Justification of the device operation principle for measuring the potential difference in tree trunks

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Abstract. Modern instruments for assessing the characteristics of plants vital state are mainly formed by measuring the parameters of gas exchange in the leaves or are based on standard humidity sensors. However, such techniques are useless in coniferous forests and have a high cost. And they cannot be applied throughout the year in many regions due to the lack of leaves in winter. The water transport processes are the most important for researches in solving problems of predicting the fire condition of forests. Aqueous solutions are weak electrolytes. Therefore, water transport can be investigated using electrical measuring instruments. The purpose of the work was substantiating of digital device operation principle for measuring the potential difference in tree trunks as a device for studying its state. For the first time, to achieve the purpose, the analysis of temperature fluctuations during the year has carried out, a theoretical concept for the influence of temperature and humidity fluctuations on the potential difference in the tree trunks and a schematic diagram of the device have proposed.

1. Introduction

It is known that water performs a whole set of functions in the life of plants [1-3]. Its physical and chemical properties determine the structure of biological macromolecules. Water participates in the thermoregulation of plants and performs a transport function for the movement of necessary for its vital function’s substances, etc. The processes of water transport in woody plants are the most interesting for researches with the aim of solving the problems of forecasting fire danger in forests. The transport of water in woody plants can be investigated using electrical measuring instruments, because aqueous solutions are weak electrolytes.

Currently fire hazard assessment in forests is carried out by analyzing the drying rate of the upper layer of the underlying surface [4-11]. To do this, the temperature and humidity of the air are measured at noon, the duration of the period without rains and the wind in an open place at an altitude of 10 m are taken into account. Some techniques take into account the length of the day. Recently, the devices have been actively developed that determine the characteristics of plant life, based on gas exchange in the leaves (photorespiration) [12-14]. However, such techniques are useless in coniferous forests. It has a high cost. At the same time, it is difficult to rely on statements that such measurements can be carried out throughout the year, because gas exchange occurs actively in foliage during the summer months in forests located in the most part of Russian Federation. Thus, the engineering of a device that would monitor the vital activity of plants during the year would take the methods of the forests state forecasting to a new level. Moreover, the ability to measure the response of plant state to changes on environmental
factors would make it possible to create models for predicting fluctuations of this state under the influence of external factors. To create such a device, it is necessary to determine, what physical characteristic of the aqueous solution transport should be measured, how to compare its value with changes in temperature and humidity of the environment, what construction of the automatic device should be chosen.

Earlier, we had proposed a multilayer concept of forests and a formalized model for assessing the relative moisture content in each layer [15]. The parameters of layers' state are interconnected. Therefore, monitoring the one of layers' state with controlled accuracy would allow us to develop a dynamic system for monitoring the state of forests. It was shown [16, 17] that measured in trunks of woody plants potential difference is an indicator of the trunk xylem state and depends on the moisture content and fluctuations in the ambient temperature. Thus, it had proposed to choose this quantity as the basis of the methodology for monitoring the one of layers' state with controlled accuracy. It is efficient to use digital tools for measuring the potential difference in tree trunks. It has high noise immunity and compatibility with computers and the ability to transmit information over long distances. The latter property is especially important when organizing modern fire safety systems [18, 19].

The purpose of the work is the substantiating of digital device operation principle for measuring the potential difference in tree trunks as a device for studying its state. According to our ideas, the substantiation should include an analysis of temperature fluctuations throughout the year, a theoretical concept of the influence of temperature and humidity fluctuations on the potential difference in the tree trunks and the principal scheme of the device.

2. Theoretical part

2.1. The analysis of temperature fluctuations throughout the year

According to general concepts, temperature fluctuations are stochastic. According to the monitoring data of the Gismeteo [20], we analyzed the average daily temperatures of the day and evening in each month over the past few years. Based on this analysis, interesting conclusions can be drawn that can lead to a fundamental concept of ideas about the processes that occur in forests during the year. The example of average daily temperatures distribution on the day and evening and the average difference of these temperatures by months during 2018 in Voronezh is shown in figure 1 (the numbers indicate the numbers of months starting in January).

![Figure 1. Analysis of monitoring data on the average daily temperature of the day and evening during 2018.](image)

Note that the data for 2018 are quite typical for our region (with the exception of a slightly low average daily temperature in March). It shows that the average temperatures of the day and evening...
practically coincide in November and December, are quite close in value in January and February, and most differ in August. If we will conduct a statistical analysis of the probability that the temperature difference of the day and evening during each month will be greater than 8 °C or equal to it, then an interesting regularity can be found for the value of the most probable difference of the analyzed temperatures. The most likely value ranges from 1-3 °C from November to February. Then, a rather smooth increasing to 5 °C occurs in March and April and an increasing to 8-10 °C is observed in August. After such a surge, the value of the most probable temperature difference for the day again returns to 1-3 °C (dashed line in the figure).

Such behaviour of the analyzed value correlates with changes in the phases of plants' vital state. The intensive movement of salts' ions in the trunks of plants and foliage formation processes take place from March to June. It can be established by electrical measuring instruments. In June and July, an active evaporation process occurs in the foliage, it leads to the occurrence of transpiration currents. In August, the foliage becomes transparent, and the role of transpiration currents is significantly reduced. The probability distribution \( P(\Delta t) \) of large changes in the temperature of the day and evening (\( \Delta t \geq 8 \) °C) during the year 2018 is shown by circles in figure 2. The dependence \( P(\Delta t) \) is nonlinear and has two maxima. This character of the dependence can be explained by the influence of the day length increasing and the associated increasing of average daily temperature in the first half of the year.

Theoretically, the resulting dependence \( P(\Delta t) \) can be explained on the basis of long-term studies [16, 17]. According to the study results, the potential difference is formed in the trunk xylem along the radius at increasing of daily temperature difference due to the piezoelectric and pyroelectric properties of wood. This potential difference is directly proportional to the temperature difference. It changes with a decreasing of the radius of the barrel. Therefore, a thermally stimulated electric field is also formed along the barrel. Salts' ions of a weak electrolyte aqueous solution begin to move orderly to the top under the influence of the forces of this field. Therefore, the probability distribution of significant temperature changes (\( \Delta t \geq 8 \) °C) shows the period of occurrence of such currents. The share of such temperature differences increases since April. But in May, foliage is finally formed, and processes that stimulate the evaporation of moisture and lower the ambient temperature begin. Therefore, the expected increasing of the significant temperature differences' probability is not observed in the forest during the day. In the framework of this approach, the distribution function \( P(\Delta t) \) can be modeled as the difference:

\[
P(\Delta t) = \begin{cases} P_{\text{even}} & \text{if } \Delta t < 1 \text{ or } 1 < \Delta t < 3 \\
P_{\text{high}} & \text{if } \Delta t \geq 8 \\
0 & \text{otherwise}
\end{cases}
\]
\[ P(\Delta t) = P_1(\Delta t) - P_2(\Delta t), \]  
where \( P_1(\Delta t) \) is the probability distribution of significant temperature changes of the day and evening \((\Delta t \geq 8^\circ C)\), \( P_2(\Delta t) \) is the probability distribution of temperature differences caused by abundant evaporation of moisture by leaves. If we assume that both of these distribution functions in relation (1) are normal (correspond to the Gauss function) in time, then (1) can be rewritten in the form:

\[ P(\Delta t) = P_0 \left[ \exp \left( \frac{t-t_1}{2\sigma_1} \right) - \delta \exp \left( \frac{t-t_2}{2\sigma_2} \right) \right], \]

where \( P_0, \delta, \sigma_1, \sigma_2, t_1, t_2 \) are parameters characterizing the maximum value and variance of each distribution. Using relation (2), the dependence \( P(\Delta t) \) was simulated (solid line in the figure 2), which is in good agreement with the monitoring data (mean square deviation does not exceed about 4%) for the following parameter values: \( P_0 = 100\%, \delta = 0.81, \sigma_1 = 2.25 \) months, \( \sigma_2 = 0.75 \) months. The distributions of \( P_1 \) and \( P_2 \) have peaks in the second and first half of July (6.8 and 6.2 months from the beginning of the year), respectively. As a result of the above reasoning, it can be assumed that two processes occur during the period of high activity of plants: transpiration and the emergence of a thermostimulated electric field in the trunks' xylem at temperature changes during the day. Both of these processes will lead to a redistribution of salts' ions along tree barrel, that will affect the potential difference along the barrel. Thus, changes in the potential difference will be formed under the influence of environmental factors such as temperature and humidity.

### 2.2. The formalized model for assessing the potential difference in the xylem of tree trunks

The processes that form the potential difference in the xylem of the woody plants' trunks lead to a redistribution of charges due to inelastic collisions of salts' ions with water molecules. A similar process had described in detail for modeling molecular processes under the influence of the electric field caused by the ambient temperature changes in [15, 16]. In the case of transpiration currents, the model can be applied with the correction that now salts' ions will be carried away by water molecule at the inelastic shock due to intermolecular interaction. It must be understood that the charge distribution forms the potential difference in both processes. And this potential difference is directly proportional to the value of the “divided” charge \( dQ \) in the system:

\[ U = \frac{dQ}{C}, \]

where \( C \) is a quantity that depends on the characteristics of the processes of charge distribution, and it is called capacity in physics. We can assume that \( dQ = Q_i N \) in the distribution of salts' ions, where \( Q_i \) is the ion charge, \( N \) is the number of ions participating in the nonuniform distribution along the barrel, then

\[ U = \frac{Q_i N}{C}. \]

Depending on the influence of external factors, the rate of change in the salts' ions fraction \((dN/N)\) is not a constant value of \( \eta \) in any part of the tree trunk. It decreases with increasing \( N \), because any system tends to a balance condition. Therefore, the following relation is valid for charge redistribution processes in the tree trunk xylem

\[ \frac{dN}{Nd\tau} = \eta - \mu N, \]

where \( \mu \) characterizes the stabilization process. If we take into account that ions are always present in the xylem at the initial moment of time, i.e. \( N = N_0 \) at \( \tau = 0 \), then equation (5) has an analytical solution

\[ N = \frac{N_0 e^{\eta t}}{\eta + \mu N_0 (e^{\eta t} - 1)}. \]

The relation for the potential difference is obtained from (4) taking into account (2)
\[
U = \frac{U_0e^{\eta}}{\eta + \mu N_0(e^{\eta} - 1)}.
\]  

3. Results and discussion

The potential difference had measured between points located along tree trunks at distances of 1.3 m and 3 m from the earth's surface. Trees grew on the territory of the Pravoberezhnoe forestry of the experimental forestry enterprise Voronezh State University of Forestry and Technologies named after G F Morozov. The potential difference in the trunks of the experimental trees' monitoring took place during daylight hours with an interval of one hour. Observations were carried out in spring (March) and in summer (July) [15-17]. The instruments and measurement method had described in [16].

The potential difference monitoring data along trunks are given for *Betula pendula* family trees of different vital state aged 34 to 50 years in figure 3. The measured potential difference depends on the characteristics of the xylem substance and the vital processes' course of the trunk biosystem [17]. Thus, the results of the potential difference observations suggest that redistribution of salts' ions occurs in the xylem of tree trunks under the influence of the main environmental factors. It can be observed by measuring the potential difference. Since the potential difference in the xylem of woody plants' trunks is quite stable over time (figure 3) than its measurements can be carried out using a standard scheme for measuring the voltage between the electrodes (figure 4) [21].

The principal scheme includes a microcontroller, an ADC, a display device, and a data recorder. A similar scheme can be implemented on the basis of modern digital equipment. The difficulty lies in reducing interference and selecting a specific element base. This task is the subject of further study. The decision to select the element base requires testing the device in natural conditions.

As the result of the study it can be argued that:

1) Fluctuations in the temperature difference between day and evening are largely determined by the processes of increasing solar activity and water evaporation by leaves of woody plants from May to September.

![Figure 3. Typical daily dynamics of potential difference along the trunks of birches of different vital state.](image-url)
2) Caused by the activation of transpiration and thermally stimulated electricity, the redistribution of salts' ions occurs in the woody plants trunks from May to September.

3) The redistribution of salts' ions can be investigated by measuring the potential difference along the tree trunk.

4) It had experimentally established that measured along the birch trunks potential difference is quite stable in time and sensitive to fluctuations of ambient temperature.

5) It can be assumed with a high degree of certainty that the potential difference along the trunks of woody plants is a response of the state of a woody plant to environmental factors' changes.

6) The physics of the potential difference formation processes allows you to simulate the value of the potential difference depending on the properties of each individual. The parameters of the model have a clear physical meaning.

7) A principal scheme of a digital device for measuring the potential difference can be built on the basis of voltage measuring circuits between the electrodes.

8) The proposed by us approach differs from the approaches considered in the works [4-14, 18, 19] as a matter of principle.

4. Conclusion
The result of the studies has been the substantiation of the operation principle for the potential difference measuring device along the woody plant trunk. And arguments have presented in favor of the assumption that the measured quantity is formed by the processes of charge redistribution caused by changes in environmental factors such as temperature and humidity.

Thus, in the presented results, the new method of monitoring the response of the state of woody plants on fluctuations of environmental factors (temperature and humidity) with the help of electrical measuring instruments has substantiated. The principle of device operation has based on fundamental theories of physics. And the measurement results have analyzed using a formalized model with parameters having a clear physical meaning.
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