Longitudinal and cross-sectional wood anatomy variability of vertical fir roots (*Abies alba* Mill.) as a record of landslide processes – an example from the Carpathian foothills

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Introduction

Changes of wood anatomy within a tree root occur when environmental conditions such as temperature, aeration, moisture, soil compaction as well as mechanical stress along the root change (Rowe, 1964; Fayle, 1968, 1975a, 1975b; Shea, 1973). The most significant anatomical changes occur when soil is removed off the root due to exposure to external conditions (Fayle, 1968; Gärtner, 2003, 2006). Analyses of changes in the structure of annual rings in tree roots are considered to be a useful tool in geomorphology and are taken into account in the context of a range of morphogenetic processes (Gärtner et al., 2001; Gärtner, 2003, 2006, 2007; Malik & Matyja, 2008; Stoffel & Bollschweiller, 2008; Corona et al., 2011). Gärtner et al. (2001), as well as Malik (2006, 2008), stressed that by analysing changes in the wood anatomy of roots exposed to external factors the intensity of past morphogenetic processes can be retraced. One of the processes which cause the exposure of roots is landsliding.

In 2010 a significant amount of rainfall occurred in Central and Eastern Europe. Activation of rainfall-induced landslides in mountain and foothill areas was the consequence of these meteorological conditions (Bartholy & Pongracz 2012). Following field investigations, one of these landslides in the Wiśnickie Foothills (Polish flysch Carpathians) was recorded and analysed in detail. The activation of the study landslide caused the exposure of roots and bending of trees. Three vegetation cycles later root samples were collected in the field and anatomical changes within the roots were analysed by referring to 2010 (when the activation of the landslide occurred). Exposed roots tend to form annual rings with a higher amount of latewood including compression wood (Alestalo, 1971; Carrara & Carroll, 1979; Gärtner, 2003, 2007; Rubiales et al., 2008; Wrońska-Wałach, 2009, 2014). Furthermore, after exposure the mechanical function of the roots starts to perform an important role as a consequence of which the entire structure of the roots' wood anatomy changes and wide wedging rings are formed (Fayle, 1968; Gärtner, 2003; Pérez-Rodríguez et al., 2007; Zielonka et al., 2014). Such assumptions were mainly based on the analysis of exposed horizontal roots. Fayle (1968) emphasised that, in the analysis of the growth pattern of roots, the location and orientation of the root within the root system is of high relevance. The growth pattern of horizontal roots differs significantly from the one which is typical for vertical roots (Fayle 1975a, b). Therefore, the main aim of the research was to detect the activity of landslide processes by means of wood anatomy analysis of exposed vertical fir (*Abies alba* Mill.) roots; the above-mentioned were rarely investigated before. This raises the question whether the record of the exposure of vertical roots by landslide processes is the same in the longitudinal and cross sectional profile of the root.

Study area

The research was carried out on a small landslide (0.14 ha) in southern Poland which was activated after spells of heavy rainfall which occurred in the Carpathian Foothills in 2010. The study area is located in the Wiśnickie Foothills (N: 49°56'47.95'' E: 20°30'21.3''). The study site was located in the headwater area of the Stara Rzeka stream where landslides are common features. The bedrock of the Wiśnickie Foothills is made of flysch which is covered by loess. The study site belongs to the lower mountain vegetation belt in which there are deciduous beech forests with common European silver fir (*Abies alba* Mill.) and beech (*Fagus sylvatica* L.). The study landslide is composed of a single niche and tongue (Figure 1) and located at 280-288 m a.s.l. The scarp of the landslide is 68 m long and 8 m high. The average annual precipitation totals in the study area for the period 1954-2012 are between 400 and 600 mm during the vegetation season. In 2010 total precipitation in May and June was about 500 mm, which was the main reason for the activation of the study landslide.

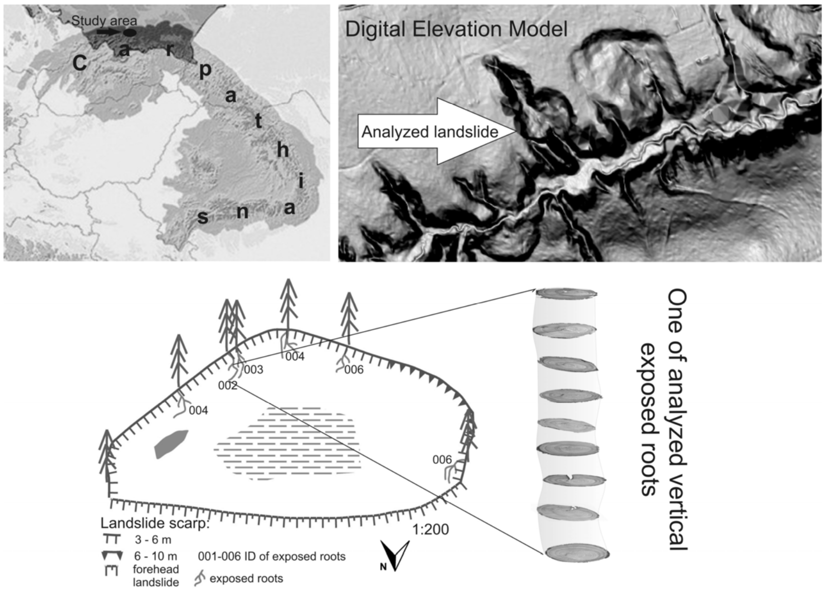

Figure 1. Study area: A – location of site in the Carpathians; B – study site – digital elevation model; C – outline of the landslide together with an example of one of the roots analysed (001-006 – roots ID)

Methods

Detailed geomorphological mapping was conducted in the study area. The activity of the landslide was investigated by exposed vertical fir roots, one of which was analysed in detail. The root was sampled 1 m from the trunk to reduce errors resulting from anatomical changes induced by stem sway, such as compression wood and false rings (Fayle 1968, 1975, LaMarche 1968). Eight samples were prepared from the root and used for further analysis. All samples were taken about 5 to 7 cm from each other to examine the anatomy of tree rings in different parts of the root. Root parts were polished and cut into 15-20 μm slides by the use of a GSL 1 Microtome (Gärtner et al. 2014). Microanalysis of root cross-sections was performed according to the procedure developed by F. Schweingruber (1990) and Gärtner et al. (2001). After laboratory preparation, images of the micro-sections were made using a polarising microscope (Nikon 50iPOL). The anatomical indicators on the basis of which the identification of the year of root exposure was established were the size of earlywood cells (EW) (Gärtner et al., 2001; Gärtner, 2003, 2006), the percentage of latewood (LW), the presence of compression wood (CW) and ring width (RW) (Bodoque et al., 2005, 2011; Corona et al., 2011; Wrońska-Wałach, 2014). Measurements of EW, LW and RW were performed using the WinCELL Pro software (Regent 2010) on each cross-section obtained from serial sectioning of the root. Visual detection of the first indication of exposure was carried out on the whole cross-section. Measurements were made on at least 30 tracheids and in four radii per cross-section (including the longest and the shortest radii) to check the differences between the anatomical indicators of tree rings (Figure 2). In addition cross-dating was carried out on the samples analysed.

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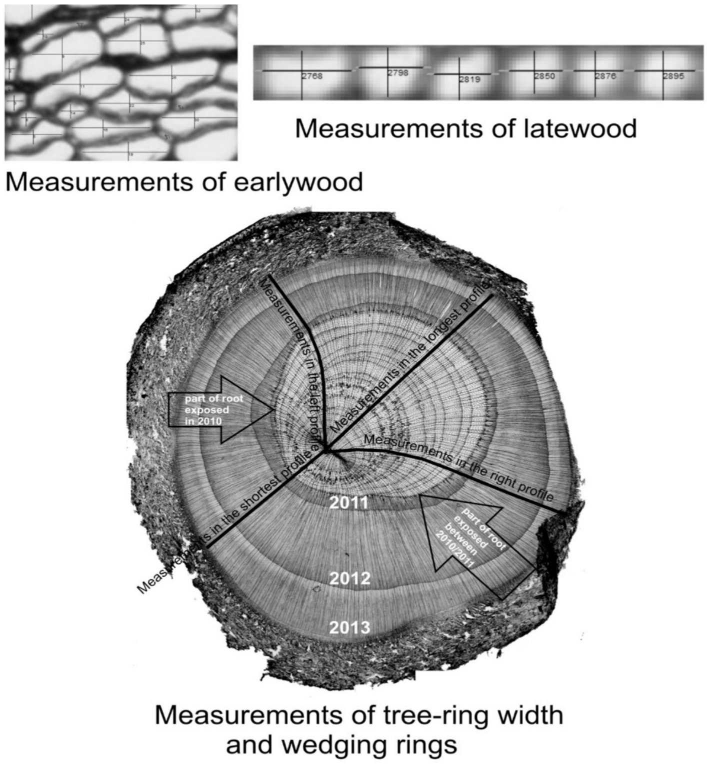

Figure 2. Root cross-section with four radii marked and an example of the anatomical indicators analysed in WinCELL.

Analyses of eccentricity and circularity were performed for every annual ring between 2008 and 2013. Within each cross-section each of these annual rings was vectorised in QGIS, creating a polygon having the shape and size of a whole root cross-section in the corresponding year. Geometric centres were calculated for each annual ring analysed in every cross-section; the actual centre of the root within each cross-section was marked as well. Distances between the actual centre of the root and the corresponding geometric centres were measured in every cross-section. These distances were presented as a percentage of the corresponding average root radii (calculated from the cross-sectional areas). The above steps allowed the dominating root-growth direction before and after exposure to be traced. The circularity of each annual ring was calculated by dividing its surface area by the surface area of a circle having the same perimeter.

Results

The analysis conducted proved that the anatomical changes along the longitudinal and cross-sectional profile of root wood are varied and occurred from 2009 to 2012 depending on the location within the root. The majority of the anatomical changes in tree rings in the roots appeared in 2010 (41%); many fewer were recognized in 2011 (30%). A relatively significant number of changes occurred in 2012 (24%) – about two years after activation of the landslide. Changes in EW were mainly recognized to have happened in 2010 (61%) and 2011 (21%). Nevertheless, in three of the cross-sections these changes did not emerge until 2012 (Figure 3). If we take into account the changes in LW, most (64%) took place in 2010, but some also occurred in 2011. In most cases (56%) increase in RW appeared two years after activation of the study landslide.
The first anatomical changes which indicate exposure were recognized in 2010, and are varied in the longitudinal profile. Maximal RW, developed in 2010, is from 436 µm in the upper part of root to 964 µm in the lower part. The analysis revealed diverse changes of EW in longitudinal profile (from 690 µm to 1119 µm) and increase of the LW content from 21% to 98%. The maximum width of the 2010 tree-rings increases suddenly in the lower part of the study root. Moreover, this ring tends to

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wedge in cross-section and longitudinal profile. In the longest radius, the 2010 ring is either reduced to one or two rows of tracheids with no signs in LW connected with exposure or has completely disappeared. Changes of anatomical indicators for the 2011 ring are less variable in longitudinal profile with no evidence of wedging.

In most of the cross-sections in the longest of the radii analysed, the increase in the percentage of LW in tree-rings appeared in 2010. However, the stem-like RW and CW did not emerge until 2011. In the shortest radius the same amount of anatomical change was recognized for rings from 2010 and 2011. In the left and right radii of cross-sections most EW changes occurred in 2010 (Figure 3). No regularity in the longitudinal profile was observed for the above-mentioned indicators.

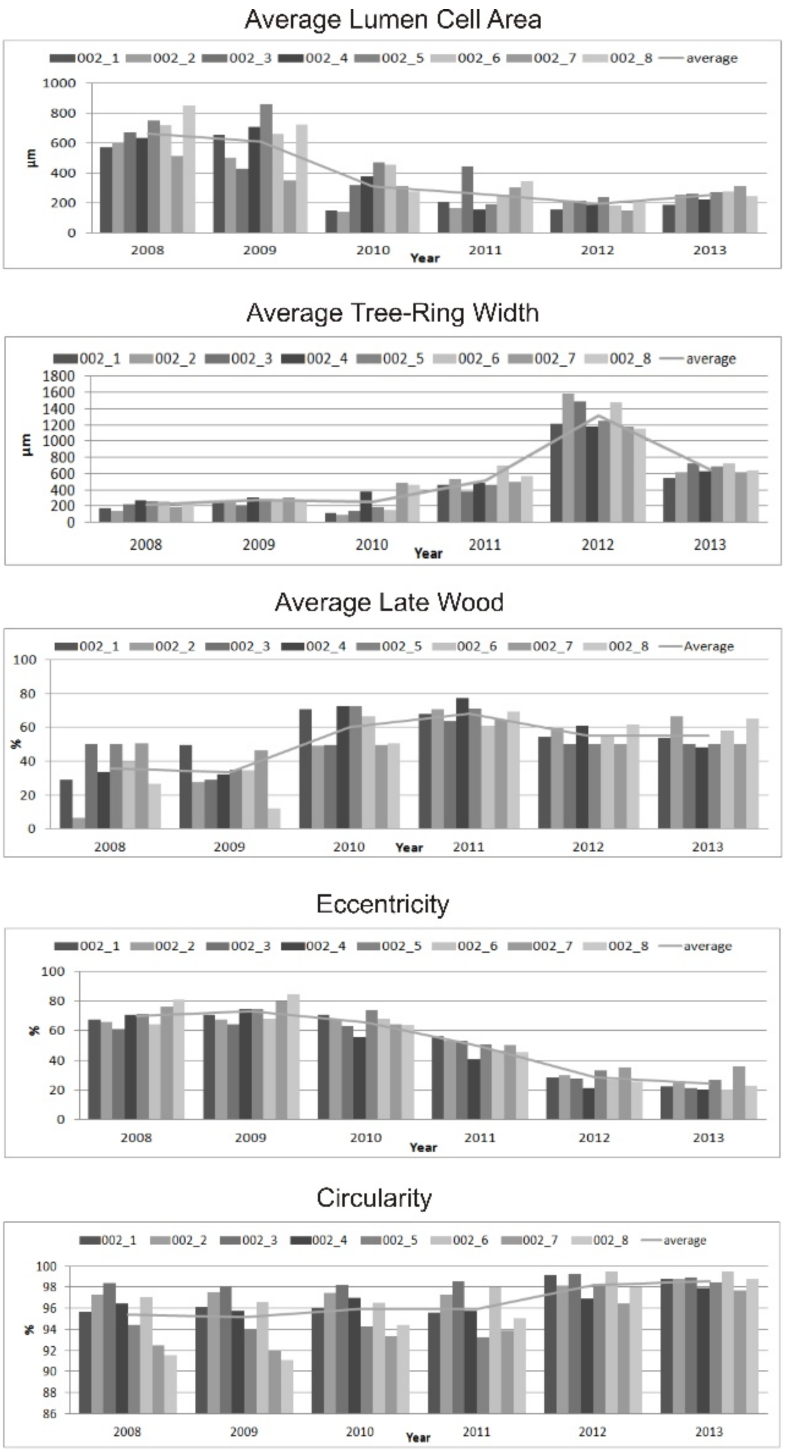

Figure 3: Variation in tree-ring wood anatomy parameters in eight cross-sections of exposed vertical fir root (002_1 – 002_8) in the period 2008-2013.

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After root exposure the eccentricity decreased from an average 72.6% in 2009 to an average 24.5% in 2013, while circularity increased from an average 95.2% to an average 98.4%. The study root was clearly increasing its eccentricity until 2009 with 9-10 wedging rings recognised. In 2010 the root eccentricity decreased in most cross-sections, mainly in the lower part of the root. The first year when eccentricity substantially decreased in the whole root was 2011 (Figure 3). In 2010 a noticeable increase in circularity was noted in the cross-sections having the highest RW which influenced average increase. After nearly no change in 2011, a substantial increase in circularity occurred in the whole root apart from one cross-section in 2012, an increase continuing in 2013.

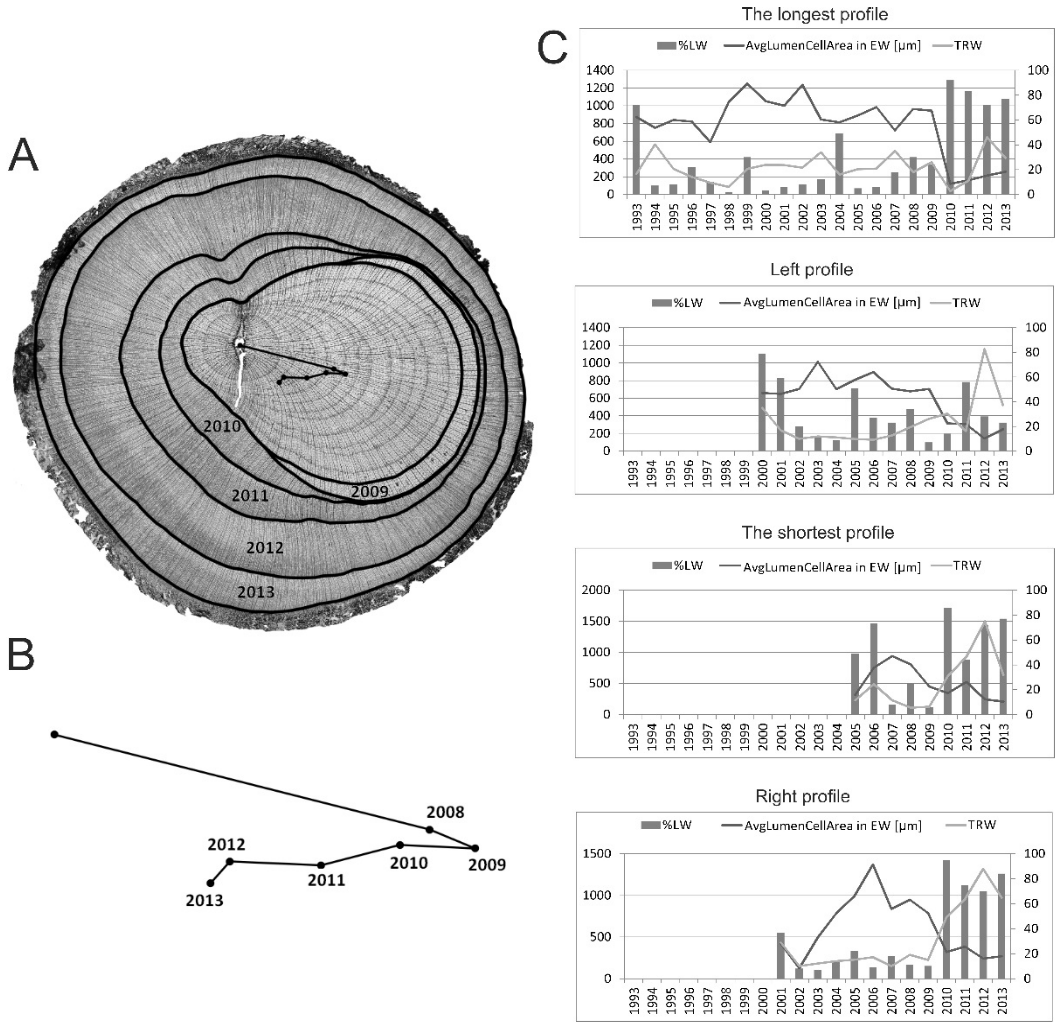

Figure 4. Characteristics of a typical root cross-section (002_8): A – growth pattern, B – geometric centre path (upper left point indicates the actual centre of the root), C – annual tree-ring parameters in four radii

Discussion

Exposed vertical fir roots have a similar tendency in overall structural change in wood anatomy to that found in horizontal roots analysed previously by different researchers (Alestalo, 1971; Carrara & Carroll, 1979; Gärtner, 2003, 2007; Rubiales et al., 2008; Wrońska-Wałach, 2009, 2014). Fayle (1968) as well as Gärtner (2003) emphasised that after exposure the mechanical function of roots starts to perform an important role, as a consequence of which the entire structure of root's wood anatomy changes. An increase in root eccentricity is usually observed after exposure. The shape of the study root as well as of other roots observed in our study area does not follow general rules. In these cases the roots are eccentric with wedging rings before exposure and are becoming concentric after exposure.

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As we consider the root exposure by landslide processes directly observed in the field, we know that the root was exposed in 2010. Therefore, we referred all wood anatomy parameters analysed to that year. In 61% of cases the changes of EW occurred in 2010 and the analysis confirmed that EW changes are the most important indicators for recognising the year of exposure (Gärtner et al., 2001; Gärtner 2003, 2007). Nevertheless, selection of a suitable root sampling location is very important. Our results showed that in some parts of the root the EW anatomical changes are shifted by about one to two years. It is also indisputable that it is necessary to analyse the whole cross-section when dealing with exposed roots as we found a clear differentiation in the EW changes in the four measured radii.

According to Malik (2006, 2008), when the changes in EW occur at the beginning of the ring, the exposure occurred in the previous year or during the dormant season. In our analysis we know that the root was exposed abruptly at the beginning of the vegetation growth period in 2010 and that the first changes in both EW and LW were already visible in 2010. The ring from 2010 is not completely formed and wedges in both cross-sections and longitudinal profile. An increase in RW and percentage of LW, which are considered as indicating upcoming root exposure (Fayle 1968; Gärtner 2003; Rubiales et al., 2008) were not observed in rings developed in 2008 and 2009, which confirms abrupt exposure in 2010. In subsequent years, the mechanical function of the root became more important, therefore the root produced CW. As secondary growth of the root, normally affected by climatic conditions, was enhanced by the production of CW (Timell, 1986; Schweingruber 1991), an increase in RW and amount of LW occurred (Figure 2, 4).

Variability in longitudinal and cross-sectional wood anatomy of vertical fir roots exposed by landslide processes may be a result of either stepwise exposure or the different response of different parts of roots to a single event. Within each part of the root the first changes of EW and LW occurred in 2010, but the signal is variable in the cross-section of the root. As it is a vertical root, when EW tracheids decrease and the average lumen size area is only varied in the cross-section of the root, the exposure of the root is more likely to be a result of a single event as a result of which variation in stress occurred along the root. The consequence of single event exposure could also be observed in terms of longitudinal changes in the 2010 tree-ring resulting in a decrease in eccentricity and an increase in circularity.

Conclusions

1. The main direction of radial growth within the root tends to change with time, especially after events which modify the distribution of mechanical stress and cause the production of compression wood. The above-mentioned seems to apply to vertical roots in general and was observed in all the roots examined originating from the study site.
2. In vertical fir roots concentricity and circularity increase after exposure. The response within the root is varied in longitudinal profile as a result of different mechanical stresses. The first ring after root exposure tends to wedge in longitudinal and cross-sectional profile and may be very narrow or missing in some places within the root.
3. In addition to the horizontal roots, the vertical roots in root systems could also be taken into account in the analysis of landslide processes. However, the analysis of a vertical fir root in one location on the root does not incorporate sufficient data on root exposure. Selection of sampling is of great importance and serial sectioning of a root seems to be the best solution.

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