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EVALUATING SIMILARITY OF RADIAL INCREMENTS AROUND TREE STEM CIRCUMFERENCE OF EUROPEAN BEECH AND NORWAY SPRUCE FROM CENTRAL EUROPE

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Abstract: Extracting cores from a tree using an increment borer has been standard practice in dendrochronological studies for a long time. Although empirical rules exist regarding how many samples to take and which methodology to apply, comparatively few studies provide quantification of the similarity of relative tree-ring-widths (TRW) around the stem circumference. The aim of this study was therefore to precisely measure the similarity of standardised TRWs around the stem circumference and to provide objective suggestions for optimal core sampling of Norway spruce (*Picea abies* Karst. [L.]) and European beech (*Fagus sylvatica* L.) growing in Central European temperate forests.

A large sample of cross-sectional discs was used from Norway spruce and European beech trees growing on various slopes, at different altitudes and biogeographic regions across the Czech Republic and Slovakia. The similarity of TRWs measured in different coring directions was analysed by testing the relativized TRW around the trunk (rTRW). Comparison of rTRWs revealed no significant differences between coring directions, indicating that the relative increment was the same around the radius. The results also showed the high similarity between the rTRWs to be independent of both slope inclination and altitude. Moreover, the reconstruction of proportional tree diameters and basal areas backward in time from one core sample and one measurement of tree diameter (basal area) at the time of sample extraction is possible with reasonable precision.

Keywords: relative tree-ring width, dendroclimatology, basal area reconstruction, core sampling, detrending.

1. INTRODUCTION

Tree-ring analysis is employed in many different research fields, including dendroecology, dendroclimatology and forest growth dynamics research (e.g. Cook and Kairiukstis, 1990; Schweingruber, 1996; Pretzsch, 2009). For such analysis, core extraction via increment borer has become standard practice (Hasenauer *et al.*, 1999; Bigler *et al.*, 2004; Carrer and Urbinati, 2006; Metsaranta and Lieffers, 2009; Fang *et al.*, 2010).

Growth varies within an individual tree, both vertically along the stem and horizontally around the stem circumference (Fritts, 1976; Schweingruber, 1996). As the

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variability along the stem is greatest at the stem base and smallest in the crown (Cook and Kairiukstis, 1990), in order to obtain the longest possible ring sequences while reducing along-stem variability, samples are usually taken at breast height. However, although it is widely accepted that collecting and averaging more than one core per tree from the same sample height reduces ring sequence discrepancies caused by variation around the circumference within the same individual (e.g. McDowell *et al.*, 2002), little research has been conducted to assess intra-tree variability (e.g. Šmelko, 1965; Šmelko, 1982; Woodall, 2008).

Pilcher *et al.* (1990) suggested that averaging data from two cores per tree can eliminate a large part of individual variability, although no experimental data were produced to support this proposal. Fritts (1976) suggested that for climate studies, two cores per tree should be collected if up to 14 trees per stand are sampled and only one core per tree if more trees are sampled. For densitometric studies, Fritts considered two cores from at least 12 trees as usually sufficient. Pilcher *et al.* (1990) stated that for ring-width analysis, a sample of two cores from each of 20 trees is recommended. If circuit uniformity of ring widths within a single tree is very high compared with the differences in annual growth among trees, then single core samples taken from a greater number of trees is preferable (Pilcher *et al.*, 1990).

A review of relevant literature suggested that most recent tree-ring studies have used only one or two cores per tree (e.g. Bigler *et al.*, 2004; Gray *et al.*, 2004; Muzika *et al.*, 2004; Büntgen *et al.*, 2006; Carrer and Urbinati, 2006; Koprowski and Zielski, 2006; Esper *et al.*, 2007; Büntgen *et al.*, 2007; Čejková and Kolář, 2009; Feliksik and Wilczyński, 2009; Bijak, 2010; Fang *et al.*, 2010; Bošeľa *et al.*, 2011; Bošeľa *et al.*, 2014; Dittmar *et al.*, 2012; Hökkä *et al.*, 2012), and studies using more than two cores or discs are less frequent (e.g. Brienen and Zuidema, 2005; Ďurský *et al.*, 2006; Van Der Maaten-Theunissen *et al.*, 2013) because they are costly and destructive. However, a number of authors sampled two cores from the same side of the tree trunk, but at different heights above the ground (e.g. Bräker and Baumann, 2006).

European beech and Norway spruce are two of the most common tree species across Europe (Tröltzsch *et al.*, 2009; Brus *et al.*, 2012) and have been widely used for dendroecological research (e.g. Gutierrez, 1988; Biondi, 1992; Dittmar *et al.*, 2003; Young-In and Spiecker, 2005; Dittmar *et al.*, 2012). Intra- and inter-tree variability in terms of ring widths, diameter at breast height and basal area have been described in detail for spruce and beech in Slovakia by Šmelko (1965; 1982). A number of factors can influence the absolute variability of ring widths around a stem circumference, including slope inclination and orientation, prevailing wind direction, tree species, crown shape, age, tree diameter and social position of a tree within a stand (Šmelko, 1982). According to previous research, the first three of these factors have the most significant impact, although their respective intensity has been found to vary (Kurth, 1959; Giurgiu, 1957; 1967). For example, Siostrzonek (1958) determined wind intensity and direction to be the prevailing factors in the case of conifers, whereas slope inclination was more significant for broadleaf species. According to Assmann (1968) and Vyskot *et al.* (1971), in most cases the basal area of trees under Central European growth conditions is elliptical in shape, with the longer axis aligned east-west in the direction of the prevailing winds.

In general, the greater the inter- and intra-tree variability of parameters such as ring width and wood density, the larger the required sample size (Hughes *et al.*, 1982). However, it is complicated and costly to measure variability within a single tree. Although several studies have been published which quantified differences in absolute radial increment around the stem circumference in relation to absolute basal area and volume increments (e.g. Assmann, 1968; Vyskot *et al.*, 1971; Šmelko, 1982), few account for the similarity between tree ring-width indices around the circumference, which is an important parameter in dendroecological studies (e.g. Woodall, 2008). Exact information regarding the differences in standardised TRWs around the stem circumference and the correlation of standardised samples taken from different sides of the tree is generally missing from most research papers. Consequently, objective information regarding the correct number of sample cores to take from an individual tree for the purpose of dendroecological study are also absent.

The main aim of the present study was therefore to provide more objective suggestions as to how many cores should be sampled from a single tree and from which side, based on some form of standardisation of tree-ring series as a main methodological step. Two tree species predominant in European temperate forests, Norway spruce and European beech, were sampled at several sites in Central Europe. The primary aim was to quantify both differences in standardised series and similarities between the standardised series sampled at different locations around the stem. The null hypothesis was that standardised tree-ring widths of the same year sampled on different sides of the same tree differ from one another only randomly. In addition, the impact of slope inclination and altitude on the similarity of standardised series was examined in order to establish the best position around the stem to take increment samples. The analyses performed also enabled an evaluation of the possibility of realistic reconstruction of proportional diameters and basal areas backward in time from one core sample and from one measurement of tree diameter (basal area) at the time of sample extraction.

2. MATERIAL AND METHODS

Experimental Material

The large-scale experimental material employed in the present study included 189 cross-sections gathered from the Czech and Slovak Republics (**Table 1**), with the selected sites located across two different bio-geographical regions (Continental and Alpine). The Alpine spruce sites were also established to cover a wide altitudinal range (450–910 m a.s.l.). As the cross-sectional discs were obtained during different time periods (1962–2011), they included trees growing during a period of rapid climate change.

Dataset 1

The first experimental dataset was obtained at Kostelec nad Černými lesy in the locality of Klíče in the Czech Republic, where a long-term permanent research plot (PRP) was established in 1953 (hereafter PRP Klíče). An even-aged spruce forest stand was also planted in 1893. The site belongs to the Černokostelec highlands, part of a geomorphological region of the Middle Czech highlands. Mean annual temperatures range from 7 to 8°C, rising to 13–14°C during the vegetation period which averages around 160 days in length. Mean total precipitation per year amounts to 610–660 mm.

In 2003, nine largest (dominant) trees in the plot were felled and disc samples taken from 1.3 m height (at breast height). Trees without any signs of stem damage were selected. In the laboratory, the discs were air-dried, sanded, scanned and tree-ring widths were measured using the WinDendro software program (Regent Instruments Inc., Quebec, Canada).

The dataset also includes a further 11 disc samples of spruce and 15 discs of beech. The spruce discs were obtained in Dobříš in the Czech Republic; sampling was performed in 2011 during the harvesting of a forest stand. The beech discs were sampled in 2005 at a site in the Kremnické vrchy Mts., Central Slovakia (48°38' N, 19°04' E). The mean annual temperature (30-year means) is 8.2°C, the mean temperature during the vegetation period is 14.9°C, the mean annual precipitation is 664 mm and mean total precipitation during the vegetation period is 370 mm. Trees were felled and discs collected from a height of 1.3 m. Compass setting was marked on the stems before felling. The diameter at breast height of these trees varied because not only did they originate from a series of PRPs established for the investigation of different shelterwood cutting methods, they also had different within-stand social positions. In the laboratory, both spruce and beech discs were dried, mounted and sanded to allow for precise measurement of ring widths. The tree-ring widths (TRW) of all samples were measured in eight cardinal directions from the pith starting from north, with a precision level of 0.01 mm. The individual ring widths of individual trees were subsequently cross-dated using standard procedures (Fritts, 1976; Cook and Kairiukstis, 1990). COFECHA (Holmes, 1983) was used for cross-dating.

Dataset 2

This dataset included 114 cross-sections of spruce sampled from a total of 12 forest stands at four different sites across the Slovak Western Carpathians: Kriváň, Vígľaš, Brezno and Oravský Podzámok (**Fig. 1**). The selected forest stands originated from natural regeneration and had been managed by thinning from below with

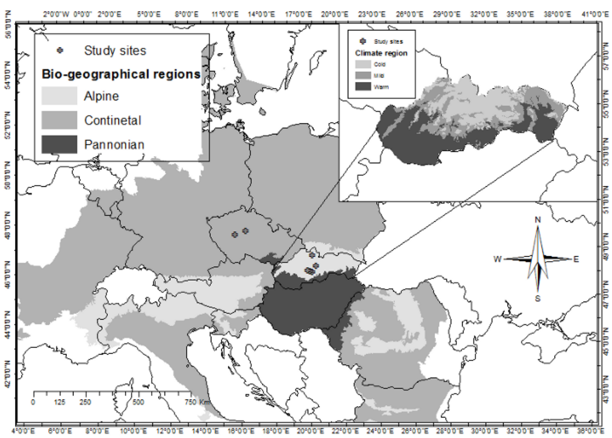

Fig. 1. *Spatial distribution of the study sites across the bio-geographical and climate regions of Central Europe.*

Table 1. *Description of the two datasets used in the study.*

Locality (dataset)	Year of sampling	Biogeoregion	Altitude (m a.s.l.)	Aspect	Slope (degrees)	Species	Age (min-max)	No. trees	No. measurements /tree
Zvolen (1)	2005	Alpine	470	W	20	beech	52-80	15	8
Dobris (1)	2011	Continental	430	W	10	spruce	100-142	11	8
Klice (1)	2003	Continental	400	N	5	spruce	96-104	9	8
Brezno (2)	1962	Alpine	880-910	N,E	17-27	spruce	70-110	29	4
Kriváň (2)	1962	Alpine	600-710	N,E,S	18-22	spruce	76-95	27	4
O.Podzamok (2)	1962	Alpine	800-900	N	10-30	spruce	75-105	30	4
Víglaš (2)	1962	Alpine	765-800	N,S,W	12-15	spruce	65-122	27	4
Zvolen (2)	1962	Alpine	457	level	0	spruce	83	1	4
Zvolen (2)	1962	Alpine	500	SE	15-20	beech	81-162	40	4

negative selection. In each stand, 10 trees were felled and discs cut at 1.3 m height, with some of the samples subsequently excluded due to technical defects in the wood (e.g. rot). Dataset 2 also included more than 40 cross-sections of beech obtained from one forest stand located in a forest enterprise zone belonging to the Technical University in Zvolen (Zvolen site). Similarly to the spruce stands, the beech stand had previously been subject to thinning from below. While the latter stand was relatively uneven-aged, its height and diameter structure was relatively homogeneous. Data collection was conducted in 1962 by the Department of Forest Management and Geodesy of the Technical University in Zvolen (Šmelko, 1982). Tree-ring widths were measured using a K. Johann digital position-meter (Type I, Nr. 98809-061, Austria) with a precision level of 0.01 cm. For spruce, the ring widths were measured in four directions (at 90 degrees to one another) starting from upslope, whereas those for beech were carried out in four cardinal compass directions starting from the north.

Statistical analysis

The first step in the analysis was the calculation of relative tree-ring widths (rTRW). rTRWs were calculated as the ratio between each tree-ring width and the cumulative sum of tree-ring widths, *i.e.* the total length of the stem radius in a particular measuring direction (Bakker, 2005). Such relativisation represents one of the simplest forms of standardising raw TRW values to remove apparent age-related reductions in ring width; here it was carried out in order to exclude dimensional differences in stem radius around the stem circumference. Widely considered one of the main principles of dendrochronology and dendroclimatology, standardisation is typically used to filter low frequency, site-age and slight competition effects from raw TRW series with the aim of explicitly revealing climatic or other environmental signals incorporated into TRW time series (Fritts, 1976; Cook and Kairiukstis, 1990). Accordingly, dimensional differences between trees and differences between rings within trees included in the various datasets were removed from our analysis; this is also the main reason why standardised (here rTRWs) and not absolute TRWs are the subject of interest in dendroecological and environmental studies.

The significance of differences in rTRW values between any two directions was investigated using paired t-test. Due to the inherent non-normal distribution of the rTRWs, a 3.6 root transformation (determined empirically) was employed in order to meet the requirements of proper t-test use. All possible pairs of rTRW series were examined for each tree. If the tests showed no significant differences in rTRWs measured in each of the various directions, the relative increment around the stem circumference was considered similar. If rTRWs in different directions were the same for the same year, absolute TRWs and cumulative radii for certain years and measuring directions would have been factors of the corresponding TRWs and radii in other directions.

Median values, non-outliers, outliers and extremes of the rTRW differences for all possible pairs of measuring directions and p-values produced by the series of paired t-tests were calculated for each of the different sampling sites in order to thoroughly explore the possible influence of environmental factors (including climate and orography) on the results. The above-mentioned statistics were employed instead of mean and standard deviation data in order to provide more detailed information regarding the nature of rTRW differences (distribution, presence of extreme values, *etc.*).

Mean differences in rTRW for all possible pairs of measuring directions for both spruce and beech were tested using Tukey's honest significance test to identify homogeneous groups.

Differences in rTRWs between pairs of measuring directions were also regressed with altitude and slope inclination in order to explore their dependence or independence on these factors.

During dendrochronological sampling it is important to minimise inter-tree variability in order to produce a mean chronology with the best possible expressed population signal (EPS, Wigley *et al.*, 1984; Cook and Kairiukstis, 1990). Analysis of variance was employed here to test for differences in inter-tree correlation between the TRW series for each different coring direction. This was performed to identify whether any particular stem side was preferable when taking a core sample for maximisation of EPS.

In case the test of inter-tree similarity between rTRW around the stem revealed no significant differences, the following transformation of tree-ring-widths to basal area (*BA*) may be applied:

$$BA_{t-n} = BA_t - (BA_t \times RI_{t-n}) \quad (2.1)$$

$$RI_{t-n} = TRW_{t-n} / \mathrm{Sum}(TRW_{ij}) \quad (2.2)$$

where t is the last year, $t\text{-}n$ is the particular year in the past, RI denotes the relative index, and TRW_{ij} is the tree-ring-width series i at the particular coring direction j.

This step was carried out in this study because basal area increment (BAI) is widely used instead of tree-ring width indices (Weber *et al.*, 2008).

All analyses were performed using the R environment (R Development Core Team, 2011).

3. RESULTS

Intra-tree similarity of relative TRWs

The results from the series of paired t-tests revealed a high similarity between rTRWs around the entire stems of individual spruce and beech trees at all study sites (**Table 2**). The null hypothesis that any differences were only random was, therefore, accepted. Only 1% of all compared pairs were found to be significantly different,

Table 2. *Mean differences and p-values obtained from series of paired t-tests for all datasets, species and localities.*

Locality	Species	Diff$^{1/3.6}$		p-value		N	
		Mean	St.Dev.	Mean	St.Dev.	Mean	St.Dev.
Dataset 1 (eight directions)							
Dobris	Spruce	0.00015	0.00264	0.5286	0.2955	131	12
Klice	Spruce	-0.00039	0.00172	0.5723	0.2596	100	2
Zvolen	Beech	-0.00004	0.00135	0.7602	0.1736	67	7
Dataset 2 (four directions)							
Brezno	Spruce	-0.00030	0.00891	0.6383	0.2371	17	3
Zvolen	Spruce	-0.00362	0.00488	0.6145	0.2354	14	0
Kriváň	Spruce	0.00169	0.00896	0.6630	0.2436	16	1
Or.Podzamok	Spruce	0.00036	0.00792	0.6452	0.2201	15	1
Zvolen	Beech	0.00112	0.00572	0.6912	0.2187	24	3
Víglaš	Spruce	0.00096	0.01013	0.5897	0.2479	14	2

Note: N — mean number of annual rings for all study trees within the dataset and its standard deviation

i.e. with a p value smaller than or equal to 0.05 (**Fig. 2**); these cases were all found in spruce from the locality of Klice and Dobris (dataset 1). However, these significantly different pairs included various combinations of directions (cardinal and slope-relative) and thus no final conclusion could be drawn with regard to any relationship with core direction. In addition, the slope inclination at the Klice site was the lowest of all study sites, with conditions optimal for spruce tree growth (430 m a.s.l., slope inclination 5–10°). These significant differences thus seemed to be random with no obvious causative factor.

The lowest variability in differences was found at the sites of Dobris and Klice, while the highest was detected at Vígľaš (**Fig. 2**). Although rTRW values around tree stems were generally similar, possible differentiating factors were nonetheless investigated. Regression analysis revealed that neither altitude nor slope inclination had any effect (**Fig. 3**, **Fig. 4**), while no significant differences were observed between any combination of coring directions for both spruce and beech in dataset 1 (**Fig. 5**). Where four measurements were made per tree (dataset 2), significant differences were found only in spruce (**Fig. 6**), with the Tukey's honest significance test identifying three homogeneous groups. The first group (*a*) comprised only the direction pair 1-3 (up- and down-slope), while certain direction pairs could be included in both *a* and *b* (1-2 and 2-3), *b* and *c* (2-4) and a combination of *a*, *b* and *c* (1-4). The third group (*c*) included only the pair 3-4 (down-slope and perpendicular to the slope). However, although significant differences between some direction pairs were reported by the non-parametric Tukey test, overall the mean differences between rTRW series around the stem evaluated by a series of parametric paired t-tests were non-significant. For beech, no differences were found between any direction pairs.

Site-level inter-tree similarity between different coring directions

As different coring directions were selected, inter-tree TRW correlations were compared using ANOVA. In

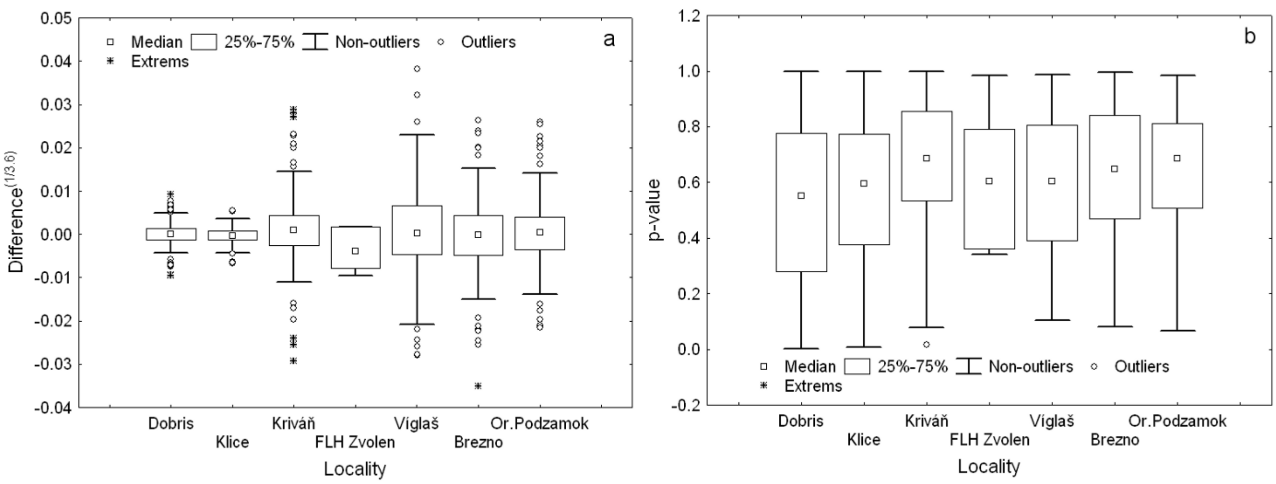

Fig. 2. *Differences in the relative tree-ring widths of spruce for all possible pairs of coring/measuring directions (a: differences; b: p-values of the paired t-test).*

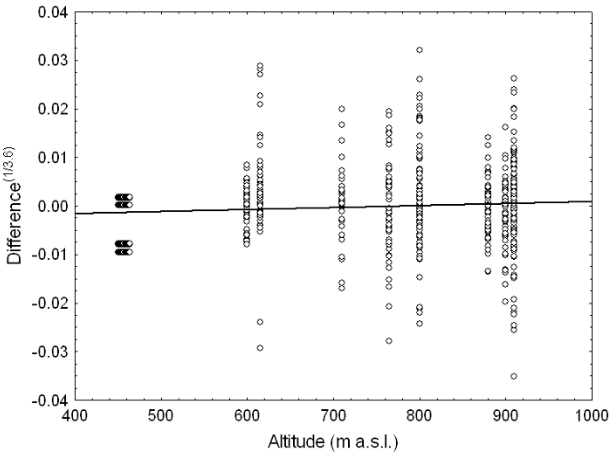

Fig. 3. *Differences in the relative tree-ring widths of spruce with varying site altitude.*

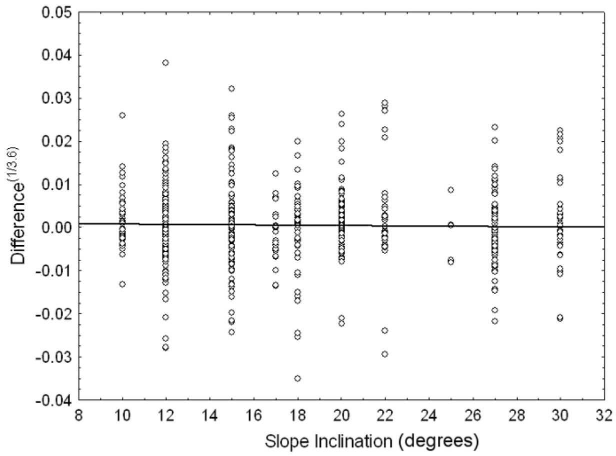

Fig. 4. *Differences in the relative tree-ring widths of spruce with varying site slope inclination.*

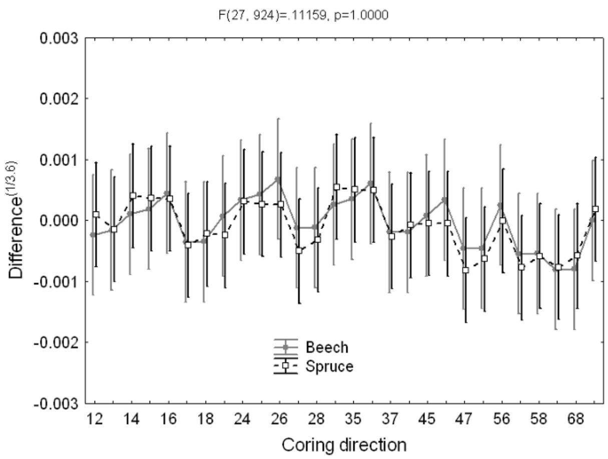

Fig. 5. *Mean difference in the relative tree-ring widths of spruce and beech for all possible coring direction pairs, and standard errors, for dataset 1 (eight coring directions). Labels 12, 14,* etc. *along the x-axis denote the pairs of the coring directions 1 and 2, 1 and 4,* etc.

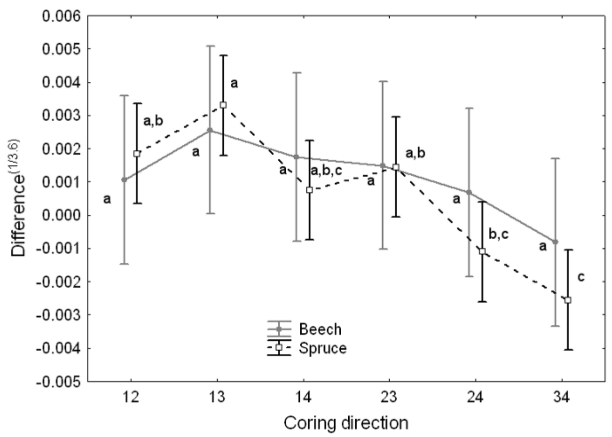

Fig. 6. *Mean difference in the relative tree-ring widths of spruce and beech for all possible coring direction pairs, and standard errors, for dataset 2 (four coring directions). Labels 12, 13,* etc. *along the x-axis denote the pairs of the coring directions 1 and 2, 1 and 3,* etc. *Small letters above each bar mean homogeneous groups as obtained from the Tukey's significance test.*

general, the results revealed no significant difference between coring directions (**Table 3**). However, two sites (spruce at Vígľaš and beech (2) at Zvolen) were characterised by significant differences in inter-tree correlation of TRW series. For these two sites the Tukey's honest significance test was applied in order to test the differences between all possible pairs. In the case of spruce at Vígľaš, two homogeneous groups were found (**Fig. 7b**). The first group (*a*) included coring direction 4 and the average between 1 and 3, and the second group (*b*) included only direction 2. In the case of beech at Zvolen (**Fig. 7a**), a possible four different homogeneous groups were identified. The highest inter-tree correlation was observed when the average measurement taken from coring directions 2 and 4 was used (group *a*), whereas the

Table 3. *ANOVA of inter-tree correlation when all core samples were taken from the same direction.*

Species (dataset)	Locality	SS	df	MS	F	P
Spruce (1)	Dobris	0.0614	11	0.0056	0.3185	0.9820
	Klice	0.3438	11	0.0313	0.4500	0.9325
Spruce (2)	Brezno	0.2549	6	0.0425	0.3937	0.8835
	Kriváň	0.4045	6	0.0674	0.6423	0.6964
	Or.Podzámok	0.4365	6	0.0728	0.7013	0.6486
	Víglaš	1.7988	6	0.2998	2.9705	0.0068
Beech (1)	Zvolen	0.0330	11	0.0030	0.0874	0.9999
Beech (2)	Zvolen	13.0464	6	2.1744	18.673	<0.001

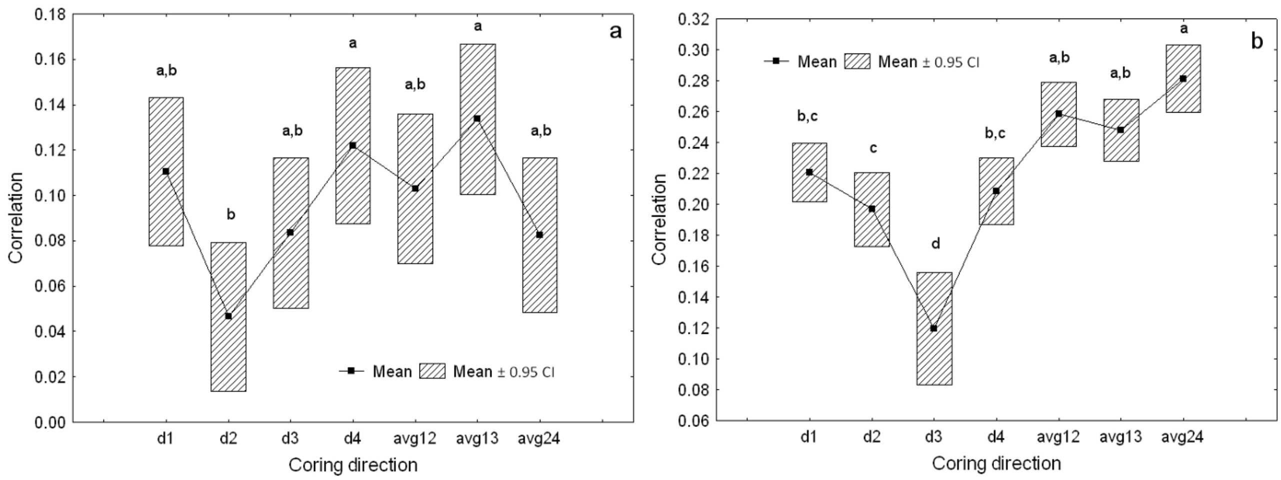

Fig. 7. *Mean inter-tree correlation and its variability with coring direction (a: Spruce at Viglas; and b: Beech at Zvolen;) (the mean correlation for direction d1 represents the inter-tree correlation for all core samples taken from direction 1). Small letters above each bar mean homogeneous groups as obtained from the Tukey's significance test.*

lowest correlation (group *d*) was found for coring direction 3 (down-slope).

4. DISCUSSION

The present study is partly based on the material and results obtained by Šmelko (1982), who focused on quantifying the variability of absolute non-standardized TRWs around tree stem circumference and on finding the main influencing factors. Šmelko compared the simple average of ring widths obtained from different coring directions and tested the null hypothesis that the average ring widths of all coring directions were equal. Unsurprisingly, the author found significant differences between almost all directions, as well as between all directions and the overall average. Similarly, Woodall (2008) analysed the relative differences between radii obtained from two core samples obtained at a 90-degree angle in ponderosa pine (*Pinus ponderosa,* Douglas ex C. Lawson). This author found differences for sapwood ranging from 15% to 24%, for inside bark (under-bark) radius from 10 to 15%, and for most recent 10-year radial growth from 20 to 27%. Woodall also found that the differences in paired core measurements were most evident in small trees, trees with small crowns and in trees on steep slopes. Indeed, both Šmelko and Woodall pointed out that, among other factors, site slope significantly influenced the shape of the stem radius. In addition, radial growth eccentricity is frequently considered a consequence of tree tilting, resulting from strong winds, debris flow, snow avalanches or soil creep (Kaennel and Schweingruber, 1995), while Woodall discovered that TRW values can also correlate with the tree size (diameter at breast height). Mäkinen and Vanninen (1999) suggested that chronologies derived from compass directions ranging between south and west contained a greater proportion of common variance than those from north to east. This finding correlates with the earlier work of Liese and Dadswell (1959), who investigated the influence of solar radiation on ring width, observing that ring widths were widest on the sunny side of the bole (as also found by Mäkinen in 1998) and that directional warming may therefore promote asymmetric growth. Moreover, according to Mäkinen and Vanninen (1999), other factors such as slope and wind direction, stem inclination and competition from neighbouring trees should all be considered when selecting the sampling direction.

However, in the present study we observed no significant differences in relative TRWs between coring directions, with the differences that were found being independent of both slope inclination and altitude. Possible explanation for contrasting findings is that the previous studies were focused on differences in absolute tree-ring widths, while our study was investigating relative changes of tree-ring widths around the tree stem. This suggests that sampling direction does not have to be considered for when obtaining cores. If the relative increments were very different along the stem radius, the tree trunk itself would seem deformed and misshapen; we therefore hypothesise that the relative TRWs around the stem radius of an outwardly regular tree must be generally very similar. Even if there is huge competition pressure caused by a neighbouring tree (or trees) located (or aggregated) to one side of the subject tree, the latter's trunk will be more or less regular with no significant defects, since trees change their relative increment around the stem radius similarly.

Nevertheless, despite the presented results suggesting that one does not have to consider sampling direction when taking core samples from spruce and beech, certain general rules may apply. For example, Pilcher *et al.* (1990) proposed a number of criteria, such as to avoid sampling in the vicinity of a wound or reaction wood, to avoid buttressing and both the up- and downslope sides of trees growing on sloping ground. In extreme growth conditions, for example at the upper distribution limit of scattered trees with flag-like crowns, asymmetric boles and eccentric annual rings, the measurement and dating of rings is possible only on a core sample taken from the side of the stem where annual ring widths are widest. This rule of sampling from the side of a tree where annual rings are widest can also be extended to forests growing in optimal ecological conditions, to both ensure the best cross-dating and to avoid problems associated with missing and double rings caused by random growth anomalies (Rozas, 2003). As mentioned by Speer *et al.* (2004), some tree species produce rings with poor circuit uniformity; in any given year, one part of the trunk may put on more woody growth than another, largely as a result of conducting tissues that differentially supply a non-symmetric stem.

Schweingruber (2007) has summarised in great detail the factors that may affect the use of tree-ring samples in dendrochronological research, including discontinuous tree growth and variable anatomical structures (wavy tree-ring patterns, displaced rings) and irregular stem cross-sections. As the author states, for genetic reasons some species exhibit strongly fluted stems; in Europe these include yew (*Taxus baccata*), juniper (*Juniperus* sp.), hornbeam (*Carpinus betulus*), some species of Rosaceae and a number of dwarf shrubs. For trees and shrubs in general, early growth (the number of years varies) is more or less concentric, in contrast to later growth which is locally inhibited, which leads to fluted stems; however, the phenomenon is mostly present in broadleaved species such as hornbeam and is less common in beech and spruce. In our study, trees had generally regular stems and were not strongly fluted to cause significant dissimilarities in relativized TRW around the stem. Indeed, a very high correlation was found between all pairs of tree-ring width series around the stem circumference for both beech and spruce in the present study. Since it is less common in spruce and beech to have lobate or fluted stems it is supposed to be easy to avoid such stems during sampling.

As stated by Grissino-Mayer (2003), trees growing on slopes should be bored at right angles to the slope direction (*i.e.* along the contour) because such trees often contain reaction wood. The same author also argued that "for many dendrochronological studies, such rings contain environmental noise unrelated to the signal being studied and should be avoided". Moreover, the ring widths of reaction wood are often dark in colour, which makes distinguishing them from the late-wood of conifers almost impossible. Reaction wood usually occurs at steep slopes or at sites of high mechanical stress (e.g. trees at a mountain ridge where wind is usual stress factor). Our study suggested that slope steepness did not have any influence on the similarity between relativized TRW. However, the study material did not include trees growing at a mountain ridge. In addition, we did not measure the presence of reaction wood of sample trees.

Finally, Mäkinen and Vanninen (1999) observed high similarity between tree-ring width indices along the height of tree stems. According to LeBlanc (1990), breast-height growth indices are suitable for the depiction of variations in the mean growth performance of a tree because of the strong relationships between breast height chronologies and whole stem growth indices.

Taking the results obtained in the present study into account, it seems enough, at least in environmental studies for which standardised TRWs (or ring-width indices) are of interest, to take one core sample per tree without having to consider the direction in which to perform the boring. However, obtaining two samples per tree does allow cross-checking of the tree-ring widths and identification of wedding rings.

Reconstruction of basal area using rTRW

Since relative TRWs were found not to be significantly different along the stem circumference one may calculate basal area retrospectively once the current basal area was measured on the tree. Calculation of basal area is important both for determining tree volume and for building tree-growth models. In addition to offering a better representation of tree productivity (e.g. LeBlanc, 1990; Tognetti *et al.*, 2000), basal area increment (BAI) series have the advantage of avoiding end-effect problems (heteroscedastic variance of tree-ring-widths along age) otherwise frequently encountered with ring-width series during the detrending process (Bouriaud and Popa, 2009).

A conventional approach for reconstructing the tree diameters (or basal areas) involves measuring the radial increment between the ring at the beginning of the study period and the outer-most ring and subtracting twice this value from the inside-bark diameter (e.g. Fulé *et al.*, 1997). However, it assumes that the chronological and geometric centres are equal and radial growth is symmetric. Later, Bakker (2005) proposed a new approach which assumes that growth is proportional around the stem. We support this approach as our result proved that the growth around the stem is proportional. This proportional method is not affected by core location.

However, the Bakker's approach can only be employed in scenarios where the pith of the stem radius is crossed (or nearly crossed and the remaining length of the diameter can be precisely estimated) and where the current basal area is measured with high precision (e.g. measurement of circumference, although problems can arise in the case of lobate tree stems). In this case, one must also measure the bark thickness to exclude it from the actual basal area (Biondi and Qeadan, 2008; Metsaranta and Lieffers, 2009). The historical reconstruction of basal area can be, however, affected also by variability of water content along the stem radius. Because core samples are air-dried before measuring, different shrinkage may occur between young (sapwood) and old (heartwood) wood. The different water content between sapwood and heartwood of the living trees was proved by several authors using tomography approach (e.g. Bierker and Rust 2010a, 2010b). While water content was different between sapwood and heartwood (with a higher moisture content of sapwood), the content was more or less stable around the radius. However, the proportion between sapwood and heartwood and the differences in moisture content is species-specific (Taylor *et al.*, 2002). The highest variability in moisture content is in the direction from bark to the pith of the stem and the moisture content is stable around the radius. This is also supported by our results which indicated high similarity of relativized tree-ring-widths around the stem circumference. When reconstructing the basal area retrospectively one needs to consider different moisture content between sapwood and heartwood. There is, however, lack of studies over Europe dealing with quantification of the differences in moisture content along the stem radius. For giant sequoias in USA, Stephenson (2000) found that the average shrinkage of cores was about 2% and he used the coefficient 1.02 for calculation of the wet length. However, such coefficients do not exist for beech and spruce in Europe and it may be a challenge for the future. Thus we hypothesise that the average shrinkage of European beech and Norway spruce cores is not so significant to cause relevant decrease of the precision of retrospective basal areas, but this hypothesis needs to be tested.

5. CONCLUSIONS

The results of the present study revealed a high similarity between the rTRWs obtained from different sides of spruce and beech tree stems in the temperate forests of Central Europe. Moreover, the null hypothesis that the difference between relative TRWs is equal to zero (or is only randomly different from zero) was not rejected, suggesting that it does not matter in which direction core sampling takes place and that one core sample per tree is sufficient. Even slope inclination and altitude showed no influence on the similarity in relative TRWs. The results also indicate that it is possible to derive basal areas backwards in time where actual basal area can be determined precisely, for instance by using the circumference measurement. However, different moisture content between sapwood and heartwood may influence the precision of the basal area reconstruction, but we hypothesise that the shrinkage is not significant enough to significantly decrease the precision of the reconstruction.

Since the inter-tree variability within a site is much higher than intra-tree variability around the stem, it is more efficient to minimise the former by maximising the number of trees sampled per site and by sampling only one core per tree. This last recommendation is especially relevant for dendroecological studies based on some form of standardisation of TRW series.

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