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Impacts of age-dependent tree sensitivity and dating approaches on dendrogeomorphic time series of landslides

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ABSTRACT

Different approaches and thresholds have been utilized in the past to date landslides with growth ring series of disturbed trees. Past work was mostly based on conifer species because of their well-defined ring boundaries and the easy identification of compression wood after stem tilting. More recently, work has been expanded to include broad-leaved trees, which are thought to produce less and less evident reactions after landsliding. This contribution reviews recent progress made in dendrogeomorphic landslide analysis and introduces a new approach in which landslides are dated via ring eccentricity formed after tilting. We compare results of this new and the more conventional approaches. In addition, the paper also addresses tree sensitivity to landslide disturbance as a function of tree age and trunk diameter using 119 common beech (*Fagus sylvatica* L.) and 39 Crimean pine (*Pinus nigra* ssp. *pallasiana*) trees growing on two landslide bodies. The landslide events reconstructed with the classical approach (reaction wood) also appear as events in the eccentricity analysis, but the inclusion of eccentricity clearly allowed for more (162%) landslides to be detected in the tree-ring series. With respect to tree sensitivity, conifers and broad-leaved trees show the strongest reactions to landslides at ages comprised between 40 and 60 years, with a second phase of increased sensitivity in *P. nigra* at ages of ca. 120–130 years. These phases of highest sensitivities correspond with trunk diameters at breast height of 6–8 and 18–22 cm, respectively (*P. nigra*). This study thus calls for the inclusion of eccentricity analyses in future landslide reconstructions as well as for the selection of trees belonging to different age and diameter classes to allow for a well-balanced and more complete reconstruction of past events.

1. Introduction

One of the most important issues of current landslide research is related to the dating of their occurrence, in spatial and in temporal terms (Corominas and Moya, 2010). Landslide chronologies thus play a key role because they provide very essential information on past activity and thereby contribute substantially to hazard assessment, in particular in areas with intensive anthropogenic use. In most cases, however, knowledge of past landslide activity remains very incomplete (Lopez Saez et al., 2012a) and archival records of past activity typically overrepresent the largest and miss the smaller events (Mayer et al., 2010; Raška et al., in press), even more so in remote areas where settlements or transport corridors have only been constructed in the recent past (Lopez Saez et al., 2012b). Detailed reconstruction of landslide chronologies has a particular merit for the recent past for which climatic records generally are available and landslide triggering thresholds can be achieved with the highest accuracy.

The highest accuracy in mass-movement dating in forests can typically be achieved with dendrogeomorphic methods (Stoffel and Bollschweiler, 2008; Stoffel and Corona, 2014), with which past activity can typically be dated to the year and sometimes even to the season. Tree-ring records have been used widely in debris flow (Bollschweiler and Stoffel, 2010; Stoffel and Wilford, 2012; Strunk, 1991), rockfall (Stoffel and Perret, 2006; Stoffel et al., 2005a,b; Trappmann et al., 2013), or snow avalanche reconstructions (Butler and Malanson, 1985; Corona et al., 2010, 2012; Schläppy et al., 2014). The dendrogeomorphic dating of landslides has a long-standing history (Alestalo, 1971; Braam et al., 1987) as well, and a wide range of methodological approaches has been proposed in the past to unveil their activity, with a focus on specific, abrupt changes in tree growth (Table 1; Stoffel et al., 2013; Corona et al., 2014). Common understanding and agreement exist that trees growing on active landslides are often deflected away from their upright position and that destabilized trees will react to tilting by forming reaction wood (Braam et al., 1987). Conifer species will form compression wood to push the tilted trunk back to the vertical position. Compression wood can be identified via its darker color and rounded cells with thicker cell walls (Timell, 1986). By contrast, broad-leaved species will form tension wood on the upper side

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Table 1
Overview of past dendrogeomorphic studies focusing on landslide activity, number of trees (and species) analyzed, and approaches used.

Author and year	Sample size	Species	Method used
Astrade et al. (1998)	41	Conniferous	Reaction wood, growth suppression
Bégin and Filion (1988)	60	Conniferous	Reaction wood, growth suppression
Bollati et al. (2012)	45	Conniferous	Reaction wood, growth suppression
Braam et al. (1987)	56	Conniferous	Eccentricity computation
Burda (2010)	35	Broad-leaved	Eccentricity computation
Carrara and O'Neill (2003)	32	Conniferous	Reaction wood, growth suppression
Carrara et al. (2003)	13	Conniferous	Reaction wood, growth suppression
Corominas and Moya (1999)	240	Not provided	Reaction wood, eccentricity
Fantucci and Sorriso-Valvo (1999)	24	Broad-leaved	Ring width anomalies
Fleming and Johnson (1994)	2	Conniferous	Eccentricity computation
Gers et al. (2001)	28	Broad-leaved	Reaction wood, growth suppression
Grau et al. (2003)	22	Broad-leaved	Ring width anomalies
Guida et al. (2008)	54	Broad-leaved	Ring width anomalies, eccentricity
Ilinca and Gheuca (2011)	20	Conniferous	Reaction wood, growth suppression
Klimeš et al. (2009)	7	Conniferous	Eccentricity computation
Lopez Saez et al. (2012a)	79	Conniferous	Reaction wood, growth suppression
Lopez Saez et al. (2012b)	403	Conniferous	Reaction wood, growth suppression
Lopez Saez et al. (2013a)	759	Conniferous	Reaction wood, growth suppression
Lopez Saez et al. (2013b)	223	Conniferous	Reaction wood, growth suppression
Malik and Wistuba (2012)	42	Conniferous	Eccentricity computation
Pánek et al. (2011)	108	Conniferous	Reaction wood, eccentricity computation
Paolini et al. (2005)	Not provided	Broad-leaved	Ring width anomalies
Shroder (1978)	220	Conniferous	Reaction wood, growth suppression
Stefanini (2004)	24	Broad-leaved	Ring width anomalies
Šilhán (2012)	73	Conniferous	Reaction wood, eccentricity computation
Šilhán et al. (2012)	48	Conniferous	Reaction wood
Šilhán et al. (2013b)	176	Conniferous	Reaction wood, growth suppression
Šilhán et al. (2014)	274	Broad-leaved	Eccentricity computation
Van Den Eeckhaut et al. (2009)	33	Broad-leaved	Eccentricity computation
Žížala et al. (2010)	21	Broad-leaved	Eccentricity computation

of the leaning trunk. Its macroscopic identification in tree-ring series is, however, difficult because of the absence of any changes in color (Westing, 1968). In both conifer and broad-leaved species, the formation of reaction wood will typically be accompanied by asymmetric trunk growth and the formation of ring eccentricity. In addition, tree tilting in landslide bodies can be such that the root system is damaged and that the tree will respond to the reduction in root mass with decreased annual increment that may last for several years. The same abrupt growth reduction can occur as a result of the loss of a major limb or partial burial of the trunk (Kogelnig et al., 2013; Stoffel et al., 2005a).

Interestingly, past dendrogeomorphic landslide reconstructions have focused largely on conifers and herein on the occurrence of reaction wood after tilting and/or abrupt growth decreases related to root damage. By contrast, only very limited efforts have been undertaken in the past to study past landslide activity in broad-leaved trees (see Table 1 for a review of published work). In addition, past studies on broad-leaved trees have focused mostly on the identification of abrupt growth decrease and tree-ring eccentricity. In the case of the latter, however, the landslide signal needs to be carefully separated from a range of other parameters that may induce eccentric tree growth, such as wind, snow creep, shape of crown, etc.

In addition, Trappmann et al. (2013) and Stoffel and Corona (2014) speculated that the sensitivity of trees to geomorphic disturbance may change with increasing tree age and/or diameter. This hypothesis has been tested recently by Šilhán et al. (2013a) with 114 Crimean pine (*Pinus nigra* ssp. *pallasiana*) trees affected by rockfall impact and demonstrated that signals in tree-ring series are best recorded at a mean age of 80 to 90 years. Comparable work has not been published to our knowledge for other tree species nor for other processes.

This study thus has two objectives, namely, the use of ring eccentricity in broad-leaved and coniferous trees and the assessment of tree sensitivity to mechanical disturbance with increasing tree age and diameter. In particular, it aims at (i) introducing a new method of landslide signal extraction from ring eccentricity in broad-leaved trees, (ii) comparing the accuracy of the approach with more commonly used dendrogeomorphic indicators in landslide dating, as well as (iii) at analyzing the sensitivity of broad-leaved and coniferous tree species to landslides and their ability to record landslide movements in their growth-ring records with increasing age.

2. Study regions

Two landslide bodies located in different physical geographic contexts have been selected to explore tree reactions to landslide movement.

The first landslide body is located in Taraktash on the southern slopes of the Crimean Mountains (Ukraine) in the vicinity of Yalta (Fig. 1). The region belongs to the Caucasus–Crimean thrust-and-fold belt, which evolved during the Mesozoic–Cenozoic (Pánek et al., 2009a,b; Saintot et al., 1999). The landslide under study is situated at the edge of a karst plateau (44°29.12′ N., 39°5′ E.) at an altitude of ~1140 m asl, and originates from a large rockslide built by virtually horizontal, thin-bedded Jurassic limestones. The study area represents the highest part of a much larger, complex slope deformation. Mapping and analysis within this study has been restricted to the highest part of slope which, is very sharply separated from the rest of the unstable mass by cliffs several hundred meters in height. The instability can be described as a block-type movement and includes lateral spreading, toppling, and incipient sliding affecting a system of rock pillars and pinnacles. The site is exclusively covered by Crimean pine (*Pinus nigra* ssp. *pallasiana*; Šilhán et al., 2012).

The second landslide body is located near Vidče in the Moravskoslezské Beskydy Mts (Czech Republic; 49°27.3′ N., 18°6.5′ E.) (Fig. 1); it belongs to a roto-translational slope deformation characterized by block movements in its upper part and a front being continuously reshaped through the undercutting of the landslide toe by the Bečva River. The landslide is located at the contact of two nappe units and contains rhythmically bedded thin layers of flysch with plastic claystones and siltstones above rigid sandstones and conglomerates. It is largely covered by a broad-leaved forest composed of sycamore maple (*Acer pseudoplatanus* L.) and European beech (*Fagus sylvatica* L.).