GIS-BASED COMPUTER CODE FOR THE EVALUATION OF FOREST FIRE SPREAD

by

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The approach to the implementation of a computer code, based on the geographic information system, for the forest fire behavior prediction is presented. Consecutive steps are considered, which include the formulation of fire spread mathematical model, classification of vegetation fuels using the forest inventory data, approximation of fire perimeter propagation, and overall arrangement of fire simulation code

Key words: *forest fire, fire spread model, flame radiation, vegetation fuel, computer simulation, fire behavior system, geographic information system*

Introduction

It is generally accepted that the forest fire research is the problem of great significance. Burning process in wild nature is a common phenomenon, but the impact of massive forest fires on environment results in severe damage to natural resources and ecological conditions. Development of a system, which allows prediction of forest fire behavior provides a highly desired tool for fire fighting practice. It has a potential to minimize suppression time and cost, and overall fire loss. Forest fire is a very complicated phenomenon for investigation. Any large forest fire (as the forest itself) is a unique phenomenon occurring in a medium of uncertain local conditions. The objectives of present research are laid within rather wide frame of the problem of forest fire modeling. The final purpose of forest fire modeling is the estimation, with reasonable accuracy, of the fire's perimeter propagation in time and space, along with other parameters, such as fire intensity at the leading edge and response time of suppression equipment. A significant number of studies have been devoted to forest fire research with the emphasis on different aspects of investigation, such as:
– fire spread model predicting local flame propagation rate as a function of forest fuel parameters, terrain and weather conditions,
– forest fuel classification, based on forest inventory data, providing parameters affecting the fire spread process,

- algorithm for approximation of fire perimeter to simulate fire propagation process and its interaction with fire suppression equipment, and
- overall design of the forest fire prediction computer code as an integral part of a general forest monitoring system with high level of compatibility between mapping and database processing.

The recognized developments for fire growth simulations, employing the geografic information system (GIS) technology, are: BEHAVE – Fire Behavior Prediction and Fuel Modeling System [1-6] and FARSITE – Fire Area Simulator [7-9].

Herewith, our contribution to this "challenging, intriguing, and poorly funded field of research" [10] is presented with primary intention to trace the above mentioned steps, stressing the weak spots and outlining the ways to the possible ways for improvement.

Fire spread model

First, a mathematical model is to be derived to predict fire local spread rate. A significant number of fire spread models related to forest fires has been proposed (see a comprehensive review by Weber [11]). According to the classification [11], statistical, empirical, and physical models are distinguished. Typical example of the empirical group is the Rothermel's model [12], on which both the BEHAVE and FARSITE codes are based. In presented study, the model of Telitsyn [13-17] is used, which has been developed essentially on the physical basis in the spirit of approaches proposed by Emmons [18], Albini [19], van Wagner [20], and Thomas [21].

The sketch of fire spread model is shown in fig. 1. The energy balance in a fuel bed moving with a steady velocity R is expressed in general form as:

$$\int_S q_S \mathrm{d}S = R\rho[C(T_S - T_0) + QM]h \tag{1}$$

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

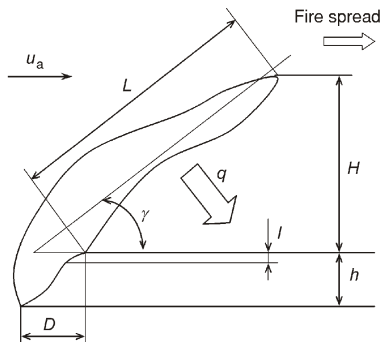$$q = \varepsilon\sigma(T_F^4 - T_S^4) \tag{2}$$

Figure 1. Physical fire spread model

The other heat transfer mechanisms (due to conduction and convection, including turbulence), which are generally not negligible could be expressed (with a certain degree of unfaithful representation) in terms of radiation heat flux introducing an appropriate value of the emissivity ε in eq. (2) unless a disagreement in physical behavior would be found out. Here, this has been done as the emissivity is determined from the experimental data on fire spread rates.

By the primary concept employed in a model [15], the two modes of heat flux are distinguished: the "inward" (glowing) radiation describing heat transfer inside a fuel bed, and the "outward" (external or flaming) one corresponding to heat flux from the flame zone absorbed by the fuel's surface. Thus, the l. h. s. of the integral in eq. (1) is written as:

$$\int_S q_S \mathrm{d}S = q_I h + q_O \Phi L \tag{3}$$

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

$$W_{eff} = \rho_1 \tag{4}$$

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

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

Fire spread rate is then derived from eq. (1) as:

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

The model has been tested [15] using large amount of available experimental data, which suggests the following approximation for emissivity:

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

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

where width of burning zone D and flame length L are considered as characteristic parameters of large-scale flame. Apparently, the dependence of emissivity upon the both parameters 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 coefficiente applies 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 surface becomes 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 it-self, buoyancy-generated velocity, flame height and flame length are estimated as follows [13, 15]:

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

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

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

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

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

$$L = \frac{H}{\sin\gamma} \tag{14}$$

Other parameters of eq. (6) are assumed to be constants as shown in tab. 1.

Table 1. Constant parameters of model

Symbol	Value	Unit
T_F	1200	[K]
T_S	573	[K]
T_0	293	[K]
C	1400	[J/kgK]
Q	26000	[J/kg]
σ	$5.6 \cdot 10^{-8}$	[W/m²K⁴]

Non-linear eqs. (6)-(14) were solved by successive substitutions to predict the fire spread rate. The convergent solution has been obtained for the whole range of investigated input data. The coefficient A_H in eq. (13) has been estimated [15] from the comparison of calculated results with the available experimental data. As a result, the values of A_H from 2 to 7 were obtained, depending upon the fuel type.

Field observations of the effect of wind on the forest fire spread rate demonstrated the nearly linear dependence [16]:

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

where R_* is the spread rate in "no-wind" conditions which is determined from eqs. (6), (10), and (11) as:

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

From analysis of eqs. (6), (15), and (16) one should note that linear dependence expressed by eq. (15) is can hardly be expected as a explicit correlation, but such an as-

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sumption is usually considered reasonable due to the nature of dependence of flame angle factor upon wind velocity through eqs. (10) and (11).

For the prediction of local fire spread rate, eq. (6) requires input information on local fuel properties such as moisture, fuel loading and density. For real forests, these parameters are not normally available as continuous functions in time and space. Hence, some discrete classification for fuel types is to be introduced.

Classification of fuels types

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. There is a number of approaches available (for example [4-9, 22-26]), using either an early adopted purely supervised evaluation, or an integrated implementation (assuming certain share of unsupervised analysis) of GIS data for estimating vegetation characteristics according to the accepted fire behavior model.

Following the latter approach [17], the formula for fire spread rate is expressed as:

$$R = k_1(k_2 - 1)(1 + k_3 U_m + k_4) \qquad (17)$$

Here k_2 is the fire danger index, k_1 the "basic" spread rate, k_3 the coefficient accounting for the effect of wind on the spread rate, U_m the wind velocity obtained from meteorological data, and k_4 the coefficient accounting for the effect of terrain slope.

The combination of factors containing k_1 and k_2 in eq. (17) represents the spread rate R_* in the absence of wind as defined by eq. (16). Unlike bulk density and fuel loading which can be assumed constant for a specific fuel , the moisture content is a function of weather conditions. According to the regulations of the Federal Forest Agency of Russia (which are used in the present study, fire danger index is counted by integer numbers from 1 (zero probability of fire) to 5 (maximal fire danger). In a physical sense, higher values of fire danger index decrease the moisture content M and thus increase the fire spread rate, eq. (6). Since the typical dependence of fire spread rate upon the moisture has low curvature profile (*e. g.* [27]), it is assumed that the fire danger index itself has a linear influence on the spread rate. The "basic" spread rate is determined from eq. (16) using the fuel properties such as bulk density, fuel loading and moisture content corresponding to "basic" condition, *i. e.* the fire danger index equal to 2.

The simplified algorithm for fuel classification presented in fig. 2 is an attempt to combine directly the inventory data and fire spread model. At present stage, the analysis is limited to spring and fall conditions as most fire dangerous seasons. Hence, the effect of green fuel component is excluded and crown properties are determined by coniferous species only. According to eq. (17), the two parameters, k_1 and k_3, have to be estimated. It is assumed here that the "basic" spread rate k_1 is affected mostly by the underwood properties, such as a type of dominant species and its density. The effect of

wind velocity on the spread rate is described by the 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 co-exist (*e. g*, a combination of high canopy closure and dry underwood species). Totally 12 types have been distinguished as indicated in tab. 2.

Table 2. Parameters of fuels classification

No.	Coniferous canopy closure [%]	k_3	Underwood		k_1 [m/h]
			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

Approximation of fire perimeter

Two approaches are generally used for the modeling of fire perimeter growth, namely, the point technique [28] and the curve expansion algorithm [29-31]. First of them, despite having conceptual simplicity of coding, faces conceptual difficulty in describing fire spread behavior, mainly due to a limited number of directions for fire propagation [8] if conventional orthogonal grid is used. Therefore, we use the second approach based on the Huygens' wavelet propagation principle, which has been applied for modeling of wildland fire by Anderson *et al*. [29], and the detailed technique of elliptical propagation of fire front as proposed by Knight and Coleman [30].

Briefly, each fire perimeter point is considered as a source of fire, propagating independently within a prescribed time step Δt. Parameters of each ellipse depend on the

local fuel properties and weather conditions at a given point at the fire front at time t. The outer envelope formed by these ellipses defines the location of fire front $F_{t+\Delta t}$ at time $t +$ $+ \Delta t$. Parameters of the ellipse with the focus located at the origin of the coordinate system and x-coordinate coinciding with direction of maximal velocity of fire spread are expressed as:

$$\frac{(x \quad c)^2}{a^2} \quad \frac{y^2}{b^2} \quad 1 \tag{18}$$

$$b \quad \sqrt{a^2 \quad c^2} \tag{19}$$

Parameters a and c are defined through the fire spread rates as:

$$a = R_{\text{front}}\Delta t - c \tag{20}$$

$$c \quad \frac{\Delta t}{2}(R_{\text{front}} \quad R_{\text{back}}) \tag{21}$$

where front and back fire spread rates are derived from eq. (17):

$$R_{\text{back}} = k_1(k_2 - 1) \tag{22}$$

$$R_{\text{front}} = k_1(k_2 - 1)(1 + k_3 U_{\text{m}} + k_4) \tag{23}$$

The algorithm for the approximation of the new fire front $F_{t+\Delta t}$ is described in full detail in [7]. Finally, some specific features describing low curvature, moderately, and sharply convex modes as well as an optimization procedure to overcome possible complicated situations (concave points, internal loops, and overlapping of fire perimeters), should be employed [7].

Framework of the computer code

General scheme of the developed computer code for the prediction of forest fire behavior is presented in fig. 2. The code is based on the GIS, which is created as a monitoring and operating tool for the management of forest resources. Two parts of the GIS, the map layers and the inventory database are inputs into the GIS graphical interface allowing problem oriented maps to be created by database processing. The fuel types map is created by using the data analysis corresponding to the fuel classification described above. As vector layers and fuel data are brought into the GIS interface, the fuel types map containing the forest area of specific location and of appropriate scale is created.

This map is transferred into the fire simulation code in the form of raster layer where the information on fuel properties and coefficients k_1 and k_3 – eq. (17), are stored as pixel's colors corresponding to fuel types introduced in tab. 2. Weather conditions, another input for the fire simulation code, provide the values of the coefficient k_2 (fire dan-
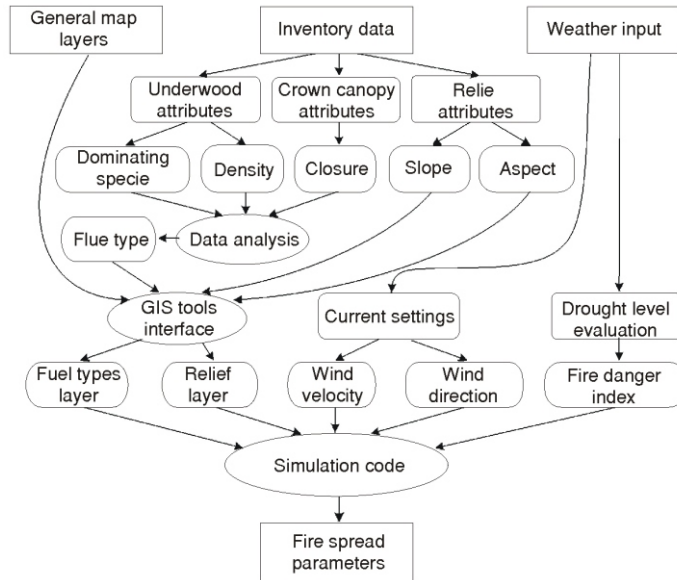
Figure 2. Framework of the computer code

ger index), as well as wind velocity and direction. Coefficient k_4 is derived from the inventory database containing the values of slope and aspect.

Example of fire spread simulation

Figures 3-5 present the results of fire spread process simulations and simultaneous construction of fire-break line. Analyzing the final location, one can evaluate the fire suppression tactics chosen (fig. 5). While the upper branch has been built up properly, the lower one contradicts the safety regulations because of very close location of the leading edge of fire front and acting facility.
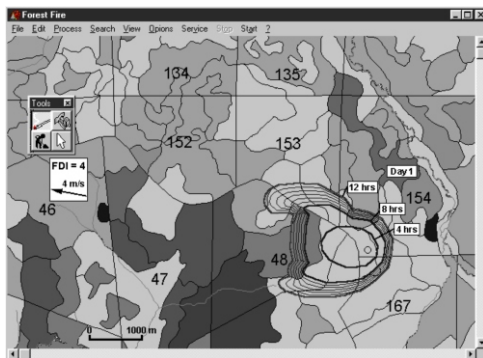

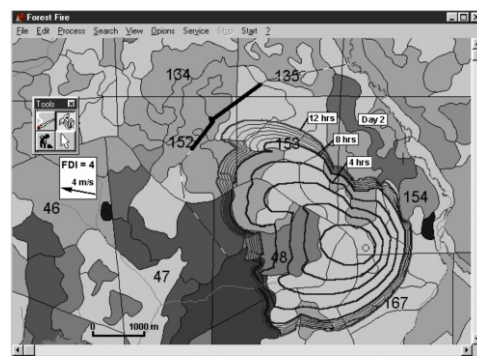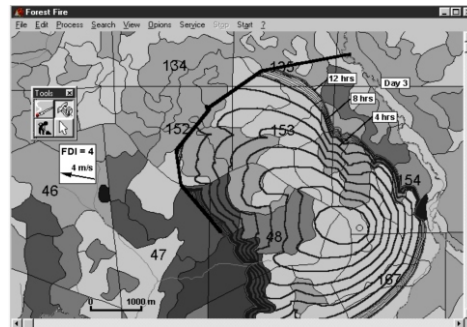**Figure 3. Fire perimeter distribution during the first day of propagation**

Figure 4. Fire perimeter distribution during the second day of propagation. The fire--break line is begun to be built up

Figure 5. Fire perimeter distribution during third day of propagation. The construction of the fire-break line is finished

Concluding remarks

The purpose of presented study has been an arrangement of the computer code for forest fire behavior prediction. Both formulation of fire spread physical model and details of programming implementation were presented. Apparently, there are a number of possible improvements on the way towards the much more comprehensive prediction system. The presented fire spread model, despite being based on fundamental physical principles, requires a lot of empirical information, which could only be obtained through the field observation of forest fires. However, some of such correlations can be replaced rather easily by more advanced models. Thus, eqs. (10)-(14) describing heat transfer in flame zone would be replaced by two-dimensional partial differential equations of momentum, energy, and mass balance, which is described in detail [32] mechanisms of radiative and convective heat transfer as well as effects of buoyancy and turbulence. Further, classification of forest fuel types can be improved by introducing additional information from inventory data such a processing of a descriptive "forest type". Finally, the integrating of remote sensing technique into the fire simulation code [33] is to be considered as a most promising direction of research.

Nomenclature

C – specific heat of fuel, $[\mathrm{Jkg^{-1}K^{-1}}]$
D – width of burning zone, $[\mathrm{m}]$
H – flame height, $[\mathrm{m}]$
h – thickness of fuel bed, $[\mathrm{m}]$
k_1 – coefficient in eq. (17), $[\mathrm{ms^{-1}}]$
k_2, k_4 – coefficient in eq. (17), $[-]$
k_3 – coefficient in eq. (17), $[\mathrm{sm^{-1}}]$
L – flame length above fuel surface, $[\mathrm{m}]$
l – free path of radiation, $[\mathrm{m}]$
M – moisture content of fuel, $[\%]$
Q – heat of vaporization, $[\mathrm{Jkg^{-1}}]$
q – heat flux, $[\mathrm{Wm^{-2}}]$
R – rate of fire spread, $[\mathrm{ms^{-1}}]$

T – temperature, [K]
U – wind velocity, [ms^{-1}]
V – buoyancy velocity, [ms^{-1}]
W – fuel loading, [kgm^{-2}]

Greek symbols

γ – angle between flame and fuel's surface, [rad]
ε – emissivity, [–]
ν – surface-to-volume ratio, [m^{-1}]
ρ – bulk density of fuel, [kgm^{-3}]
σ – Stefan-Boltzmann constant, [$\text{Wm}^{-2}\text{K}^{-4}$]
Φ – flame angle factor, [–]

Subscripts

0 – initial
eff – effective
F – flame
I – inward
m – meteorological data
O – outward
S – surface

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