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ANALYSIS AND VISUALIZATION OF NUMERICAL RESULTS OF SURFACE FOREST FIRES MODELING

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The problem of computer modelling of the spread of surface forest fires in a twodimensional formulation is considered. The results of numerical experiments investigating possible scenarios of how fire spreads in different directions and its behaviour near fuelbreaks are presented. Several qualitative differences in geometry and dynamics of temperature density maps and oxygen concentration stream plots are determined and illustrated with graphics for various shapes and sizes of fuelbreaks and wind velocities.

***Keywords*:** surface forest fire; wildfire; fire front dynamics; fuelbreak shape; fuelbreak size; wind velocity; software; oxygen concentration stream plot.

Introduction

The influence of forest fires on the ecology and the environment is well known. It has negative social and economic consequences ([1]). In the territories of many regions, emergency situations caused by forest fires occur at regular intervals, and at the same time, the success in their prevention and extinguishing does not increase. Therefore, it is important to search for new solutions, technologies to reduce the intensity and duration of fires. The development of mathematical, computer models of forest fires began in the middle of the last century and continues throughout the world nowadays ([2]).

In most of the computer models, the process of forest fire propagation is described and analyzed only for homogeneous environments. However, in reality, a homogeneous distribution of forest fuel (mosses, litter, grasses, shrubs, trees, etc.) is extremely rare. It is known that some observed effects of forest fires are caused precisely by heterogeneity. In this work, the features of forest fires spread in case of the inclusion of fuelbreaks [3–4] of various shapes and sizes are modelled, visualized, and discussed.

Forest fires are a multiscale phenomenon both in space and time. The article ([5]) suggests three scales: flame, wildfire, and fire regime. We can define the triangle: (Topography/Forest Fuel/Weather).

Most of the currently used computer models of forest fires, as a rule, set as their ultimate goal the answer to the question, what are the velocities and directions of the spread of forest fires at the macro level. At this scale, the velocity is determined by comparing the positions of the fronts of burned forest regions at successive time points. The novelty of this work is the emphasis on the study of not only the areas of burnt vegetation, but also on related factors and causal processes that can be detected in specific areas. Here we study the dynamics of the appearance (or loss) of gases, changes in their position and temperature. Physicochemical processes of combustion and pyrolysis, heating and evaporation of liquids from wood micropores, convective and buoyancy-driven flow of gases, thermal radiation, and other factors are taken into account. At the same time, emphasis is placed on the method of analysis and interpretation of results implemented by the use of cognitive graphics, which makes it possible to establish new qualitative features of the processes. By visualizing the oxygen concentration gradient lines superimposed over the temperature isolines and the density distribution of combustible vegetation, it is possible to recognize trends in the movement of fire fronts on a smaller scale. It becomes possible to determine the influence of such factors as the presence, size, and shape of fuelbreaks, and wind velocities on the speed and direction of the fire front.

In the presented research, the theoretical model of professor A.M. Grishin is used. It is considered to be the most complete mathematical description of the spread of fires in forests and peat bogs. After the publication of the mentioned monograph, many researchers ([4–6]), including the authors of this work, use Grishin's descriptions as a basis and modify them for practical use [7], ensuring that the specific conditions of the territories and climate are taken into account.

According to the existing reviews [2], mathematical (computer) models of forest fires are usually classified as physical, semi-empirical (including statistical), and simulation. The authors of this article use a physical model describing processes in the form of a system of partial differential equations of mathematical physics – the mathematical model of forest fires spread described in detail in [8–9]. In some aspects, the tools used are special: modelling and visualization are performed in the computer algebra system *Wolfram Mathematica*, the results are partly stored in a relational database, partly in files. The implemented numerical methods are almost traditional, but we use adaptable grids both in space and in time.

1. Summary of the main results of numerical experiments

During a discussion session at CSIST'22 congress the authors of this work will demonstrate animations and video materials illustrating the dynamics of fire front spread, the evolution of scalar and vector digital fields of characteristics calculated in the model. Here we note just the most important conclusions which are identified during the analysis of experiments results [9–11].

Modelling the influence of glade sizes. Mathematical model considers the options for the development of fires on areas of a forest with the uniform density of forest fuel with inclusions in which there is no forest combustible material – round glades of various sizes.

Small glades have an area of 2.25 square meters, the medium size is 4.5 square meters (twice as large), and large is 18 square meters, i.e., four times the area of the middle glade.

Calculations are held at an equilibrium wind speed at the middle of the flame height V = 1.5 m / s for three different sizes of fuelbreaks. The geometry differs only in the area of the clearings. The contour of the boundaries of the fuelbreaks and the positions of their centers relative to the combustion centre are the same for all three options. The distributions are rendered at the same points in time.

The results can be interpreted as follows. During the first stage, the line of the fire contour breaks after meeting the glades. In the second stage, the fire "goes around" the glades. Fire propagation stops in the direction opposite to the direction of the wind. In the direction of the wind and across (perpendicular) to the direction of the wind, independent flanks meet together and the fire continues to spread as a united front. There is an evident difference in the front configurations after overcoming fields of different sizes. During the second stage the "upper front" began to move upward and to the direction opposite to the wind direction.

Using vectors, the software visualizes stream plots that illustrate current flow directions for oxygen concentrations. Note that only the directions are significant, the relative lengths of the vectors do not indicate the magnitude of the rate of change in concentration. The vectors are shown only in the fire zone, in areas not affected by the fire, the values of the simulated gas concentrations and temperatures are constant, the gradient is zero.

Let's note the features of the results. During the second stage (at times 140 and 195) "middle" streamline runs from right to left through the centre of the "left" fuelbreak. However, when the size of each fuelbreak increased, the corresponding "middle" streamline passes "below" the centre of the glade. This effect can be interpreted by the fact that there is no glade at the bottom (contrary to the top) and the process of combustion (disappearance of oxygen) in above and below areas does not occur symmetrically.

Let's point out a general pattern. Because combustion (increase in temperature) is a process inextricably linked with a decrease in oxygen concentration, then near the combustion fronts [5], oxygen stream plots are collinear with the directions of movement of the edges of the fire.

Modelling the influence of fuelbreak forms on forest fire processes. These particular series of computational experiments are intended to demonstrate the difference in the behavior of a forest fire depending on the shape of the glades [10] encountered in the path of the fire: rectangles, squares, and circles.

Please note that the difference is in the shapes of fuelbreaks, but the areas are the same. The time points shown in the figures also coincide. The calculations were carried out at an equilibrium wind speed at the middle of the flame height $V = 1.5$ m/s.

The following interpretation of the results seems to be justified. While passing the glades, the fire front breaks into independent parts, which go around them. In the direction opposite to the wind speed the propagation stops. Along the wind direction and "perpendicularly" to it, the autonomous parts of the fire front close again, and the fire spreads as a united front. There is a noticeable difference in the resulting configuration of the front isotherms after overcoming different forms of glades. The question of whether these differences will grow in time, or whether the fronts will take the same configuration, requires a separate study.

Let us note the differences in the dynamics of the fire, which are noticeable when analyzing the stream plots. At the time of final stage of process, in the case of square and circle fuelbreaks, the stream plots are directed from right to left. However, for rectangular fuelbreaks, this direction is not observed in the evolution of oxygen concentration. Apparently, this is because the left front of the fire is "more closed" in comparison with the cases considered.

Taking into account the influence of wind speed. The influence of the wind speed on the nature of the forest fire spread is discovered. In the performed computational experiments, in terms of geometry, the case of circular fuelbreaks of "small" size is considered. In addition to the calculation for the wind speed $V = 1.5$ m/s, we provide the results of two additional series of calculations, which differ only by the wind speeds V, which are equal to 1 and 2 meters per second, respectively Result for $V = 1$ m/s is of particular interest. At low wind speeds, fire fronts overcome the glades in all directions, including the direction against the wind. It should also be noted that the width of the burning line in the direction of the wind is narrower than on the flanks, and in the rear this width is maximum. At time of concluding stage of process, it is noticeable that the point of the minimum oxygen concentration is shifted to the right (to the direction of the wind), relative to the centre of the initial fire occurrence. The most likely reason is the influence of convective transport due to wind force.

2. Discussion and future research

The results presented illustrate the dynamics of the distributions of temperatures and bulk density of combustible forest materials. In general, the developed computer model calculates the distributions of six variables, which make it possible to estimate, in particular: the amount of released water vapour, the formation of polluting gases, coal, and ash.

It should be noted that due to the complexity of the calculations, the use of this computer model in real-time is impossible. At the same time, since all the results obtained in computational experiments are recorded into the database, the collections of typical process scenarios are automatically filled with the appropriate means of the software complex. Intelligent data processing is possible [12], including the creation of electronic catalogues, the introduction of identifiers-classifiers of scenarios for calculating the development of fires in terms of attribution to typical territories and climatic conditions. The corresponding catalogues of representative scenarios can be used in conjunction with semi-empirical models [13].

The main direction of the software package improvement will be the addition of tools with clustering and neural network functions, their application in the preprocessing of initial distributions data, and interpretation of calculation results. Special attention will be paid to recommendations and presentation of options for using artificial intelligence tools [14] for the following tasks: a) creation of test cases for training a neural network based on the database of numerical results of forest fires propagation; b) neural network usage for prediction in real-time the propagation velocity of the fire contour depending on the categories of territories, climatic conditions, density of distribution of forest vegetation; c) classification of forest areas into categories (density of forest fuel material, or its absence, moisture content, height of the forest canopy and other characteristics) using satellite or aerial images.

Conclusion

Using computer modelling tools, we estimated the influence of each of the following factors on the speed and direction of fire propagation: a) the presence or absence of fuelbreaks in the fire path; b) several shapes of fuelbreaks; c) the area of the fuelbreaks; d) wind velocities and direction.

The lines of oxygen concentration gradients in forest fire regions are calculated and visualized. The detected features of their configuration near the fuelbreaks are discussed.

Many computational experiments have been carried out, and the database with forest fires modelling results has been accumulated. The future research directions including the use of neural network tools are outlined.

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