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ANNUAL RING ANALYSIS OF THE ROOT SYSTEM OF SCOTS PINE

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ABSTRACT

The aim of the paper was to find a relationship (possibilities of synchronization) between the width of annual rings of a root system and the width of annual rings of the tree stem. The finding of a common signal between annual rings of a root, of the whole root system and of the tree stem should contribute to the better knowledge, description and use of roots as the source of a potential ecological registration. An annual ring analysis was carried out in the stem and root part of Scots pine (*Pinus sylvestris* L.). It has been found that annual ring curves of annual ring widths from particular horizontal roots can be very reliably synchronized. Annual ring curves of annual ring widths from a root system can be reliably synchronized with annual ring curves from the tree stem.

KEY WORDS: root system, annual ring, annual ring analysis, Scots pine, synchronization

INTRODUCTION

Very few attention was paid to problems of the annual ring analysis of a root system yet. We can find only few publications dealing width the problems. The aim of the paper was, thus, to find a relationship (possibilities of synchronization) between annual rings of a root system and annual rings of the tree stem. Glock (1937) was very pessimistic as for a possibility to obtain some ecological information from roots. According to his opinion roots do not provide nearly any ecological record which could be possible to read. Later, however, it succeeded to synchronize annual ring widths from the large roots of two Douglas fir trees in southern Arizona (Schulman 1945). In other studies, extreme growth changes were found within one root (Fayle 1968, Krause and Eckstein 1993).

The shape of roots and thus the course and form of annual rings is affected by the character of stress. A number of factors affects the shape of a cross section. Stress history of a tree is recorded in the form of root cross sections. Stress (pressure, tension) caused by wood bending is extreme particularly for primary roots and roots close to stem. Effects of bending stress result in the "eight-shaped" cross section of a root with symmetrical annual rings. Roots subject to tension stress create a circular cross section with regular centric annual rings. Under simultaneous effects of tension and bending stress the formation of eccentric annual rings occurs and, thus, eccentric cross section of a root (Mattheck and Breloer 1995).

Dendrochronological studies carried out on roots are very difficult because the anatomical structure of the root wood often markedly differs from the anatomical structure of the stem wood. As compared to annual rings of a stem limits of annual rings in roots are less distinct both on a macroscopic and microscopic level (Fig. 1). Missing and false annual rings represent a considerable problem for annual ring analyses. These annual rings are very frequent in roots (Wagenführ 1999, Schweingruber 1996).

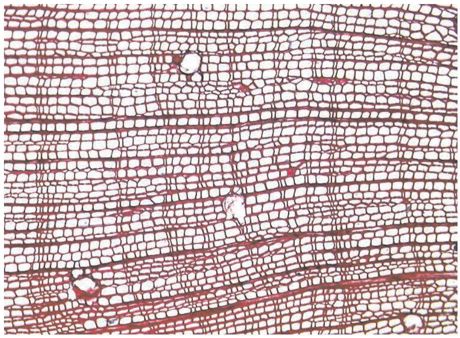

Fig. 1: The cross section of the Scots pine root 3.2 m from the tree stem

Variability of growth within roots causes sudden changes in the annual ring width. This phenomenon is very common as well as atypical growth structures visible on the cross section of roots. Annual ring widths in roots markedly change throughout years being very variable in particular parts of the same root (Fayle 1968, Krause 1992).

Annual ring widths along the horizontal root length are always narrow at a distance > 40 cm from the tree stem whereas at a distance of 10-35 cm, annual rings are always wide (Krause and Eckstein 1992).

MATERIAL AND METHODS

For the purpose of our research, one sample tree of Scots pine (*Pinus sylvestris* L.) was selected in Forest District Utechov (49° 14´ N; 16° 36´ E), Training Forest Enterprise Křtiny. The tree was felled and its root system was subsequently uncovered (Figs. 2, 3) by air flow using a special apparatus AIR-SPADE (Nadezhdina and Čermák 2003). Three disks 5 cm thick were taken from the tree stem 0.3, 1.3 and 5 m from the tree foot by means of a power saw. From five main horizontal roots ten samples were taken 5 cm thick at a distance maximally 35 cm from the stem foot. The samples were taken again by means of a power saw. One of the horizontal roots was taken in its whole length (8 m). From this root, samples were cut 0.2, 1.2, 2.2, 3.2, 4.2, 5.2, 6.2 and 7.2 m from the tree stem. Annual ring widths were measured on a cross section. In order annual rings to be well measurable the sample surface was machined by sanding. For this operation belt and disk sanders were used (Rybníček 2004). Where it was not possible to carry out measurements on macroscopic samples permanent microscopic preparations were made by standard methods (Vavrčík and Gryc 2004, Ives 2001).

Fig. 2: A general view of the Scots pine root system

Fig. 3: A detail of Scots pine horizontal roots

Sample measurements

Wood samples from the tree stem and samples from main horizontal roots taken at a distance of < 35 cm from the stem were measured on a special measuring table equipped with a sliding screw mechanism and an impulsemeter recording an interval of the table board shift and thus the annual ring width. From here, information is transferred to a computer which is equipped with PAST 32 program (Rybníček 2004). The sample was always measured from the wood pith (from the oldest annual ring) towards a periphery and always across the following annual ring, namely in two directions in the sample compression part. After the measurement and data storage, it is possible to observe the annual ring sequence in the shape of a curve and to correct possible errors in the measurement (Schweingruber 1983). Annual wood increments were measured accurate to 0.01 mm.

Microscopic preparations of samples taken from one main horizontal root 1.2, 2.2, 3.2, 4.2, 5.2, 6.2 and 7.2 m from the tree stem were evaluated using the LUCIA program. Values of annual ring widths measured on microscopic preparations were then transferred to the PAST 32 program.

Synchronization of curves

Synchronization of measured annual ring curves from particular samples was a following step after measuring the annual ring width. The curves always from one root were compared with one another. From well synchronized curves a mean curve was created for the given root. The mean curve will stress common extremes related to climatic changes and suppress all other oscillations caused by other effects (Cook and Kairiukstis 1990). Then, the synchronization was carried out of mean curves from particular main horizontal roots. An average curve for the whole horizontal root system was created from well synchronized curves.

The average curve of the whole horizontal root system created in such a way was synchronized with an average curve from the tree stem, namely both with curves from particular stem heights (0.3, 1.3 and 5 m) and with the average curve of the whole stem.

The program apposes average curves and looks for the highest values of statistic parameters. The rate of similarity between curves is assessed by means of a correlation coefficient and the "coefficient of synchronization". These calculations serve for the optical comparison facilitation of both curves which is decisive for final synchronization. If some of determined positions show a sufficient statistical value then both curves have to meet at the optical comparison in the majority of marked minima and maxima (Cook and Kairiukstis 1990).

Statistical calculations

a) Synchronization

This value represents a percentage of the directional coincidence of curves in the overlapping interval. Synchronization is calculated as follows:

1. Values are assigned to the curves by one-year intervals. Potential values are: –1 for the decreasing trend of a curve, 0 for stagnant trend and +1 for years with an increasing trend.
2. The second step consists in the comparison of digitalized values of the overlapping part and the sum of one-year intervals with the consistent trend of curves..
3. The number of consistent years to the number of all overlapping years gives a value of synchronization (0 to 100%).

Generally, the synchronization should not be lower than 55%. This test provides fast information if the value of synchronization (in the interval of overlapping the curves) is statistically significant or not.

b) T-Test

T-Test is based on the comparison of curves (in overlapping parts) as two data series. The rate of similarity is calculated by means of correlation and its statistical significance is assessed by the Student's t-test.

Original data are transformed before the actual statistical calculation. The transformation is necessary to fulfil statistical conditions which are required for using the t-test (normality of distribution, removal of autocorrelation). Both the tests mentioned below differ in the method of data transformation which are then used for the correlation coefficient calculation (PAST 2000):

Baillie/Pilcher transformation: Hollstein transformation:

$$ybp_i = \ln\left(\frac{5y_i}{y_{i-2} + y_{i-1} + y_i + y_{i+1} + y_{i+2}}\right) \quad yh_i = \ln\left(\frac{y_i}{y_{i+1}}\right)$$

Transformed and indexed data series of a standard and sample are used for the correlation coefficient calculation (being represented by s_i and r_i variables in the following formula) (PAST 2000):

$$c_{coeff} = \frac{\sum_{i-x..y}(s_i - \overline{s})(r_i - \overline{r})}{\sqrt{\sum_{i-x..y}(s_i - \overline{s})^2 (r_i - \overline{r})^2}}$$

x, y: limits of overlapping the curves; r_i, s_i : values of annual rings for transformation; : mean values of transformed annual ring series

The final value of the t-test is as follows (Stone 1963):

$$t_{bp} \mid t_{ho} = \frac{c_{coeff}\sqrt{n-2}}{\sqrt{(1 - c_{coeff}{}^2)}}$$

n: the number of overlapping years

At overlapping the curves by at least twenty annual rings (our smallest overlapping) the critical value of the Student's t-distribution at 0.1% significance level is 3.850 (Šmelko and Wolf 1977). At the t-test value lower than 3.85 the probability of positive correlation of curves is only small. On the other hand, values higher than 5 signalize, with high probability (at the sufficient overlapping of curves), identical chronological categorization of samples.

c) Length of overlapping the curves

The length of the curves overlapping is an important value. The longer the overlapping of curves the higher reliability of mutual synchronization. The table gives values of a correlation coefficient at 1% significance value depending on the length of overlapping the segments (Tab. 1) (Grissino-Mayer 2001).

Tab. 1: Values of the critical correlation coefficient in relation to the length of overlapping

Segment length	Critical correlation coefficient at 1% significance level
10	0.7155
15	0.5923
20	0.5155
25	0.4622
30	0.4226
35	0.3916
40	0.3665
50	0.3281
60	0.2997
70	0.2776
80	0.2597
90	0.2449
100	0.2324
120	0.2122

RESULTS

Synchronization of annual ring curves within particular roots

The lowest value of the t-test is 4.79 (measurements L3466 and L3464). Of course, also this value is sufficient because in overlapping curves of at least thirty annual rings the critical value of the t-test at 0.1% significance level is 3.64. On the other hand, the highest values of the t-tests (13.97 and 14.91) are shown by the mutual synchronization between measurements L3459 and L3458 (Tab. 2). The value of synchronization of curves ranged about 80%. The correctness of mutual synchronization of annual ring curves is also demonstrated by the accordance of curves in the majority of extreme values (Figs. 4, 5, 6, 7).

Tab. 2: Synchronization of annual ring curves from particular roots

Root	Samples compared	T-test 1 (according to Baillie & Pilcher)	T-test 2 (according to Hollstein)	Synchronization of curves in %	Overlapping the sample with a standard in years
1	L3459 × L3458	13.97	14.91	83	49
2	L3462 × L3463	7.77	8.76	83	44
3	L3466 × L3464	4.79	7.15	77	49
3	L3466 × L3465	5.47	7.55	73	42
3	L3466 × L3468	9.84	10.86	83	43
5	L3472 × L3474	7.1	6.33	79	33

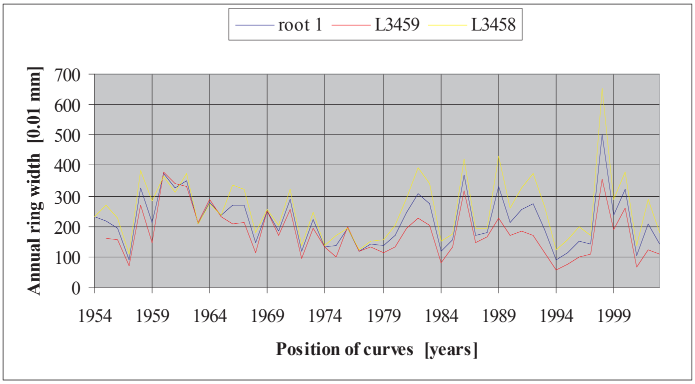

Fig. 4: Synchronization of annual ring curves from root 1 and their mean curve – root 1 (blue)

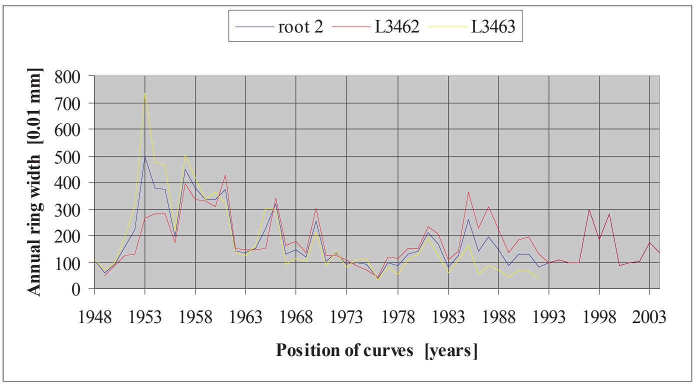

Fig. 5: Synchronization of annual ring curves from root 2 and their mean curve – root 2 (blue)

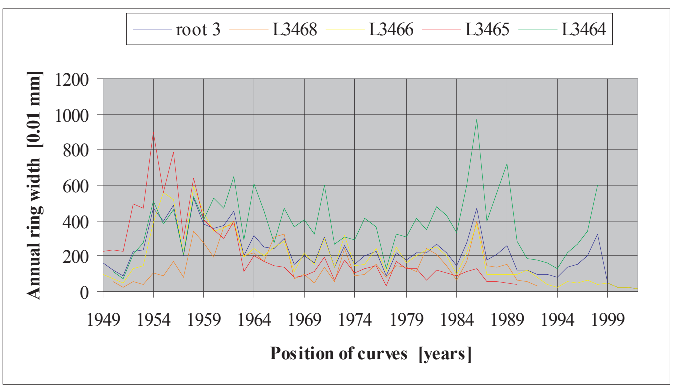

Fig. 6: Synchronization of annual ring curves from root 3 and their mean curve – root 3 (blue)

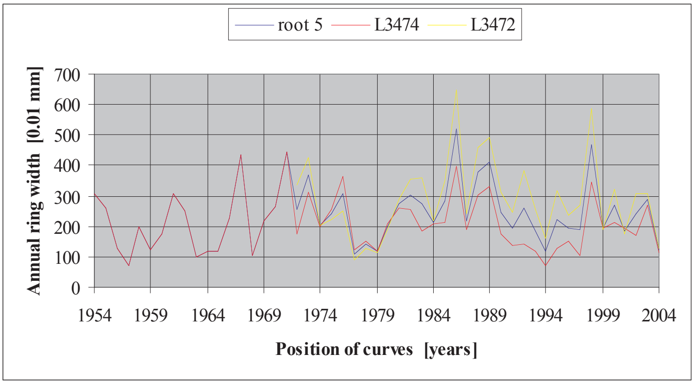

Fig. 7: Synchronization of annual ring curves from root 3 and their mean curve – root 3 (blue)

Synchronization of mean annual ring curves of particular roots

In the synchronization of mean curves from particular annual rings the lowest value of the t-test is 3.72 (root 2 and root 3). Nevertheless, the value is sufficient because at overlapping the curves of forty annual rings the critical value of the Student's t-distribution increases at 0.1% significance level to a value of 3.551. On the other hand, the highest values of t-tests (8.24) are shown in the mutual synchronization between mean curves of root 1 and root 2 (Tab. 3). The correctness of mutual synchronization is demonstrated by the consistency of curves in the majority of extreme values (Fig. 8).

Tab. 3: Synchronization of mean annual ring curves from particular roots

Compared curves	T-test 1 (according to Baillie & Pilcher)	T-test 2 (according to Hollstein)	Synchronization of curves in %	Overlapping the samples with a standard in years
Root 2 × root 1	6.10	8.24	79	50
Root 2 × root 3	3.72	7.09	72	54
Root 2 × root 5	6.52	7.05	79	51

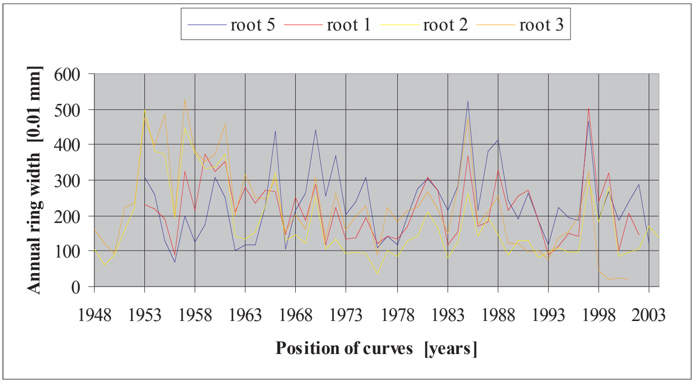

Fig. 8: Synchronization of mean annual ring curves from particular roots

Synchronization of the mean annual ring curve from the whole root system with a mean curve from the tree stem

The lowest value of the t-test (4.59) occurs in the synchronization of a mean annual ring curve of the root system with mean curves from particular heights of the tree stem, namely in a mean curve from the stem height of 1.3 m.

The highest values of t-tests are demonstrated by synchronization of the annual ring curve of a root system with a mean curve from the stem height of 5 m (Tab. 4). The correctness of mutual synchronization is demonstrated by the consistency of curves in the majority of extreme values (Fig. 9).

Tab. 4: Synchronization of mean annual ring curves from the whole root system with a mean curve of the whole stem, mean curve of the stem from a height of 0.3 m, 1.3 m and 5 m

Compared curves	T-test 1 (according to Baillie & Pilcher)	T-test 2 (according to Hollstein)	Synchronization of curves in %	Overlapping the sample with a standard in years
Mean curve of the root system × mean curve of the whole stem	6.82	6.88	69	56
Mean curve of the root system × mean curve of the stem (0.3 m)	6.07	5.87	71	56
Mean curve of the root system × mean curve of the stem (1.3 m)	4.59	5.04	63	55
Mean curve of the root system × mean curve of the stem (5 m)	6.70	7.33	70	49

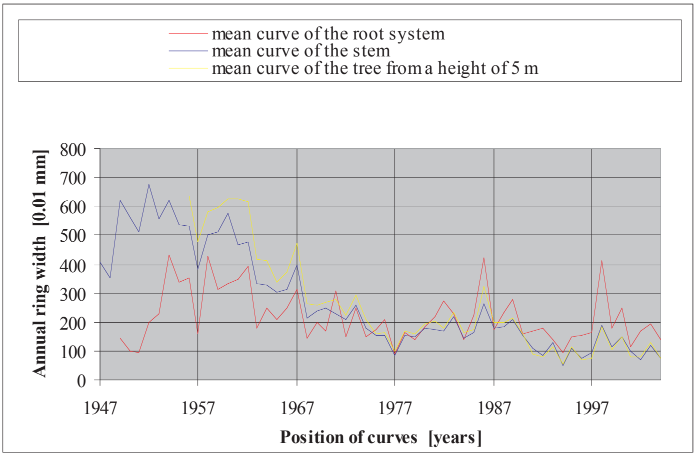

Fig. 9: Synchronization of a mean annual ring curve of the whole root system with a mean annual ring curve of the whole stem and a mean annual ring curve from the stem height of 5 m

Synchronization of the mean annual ring curve of the whole root system with the annual ring curve of a root 1.2 m from the stem

Values of t-tests in synchronization of the mean annual ring curve of the whole root system and the mean curve of a cross section 1.2 m from the tree stem range again above the limit of the critical value of the Student's t-distribution for 0.1% significance level. The value of mutual synchronization of curves is 83% (Tab. 5). Curves are consistent in the majority of extreme values (Fig. 10).

Tab. 5: Synchronization of the mean annual ring curve of the whole root system with the mean curve of a root 1.2 m from the stem

Compared curves	T-test 1 (according to Baillie & Pilcher)	T-test 2 (according to Hollstein)	Synchronization of curves in %	Overlapping the sample with a standard in years
Root 1.2 m × mean curve of a root system	4.95	6.12	83	24

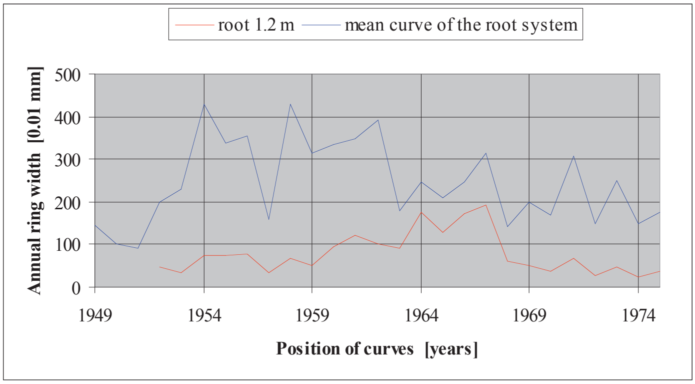

Fig. 10: Synchronization of a mean annual ring curve of the whole root system with the mean curve of a root 1.2 m from the stem

Mean width of the root annual rings

The diameter of a root 0.2 m from the tree stem is 251 mm. The diameter of a root 1.2 m from the stem is 61 mm. The diameter of a more remote root is consequently more than 4 times smaller. The mean width of annual rings at a height of 1.3 m above the ground is 2.05 mm. The mean width of annual rings in a root 0.2 m from the stem is 2.18 mm. The mean width of annual rings in a root 1.2 m from the stem decreased to 0.4 mm. Even farther, the annual ring width is roughly constant ranging about 0.5 mm (Fig. 11).

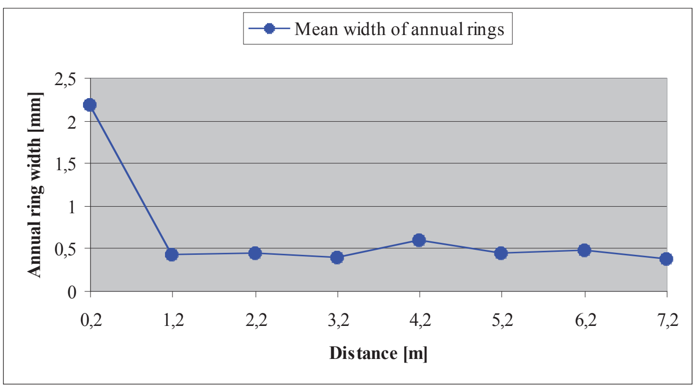

Fig. 11: Annual ring width along the length of the Scots pine horizontal root

DISCUSSION AND CONCLUSIONS

It succeeded to synchronize four of five main horizontal roots. A mean annual ring curve of these four horizontal roots was reliably synchronized with the mean annual ring curve from the tree stem. The highest values of statistic indicators showed synchronization of the mean annual ring curve from the root system with a mean annual ring curve from the stem height of 5 m. However, a trial to synchronize annual ring curves within a root along its length was not so successful. It succeeded to synchronize only one annual ring curve of the root cross section 1.2 m from the stem. The measurement of annual ring widths on more remote cross sections from the stem was not possible by means of a measuring table with PAST 32 program due to the small width of annual rings. Therefore, microscopic preparations had to be prepared which were photographed and measured in LUCIA program. Values of the annual ring widths were converted to the PAST program. However, mutual synchronization of these annual rings was not possible due to often indistinct limits of particular annual rings and frequently occurring false annual rings (Schweingruber 1996). For these reasons measurements of the samples was considerably inaccurate and, thus, the mutual synchronization was nearly impossible (Fayle 1968). A radical decrease in the root diameter depending on a distance from the tree stem was demonstrated (Krause and Eckstein 1992). The diameter of a root at the stem was more than 4 times higher than the diameter of a root 1.2 m from the stem.

The mean annual ring width in a stem at a height of 1.3 m above the ground is 2.05 mm. The mean annual ring width in a root 0.2 m from the stem is 2.18 mm. A fact that the mean annual ring width in a root 0.2 m from the stem is nearly the same as the annual ring width in a stem at a height of 1.3 m above the ground is caused by a fact that annual ring widths of roots are measured in a pressure zone where abnormally wide annual rings are created. The mean width of annual rings in a root 1.2 m from the stem is 0.4 mm. In greater distances, the width of annual rings is virtually constant ranging about 0.5 mm. These values fulfil a condition that the root diameter (as well as annual ring width) rapidly decreases at a distance > 40 cm from the tree stem (Krause and Eckstein 1992).

It is of interest that the last annual ring in the stem was terminated by late wood and, on the other hand, last annual rings in roots were terminated by early wood. The fact can be caused by more reasons. Firstly, the root system could get dry in spring or at the beginning of summer and, thus, late wood was not created. Other potential reasons can consist in complex physiological processes of the root growth.

The subject of our research was only one tree. Therefore, it is necessary to assess results of our study with a certain detached point of view. Nevertheless, the new findings are very valuable shifting the annual ring research a step further. Next research should deal with the analysis of vertical roots where we can expect better synchronization within one root along its length. In vertical roots, it is possible to suppose better synchronization because they are the direct extension of a stem in soil (Köstler et al. 1968).

The study has demonstrated that horizontal roots of Scots pine (*Pinus sylvestris* L.) can be a very suitable source of an ecological signal particularly as for roots maximally 40 cm from the tree stem. It has been proved that annual ring curves from particular roots are mutually synchronizable. In part, it is possible to synchronize annual ring curves from particular cross sections of one root with a various distance from the stem. Curves of annual ring widths from a root system can be reliably synchronized with annual ring curves from the tree stem. Achieved results make possible further follow-up research which could result in the perfect description of the whole tree.

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