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ORIGINAL ARTICLE

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Is ray volume a possible factor influencing ring shake occurrence in chestnut wood?

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Abstract Radially oriented ray tissue is important for regulating radial strength of wood. The present study was undertaken in order to assess whether radial rays influence ring shake occurrence in chestnut wood (*Castanea sativa* Mill.), a species very prone to ring shake. Ray volume fraction was measured on tangential samples from two sets of wood discs, either with or without ring shake, collected from three coppice stands in the southern part of the Swiss Alps. Our data indicate that ring shaken trees tend to exhibit higher ray volume than unshaken ones. This rather unexpected finding could be partly explained if biomechanical processes that control and determine the inner architecture of the tree are considered.

Keywords Wood rays · *Castanea sativa* · Ring shake · Radial strength · Biomechanics

Introduction

Wood rays are known to play a key role in parallel-to-grain cracks occurring in wood. According to Mattheck and Kubler (1995), wood rays were shown to be structural points of weakness as well a reinforcement depending on the direction of load: they act as planes of weakness in wood that is subjected to tensile stress in a tangential direction but also as a reinforcing structure in wood that is subjected to tensile stress in a radial direction. The importance of ray tissue for the radial strength of wood has been demonstrated in several ways. Firstly, mechanical observations have shown that wood species displaying an elevated proportion of rays exhibit higher values of radial strength (Kollmann 1956; Schniewind 1959; Keller and Thiercelin 1975; Beery et al. 1983; Zipse 1997; Eckstein et al. 1998; Burgert et al. 2001; Tschegg et al. 2001). Secondly, thanks to recent technological progress permitting measurement of the radial properties of single isolated multiseriate wood rays, it has been demonstrated that in beech wood radial rays are about 10 times stiffer than axial tissues in the radial direction (Badel and Perré 1999) and about 3 times stronger than entire beech wood in its dry state (Burgert and Eckstein 2001). Thirdly, observations performed on spruce wood subjected to radial tensile failure tests and bending tests parallel to the grain have evidenced that cracks along growth ring borders were frequently arrested or became discontinuous at wood rays, indicating that breaking a wood ray across its longitudinal axis requires a high work of fracture (Bodner et al. 1997). Finally, confirming the hypothesis advanced by Mattheck and Kubler (1995) and by Eckstein et al. (1998), it has also been shown that living trees are able to adapt to new radial stress by modifying the orientation (Burgert et al. 1999) and the relative volume (Albrecht et al. 1995) of radial rays. On the basis of these numerous observations we can therefore conclude that in the radial direction rays constitute an almost ideal "fibre reinforced" tissue that improves the resistance of wood against tangential crack initiation and propagation.

Ring shake is a defect in chestnut (*Castanea sativa* Mill.) that consists of a separation that mainly forms in the (weakest) tangential plane in the ligneous tissue along the annual growth ring (Chanson et al. 1989) (Fig. 1). Given that reduced radial strength is thought to be one of the major causes of ring shake (Fonti et al. 2002), it could therefore be interesting to analyse the relationship between ray characteristics and ring shake occurrence in chestnut wood. This study explores from an anatomical point of view whether there are differences in the quantitative ray volume fraction that may help to explain why some individuals develop the defect while some others, grown under the same stand conditions, do not.

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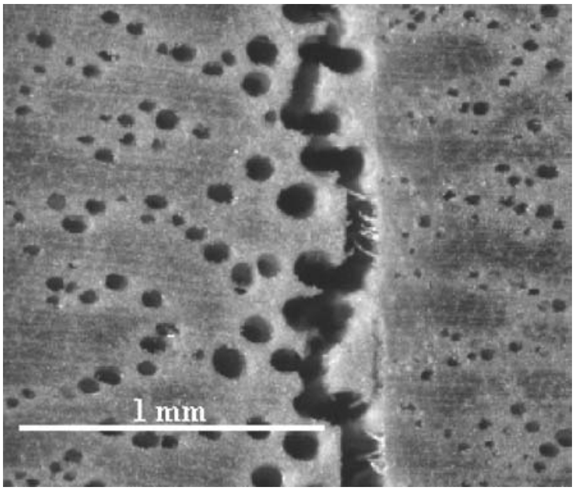

Fig. 1 Example of ring shake developing across the earlywood vessels of chestnut wood. Due to its particular wood structure, which is characterized by ring-porous wood and by small uniseriate radial rays, it is reasonable to suppose that the wood is particularly weak against stress acting along the radial axis. In fact, on one hand the earlywood vessels provide a fragile plane where ring shake can easily develop, while on the other hand the rays have an important role in offering resistance to cracks developing. This could therefore explain why, compared to other wood species, chestnut is so inclined to develop ring shake (Fonti et al. 2002

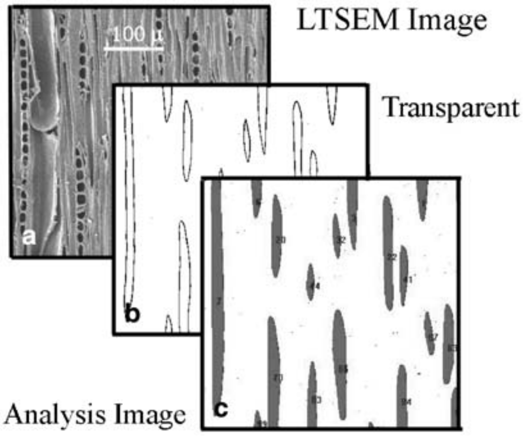

Fig. 2a–c Measurement procedure to provide images for the analysis. **a** The tangential section was captured using LTSEM, **b** a transparency was overlapped on the captured image and the perimeter of each single ray was drawn on the transparency. The transparent image was then digitised and used for the image analysis measurements, and **c** each single ray was recognised, shaded and subsequently measured

Materials and methods

C. sativa samples were obtained from three mature coppice stands situated in southern Switzerland. The last coppicing of the stands was in 1946–1951 for Novaggio, in 1950 for Gerra and in 1940–1955 for Bedano. From each stand discs about 5 cm in thickness were gathered from the bases (0.5 m aboveground) of at least 50 dominant or co-dominant chestnut shoots. After collection the discs were firstly air-dried for about 1 year to a moisture content of 12–15%. Afterwards, in order to perform a comparative analysis, one group consisting of 10 shake-free and another one formed by 10 extremely ring shaken discs (defined as dried discs displaying ring shake failure of more than 50 cm total length) were sampled from each site from all the gathered discs looking for similar representativeness of disc diameters in both categories. A strip 2 cm wide was chosen, including the pith but avoiding knots and other visible defects, across the minimum diameter of each disc. The minimum diameter was preferred in order to minimize the presence of reaction wood. After re-wetting wood strips (storing in water for 3 days), tangential sections were cut for the yearly ring corresponding to the growth years 1960, 1967, 1974, 1981, 1988 and 1995 and subsequently refined with a sliding microtome to obtain a clear surface. Each tangential section was observed with a low-temperature scanning electron-microscope (LTSEM) (Frey et al. 1996) and five 0.17 mm^2 wood images were randomly captured at a magnification of ×200. In total 1,800 images were collected. In order to measure the relative ray volume fraction a transparency was applied to each photographed image and rays were manually transferred to the transparency. Then, after digitisation of the transparency, measurements were performed using the "image pro plus" digital analysis program (Fig. 2), which permitted identification of and measurement of the surface covered by rays and its relation to the total tangential section surface considered (relative ray volume fraction).

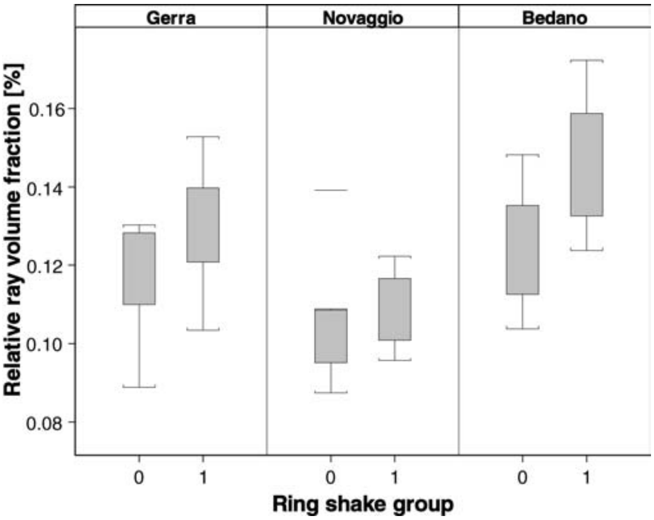

Fig. 3 Box plot of relative ray volume distinguishing between sites and groups: The plot data refers to the mean value calculated for each tree. 0= group without ring shake, 1= group with ring shake. Comparison of mean (*t*-test) between group 0 and 1 has given the following *P* values: Gerra =0.1118, Novaggio =0.3483, and Bedano =0.0074

Table 1 Relative ray volume fraction of all trees (ring shaken or not) among sites

Relative ray volume fraction (%)	Gerra	Novaggio	Bedano	All trees
Number of trees	20	20	20	60
Minimum	8.89	8.74	10.38	8.74
Maximum	15.28	12.23	17.23	17.23
Mean[a]	12.28	10.65	13.59	12.18
SD[a]	1.58	1.20	1.91	1.98

[a] The mean value and standard deviation refer to the mean value of the characteristic for each individual tree

Results and discussion

The relative ray volume fraction of all chestnut tree samples studied was in the range between 8.7% and 17.2%

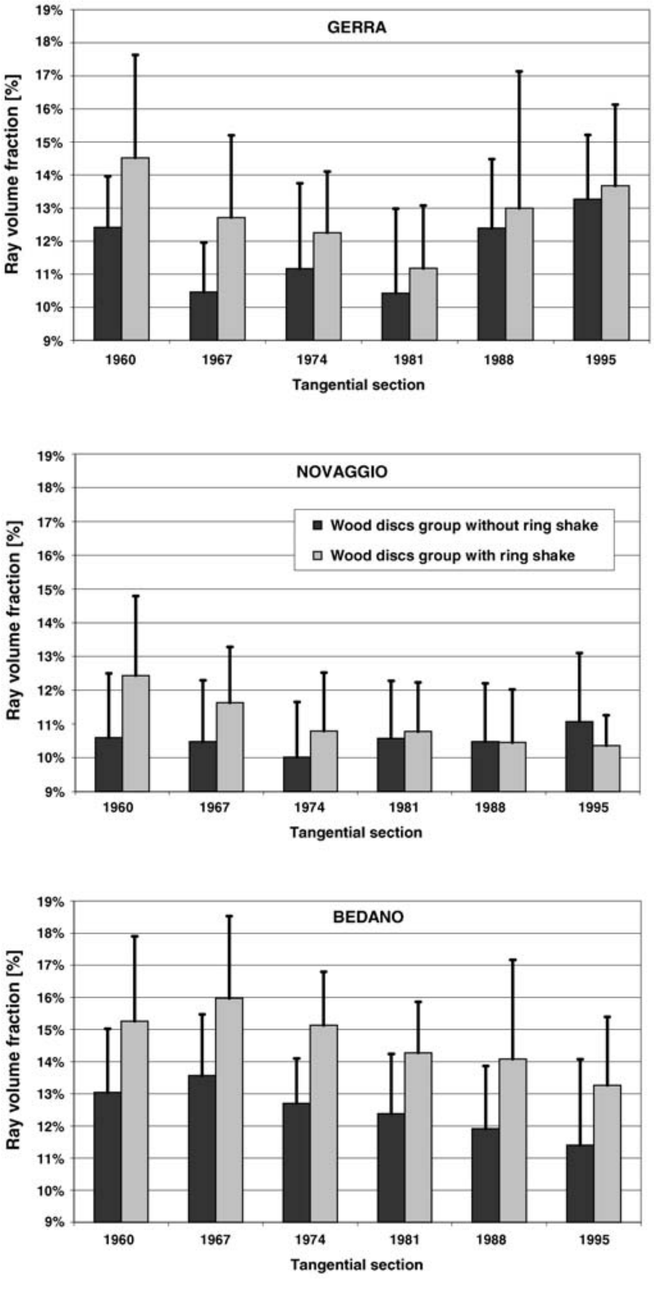

Fig. 4 Mean values and standard deviation of the relative ray volume fraction along the radial axes (for each tangential section considered) differentiating among stands and wood disc groups with and without ring shake

with a mean of 12.2% (Table 1) confirming the results (Burgert et al. 2001) that place chestnut wood amongst hardwood species that display a low volume of rays. Nevertheless these amounts seem to depend on the stand conditions because differences in mean ($P<0.05$, ANOVA one-way analysis) were observed between the three stands.

Assuming that radial rays effectively have a strengthening function along the radial axis of the wood, we therefore expected to observe a higher volume fraction of rays in chestnut trees without ring shake than in those displaying this defect. However, results obtained from our study cannot confirm this expectation. As Fig. 3 shows, no lower values between ring shaken and not ring shaken groups within the same site have been found. In contrast, ring shaken trees tended to have a higher volume of rays, even if the difference in mean was only significant for the stand of Bedano ($P<0.05$, *t*-test). This trend was fully confirmed along the entire radial axis, as shown in Fig. 4. Here we found that the tangential section taken from ring shaken trees always displayed a higher volume of rays than the unshaken ones, for all three stands.

In attempting to interpret this surprising result, we have to consider the biomechanical processes stimulating the ring shaken trees to produce more rays than the unshaken trees. In this case it is plausible that, in order to face higher stress levels and therefore confront the problem of ring shake, growth-stress-overloaded trees might generally create more rays than the stress-poor ones. But when the tree falls and the internal wood balance is destabilized, some of the stress can be released (Chanson et al. 1989) and new cracks can develop. In fact, most ring shakes have already occurred at that time, i.e. in fresh fallen timber (Fonti and Macchioni, unpublished data). The stress-overloaded trees (those with a higher ray volume fraction) then have more stress to release, which in some cases is so strong that the enlarged volume of rays may not be able to counteract. The expected outcome is therefore consistent with that observed in this study, even if apparently contradictory, where trees with ring shake display a larger volume fraction of radial rays than the unshaken ones.

Our study showed that the ray volume fraction does not directly influence the development of ring shake in chestnut wood. However, the results suggest that the ray volume fraction could likely be an indicator of the amount of growth stress which occurred in the living trees, and which could play an important role in the development of ring shake in chestnut.

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