МАТЕМАТИЧНЕ ТА КОМП'ЮТЕРНЕ МОДЕЛЮВАННЯ

МАТЕМАТИЧЕСКОЕ И КОМПЬЮТЕРНОЕ МОДЕЛИРОВАНИЕ

MATHEMATICAL AND COMPUTER MODELING

UDC 519.6+913

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GIS-TECHNOLOGIES AND MATHEMATICAL SIMULATION TO PREDICT LIGHTNING-CAUSED FOREST FIRE DANGER

Context. The components of the geoinformation system for monitoring, forecasting and assessment of forest fire danger caused by thunderstorm activity are developed.

Objective of the work is to create an embedded software tool for physically based forecasting, monitoring and evaluation of the probability of forest fire occurrence as a result of the impact of a lightning discharge on a tree trunk.

Method. Structural analysis is used to design elements and information flows inside and outside of the developed geographic information system. Mathematical modeling is used to determine the parameters of tree ignition by the cloud-to-ground lightning discharge. Mathematically, the process of tree trunk heating is described using a system of non-stationary heat conduction equations with a source part responsible for the heat release according to the Joule-Lenz law in the core of the tree trunk. The finite difference method is used to solve the differential heat equation. Finite-difference analogues are solved by the double-sweep method. Program realization is implemented in the built-in high-level language. The probability theory (conditional probability) is used to develop a probabilistic criterion for forest fire danger estimation.

Results. A software tool is developed to estimate the tree ignition delay time as a result of the impact of a cloud-to-ground lightning discharge. The GIS-system component is developed in the high-level programming language Python. We have obtained probability distribution of forest fire occurrences from thunderstorms for the territory of the Timiryazevsky forestry in the Tomsk region is obtained.

Conclusions. We have proposed a physically proved method for forecasting, monitoring and assessing forest fire danger caused by thunderstorm activity. The deterministic mathematical model is used to simulate tree ignition by the cloud-to-ground lightning discharge in conjunction with the probabilistic criterion for assessing forest fire danger. We have analysed forest fire danger for a typical territory of the Tomsk region (Timiryazevskiy forestry).

Keywords: GIS, Mathematical modeling, Forest fire danger, Forecast, Thunderstorm activity, Probability criterion.

NOMENCLATURE

FWI is a Fire Weather Index;

FBP is a Fire Behavior Prediction;

GIS is a Geoinformation system;

P_j is the probability of a forest fire for the j^{th} interval on the controlled forested area;

$P(A)$ is the probability of anthropogenic load;

$P(A_j/A)$ is the probability of a high temperature source presence on the j^{th} day;

$P_j(FF/A,A_j)$ is the probability of a forest fire due to anthropogenic load on the forested area;

$P(M)$ is the probability of dry thunderstorms in the forested area;

$P(L_j/L)$ is the probability of a cloud-to-ground lightning discharge;

$P_j(FF/L,L_j)$ is the probability of a forest fire due to lightning when dry thunderstorms may occur in the forested area;

$P_j(D)$ is the probability of a fire due to weather conditions of forest fire maturation (the probability of the fact that the forest fuel layer is dried);

j is the day of a fire danger season;

N_A is the number of days during a fire danger season when the anthropogenic load is sufficient to ignite forest fuel;

N_{FA} is the number of fires due to anthropogenic load;

N_{FT} is the total number of fires;

N_L is the number of days when lightning occurred (during dry thunderstorms);

N_{FS} is the total number of days in a fire danger season;

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N_{FL} is the number of fires due to lightning (during dry thunderstorms);

N_{FD} is the number of fires on the specific day of week;

N_{FW} is the total number of fires during week;

N_{LH} is the number of cloud-to-ground lightning discharges passed at the definite hour starting from 00.00 o'clock;

N_{LD} is the total number of cloud-to-ground lightning discharges per day;

NI_D is the value from the Complex Meteorological Index for the day, which the forecast is realised for;

NI_{MAX} is the maximum value of the Complex Meteorological Index;

t_a is a air temperature;

d is a dew point temperature;

n is the number of days after the last rain;

T_i is a temperature;

ρ_i is a density;

c_i is a thermal capacity;

λ_i is a heat conductivity;

i is the internal part of a tree trunk (core) (i=1) and the bark (i=2);

α is a heat transfer coefficient;

J is a current;

U is a voltage;

r is a coordinate;

t is a time;

e is the index that corresponds to environmental parameters;

0 is the index that corresponds to the parameters at the initial moment of time.

INTRODUCTION

The remote areas of forested territories are characterized by widely spread forest fires caused by thunderstorm activity [1]. A large amount of burnt area is noted for such fires [2]. Such fires in forests are detected with delay when the ignition has already reached a big fire. It is impossible or ineffective to extinguish fires in the taiga zone. Fires go out when flush period begin or the whole forest area has burnt out before the fire comes across a natural barrier (for example, a river).

The most promising approach is to predict forest fire risk and to carry out preventive measures within the controlled forested territories in such situations [3]. Various forest fire danger forecast systems taking into account lightning activity have been developed in different countries [4–6]. However, all these systems have no physical basis and are mainly based on the analysis of the statistical information on forest fires and the characteristics of forests [7].

The purpose of the work is to create an embedded software tool for physically based forecasting, monitoring and evaluation of the probability of forest fire occurrence as a result of the impact of a lightning discharge on a tree trunk.

1 PROBLEM STATEMENT

Cloud-to-ground lightning discharge leads to ignition and defragmentation of the tree with the formation of particles heated to high temperatures. Such particles fall down and ignite a forest fuel layer. As a result, there is a surface forest fire. The process of contact of the discharge channel and tree is stochastic, but the tree ignition might be described by a deterministic mathematical model. Therefore, it is necessary to develop a software tool that would allow the calculation of the conditions for the ignition of a tree as a result of the cloud-to-ground lightning discharge. Electronic maps are needed to visualize areas with the highest probability of forest fire occurrence.

2 REVIEW OF THE LITERATURE

A lightning discharge is one of the causes of forest fires. Lightning is an electric discharge conditioned by the division into positive and negative discharges in the clouds that leads to the difference in potentials in a range of 10–100 mV [8]. Water is necessary in all three phases (solid, liquid, and gas) [9] so that the division into discharges occurs.

According to the development conditions, storms are divided into the air-mass and frontal ones. The air-mass storms over a continent occur due to local air heating from the ground surface. It leads to the development of rising flows of local convection and to the formation of heavy cumulonimbus clouds in them. The frontal storms occur on the borders of warm and cold air masses [10]. There may be cloud-to-cloud and cloud-to-ground discharges. Around 90 % of cloud-to-ground discharges are negative, and the nature of the remaining 10% of positive discharges is not entirely clear [11]. The cloud-to-ground discharges cause forest fires [12]. The energetic characteristics of positive and negative ground storm discharges are different, and these differences are substantial in terms of igniting forest fuel. All the energy reaches surface in one stroke due to the vast majority of positive discharges, while a multi-stroke is typical for the negative discharges [13].

The full statistics for cloud-to-ground storm discharges have been collected within the functioning of the US National Lightning Detection Network [14]. This system can identify most of the cloud-to-ground lightning discharges in the USA and Canada with the spatial resolution of several kilometers and determination accuracy in time approximately 1 msec. The data on the stroke polarity, stroke peak current, and stroke complexity are archived when the system is operating (if it is a single or multi-stroke).

The lightning-caused forest fires equaled approximately 37 to 53% of the area where fire had spread with a relative number of approximately 8.8–17.5% in Russia between 1992 and 2000 [15]. Dry storms, which cause mass ignitions in large territories, often create a very intensive fire incident situation [16].

The Canadian Forest Fire Danger Rating System has two main sub-systems (modules): Canadian Forest Fire Weather Index System and Canadian Forest Fire Behavior Prediction System. Two other elements (Fuel Moisture System and Canadian Forest Fire Occurrence Prediction System) are not developed for the whole country, but there are regional versions of these systems [17].

The Canadian method to predict forest fire danger [4] relies on the analysis of a large number of statistical data, according to which they form the tables of fire danger dependence on different factors. The moisture content in forest fuels is predicted depending on weather conditions within the FWI sub-system, whereas the forest fire front behavior is forecasted for different forest plant communities within the FBP one.

The system logical structure [4,5] represents the abstract model of different factors and conditions that impact on the process of fire occurrence and spread.

All forest fuels are divided into nine typical models. The system suggests dividing the separately protected areas into physically and geographically homogeneous parts. Each area must correlate with one of nine models. Fire danger is evaluated for each considered area separately. The final fire danger evaluation uses many tables and corrections obtained according to empirical data.

The Canadian and American methods are similar in their structure, approaches, and fire danger index formation principles. Therefore, they both have similar advantages and disadvantages.

The European Forest Fire Information System [6]. The most progressive component of the system repeats the subsystem of the Canadian Forest Fire Danger Rating System. This system has the same characteristics and uses the Earth remote sensing data.

3 MATERIALS AND METHODS

We have obtained a formula to estimate the probability of a forest fire to occur for the *j*-th time interval of a forest fire season using the basic principles of probability theory [18]:

$$P_j = \lfloor P(A)P(A_j / A)P(FF / A, A_j) + \\ + P(L)P(L_j / L)P(FF / L, L_j)\rfloor P(D) . \quad (1)$$

The authors offer to define the probability through the frequency of events and use statistical data for the definite forestry in order to determine all multipliers in formula (1).

Obviously, the more cases are considered for this forestry, the bigger is the accuracy to determine the probability of forest fire occurrence. Therefore, it is necessary to register all the fire danger season parameters (N_A, N_{FA}, N_{FT}, N_L, N_{FS}, N_{FL}, N_{FD}, N_{FW}, N_{LH}, N_{LD}) in forests every year.

Formula (1) contains multiplier $P_j(D)$. This is the probability of fire danger caused by meteorological conditions. This probability has been calculated through the time for forest fuel layer to dry in the previous work [19]. However, it is hard to implement such method on the whole territory of the Russian Federation at present, because it is necessary to have the information about the initial moisture content of forest fuel in order to model the process of drying the forest fuel layer. The present paper offers to use a compromise solution. We suggest calculating the probability through meteorological conditions using the Complex Meteorological (Nesterov) Index, which has been approved in the state standard. The range of this index starts from zero and has no upper border. However, it is possible to set its upper border as a maximum possible value during a fire danger season. We normalize the Complex Meteorological Index to maximum value 1 (one) to estimate the probability of forest fire danger [18]:

$$P_j(D) = \frac{NI_D}{NI_{\max}} . \quad (2)$$

The variation range of forest fire danger probability caused by meteorological conditions will be from 0 to 1.

The Complex Meteorological Index is calculated by formula [7]:

$$NI = \sum_n t_a (t_a - d) . \quad (3)$$

Fire danger is calculated by the above-stated method. It differs slightly in different regions within the same forest. GIS allows the visualisation of fire danger maps for the quantitative analysis of wildfire risk. It is important to analyse the spatial distribution of forest fire danger probability in order to delineate and prioritise the particularly susceptible forested areas.

The research [20] suggests the simple mathematical model of tree ignition by a cloud-to-ground lightning discharge, namely the thermophysical mathematical model of deciduous tree ignition.

The electric current passage is different in the trunk of a deciduous and coniferous tree [21]. This is due to the fact that moisture is transported in the massive central part in broad-leaved trees. The damper central part is an electric current conductor.

4 EXPERIMENTS

We consider the following physical model. A cloud-to-ground lightning discharge strikes in a tree trunk at the fixed moment of time. The electric current of the cloud-to-ground lightning discharge passes along the trunk. It is supposed that heat is emitted in the core according to the Joule-Lenz law. The electric current is supposed to have the same parameters in various trunk sections. Moisture evaporation is neglected within current research, but it is not difficult to describe this process by the Knudsen-Lengmuir equation [22]. The wood is heated up due to the Joule heat emission as a result of electric current passage. The wood ignites when it achieves the critical thermal fluxes to ignition surface and critical temperature. The tree trunk is modeled by a cylinder. We consider the representative section of the trunk. Fig. 1 shows the decision area scheme.

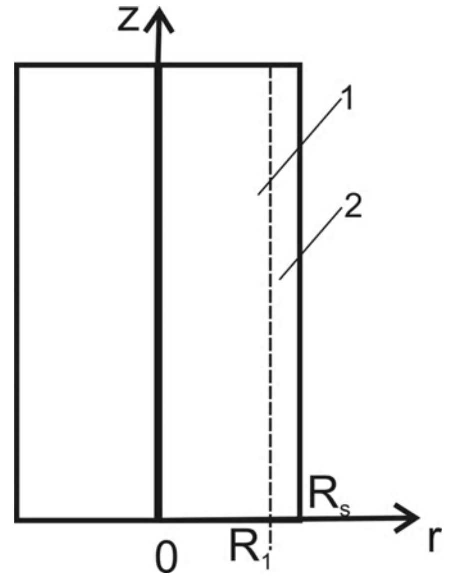

Figure 1 – Decision area scheme: 1 is core, 2 is bark

The system of non-stationary differential equations mathematically describes the process how the cloud-to-ground lightning discharge heats up the tree trunk before ignition [20]:

$$\rho_1 c_1 \frac{\partial T_1}{\partial t} = \frac{\lambda_1}{r} \frac{\partial}{\partial r}\left(r \frac{\partial T_1}{\partial r} \right) + JU, \tag{4}$$

$$\rho_2 c_2 \frac{\partial T_2}{\partial t} = \frac{\lambda_2}{r} \frac{\partial}{\partial r}\left(r \frac{\partial T_2}{\partial r} \right), \tag{5}$$

Boundary conditions for equations (4)–5):

$$r=0,\ \lambda_1 \frac{\partial T_1}{\partial r} = 0, \tag{6}$$

$$r=R_1,\ \lambda_1 \frac{\partial T_1}{\partial r} = \lambda_2 \frac{\partial T_2}{\partial r},\ T_1 = T_2 \tag{7}$$

$$r=R,\ \lambda_2 \frac{\partial T_2}{\partial r} = \alpha(T_e - T_2), \tag{8}$$

Initial conditions for equations (4)–(5):

$$t=0,\ T_i(r) = T_{i0}(r). \tag{9}$$

The formulated system of equations (4)–(5) with boundary and initial conditions (6)–(9) is solved by a finite difference method [23]. A double-sweep method in combination with a fixed point iteration method [23] has been used to decide the difference analogues of one-dimensional equations.

The following ignition scenario was considered. The negative cloud-to-ground lightning discharge (approximate duration is 500 ms, approximate stroke peak current is 23.5 kA, and approximate voltage is 100 kV) influences on a wide-leaved tree, for instance, birch. Fig. 2 shows the temperature distribution on the tree trunk radius in various moments of time before and at the moment of igniting by electric current (initial temperature 300 K).

Table 1 represents the cloud-to-ground lightning discharge parameters and ignition conditions depending on the voltage of the cloud-to-ground lightning discharge obtained by solving problems (4)–(9). The analysis of dependences presented in Fig. 2 shows that the tree trunk is heated up to the ignition temperature (more than 1000 K) by the considered cloud-to-ground lightning discharge. The analysis of results (Fig. 3 and Fig. 4) shows that the ignition conditions of a wide-leaved tree are reached at the critical temperature (801 K) and value of thermal flux (268 kW/m^2) for a typical cloud-to-ground lightning discharge.

We have established the ignition limits for a tree trunk during the action of the electric discharge at various voltages (Table 1) and currents (Table 2). When the current is less than 23.5 kA and voltage is 1–90 kV, ignitions fail to occur during the action of the cloud-to-ground lightning discharge.

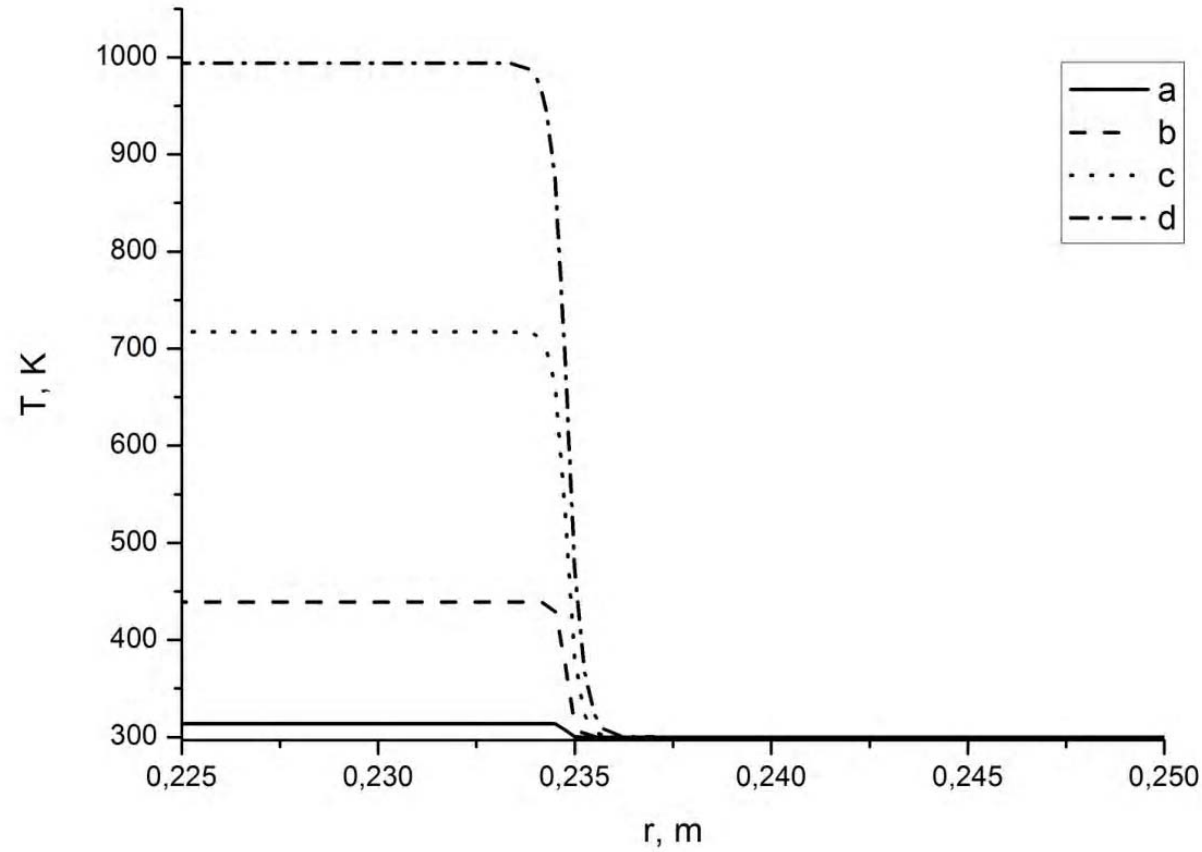

Figure 2 – Temperature distribution on tree trunk radius at various moments of time (discharge action duration is 500 ms):
a – t=0.01 sec; b – 0.1 sec; c – 0.3 sec; d – 0.5 sec

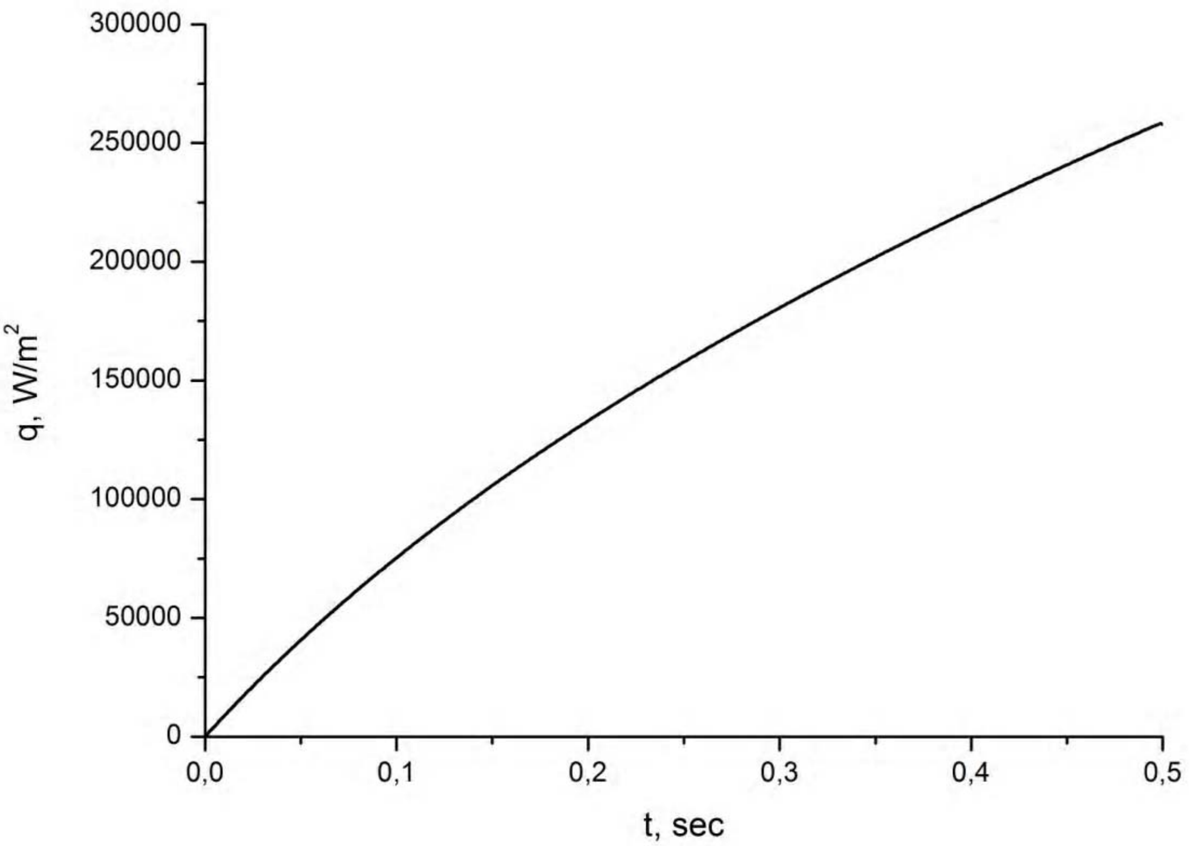

Figure 3 – Heat flux dependence on time from core to ignition surface

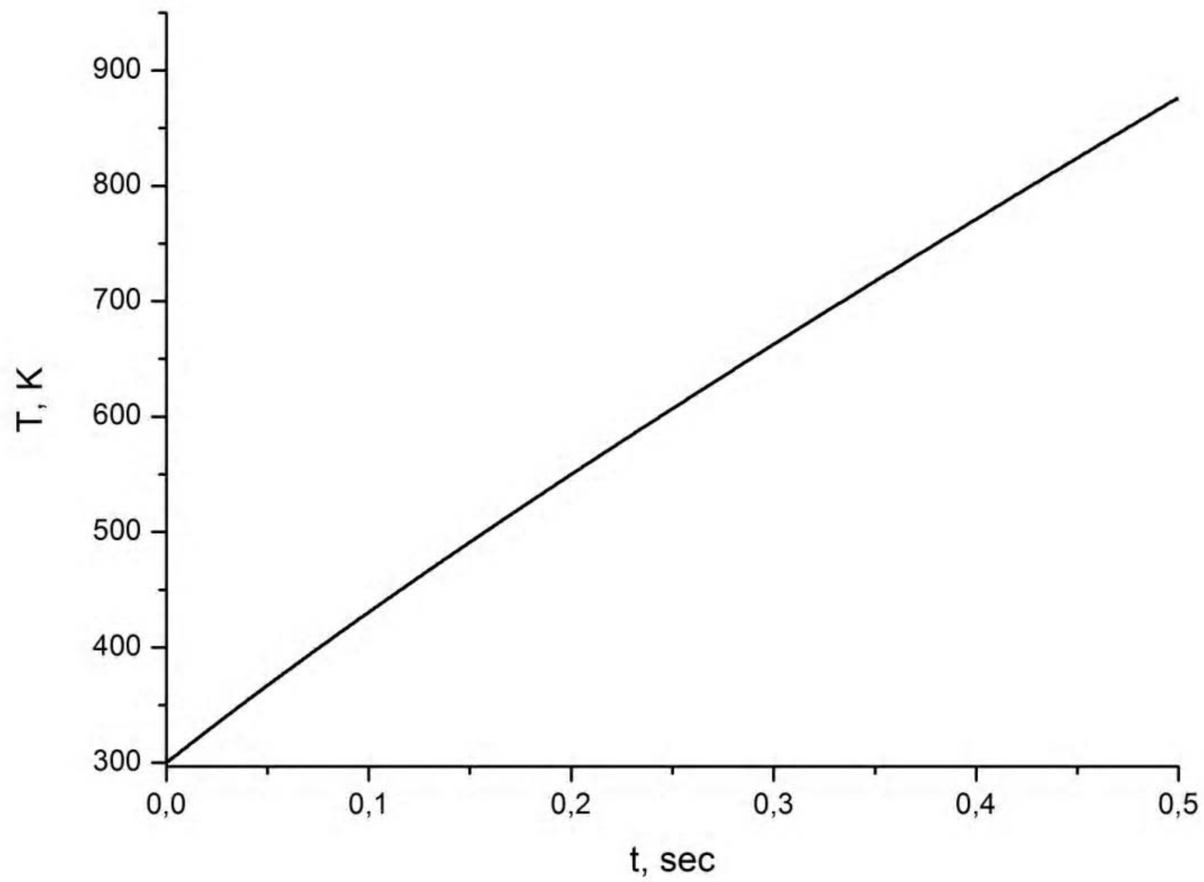

Figure 4 – Ignition surface dependence on time

Table 1 – Ignition condition of tree depending on voltage of the discharge at current J=23.5 kA

Voltage, U, kV	Ignition occurrence	Surface temperature, K	Heat flux from core to surface, kW/m^2
1–85	No	<801	<210
90	Yes	801	226
95	Yes	801	230
100	Yes	801	232
105	Yes	801	235
110	Yes	801	238

Table 2 – Ignition condition of tree depending on current of the discharge at voltage U=100 kV

Current, J, kA	Ignition occurrence	Surface temperature, K	Heat flux from core to surface, kW/m^2
1–20	No	<801	<210
23.5	Yes	801	232
30	Yes	801	245
35	Yes	801	253

5 RESULTS

GIS enables us to use the mathematical model program for quantitative assessment of the probability of lightning-caused forest fire danger. The algorithms of geographical information system for quantitative assessment of forest fire danger are implemented in the Python language embedded into ArcGIS [24]. The quantitative estimation is carried out relying on the remote sensing data, land forest taxation, and statistical information. The criteria to assess forest fire danger are defined relying on the probability theory, and its values are within the range from 0 to 1. The calculations are made with the accuracy up to 0.0001. The forest taxation descriptions of stratums (Fig. 5) are presented below in the table in MS Excel format (national language).

FFstormactivity.tbx program tool solves the problem to forecast the fire danger of forest a quadrant relying on the information about stratum composition and statistical information on lightning-caused forest fires and visualizes the obtained information on an electronic map. Python is the source language for FFstormactivity program [24].

FFstormactivity program tool contains seven forms. It provides two variants to solve the task: complex and stage-by-stage with the control of result. Main stages:

1. Data import from the Excel table to the autonomous geodata base table.
2. Fire danger determination for a forest stratum.
3. Fire danger probability estimation for a forest quadrant according to the forest taxation descriptions.
4. Statistical data import to the geodata base.
5. Estimation of lightning-caused fire danger probability.
6. Attributive and autonomous tables connection.
7. Map formation according to a legend.

The algorithm, how the program tool works, is presented by a series of figures showing the main steps of the analysis and information processing by this tool (Fig. 6–10). ArcGIS options are also used for scheme constructions.

FFstormactivity program tool uses the following methods:

1. AddField is to add a field. The program adds a field.
2. CalculateField is to calculate the field value. To determine the fire danger of a stratum, to assess the probability of forest fire danger on the quadrant of the level.
3. Statistics_analysis is the total statistics. To calculate the total quantity of stratums in each quadrant and the quantity of the fire-dangerous ones.
4. JoinField is to connect the fields. The connection between two tables takes place on the basis of a key field.
5. ApplySymbologyFromLayer_management is to add the layer symbols. To form the layer of quadrants according to the fire danger level.

The program tool start-up begins with ArcToolbox. It is necessary to specify the initial data in the dialog window that appears after start-up. The Russian interface is used in the current version of GIS-system.

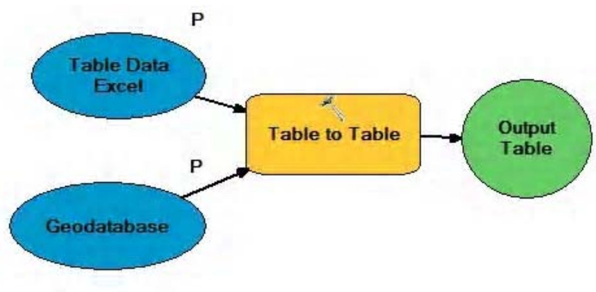

Figure 6 – Data import from Excel table to autonomous geodata base table

uchastok	kvart	vydel	area	sostav	age
Калтайский	1	1	43.7	СЕНОКОС	
Калтайский	1	2	2	БОЛОТО	
Калтайский	1	3	7.6	7Б2Л1С	Б - 75, Л - 120, С - 120
Калтайский	1	4	14.8	7ИВ3Б	ИВ - 30, Б - 35
Калтайский	1	5	19	7ИВ3Б	ИВ - 30, Б - 35
Калтайский	1	6	18.3	8Б2Л	Б - 65, Л - 120
Калтайский	1	7	5.5	7Б2Л1С	Б - 75, Л - 120, С - 120
Калтайский	1	8	5.6	5С2К1Л2Б	С - 140, К - 160, Л - 140, Б - 75
Калтайский	1	9	5.3	5К2Е1С2Б	К - 180, Е - 140, С - 140, Б - 85
Калтайский	1	10	1.2	ОЗЕРО	

Figure 5 – Table of forest taxation data in MS Excel format

Figure 7 – Determination of fire danger for stratum according to forest taxation descriptions (a) and estimation of fire danger probability of forest quadrant according to forest taxation descriptions (b)

Figure 7 shows the algorithm to form the table that lists the level of forest fire risk, which is characteristic for each quarter of a forest taxation site. Each sub-step of the algorithm is formed by an attribute table. First, we add the field, which is responsible for the allotment of forest fire danger level and statistics on forest fire incidents. Then the data processing is performed to be entered in the next table. An intermediate table is formed again, and later it is integrated with the data of the summary statistics on forest fires. As a result, the field is calculated according to the level of forest fire danger. The next step is to calculate the probability of forest fire on the controlled territory. After a series of intermediate calculations the attribute table is generated to estimate the probability of forest fires on the territory of a forest taxation quarter.

The tool implementation results in creating:

1. The table that assesses the probability of the lightning-caused fire danger of a forest quadrant with regard to the forest vegetation conditions

2. The thematic map that displays the fire danger levels of a forest quadrant (Fig. 11).

The forest fire danger levels in fig. 11 correspond to the following gradation:

1: 0.001852–0.030000.

2: 0.030001–0.060000.

3: 0.060001–0.090000.

The minimum is 0.001852; the maximum is 0.08333.

6 DISCUSSION

The analysis of foreign forest fire danger forecast systems shows that they show high operational qualities in their countries. However, it is difficult to apply them in other countries as it is necessary to carry out the whole range of works to analyse and adjust empirical formulas for new forested territories.

All foreign systems usually offer the abstract index of forest fire danger. The present research offers the new probabilistic approach to estimate the most probable

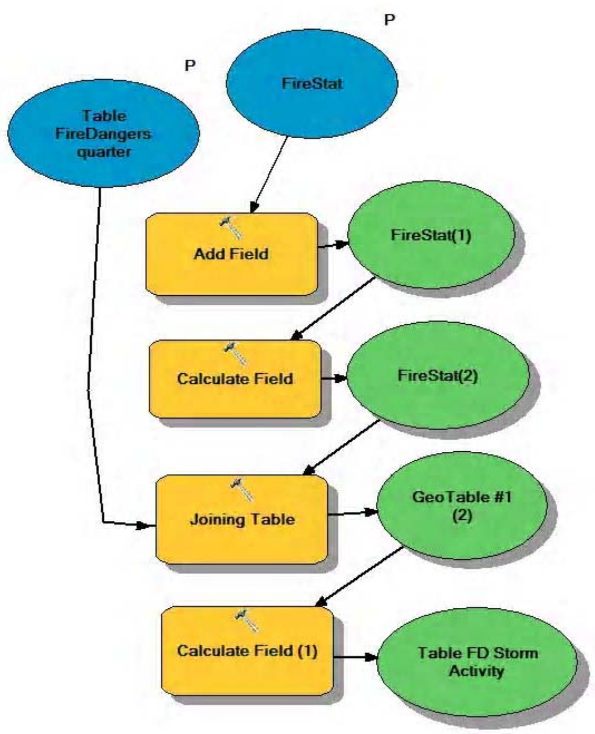

Figure 8 – Assessment of fire danger probability caused by storm activity

scenarios of forest fire danger. The definite scenario can be calculated using the deterministic mathematical model describing how the cloud-to-ground lightning discharge ignites a tree. We have developed GIS-system to forecast the lightning-caused forest fire danger. The system reserves the layers for the subsequent implementation of the deterministic component based on the mathematical model of tree ignition by a cloud-to-ground lightning discharge.

CONCLUSIONS

We offer the new physically proved approach to forecast the lightning-caused forest fire danger as a result of the current research. The analysis of the methods based on statistical data shows that it is impossible to estimate adequately the probability of lightning-caused forest fires. We offer to use the deterministic models of tree ignition by a cloud-to-ground lightning discharge and the probabilistic criterion to estimate forest fire danger. The statistical approach analysis has been carried out in the territory of the Timiryazevskiy local forestry of the Timiryazevskiy forestry in the Tomsk region. The technologies of geographic information systems are used to visualize spatial data. ArcGIS software enables the program of algorithms to be implemented.

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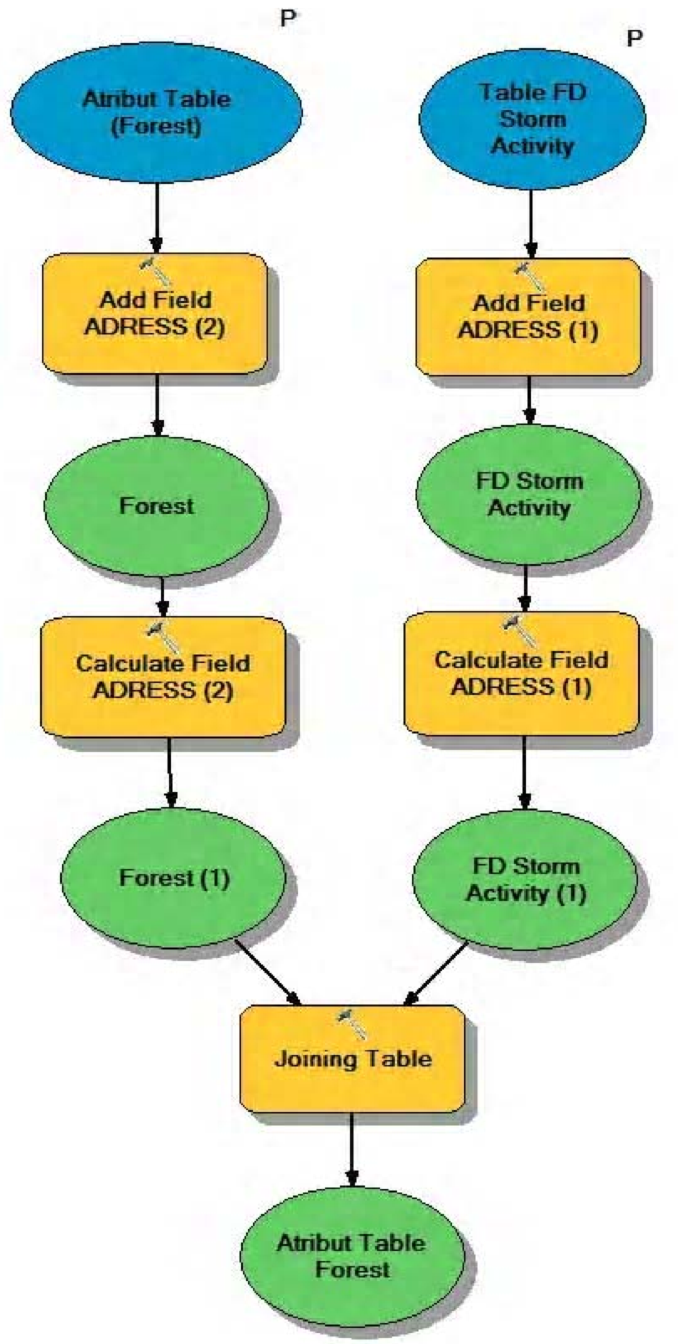

Figure 9 – Attributive and autonomous tables connection

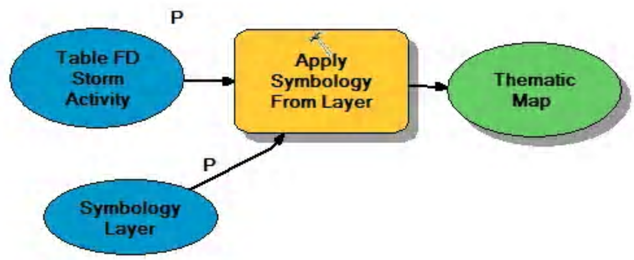

Figure 10 – Map formation according to legend

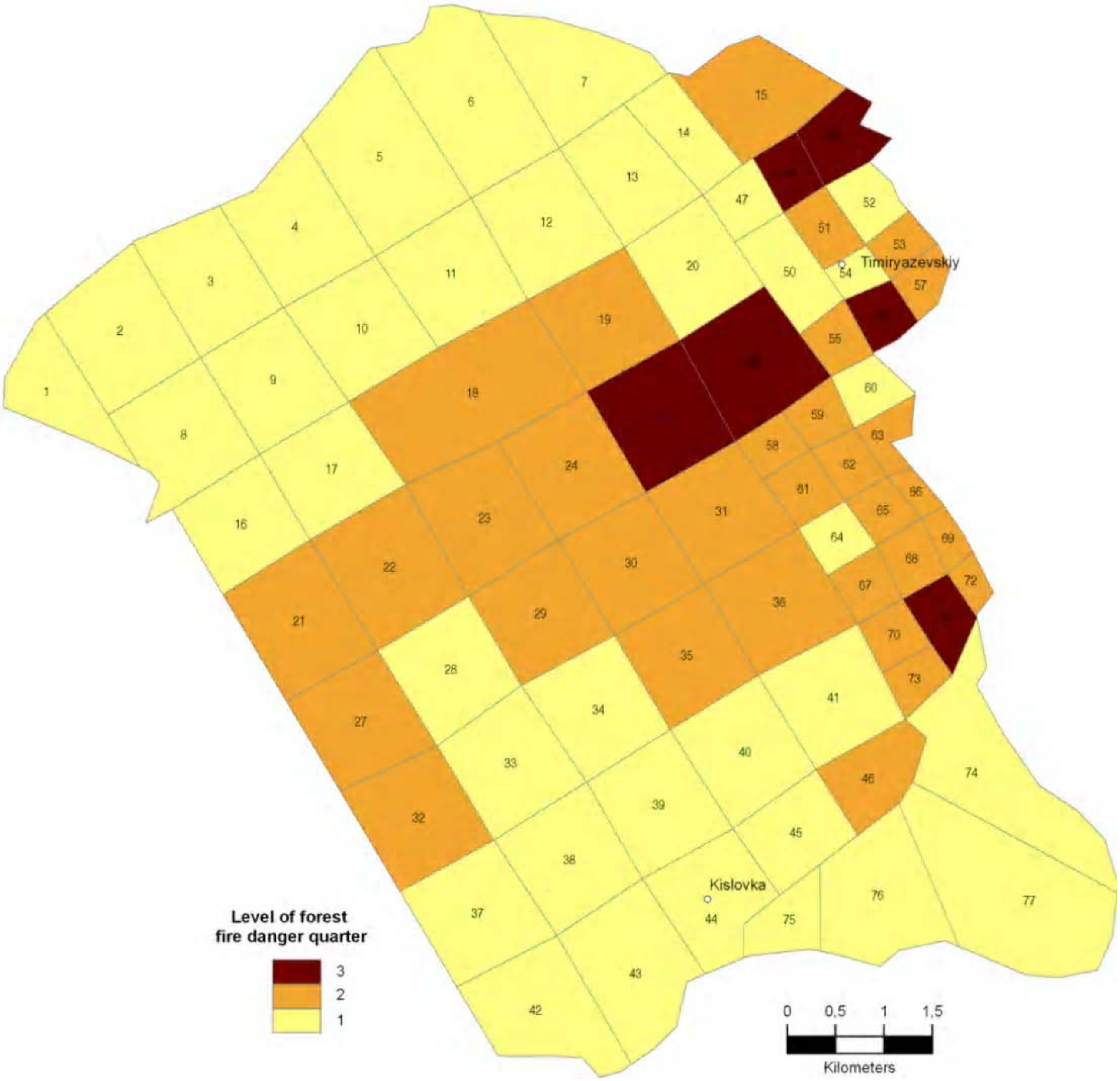

Figure 11 – Map of lightning-caused forest fire danger on territory of Timiryazevskiy local forestry of Timiryazevskiy forestry in Tomsk region

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ГЕОІНФОРМАЦІЙНІ ТЕХНОЛОГІЇ ТА МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ ЯК ІНСТРУМЕНТ ПРОГНОЗУВАННЯ ЛІСОВОЇ ПОЖЕЖНОЇ НЕБЕЗПЕКИ ВІД ГРОЗ

Актуальність. Розроблено компоненти геоінформаційної системи для моніторингу, прогнозування та оцінювання лісової пожежної небезпеки, обумовленої дією грозової активності.

Мета роботи – створення програмно-апаратного інструменту для фізично обгрунтованого прогнозування, моніторингу та оцінювання ймовірності виникнення лісової пожежі в результаті впливу грозового розряду на стовбур дерева.

Метод. Структурний аналіз використаний для проектування елементів і потоків інформації всередині і ззовні розробленої геоінформаційної системи. Математичне моделювання використано для визначення параметрів займання дерева наземним грозовим розрядом. Математично процес розігріву стовбура дерева описується за допомогою системи нестаціонарних рівнянь теплопровідності з джерельним членом, що відповідає за тепловиділення за законом Джоуля-Ленца в серцевині стовбура дерева. Метод кінцевих різниць використаний для вирішення диференціальних рівнянь теплопровідності. Кінцево-різницеві аналоги вирішені методом прогонки. Програмна реалізація виконана на вбудованій мові високого рівня. Теорія ймовірності (умовна ймовірність) використана для розробки імовірнісного критерію лісової пожежної небезпеки.

Результати. Розроблено програмний інструмент для оцінки часу затримки запалювання дерева в результаті впливу наземного грозового розряду. Компонент ГІС-системи розроблений мовою програмування високого рівня Python. Отримано розподіл ймовірності виникнення лісових пожеж від гроз для території Тимирязівського лісництва Томської області.

Висновки. Запропоновано фізично обгрунтований метод прогнозування, моніторингу та оцінювання лісової пожежної небезпеки, обумовленої дією грозової активності. Детермінована математична модель запалювання дерева наземним грозовим розрядом використана в сукупності з імовірнісним критерієм для оцінки лісової пожежної небезпеки. Проведено аналіз лісової пожежної небезпеки для типової території Томської області (Тимирязівське лісництво).

Ключові слова: ГІС, Математичне моделювання, Лісова пожежна небезпека, Прогноз, Грозова активність, Імовірнісний критерій.

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ГЕОИНФОРМАЦИОННЫЕ ТЕХНОЛОГИИ И МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ КАК ИНСТРУМЕНТ ПРОГНОЗИРОВАНИЯ ЛЕСНОЙ ПОЖАРНОЙ ОПАСНОСТИ ОТ ГРОЗ

Актуальность. Разработаны компоненты геоинформационной системы для мониторинга, прогноза и оценки лесной пожарной опасности, обусловленной действием грозовой активности.

Цель работы – создание встроенного программного инструмента для физически обоснованного прогноза, мониторинга и оценки вероятности возникновения лесного пожара в результате воздействия грозового разряда на ствол дерева.

Метод. Структурный анализ использован для проектирования элементов и потоков информации внутри и извне разработанной геоинформационной системы. Математическое моделирование использовано для определения параметров воспламенения дерева наземным грозовым разрядом. Математически процесс разогрева ствола дерева описывается с помощью системы нестационарных уравнений теплопроводности с источниковым членом, отвечающим за тепловыделение по закону Джоуля-Ленца в сердцевине ствола дерева. Метод конечных разностей использован для решения дифференциальных уравнений теплопроводности. Конечно-разностные аналоги решены методом прогонки. Программная реализация выполнена на встроенном языке высокого уровня. Теория вероятности (условная вероятность) использована для разработки вероятностного критерия лесной пожарной опасности.

Результаты. Разработан программный инструмент для оценки времени задержки зажигания дерева в результате воздействия наземного грозового разряда. Компонент ГИС-системы разработан на языке программирования высокого уровня Python. Получено распределение вероятности возникновения лесных пожаров от гроз для территории Тимирязевского лесничества Томской области.

Выводы. Предложен физически обоснованный метод прогноза, мониторинга и оценки лесной пожарной опасности, обусловленной действием грозовой активности. Детерминированная математическая модель зажигания дерева наземным грозовым разрядом использована в совокупности с вероятностным критерием для оценки лесной пожарной опасности. Проведен анализ лесной пожарной опасности для типичной территории Томской области (Тимирязевское лесничество).

Ключевые слова: ГИС, Математическое моделирование, Лесная пожарная опасность, Прогноз, Грозовая активность, Вероятностный критерий.

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