Local Variability of Electric Potential Differences on the Trunk of *Quercus cerris* L.

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Abstract – Electric potential differences (EPD) had been continuously recorded for four years from 1997 until 2001 between electrodes inserted in sixteen selected sites of the trunk of a turkey oak (*Quercus cerris* L.). In our earlier paper (Koppán et al. 2000), by using this method we revealed the annual variation of amplitudes of diurnal sap-flow fluctuation. In this paper a comparative analysis is carried out in order to study the local variability of sap-flow within the trunk. Values of EPDs were compared at four different height levels and four different exposures of the trunk. A significant difference can be shown between the channels of Eastern and Western side, while the deviations between the height levels are slight. The most likely reason for the differences between the channels is structural inhomogeneity.

electric potential difference / *Quercus cerris* / bioelectricity

Kivonat – Elektromos potenciálkülönbségek lokális változása *Quercus cerris* L. törzsén. 1997-től négy éven keresztül mértünk elektromos potenciálkülönbségeket egy csertölgy (*Quercus cerris* L.) törzsébe ültetett tizenhat elektród segítségével. Egy korábbi dolgozatban (Koppán et al. 2000) kimutattuk a napi fanedv-áramlás amplitúdójának éves változásait. Ebben a tanulmányban az egyes csatornák összehasonlító elemzését mutatjuk be. Azt vizsgáljuk, hogy az elektromos potenciálkülönbségek (EPD) a fatörzs négy magasságszintjén, és a négy égtáj szerint hogyan különböznek egymástól. Szignifikáns különbség mutatható ki a keleti és nyugati oldal csatornái között, míg a szintek szerinti különbség csekélynek mondható. A csatornák közt tapasztalt különbségek legvalószínűbb oka a fatörzs szerkezeti inhomogenitása.

elektromos potenciálkülönbség / csertölgy / bioelektromosság

1 INTRODUCTION

Bioelectric phenomena at tissue and organism level are sometimes less known in plants than in animals, although the problem of plants seems to be simpler than that of animals or humans. Electrical measurements on plants especially on trees have proven to be very difficult. Investigation of bioelectric phenomena of trees became widespread at first in the fifties and sixties (e.g. Fensom 1962), then in the early '90s, when automatic measuring techniques became available. One of such studies was the experiment carried out by Morat et al. (1994) at the Earth Physics Institute of Paris. (This experiment was motivated

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merely by geophysical considerations. Namely, that the natural telluric field is strongly distorted in the vicinity of trees.)

Our first project on this subject (in 1995) was a direct adaptation of the French experiment (Koppán et al. 1999). Based on these experiments we planned a new research which was started in 1997. We continuously measured electric potential differences (EPD) by using electrodes inserted into the sapwood of turkey oaks (*Quercus cerris* L.) for four years. The experiment was completed later with a direct measurement of sap-flow by using Granier's radial flowmeter technique (Granier 1987). Most important environmental parameters such as temperature, air humidity, atmospheric electricity, geomagnetic and geoelectric field were also recorded.

The main purpose of this research was the investigation of the temporal and spatial variations of electric potential differences measured on the tree trunk. After determining the variations of the electric potential differences and their characteristics the next step was to define which internal processes and environmental parameters might be the source for the formation and changes of the electric potential differences. On the basis of the correlation between EPD and sap-flow, a new sap-flow monitoring method can be developed.
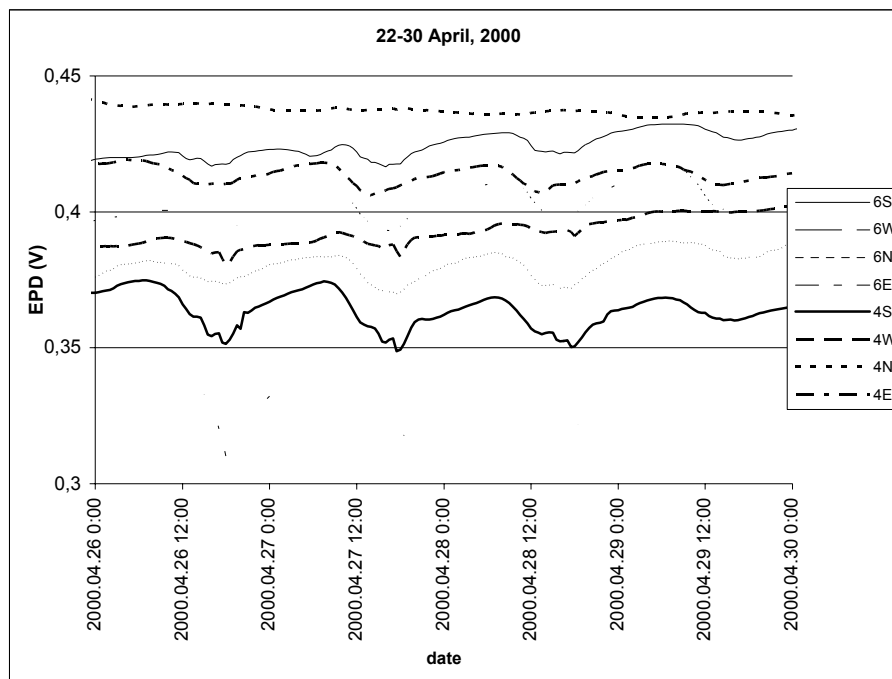

Figure 1. Sample data series of measured EPDs (26-30. April, 2000).

Previously we observed characteristic daily variations *(Figure 1)* and an annual fluctuation of the mean amplitude of these diurnal variations (Koppán et al. 2000a). We found a remarkable correlation between EPD and the sap flux density data, indicating, that sap streaming due to transpiration and root pressure generates the largest part of measured potential differences (Koppán et al. 2000b, Koppán et al. 2002). In all these papers the measuring channels were considered together. Their mean value was used to determine the typical behavior. Although the general characteristics of the observed daily variations are similar for each channel, there are slight differences between them.

In the present paper we investigate the spatial variations of EPDs, namely how the EPDs measured by single channels differ from each other, how significant these differences are, and whether some regularity in these differences is discoverable or not. We also investigate how the position (height, exposure) of electrodes – independently of other factors – can affect the EPDs.

2   MATERIALS AND METHODS

The EPD measurement were started in the "Széchenyi István" Geophysical Observatory of Hungarian Academy of Sciences, on 14 July, 1997. As shown in *Figure 2*, sixteen non-polarizing electrodes were inserted beneath the cambium into the sapwood of a turkey oak (*Quercus cerris* L.) at four height levels (at 0, 2, 4 and 6 m), and at each height level four electrodes (corresponding to S, W, N and E sides of the tree) were installed. The EPDs were measured between the trunk electrodes and a common ground. The sampling interval was kept as short as 1 sec, and 1 minute mean values were continuously recorded.

In order to determine the local variability of EPD on the trunk, we carried out a comparative analysis, by using four time intervals, each of them lasting several months *(Table 1)*. As a first step we computed the Pearson's correlation coefficients (see formula 1) between each possible pairs of the 16 measuring channels *(Tables 3-6)*.
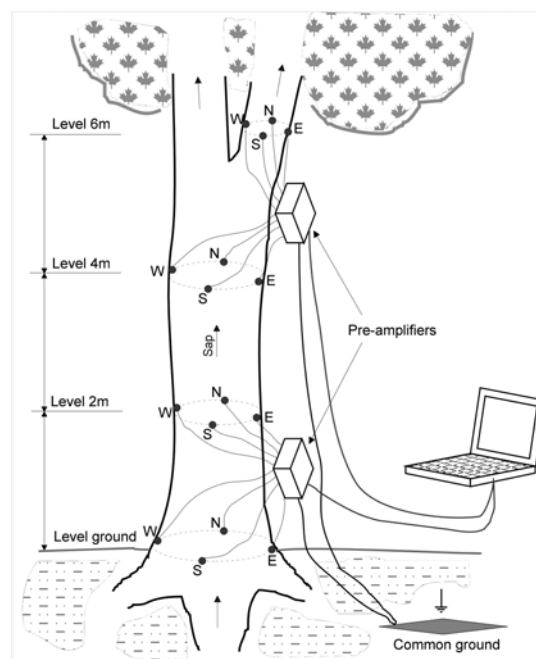
Figure 2. The EPD measuring system

$$\rho_{x,y} = \frac{\text{cov}(x,y)}{\sigma_x \cdot \sigma_y} = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \overline{x})^2} \cdot \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \overline{y})^2}} \qquad (1)$$

Table 1. Time intervals for correlation analysis (sampling interval=30 min)

Sample number	Date	Data number/channel
1	07 May – 21 November, 1998	9532
2	16 January – 31 May, 1999	6528
3	15 July – 31 December, 2000	7776
4	01 January – 16 May, 2001	6528

Correlation matrices give information only on the overall relationship between channels. In order to study possible time processes, a time delay study was also carried out. Thus, as a next step we investigated the effect of the exposure and of the height of electrodes on the time series of EPD daily variations. For this purpose eight (at least six day long) time intervals having sunny and undisturbed weather conditions were selected *(Table 2)*.

Table 2. Time intervals for investigation of the effect of the exposure (sampling interval=1 min)

Sample number	Date	Data number/channel
5	07-15 May, 1998	12960
6	08-20 August, 1998	18720
7	01-07 April, 1999	10080
8	12-20 September, 1999	12960
9	22-30 April, 2000	12960
10	10-21 August, 2000	17280
11	23-30 April, 2001	11520
12	14-19 August, 2001	8640

3 RESULTS

3.1 Correlation coefficients between any two ones of the 16 channels

Pearson's coefficients are shown for the time intervals 1, 2, 3, and 4 in *Table 3, 4, 5 and 6*. It is clearly seen that a strong correlation exists between different height levels and between different exposures, but the correlation values are not constant with time.

Table 3. Pearson's correlation coefficients of the 16 channels (07 May – 21 November, 1998)

	6S	6W	6N	6E	4S	4W	4N	4E	2S	2W	2N	2E	0S	0W	0N	0E
6S	1															
6W	.843*	1														
6N	.721*	.679*	1													
6E	.748*	.698*	.555*	1												
4S	.369*	.386*	.425*	.266*	1											
4W	.080*	.093*	.252*	.089*	.871*	1										
4N	.575*	.506*	.366*	.457*	.648*	.375*	1									
4E	.254*	.314*	.310*	.381*	.812*	.740*	.566*	1								
2S	.508*	.395*	.358*	.250*	-.734*	-.720*	-.094*	-.767*	1							
2W	.123*	.109*	.318*	-.118*	-.580*	-.406*	-.662*	-.696*	.699*	1						
2N	.235*	.131*	.336*	-.098*	-.482*	-.454*	-.255*	-.575*	.589*	.661*	1					
2E	.225*	.256*	.349*	-.026*	-.537*	-.472*	-.400*	-.611*	.651*	.826*	.602*	1				
0S	.558*	.521*	.324*	.353*	-.399*	-.690*	.497*	-.249*	.469*	.096*	.364*	.376*	1			
0W	.235*	.207*	.443*	.119*	-.439*	-.356*	-.517*	-.425*	.573*	.800*	.722*	.740*	.282*	1		
0N	.398*	.292*	.287*	.101*	-.703*	-.760*	.007*	-.693*	.771*	.602*	.731*	.701*	.691*	.624*	1	
0E	.331*	.270*	.322*	.099*	-.523*	-.538*	-.083*	-.577*	.676*	.629*	.692*	.757*	.640*	.710*	.823*	1

  * Correlation is significant at the 0.01 level (2-tailed).
  N=9532/channel

Table 4. Pearson's correlation coefficients of the 16 channels (16 January – 31 May, 1999)

	6S	6W	6N	6E	4S	4W	4N	4E	2S	2W	2N	2E	0S	0W	0N	0E
6S	1															
6W	.923*	1														
6N	.941*	.890*	1													
6E	.953*	.891*	.877*	1												
4S	.561*	.564*	.631*	.437*	1											
4W	.207*	.238*	.135*	.184*	.386*	1										
4N	-.076*	-.241*	.041*	-.054*	.025**	-.189*	1									
4E	.862*	.893*	.782*	.828*	.462*	.442*	-.340*	1								
2S	.926*	.899*	.930*	.839*	.728*	.248*	-.101*	.806*	1							
2W	.956*	.939*	.941*	.886*	.638*	.266*	-.149*	.883*	.962*	1						
2N	.817*	.787*	.881*	.732*	.765*	.210*	.084*	.675*	.892*	.868*	1					
2E	.938*	.917*	.911*	.898*	.604*	.247*	-.110*	.841*	.931*	.958*	.863*	1				
0S	.819*	.760*	.834*	.783*	.473*	-.139*	.090*	.624*	.766*	.795*	.724*	.817*	1			
0W	.849*	.872*	.828*	.842*	.269*	.088*	-.111*	.824*	.762*	.841*	.629*	.830*	.769*	1		
0N	.682*	.602*	.741*	.680*	.380*	-.250*	.332*	.423*	.620*	.636*	.664*	.676*	.875*	.675*	1	
0E	.684*	.633*	.737*	.683*	.512*	-.106*	.256*	.494*	.676*	.689*	.746*	.709*	.807*	.598*	.878*	1

  * Correlation is significant at the .01 level (2-tailed).
  ** Correlation is significant at the .05 level (2-tailed).
  N=6528/channel

Table 5. Pearson's correlation coefficients of the 16 channels (15 July – 31 December, 2000)

	6S	6W	6N	6E	4S	4W	4N	4E	2S	2W	2N	2E	0S	0W	0N	0E
6S	1															
6W	.139*	1														
6N	.789*	-.224*	1													
6E	.680*	-.372*	.919*	1												
4S	.847*	-.103*	.902*	.848*	1											
4W	.822*	.333*	.661*	.525*	.695*	1										
4N	.733*	-.092*	.867*	.785*	.857*	.659*	1									
4E	.907*	.163*	.792*	.654*	.853*	.891*	.783*	1								
2S	.869*	.067*	.822*	.744*	.906*	.810*	.809*	.905*	1							
2W	.811*	.353*	.657*	.523*	.736*	.866*	.648*	.855*	.842*	1						
2N	.915*	.059*	.859*	.755*	.909*	.828*	.834*	.949*	.935*	.842*	1					
2E	-.157*	.785*	-.422*	-.525*	-.304*	.036*	-.292*	-.125*	-.150*	.165*	-.189*	1				
0S	.902*	.069*	.825*	.750*	.899*	.820*	.795*	.912*	.920*	.821*	.926*	-.189*	1			
0W	.471*	.034*	.710*	.613*	.609*	.541*	.652*	.516*	.566*	.627*	.578*	-.007	.596*	1		
0N	.652*	.216*	.674*	.595*	.725*	.712*	.703*	.732*	.766*	.810*	.775*	.115*	.745*	.768*	1	
0E	.847*	.088*	.832*	.755*	.872*	.847*	.797*	.879*	.914*	.867*	.894*	-.125*	.915*	.688*	.837*	1

  * Correlation is significant at the 0.01 level (2-tailed).
  N=7776/channel

Table 6. Pearson's correlation coefficients of the 16 channels (01 January – 16 May, 2001)

	6S	6W	6N	6E	4S	4W	4N	4E	2S	2W	2N	2E	0S	0W	0N	0E
6S	1															
6W	.641*	1														
6N	.708*	.732*	1													
6E	.796*	.710*	.925*	1												
4S	.698*	.692*	.892*	.879*	1											
4W	.682*	.861*	.662*	.684*	.641*	1										
4N	.446*	.802*	.717*	.663*	.714*	.781*	1									
4E	.487*	.742*	.756*	.698*	.684*	.720*	.768*	1								
2S	.335*	.033**	.370*	.390*	.441*	.044*	.209*	.094*	1							
2W	.454*	.646*	.549*	.518*	.619*	.586*	.686*	.590*	.326*	1						
2N	.528*	.548*	.798*	.738*	.849*	.460*	.634*	.549*	.567*	.586*	1					
2E	.442*	.844*	.563*	.532*	.560*	.724*	.811*	.649*	.129*	.708*	.499*	1				
0S	.484*	.651*	.703*	.630*	.727*	.625*	.716*	.669*	.299*	.608*	.655*	.570*	1			
0W	.626*	.824*	.658*	.634*	.704*	.839*	.755*	.625*	.149*	.648*	.579*	.686*	.756*	1		
0N	.455*	.804*	.559*	.506*	.601*	.802*	.766*	.673*	.002*	.634*	.465*	.735*	.751*	.841*	1	
0E	-.187*	-.141*	-.422*	-.419*	-.386*	.030**	-.079*	-.174*	-.061*	.057*	-.291*	.011	-.047*	.028**	.141*	1

  * Correlation is significant at the .01 level (2-tailed).
  ** Correlation is significant at the .05 level (2-tailed).
  N=6528/channel

Two different, compact presentations of the correlation relationships are shown in *Tables 7 and 8*. In *Table 7* correlation matrices are shown for the four different height levels (when the mean value of exposures is considered), while in *Table 8* correlation coefficients are shown between any two exposures (N, E, S and W), when the height of electrodes is eliminated by the mean value of the corresponding channels. The correlation is strong between levels 0m and 2m, and also between 4m and 6m. Other coefficients may be small and sometimes change sign.

Table 7. Correlation between mean of the level-averages

Sample 1 (07 May – 21 November, 1998)

	6m_avg	4m_avg	2m_avg	0m_avg
6m_avg	1			
4m_avg	0.413	1		
2m_avg	0.290	-0.666	1	
0m_avg	0.390	-0.336	0.797	1

Sample 2 (16 May – 21 November, 1999)

	6m_avg	4m_avg	2m_avg	0m_avg
6m_avg	1			
4m_avg	0.755	1		
2m_avg	0.955	0.797	1	
0m_avg	0.888	0.556	0.846	1

Sample 3 (15 July – 31 December, 2000)

	6m_avg	4m_avg	2m_avg	0m_avg
6m_avg	1			
4m_avg	0.941	1		
2m_avg	0.844	0.912	1	
0m_avg	0.904	0.921	0.899	1

Sample 4 (01 January – 16 May, 2001)

	6m_avg	4m_avg	2m_avg	0m_avg
6m_avg	1			
4m_avg	0.894	1		
2m_avg	0.750	0.762	1	
0m_avg	0.680	0.813	0.663	1

Table 8. Correlation between mean values of exposures

Sample 1 (07 May – 21 November, 1998

	S_avg	W_avg	N_avg	E_avg
S_avg	1			
W_avg	0.666	1		
N_avg	0.900	0.644	1	
E_avg	0.813	0.693	0.760	1

Sample 2 (16 May – 21 November, 1999)

	S_avg	W_avg	N_avg	E_avg
S_avg	1			
W_avg	0.907	1		
N_avg	0.907	0.787	1	
E_avg	0.943	0.946	0.866	1

Sample 3 (15 July – 31 December, 2000)

	S_avg	W_avg	N_avg	E_átl
S_avg	1			
W_avg	0.763	1		
N_avg	0.946	0.75	1	
E_avg	0.954	0.823	0.956	1

Sample 4 (01 January – 16 May, 2001)

	S_avg	W_avg	N_avg	E_avg
S_avg	1			
W_avg	0.084	1		
N_avg	0.835	0.408	1	
E_avg	0.308	0.874	0.626	1

3.2 EPD time delays between different height levels and exposures

The maximum values of the daily curves of EPDs occur normally around 6-7 a.m., while the minimum values are in the afternoon, somewhere around 16-17 hours *(Figure 3)*. Usually the eastern channels reach the maximum first (6:32±43 min). They are followed by the northern, western and southern channels (6:54±26, 7:06±20 and 7:11±26 min respectively). In the afternoon hours the eastern channels reach the minimum at first (15:09±34 min), followed by the southern and northern channels (16:22±51 and 16:28±43 min respectively). In the afternoon it is the western side of the tree where the EPD has the largest time delay (17:29±09 min).
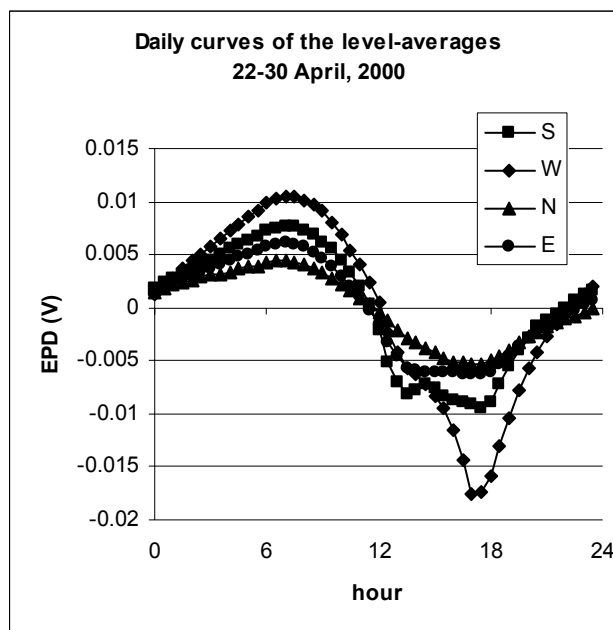
Figure 3. Typical daily EPD curves: four different height-averaged exposures.
Time interval: 22-30 April, 2000

Table 9.   Time of maximum and minimum positions as a function of exposure
(The values marked with * were considered as distorted and therefore they were
not taken into consideration)

Sample	Maximum position (hours)				Minimum position (hours)			
	S_max	W_max	N_max	E_max	S_min	W_min	N_min	E_min
5	0:00*	6:32	6:28	6:09	16:23	17:16	17:26	12:23*
6	6:30	0:35*	6:05	5:36	16:27	17:27	15:59	14:01
7	7:28	7:40	7:55	7:50	13:11*	17:56	16:43	15:21
8	8:19	7:48	7:41	7:44	17:28	17:28	14:18	15:24
9	7:00	6:59	7:06	7:04	17:36	17:11	17:19	14:50
10	6:49	6:54	6:46	5:35	16:57	17:33	16:01	14:57
11	6:59	7:04	6:46	5:06	14:29	17:27	17:17	12:45*
12	7:18	6:48	6:30	7:12	15:14	17:39	16:44	16:21
Average	7:11	7:06	6:54	6:32	16:22	17:29	16:28	15:09
St. deviation	0:35	0:27	0:37	1:03	1:08	0:13	1:02	0:46
Conf. interval (α=0.05)	0:26	0:20	0:26	0:43	0:51	0:09	0:43	0:34

In *Table 10* the effect of height levels is shown. Although it can be shown that on average the channels at the 4m height level arrive to their maximum and minimum values first (6:55±19 and 17:05±27 min respectively) and the channels at the 6m height level reach the minima last (17:31±27 min), the deviations are not fundamentally significant between the height levels.

Table 10. Time of maximum and the minimum position as a function of height level
*(The values marked with * were considered as disturbed, and therefore they were not taken into consideration)*

Sample	Maximum position (hour)				Minimum position (hour)			
	6m_max	4m_max	2m_max	0m_max	6m_min	4m_min	2m_min	0m_min
5	7:31	6:57	2:56*	2:34*	17:42	16:18	17:12	17:11
6	6:43	6:21	23:41*	23:37*	16:36	16:06	17:01	6:39*
7	7:55	7:32	7:43	7:57	18:06	17:34	17:42	17:37
8	8:58	7:03	8:15	23:48*	17:54	17:28	0:45*	0:56*
9	8:14	7:37	7:10	6:23	18:05	18:04	17:12	17:11
10	5:39	6:49	6:43	7:36	17:35	16:57	17:33	17:29
11	6:21	6:21	7:35	7:38	11:12*	17:04	17:24	17:30
12	6:31	6:42	7:24	7:45	16:45	17:10	17:12	16:41
Average	7:14	6:55	7:28	7:27	17:31	17:05	17:19	17:16
St. deviation	1:06	0:28	0:31	0:37	0:36	0:38	0:14	0:20
Conf. interval (α=0.05)	0:46	0:19	0:24	0:29	0:27	0:27	0:10	0:15

4   DISCUSSION

In our earlier papers we proved that the EPD curves show characteristic daily fluctuations, and their amplitudes have a characteristic annual variation. By means of direct sap-flow measurement we also proved that these EPDs are connected to the sap-flow.

The electric potential differences, measured at different levels and directions, are similar. However, there are some differences. Correlation 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. As a null-hypothesis we assumed that same quantity of sap flows across any chosen cross-section of the trunk. The path and sap-flow density can vary in the sap-wood (the individual xylem vessels transport different quantities of sap). The hydroactive xylem section is very thin, practically a few rings of cells (Granier et al. 1994), and it is very susceptible to embolization and cavitation. Observations showed that the transportation goes 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.) This hypothesis is confirmed by the fact that based on the correlation analysis we could not find any regularity in the deviations between the channels in the four years of the experiment. The correlations of the channels change from year to year and this presumes a yearly varying effect, which is the altering of the xylem-structure by the nascent annual rings.

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 the maximum and the minimum values the earliest and the channels of the western side reach the minimum values the latest. There is no significant difference between the southern and northern channels. The differences cannot be fully explained by the exposure and unfortunately it was not possible investigate the structural inhomogeneity.

Some details of the observed phenomena still remain unexplained. In the future we plan to study the external effect on EPD measurements in details.

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