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Original article

Dendrochronology as a source of data for landslide activity maps – an example from Beskid Żywiecki Mountains (Western Carpathians, Poland)

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ABSTRACT

We applied dendrochronological methods for dating landslide activity in the study area (3.75 km^2), on the slopes of Sucha Mountain (1040 m a.s.l.), in the Beskid Żywiecki Mountains, in the Western Carpathians. 46 sampling sites were distributed throughout the study area. At each site we sampled 1-3 coniferous trees: Norway spruces (*Picea abies* Karst.) and/or silver firs (*Abies alba* Mill.). From each tree 2 cores were sampled: one from the upslope and the other from the downslope side of the stem. Based on tree-ring widths measured for opposite sides of stems we have calculated eccentricity index values and dated past landslide events. Mean frequency of landslides was obtained for each sampling site. Finally, the data was interpolated into a map of landslide activity. Inverse Distance Weighting (IDW) interpolation has been applied. For most of the study area we found medium (19 sites) and low (23 sites) levels of landslide activity. The highest level of activity was recorded for the largest landslide slope and for the one small landslide. The study conducted on Sucha Mountain has shown that dendrochronology can be an effective method for analysing landslide activity and may be useful in further studies, including those for landslide hazard and risk assessments.

KEY WORDS: dendrochronology, landslides, growth eccentricity, Western Carpathians

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1. Introduction

Landslides are a common geodynamic hazard in mountainous regions worldwide, including the Polish part of the Carpathian Mountains. They pose a threat to infrastructure, cause significant financial losses and even fatalities (Wojciechowski, 2007; Cui et al., 2009; Baroň et al., 2011). Over 95% of all landslides in Poland have occurred in the Carpathian Mts (Rączkowski & Mrozek, 2002). Extreme landslides, endangering people and infrastructure, have occurred several times in the Western Carpathians, e.g. in: 1997, 1998, 2000, 2001, 2006, 2010 (Bajgier-Kowalska, 2004–2005). One of the landslides which was active in 2001 was the Lachowice landslide (the Beskid Makowski Mountains) which affected an area of about 10 ha and displaced 5 million tons of colluvia destroying 15 residential buildings and damaging 35 others (Bajgier-Kowalska, 2004–2005). In 1997, over 20,000 landslides took place in the Polish Carpathian Mts, during the most catastrophic landslide events caused by rainfall and floods. Long-term precipitation in May-June and September in 2010 resulted in the activation of old landslides, the formation of new landslides and the destruction of infrastructure on a smaller scale (compared to 1997). Landslides in 2010 occurred in Poland, Czech Republic and Slovakia, but the greatest damage was observed in the Polish Carpathians (1 345 active landslides, 1 709 damaged buildings; data according to the Polish Geological Institute). One of the landslides activated in 2010 was a landslide on the Prusów Mountain in Milówka, adjacent to the study area. The landslide destroyed a road and 9 buildings (Wistuba et al., 2014).

The above examples prove the importance of analyses of landslide activity for hazard prevention and risk management. There are few effective methods available for the recognition and monitoring of active landslides. Among these geomorphological, geological, geophysical and geodetic methods can be applied (Carrara et al., 2003; Migoń et al., 2010; Kamiński, 2015). However, these methods are often expensive to apply (resulting in a small number of landslides covered by monitoring, e.g. inclinometric monitoring). In addition, data on landslide activities have are only been obtained since the monitoring system was first established (Bednarczyk, 2015) which is usually a very short period as the above mentioned methods are relatively new. The application of dendrochronological methods could potentially complement the gaps in the existing set of research methods and improve the understanding of landslide activity and risk.

During their radial growth tree stems produce annual rings which may provide a year-by-year record of past environmental disturbances, such as landslides. Trees growing on landslide slopes have tilted and bent stems (Fig. 1). Stem deformations affects the structure of wood and tree-rings (Stefanini, 2004; Wistuba et al., 2013). Trees develop ring eccentricity, which is the tendency for a single tree to develop wider rings on one side of the stem compared to the opposite side (Wistuba et al., 2013). Thus, eccentricity is a feature of the wood anatomy diagnostic for active landslides. There are numerous examples of the application of dendrochronology in landslide research (Guida et al., 2008; Migoń et al.,2014), including ring eccentricity (e.g. Braam et al., 1987; Corominas & Moya, 2010; Malik & Wistuba, 2012; Migoń et al., 2014). There are, however, only a few examples of the practical applications of dendrogeomorphic methods (e.g. Catani et al., 2005; Stoffel, 2005; Lopez Saez et al., 2012; Malik et al., 2016). The authors used diverse methods of landslide mapping, e.g.: by attributing the time elapsed between single landslide events to single injured trees (Stoffel, 2005) or by developing landslide hazard and risk maps using GIS techniques (Catani et al., 2005).

In our study conducted in the Beskid Żywiecki Mountains (Western Carpathians, Poland) we have used tree-ring eccentricity to develop a map of landslide activity. The aim of the study was to check the usefulness of dendrochronological methods for landslide activity mapping and to check their potential use in further preparation of hazard and risk maps.

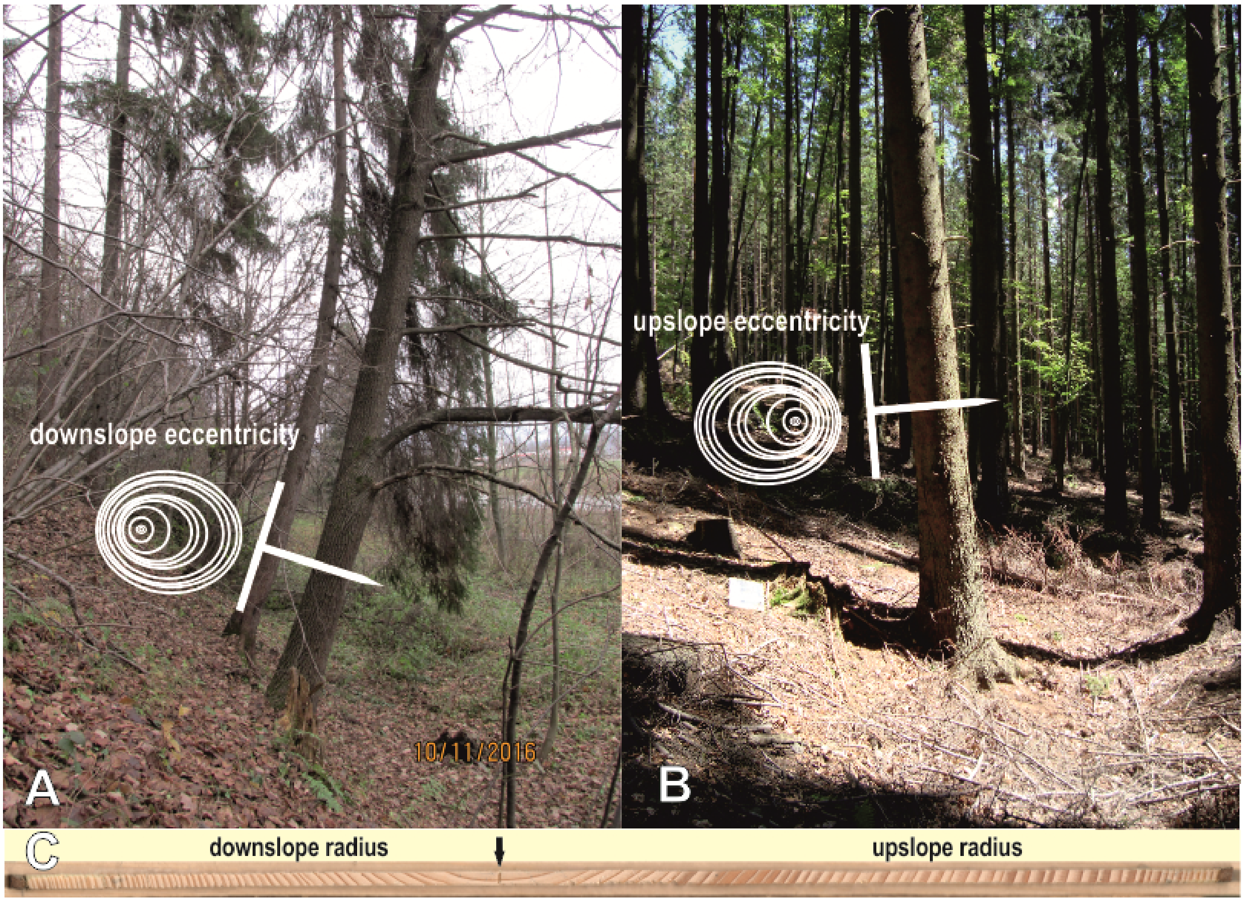

Fig. 1. Trees tilted due to slope movement: (A) in stems tilted downslope – downslope eccentricity develops, in stems tilted upslope – upslope eccentricity develops (B) and (C) an example of eccentric core taken from a Norway spruce stem tilted upslope

2. Study area

The study area is located on the slopes of Sucha Mountain (max 1040 m a.s.l.) (Fig. 2B), in the Beskid Żywiecki Mountains, Western Carpathians, in the southern part of Poland (Fig. 2A). The tested area of 3.75 km² lies between the Salomonka and Soła valleys. The bedrock of the study area is composed of sandstones and shales of the Magura nappe, flysch deposits typical for the region (Stupnicka, 2007). The test area included landslides of various types (e.g. flow-type, extensive rotational landslides) and size (between 80 and 1000 m wide, 70 and 900 m long). The majority of landslides represents a moderately steep slope gradient (5 to 15°). Headscarps and secondary scarps are exceptions with slope inclinations exceeding 25°. Also in the headwaters of the V-shaped valleys and lower part of the slopes of the valleys, the slope gradients exceed 25° (in extreme cases exceed 45°). Landslides affect slopes of different aspects, primarily slopes facing N and NE (based on the digital elevation models analyses from LiDAR data).

According to Hess (1965), the area of the present research is situated in the cold climatic zone with average temperatures of 2–4°C and a precipitation of between 1150–1350 mm. The average annual precipitation at the nearby gauging station (Żabnica, 550 m n.p.m.) is 1136 mm. Snow cover lasts for about 120-150 days, from December in the highest part of the mountains, while in the Soła valley it lasts between 80-100 days (Szczepanek, 2003). Winds from a south-western and western direction prevail. Most of the study is covered with forest and belongs to the lower montane vegetation belt, where deciduous beech forests with common beech (*Fagus sylvatica* L.) and silver fir (*Abies alba* Mill.) occur (Seneta & Dolatowski, 2008). However, at present the study area is planted with, monoculture forests with Norway spruce (*Picea abies* Karst.) and rarely silver fir.

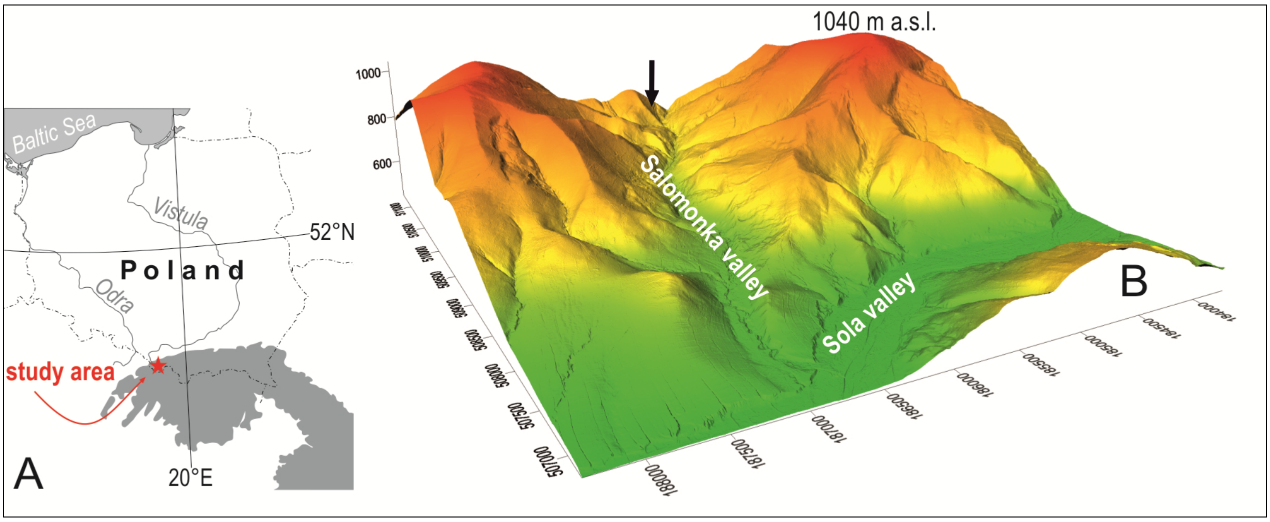

Fig. 2. Location of the study area in the Western Carpathians (A), in the Beskid Żywiecki Mountains and on the slopes of Sucha Mountain (B). An arrow marks the location of the reference slope

3. Methods

Dendrochronological samples were taken at 46 sampling sites spread over the test area. Their location was determined based on the relief (i.e. distribution of slopes) observed on DEM images from LiDAR data. Orthophotos were also used to determine the range of coniferous forests suitable for sampling. At each point we sampled 1-3 coniferous trees, depending on the availability of healthy specimens. We sampled Norway spruces (*Picea abies*) and/or silver firs (*Abies alba*). From each tree two cores were sampled at breast height according to the slope direction: one core was taken from the upslope side of a stem and the other from the downslope side of a stem. Samples were a subject of standard dendrochronological processing and tree-ring widths were measured (with 0.01 mm accuracy). Next, tree-ring widths measured on opposite sides of single stems were recalculated into eccentricity index values (Fig. 3). We used the method of the per cent eccentricity index (according to Wistuba et al., 2013). Landslide events were dated using reference thresholds (average levels of eccentricity typical for a nearby stable slope). Values of reference thresholds were - 38.81% for downslope events and 32.79% for upslope events being average levels of eccentricity in 10 trees growing on a stable slope adjacent to the study area (Fig. 2). The obtained dating results allowed us to determine the mean frequency of landslide events at each sampling site. Next, based on the mean frequency of landslides, a map of landslide activity was developed using Inverse Distance Weighting (IDW) interpolation. Landslide activity mapping was performed using ESRI ArcInfo 10 software.

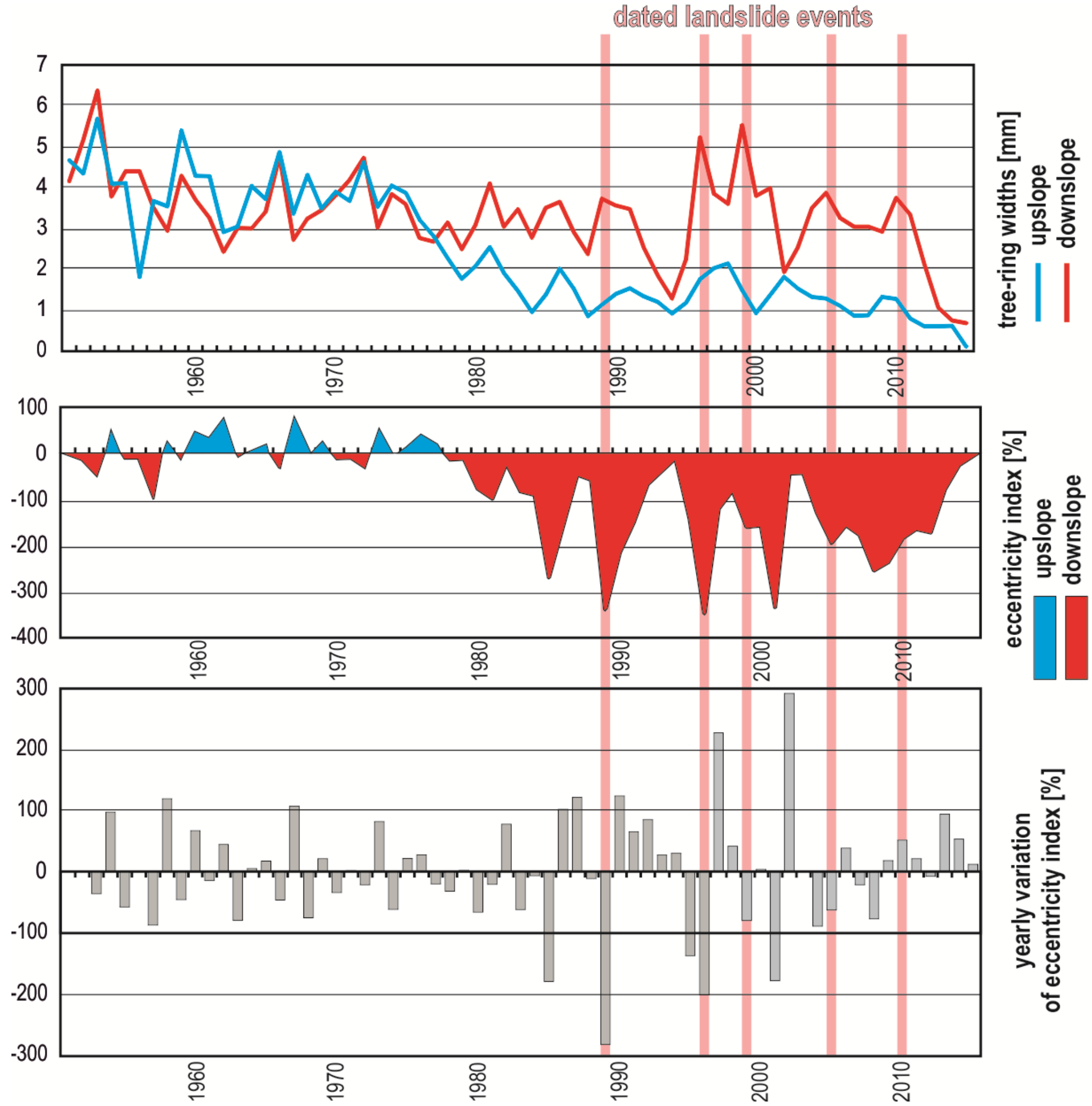

Fig. 3. Dating of landslides recorded in the stem of a single Norway spruce from the study area: tree ring widths [mm], eccentricity index [%] and its yearly variation [%]

4. Results

The dendrochronological record covers the period from 1883 to 2015. Sampled trees were 15 to 133 years old, but only a few of them were very young. Average frequency of landsliding events dated for each sampling site varies from 0 events/10 years to 4,29 events/10 years (Fig. 4). Most of the sampling sites represent an average frequency of 0.61 to 1.2 events/10 years and 1.21 to 1.8 events/10 years. The highest landslide activity (an average of >2.4 events/10 years) was obtained for the lower part of the body of the largest landslide (on the left side of the River Salomonka valley) and for the lower part of the body of the small landslide (on the right side of the River Soła valley). Landslide activity in study area is therefore diverse. Besides slopes with landslide relief a medium frequency of landslide events is also typical for some slopes devoid of landslide relief (Fig. 4). At the same time landslide slopes can be found with a low frequency of events.

Based on the results of dendrochronological dating and their interpolation we have obtained a landslide activity map (Fig. 5) with an average frequency of landslide events dated from tree rings. For most of the study area we have found medium (found in 19 sites with an average frequency of 1.21-2.4 events/10 years) and low (found in 23 sites with an average frequency of 0.00-1.2 events/10 years) levels of landslide activity. The highest level of activity was recorded for the largest landslide and for the one small landslide and the lowest, for the smallest landslides of landslide relief in the study area (Fig. 5). The range of areas with medium and high activity overlaps with the range of landslide relief visible on the digital elevation model (DEM) from airborne LiDAR data (Fig. 5). However, there are some cases of slopes devoid of any signs of landslide relief present at low and medium levels of landslide activity dated from the tree rings (Fig. 5). Probably those slopes have been subjected to initial landsliding, not yet visible in the slope relief.

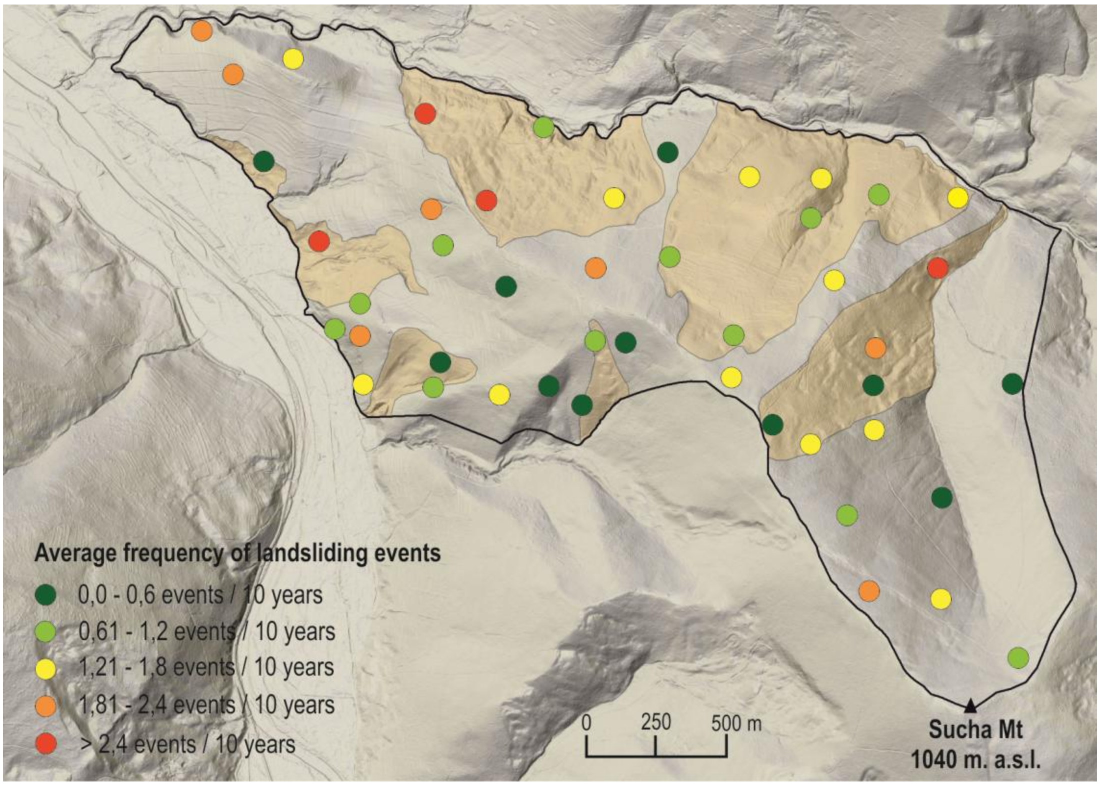

Fig. 4. Average frequency of landslide events dated in each sampling site (shaded relief map based on the DEM from LiDAR data; data source: Central Office for Geodetic and Cartographic Documentation, Poland)

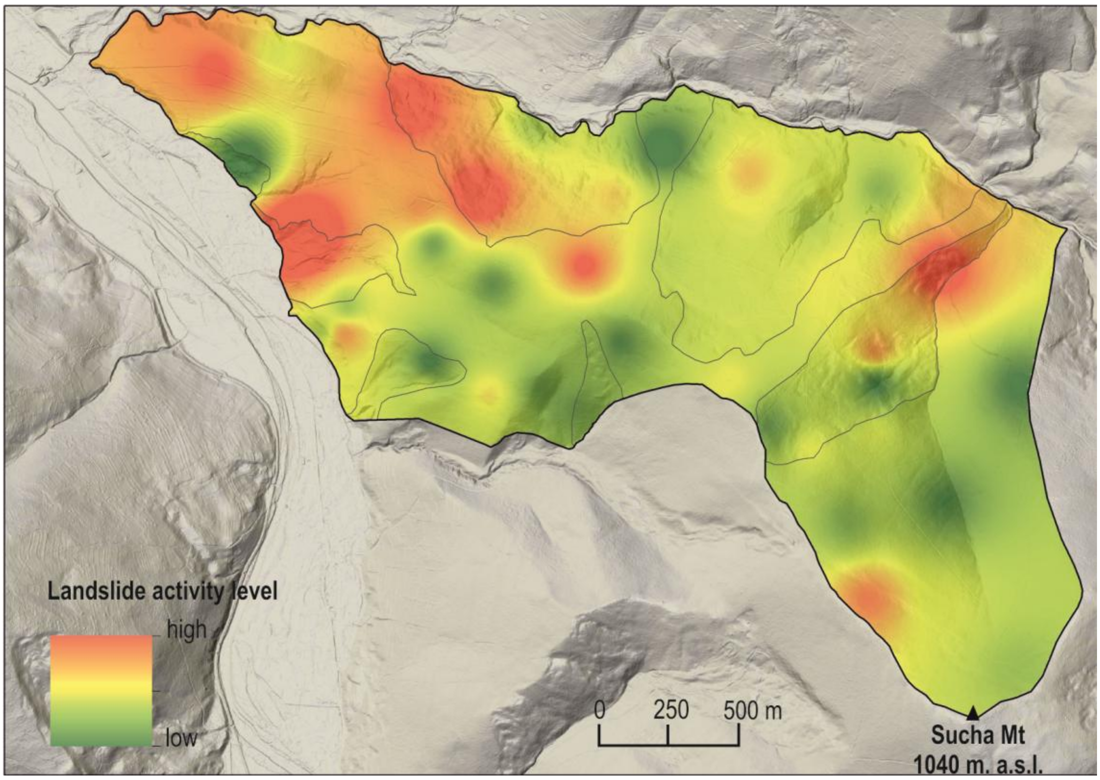

Fig. 5. Map of landslide activity on the Sucha Mountain massif determined on the basis of the results from the analysis of tree-ring eccentricity (shaded relief map based on DEM from LiDAR data; data source: Central Office for Geodetic and Cartographic Documentation, Poland)

5. Discussion

Dendrochronological methods can be used successfully in geomorphology, e.g. in the analysis of landslides (MALIK ET AL., 2016), debris flows (MALIK & OWCZAREK, 2009), fluvial erosion (MALIK & CISZEWSKI, 2008), flooding (ZIELONKA ET AL., 2008). In most cases, dendrochronological data from landslides is used for detailed spatio-temporal analysis of one landslide form (ŁUSZCZYŃSKA & WISTUBA, 2015; NAWROCKA, 2013) or to compare the results of dendrochronological analyses with data on triggering factors, such as heavy rainfall, earthquakes (ŠILHÁN ET AL., 2012). On the other hand, mapping geomorphological processes is becoming increasingly popular. At the end of the 1960s the entire area of the Polish Flysch Carpathians was checked for the presence of landslides (RĄCZKOWSKI, 2007). The inventory was based on geomorphological field observations which were then presented on maps showing the extent of landslide slopes. At present, landslide mapping is mainly conducted with the use of statistical methods and GIS techniques (CATANI ET AL., 2005). Most landslide mapping studies have been based on susceptibility maps. Therefore, they provide mainly estimates of where the landslides are expected to occur (e.g. GUZZETTI ET AL., 2005). The assessment of landslide susceptibility and risk can be conducted using e.g. aerial-photo interpretation, field surveys and remote sensing techniques such as DIn- SAR and PS-InSAR. However, data obtained using these listed methods provide only partial information on landslide history, as they are available only for the short period since the beginning of these measurements. The application of dendrochronological methods allows us to develop maps of landslide activity based on data sets covering tens or even hundreds of years. The method proposed in this paper is based on extensive data from past landslides and provides a significant addition to existing methods for prediction of spatial and temporal reactivation of landslides. Maps of the probability of landslide reactivation, based on dendrochronological analyses, were also developed using Poisson distribution for the Pra Bellon landslide (French Alps) (LOPEZ SAEZ ET AL., 2012). This approach allows for the determination of quantitative probabilities of reactivation estimated directly from the frequency of past landslide events. So far, the interpolation of dendrochronological analyses results is still uncommon, however, our study shows that dendrochronological methods can be successfully applied to develop interpolated maps of landslide activity.

Dendrochronological studies conducted in the area of Sucha Mountain have allowed us to distinguish landslides currently active from relict landslides, active in the past and relatively stable now (Fig. 4, 5). Also in the case of slopes without any landslide relief, it was possible to divide them into stable slopes and slopes which despite the lack of landslide relief show dendrochronological signs of landsliding, probably of an initial character (Fig. 4, 5). Such areas are endangered by mass movements and should not be inhabited or be subject to development. Similar observations from the landslide in the Southern Apennines were described by GUIDA ET AL. (2008). The authors assessed a large, reactivated landslide system on the basis of dendrochronological and geomorphological analyses and instrumental measurements.

Although our research shows that dendrochronology has significant potential for studying and presenting the spatial distribution of landslide activity the method also has some weaknesses. The method of interpolation of dendrochronological results into a map of landslide activity needs further testing and improvement to eliminate or reduce errors. E.g. during the interpolation process the boundaries within the interpolated area should be determined, perhaps dividing landslide slopes and slopes without landslide relief, and preventing the interpolation between opposite valley sides. Next, the map of landslide activity based on the results of dendrochronological dating can be combined with land use maps and local plans of spatial development. This will allow us to highlight stable areas, potentially safe for existing buildings and future development, and landslide active areas, potentially endangered by infrastructure damage. Further improvement and testing the methods proposed in this paper should allow for a better assessment of landslide hazard and risk in mountain areas.

6. Conclusions

(1) Through analysing the eccentricity of tree-rings of *Picea abies* and *Abies alba* growing in the study area the spatial variation in landslide activity was analysed: from stable slopes, where no events of landslides were recorded to slopes where the average frequency of landslide events was up to 4.29 events/10 years.

(2) Results of dendrochronological dating were interpolated into a map of landslide activity, which proved to be useful for landslide activity mapping and is a promising approach for detecting slopes with high landslide hazard and those

potentially threatened by catastrophic mass movements.

(3) Maps of landslide activity based on tree-ring analyses can be used for further preparation of hazard and risk maps useful for disaster prevention, as well as for planning potential engineering works.

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