schematic of movement of point C on the fire boundary within dt time interval.

From differential geometry, it can be proved that the slope of tangent line of old boundary at point C is equal to that of new boundary at point C'. Point C propagates to point C' on the new boundary without changing the slope of tangent line. Define L as a foundational increment of the distance for point C propagating from C to C' in dt time. It can be expressed below:

$$\mathrm{L}=R\cdot dt\cdot\frac{k-\sqrt{k^2-1}}{k-\sqrt{k^2-1}\cos\Omega} \quad (6)$$

here dt is time step; Ω is the angle of direction of foundational increment. It can be obtained

$$\Omega=\mathrm{arcctg}\left(\pm\sqrt{k^2-1}\cdot\sqrt{1+k^2\tan^2(\gamma-\theta)}-k^2\tan(\gamma-\theta)\right)+\theta \quad (7)$$

where γ is tangent slope; θ is the angle of maximum velocity direction in the $o'x'y'$ coordinate system. In Eq.7 the positive and negative signs are determined by the direction of normal line of the envelope.

Thus the new location can be determined by,

$$\begin{cases} x_i^{t+dt}=x_i^t+\mathrm{L}_i\cos\Omega_i\sin\theta_s+\mathrm{L}_i\sin\Omega_i\cos\varphi\cos\theta_s \\ y_i^{t+dt}=y_i^t-\mathrm{L}_i\cos\Omega_i\cos\theta_s+\mathrm{L}_i\sin\Omega_i\cos\varphi\sin\theta_s \\ z_i^{t+dt}=\mathrm{Z}(x_i^{t+dt},y_i^{t+dt}) \end{cases} \quad (8)$$

where φ is slope; θ_s is the angle of the upslope direction in the OXY coordinate system.

Therefore the new boundary at t+dt moment has been resolved by determining points $C_i^{t+dt}(i=1,2,\cdots,N)$.

In Fig.2, an $o''x''y''$ coordinate system is set up in the surface determined by three point C_{i-1}, C_i, and C_{i+1}. X"-axis is the line through C_{i-1} and C_{i+1}. Point O" is the centre of $C_{i-1}C_{i+1}$. Boundary segment through C_{i-1}, C_i, and C_{i+1} can be fitted with a parabola of which the symmetrical axis is y"-axis. The parabola can be expressed below

$$x''^2=2a_1(y''-a_2) \quad (9)$$

here a_1 and a_2 are coefficients.

The length of arc $C_{i-1}C_i$ can be obtained

$$C_{i-1}C_i=\frac{a_1}{2}\sqrt{\frac{2x_i''}{a_1}(1+\frac{2x_i''}{a_1})}+\ln(\sqrt{\frac{2x_i''}{a_1}}+\sqrt{1+\frac{2x_i''}{a_1}}) \quad (10)$$

Thus the perimeter of fire boundary can be determined by

$$\mathrm{P}=\sum_{i=1}^{\mathrm{N}}C_{i-1}C_i \quad (11)$$

In Fig.3, fire field in space is projected on the plane surface in OXY coordinate system which is divided by rectangular grids. The angles of projection in every cells are different from each other. Area of fire field can be calculated by

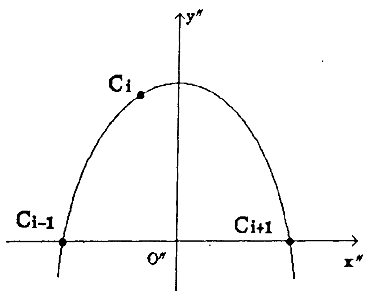


Fig.2 Boundary segment fitting with parabola

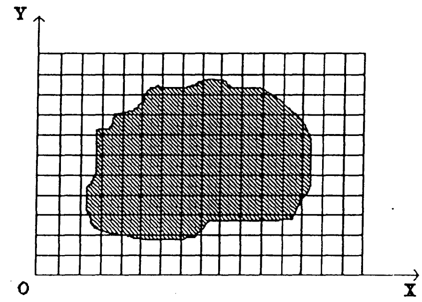


Fig.3 Projection of fire field in coordinate OXY

$$S=\sum_{i=1}^{N}\frac{S_i}{\cos\varphi_i} \tag{12}$$

where S_i is area of each shadow block; φ_i is the angle of slope of each cell.

3. THE COMPUTER SYSTEM

3.1 Numerical Computation Method[4]

Ground surface is divided by rectangular grids which have the same length at the directions of x-axis and y-axis, respectively. Moving grids are established on the boundary line of a fire. The grid point C_i has the data structure of $\{x_i,y_i,z_i,L_i,R_i\}$. Here (x_i,y_i) marks the location for point C_i; z_i records the height; L_i records the serial number of the left point and R_i records the serial number of the right point.

In the process of computation, the cell (j,k) at which the point C_i^t is located should be conformed at first by its coordinate (x_i^t,y_i^t), then the velocity of fire spread of the point C_i^t can be calculated by Eq.2, Eq.3, and Eq.4.

Fitting three points C_i^t, left point C_{Li}^t, and right point C_{Ri}^t with parabola of which the axis perpendicular to the line between C_{Li}^t and C_{Ri}^t, and regarding this parabola as the boundary at C_i^t, the slope of tangent line of boundary at C_i^t is equal to that of the parabola. Then the new location of the point C_i^{t+dt} can be determined by Eq.6, Eq.7, and Eq.8.

To every grid points $C_i^t(i=1,2,\cdots,N)$ on the old boundaries, the same computation procedures are taken to determine the new location. The new boundary is determined by points $C_i^{t+dt}(i=1,2,\cdots,N)$. Then perimeter of the boundary and the area of fire field can be estimated by Eq.10, Eq.11, and Eq.12. Fig.4 shows the computation procedures.

3.2 Overall Design of System

The system is designed as Object-Oriented (OO) style, by use of the most widely used language C++. The data of each module is independent on those of another modules. Then every module is a package. If the customer add functions or increase the level in this system, the only thing will do is to add new packages or revise the inner part of some packages. The

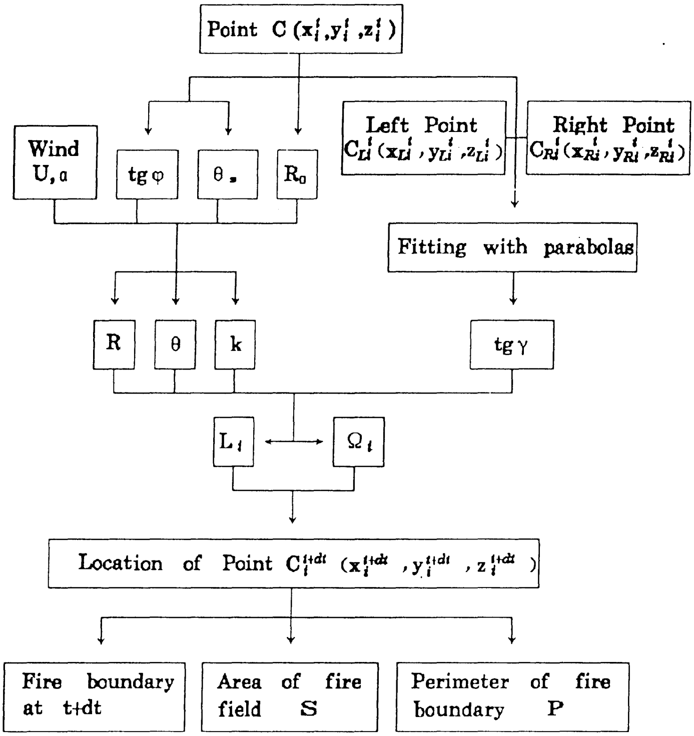


Fig.4 Computation Procedures

revision of one part have little influence on the others. These advantages will make convenience for maintenance.

In order to have a good interface between personnel and computer, the system uses Turbo Vision menu techniques to make multiple level menu, in which window can be overlapped. The item in the menu can be selected through keyboard or mouse.

The system is composed of main program, input, computation, and output program. The structure of the system and function of each part are shown in Fig.5.

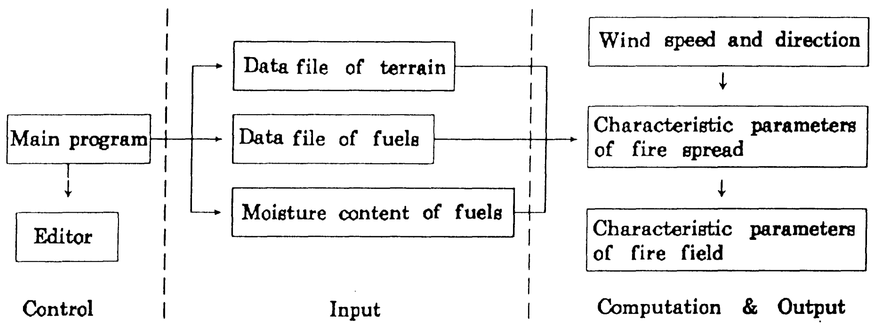


Fig.5 Structure of the system

To a certain area in forest, terrain datum and datum of fuel distributions must be obtained at first. When predicting calculation is done, terrain and fuels distribution are imported from data files. After importing current moisture content of fuel, the program of computation can predict fire boundaries and show results on screen in graphical mode. In the process of calculation, customers can change speeds and direction of wind whenever necessary. Thus, estimation of the boundaries of fire spread under any circumstances can be realized.

3.3 Graphically-Displayed Output

In this system the method of drawing contour lines is used to display the terrain of a certain zone of the forest.

To some typical fuel types, including non-fuel zone, river, etc., different patterns and colours for filling are designed. Filling each cell of fuels with a certain mode of the fuel types, the distribution of fuels can be seen on the screen.

To realize graphically displayed output on screen, first of all, the coordinates of all grid points on the moving grid must be changed to the corresponding coordinates of the screen which make up a polygon. Then fire boundary can be drawn on screen by using the function of drawing and filling a polygon. Displaying fire boundaries at each moment continuously, it can make vivid pictures of spreading fires.

Fig.6 is an example of system output. The left rectangle is the window show terrain and fuels distribution of a certain zone in forest. Fire spreading process are simulated in it, too. The right and upper rectangle is a window which can amplify a certain part of fire spreading areas. There is a clock which show burnt time and a direction clock which show direction of wind. Near the bottom of the screen there is a slender rectangle in which the length of a coloured block represents speed of wind. All kinds of function keys of system are shown in the bottom line of figure. Computation can be paused or broken by these keys. Then, time interval or speed and direction of wind can be changed whenever necessary and different field can be chosen to amplify.

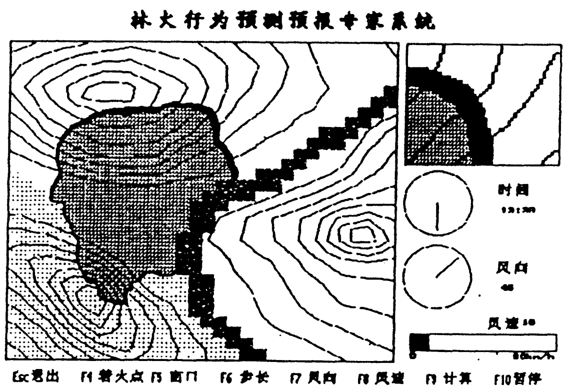
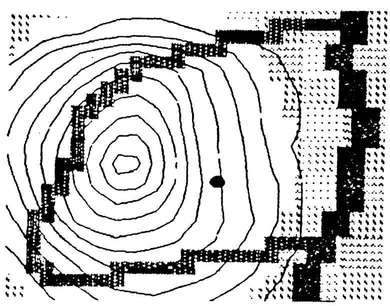


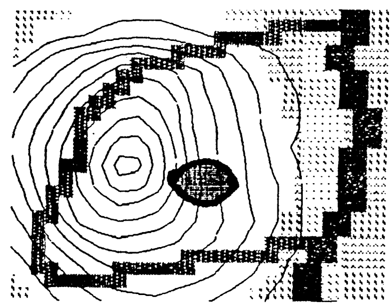
Fig.6 Graphically-displayed output

4. RESULTS AND DISCUSSIONS

Fig.7 is an example for predicting fire boundary for more than one type fuel distributions, under a more complex terrain condition which has the area of $500m$ x $500m$. Tab.1 shows the area of fire fields and perimeter of fire boundaries under different stages of fire spread. A series of circular lines in the picture are contour lines which represent a mountain. The balance of height between two contour lines are $8m$. The black belt on the right side of the mountain represents a river with the width of $40m$. The thin black belt



(a)



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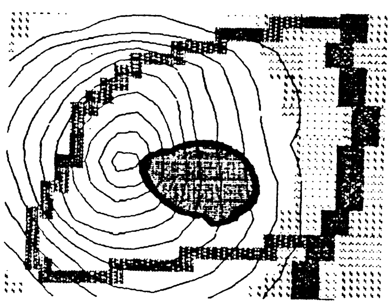
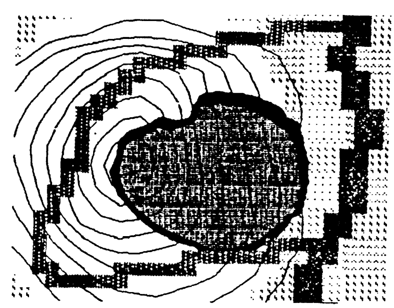
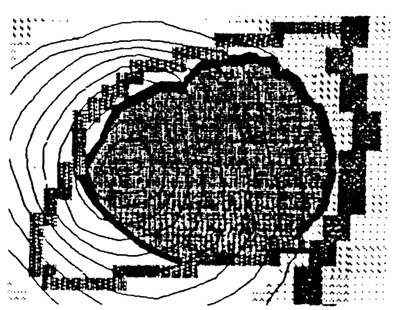


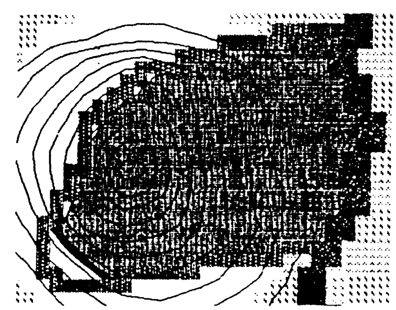
(c)



(d)



(e)



(f)

Fig.7 Distributions of boundaries of fire spread over several kinds of combustible materials with complicated terrain. (a) 20 minutes after ignition; (b) 1 hour and 20 minutes after ignition; (c) 2 hours and 40 minutes after ignition; (d) 3 hours and 50 minutes after ignition; (e) 5 hours and 10 minutes after ignition; (d) 7 hours and 40 minutes after ignition.

winding on the mountain is a man-made firestop road. And the width of the road is 20*m*. The test was done in the circle which is composed of the firestop road and the river. In point shadow regions short grass grows, with 0.30*m* in depth, 0.18kg/m^2 in fuel load, and 20% in moisture content. Brushes with 0.30*m* in depth cover in white regions, which have the same fuel parameters as the example above. At the initial stages of the test there are no wind. The distributions of fire boundaries which are simulated by this system are shown in Fig.7. Fig.7(a) gives the boundary distribution of the fire within 20 minutes after ignition. Compared the shapes of fire boundaries within 1 hours 20 minutes and 2 hours 40 minutes after ignition (Fig.7(b), Fig.7(c)), it can be seen that the fire spreads fast along the upslope direction although the slope is not so sharp. Tab.1 also shows that area of fire fields and perimeter of boundary are increased rapidly at the same time. At the time of two hours and forty minutes after ignition, there is a wind above the test areas, which has the speed of 3*km/h* and with the direction of east to south 55° . One hour and ten minutes later, part of the fire boundary comes across the firestop road and stop moving foreword (Fig.7(d)). In addition, at the same time downslope fire changes to plain fire. These are very close to the test results. Within 5 hours and 10 minutes after ignition, main areas in the circle regions is burnt by the fire (Fig.7(e)). The fire is close to extinct at the time of 7 hours and 40 minutes after ignition (Fig.7(f)). The area of fire regions and perimeter of fire boundaries are nearly not changed (Tab.1).

Tab.1 Area of burnt zones and length of boundaries under different stages

t	0:20	1:20	2:40	3:50	5:10	7:40
S(m^2)	278.3	3819.1	12031.0	35139.1	62222.8	68750.6
P(m)	67.2	258.5	450.7	750.9	1000.5	1250.4

Tab.2 shows the Comparisons of fire spread velocities between calculated results and wildland tests. The 1st and the 2nd tests were done in a middle- age Pinus Massoniance forest in Shunchang areas, Fujian Province. The 3rd and the 4th were done in a middle-age Pinus Yunnanensis forest in Yipinglang areas, Yunnan Province. Fuel types, terrain and weather conditions of each test are given in Tab.2. It can be seen that the relative errors between calculated results and wildland tests are all less than 30%. The calculated results are close to the reality.

Tab.2 The Comparisons of fire spread velocity between calculated results and wildland test results

	Slope	wind		dead fuel			live fuel			R (upslope)			R (downslope)		
	%	U m/s	α °	depth m	load kg/m^2	M_f %	depth m	load kg/m^2	M_f %	Exp. km/h	Cal. km/h	Error %	Exp. km/h	Cal. km/h	Error %
1	44.5	3.60	339	0.20	1.92	23.4	1.6	1.23	57.2	0.402	0.427	6	0.0756	0.059	22
2	44.5	8.28	24	0.20	1.92	23.4	1.6	1.23	57.2	0.600	0.708	18	0.0804	0.071	12
3	67.5	—	—	0.10	1.15	19.1	1.2	0.18	84.2	0.276	0.234	15	0.0156	0.017	9
4	36.4	—	—	0.12	1.25	18.8	1.3	1.21	83.5	0.252	0.218	13	0.0150	0.016	7

5. CONCLUSIONS

Based on the model for estimating surface fire behaviors, by means of modern software compiling techniques, a computer system has been successfully established.

The system can give reasonable and reliable results for ground fires under the circumstance of complicated distributions of fuels (include non-fuel zone, river, etc.), the circumstance of sharply changing terrain, and complex weather conditions such as speed and direction of wind that maybe change at any time.

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