Selection of Fire Spread Model for Russian Fire Behavior Prediciton System

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Abstract
Mathematical modeling of fire behavior prediction is only possible if the models are supplied with an information database that provides spatially explicit input parameters for modeled area.
Mathematical models can be of three kinds: 1) physical; 2) empirical; and 3) quasi-empirical (Sullivan, 2009). Physical models (Grishin, 1992) are of academic interest only because current vegetation monitoring techniques make it virtually impossible to parameterize the model precluding its general application in wildland fire management (Sullivan, 2009). Empirical models (Vonsky, 1957; Amosov, 1964; Korovin, 1969) can give satisfactory results but only for the fires on areas from which experimental data were obtained and generalized.
Quasi-empirical models include empirically derived physical and chemical properties of the fuels thereby extending their potential application to many vegetation types. Among quasi-empirical models, Rothermel's (1972) model is the basis for the US National Fire Danger Rating System (Deeming et al., 1978), the BEHAVE-Plus (Andrews et al., 2005) and FARSITE (Finney 1998) models (FBP). Development of the US FBP System became possible owing to creation of an information database through division of vegetation into "fuel models" (Anderson, 1982; Scott, Burgan, 2005). However, the characteristics are rather rough because the number of fuel models is limited and the diversity of the vegetation cover is large in terms of fire science.
Russian quasi-empirical models (Telitsin, 1973; Konev, 1984; Gusev, 2005; Dorrer, 2008) do not provide the vegetation fuel (VF) data base necessary to apply their models. The creation of the VF information database was developed theoretically and practically only for the model developed at the Sukachev Institute of Forest (Sofronov, 1967; Volokitina, Sofronov, 2002).
The mathematical model used for surface fire growth prediction is very simple: $Vx = Vo \cdot Kw \cdot Kr \cdot K\varphi$, where Vo – no-wind-no-slope spread rate, m/minute; Kw – variable wind coefficient; Kr – variable relative humidity coefficient; Kφ - variable slope coefficient. No-wind-no-slope spread rate shows the capacity of fire to spread over the given fuel under "standard" combination of dynamic external factors (wind – 0 m/s, slope - 0°, and relative humidity – 40%). On the basis of experimental data and observations on fires, the no-wind-no-slope spread rate was determined for each type of a primary fire carrier depending upon the fire weather index (Sofronov, Volokitina, 1990). Relative influence of wind, slope, and humidity on fire spread rate was established during experimental prescribed burns and fire experiments (Sofronov, 1967).
A computer program has been developed for surface fire growth prediction.
Keywords: forest fires, fire growth models, fire behavior prediction, information database, GIS

1. Introduction

Fire behavior prediction is realized through mathematical modeling. Application of any model is possible only if an information database is available for it. Therefore, a most important element of all national FBP systems is development of methods and technologies for information database creation. The main part of the information databases is data about vegetation fuels on the landscape.

The most complicated is the creation of an information database for FBP since it should give pyrological description to all vegetation plots on the landscape as inputs for the mathematical models. Creation of reliable information databases for mathematical models depends upon the complexity of the modeled objects and processes.

2. Russian model classification and description

In Russia, mathematical models are divided into three kinds: 1) analytical; 2) experimental-statistical; and 3) mixed experimental-analytical (Dorrer, Kurbatsky, 1978). According to Sullivan (2009), they are 1) physical, 2) empirical, and 3) quasi-empirical – respectively.

Analytical (or physical) models consider processes on a fundamental level. They analyze burning of a vegetation fuel (VF) layer on the basis of heat transfer and mass transfer laws and gas dynamics involving a large number of physiochemical VF characteristics (specific heat, elementary composition, ash content, compactness, surface area-to-volume ratio, moisture content, etc.) and environmental characteristics (air temperature, humidity, wind direction and speed, slope steepness, etc.). An example of this from the Russian literature is an air-thermo-chemical model of a forest fire developed by Grishin (1992). It contains a few dozens of equations and boundary (terminal) conditions describing three-dimensional processes of heat and mass transfer, phase and chemical transformations during burning and so on. Current vegetation monitoring techniques make it virtually impossible to parameterize the model precluding its general application in wildland fire management.

One example of a model of this type which has seen widespread use beyond the domain of its experimental base is the Canadian Forest Fire Behavior Prediction system (Forestry Canada …, 1992). It is based on empirical formulae and tables covering 16 standard VF complexes (fuel types) which, unfortunately, do not reflect the whole variety of Canadian vegetation.

Russian examples of empirical models include those by Vonsky (1957), Amosov (1964), Korovin (1969). In spite of their simplicity, such models can give satisfactory results but only for the fires on areas from which experimental data were obtained and generalized. Since there are numerous plot categories and multiple fire experiments on all categories is next to impossible, an information database cannot be complete, therefore application of models of this type is limited.

In contrast to empirical models, mixed experimental-analytical (or quasi-empirical) models include empirically derived physical and chemical properties of the fuels thereby extending their potential application to many vegetation types. Among quasi-empirical models, Rothermel's (1972) model is perhaps the most widely used. The model predicts rate of spread at the head of the fire assuming the fire is burning upslope with the wind. To predict for other locations on the fire perimeter the slope and wind are reduced accordingly. Rothermel's model is the basis for the United State's National Fire Danger Rating System (Deeming et al., 1978), the BEHAVE-Plus (Andrews et al., 2005), and FARSITE (Finney, 1998) models. Development of the US FBP System using Rothermel's model became possible owing to creation of an information database through derivation of standard characteristics of vegetation, i.e. through its division into pyrological types – "fuel models". The number of fuels models increased from initial 13 (Anderson 1982) to an optional set of 40 (Scott, Burgan, 2005). There are identifiers helping to choose a fuel model for each plot. For boreal forests which dominate in Russia, there are no fuel models. The advantage of the standard method is that each plot obtains pyrological characteristics necessary for fire behavior prediction. However, the characteristics are rather rough because the number of fuel models is limited and the diversity of the vegetation cover is huge in terms of fire science.

Among Russian quasi-empirical models, there are models by Telitsin (1973), Konev (1984), Gusev (2005), Dorrer (2008) and other.

Telitsin's mathematical model (1973) contains a simple formula for frontal surface fire spread rate (V):

$$V = 1{,}6 \cdot 104 \cdot \delta / \rho \cdot (15 + w)2 \cdot (1 - \cos\alpha)2$$

The formula infers that the frontal fire spread rate (V) is directly proportional to the depth of the layer consumed (δ, m) and inversely proportional to the layer compactness (ρ, kg / m2) and the squared moisture content (w, %). The fire spread rate is also much dependent upon the angle of the flame (α, degrees). The flame angle is, in its turn, influenced by the wind and slope steepness. There are theoretical formulae to calculate coefficients of wind and slope direct impact on the fire spread rate.

It should be noted that the depth of the consumed layer and its moisture content are variable values depending upon the layer structure and specific conditions of moistening and drying. Special programs are needed to calculate these values, i.e. this model lacks information database.

Konev's mathematical models (1984) include two: 1) one of the analytical type considers a complex heat-mass exchange between the burning zone and the initial matter; 2) another one of the experimental-analytical type is simple: no-wind-no-slope fire spread rate is multiplied by the coefficient reflecting burning conditions. The burning conditions include impact by wind speed and direction (in relation to the fire edge) as well as slope steepness. The regularities were obtained both analytically and by generalization of published experimental data. A constant no-wind-no-slope fire spread rate is attributed to some types of primary fire carriers in spite of the fact that it actually differs considerably with drying of the fire carrier layer.

Gusev's mathematical model (2005) is a modified Rothermel's model (1972). The modifications were as follows: subclasses of forest fuels were introduced, approximations for s number of characteristics were changed, etc. According to Gusev, application of this model in practice is limited because of its complexity. Therefore, Gusev suggested a simplified model. The formula for frontal surface fire spread rate (v) under no-slope conditions is:

$$v = \exp (a1 + a2U + a3M + a4U2 + a5M2 + a6UM),$$

where U – wind speed under the forest canopy, m/s; M – moisture content of surface fuel fire carriers, 0,01· % ; a1 . . . . . a6 – coefficients constant for given surface fuels.

Rear and flank fire spread rate (vr) is calculated by an empirical formula:

$$vr = v \exp [A (\cos 4 \alpha/2 - 1)],$$

where A = 0,974 U 0,1466 – empirical coefficient; α – angle between the fire spread direction and wind direction.

The author also suggests mathematical models assessing moisture content of surface fuels in rainless periods, interception (retention) of precipitation by stand canopy, wind speed in the forest, parameters of a convection column, travel distance of burning particles, parameters of a spot fire, potential for a surface fire to crown, etc. Nonetheless, the system of models does not take into account: retention of solar radiation by the forest canopy (a most important factor of VF drying); well-known regularities of precipitation distribution under the forest canopy; probable number of burning particles capable to start ignitions; duration of a fire edge contact with a fire barrier as a most important factor assessing the possibility for a fire to get over a barrier; presence of oxygen in the convection flow when assessing the possibility of involvement of the canopy in fire propagation, etc.

All Gusev's models have coefficients related with special features of specific kinds of stands. The information database has a selective character and includes only pine stands with lichen, green moss and grass cover which are found in the central taiga and forest-steppe zones of the European part of Russia.

Dorrer's mathematical model (2008) describes forest fire spread as a running wave in a heterogeneous and anisotropic medium. On the basis of the methods of Hamilton's mechanics, a geometrical theory was developed of propagation of flat forest fire fronts; formulae were given for calculations of fire contours, fire perimeters and areas; numerical algorithms were developed for fire front graphical representation both of an imitation type and based on the method of flexible grids. In essence, this is a whole complex system modeling forest fire propagation and suppression including a number of subsidiary mathematical models, for instance, models of spatial structure of forest fuel layers, dynamics of fuel moisture content, etc. The system has been developed for more than 30 years. The results were published in the monograph (Dorrer, 2008). The issue of a wide information database provision of this system was not sufficiently developed.

Creation of a VF information database was developed theoretically and practically only for the model developed at the Sukachev Institute of Forest (Sofronov, 1967; Sofronov, Volokitina, 1990; Volokitina, Sofronov, 2002).

3. Sukachev Institute of Forest model description and application

In the Sukachev Institute model, an individual method was applied as the main method to pyrologically characterize vegetation plots. The individual characteristics in this method are composed of standard elements which reflect information about components of the VF complex, about conditions of moistening, drying and burning of a plot. All this is shown in the fine-scale VF maps and in the pyrological descriptions enclosed with them. Methods and a technology were developed for making such maps based on forest inventory data or in the process of forest inventory.

The mathematical model used for surface fire growth prediction is very simple:

$Vx = Vo \cdot Kw \cdot Kr \cdot K\varphi$,

where Vo – no-wind-no-slope spread rate, m/minute;

Kw – variable wind coefficient;

Kr – variable relative humidity coefficient;

Kφ – variable slope coefficient.

No-wind-no-slope spread rate shows the capacity of fire to spread over the given fuel under "standard" combination of dynamic external factors (wind – 0 m/s, slope – 0°, and relative humidity – 40%). On the basis of experimental data and observations on fires, the no-wind-no-slope spread rate was determined for each type of a primary fire carrier depending upon the fire weather index (Sofronov, Volokitina, 1990). Relative influence of wind, slope, and humidity (i.e. variable coefficients Kw, Kr, Kφ) on fire spread rate was established during experimental prescribed burns and fire experiments (Sofronov, 1967).

Analysis of experimental data and observation on active fires allowed to determine no-wind-no-slope fire spread rate (m/ min.) for each type of a primary fire carrier depending upon the drought level (related to fire weather index), surface combustion heat (mJ/m2), consumable fuel load (kg/m2) and other characteristics (Sofronov, Volokitina, 1990; Volokitina, Sofronov, 2002).

Knowing the no-wind-no-slope spread rate and taking into account the relative impact of the aforementioned factors on spread rate it is possible to calculate the actual spread rate under any value of these factors. This allows prediction of surface fire growth and its development into crown fires.

Computer programs are being developed for making vegetation fuel maps and for fire behaviour prediction in plain conditions on the example of the Chunsky Forest Office area (within the framework of the State Contract of the Institute of Forest with the Forestry Agency of the Krasnoyarsk krai, 2008-2010) and in mountain conditions on the example of the State Nature Reserve “Stolby” (owing to the Agreement of the Institute of Forest with the Institute of Space Research and the Central Airbase of Avialesookhrana).

The basis of the developed FBP program is the application of VF maps. A table is automatically made with burning indices for given seasonal and weather conditions on the basis of the pyrological description. Then one can interactively observe the dynamics of fire growth as time series of vector fire edge contours from the given contours of initial fire areas. The main statistical and dynamic characteristics are calculated for each fire contour at a given time (burnt area, fire perimeter, rate of their changes for an interval). The program also calculates the necessary resources for fire suppression taking into account pyrological characteristics of vegetation on each specific fire.

Retrospective tests of the elaborated programs carried out using data about past fires in the Chunsky Forest Office area and in the Nature Reserve “Stolby” showed overall good performance.

4. Conclusion

A practical and practicable model of fire growth has been chosen as a result of analysis of the existing models. It is used as a foundation for development of software for fire behavior prediction in plain and mountain conditions. Examples of information databases in GIS are created for fire behavior and fire effects prediction.

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