Arrangement of the Computer Code for the Prediction of Forest Fire Spread

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ABSTRACT

The computer code for the prediction of forest fire behavior is presented. Basic concept of study is a combined approach to the problem, including the original formulation of fire spread mathematical model based on the radiation heat transfer mechanism, classification of natural fuels using the forest inventory data and programming realization of fire simulation code which is compatible with commonly used geographic information system.

KEYWORDS – Fire spread model, Flame radiation, Forest fire, Vegetation fuel, Computer simulation.

NOMENCLATURE

C - Specific heat of fuel;
D - Width of burning zone;
H - Flame height;
h - Thickness of fuel bed;
L - Flame length above fuel surface;
l - Free path of radiation;
M - Moisture content of fuel;
Q - Heat of vaporization;
q - Heat flux;
R - Rate of fire spread;
T - Temperature;
U - Wind velocity;
V - Buoyancy velocity;
W - Fuel loading;

Greek

γ - Angle between flame and fuel's surface;
ε - Emissivity;
ρ - Bulk density of fuel;
ν - Surface-to-volume ratio;
σ - Stefan-Boltzmann constant;
Φ - Flame angle factor;

Subscripts

0 - Initial;
eff - Effective;
F - Flame;
I - Inward;
m - Meteorological data;
O - Outward;
S - Surface;

INTRODUCTION

The development of the computer code for the prediction of forest fire behavior provides highly desired tool for fire fighting practice. The implementation of such work faces highly contradictory requirements. The final product must: be comprehensive to describe the natural fuel's burning; be universal and should not depend upon the specific condition; be automated and need a minimal supervised control; be simple in use; and, finally, be able to predict fire behavior with appropriate accuracy. Following these purposes, the solution of problem includes several steps.

First, a mathematical model of forest fire spread has to be involved to predict the spread rate. A significant number of such models has been proposed (see a comprehensive review of Weber [1]). In presented study the model of Telitsyn [2-4] is used, the details are described in next section. Then, the algorithm for approximation of fire perimeter is needed to simulate the fire propagation process. Commonly, two approaches are used [5-7]: a point technique and wave principle of which the latter one is used here due to its higher accuracy, despite a much complicated realization. Next step, surely the most complicated and unsolved, is fuels classification [8-10], actually, obtaining the parameters affecting the fire spread process from characteristics of forest itself. A simplified algorithm is proposed below, using the standard inventory data. Finally, as achieved in study [11], the developed computer code is to be arranged as an integrated part of a general system for monitoring of forest resources with high level of compatibility between mapping, and database processing.

FIRE SPREAD MODEL

The energy balance in a fuel bed moving with a steady velocity R is expressed in general form as

$$\int_S q_S dS = R\rho\left[C(T_S - T_0) + QM\right]h. \tag{1}$$

Since radiation is assumed here to be dominant heat transfer mechanism the heat flux is expressed by Stefan-Boltzmann law:

$$q = \varepsilon\sigma(T_F^4 - T_S^4). \tag{2}$$

The other heat transfer mechanisms (due to conduction and convection, including turbulence) which possibly are not negligible can be expressed, with a certain degree of roughness, in terms of radiation heat flux by introducing an appropriate value of emissivity ε in Eq.(2) unless a physical disagreement be found out. Actually this has been done because emissivity has been determined through experimental data on fire spread rates. By the primary concept employed in a model [2-4] presented in this study, two modes of heat flux have been distinguished: the 'inward' radiation describing the heat transfer inside a fuel bed and the 'outward' (external or flaming, by other words) one corresponding to heat flux from the flame zone absorbed on a fuel's surface along a fuel bed. Thus, the left-hand integral of Eq.(1) is written as

$$\int_S q_S dS = q_I h + q_O \Phi L. \tag{3}$$

Two different modes of heat flux correspond to different physical meanings of fuel loading. While the inward heat flux relates to the overall fuel loading of fuel bed in conventional sense $W = \rho h$, the outward heat flux absorbed on a fuel's surface heats up the thin fuel's layer adjacent to surface. For this case the effective fuel loading is expressed as $W_{eff} = \rho_{eff} h_{eff}$ where ρ_{eff} is a density of particles of which the foliage consists. Involving the free path of radiation in a fuel, the effective fuel loading can be expressed as

$$W_{eff} = \rho l, \tag{4}$$

where free path of radiation is determined through the correlation between fuel's bulk density, particles density and surface-to-volume ratio:

$$l = \frac{1}{\nu}\frac{\rho_{eff}}{\rho}. \tag{5}$$

Thus, the formula for fire spread rate is derived from Eq.(1) as

$$R = \frac{\varepsilon_I \sigma (T_F^4 - T_S^4)}{\rho\left[C(T_S - T_0) + QM\right]}\left(1 + \frac{\varepsilon_O \Phi L}{\varepsilon_I l}\right). \tag{6}$$

The model has been tested [2] using a large amount of available experimental information that resulted the following approximation for emissivity:

$$\varepsilon_O = 1 - e^{-0.16D}, \tag{7}$$

$$\varepsilon_I = 1 - e^{-0.16(D+0.4)}. \tag{8}$$

Apparently, the dependence of emissivity upon the width of burning zone shows the same correlation for both introduced modes of heat flux, but some correction factor (0.4) is included into the formula for inward radiation emissivity, Eq.(8). This coefficient stands for the case of fire of minimal intensity (for example, the fire spreading downward along a vertical layer of fuel or fire spreading opposite to the strong wind) where flame length over the fuel's surface became negligible and outward heat flux vanishes in Eq.(6). Such fire spread process is governed by heat transfer from glowing ember to virgin fuel. The additional correlation for burning zone width, flame angle factor, angle itself, buoyancy velocity, flame height and flame length are estimated as follows [2-4]:

$$D = l + \frac{\varepsilon_O \Phi L}{\varepsilon_I}, \tag{9}$$

$$\Phi = \frac{1 + \cos\gamma}{2}, \tag{10}$$

$$\cos\gamma = \frac{U}{\sqrt{U^2 + V^2}}, \tag{11}$$

$$V = 2.5H^{0.5}, \tag{12}$$

$$H = A_H (WR)^{0.5}, \tag{13}$$

$$L = H / \sin\gamma, \tag{14}$$

and other parameters of Eq.(6) are assumed to be constants [2- 4]: $T_F = 1200\,K$; $T_S = 573\,K$; $T_0 = 293\,K$; $C = 1400\ J/(kg \cdot K)$; $Q = 26000\ J/kg$ and $\sigma = 5.67 \cdot 10^{-8}, W/(m^2 K^4)$.

The non-linear equation (6) for the prediction of fire spread rate was solved by successive substitutions. The convergent solution has been achieved for whole range of investigated input data. The coefficient A_H in Eq.(13) has been estimated [2] through the comparison of calculated results with available experimental data. It resulted $A_H = 2...7$ depending upon the fuel's type. Field observations of the effect of wind on the forest fire spread rate showed the nearly linear character [3]:

$$R = R_*(1 + kU), \tag{15}$$

where k is a constant close to unity and R_* is the spread rate in 'no-wind' conditions which is determined from Eqs.(6), (10) and (11) as

$$R_* = \frac{\varepsilon_l \sigma (T_F^4 - T_S^4)}{\rho [C(T_S - T_0) + QM]} \left(1 + \frac{\varepsilon_O H}{2\varepsilon_l l} \right). \tag{16}$$

From analysis of Eqs.(6), (15) and (16) one should note that linear dependence expressed by Eq.(15) is rather hardly expected as an explicit correlation, but such assumption is usually considered reasonable due to character of dependence of flame angle factor upon wind velocity through Eqs.(10) and (11).

For the prediction of local fire spread rate the employment of Eq.(6) requires the information on local fuel properties such a moisture, fuel loading, density which, relating to the investigation of fire spread process in the conditions of real forest, are not available as a continuous parameters in time and space. Hence, some discrete classification is to be introduced for fuel types within which the overall fuel's characteristics are assumed to be uniform.

CLASSIFICATION OF FUELS TYPES

In order to approach the mathematical model to practical needs, the formula for fire spread rate is expressed as

$$R = k_1(k_2 - 1)(1 + k_3 U_m). \tag{17}$$

Here k_2 is Fire Danger Index, k_1 is 'basic' spread rate, k_3 is coefficient standing for effect of wind on the spread rate and U_m is wind velocity obtained from meteorological data.

The combination of factors containing k_1 and k_2 in Eq.(17) represents the spread rate R_* under the absence of wind as defined by Eq.(16). Unlike a bulk density and fuel loading which can be assumed constant for some fuel type, the moisture content is a certain function of weather. According to regulations of Federal Forest Service of Russia, Fire Danger Index is counted by integer numbers from 1 (zero probability of fire) to 5 (maximal fire danger). In physical sense, higher values of Fire Danger Index decreases the moisture content M in Eq.(6) which has an influence of inverse proportion on the fire spread rate. Thus, it is assumed the Fire Danger Index itself has a linear influence on the spread rate. The 'basic' spread rate k_1 is determined from Eq.(16) using the fuel's properties such a bulk density, fuel loading and moisture content corresponding to 'basic' condition, i.e. when the Fire Danger Index is 2.

The next step toward the development of practically applicable model is getting over the gap between characteristics required to calculate the fire spread rate and information on forest properties available from inventory data which don't reveal explicitly a single parameter ever mentioned above. The typical approach (for example [8,9]) to do that is a supervised evaluation of vegetation characteristics according to accepted fire behavior model. The result is a mostly descriptive matter with limited use of quantitative parameters of standard inventory data. Since computer database is being used for inventory data collection and analysis the partial use of unsupervised data processing is a way to automate this work. Such problem has been studied in [11], but the algorithm of fuels layer creation has not been described in details.

The simplified algorithm for fuels classification presented below is an attempt to combine directly the inventory data and fire spread model. On the present stage the analysis is limited by the condition of spring and fall season as a most fire dangerous period. Hence, the effect of green fuel component is excluded and crown properties are determined by coniferous species only. According to Eq.(17), two parameters, k_1 and k_3, have to be estimated. As it is assumed here the 'basic' spread rate k_1 is affected mostly by the underwood characteristics such a type of dominant species and its density. The effect of wind velocity on the spread rate is described by coefficient k_3, which depends upon the canopy closure of conifers. Both coefficients are divided into four categories, which give 16 possible fuels types. However, not all of them can exist such a combination of high canopy closure and dry underwood species. Totally 12 types have been distinguished as indicated in Table 1.

Table 1. Parameters of fuels classification.

No.	Coniferous canopy closure, percent	k_3	Underwood		k_1, *m/hour*
			Type of species	Density	
1	0-20	1.0	Non-moist	Any	12
2	0-20	1.0	Moist	Low	10
3	0-20	1.0	Moist	Moderate	4
4	0-20	1.0	Moist	High	2
5	20-40	0.5	Non-moist	Any	12
6	20-40	0.5	Moist	Low	10
7	20-40	0.5	Moist	Moderate	4
8	20-40	0.5	Moist	High	2
9	40-60	0.3	Non-moist	Any	4
10	40-60	0.3	Moist	Any	2
11	60-80	0.1	Non-moist	Any	4
12	60-80	0.1	Moist	Any	2
	80-100	0.1	Any	Any	2

FRAMEWORK OF COMPUTER CODE

The general scheme of developed computer code for the prediction of forest fire behavior is presented in Fig.1. the code is based on the geographic information system

(GIS) which is being currently created as a monitoring and operating tool for the management of forest resources. GIS considered here is arranged on the base of ArcTools and compatible softwares as adopted by Russian Forest Service for Khabarovsk Territory. Two parts of GIS, the map layers and inventory database are inputs for ArcView graphical interface allowing to create a problem oriented maps by involving some data processing. The fuel types map is created by using the data analysis corresponding to fuels classification described in previous section. As vector layers and fuels data are brought into ArcView interface the fuel types map containung the forest area of specific location and of appropriate scale is created. This map is transfered into fire simulation code in the form of raster layer where information on fuels characteristics, coefficients k_1 and k_3 of Eq. (17), are stored as pixel's colours corresponding to fuel types introduced in Table 1. The weather condition, another input for fire simulation code, provide the values of the coefficient k_2 (Fire Danger Index) and wind's velocity and direction.

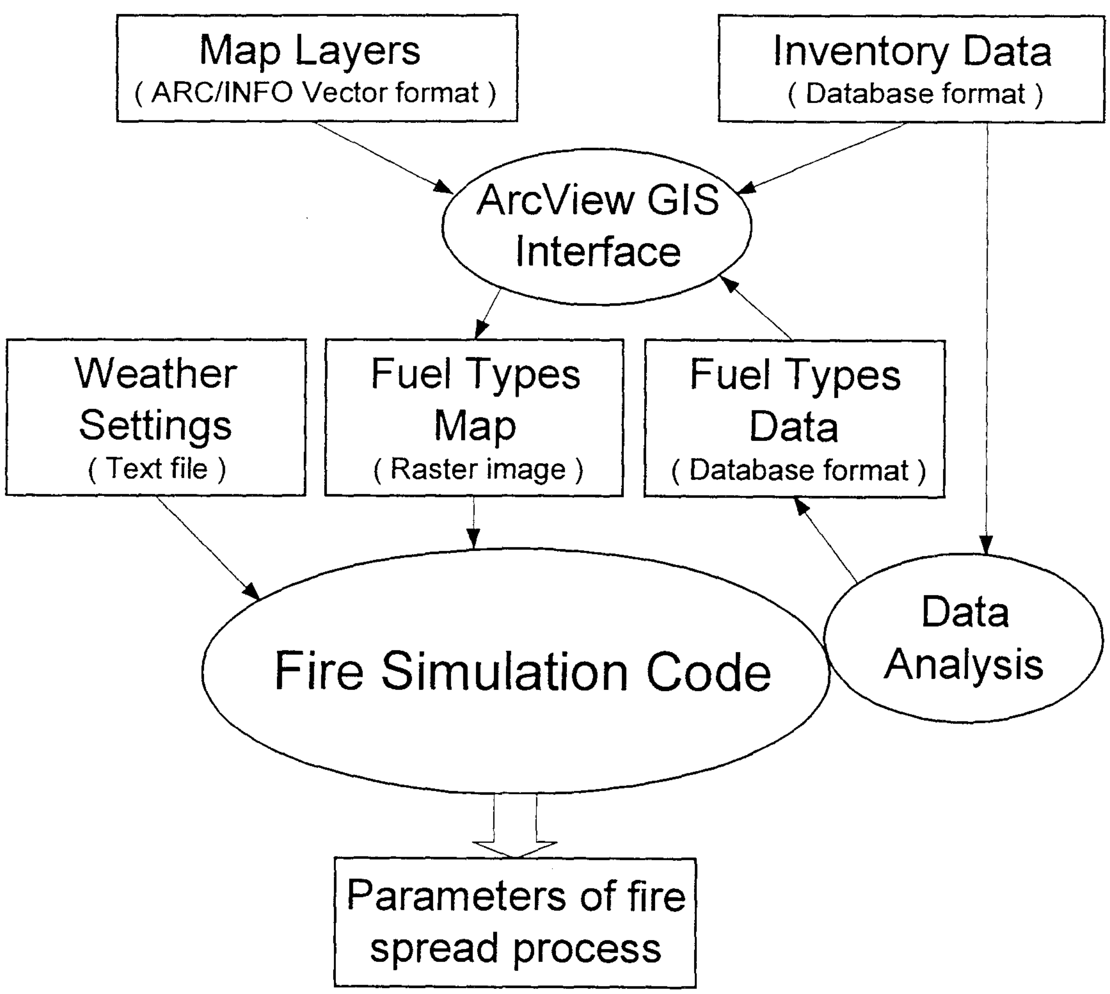

Fig.1 Framework of the computer code.

The algorithm for the approximation of fire perimeter is based on the Huygens' wavelet propagation principle [5] and optimization procedure [7] for overcome the possible complicated situations such a concave points, internal loops and overlapping of fire perimeters.

EXAMPLE OF FIRE SPREAD SIMULATION

Figures 2-4 present the results of simulation of fire spread process and simultaneous construction of fire-break line. Analysing the final location, one can estimate the tactics chosen for fire suppression. While the upper branch was built up properly, the lower one contradicts the safety regulations because of very close location of leading edge of fire front and acting facility.

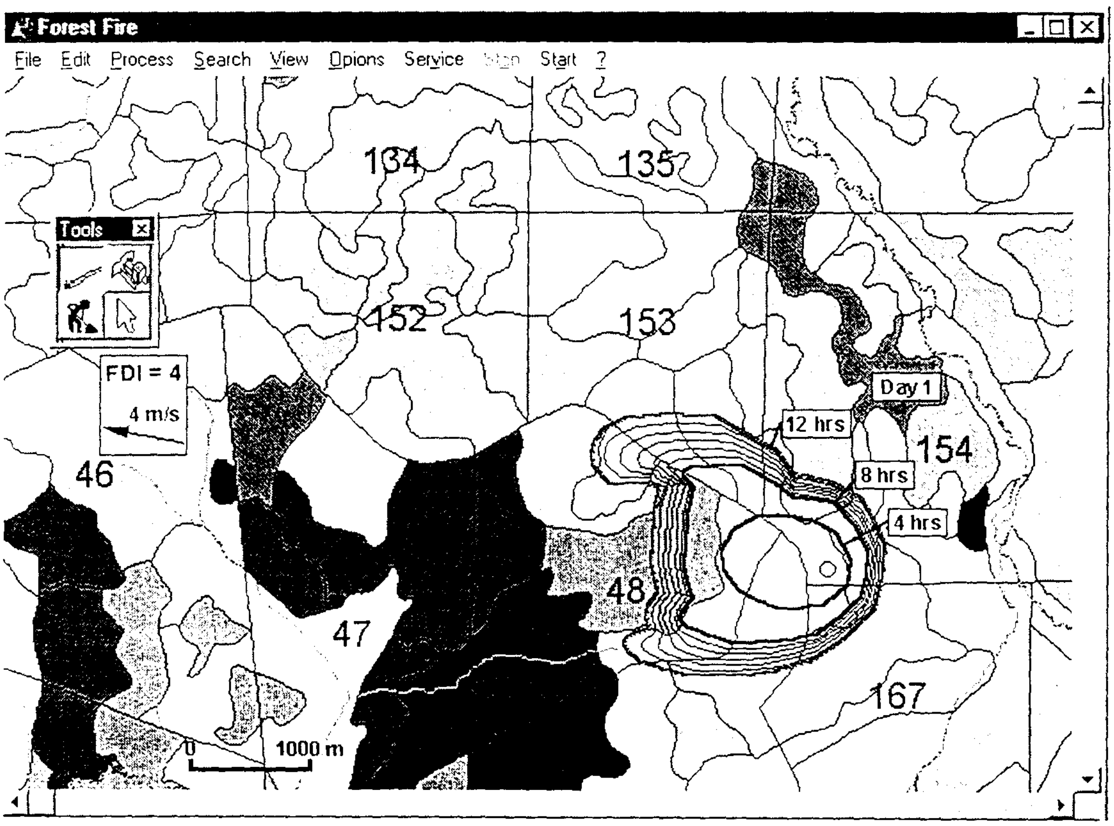

Fig.2 Fire perimeter distribution during the first day of propagation

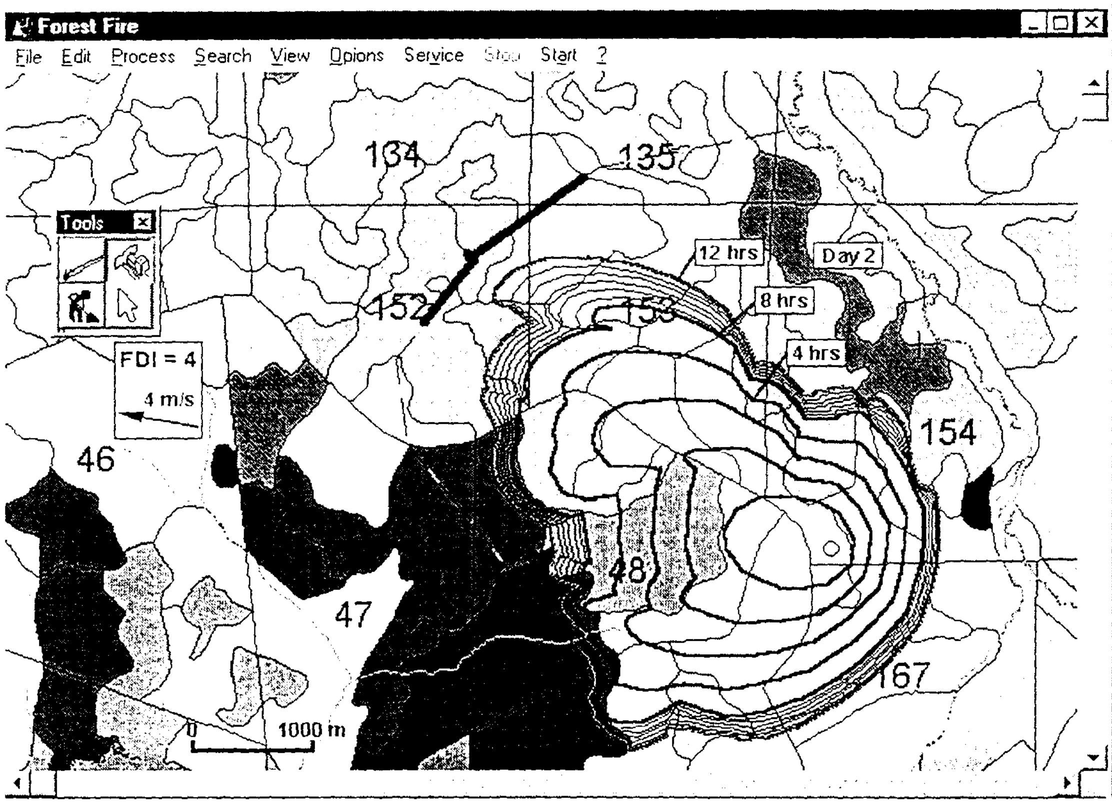

Fig.3 Fire perimeter distribution during the second day of propagation. The fire-break line is begun to build up.

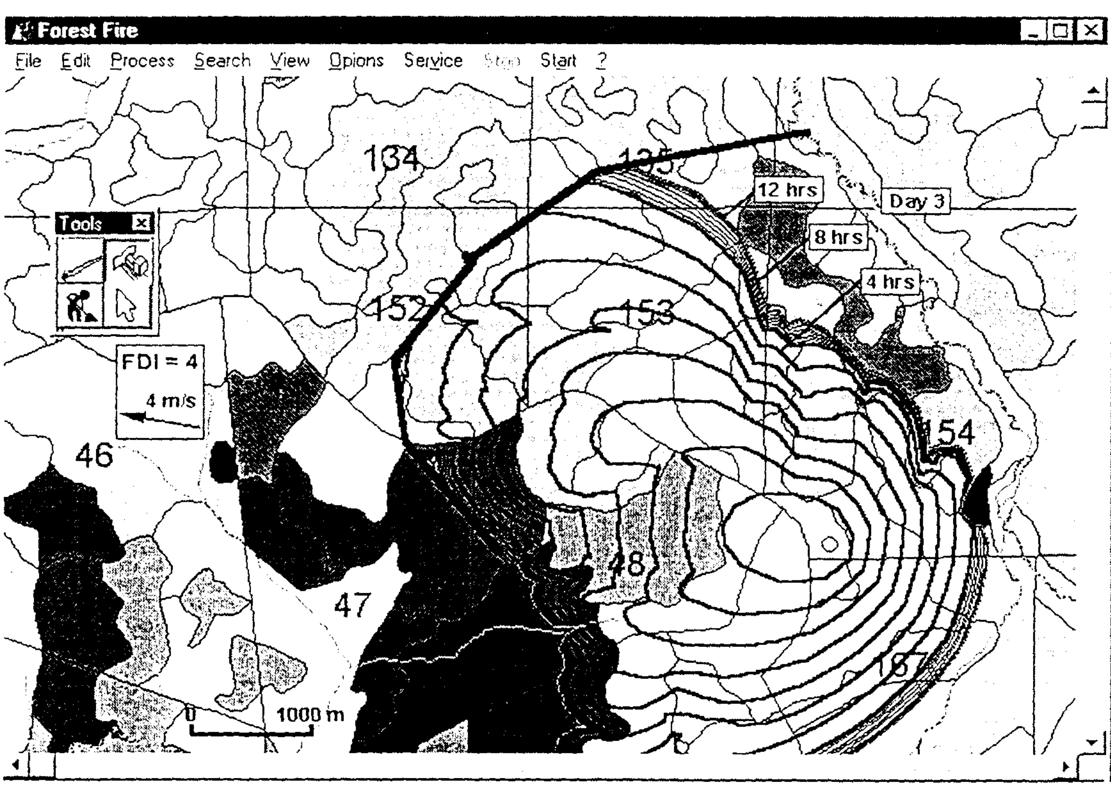

Fig.4 Fire perimeter distribution during third day of propagation. The construction of fire-break line is finished.

CONCLUSIONS

As it has been pointed out the purpose of presented study is an arrangement of computer code for forest fire simulation based on the combined approach to the problem, from the formulation of fire spread physical model to the details of programming technique. Apparently, the main question is arisen immediately: how close (or, most probably, far) the results of simulation are from the reality? The question proceeds the answer: if the disagreement between them is substantial there is a particular way to overcome it at any step, from (in back direction) programming errors to physical background of heat transfer mechanism because all of them are under control. Following that, the further investigation should be based on the data of real fire observations which is the only criterion for verification of theoretical assumptions.

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