WORKING PAPER

A SPATIAL MODEL OF LONG-TERM FOREST FIRE DYNAMICS AND ITS APPLICATION TO FORESTS IN WESTERN SIBERIA

M.Ya. Antonovski
M.T. Ter-Mikaelian
V.V. Furyaev

December 1989
WP-89-109

IIASA
International Institute
for Applied Systems Analysis

A SPATIAL MODEL OF LONG-TERM FOREST FIRE DYNAMICS AND ITS APPLICATION TO FORESTS IN WESTERN SIBERIA

M.Ya. Antonovski
M.T. Ter-Mikaelian
V.V. Furyaev

December 1989
WP-89-109

INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
A-2361 Laxenburg, Austria

FOREWORD

This paper will also appear as a chapter in the book *Ecosystems Analysis and Simulation of the Global Boreal Forest*, edited by Professor H.H. Shugart, and to be published by Cambridge University Press.

The authors started work on the model described in this paper in 1987 and published their earlier findings in an IIASA Working Paper entitled "On Spatial Modelling of Long-Term Forest Fire Dynamics" (WP-87-105). The model was tested using data on long-term forest fire dynamics in North America and western Siberia. The paper gives, as an example, changes of forest patterns caused by changes in climatic parameters. This example is chosen because the probabilities of forest-fire dynamics and fire transfers are largely determined by climatic factors. Dependence on climate provides an opportunity to predict forest changes for different scenarios of climate change.

Bo R. Döös, Leader
Environment Program

ACKNOWLEDGMENTS

The authors wish to express their gratitude to Dr. P.A. Kolosov and Dr. M.D. Korzukhin, from the Natural and Climate Monitoring Laboratory, USSR, for their invaluable help with this work.

ABSTRACT

This paper is devoted to developing a spatial model of wildfires in forests. Wildfires are a dominant factor in controlling the structure and life of boreal forest communities. The main parameters controlling the simulation of fire dynamics are: probability of occurrence of fire source during one year per square unit, probability of fire maturity of cell in k-th state of n-th successional line during one year, and fire spread probability for cell in a stage of some successional line during one year per square unit. The dependence of forest fire dynamics on climatic conditions is reflected in such general climatic parameters as mean seasonal air temperature, seasonal sum of precipitations, and maximum period between two successive rains during one season. Testing of the model is based upon data on long-term forest fire dynamics in North America and western Siberia.

CONTENTS

1. INTRODUCTION 1

2. THE APPROACHES AVAILABLE 1

    2.1. Short-Term Spatially Distributed Models 1

    2.2. Long-Term Locally Distributed Models 2

        2.2.1. Statistical models 2
        2.2.2. Markovian models 2
        2.2.3. Gap-models 3

    2.3. Spatially Distributed Long-Term Models 3

3. OBJECT OF THE STUDY 4

4. FORMULATION OF THE MODEL 6

5. DESCRIPTION OF THE TEST REGION 7

6. VERIFICATION OF THE MODEL 10

7. CONCLUSIONS 16

REFERENCES 17

FIGURES 19

A SPATIAL MODEL OF LONG-TERM FOREST FIRE DYNAMICS AND ITS APPLICATION TO FORESTS IN WESTERN SIBERIA

M.Ya. Antonovski, M.T. Ter-Mikaelian** and V.V. Furyaev****

1. INTRODUCTION

In this paper we will present our achievements in developing a spatial model of long-term forest fire dynamics. By 'long-term' we mean dynamics over hundreds or thousands of years rather than changes in forest patterns over one fire season. By the word 'spatial' we denote a model that describes the dynamics of large nonhomogeneous (from the ecological viewpoint) forested territory taking into account interactions between adjacent landscape units.

Wildfires are a dominant factor controlling formation and maintenance of boreal forest communities. In fact, present boreal forests represent a mosaic of different areas each of post-fire origin. The dynamics of this mosaic depends on the fire regime, i.e., on the periodicity and extent of fires. An understanding of the mechanism of the influence of wildfires on boreal forests is therefore the key to correct description of their present and future behavior. However, in the early stage of our work on modeling forest fire dynamics we encountered a variety of opinions both on the general behavior of boreal forests and on different factors controlling fire processes; the following brief review reflects partially this variety.

2. THE APPROACHES AVAILABLE

For our purposes it is possible to classify models first as to whether they are locally or spatially distributed and second as to whether they are short-term or long-term. The following discussion does not pretend to be a complete review of existing models; it is intended to help us formulate main questions to be answered. Since we are particularly interested in modeling long-term forest fire dynamics over large areas we will discuss only the models which are most closely related to our interests and purposes.

2.1. Short-Term Spatially Distributed Models

The models of this group simulate the pattern of a single forest fire. In all models a forest is considered to be a homogeneous surface conductor of fire; the rate of fire spread is assumed to dependent on spread direction (thus the influence of wind is taken into account). There exist two approaches to modeling fire process of this kind.

In Bajenov (1982), for a currently burning point on the surface, the neighborhood of points which will be ignited in the next moment is determined. The 'burning spot' is the conjunction of points currently burning and already burned, taken with their neighborhoods. Thus, a process of unfading fire spread is defined and the problem of localizing the

---

* International Institute for Applied Systems Analysis, Laxenburg, Austria.
**Natural Environment and Climate Monitoring Laboratory, Moscow, USSR.
***Institute of Forestry, Krasnoyarsk, USSR.

'burning spot' is investigated analytically. This approach seems to be of more theoretical rather than practical interest.

The technique used in another approach (Vorobiyov and Valendik 1978, Vorobiyov and Dorrer 1974, O'Regan et al. 1976) is simulation of random fire spread on a grid with certain probabilities of fire spread from one cell to adjacent ones. (The partial case of this fire process (with probabilities of fire spread equal to 1 is a discrete analogue of the process defined in Bajenov (1982).) In models using this approach a number of problems are used to be studied, for example, calculation of mean size of a single fire; model tests coincide satisfactorily with results of field experiments. For our purposes this approach is convenient for modeling fire processes during one fire season.

2.2. Long-Term Locally Distributed Models

These can be conventionally subdivided into three groups. Let us discuss them in consecutive order.

2.2.1. Statistical models

Statistical models usually describe either distribution of fire intervals (i.e., period of time between two successive fires) or age structure of studied area (Johnson 1979, Johnson and Van Wagner 1985, Suffling 1983, Van Wagner 1978); here and below by the term 'age structure' we denote not age structure of a stand but the overall age structure of a large forested area (i.e., the parts of an area occupied by forest of a certain age, the age being equal to the length of time since the last severe fire). In both cases either negative exponential distribution or Weibull distribution is used to describe observed data. The main features of these models are the following.

First, they are helpful for predicting fire occurrence within a concrete area, but they are useless for describing spatial effects of forest fire dynamics such as the size of a single fire, the part of an area burned per year, etc. 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 area burned per year, or the like. However, estimation of the parameters of these distributions will cause a nonproportional increase in requirements for field data, so this way seems hopeless.

Second, the parameters of distributions cannot usually be physically interpreted as this would restrict the possibilities of models of this kind and especially their application to predictions of future forest patterns.

2.2.2. Markovian models

These models simulate dynamics of a single plot (which is considered to be ecologically homogeneous) as a random trajectory of the Markov chain (Hall et al. 1987, Kessel 1982, Korzukhin and Sedych 1983, Martell 1980). The succession line represented in the plot is divided into successional stages. These stages compose the set of possible states of the Markov chain. The set of possible transitions with corresponding probabilities is defined within the set of states. The transition probabilities are assumed to be constant, i.e., they do not change with time. Fires correspond to transitions into stages with lower age; in particular, severe fires correspond to transition into 'zero state', i.e., state with age equal to 0 (completely burned area).

The model developed in Kessel (1982) seems to be most complete. Kessel also raises, for the first time, a question about the necessity of including in the model the interaction between adjacent forest plots. Moreover, he proposes concrete kind of interaction to be included in the model, namely seed propagation from one forest plot to adjacent ones. Unfortunately we did not see his more recent papers, although as it followed from his text, the work on creating such a model was already in progress.

The description of a single plot used in Markovian models seems to us most reasonable at the moment; to us a more detailed description (e.g., including in a model the number of trees within the plot, their age structure, biomass, etc.) is premature. At the same time we again need to emphasize that correct simulation of spatial aspects of forest fire dynamics requires including in the model processes of spatial interaction. The kind of interaction proposed by Kessel is essential but not sufficient because occurrence of major fires burning large forested areas is hardly probable in the model in which probability of burning is independent of what is happening in adjacent plots. In other words, fire spread simulation should be obligatory added.

2.2.3. Gap-models

These models simulate succession within a small plot (equal to 1/12 ha). A number of gap-models (Bonan 1988, Kercher and Axelrod 1984, Shugart and Noble 1981) simulate influence of fires on trees' growth, mortality and reproduction. The merit of these models is that they describe the dynamics of a gap in detail. At the same time this merit is a shortcoming from the viewpoint of spatial modeling. Theoretically it is possible to simulate the dynamics of large area as mutual dynamics of a great number of interacting gaps. However, for the present state of computer development, running such a 'multigap-model' would require so much computer time that this approach seems to be completely impractical.

A few general remarks on locally distributed long-term models should be made. Forest fire dynamics, as it is simulated in Markovian models, indispensably lead to settlement of a stable state. The state of a forest is considered to be stable if its age structure does not change over long periods of time. It is obvious that age structure is stable only in the case when it is monotonously decreasing. In fact, the same assumption is made in statistical models dealing with negative exponential distribution although it is validated only in the paper by Van Wagner (1978). However, most age structures are not monotonously decreasing; they have at least one obvious global peak and a number of local ones (Furyaev and Kireev 1979, Heinselman 1973, Suffling 1983, Tande 1979). The hiatus in age structures after 1900 is usually explained through fire control. To us this assumption should be tested carefully because there is another reason for doubting monotonously decreasing shape of the age structure, namely, there are irregular fires of high intensity that burn large forested areas and therefore cause peaks in age structure. The following is a quotation from Heinselman (1973): " ...And before 1900 there is 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 fact, we have two alternatives. The first is to assume that forests are in general in a stable state (in the sense of stability of age structure); currently observed nonmonotonous age structures are intermediate between two stable states of forest, the change of states being caused by external factors (increasing fire control). The second hypothesis is that the state of forest is generally unstable; this hypothesis involves another question, namely whether the unstability of a forest is caused by climatic fluctuations or whether it can be explained by internal reasons (as a possible reason one could mention the accumulation of large amounts of fuel over large areas which is favorable for the occurrence of major fires). We will return to this problem later, because we consider it very important for the correct modeling of forest fire dynamics.

2.3. Spatially Distributed Long-Term Models

Unfortunately this group is most poor. In fact only the model created by Marsden (1983) includes interaction between forest plots during dynamics, i.e., the probability of transition from fire-burned plot to the next successional stage includes as a multiplier the ratio of plots at reproductive age to the total number of plots; thus he realizes the proposal made by Kessel (1982). The insufficiency of including only this type of spatial interaction was discussed above.

Let us now resume the questions to be answered in the first place, which were formulated during this brief review on existing approaches:

1. Are present boreal forests in a stable state or is this state essentially unstable?
2. To what extent is the size of wildfires controlled by fluctuations in climatic parameters? In other words, is it really necessary to include processes of spatial interaction between adjacent forest plots when modeling the spatial effects of forest fire dynamics or can the dynamics be explained solely in terms of fluctuations in climatic variables?

In Antonovski and Ter-Mikaelian (1987) and Ter-Mikaelian and Furyaev (1988), we presented the first version of a spatial model of forest fire dynamics. In this model a large forested area was simulated as a grid, each cell representing a forest stand. The Markovian model was used for simulating the dynamics of a single cell, with fire spread and seed propagation included as the interaction processes. The model was verified using data on long-term forest fire dynamics in North America (Heinselman 1973, Tande 1979). The following conclusions were drawn from the result of this testing of the model:

a) Boreal forests are not in a stable state but there is a stable fire regime in which during most years only a small area of forest is burned, with years of major fires occurring at irregular intervals.

b) There is a 'synchronization' effect of forest over a large area, presumably related to the accumulation of a similar, large amount of combustible material over the area. This can be shown by doing model runs with constant probabilities of forest fire maturity, which is a key parameter. The effect leads to the fire regime described above, even when the influence of climatic fluctuations is eliminated (i.e., key model parameters are constant). This proves the necessity of a spatial approach to modeling fire dynamics for large forested areas.

We consider these results to be a good background for further development of a spatial model of forest fire dynamics. The particular aim of this paper is to include the influence of climate in this model.

3. OBJECT OF THE STUDY

In this model we use a landscape approach to describe forest dynamics. The essence of this approach is the following. The area to be modeled is subdivided into ecologically homogeneous plots, otherwise known as 'cells'. This is a usual procedure in geographical studies, with the rank of cells depending on the problem under consideration and the available data. In all cases an area is entirely covered by a mosaic of cells.

Each cell of a given type has its own set of ecological conditions. Each type of cells is characterized by fire frequency and by only one type of post-fire successional dynamics (successional line). This last feature is a basic merit of the landscape approach because it allows the accurate prediction of the process of forest development after fire. For each successional line we consider only one sequence of successional stages (ignoring secondary successional lines). The duration of each successional stage in the absence of fire is considered to be constant and equal to the mean duration of the stages). Thus the complete area represents a mosaic of cells each of which is characterized by the number of successional lines and number of successional stages. According to our assumptions formulated above, a particular successional stage will correspond to a particular age of forest, which will be equal to the length of time since the last severe fire.

Three types of spatial interaction between forest cells are known to take place during forest fire dynamics. These are the spread of fire from one burning cell to adjacent ones, seed propagation and the spread of insects. We will consider only the first two types and shall now look at these in more detail.

First of all let us describe an idealized mechanism for the influence of fire on a mosaic of cells. We are concerned only with severe fires, after which the vegetation of a cell is completely burned.

Let us assume that within a particular cell a source of fire occurs. If the vegetation in this cell is dry enough or in other words 'ready for burning', (i.e., in a state of fire maturity), then fire occurs and the vegetation in the cell is completely burned. If the vegetation of adjacent cells is not fire-mature then the fire stops on the margins of the burned cell; otherwise, fire is transferred to all adjacent fire-mature cells and the process continues. In this idealization, it is essential that the final pattern of the fire-burned area coincides with the conjunction of a few adjacent cells; this saves us from the necessity to consider the problem of changing sizes of cells during forest dynamics.

According to the mechanism described above, occurrence and spread of fire involve three events: the occurrence of a source of fire within a cell; the existence of fire-mature vegetation in this cell; and the spread of fire from the burning cell to adjacent ones. The most convenient parameters with which to characterize this process are the probability of the occurrence of a source of fire, the probability of fire maturity of a cell and the probability of the spread of fire from one cell to an adjacent one. As our goal is to describe long-term forest dynamics it seems reasonable to set the temporal step of this simulation at one year. A few comments on the parameters determining these probabilities should be made.

1. We do not distinguish between natural and man-induced sources of fire; a source of fire is simply caused by some or other external factor. The probability of the occurrence of a source of fire is independent of a cell's successional stage.
2. The probability of fire maturity of a cell depends strongly on the successional stage of the cell and the climatic conditions of the current year.
3. The probability of the spread of fire depends both on the successional stage of a cell (because the successional stage determines chances of the fire being able to overcome various natural obstacles such as rivers, open areas, etc.) and on climatic conditions (most importantly direction and speed of wind).
4. We assume all these probabilities to be independent of the location of a cell within the area under consideration.

Let us turn now to the mechanism for seed propagation. To include this in the model requires firstly the determination of the reproductive age of all species in the area under consideration and secondly, the determination of the probability distribution functions of the seed propagation distances (or at least mean values of these distances), again all species. Knowledge of the probability distribution functions is necessary for calculating the number of seeds available to each fire-burned cell. This consideration clearly requires that all secondary successional lines be taken into account. In order to simplify the model we opted for using the following idealization of the seed propagation process.

For each successional line represented in the area to be modeled we define 1) the reproductive stage and 2) the mean seed propagation distance averaged over all species. By reproductive stage we denote the successional stage by which all species represented in this line are assumed to have attained reproductive age, and therefore all seeds necessary for complete regeneration of this line are available. For each fire-burned cell one determines whether there exists a cell of the same type (i.e., belonging to the same successional line) with vegetation at a reproductive stage. If such a cell is available and the distance between this cell and the fire-burned cell is less than or equal to the seed propagation distance of the successional line to which both cells belong, then the fire-burned cell is assumed to be invaded and succession begins; otherwise the cell is assumed to be uninvaded.

4. FORMULATION OF THE MODEL

There are two possible approaches to formulating the spatial model of forest dynamics described in the previous section. The first approach is to construct a system of differential equations that describes the dynamics in terms of those parts of the area occupied by forest at the same successional stage; these equations should be essentially nonlinear in order to describe spatial interactions between cells during the dynamics. The second approach is to construct a simulation model that produces random trajectories over a large area according to the mechanisms described above. We have adopted the second approach because it is more convenient in terms of including spatial interactions in the model.

Let us now turn to the formulation of the model. From the assumptions made above, it is seen that the parameters 'successional stage of cell' and 'age of cell' (i.e., the time after the last severe fire) are in fact equivalent. This means that if the successional stage of a cell is known, the age can easily be calculated, and vice versa. In the formulation of the model we will use only the parameter 'age of cell' in order to avoid possible confusion.

Consider a grid of size $L \times M$, where L is the number of rows and M the number of columns. The grid is a model pattern of a forested area; each cell of the grid represents a stand. In order to exclude possible marginal effects during dynamics the grid is assumed to be closed, i.e., cells $(i,1)$ and $(1,j)$ are considered to be adjacent to cells (i,M) and (L,j) respectively, for $i = 1,...,L$, $j = 1,...,M$. The total number of successional lines represented in the grid is equal to N. Thus the state of each cell at time t is determined by the coordinates (n,k), where n is the number of the successional line to which this cell belongs, and k is the age of the cell.

Let R_n be the reproductive age of the n-th successional line and D_n be the mean seed propagation distance of the n-th line. This last parameter means that if cell (i,j) is at a reproductive age (i.e., its age is greater than or equal to R_n), the seeds from this cell can be transferred to all cells (i_1,j_1) that satisfy the condition

$$|i_1 - i| + |j_1 - j| \le D_n \ . \tag{1}$$

Consider now the parameters controlling fire processes. Let Q be the probability of occurrence of a source of fire in one cell during one year. Let $P_{n,k}$ be the conditional probability that the vegetation of a cell whose state is (n,k) will burn should a source of fire occur within it. (From now on we refer to this probability as the probability of fire maturity.) Let $V_{n,k}$ be the conditional probability that fire from a burning cell in a state (n,k) will spread to adjacent cells (i.e., the fire spread probability). We have omitted here the index t, indicating the dependence of these probabilities on time t, which is in fact dependence on climatic conditions. For details of inclusion of this dependence in the model, see Section 5. Finally, we assume the probabilities Q, P and V to be independent of the location of a cell within the grid.

The dynamics of the grid during one year (the temporal step of the model) are simulated in the following manner.

At the beginning of year t, cell (i,j) is in state (n,k). During year t the cell may be ignited; ignition may either occur within the area of the cell (the probability of this event is equal to Q) or it may be initiated from an adjacent cell which is already burning, i.e., $(i-1,j)$, $(i+1,j)$, $(i,j-1)$, $(i,j+1)$. After being ignited the cell may burn with a probability $P_{n,k}$; if so the cell in its turn becomes a source of fire for adjacent unburned cells and the spread of fire may occur with a probability equal to $V_{n,k}$. Adjacent cells may then burn with probability P depending on their state, and so on.

If burned, a cell changes its state to $(n,0)$; as mentioned above, only severe fires are taken into account. If seeds of the n-th successional line are available (i.e., there exists at least one cell in the state (n,s), $s \geq R_n$, which satisfies condition (1)), the succession process will begin. The state of the cell will change again and at year $t+1$ become $(n,1)$. If no seeds are available, the cell will remain unoccupied in state $(n,0)$.

If a cell is not burned, its age increases, with its state changing to $(n,k+1)$.

There are a number of comments on differences between this model and the previous version presented in Antonovski and Ter-Mikaelian 1987:

- In the previous version it was assumed that if a cell attained age T_n (the maximum longevity of the n-th successional line) without burning, it self-destroyed and succession began again. In the current version we have abandoned this assumption considering it to be unrealistic. At the same time, we have included a new parameter improving the quality of model verification, namely the comparison during model runs of the maximum ages of cells with those obtained from field data. For more details see Section 6.
- In the previous version, the process of fire spread was controlled by a single set of parameters P. It was assumed that fire would always spread from a burning cell to adjacent ones. In the current version we have divided the fire spread process into two parts. The first is the burning of a cell, controlled by parameter P, and the second is the spread of fire, controlled by parameter Q. The reasons for this were the following:

- The assumption that fire always spreads from a burning cell to adjacent ones is not correct. The fire spread process is evidently controlled not only by fire maturity of the forest but also by various obstacles (such as rivers, lakes, open areas, etc.), as well as by wind direction and speed.
- The use of probabilities of fire maturity in the current version was decided upon because these probabilities could easily be changed depending on climatic conditions. At the same time, the only way of estimating the accuracy of probabilities used in the previous version was to compare results of model runs with observed data; this made them virtually useless for investigating the effect of climatic fluctuations.
- Measurements of fire maturity carried out in a test region in western Siberia showed that the probability of forest fire maturity decreased markedly with the age of the forest. If this probability were the only parameter controlling the fire spread process, it would cause an irreversible aging of cells in the model. On the other hand, tests of the previous version of the model using North-American forests showed that only when this probability increased with the age of forest did the results of model runs correspond to observed data.

This forced us to consider two sets of 'fire probabilities' instead of the one used before. The following sections contain additional details on these probabilities.

5. DESCRIPTION OF THE TEST REGION

The region chosen for testing the model was a forested area in western Siberia. This region was studied for 20 years by one of the authors, who carried out numerous field experiments there. The results of this study are presented in Furyaev and Kireev (1979). Here we will give only a brief summary of those data important for model testing.

The area studied is situated on the Kas-Eniseyskaya plain in western Siberia at a latitude of 59°N and a longitude of 90°E, and it covers an area of 165,000 ha. Four main successional lines are represented in the area. These are:

1. Fir-tree forests on loamy soils;
2. Spruce forests on humid loamy soils;
3. Spruce forests on damp peaty loamy soils;
4. Pine forests on sands.

In the following description we will use these numbers to refer to the different successional lines.

Table 1 shows the percentage of the total area occupied by forests of each successional line.

Table 1: Percentage of area occupied by each successional line.

Number of line	1	2	3	4
Area occupied (% of total)	11.1	34.4	25.2	29.3

It is necessary to emphasize once more that successional lines are distinguished on the basis of a landscape approach (types of soils are taken into account). This means that we consider the area occupied by each successional line to be the same over all trajectories of forest dynamics, which allows us to predict accurately the post-fire successional process for each cell.

All successional lines are divided into 8 stages. The division was performed according to a scheme developed in Kolesnikov (1956) and Kolesnikov and Smolonogov (1960). For our purposes complete names of these stages are unimportant so we shall not list them here. The important information we need from this division is the length of each stage together with corresponding characteristics. *Table 2* shows the age margins for each stage; as mentioned above, primary successional lines only are considered.

Table 2: Age margins of successional stages (years).

No. of stage	1	2	3	4	5	6	7	8
Age margins	0–1	2–15	16–40	41–80	81–120	121–160	161–180	> 180

For fourth successional lines, stages 7 and 8 cannot be distinguished; therefore the following tables contain data for the fourth line for stages 1–6 only.

Maximum longevities of lines as they were recorded during field experiments are presented in *Table 3*.

Table 3: Maximum longevities of successional lines (years).

Number of line	1	2	3	4
Maximum longevity	250	300	300	320

Table 4 shows the average stand biomass for each stage within each successional line.

Table 4: Total stand biomass of stage (m^3/ha).

	Number of stage							
No. of line	1	2	3	4	5	6	7	8
1	0	25*	110	215	290	280	280	260
2	0	25*	105	172	182	240	280	260
3	0	10*	38*	54	140	148	205	240
4	0	47	82	188	280	300	–	–

*Data marked with asterisks were not measured and have been calculated using interpolation.

Table 5 presents data on the fire-danger index (FDI) used in Soviet forestry. This index is calculated as the sum of air temperature at 13.00 hours (AT) multiplied by air humidity at 13.00 hours (H) for each day over the period since the last 'rainy' day (i.e., day on which precipitation was greater than or equal to 3 mm):

$$FDI = \Sigma \, (AT \cdot H) \ . \tag{2}$$

In the study area series of field experiments were carried out to estimate critical values of FDI. For each successional line and for each successional stage a certain cell was ignited daily. On the day on which ignition led to settlement of fire, the value of the FDI was calculated with the help of meteorological data. The value obtained was the critical value of the FDI at which the forest attained a state of fire maturity. A summary of these values is presented in *Table 5*.

Table 5: Critical values of FDI (thousands of mbar · degree).

	Number of stage							
No. of line	1	2	3	4	5	6	7	8
1	0	0.5	1.0	1.2	3.0	3.3	5.5	8.0
2	0	0.5	0.9	1.0	2.8	3.0	5.8	8.2
3	0	1.0	1.2	1.5	3.2	3.8	6.2	8.6
4	0	0.3	0.5	0.6	0.8	1.2	–	–

The period from 1 May to 30 September (153 days) was taken as the fire-dangerous period. By the term 'fire dangerous' we denote a period during which wildfire can occur. Thus with the help of *Table 5*, probabilities of fire maturity can be calculated for each fire-dangerous season. These probabilities are equal to the number of days during the season which have an FDI higher than the appropriate critical value, divided by 153.

Let us now turn to fire dynamics of the area under consideration. One of the most important merits of the study area for model testing is that parts of its fire history have been reconstructed. To our knowledge, studies involved with reconstructing forest-fire history have been undertaken for three regions in North America and for the present study area in western Siberia. The results of these studies are presented in Heinselman (1973), Furyaev and Kireev (1979), Tande (1979), and Payette (in press). Payette's paper is especially notable as it contains excellent detailed data on fires over the period 1894–1984 for a large area (about 54,000 km^2). Data on the fire history of the study area are not so detailed but cover a period from the beginning of the 18th century until 1970. The following table contains the dates of fire years together with the corresponding percentage of area burned.

Table 6: Fire years and percentage of area burned.

Year	Area burned (%)	Year	Area burned (%)	Year	Area burned (%)
1700	6	1830	18	1920	11
1787	5	1842	5	1921	14
1788	10	1860	44	1930	24
1793	16	1866	5	1931	8
1806	13	1870	84	1933	19
1808	15	1888	19	1946	17
1819	12	1891	7	1950	8
1820	5	1896	23	1952	12
1825	6	1909	5	1956	38
1829	5	1915	84	–	–

The dynamics of the percentage of the area burned during each fire year are shown in ***Figure 1a***. Using these data it would be useful to calculate and present the corresponding distribution of percentage of area burned over the period; this distribution is of considerable value for model testing. Suppose that during a period of time T the number of years with fire recorded is equal to S. Let us denote S_{1-10} as the number of fire years during which the area burned was between 1% and 10% of the total area. By the same method we can define S_{11-20}, S_{21-30}, etc., with their sum being equal to S. The resulting set of quantities $S_{1-10/S}$, $S_{11-20/S}$, ... gives us a distribution of the percentage of area burned over the total period, constructed with a size step of 10%. This distribution for the area under consideration is presented in ***Figure 1b***.

6. VERIFICATION OF THE MODEL

Verification of the model requires firstly estimation (or calculation if possible) of values of the model parameters and secondly, formulation of the criteria for fitting the model to the observed data. First of all we will recap the model parameters. Before doing this there is one point worth noting. The model was formulated in terms of 'age of cell' although it was pointed out that the terms 'age of cell' and 'stage of cell' are in fact interchangeable. This is so in this case because we are considering only primary successional lines, and specification of successional stages is nothing more than division of these lines into segments of fixed lengths. Thus the model was formulated in terms of 'age of cell' simply to avoid additional explanations connected with the transition of cells from one successional stage to the next one. However, for verification purposes the use of 'stages' is very helpful because firstly, it decreases the number of model parameters and secondly, data available are related to successional stages (and there is not enough detailed data to connect them directly with ages of cells). Therefore in this section, further description and use of parameters will be given in terms of 'stage of cell'. Values of parameters are assumed to be constant within each stage, so that for each stage mean values of the parameters (i.e., averaged over this stage) are used.

Thus the model parameters are:

N – number of successional lines represented over forested area;
R_n – reproductive stage of n-th successional line;
D_n – seed propagation distance for n-th successional line;
Q – probability of occurrence of fire source during one year per square unit;
$P_{n,k}$ – probability of fire maturity of cell in k-th stage of n-th successional line during one year;
$V_{n,k}$ – fire spread probability for cell in k-th stage of n-th successional line during one year per square unit.

The main parameters controlling the simulation of fire dynamics are Q, P and V. As described above, values of the parameter P can be calculated from the results of field measurements; values of the parameters Q and V can only be estimated by comparing observed data on forest fire dynamics with those simulated by the model. According to data presented in the previous section we have to estimate at least 33 parameters, namely the probability of the occurrence of a fire source Q, and the set of fire spread probabilities $V_{n,k}$, $n = 1,...,4$; $k = 1,...,8$. To begin verification of a model with 33 unknown parameters is a difficult task of questionable value. Therefore in order to decrease the number of parameters to be estimated we will consider one generalized successional line over the whole area. The characteristics of this line are presented in *Table 7* and were obtained as weighted sums of the corresponding characteristics of the four successional lines represented in the test area (*Tables 3–5*) according to the percentage of the area occupied by each line (*Table 1*).

Table 7: Characteristics of generalized successional line.

Number of stage	Age margins of stage (years)	Total stand biomass (m^3/ha)	Critical values of FDI (10^3 mbar · degree)
1	0–1	0.0	0.0
2	2–15	28.3	0.55
3	16–40	83.1	0.85
4	41–80	154.4	1.00
5	81–120	213.9	2.30
6	121–160	240.6	2.65
7	161–180	267.9	4.45
8	> 180	266.8	6.10

Since the number of successional lines N is equal to 1, from now on we will omit the first subscript n. The number of successional stages k varies from 1 to 8.

The forest area to be modeled was simulated as a grid of 25 × 25, with each cell representing 264 ha of test area. The reproductive stage R was set to 4; thus the mean reproductive age of the forest was 60 years. Seed propagation distance D was set to 2 (in cells), which means that maximum seed propagation distance was 4 km.

We must now consider the dependence of 'fire probabilities' on climatic fluctuations. Let us first turn to the probabilities of fire maturity P_k. As shown above, P_k can be calculated as the ratio of days with an FDI higher than the corresponding critical value to the total length of the fire-dangerous season. In order to study the dynamics of P_k, hydrometeorological data from the station nearest to the test area were considered. These data comprise daily measurements (four times a day) of the main hydrometeorological parameters for the period 1936–1980. With the help of these data, the time series of P_k, $k = 2,...,8$ ($P_1 = 0$) was calculated. *Figure 2a* shows the time series of P_4 (which corresponds to a critical value of FDI of 1000 mbar · degrees; see *Table 7*). For $k = 2,...,8$, an autocorrelation function was constructed in order to check whether there existed a trend in values of P_k; no trend was found.

Our next step was to link P_k with some general climatic parameters. This was important for two reasons: firstly, to avoid detailed simulation of parameters AT and H during each fire-dangerous season and secondly, to produce a tool for constructing various scenarios of possible climatic changes in terms of some general parameters. To achieve this, methods of linear regression were used. The climatic parameters initially used as predictors were:

a) mean annual air temperature;
b) mean seasonal air temperature;
c) annual sum of precipitation;
d) seasonal sum of precipitation;
e) mean seasonal period between two successive rains;
f) maximum seasonal period between two successive rains;
g) minimum seasonal period between two successive rains.

By 'seasonal' we mean that the parameter is averaged over the fire season which runs from 1 May until 30 September.

This list was reduced with the help of stepwise regression. Parameters selected as significant were b), d) and f) for P_k, $k = 2,...,6$, and b) and f) for P_k, $k = 7,8$. For the reduced list of parameters, coefficients of the following linear regression equation were estimated

$$P_k = a_{1k} \cdot TR + a_{2k} \cdot MP + a_{3k} \cdot PR + a_{4k} \ , \tag{3}$$

where TR – mean seasonal air temperature;
MP – maximum seasonal period between two successive rains;
PR – seasonal sum of precipitation.

Coefficients a_{jk}, $j = 1,...,4$, $k = 2,...,8$, and corresponding multiple regression coefficients are presented in *Table 8*.

An example of estimated values of P_4 is shown in *Figure 2b*.

Since the problem of simulating probabilities of fire maturity P_k is reduced to simulating parameters TR, PR and MP, we studied dynamics of these parameters. *Figures 3, 4* and *5* show the dynamics of TR, PR and MP respectively for the period 1936–1980.

Table 9 contains a matrix of correlation coefficients between the three parameters.

Low values of correlation coefficients allowed us to simulate the dynamics of TR, MP and PR independently. This result agrees with the conclusion made in Budyko and Izrael (1987) that there was no significant correlation between the dynamics of mean annual air temperature and annual sum of precipitation for western Siberia.

For each parameter an autocorrelation function was constructed; no trends were found. This meant that the time series of each parameter could be considered as a sequence of values of a randomly distributed variable. For each parameter a series of tests was carried out in order to fit a probability distribution which satisfactorily described sample data. *Table 10* summarizes the results of these tests. It should be noted that parameters of normal distribution for TR and PR were estimated by using standard

Table 8: Regression coefficients and multiple regression coefficients of equation (3).

Number of stage k	Regression coefficients a_{1k}	a_{2k}	a_{3k}	a_{4k}	Multiple regression coefficient
2	.0511	.00363	-.00065	-.0973	0.824
3	.0491	.00561	-.00063	-.2217	0.858
4	.0509	.00625	-.00064	-.2954	0.850
5	.0326	.00677	-.00017	-.3780	0.780
6	.0232	.00660	-.00019	-.2705	0.794
7	.0109	.00681	.0000	-.2354	0.798
8	.0068	.00493	.0000	-.1660	0.764

Table 9: Correlation matrix between *TR*, *MP* and *PR*.

	TR	*MP*	*PR*
TR	1.000		
MP	0.136	1.000	
PR	-0.424	-0.466	1.000

methods; parameters for Pearson's III type distribution were estimated with the help of scales of coordinates rectifying theoretical distribution curves. This method was developed by P. Kolosov in a series of works (see, for example, Kolosov and Liseev 1987). For each parameter a Kolmogorov–Smirnov one-sample test against theoretical curves was carried out; corresponding probabilities are given in *Table 10.*

Table 10: Probability distributions for *TR*, *PR* and *MP*.

Parameter	Type of distribution	Mean	Standard deviation	Skewness	K–S test
TR	Normal	12.85	0.652	0.0	0.668
PR	Normal	273.5	52.65	0.0	0.372
MP	Pearson's III type	22.49	6.29	1.0	0.379

Thus, in summary, the probabilities of fire maturity P_k, $k = 1,...,8$ were simulated as a function (equation (3)) of mean seasonal air temperature (*TR*), seasonal sum of precipitation (*PR*) and maximum seasonal period between two successive rains (*MP*); coefficients of (3) are given in *Table 8.* At each step of the model values of *TR*, *PR* and *MP* were generated independently as sample values from the corresponding probability distributions; parameters of these distributions (given in *Table 10*) were assumed to be constant over all model trajectories.

Let us turn now to probabilities of fire spread V_k, $k = 1,...,8$. Since values of V_k are unknown and should be estimated as a result of model runs, we assumed them to be constant over all trajectories to be modeled. This is equivalent to assuming that climatic conditions (e.g., windrose) in the test area which determine these probabilities are stable. For the initial assessment we assumed probabilities of fire spread to be proportional to total stand biomass of 1 ha of cell as given in *Table 7*. As mentioned earlier, the probability of fire spread depends on fire's ability to overcome natural obstacles. This ability is determined by intensity which is related to stand biomass.

The final parameter to be considered is the probability Q of fire occurrence within one cell during one year. This parameter should also be estimated as a result of comparing model results with observed ones. An initial value of 0.001, obtained in model runs for North-American forests (see Antonovski and Ter-Mikaelian 1987), was taken.

Let us now discuss the criteria of model verification. Since our model produces random trajectories of forest fire dynamics, it seems pointless to directly compare a single trajectory with one reconstructed from field data. However certain characteristics being averaged over these trajectories are stable enough to be compared with corresponding characteristics of real forest fire dynamics. The distribution of percentage of area burned per year was taken as one such characteristic; the construction of this distribution was described in the previous section. This method was successfully used in Antonovski and Ter-Mikaelian (1987) and Ter-Mikaelian and Furyaev (1988) and will now be described briefly. Each model trajectory is divided into periods of length T years; for each period the distribution of percentage of area burned per year is plotted and compared with that constructed from field data; the same is done for the distribution constructed for the whole trajectory. In our model runs, T was taken equal to 300. Since our model is driven by a set of randomly generated parameters it is impossible to obtain a model trajectory for which the distribution of percentage of area burned per year, constructed for different periods T, coincide completely. On the other hand, we did not know whether the observed distribution constructed for the period 1700–1970 (see *Figure 1b*) would coincide completely with an analogous distribution for another period, for example, 1400–1700, should data on fire dynamics during this period be available. Therefore coincidence between the observed distribution and the distribution for a single period T was taken as a criterion of model fitting. The distribution for the whole trajectory was followed in order to check whether its pattern was stable from the qualitative viewpoint.

As a second criterion, the mean number of years with fires per 100 years, obtained from the model, was compared with the actual value (the most recent value can be calculated from *Table 6* and is equal to 10.7).

Finally, the mean age of forest in the last (8-th) stage, obtained from the model, was compared with that observed in real forests. From *Table 3* it can be calculated that the actual upper limit of forest age is approximately 300 years. Thus lower and upper age margins of the 8-th successional stage are 181 and 300 years, respectively, with a corresponding mean age of 240 years. This value was compared with the mean age of cells in the 8-th stage as calculated by the model. Since in the model the 8-th stage was assumed to be unlimited (see Section 4, p.000), this comparison gives us a third criterion on the quality of model fitting to field data.

Using these criteria, numerous computer experiments on model runs were carried out. During these experiments, values of Q and V_k, $k = 1,...,8$ were varied in order to obtain the best correspondence between model results and observed data. The best results were obtained for the following values of Q and V_k:

$$Q = 0.0004 \;, \quad V_k = \{0,0.47,0.47,0.5,0.65,0.725,0.8,0.8\} \;. \tag{4}$$

The distribution of percentage of area burned per year which coincided most with the observed one, was obtained for the period 1200–1500; both distributions are shown in *Figure 6a*. *Figure 6b* shows the dynamics of the percentage of area burned per year for the same period. The total length of the trajectory simulated was 3000 years. The mean number of years with fires per 100 years for set (4) was 9.5; the mean age of forest in the 8-th stage was 261 years.

A few comments on the results of the model verification should be made. The first is concerned with the difference in modeled and observed distributions of percentage of area burned per year. As can be seen from *Figure 6a* the percentage of years with fires belonging to the smallest size class (0–10%) is higher in the model runs than in real forests. This difference is most likely to be due to a shortage of data on small fires. It is clear that field reconstruction of all small fires during the last 270 years is impossible; *Table 6* contains only years with fires large enough to burn at least 5% of the total area. In our model runs, even one cell being burned a year (which corresponds to 0.16% of the model area) contributes to the first size class of area burned per year, leading to a warped distribution compared with the reconstructed one.

The next point concerns estimated values of V_k. Our hypothesis regarding proportionality between probabilities of fire spread V_k and stand biomasses of corresponding stages is not completely valid, as illustrated by *Figure 7*. One of the curves represents plotted values of (4) and the other has been plotted proportional to stand biomass with a coefficient of 0.003. The difference is high for the first stages and tends to zero with increase in stage number. One possible explanation is that the biomasses presented in *Table 7* do not include the lower layer of vegetation (mosses, grass, bushes, etc.). The contribution of this layer to total biomass is high for juvenile forests and low for mature forests. At the same time it is obvious that, being a conductor of fire, this layer increases the probability of fire spread.

This section describes an example of a model prediction of the effect of changing climatic conditions on forest fire dynamics. Since driving climatic parameters in the model are mean seasonal air temperature, seasonal sum of precipitation and maximum period between two successive rains during one season, it is possible to create an arbitrary scenario of their changes in time and simulate corresponding forest dynamics. Since mean seasonal air temperature is perhaps the most pertinent climatic parameter to investigate, we undertook a series of model runs for different values of this parameter. In these runs we varied only mean values of this variable, leaving its standard deviation and type of probability distribution unchanged. All other parameters were left unchanged (i.e., their values were set to those obtained in the process of model verification; see previous section). It should be emphasized that we simulated forest fire dynamics under the new climatic scenario with stable parameters of the corresponding probability distributions and not the transitional period from the previous climatic scenario to the new one (although this would also have been possible). *Figures 8a–8d* present the results of these runs.

Figure 8a shows the dependence of the number of years with fires per 100 years on mean seasonal air temperature. It is obvious that higher air temperature causes greater fire maturity of forests which in turn leads to an increase in the number of fire years per 100 years. The shape of the curve showing an increase in mean size of area burned per year (*Figure 8b*) is also expectable. With the help of these data one can easily calculate the corresponding fire rotation periods; fire rotation period is inversely proportional to mean size of area burned per year and represents the period of time during which a particular area will be completely burned.

In contrast, results shown in *Figure 8c* are somewhat unexpected; in this figure we see the mean size of area burned per year with fire decreasing as mean seasonal air temperature increases. There is a possible explanation for this. We have seen that the probability of fire maturity decreases with the age of the forest. Decrease in mean seasonal air temperature leads to a decrease in the probability of fire maturity, resulting in a decrease in the number of years with fires, with a simultaneous increase in mean age of forest over the study area. At the same time, the size of the fire-burned area increases because the conditional probability of igniting a cell adjacent to the one already burning increases. In other words it is more difficult to ignite an older forest but if it is ignited it burns over larger areas.

Finally, ***Figure 8d*** shows the dependence of mean total biomass of forest on mean seasonal air temperature. One should take these results with caution: being largely concerned with the simulation of spatial forest dynamics over large areas, we neglected a detailed description of a single cell's growth, particularly its dependence on climatic conditions. Therefore changes in total biomass presented in ***Figure 8d*** are linked with changes in mean age of forest. This means that our model does not take into account possible increases in biomass of a single cell caused by increase in mean seasonal air temperature. These increases could significantly change the shape of the curve presented in ***Figure 8d.***

Nevertheless we consider these results to be a valuable first step toward predicting changes in patterns of large forested areas caused by possible climatic changes. We hope that the next stage in the development of our model will include a more detailed description of a single cell's growth, making the predictions more accurate.

7. CONCLUSIONS

Of the findings detailed in this paper we consider three aspects to be of particular importance.

First, the model successfully simulates the effect of pulsing of a fire-burned area. This effect is reflected in the bimodal shape of the distribution of area burned per year and corresponds to a fire regime in which, during some years only, a small area of forest is burned with years of major fires occurring irregularly. This regime is the most important feature of the dynamics of large forested areas; its correct description requires the use of spatial models incorporating interaction of different forest cells during dynamics.

Second, the dependence of forest fire dynamics on climatic conditions was taken into consideration. This dependence allowed the linking of forest dynamics with such general climatic parameters as mean seasonal air temperature, seasonal sum of precipitations and maximum period between two successive rains during one season. Being general, the future behavior of these parameters and thus the future behavior of forests over large areas can more easily be predicted. An example of a such prediction was given in the previous section. A model driven by hydrometeorological parameters for use by fire-controlling organizations would be useless because detailed prediction of their seasonal changes is unlikely to be possible for some time.

Finally, a further finding is concerned with the use of 'fire probabilities'. One of the model outputs was the mean probability of a cell burning over the model trajectory; in order to obtain these probabilities, at each model step the number of cells burned in the k-th stage (for $k = 1,...,8$) was divided by the total number of cells in the k-th stage. Averaging this ratio over the complete model trajectory gave us mean probabilities of fire burning; these probabilities are shown in ***Figure 9.*** It can be seen that they differ significantly from the probabilities of fire maturity and fire spread used directly in the model. This difference reflects the difference between local and spatial models of forest fire dynamics. Indeed, probabilities of fire maturity and fire spread refer to the local scale and reflect the state of a single cell. When being used in spatial models with interaction of cells they lead to completely different probabilities of a cell's burning, which already reflects spatial aspects of forest dynamics. Two warnings follow from this difference. The first is connected with discussion on the shape of dependence of fire probabilities on forest age; an examples of such discussion can be found in Heinselman (1981) and Van Wagner (1983). In these discussions it is necessary to distinguish carefully between 'local' probabilities of a cell's burning (which are in fact probabilities of fire maturity and can be calculated from field experiments and meteorological data) and 'spatial' probabilities of a cell's burning, which can be obtained from observed wildfires. As our example shows, shapes of dependence of these probabilities on forest age are completely different. The second warning is connected with the use of results obtained from locally distributed long-term models dealing with wildfires. Were these results to be expanded to represent mean dynamics of a large area, then observed probabilities of a cell's burning should be used; the use of local probabilities of fire maturity would lead to correct simulation of stand dynamics but would distort patterns of large forested areas.

REFERENCES

Antonovski M.Ya. & Ter-Mikaelian M.T. (1987). On spatial modeling of long-term forest fire dynamics. Working Paper WP-87-105. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Bajenov V.V. (1982). Modelling fire forest spread and its localization. In *Modelling of processes in nature-economics systems*. pp. 72-79. Novosibirsk: Nauka. (In Russian.)

Bonan G.B. (1988). Environmental processes and vegetation patterns in boreal forests. Ph. D. Dissertation. pp. 286. Charlottesville, Virginia.

Budyko, M.I. & Izrael, Yu.A.(eds.) (1987). Anthropogenic climatic changes. 406 pp. Leningrad: Gidrometeoisdat. (In Russian).

Hall F.G., Strebel D.E., Goetz S.J., Woods K.D., & Botkin D.B. (1987). Landscape pattern and successional dynamics in the boreal forest. In *Proceedings 1987 IEEE International Geoscience and Remote Sensing Symposium* pp. 473-482. Ann Arbor: University of Michigan.

Furyaev V.V. & Kireev D.M. (1979). A landscape approach in the study of postfire forest dynamics. 159 pp. Novosibirsk: Nauka. (In Russian.)

Heinselman M.L. (1973). Fire in the virgin forests of the Boundary Waters Canoe Area, Minnesota. *Quaternary Research,* **3**, 29-382.

Heinselman M.L. (1981). Fire and succession in the conifer forests of Northern North America. In *Forest succession: concepts and application*. pp. 374-405. New York: Springer Verlag.

Johnson E.A. (1979). Fire recurrence in the subarctic and its application for vegetation composition. *Canadian Journal of Botany,* **57**, 1374-1379.

Johnson E.A. & Wagner C.E.Van. (1985). The theory and use of two fire history models. *Canadian Journal of Forest Research,* **15**, 1: 214-220.

Kercher J.R. & Axelrod M.C. (1984). A process model of fire ecology and succession in a mixed-conifer forest. *Ecology,* **65**, 6: 1725-1742.

Kessel S.R. (1982). Creation of generalized models of secondary succession of plants. In *Biosphere Reserves. Proceedings of Second American-Soviet Symposium*. pp. 183-213. Leningrad: Gidrometeoizdat. (In Russian.)

Kolesnikov B.P. (1956). Cedar forest of the Far East. Proceedings of Far Eastern department of Academy of Sciences USSR, 2(4): 261. (In Russian.)

Kolesnikov B.P. & Smolonogov E.P. (1960). On some appropriatenesses in regeneration of cedar forests in Zauralskoye Priobye region. In *Problems of cedar*. pp. 21-31. Novosibirsk. (In Russian.)

Kolosov P.A. & Liseev A.A. (1987). Assessment method for probability distribution curve by short-period climatic observations. In *Problems of ecological monitoring and ecosystem modeling*. **10**, 225-237. Leningrad: Gidrometeoizdat: (In Russian.)

Korzuhin M.D. & Sedych V.N. (1983). On background monitoring of West Siberian forests. In *Problems of ecological monitoring and ecosystems modeling.* **6**, 122-130. Leningrad: Gidrometeoizdat, (In Russian.)

Marsden M.A. (1983). Modelling the effect of wild fire frequency on forest structure and succession in the Northern Rocky Mountains. *Journal of environmental management,* **16**, 1: 45-62.

Martell D.L. (1980). The optimal rotation of a flammable forest stand. *Canadian Journal of Forest Research,* **10:** 30-34.

O'Regan W.G., Kourtz P., & Nozaki S. (1976). Bias in the contagion analog to fire spread. *Forest Science,* **22**, 1: 61-68.

Payette S. Recent fire history of the Northern Quebec biomes, (in press). *Ecology.*

Shugart H.H. & Noble I.R. (1981). A computer model of succession and fire response of the high altitude Eucalyptus forest of the Brindabella Range, Australian Capital Territory. *Australian Journal of Ecology,* **6**, 149-164.

Suffling R. (1983). Stability and diversity in boreal and mixed temperate forests: a demographic approach. *Journal of Environmental Management,* **17:** 359-371.

Tande G.F. (1979). Fire history and vegetation pattern of coniferous forests in Jasper National Park, Alberta. Canadian *Journal of Botany,* **57**, 1912-1931.

Ter-Mikaelian M.T. & Furyaev V.V. (1988). Model of spatial-time forest dynamics under fire impact. In *Problems of ecological monitoring and ecosystem modeling,* **11**, 260-275. Leningrad: Gidrometeoizdat. (In Russian.)

Vorobiyov O.Yu. & Dorrer G.A. (1974). Probabilistic model of forest fire spread. In *Problems of Forest Pyrology.* pp. 118-134. Krasnoyarsk. (In Russian.)

Vorobiyov O.Yu. & Valendik E.N. (1978). Probabilistic modeling forest fire spread. **159.** Novosibirsk: Nauka. (In Russian.)

Wagner C.E.Van. (1978). Age-class distribution and the forest fire cycle. *Canadian Journal of Forest Research,* **8**, 220-227.

Wagner C.E.Van. (1983). Fire behavior in northern conifer forests and shrublands. In *SCOPE 18. The Role of Fire in Northern Circumpolar Ecosystems.* pp. 65-80. New York: John Wiley and Sons.

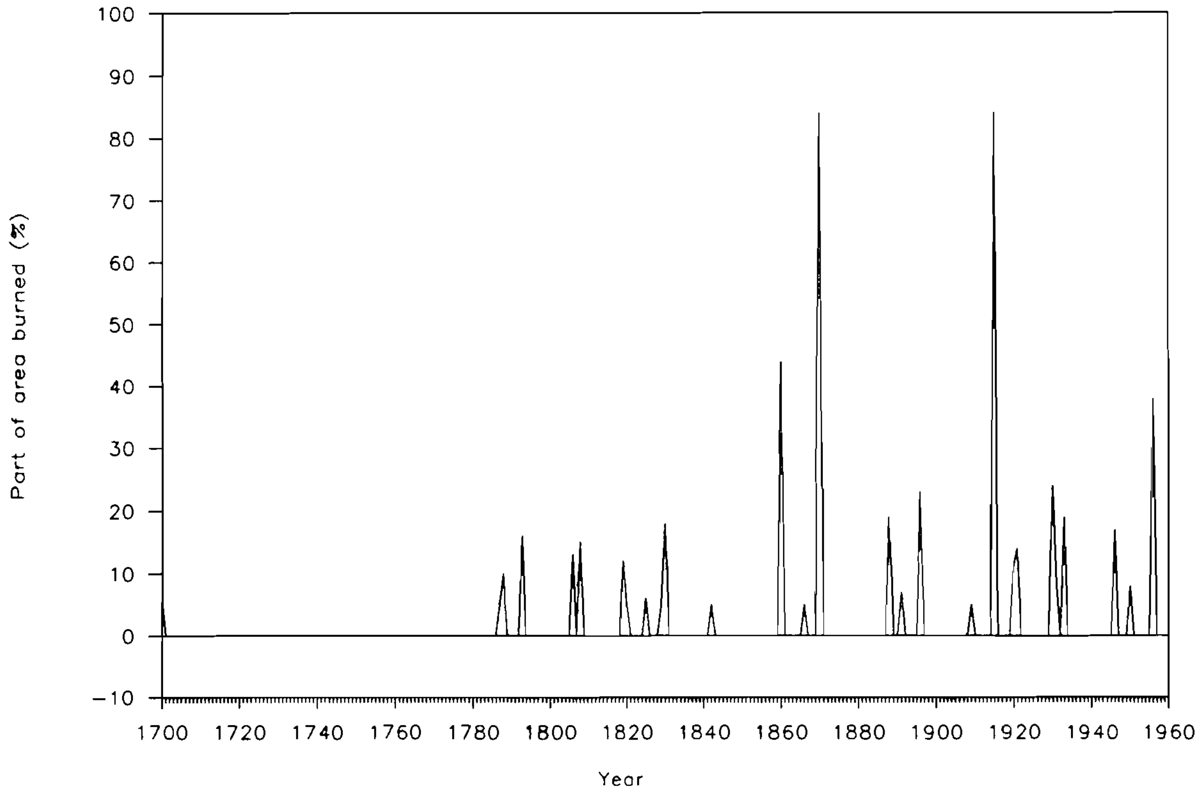

Figure 1a. Burned area dynamics per year on Kas-Eniseyskaya plain.

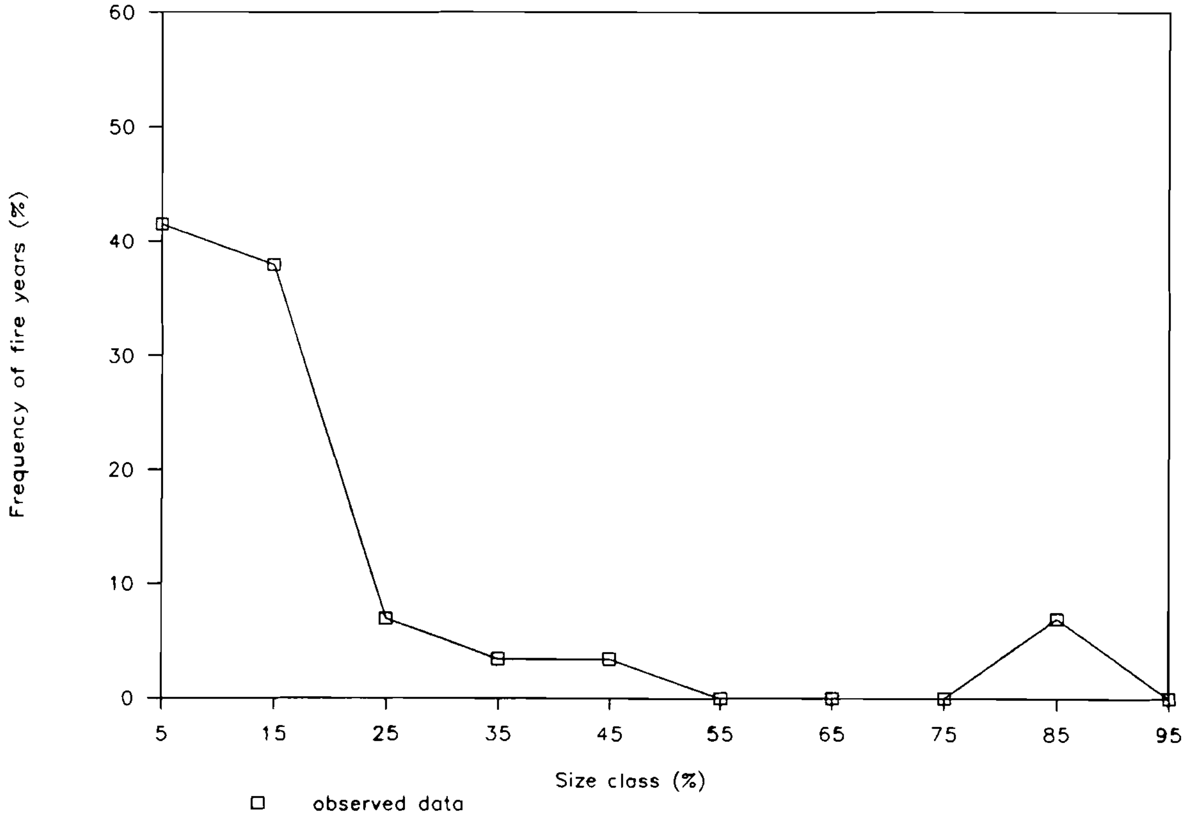

Figure 1b. Burned area distribution per year (observed data).

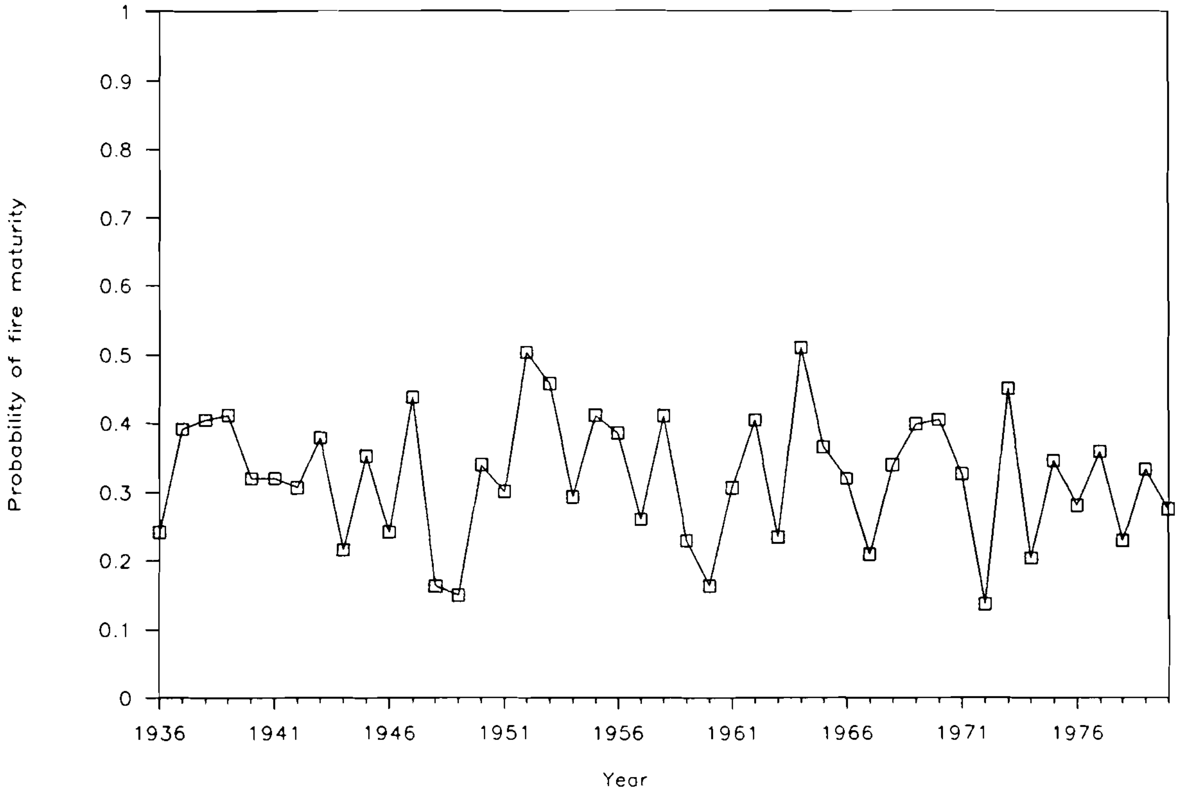

Figure 2a. **Fire maturity probability dynamics for FDI equal to 1000 mbar · degrees.**

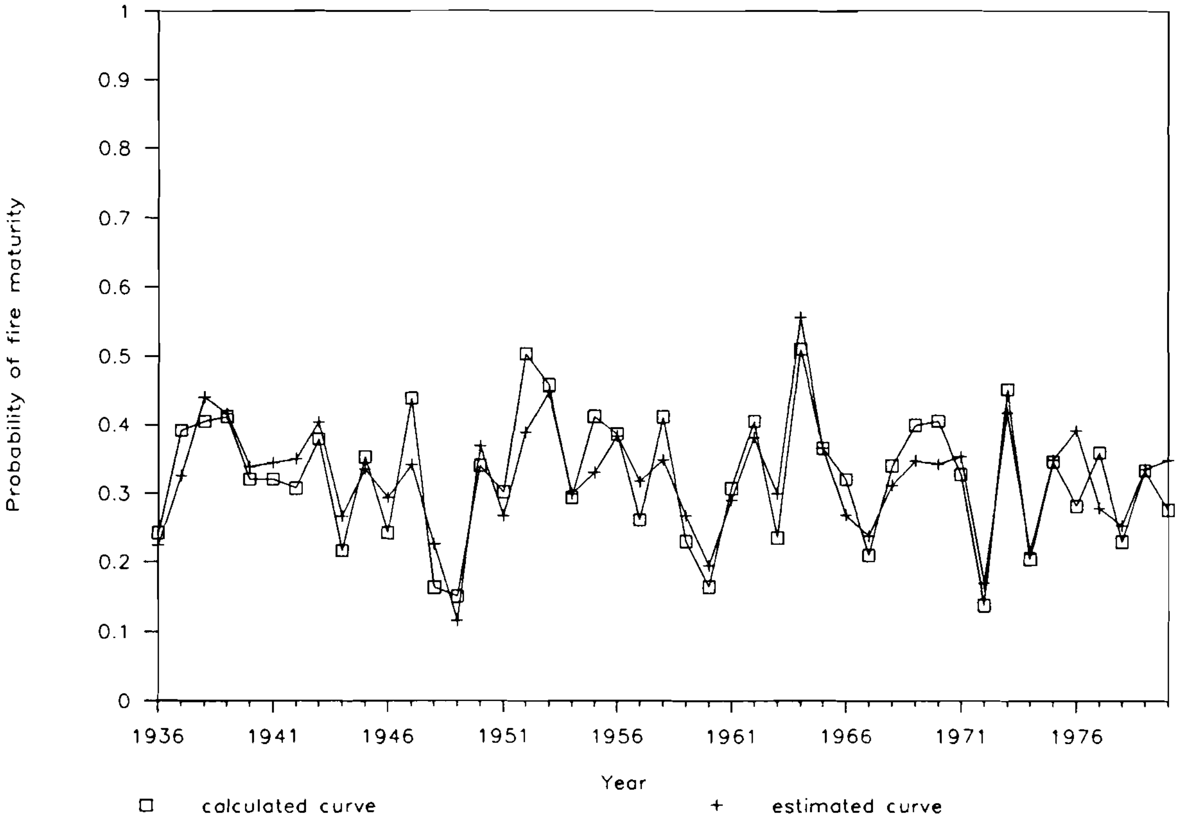

Figure 2b. **Fire maturity dynamics (calculated and estimated probabilities).**

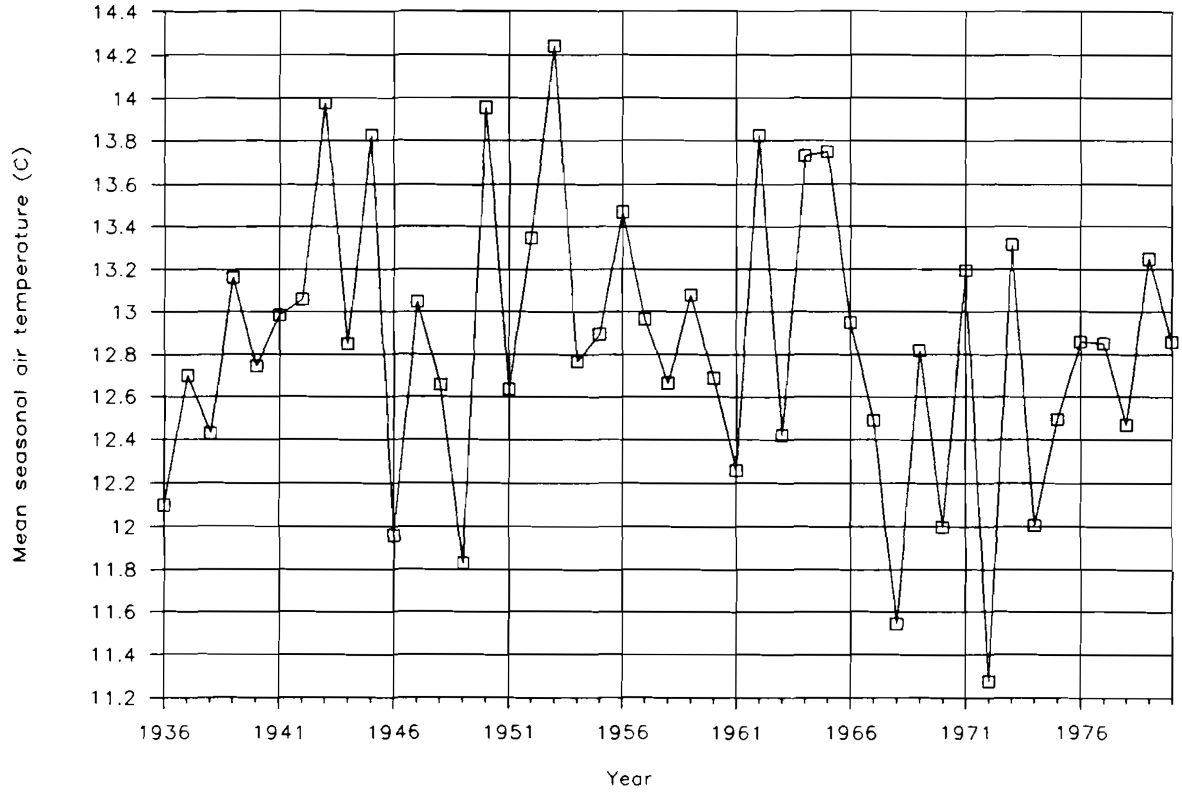

Figure 3. **Mean air temperature dynamics (averaged over fire seasons).**

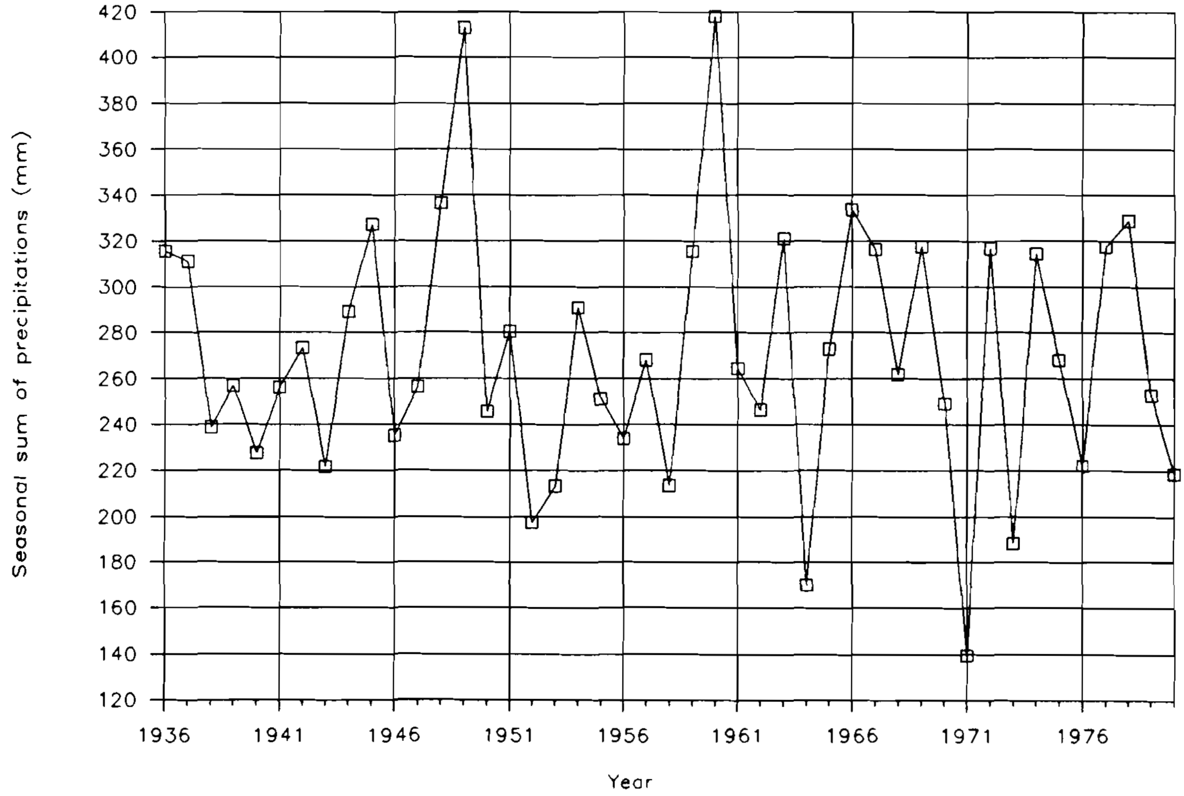

Figure 4. **Precipitation sum dynamics (seasonal).**

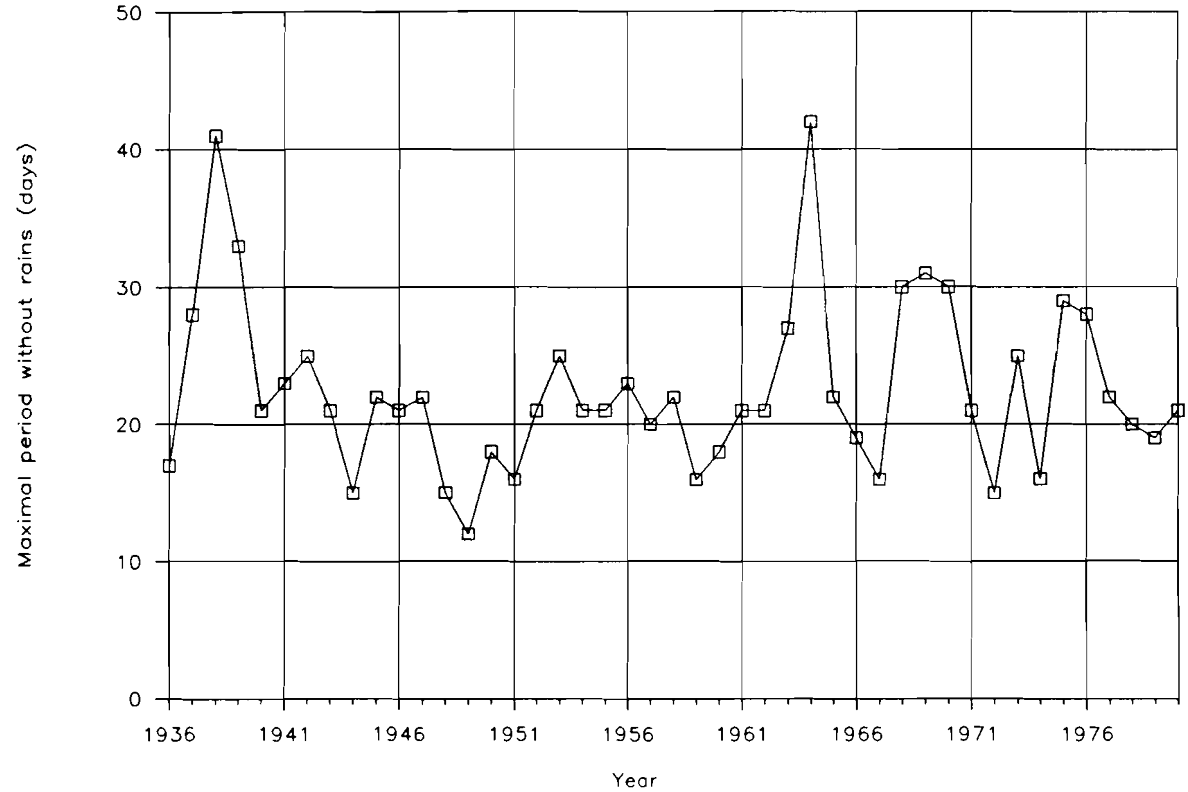

Figure 5. Dynamics of maximal period between two successive rains.

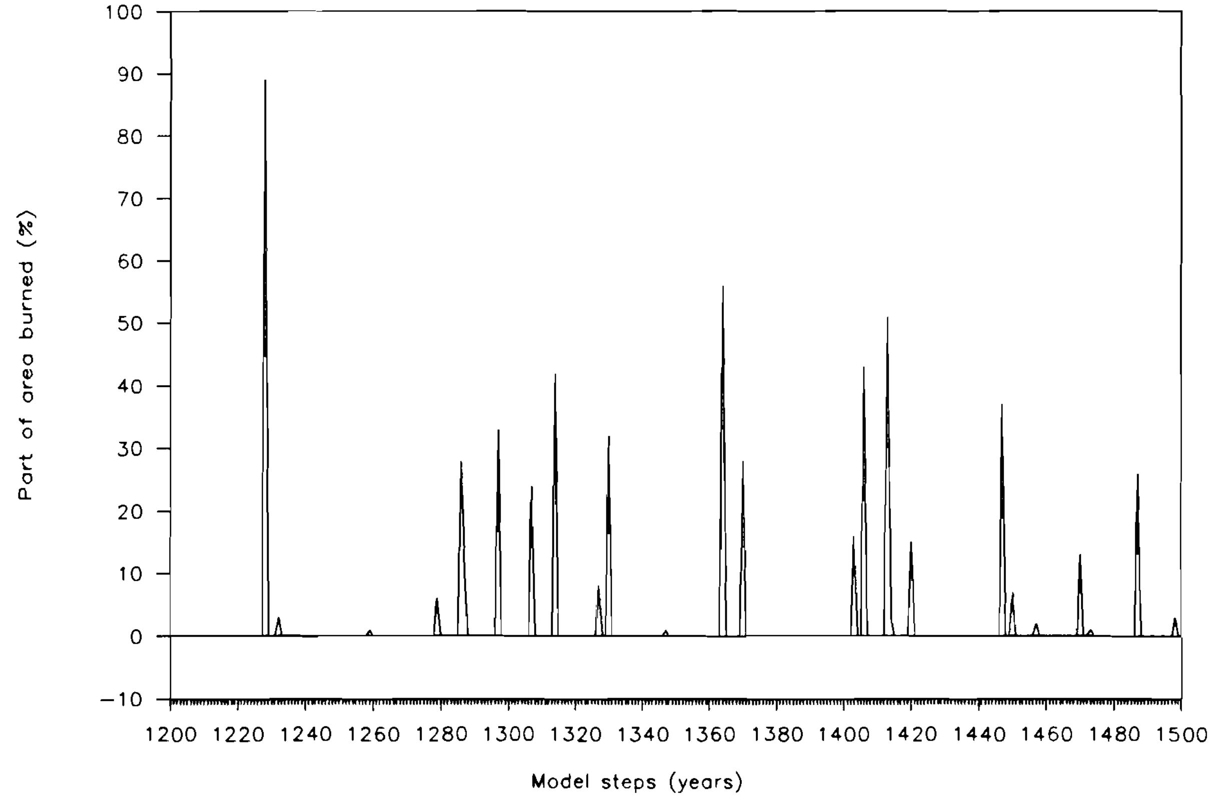

Figure 6a. Burned area dynamics per year (model trajectory).

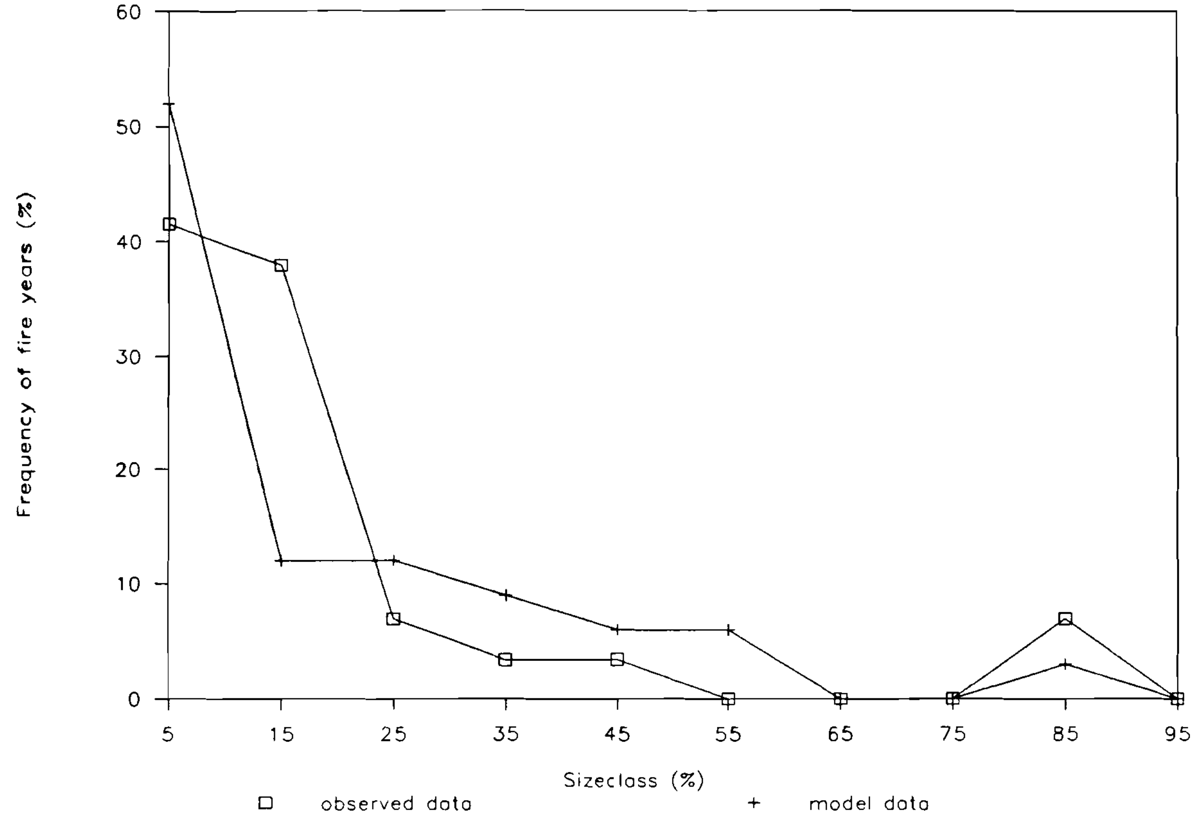

Figure 6b. **Distribution of parts of area burned per year (observed and model data).**

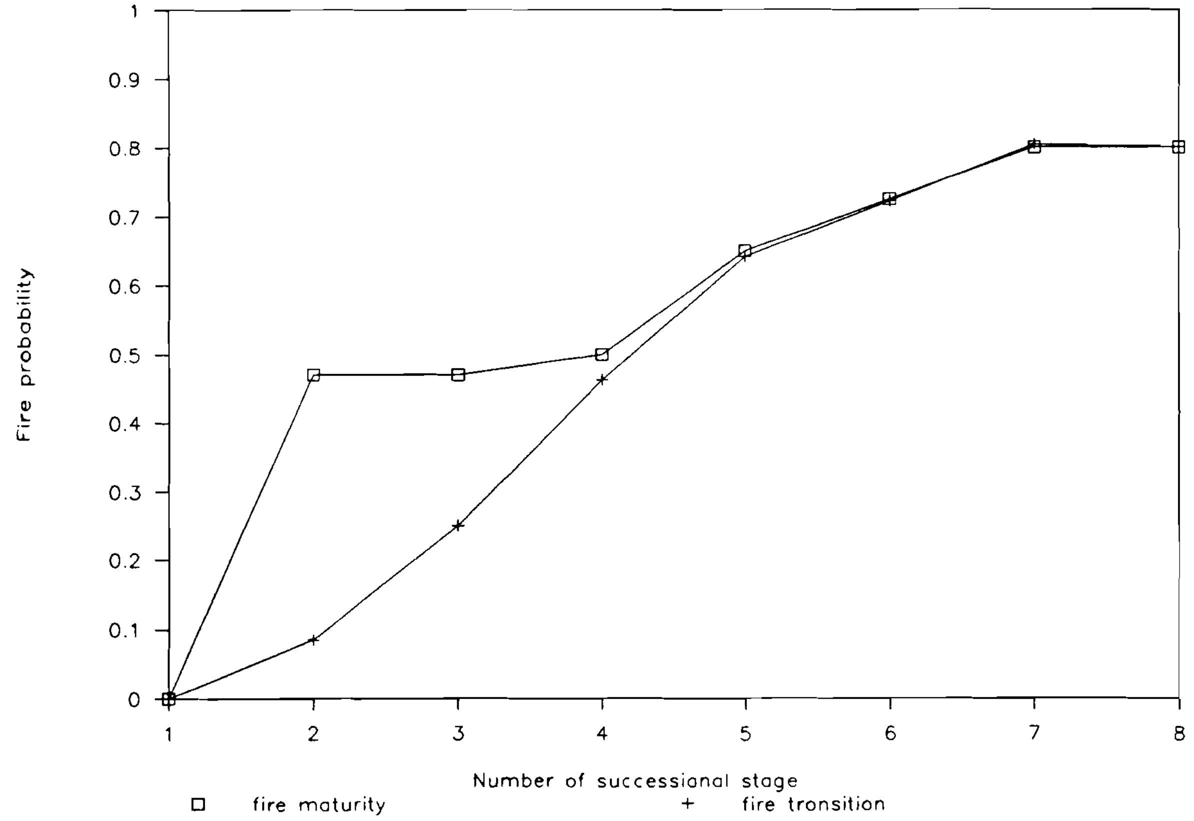

Figure 7. **Fire transition probabilities (model estimation and hypothesized one).**

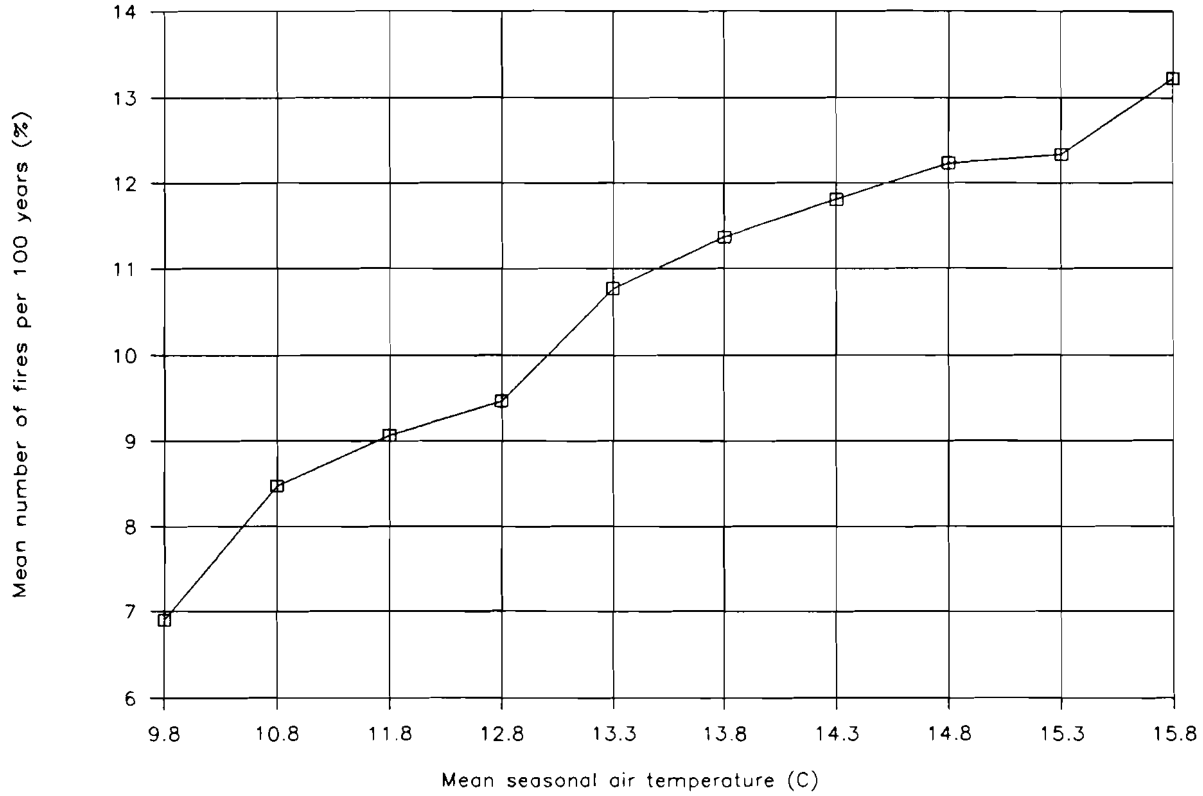

Figure 8a. **Dependence of mean fires number per 100 years on mean air temperature.**

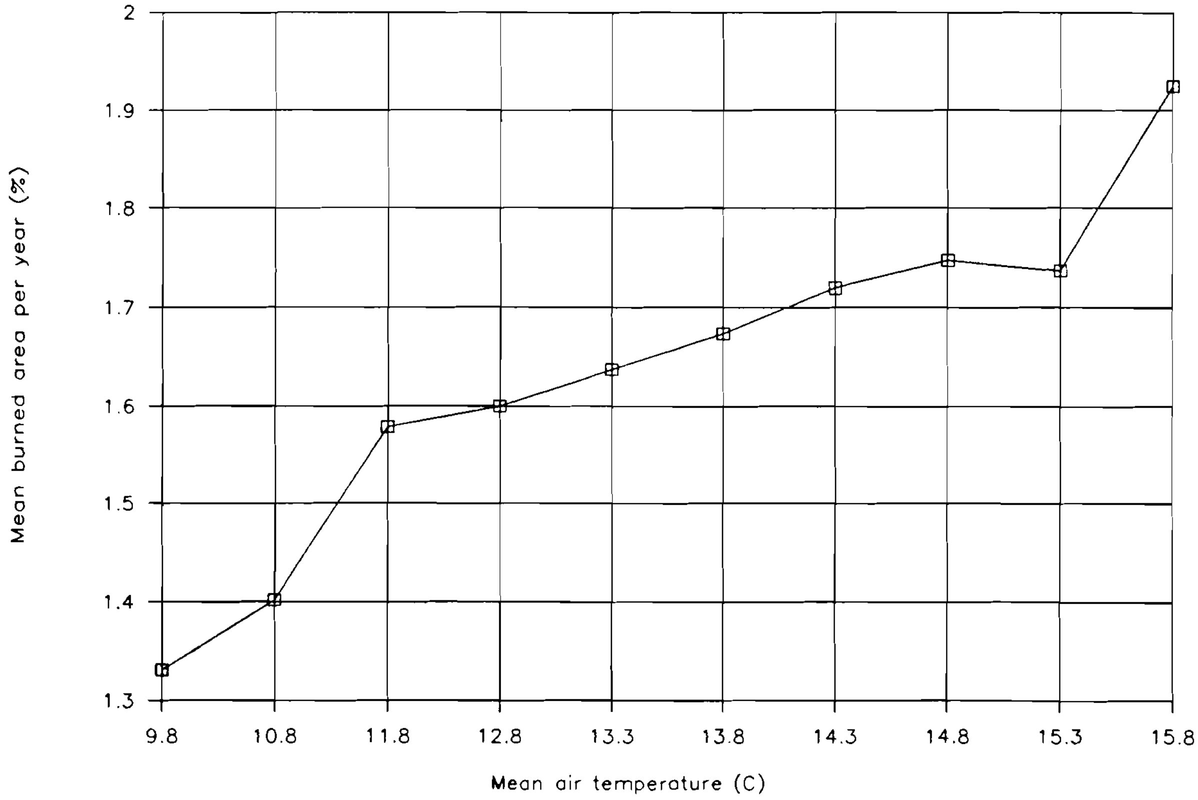

Figure 8b. **Dependence of mean area burned per year on mean air temperature.**

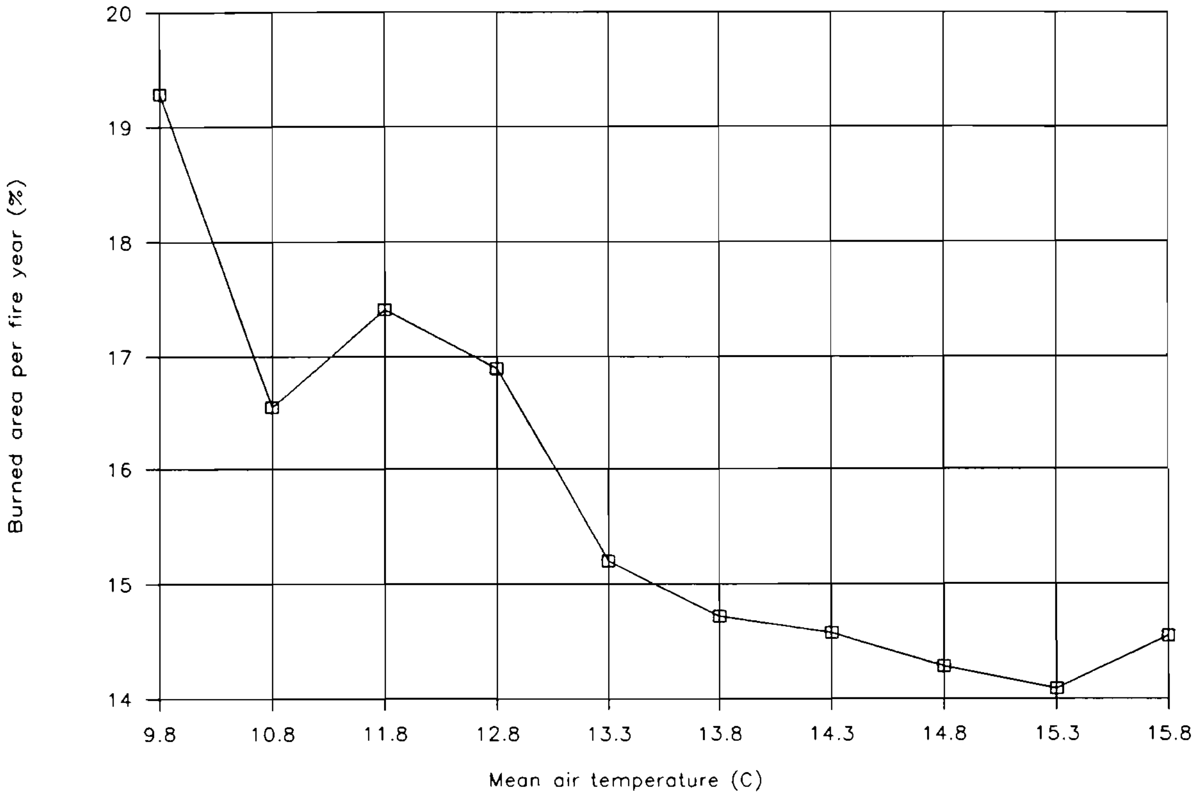

Figure 8c. **Dependence of mean area burned per fire year on mean air temperature.**

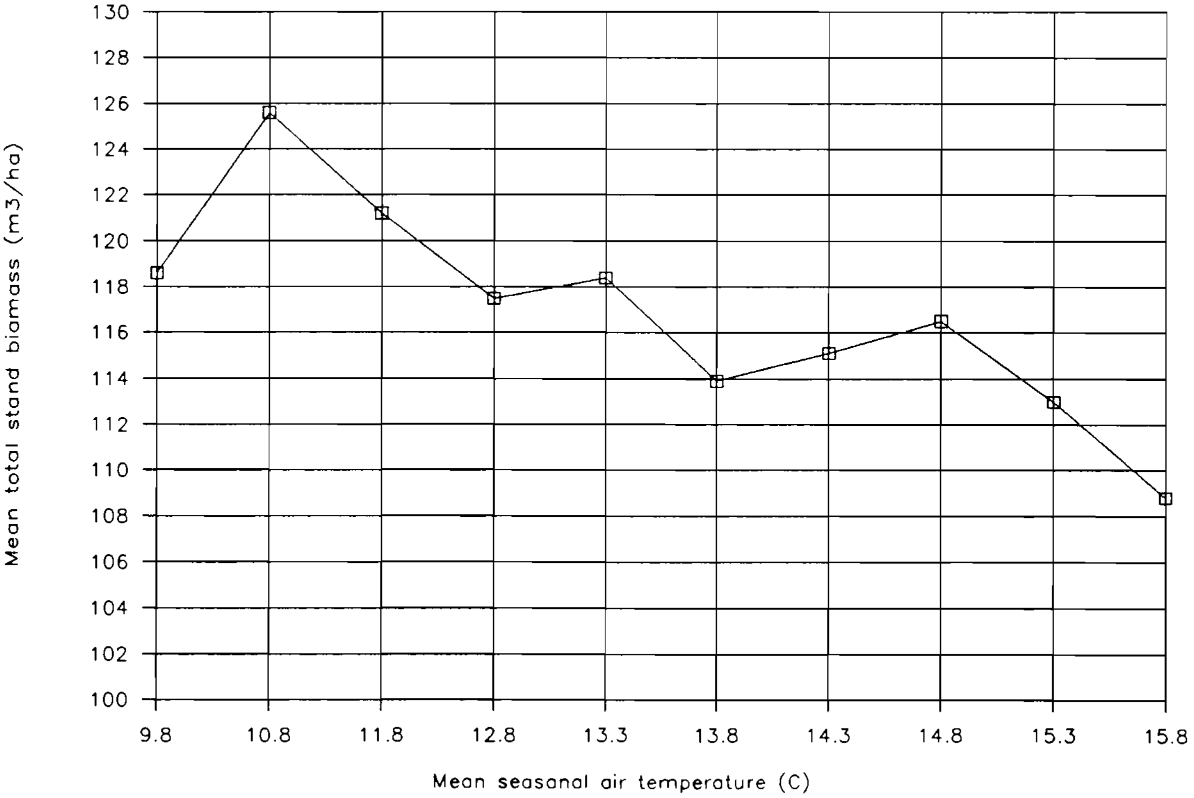

Figure 8d. **Dependence of mean total stand biomass on mean seasonal air temperature.**

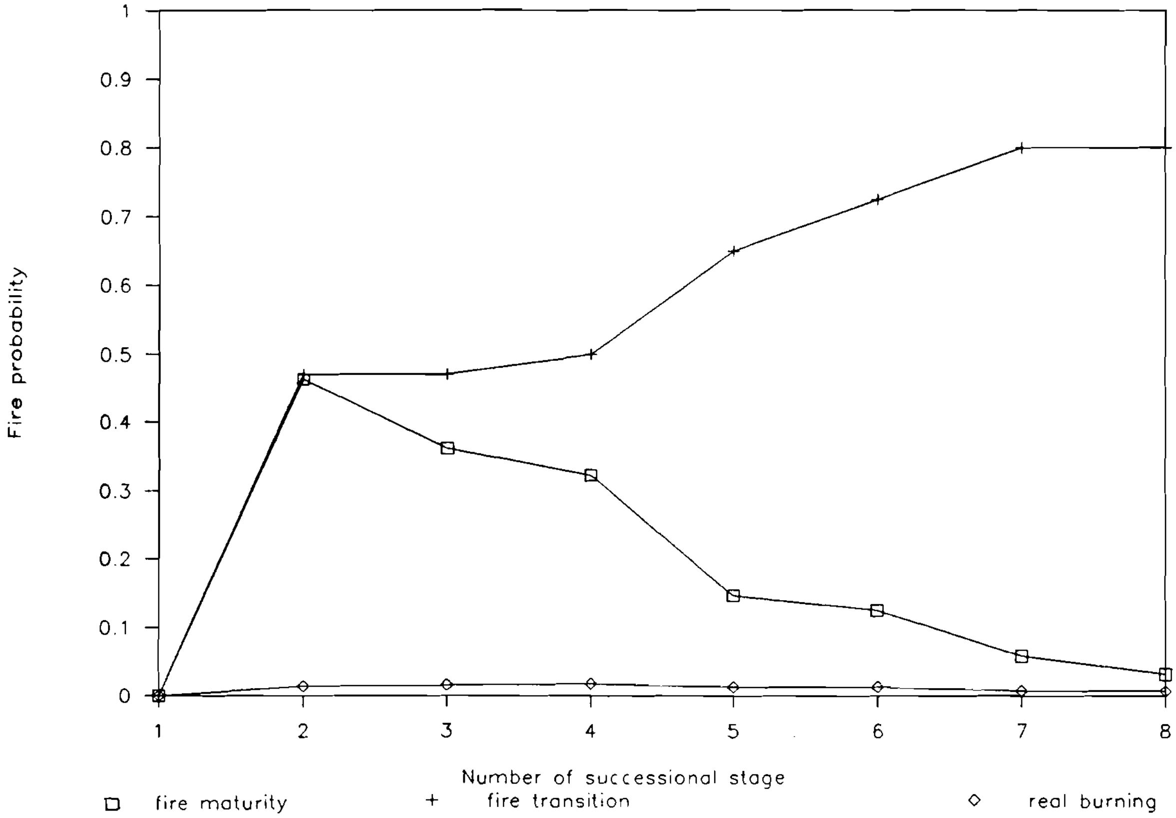

Figure 9. **Probabilities of fire maturity, fire transition and real burning.**