WORKING PAPER

ON SPATIAL MODELLING OF
LONG-TERM FOREST FIRE DYNAMICS

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November 1987
WP-87-105

International Institute
for Applied Systems Analysis
A-2361 Laxenburg/Austria

IIASA

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Foreword

This paper introduces a new approach to spatial modelling of long-term fire dynamics in boreal forests, and is an important contribution to the literature in that field.

M.T. Ter-Mikhaelian was a YSSPer (Young Scientists' Summer Program) at IIASA working with Professor Antonovski in the summer of 1987. This paper is a credit to them both.

R.E. Munn
Leader
Environment Program

Abstract

The dynamics of forest fires over large territories is of great practical interest. Previous theoretical works are concerned mainly with point source fire models, and the transition from point source to area models - large scale - even simple models, is a shift forward. Certainly, the term "simple" has relative meaning in that it is relative to the level of achievement in an applied domain. However, it is very interesting that, to the authors, even such a simplified model appears not very trivial.

As regards the stable state of the forest and the dependence of fire probability on the age of the forest, this conclusion can only be checked with models, as the time required for natural observations is much too long. In the model described in this paper (see figure below), we do not claim to have created a quantitative model with which we could give a prognosis of the dynamics of specific forest regions. However, we can say that we have reached the following conclusions:

1. The absence of contemporary boreal forest of stable (in the absence of constant in time age-structure of forest) state, instead of that - the stable fire regime, which is characterized by the large amount of fire year with little fired territory during the year, and irregular fires of great intensity. An explanation in the frame of a model - effects like "synchronization" of forest formed processing (it must be an accumulation of a large amount of combustible material over a large area.) In our model this regime has settled after 2000 years (steps) and long term support (>10000).

2. The probability of burning a forest increases monotonically with increase in forest age.

For a more accurate quantitative description of fire dynamics in forests, we must of course take into account the different primary and secondary succession lines, their ecological characteristics, climate fluctuations and so on.

Brief description of model

Forest territory - regular square lattice; each grid square is a forest plot of some age τ, $\tau=0,\ldots,N$, i.e., τ- is a state of grid square at a given moment in time.

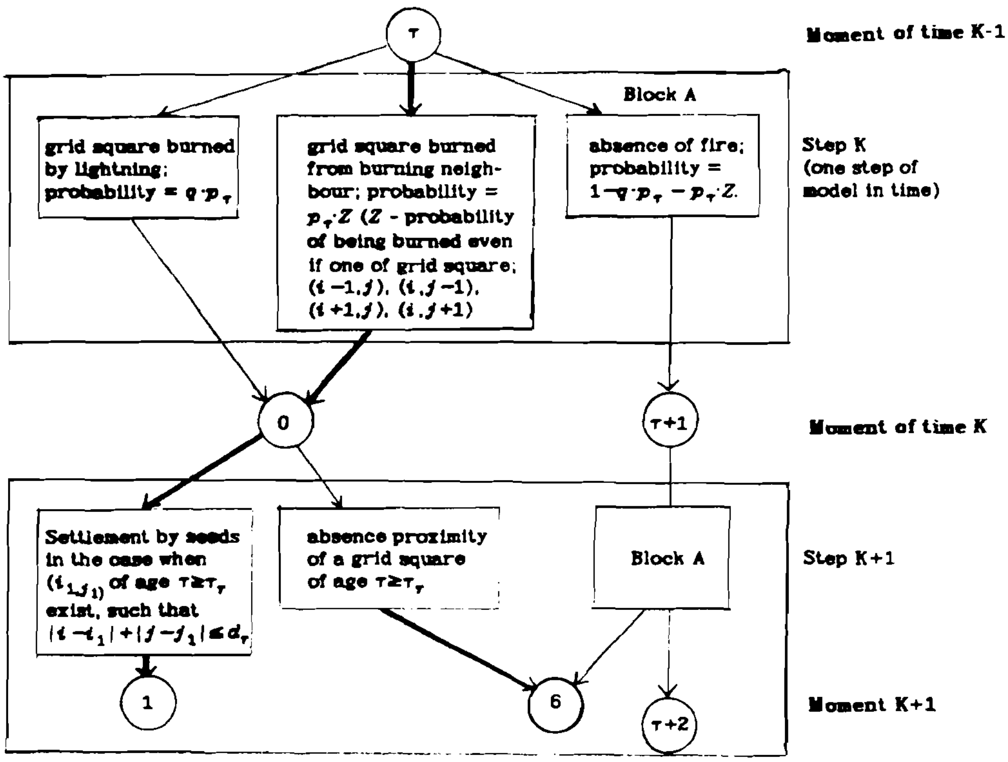
Parameters of model: q - probability of lightning in one grid square for one time step;

$\{p_\tau, \tau=1,\ldots,N\}; p_\tau$ - probability of burning of one grid square in state τ when fire exists;

τ_r - material age (age, where τ_0 is the initial age when there are just enough seedlings to settle neighbouring grid square; d_r - maximal distance of transfer of seeds; the seeds from grid square (i,j) of age $\tau=>\tau_r$ transporting in each grid square (i_1,j_1) for which

$$|i-i_1| + |j-j_1| \le d_r \,.$$

Dynamic of one grid square (i,j).



Circles denote the state of grid square;

Squares denote events (with corresponding probabilities) which caused a transition from one state to another;

Thick arrows are the transition in the state, caused by spatial interrelation.

ON SPATIAL MODELLING OF LONG-TERM FOREST FIRE DYNAMICS

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1. INTRODUCTION

In this paper we formulate a simple spatial model of long-term forest dynamics including the influence of wildfires. By the word "spatial" we denote models that describe the dynamics of large nonhomogeneous (from the ecological viewpoint) forested territory taking into account interactions between adjacent landscape units. By "long-term" we mean dynamics on a timescale of order 10^2 - 10^3 years, rather than changes in forest patterns during one fire season.

Wildfire is a dominant factor that determines formation and maintenance of forest communities (Furyaev, Kireev, 1979; Heinselman, 1973; Heinselman, 1981; Tande, 1979). Present boreal forests represent a mosaic of spots, each of postfire origin. The structure and composition of this mosaic (diversity, mean size of a single spot, age structure of territory etc.) depend on the fire regime, viz., periodicity and extent of fires. In our opinion, the only possible way of understanding the present pattern of vegetation over large areas and especially of predicting its future behaviour under possible variations of exogeneous parameters is to formulate spatially distributed models of forest fire dynamics and to verify these models by selected data on fire history over long periods of time ($\approx 10^2$ year). Let us briefly review existing models and discuss possible ways of modelling the spatial effects of forest fire dynamics.

2. THE APPROACHES AVAILABLE.

For our purposes, it is possible to classify models firstly as to whether they are locally or spatially distributed and secondly as to whether they are short-term or long term. Unfortunately we have not found any published studies on forest fire modelling that are simultaneously spatially distributed and long-term. Therefore, we shall list and briefly discuss models most closely related to our interests and purposes.

Among spatially distributed models, it is necessary to mention those that simulate the pattern of a single forest fire (Vorobiyov, Valendik, 1978; Vorobiyov, Dorrer, 1974; O'Regan et al., 1976). The technique used in these models is simulation of fire expansion on a grid with certain probabilities of fire transfer from one grid square to adjacent ones. This approach is also convenient for modelling fire processes over large areas. The models that deal with analytical expressions for the description of fire spread (Bajenov, 1982; Dorrer, 1979) seem to be useless for our purposes because they need detailed input information that is unavailable for large areas.

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The long-term models can be conveniently subdivided into two groups: statistical and more specific Markov chain type models. Statistical models usually describe either the distribution of fire intervals (i.e., period of time between two successive fires) or age structure in the area studied (Johnson, 1979; Johnson, Van Wagner, 1985; Rowe et al., 1975; Van Wagner, 1978). (Here and below by the words "age structure" we denote not age structure of a stand but the distribution of a large forested area, i.e., the parts of the territory occupied by forest of certain age; age of forest is equal to the length of time since the last severe fire). In our opinion, the shortcomings of these models are the following. Firstly, they are useless for describing spatial effects of forest fire dynamics such as the size of a single fire, fraction of the territory burned per year, etc. (this defect is common to all long-term models listed); it is theoretically possible to expand these models and make them spatially distributed, e.g., to consider two-dimensional statistical distributions of fire intervals and size of territory burned per year, or something like that; however, estimation of the parameters of these distributions will cause a nonproportional increase in requirements for field data, so this way seems hopeless.

The second shortcoming of statistical models is that the parameters of distributions usually cannot be physically interpreted; this restricts the possibilities of models of this kind and especially their application to predictions of future forest patterns.

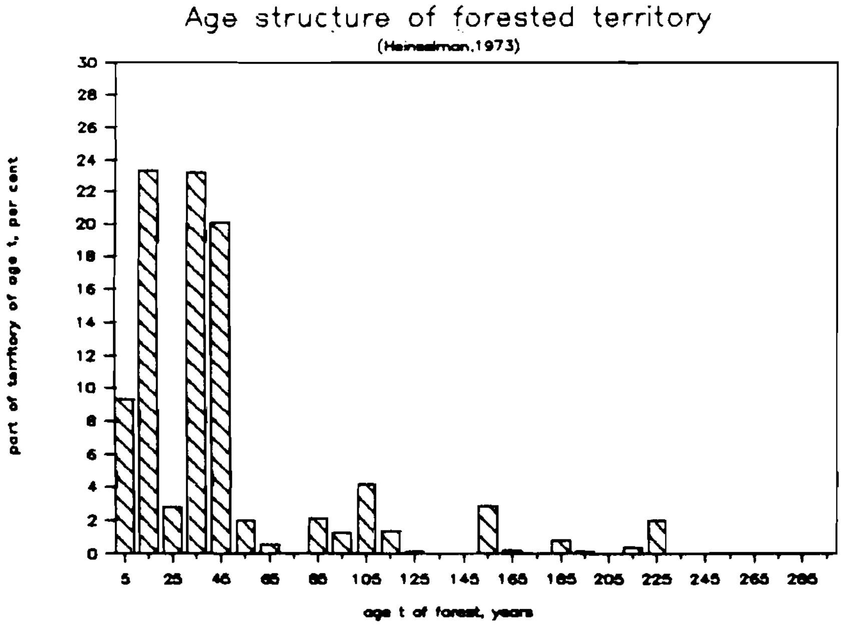
The only paper in which the type of distribution is validated, is that of Van Wagner (Van Wagner, 1978). In this paper, forest area is considered as consisting of large numbers of even-aged equal-sized stands, each having an annual probability of burning p independent of age of stand; it follows from these assumptions that the age structure of the study tends to be negative exponential. However, most age structures are not even monotonously decreasing; they have at least one obvious global peak and a number of local ones (Furyaev, Kireev, 1979; Heinselman, 1973; Suffling, 1983; Tande, 1979). The hiatus in age structures after 1900 is usually explained through fire control. It is difficult for us to judge whether there was a jump in the efficiency of fire control in North America and Australia at the beginning of the last century, but we are sure that this is not true for West Siberia, where age structures look quite similar to those shown in the papers mentioned above.

There is another reason for doubting monotonous decreases with age in parts of the territory occupied by forest of that age, namely, there are irregular fires of high intensity that burn large forested areas and therefore cause peaks in age structure; here is a quotation from Heinselman, (1973):

> "... And before 1900 there was a gradual decline in year classes with time punctuated by irregular, but also declining, ***jumps*** in year class areas for the major fire years".

In Figure 1, the age structures from Heinselman (1973) and Tande (1979) are shown; parts of these age structures relating to the period after 1910 are omitted. We shall return to the problem of major fires later. Now let us turn to markovian models.

First of all it is necessary to mention the paper by Shugart et al. (1973); although the model described in this paper does not deal with wildfires, it is a pioneer model in which for the first time (to our knowledge) succession lines were considered as sequences of successional stages with corresponding probabilities of transition from one stage to another. This approach was later developed for a description of forest fire dynamics (Cherkashin, 1981; Kessel, 1982; Korzuhin, Sedych, 1983; Marsden, 1983; Martell, 1980); this was achieved by assigning to



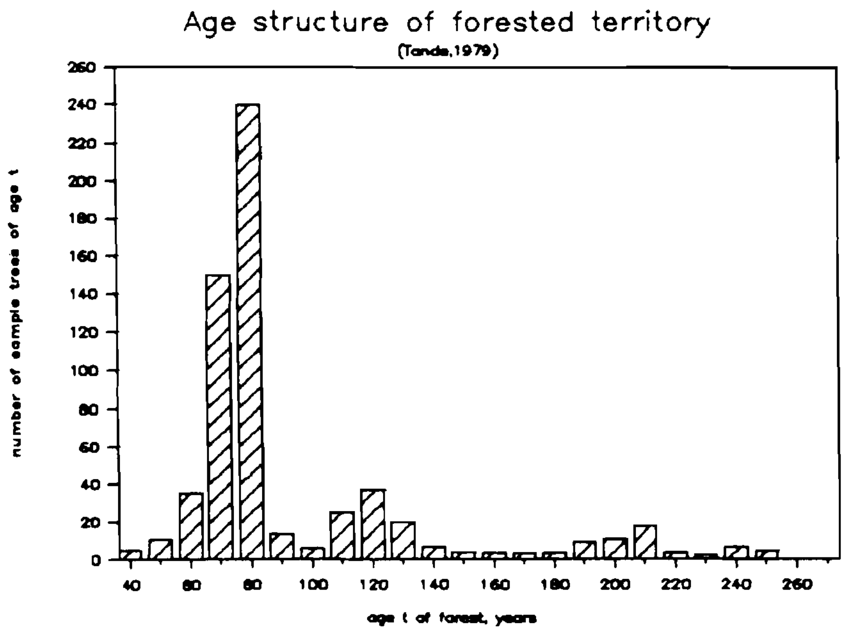


Figure 1: Age structure constructed with help of data on fire history from Heinselman, 1973 and Tande, 1979.

each stage the probability of burning during one year (i.e., the probability of transition to an initial successional stage).

Unfortunately these models are not suitable for describing spatial effects of forest fire dynamics; in fact they deal with an isolated stand, because the probabilities of its burning as well as the times between fire and recommencement of the successional process are independent of what is happening in adjacent stands. Only the paper written by Kessel (1982) contains a discussion of the problem of interaction between stands. The method proposed in this paper consists of including a transfer distance for seeds and so making the postfire dynamics of each stand dependent on the state of adjacent stands; however, this proposal has not been realized in the literature.

Nevertheless, this approach seems to be most convenient for the first steps towards spatial modelling of long-term forest fire processes; at the moment when our purpose is first of all to test new modelling techniques for the description of spatial effects of interaction between stands, more detailed models of stand dynamics would only complicate our study with little benefit.

For similar reasons, we are not going to use gap-models containing wildfire influence blocks even if well fitted with numerous field data (Kercher, Axelrod, 1984; Shugart, Noble, 1981). In principle, it is possible to consider a large forested area as a mosaic of gaps and to describe the dynamics of each gap by one of the gap-models adding interactions between gaps; however, for the present state of computer development, running of such "multigap-models" would require so much computer time that this approach seems to be completely impractical.

3. FORMULATION OF THE MODEL.

Let us turn to the formulation of the model. An idealized description of long-term forest dynamics is as follows. Consider a forest landscape mosaic containing ecologically homogeneous domains. Assume that each domain determines the succession line over it; so we need take into account only the main succession lines, not the secondary ones. For simplicity, let us suppose that there is only one succession line over the territory to be modeled (consideration of only one succession line does not reduce the generality of the model and is taken only in order to decrease the number of unknown parameters). So the domains differ only by age (that is, the time after the last severe fire). We describe the dynamics of a single domain in the following manner (see Figure 2).

Let t be the age of a domain; during one year a lightning-caused fire may occur and the domain may ***completely*** burn (Figure 2a); so only severe fires are taken into account. Let Q be the probability of a lightning stroke per one square unit of area during one year and P be the probability that the domain burns in the case of an ignition source (lightning in the present case); P obviously should depend on the domain's age t and should reflect the "fire maturity" of forest-occupying domain.

When the domain burns, the fire can be transferred to adjacent domains, burning with probabilities P, the indices corresponding to their ages, and so on, until this transfer process is interrupted always on the borders of domains, i.e., the pattern of fire-burned territory coincides with the conjunction of a few adjacent domains.

If the domain is neither burned from lightning nor from a "burning neighbour", its age increases and becomes $t+1$. If there are domains with forest at reproductive age near the domain burned, the succession process is started; otherwise it stays unoccupied. So the spatial aspects of the dynamics become ap-

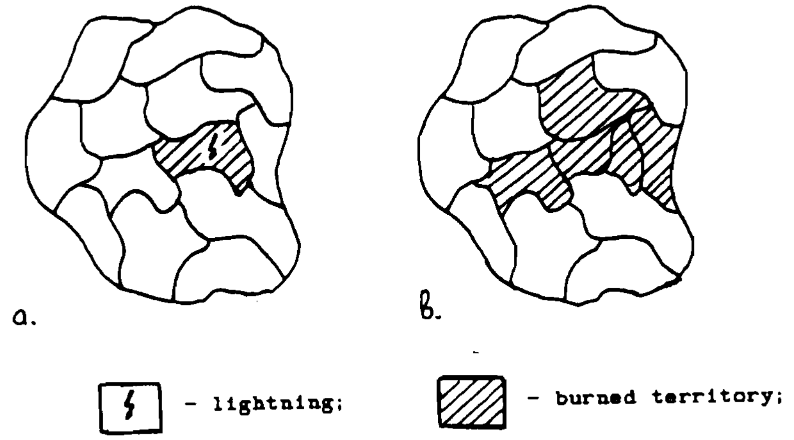


Figure 2: Idealized patterns of fire burned territory: a) only one domain burned; (b) few domains burned.

parent in the fire-transferring and seed-transferring mechanisms.

Two different approaches to modeling the dynamics described above are; to construct a system of nonlinear differential equations that describe the dynamics in terms of those parts of the territory occupied by forests of the same age; second, to construct a simulation model that produces random dynamic trajectories over a large area. The merit of the first approach is that it gives the possibility of mathematical investigation of the model, e.g., to investigate the problem of a stable state's singularity, to analyse the dependence of a stable state's existence on parameters of the model, and so on. The convenience of the second approach is that after being fitted, the models can be used for forecasting future spatial patterns (in other words, the map) of concrete landscapes under various possible scenarios of exogeneous parameters' behavior; for this reason, we used the second approach.

Our model forest area was simulated as a grid 50×50. Each vertex represents a stand, so all stands were considered to be of equal size. In order to exclude possible "border effects", the grid was closed, i.e., vertices $(i,1)$ and $(1,j)$ were considered to be adjacent to $(i,50)$ and $(50,j)$, respectively for $i,j=1,\ldots,50$ (i and j are the numbers of rows and columns in the grid, respectively). All vertices represent one succession line whose maximal longevity is equal to N. The dynamics of the grid was simulated in accordance with the idealized scheme described above.

The assumption was taken that in the case when a stand attains age N without burning, it self-destroys and succession begins again (this assumption was used again for closing the model).

4. MODEL PERFORMANCE TESTING.

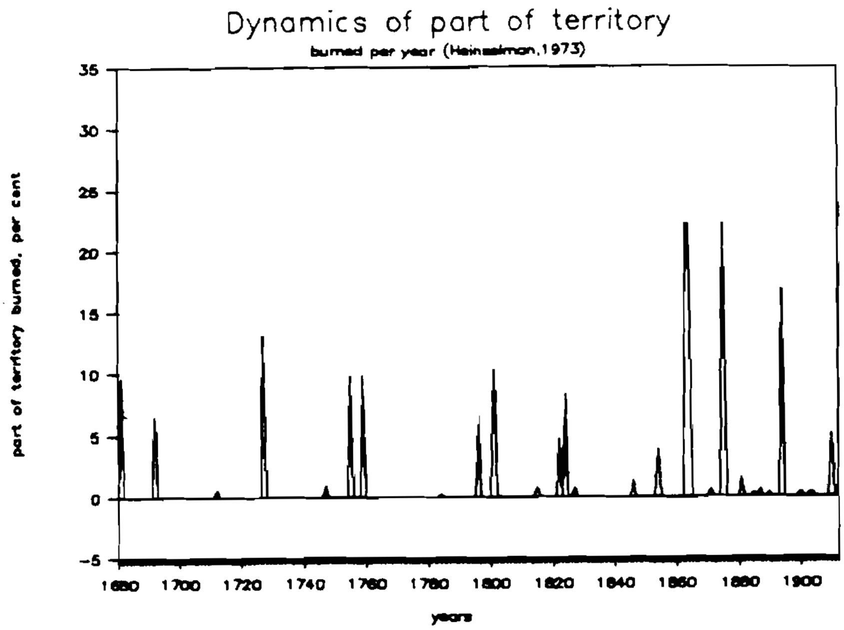
In order to be convinced of the model's viability, we had to verify it with some field data. The unknown parameters of the model are Q and P_i, $i=1, \ldots, N$. Not only are estimates of these parameters absent but even the shape of P_i is unknown, i.e., whether they increase with the growth of i, whether they are uniformly distributed, and so on (for discussion of this problem see Heinselman (1981)). Our first plan was to estimate the values of P_i by adjusting the age structures obtained in the model to those observed in real forests, but this plan had to be abandoned when we found that natural age structures are not stable. Therefore we decided to attempt to include in the model the effect mentioned above, namely, the pulsing of that part of territory burned per year. Let us remember the heart of the problem. The empirical data on a long-term fire history (from Heinselman, 1973, and Tande, 1979) show that in most years with fires, a small part (approximately a few percent) of the territory is burned during a single year. In a few fire years, a large part of the area is burned per year (about 25% according to Heinselman (1973) and more than 50% according to Tande (1979)). In Figures 3 and 4 the dynamics of parts of territory burned per year and the distribution of these parts over a long period of time are shown; in Heinselman (1973) the total area burned during 1863-1864 is given under 1864, because 1963-64 burns cannot be separated; when plotting the figures we divided this area into two equal parts; the same procedure was used with data on the 1755 and 1759 burns.

It may be possible to explain this effect from fluctuations of climatic parameters. But the second essential condition of such an irregularity is that large wildfires need a large amount of fuel; the flammability of this fuel depends strongly on its age, so there is a kind of auto-coordination of the forest over a large area that provides an opportunity for wildfires. If major fires could be explained through fluctuations of climatic parameters it would mean that the distribution of these parameters over a long period of time is at least bimodal (because peaks in the distributions of the fraction of territory burned per year are obvious) in order to cause corresponding peaks in fire intensity. Thus we believe that it is necessary to try to obtain at least a qualitatively plausible pattern in the model with deterministic parameters and only then to add random fluctuations caused by exogenous parameters.

For model runs we took $N=300$. In order to decrease the number of parameters, P_i, we divided all succession lines to five stages of equal longevity, the probability of burning being constant within each stage. The reproductive age and transfer distance of seeds were taken as 60 and 5 respectively; the last number means that if (i,j) is at a reproductive age, the seeds from this vertex can be transferred to all vertices (i_1,j_1) that satisfy the condition

$$|i_1-i| + |j_1-j| \leq 5 .$$

We used a uniform initial age structure of area; that means that the number of vertices at age i was considered to be equal to $1/N$ and the corresponding initial state of the grid was generated. The parameters Q and P_i, $I=1, \ldots, 5$ (here I is the number of the stage) were searched in order to adjust the distribution of burned parts to observed ones. During the model's run a 300-year period was tak-



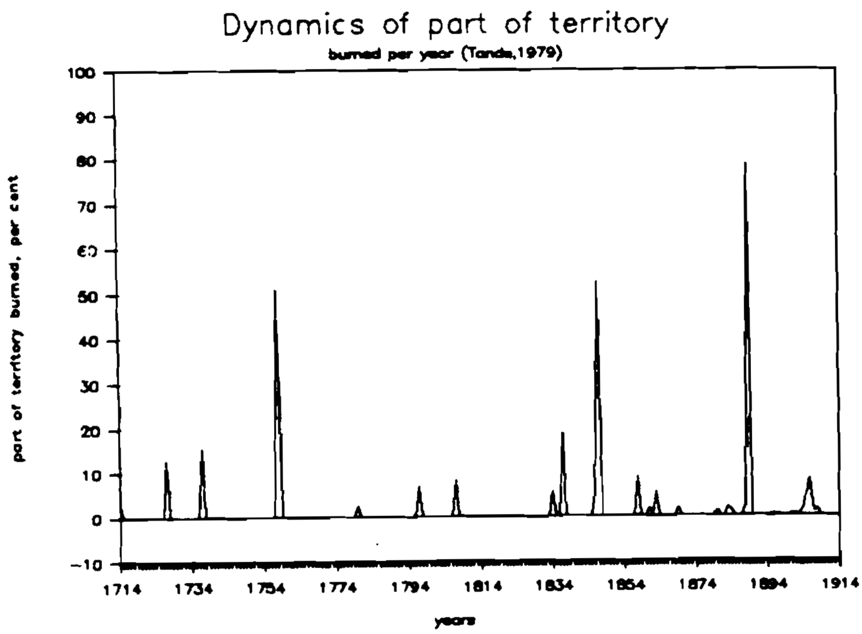


Figure 3: Dynamics of parts of territory burned per year.

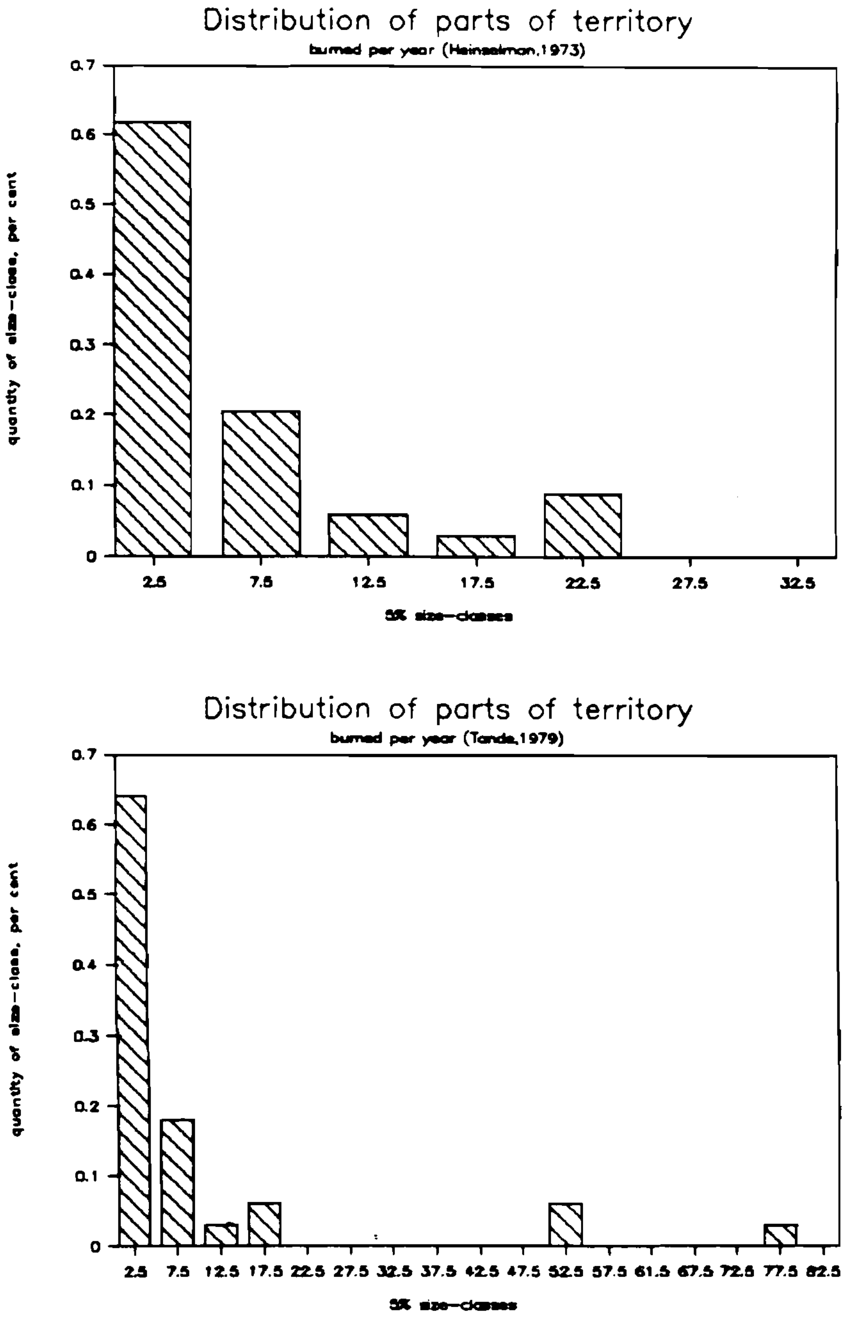


Figure 4: Distributions of parts of territory burned per year.

en for constructing these distributions.

The results are the following. The values of Q and P were obtained for which the model and natural distributions of fractions of territory burned per year are similar. These values are $Q = 0.001$ and $P = \{0.1, 0.15, 0.2, 0.6, 0.7\}$ for the distribution from Heinselman (1973) and $Q = 0.001$ and $P = \{0.1, 0.15, 0.2, 0.65, 0.75\}$ for the distribution of Tande (1979). The regime in which the pulsing part is burned occurs after 1500 years (i.e., 1500 steps of model running) for the first set of values Q and P and after 1800 years for the second one. Average numbers of fire seasons for one 300-year period are equal to 50 and 30, respectively. The distributions obtained are shown in Figure 5.

The uniform and monotonously decreasing shapes of P were also tested; both resulted in monotonously decreasing shapes of the distribution of the fraction of area burned per year. Increasing values of P_4 and P_5 lead to a periodical regime with the fraction of territory burned during one fire season being more than 80%.

5. CONCLUSION

The results seem to be successful. Of course we appreciate the roughness of the model (in our opinion, the main assumptions to be corrected are assuming a single succession line over the entire area and assuming that all stands are of equal size) so we are not going to insist on the quantitative exactness of parameter estimations. Nevertheless, the following conclusions seem to be non-controversial:

1. Boreal forests are not in a stable state (in the sense of stability of age structures) but there is a stable fire regime, i.e., fire years in which a small part of the territory is burned alternate with major fire years occurring irregularly; this conclusion arises firstly from the nonmonotonous shapes of the age structures and secondly from convergence of the dynamics of that part of the territory burned per year with the pattern described above; thereafter a stable pattern is maintained.

2. The probabilities of burning increase with the age of the forest. Other alternative patterns of the probability vector result in patterns of distribution of fractions of area burned per year different to the observed ones.

3. The pattern of the probability vector is almost a step function; we mean that there is a jump from P_3 to P_4. Our attempts to make the pattern smooth were unsuccessful. This fact suggests that the deterministic mechanism of autocoordination of the forest is insufficient to explain the phenomenon of major fires (because such big differences in values of burning probabilities between stages is hardly probable); so there should be a combination of auto-coordination and fluctuations of climatic parameters that affect forest dynamics. Simultaneously this fact indicates the direction of future investigations: to take as a starting point a vector of burning probabilities of the type obtained in our model (i.e. with values increasing with forest age) and to add random fluctuations of climatic parameters in accordance to their statistical distributions constructed with the help of long-term observations.

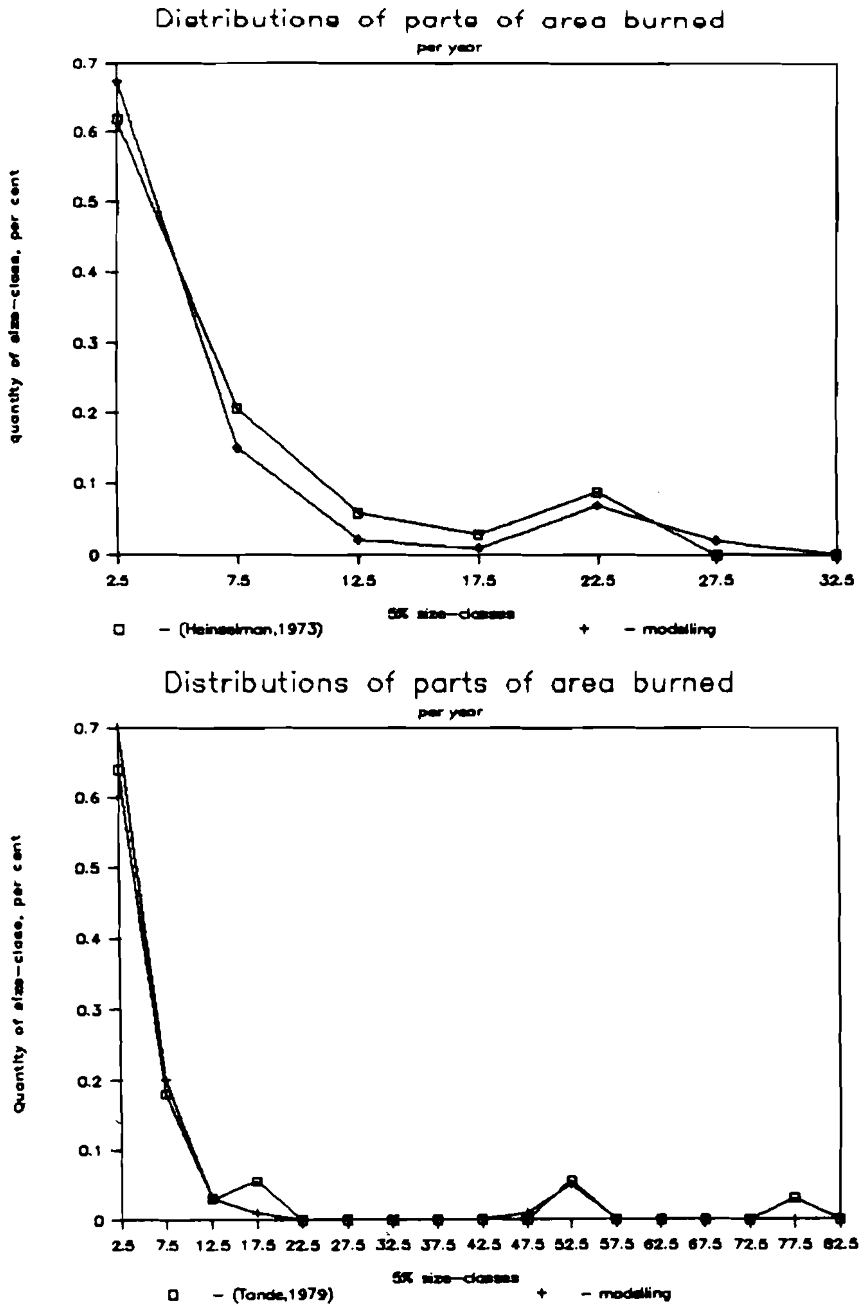


Figure 5:Natural and modeled distributions of parts of territory burned per year; for parameters' value see text.

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Acknowledgement

The authors wish to express their gratitude to Professor Ted Munn for his help.