Game-Method Model for Field Fires

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Abstract. Every year about 45000 forest fires occur in Europe, burning half a million hectares of land, some of which protected zones with rare species of the flora and fauna. The existing methods for wildland modeling are very complicated and their realizations need a lot of computational capacity. That is why we will use another approach based on the game-method theory, which consume less computational resources.

1 Introduction

The study of wildland fire should begin with the basic principles and mechanisms of the combustion process — fire fundamentals. Fire behavior is what a fire does, the dynamics of the fire event. An understanding of the fundamentals of wildland fire is important for some very practical reasons. The combustion process can be manipulated to some extent: Retardants can be applied to affect the combustion process: fuel arrangement can be altered for hazard reduction; and appropriate environmental conditions can be chosen for prescribed fire to reduce smoke impacts, achieve desired fuel reduction, and still retain control of the fire. The need to understand wildland fire fundamentals is even more pressing than it was in the past. In earlier times the focus was on describing the aspects of fire that are important to suppression efforts. That continues to be high priority. In addition, there is now increasing emphasis on characterizing fire for its effect on vegetation and for the smoke it produces [4].

The basis for the fire modeling is the Rothermel model for the behavior of surface fires [5]. It calculates for any given point local intensity and spread parameters for the head of a surface fire. Inputs for the model are a two-dimensional wind field, terrain parameters, fuel moisture and a detailed description of the fuel bed, based on the local behavior output by the Rothermel model and on a model for the local shape of fire spread.

The mathematical models require descriptions of fuel properties as inputs to calculations of fire danger indices or fire behavior potential. The set of parameters describing the fuel characteristics have become known as fuel models and can be organized into four groups: grass, shrub, timber, and slash. Fuel models for fire danger rating have increased to twenty while fire behavior predictions and

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applications have utilized the thirteen fuel models tabulated by Rothermel [5] and Albini [1]. Each fuel model is described by the fuel load and the ratio of surface area to volume for each size class; the depth of the fuel bed involved in the fire front; and fuel moisture, including that at which fire will not spread, called the moisture of extinction.

The fire models used nowadays by wildland fire managers are specified to distinct types of fire behavior. There are separate models for surface fires, crown fires, spotting, and point-source fire acceleration. These behaviors are really abstractions of an overall three-dimensional process of unconfined combustion that links implicitly to the environment through heat and mass transfer feedbacks.

In this work we will focus on game-method principle, which is easy to understand, use, and implement, when we are trying to model spreading of a wildland fire. This model can be used also by non specialist in the forest fires field for learning and describing this phenomenon. The game-method model differs from the other models with the usage of small amount of computational recourses. Most of the developed mathematical models require descriptions of fuel properties as inputs to calculations of fire danger indices or fire behavior potential. They are so sophisticated that their resulting simulations have predictions which cannot be tested analytically. In nature, the natural consistency of a given model is usually tested by calculations of sets of simple experiments (e.g a hydrodynamics code is always tested by calculations of shock tube experiments). However, often such tests are impossible or ambiguous. In such cases, a more basic question arises — the correctness question, in the sense that all applied conditions and restrictions are valid, no additional conditions and restrictions are applied; and the model rules are not contradictory among themselves. In other words, we mean correctness in the mathematical and logical sense (completeness, conservativeness and consistency). That is why in the paper we focus on the game-method model [2] and we apply it on field fires.

2 Description of the Game-Method Model

The combinatorial game-method has mostly theoretical applications in astronomy for example, but we will try to show its possible application in fire spreading problem.

Let a set of symbols S and n-dimensional simplex (in the sense of [3]) comprising n-dimensional cubes (at $n = 2$, a two-dimensional net of squares) be given. Let material points be found in some of the vertices of the simplex and let a set of rules A be given, containing:

- rules for the motions of the material points along the vertices of the simplex;
- rules for the interactions among the material points.

Let the rules from the i-th type be marked as i-rules, where $i = 1, 2$.

Each material point is a set by a number, n-tuple of coordinates characterizing its location in the simplex and a symbol from S reflecting the peculiarity of the material point (e.g. in physical applications — mass, charge, concentration, etc.).

We shall call an initial configuration every set of $(n+2)$-tuples with an initial component being the number of the material point; the second, third, etc. until the $(n+1)$-st — its coordinates; and the $(n+2)$-nd – its symbol from S. We shall call a final configuration the set of $(n+2)$-tuples having the above form and which is a result from a (fixed) initial configuration by a given number of applying the rules from A.

Once applying a rule from A over a given configuration K will be called an elementary step in the transformation of the model and will be denoted by $A_1(K)$. In this sense if K is initial configuration, and L – a final configuration derived from K through times applying regulations from A, then configurations $K_0, K_1, ..., K_m$ will exist, for which $K_0 = K, K_{i+1} = A_1(K_i)$ for $0 \leq i \leq m-1, K_m = L$, (the equality "=" is in the sense of coincidence in the configurations) and this will be denoted by

$$L = A(K) \equiv A_1(A_1(...A_1(K)...)).$$

Let a rule P be given, which juxtaposes to a combination of configurations M a single configuration $P(M)$ being the mean of the given ones. We shall call this rule a concentrate one. The concentration can be made over the values of the symbols from S for the material points, as well as over their coordinates, however, not over both of them simultaneously. For each choice of the rule P one should proceed from physical considerations.

For example, if k-th element of M $(1 \leq k \leq s$, where s is the number of elements of $M)$ is a rectangular with $p \times q$ squares and if the square staying on (i,j)-th place $(1 \leq i \leq p, 1 \leq j \leq q)$ contains number $d^k_{i,j} \in \{0,1,...,9\}$, then on the (i,j)-th place of $P(M)$ stays:

– minimal number

$$d_{i,j} = \left[\frac{1}{s}\sum_{k=1}^{s} d^k_{i,j}\right],$$

– maximal number

$$d_{i,j} = \left\lceil\frac{1}{s}\sum_{k=1}^{s} d^k_{i,j}\right\rceil,$$

– average number

$$d_{i,j} = \left[\frac{1}{s}\sum_{k=1}^{s} d^k_{i,j} + \frac{1}{2}\right],$$

where for real number $x = a + \alpha$, where a is a natural number and $\alpha \in [0,1)$: $[x] = a$ and

$$\lceil x \rceil = \begin{cases} a, & \text{if } \alpha = 0 \\ a+1, & \text{if } \alpha > 0 \end{cases}$$

Let B be a criterion defined from physical or mathematical considerations. On given two configurations K_1 and K_2 it answers the question if they are close to

each other or not. For example, for two configurations K_1 and K_2 having the form from the above example,

$$B(K_1, K_2) = \frac{1}{p.q} \sum_{i=1}^{p} \sum_{j=1}^{q} |d_{i,j}^1 - d_{i,j}^2| < C_1$$

or

$$B(K_1, K_2) = \left(\frac{1}{p.q} \sum_{i=1}^{p} \sum_{j=1}^{q} \left(d_{i,j}^1 - d_{i,j}^2\right)^2 \right)^{\frac{1}{2}} < C_2,$$

where C_1 and C_2 are some constants.

For the set of configurations M and the set of rules A we shall define the set of configurations

$$A(M) = \{L | (\exists K \in M)(L = A(K))\}.$$

The rules A will be called statistically correct, if for a great enough (from a statistical point of view) natural number N:

$$(\forall m > N)(\forall M = \{K_1, K_2, ..., K_m\})$$

$$(B(A(P(M)), P(\{L_i | L_i = A(K_i), 1 \leq i \leq m\})) = 1). \quad (1)$$

The essence of the method is in the following: the set of rules A, the proximity criterion B and the concentrate rule P are fixed preliminarily. A set of initial configurations M is chosen and the set of the corresponding final configurations is constructed. If the equation (1) is valid we can assume that the rules from the set A are correct in the frames of the model, i.e. they are logically consistent. Otherwise we replace part (or all) of them with others. If the rules become correct, then we can add to the set some new ones or transform some of the existing and check permanently the correctness of the newly constructed system of rules. Thus, in consecutive steps, extending and complicating the rules in A and checking their correctness, we construct the model of the given process. Afterwards we may check the temporal development (as regards the final system of rules A) of a particular initial configuration.

In the method of modelling generally one works over one or several particular configurations. However here we check initially the correctness of the modelling rules and just then we proceed to the actual modelling. This is due to a great deal to the fact that we work over discrete objects with rules convenient for computer realization. Thus a series of checks of the equation (1) can be performed and just to construct the configuration $A(K)$ for a given configuration K and a set of rules A.

Here we will start describing our model: Let have a matrix NxM, which will be an abstract description of the surface of a forest. The visualization will be a net NxM with bins containing numbers from 0 to 9. Those parameters are representation of the coefficient of burning. The 0 would be totally burned or nothing to burn status of the bin (in case of river, rock, lake etc.) and everything in the range from 1 to 9 will be thickness of the forest trees in each bin. Another

parameter will be the vector of the wind with its direction and intensity of blowing. In our software application we can include a flag for showing the state of each bin in the moment of the started fire. The flag is 1 if the bin is burning and it is 0 if not. In our simulation the fire starts from the central bin, of course it can start from any bin.

The bins coefficients represent how long the bin will burn till be totally burned. In this paper we consider the simplest case without wind. Thus the fire is distributed in all directions with the same speed. So if the state of the bin is 1 (burning) every time step (iteration) the burning coefficient decrease with 1 till it becomes 0 (totally burned). If the state of the bin is 0 (not burning) and the state of all neighbor bins are 0, then the burning coefficient states unchanged. If the state of the bin is 0 and the state any of the neighbor bins was 1 in a precedence iteration, then the state of the bin becomes 1. Thus with this model we can trail the development of the fire in every time moment.

3 Experimental Results

In this section we prepare several test problems. Our test area is divided on $N \times M$ bins. On real problem one bin can be 10 square meters. To generate tests we generate random numbers from 1 to 9 for burning coefficients. We start burning from the central bin and burning process continues till the fire reaches borders of the area. We generate K tests (simulations). To check the correctness of the algorithm, we calculate the average area by averaging every bin with respect to all simulated areas:

$$b_{ij} = \frac{1}{K} \sum_{n=1}^{K} a_{ijn} \tag{2}$$

We do the same for burned areas (resulting areas):

$$c_{ij} = \frac{1}{K} \sum_{n=1}^{K} a'_{ijn} \tag{3}$$

After that we apply the method on average initial area and the result is the burned area d_{ij}. We compare c_{ij} with d_{ij} for every i and j. On Figure 1 the

Table 1. The development of the fire

3	9	8	9	2	6	4	2	9	3	9	8	9	2	6	4	2	9	3	9	8	9	2	6	4	2	9
3	4	5	3	9	4	9	3	7	3	4	5	3	9	4	9	3	7	3	4	5	3	9	4	9	3	7
3	2	8	5	2	4	7	5	8	3	2	8	5	2	4	7	5	8	3	2	7	4	1	3	7	5	8
9	5	9	4	8	0	6	8	8	9	5	9	3	7	0	6	8	8	9	5	8	2	6	0	6	8	8
8	8	2	8	2	0	4	3	7	8	8	2	7	1	0	4	3	7	8	8	1	6	0	0	4	3	7
4	4	5	8	6	0	1	1	5	4	4	5	7	5	0	1	1	5	4	4	4	6	4	0	1	1	5
6	2	8	1	4	5	9	1	4	6	2	8	1	4	5	9	1	4	6	2	7	0	3	4	9	1	4
1	9	1	6	2	1	1	3	7	1	9	1	6	2	1	1	3	7	1	9	1	6	2	1	1	3	7
3	9	9	5	9	1	1	5	2	3	9	9	5	9	1	1	5	2	3	9	9	5	9	1	1	5	2

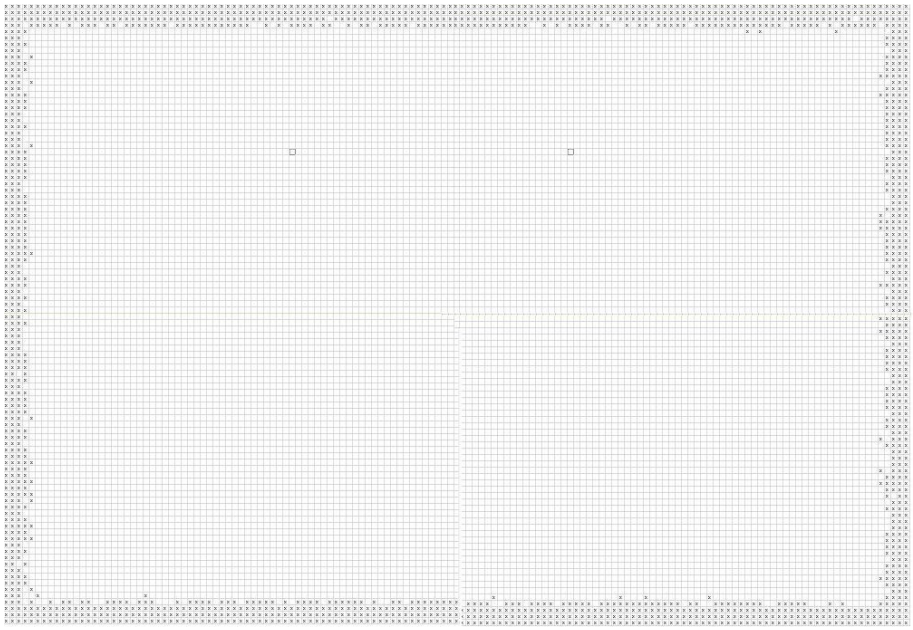

Fig. 1. Differences between average on the result areas and result on average initial areas, the different bins are market with X

different bins between the average result areas and result on average initial areas are marked with X. We prepared an example where the area consists of 143 × 143 bins. We generated 30 simulations. We apply the method on every of the simulation and on the average area where the value of the bin (i, j) is an average of the bins (i, j) of all 30 simulations. We average the resulting areas and compare with the result of the average area Figure 1. Only 914 bins, which are 4% of whole area, are different and they are on the boundary, so called boundary effect. So we can conclude that the results are statistically similar and the method is correct.

Table 2. The area after the third time step

o o o o o o o o o	o o o o o o o o o	o o o o o o o o o	o o o o o o o o o
o o o o o o o o o	o o o o o o o o o	o o o o o o o o o	o X X X X X X o o
o o o o o o o o o	o o o o o o o o o	o o X X X X o o o	o X X X O X X o o
o o o o o o o o o	o o o X X o o o o	o o X X X o o o o	o X X X X o X o o
o o o o X o o o o	o o o X X o o o o	o o X X O o o o o	o X X X O o o o o
o o o o o o o o o	o o o X X o o o o	o o X X X o o o o	o X X X X o O o o
o o o o o o o o o	o o o o o o o o o	o o X O X X o o o	o X X O X X X o o
o o o o o o o o o	o o o o o o o o o	o o o o o o o o o	o X O X X O O o o
o o o o o o o o o	o o o o o o o o o	o o o o o o o o o	o o o o o o o o o

We prepare a small example with 9×9 bins. We want to show how the method works and how the fire is dispersed. On the first table is the initial area with the burning coefficients in the every bin. The coefficient 0 means unburned material. On the Table 1 we observe the decreasing of the burning coefficients.

On the Table 2 we show the fire dispersion and how the fire surround unburned area. The bins with o are without fire. The bins with X are burning bins. The bins with O are totally burned.

4 Conclusion

On this paper we describe method of modelling wildland fire using games theory. We focused on simplified example when the area is flat and without wind. Our model can trace the fire and predict its development which is very important to bring it under control and to prevent it to cause large damages. In a future works we will complicate the model including areas which are not flat and meteorological data as wind and humidity. Thus our model will become more flexible and applicable in different situations. We will use real data from a past wildland fire and compare how well we model the development of the process.

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