University of West-Hungary

PhD thesis

Variations of the natural electric potential differences occurring on tree trunks and their relationship with the xylem sap flow

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Sopron

2004

1. The research objective and its history

Scientist are more or less familiar with factors affecting the growth and life functions of living creatures. A significant portion of those factors has already been connected to various biological phenomena of the flora and animal kingdom. Periodically, a need arises to simply monitor the different phenomena in plants, for example, to gain information on the health of a tree through a measurement of a single parameter.

The bioelectric phenomena of plants were intensively studied in the 1950's and 60's all over the world. (Such investigations were also conducted at the university in Sopron: Etele Csanády carried out experiments to discover a correlation between the growth of a tree and its measurable electric potential.) In the 1990's the examination of these phenomena gained a new momentum with the advent of computerized data gathering. In 1992 Morat and his colleagues at the Paris Geophysical Institute measured the electric potential differences in the trunk of an 80 years old horse-chestnut tree, using two parallel channels of electrodes, during a two-month period. This study had mainly geophysical purposes. They tried to find the cause of distorted telluric measurements if the telluric electrodes had been placed close to a living tree. The author of this dissertation replicated that experiment when he measured electric potential differences between 1995 and 1996 at the Botanical garden of Sopron University by placing two parallel electrode pairs on the trunk of a young beech tree (*Fagus sylvatica* L.).

Despite earlier investigations, the methodology of measurement of the electric field that accompanies the life functions of an organism is still undeveloped, especially, in regard to the electric field pertinent to the whole plant and not only its cells. There are still experiments to be carried out to determine the relationship between the life functions of the tree and the measured electric potential difference. Furthermore, the effect of the environment on the electric potential difference is still ambiguous. Therefore there is still a demand for observations of trees in their environment, in a unified system.

While planning the research for this dissertation the main purpose was the investigation of the temporal and spatial variations of electric potential differences measured on the tree trunk. It was also necessary to find out how these changes can be observed, since previous works and similar experiments showed that the use of a double electrode pair is insufficient for such an experiment.

After determining the variations of the electric potential differences and their characteristics the next step was to define which internal processes or phenomena might be the source for the formation and changes of the electric potential differences. The most important task was to determine correlation between the electric potential difference and the xylem sap flow.

An additional goal was to ascertain which environmental parameters might also influence the electric potential difference if those internal processes can not fully explain the changes. This essentially means the revelation of the relationship between the tree and the environment through electrical measurements.

2. Methodology of experiments

Measurements

The electric potential differences were continuously measured between 17.05.1997 and 28.02.2002 at the Széchenyi István Geophysical Observatory. For the measurements 16 electrodes were implanted into the trunk of a ca. 40-year-old Turkey oak (*Quercus cerris* L.) Through a period of six months, measurements were carried out simultaneously on two trees. Since there is no precedent in the scientific literature, the measuring system was a definite innovation. The measuring electrodes were placed at four different levels (at 2 m intervals from the ground level to a height of 6 m) and in different directions (corresponding to the four points of the compass). Thus, the measurements did not only record the electric potential difference between electrode pairs implanted in tree trunks, as was the case in experiments of Morat and his colleagues, but they recorded the electric potential difference between the ground-based electrode and any single electrode. This made possible the measurement of the electric potential difference between any two electrodes.

The sap flow was measured with the help of an instrument designed on the basis of a Granier-type radial flowmeter. The heating elements of the thermocouples were placed in holes drilled in the sapwood 1 m above the ground, in the four directions of the compass. The reference probes were implanted 15 cm below them. The speed of the sap flow was measured between 14.07.1999 and 27.12.1999.

The meteorological parameters (temperature, relative humidity, wind speed, radiation and precipitation) were provided by the meteorological station of the Observatory. The atmospheric electric potential gradient and the geomagnetic and telluric data series also came from the measurements at the Observatory.

Processing of the data

The measurement of the electric potential difference yielded a much longer and sustained data than previously known. The gathered data were then put through time series and correlation analysis by the author. Similarly, the thermometric sap flow was also underwent a time series analysis. The correlation between the electric potential difference and sap flow data, as well as the environmental parameters was determined by factor and regression analysis.

3. Summary of new scientific results

I. The author developed a system capable of continuously observing the electric potential difference on tree trunks.

Based on earlier experiments, the developed multi-electrode system is able to record the spatial and temporal variations of the electric potential differences on a tree trunk. The permalloy electrode (Ni/Fe – 80/20) has a low contact resistance and destroys the xylem vessels due to its geometry as little as possible. The electrodes were put into the sapwood at different levels and at each level in different orientations. The high resistance ($R \geq 10^{10}\ \Omega$) differential amplifier is an important part of system. This prevents a distortion of the incoming signal. The reference electrode is made out of lead, which when placed at the right depth in the ground, has a low and almost constant transition resistance. The sensitivity of the system is 10^{-5} V (the measured electric signals are of an order of mV's). The sampling interval is 1 sec. and 1 minute average values are recorded.

II.a The author got detailed spectra amplitude vs. period in the period range 1 minute-1 year by the statistical analysis of the electric potential difference data.

A summary of new results related to short and medium period range (few hours and daily) changes

The electric potential differences on tree trunks change over time. The most noticeable mid-range variation is the regular daily fluctuation whose amplitude is a few tens of mV. The daily activity is most likely related to the transpiration's daily rhythm. This daily movement has a morning (6-7 h LT) maximum and an afternoon (15-17 h) minimum. At certain times, verifiably due to storm activity, the maximum and minimum reverse their position. The duration of the phase changes is one or two days at most, and can be observed on all channels. (There were however, phase changes with a duration of a few weeks that were only observed on a single channel.) The 24-hour variations are complemented by periods of 12 hours, and often but not always, by periods of 8 hours. The amplitude of the 12-hour period is about a third of the daily variation. In the case of the 8-hour period, it is about a fifth-tenth of it. No data related to this short period variations can be found in the literature.

A summary of new results related to long period range changes

The analysis of the longest continuous (about 8 months) and complete data sequence did not show changes over periods longer than 24 hours that would appear on all channels. (This result does not appear to support the conclusions of authors who established a 27 day period in their electric potential difference data series measured in living trees that could be related to the Moon's gravitational force.)

An analysis of a two-year (13.08.1997-30.09.1999) electric potential difference data sequence shows a maximum in winter and early spring, as well as a minimum in summer and early autumn. According to the author the seasonal fluctuation is a result of the change of the tree's specific resistance.

II.b. The author showed the changes of the amplitude of the 24-hour period during a year by the statistical analysis of the electric potential difference data.

The amplitude of the daily variation of the electric potential differences changes over time. The average amplitudes of 32 samples, collected over a two-year period (November 1997-October 1999) provided a seasonal change of the amplitude of the daily variation. Analyzing the four channels from the 6 m level separately, one can observe that outside the vegetation period, in the dormant period, the channels show roughly similar results: the average amplitudes are less than 5 mV in this period. During frondescence the amplitude of daily variations rises overnight. Some channels reach a maximum amplitude of 25-30 mV (the value of the maxima depends on meteorological conditions of the given year: in 1999 the maxima reached only half of the levels from 1998). During maximum transpiration, in June and early July, a second peak is observed in both years 1998 and 1999. On some channels this second peak appeared with a delay and with higher amplitude than the spring one. (In late August and September some channels had also a third, local peak with an amplitude less than the spring and summer peaks.)

II.c. The author showed a heterogeneous spatial distribution of electric potential differences in the trunk of a standing tree by the analysis of the electric potential difference data.

The electric potential differences, measured at different levels and directions, are similar. However, there are some differences. Correlation and cluster analysis based on four, 16-channel data sequences gathered over a few months, show that the most likely reason for the differences between the channels is structural inhomogeneity. The hydroactive xylem section is very thin, practically a few rings of cells, and it is very susceptible to embolization and cavitation. Observations showed that the transportation is going on in a very complex, three-dimensional network, in the direction of the lowest hydraulic resistance. (In this system the hydraulic resistance can be affected by many factors, such as temperature, ion content of the transported sap, mechanical damage, etc.)

The studies carried out for the determination of differences depending on the position of the electrodes (level and direction) show that the channels on the eastern side reach earliest the maximum (6:32±43 min) and the minimum values (15:09±34 min) as well as the channels of the western side reach latest the minimum values (17:29±09 min). There is no significant difference between the southern and northern channels (maxima: 7:11±26 and 6:54±26 min; minima: 16:22±51 and 16:28±43 min).

III. The author proved the relationship between the electric potential differences measured on the trunk and the xylem sap flow.

The thermometric sap flow data series has similar periodicities (24, 12 and 8 hour periods) to the electric potential difference. (These results are supported by a cross-spectral analysis of sap flow and electric potential difference data). The 24 hour period reaches its minimum around 6-7 h and its maximum at noon. The daily amplitude has a seasonal variation affected by the weather and in the observed time period it was similar to the seasonal changes of the electric potential differences. Similarly, long-range observations did not show any regular change in periods longer than one day.

The correlation analysis of the sap flow and electric potential difference data showed a firm connection between the two data series. This proved experimentally the relationship between the electric potential difference and sap flow. In the scientific literature so far, there is no hint of a research that would measure and compare these two parameters

According to cross-correlation analyses the electric potential differences follow the changes of the sap flow with a delay of few hours. The most likely reason for this phase lag is the change of the conductivity of the xylem sap (depending on the ion content and temperature.) This phenomenon does not have a significant influence on the measurement of the thermometric sap flow; however, it does have a considerable effect on the electric potential difference. The author supports this with a circumstantial evidence. An experiment carried out in Vienna on cut-down stem segments showed a linear connection between streaming potential and sap flow when conductivity is constant. In contradiction to this, the quotient curve of the potential differences and of the flow speed on the observed trunk, show a definite daily periodicity. This would imply the conductivity of the sap has also a daily variation. Whether this is caused by a daily change of the concentration or temperature is still unknown.

IV. The author revealed the relationship between the electric potential difference and environmental factors by statistical evaluation.

Due to a lack of understanding of the changes of the ion content of the xylem sap, it is difficult to describe the electrochemistry (streaming potential, electrode potentials, and concentration potentials) of the electric potential differences. However, it is possible to identify the environmental factors that directly or indirectly (through the sap flow) affect the electric potential differences with the help of multi-variate data analysis (factor and regression analysis).

In the first step, the author determined by factor analysis those environmental factors (first of all temperature, relative humidity, radiation and atmospheric electrical potential gradients) that have the closest relationship with measured electric potential differences.

Regression models including electric potential difference as a dependent variable and sap flow as well as environmental parameters, as predictors showed how different variables affect the electric potential changes. Namely, amongst the environmental parameters temperature, relative humidity, atmospheric electric potential gradients and telluric currents have the closest statistical relationship with electric potential differences. The first two of these factors affecting transpiration appear with higher regression coefficients than the latter two, which most likely have only slight effect on the electric potential differences.

The assessment of the results is made difficult by the fact that the effects of many external and internal factors appear simultaneously which makes it impossible to separate them.

4. Utilization of the results of the dissertation

Results obtained by this analysis provide us with new details on the transpiration and sap flow of the Turkey oak. They provided indirect information into such, thus largely unknown phenomena, as the change of the conductivity of the xylem sap. Besides the theoretical value of this results, the measuring method of the electrical potential difference, in conjunction with the empirical formula determined by regression analysis, may be used in the future for the determination of the sap flow. It has to be noted, though, that compared with thermometric measuring techniques, the measurement of the electric potential difference in its present form is much more affected by environmental factors, noises. Therefore, it can be mostly applied in electrically noiseless and precipitation free weather conditions.

5. Directions for further research

The most pressing problem in the study of the electric potential difference is that a solution has to be found for the monitoring of xylem sap element composition. This would enable the determination of the electric potential difference by electrochemical phenomena, thus enabling the creation of a much more detailed model. Additional physical and chemical observation of the sap flowing in the xylem vessels, as well as its better understanding (in respect to the electro osmosis, for example) is also necessary in order to be able to use the measurement of the electric potential difference as a tool for the estimation of sap flow in plants.

To be able to grasp the effect of the structure of a tree, measurements of the electric potential difference should be supplemented with some type of tomographic method. The most reasonable procedure would be mobile computer tomography (CT), which would enable us the measurement on every level from time to time. An alternate to the CT, though much more inaccurate solution, would be the development of an impendence tomograph, that could gather information on the specific resistance and thus the spatial distribution of the humidity in the trunk.

The measurement of the electric potential differences should be extended to other species in form of simultaneously accomplished measurements. This would enable us to determine by species the parameters of the empirical relations suitable for the estimation of the sap flow.

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