Innovative approach to the assessment of moisture content of forest areas within the framework of the fundamental multi-layered concept

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Abstract. Modern methods of assessing the state of forests are verbal (descriptive). They are usually based on the assessment of environmental factors (air and soil pollution, meteorological data, etc.). The models are deterministic or probabilistic in nature (sometimes the combination of these approaches is observed). Forests are multi-tiered complex systems. The study of such complex systems is poorly designed and fragmentary at the moment. The simulation does not have a serious fundamental concept. The reasons are due to the lack of experimental methods for measuring the main characteristics of the state of forests with controlled accuracy. The fundamental concept of multi-layered representation of forests is justified in the article. The concept enables to develop a formalized model for assessing the relative moisture content in each layer at any time. The current state parameters have a transparent physical meaning. The concept takes into account the impact of the object of such natural factors as rainfall and evaporation rate on the state of the object. The potential difference measured along the radius of the tree trunks with changes in ambient temperature can be an indicator of the moisture content of tree trunks.

1. Introduction

Forests play an important role on the Earth. They are a renewable source of oxygen on the planet. Forests save the genetic diversity of the biosphere and purify water runoff, contribute to the accumulation of groundwater and humus in the soil [1-2]. In Russia, forests occupy 45% of the total area, and timber reserves make up one fifth of all the world reserves [2-3]. Thus, Russia is one of the largest sources of wood, and the state of forests is one of the most important factors in the country's welfare.

Modern methods of assessing the state of forests are verbal (descriptive) in nature and are based on the assessment of environmental factors (air and soil pollution, meteorological observations, etc.). This question is the most developed one in fire forecasting systems [4-5]. In the Canadian FWI Fire Hazard Forecast System, fire hazard monitoring is based on the estimation of the drying rate of the uppermost layer (1–2 cm thick) of the reference fuel. Such factors as air temperature, relative humidity of air at 12.00–13.00 o'clock in the afternoon, duration of the period without rains, wind at a height of 10 m in an open place are taken into account. Wind is excluded from the drying factors of the middle layer in the Canadian reference fuel. The seasonal duration of the day is added. The relative humidity of the air is excluded from the drying factors of the lowermost layer. In the American national fire hazard rating
system (first NFDRS – 72, then NFDRS – 78), all vegetable combustible materials (WGM) are divided into two major categories: dead and alive. It is believed that living plants are always able to maintain their high moisture content, while the moisture content of the dead WGM depends on the processes of their wetting and drying under the influence of weather conditions. Time of drying is analyzed at the evaluating process. In Russian systems, the forecast is based on meteorological data (Nesterov's system) or simulates the process of drying a layer of combustible materials on the underlying surface, anthropogenic load and the effect of dry thunderstorms [6-7].

Analysis of the literature data shows that the existing fire hazard forecast models are deterministic or probabilistic in nature (sometimes, the combination of these approaches is observed) [8]. At the same time, the models do not take into account the complexity of the forests, the mutual influence of their components and the dynamics of moisture content throughout the year. Thus, at present, modeling of the forests state does not have a serious fundamental concept. The reasons are associated with the lack of experimental methods for measuring the main characteristics of the state of forests with controlled accuracy.

The purpose of the work is substantiating the fundamental concept for creating a base of formalized modeling of the forests state. The concept should include a verbal model of the object, taking into account the purpose of the study, methods for measuring characteristics with controlled accuracy and an assessment of the influence of external factors. The main output characteristics of the model will be the critical values of the forests state parameters.

2. Theoretical part

2.1. Concept justification
In the first approximation, we can assume that the forest contains several complex layers: a layer of tree stands, undergrowth and air, ground cover, tree litter, forest floor, deposits of combustible materials and humus, a layer of incombustible materials [9]. Within the framework of this approach, it is convenient to present the forest in the forecast of natural disasters as a multi-layer complex structure (see figure 1).

The main characteristic of each layer is its moisture content, since this parameter characterizes the level of resistance to fire and the viability of each layer. Therefore, the state of forests is conveniently described by the function of dependence on moisture content at the current time. Then the first characteristics of the layers will be the permeability parameters of each layer for external factors that affect the change in their moisture content.

All known forecasting models of forest fires take into account the effects of precipitation, sunlight, evaporation, dry thunderstorms and anthropogenic factors. It does not take into account the level of moisture accumulated by the beginning of the dry period, and the convention of moisture between the layers. Since the anthropogenic factor and the probability of dry thunderstorms characterize the likelihood of the formation of a source of ignition, they can be ignored when assessing the state of the forest massif. Thus, there remain three natural factors, the influence of which is carried out
independently of each other. Therefore, the complex interaction of external conditions can be modeled using the superposition principle known in classical physics.

The influence of precipitation can be considered a positive factor that increases the moisture content in the forest layers. Each layer has its own parameter for permeability for precipitation and its ability to accumulate. The first layer usually consists of stands of several tiers, shrub undergrowth and air, therefore its permeability is largely determined by the humidity of the environment, and its ability to accumulate is the moisture content of the trunks along which moisture transfer occurs. The ground vegetation cover contains species that do not regulate, absorb, but not hold, and accumulate moisture content. The moisture content of litter and litter is determined by the physical laws of moisture and drying. There are many models for estimating the drying rate of flammable materials. Experimental studies and field experiments will require the determination of the dynamics of moisture content of the first and second layer.

2.2. Formalized model for assessing the dynamics of moisture content

In the framework of the proposed concept, the rate of change in moisture content can be estimated based on simple assumptions.

The rate of relative change in moisture content in the layer \( \frac{d m_i}{m_i dt} \) is determined by the superposition of the influence of the above factors, which are evaluated as the relative change in the proportion of moisture stimulating this factor. Then for the \( i \)-th layer

\[
\frac{d m_i}{m_i dt} = \chi_i = \tau_{oi} - \tau_{ei}.
\]

(1)

where \( \tau_{oi} \) is the proportion of moisture accumulated per unit time in the layer as a result of precipitation or from groundwater, \( \tau_{ei} \) is the proportion of moisture evaporating per unit time depending on external conditions. Since the process of accumulation of moisture tends to saturation (depending on external conditions), therefore, the rate of accumulation decreases with increasing moisture content. Therefore, the ratio (1) is converted to the form:

\[
\frac{d m_i}{m_i dt} = \chi_i - \beta_i m_i.
\]

(2)

Where \( \beta_i \) characterizes the change in the rate of relative accumulation because of the saturation in each layer. The solution of the differential equation (2) is found analytically:

\[
\frac{m_i}{m_{oi}} = \frac{e^{\chi_i t}}{1 + \kappa m_{oi}(e^{\chi_i t} - 1)}.
\]

(3)

The relation (3) enables to estimate the relative moisture content by the parameters determined empirically: \( m_{oi} \) is the initial moisture content in the layer, \( \chi_i \) is the relative accumulation rate due to external factors, \( \kappa = \chi_i / \beta_i \) is the coefficient characterizing the ratio of the processes of saturation and accumulation in each layer. Thus, the multi-layered concept allows to determine the moisture content in forests at any time. At the same time, the state parameters at the current time have a transparent physical meaning. Relation (3) shows that the moisture content of forests, as well as the state of any physical system, under unchanged external conditions tends to a certain stationary value that varies slightly over time.

An indirect proof of the adequacy of the proposed conceptual approach is the stationary temperature distribution along the barrel radius, since the stationary temperature in the layer is largely determined by its moisture content, because water has a high heat capacity.

Since the parameters of the state of each layer are interrelated, observation of the state of one of the layers with controlled accuracy would allow the development of a dynamic system for monitoring the state of forests.
3. Experimental part
We have previously found that because of the inhomogeneous temperature field resulting from poor thermal conductivity of wood when the ambient temperature changes by $\Delta T$, an electric field appears in the radial direction [10-12]. And the potential difference of this field depends on the state and humidity of the xylem.

Under natural conditions, measurements of the potential difference along the radius of a tree trunk were carried out in trees of deciduous species of the Populus tremula and Betula pendula families aged 34 to 50 years in the territory of the Right-Bank forestry of the experimental forestry enterprise VSUFT. Trees grew in relatively similar conditions. The measurement technique is described in [13]. Figure 2 shows the results of measuring the potential difference between the center and half of the radius of the trunk in birches of different life conditions during the day.

![Figure 2. Daily dynamics of the potential difference between the center of the trunk and half the radius: 1 – birch No 1, 2 – birch No 2, 3 – birch No 3.](image)

4. Results and discussion
Experimental studies have shown that with identical fluctuations in the ambient temperature along the trunk radius, a stable potential difference occurs, which is characteristic of each individual (see figure 2). It is seen that the state of tree stands tends to stationary with unchanged external conditions.

It should be noted that with a sharp increase in temperature, the investigated potential difference will change its value. The moisture content of wood should also affect the magnitude of this indicator due to the electrophysical properties of water. This follows from laboratory studies of the potential difference that occurs in thin layers of birch wood placed in an inhomogeneous temperature field [14]. The potential difference increases by 1.5 times with increasing humidity of wood samples from 8 to 40%. Therefore, the development of an amplifier circuit with a microcontroller could transfer monitoring of the state of tree stands to a different technological level.
Integrated operational amplifiers (OA) integrated circuits are used to increase the amplitude of very weak input signals. The gain and the supply voltage of the op-amp are chosen such that the input signals of the microcontroller (MC) in the range of analog signals in the range (–50 - +50mV), which corresponds to some individuals of the Betula family. Figure 3 shows two simplest schemes on a single OA that can be used to monitor the status of the xylem of trunks within the framework of the proposed conceptual approach. It is necessary to conduct large-scale studies for identification the correlation between the potential difference and the moisture content in the wood of various tree species for developing a test sample of the device in accordance with the proposed scheme. Preparations for such studies are ongoing.

5. Conclusion
As the result of the research it can be argued that:

1) The proposed fundamental concept allows the development of a formalized model for the dynamics of moisture content in forests when external factors change;
2) The moisture content of forests under unchanged external conditions tends to a certain stationary value, which varies little over time;
3) Within the framework of the proposed concept, the parameters of the state at the current time have a transparent physical meaning;
4) It was established experimentally that with the same fluctuations of the ambient temperature along the trunk radius, a stable potential difference occurs, which is characteristic of each individual;
5) The investigated potential difference is an indicator of the xylem state of the trunk, depends on the moisture content and fluctuations of the ambient temperature, therefore it can be the basis for the method of monitoring the state of one of the layers with controlled accuracy;
6) The implementation of the device for monitoring the potential difference along the trunk radius can be performed using amplification circuits on single operational amplifiers with a microcontroller;
7) Since the parameters of the state of each layer are interrelated, observation of the state of one of the layers with controlled accuracy would allow developing a dynamic system for monitoring the state of forests.

Thus, the result of the research was the fundamental concept of multi-layered representation of forests, which allows you to develop a formalized model for assessing the relative moisture content in each layer. The proposed approach takes into account the impact on the state of forests of such natural factors as rainfall and evaporation rate.
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