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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
Žižala 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.).

3. Material and methods

3.1. Fieldwork

In the field, two increment cores were sampled from each tree with visible signs of landslide disturbance (mainly trunk tilting or bending) using a Pressler increment borer (max. length and diameter of cores: 40×0.5 cm). In the case of broad-leaved trees, a core was taken from the upper side of the trunk, i.e., at the location of presumed presence of tension wood. In the case of conifers, the core with presumed disturbance signals was sampled from the lower side of the trunk, i.e., within the stem segment in which compression wood can be expected. Tension and compression wood samples were taken at the height of largest tree trunk bending. A second increment core was sampled for control but also served the calculation of ring eccentricity. The control samples were taken at an angle of 90° from the first core in the conifers and in the broad-leaved species as this location has been shown to correspond with the area within the cross section of a tree where eccentricity values are representative and where the risk of missing rings is lower than at the side facing reaction wood (Braam et al., 1987). Moreover, we sampled 30 reference trees of each species at sites located outside the landslide bodies but where growth and microclimatic conditions are still similar to those at the landslide locations. In the case of the reference trees, sampling focused on the oldest trees and was limited to trees lacking any signs of geomorphic disturbance. Two increment cores were extracted from each specimen at positions perpendicular to the slope. A reference chronology was then built with these trees using a double detrending procedure in ARSTAN (Cook, 1983).

3.2. Laboratory approaches

Samples were prepared and processed according to standard procedures described in Bräker (2002) and Stoffel and Bollschweiler (2008). Individual steps included sample drying, gluing on woody

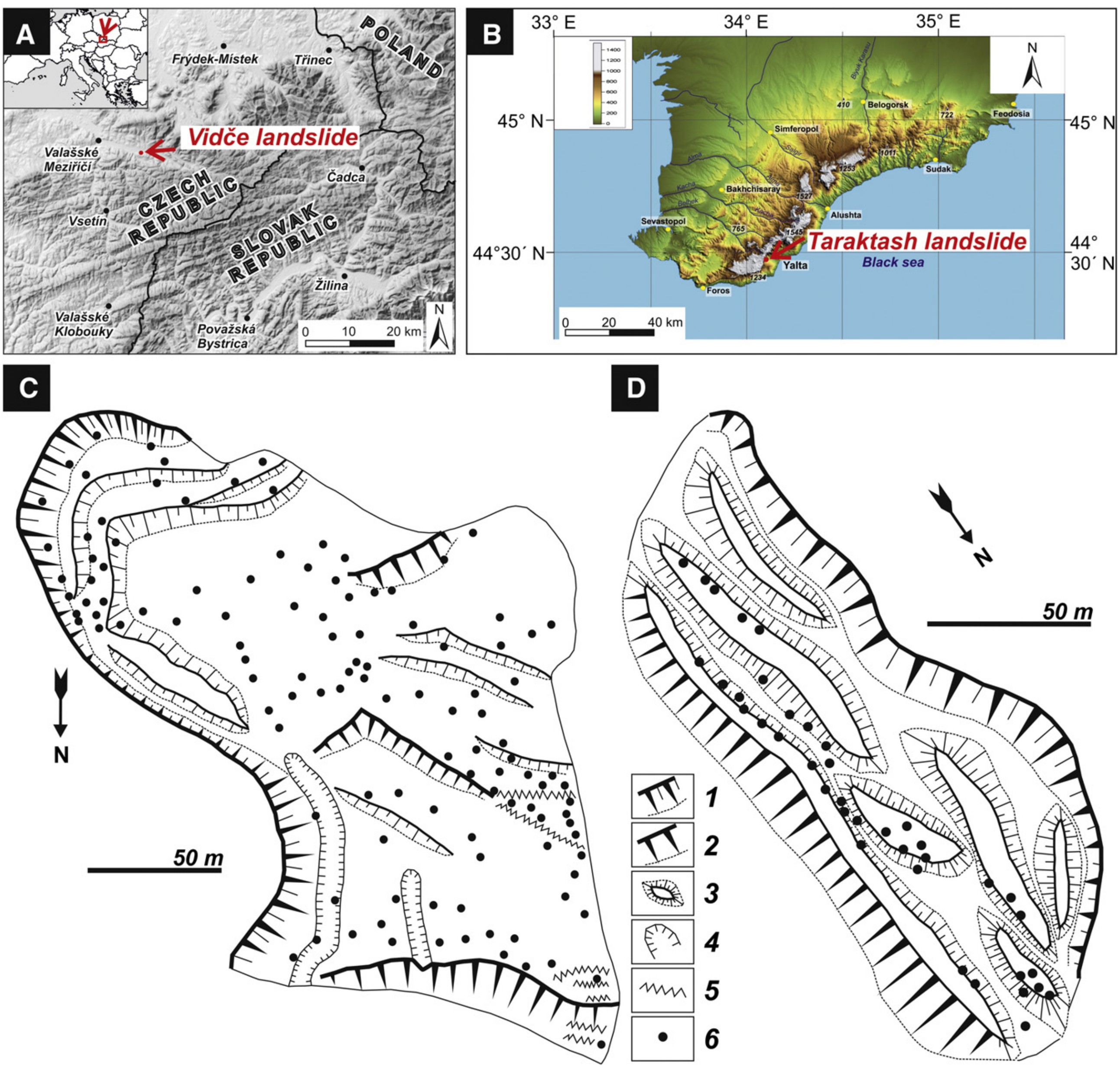

Fig. 1. Location of studied landslides: (A, C) Vidče landslide; (B, D) Taraktash landslide (1 — head scarp, 2 — minor scarp, 3 — landslide block, 4 — gully, 5 — tension cracks, 6 — sampled tree).

supports, surface sanding and polishing, ring counting, and ring-width measurements (accuracy 0.01 mm) using a TimeTable connected to a PC and software PAST4 (VIAS, 2005). Individual increment curves were then compared with the reference chronology (using graphical and statistical tools provided by the dating software) to localize and correct possible false and/or missing rings. In a subsequent step, tree-ring eccentricity e (values 0–1) was calculated using the formula presented by Braam et al. (1987):

$$e = \frac{a-c}{a+c} \qquad (1)$$

where a is tree-ring width on the side of presumed reaction wood, and c is the width of the corresponding tree ring but at a position perpendicular (90°) to the direction of a (Fig. 2A).

3.3. Landslide event determination and chronology reconstruction

Two methodological approaches were used in this study to date past landslide movements. First, and for both species analyzed, tree-ring eccentricity was quantified by weigthing individual e values following the procedure described in (Klimeš et al., 2009; Fig. 2A). Subsequently, we selected those years from the tree-ring chronology for which an increase in eccentricity could be observed. The focus here was on sudden changes in tree-ring eccentricity, which can be interpreted as a tree's reaction to tilting. Tree-ring eccentricity is visible in the growth-ring series in the form of asymmetric growth. Based on the magnitude of eccentricity changes, landslide signals in trees were divided into four categories and defined as very strong ($e > 0.5$ in at least two subsequent rings; this signifies at least 100% change in eccentricity as compared to undisturbed rings), strong ($e > 0.5$ in first and $0.5 > e > 0.25$ in the second ring; again at least 100% change in comparison with previous undisturbed trees), weak ($0.5 > e > 0.25$ in the first ring and $e > 0.5$ in the second ring), and very weak ($0.5 > e > 0.25$ in at least two subsequent rings; Fig. 2A).

In the case of the conifers (*P. nigra*) sampled at Taraktash landslide, we also performed a classic analysis of macroscopically visible reaction wood cells in the tree-ring record (by using the second approach). Here, the first ring showing compression wood was considered the year of landslide initiation or reactivation (Fig. 2B).

For both approaches, landslide activity across the study sites was then analyzed with Shroder's (1978) *It* index:

$$It = \frac{\sum R_t}{\sum A_t} \times 100\ \% \qquad (2)$$

where R_t is the number of trees showing growth disturbances (GD; i.e., the initiation of eccentricity or compression wood in our case) in year t, and A_t is a total number of sampled trees alive in year t. Following Lopez Saez et al. (2012a), only years for which the $It \geq 10\%$ and $GD \geq 5$

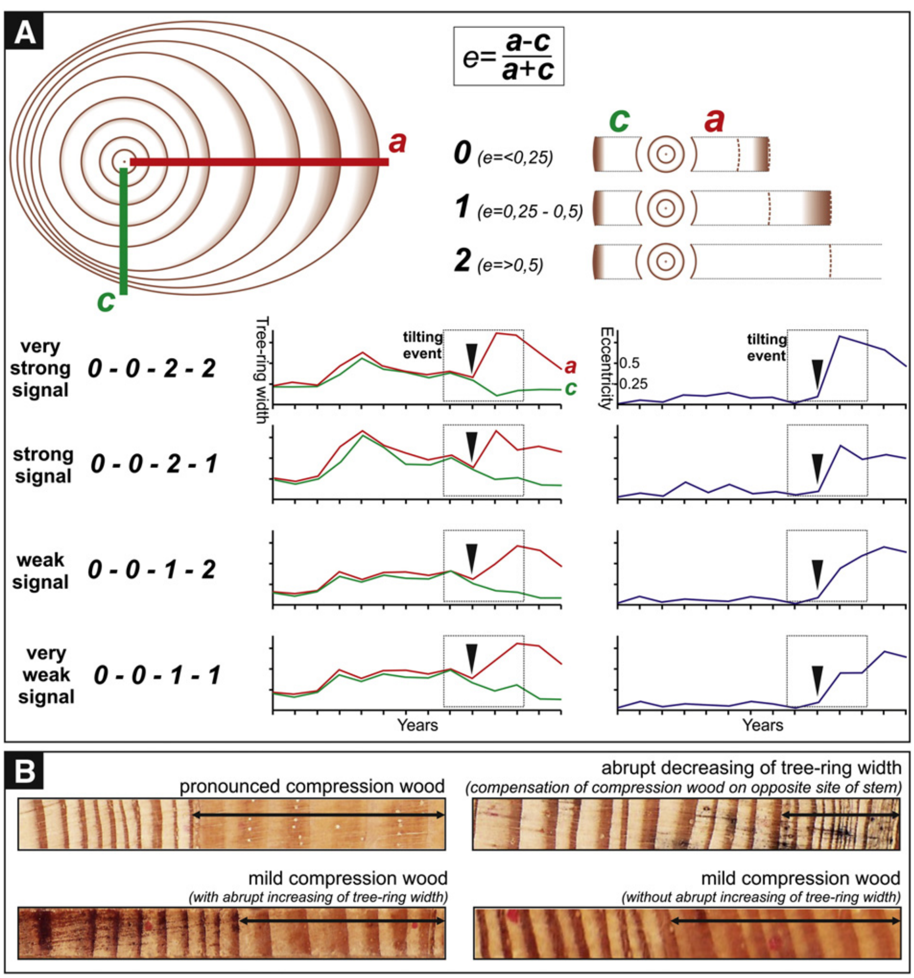

Fig. 2. Approaches used to date landslide activity: (A) extraction of landslide signals from a series of tree-ring eccentricity values. Calculated eccentricity values were divided into three categories with weights of 0, 1, or 2 (minimal eccentricity to maximal). Landslide signal was determined as a moment of abrupt eccentricity increasing (e.g., pattern 0–0–2–2 means that at least two tree rings with eccentricity lower than 0.25 must be followed by at least two rings with eccentricity higher than 0.5); (B) illustration of reaction (compression) wood in a tree-ring series of *Pinus nigra*.

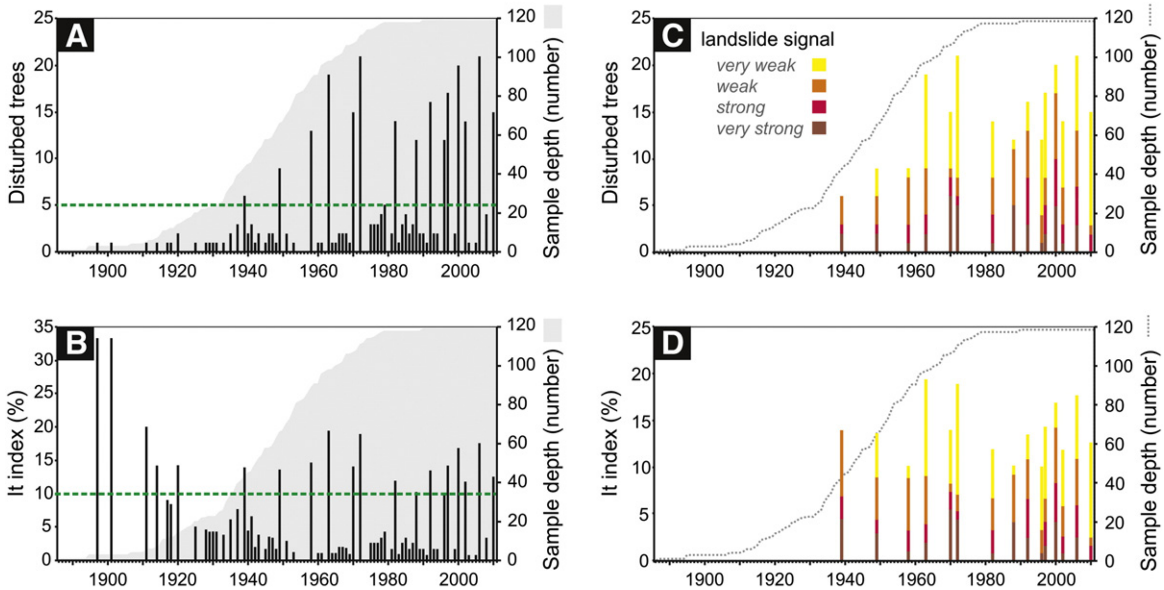

Fig. 3. Dating of landslide movements based on tree-ring eccentricity observed in *Fagus sylvatica* trees from Vidče landslide. (A) Number of disturbed trees showing landslide signals in individual years; (B) *It* values for individual years; (C) number of disturbed trees; and (D) *It* values including a representation a category of landslide signal.

thresholds were exceeded have been considered landslide years. As the presence of reaction wood does not necessarily imply the presence of tree-ring eccentricity (Fig. 2B; Šilhán, 2012), we compared the results of *P. nigra* for which data from both approaches was available.

In a final step, we tested the hypothesis of Trappmann et al. (2013) and Stoffel and Corona (2014) according to which increasing tree age and diameter might affect the sensitivity of trees to react to disturbance and/or their ability to record a landslide movement in their growth-ring record. The sensitivity analysis was tested for the eccentricity and for the compression wood approaches. We therefore determined the number of GD recorded in all trees and for individual periods of their life. We used a decadal resolution but also assessed changes in sensitivity at 2-cm intervals from pith to bark. Tree sensitivity was expressed as the number of GD per tree, and the occurrence of reactions analyzed over time. In the case of eccentricity values, we not only assessed the number of GD over time, but also analyzed possible changes in the magnitude of recorded landslide signals (i.e. very strong to very weak).

4. Results

4.1. Sampled trees

A total of 78 increment cores were taken from 39 knee-like bended *P. nigra* trees growing on the Taraktash landslide. The average age of trees was 204.6 years (SD: 68.1 years); the youngest tree was 91 years old, whereas the oldest specimen exhibited 412 growth rings at the time of sampling.

On the Vidče landslide we sampled 119 *F. sylvatica* trees with 238 increment cores. The average age of trees was significantly younger with 66.5 years (SD: 19.4 years) in this case. The youngest and oldest

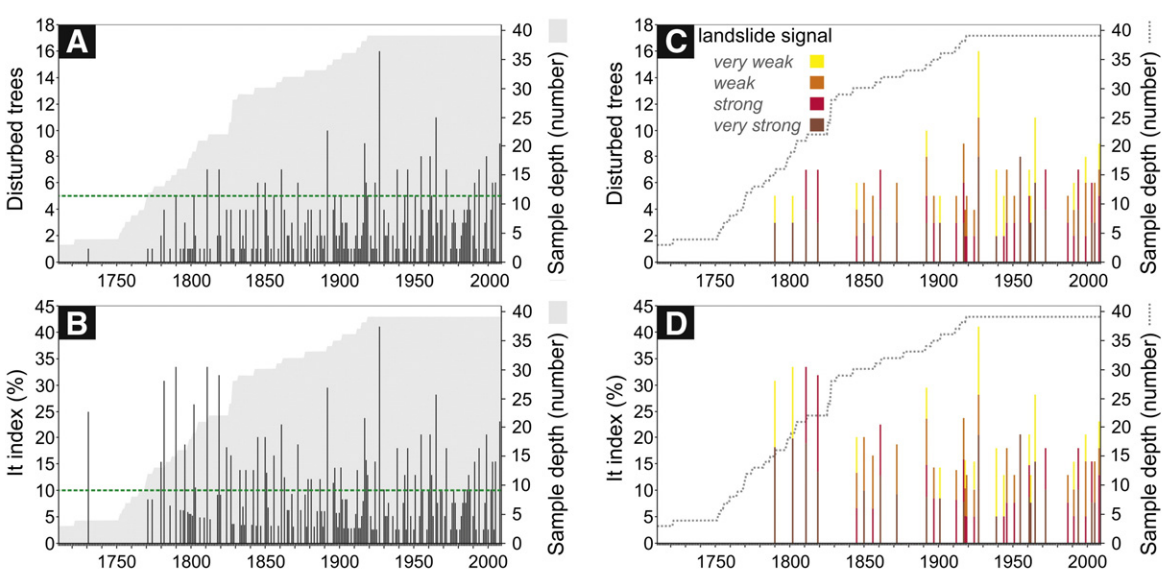

Fig. 4. Landslide dating based on tree-ring eccentricity in *Pinus nigra* from Taraktash landslide: (A) number of disturbed trees showing landslide signals in individual years; (B) *It* values in individual years; (C) number of disturbed trees; and (D) *It* values with the representation of a category of landslide signals.

Table 2
Persistence of eccentric growth in trees based on a threshold of $e > 0.25$.

Landslide signal	Taraktash (*P. nigra*)	Vidče (*F. sylvatica*)	Mean duration (tree-rings)	Stdev
	Mean duration (tree-rings)	Stdev		
Very weak	2.8	1.1	2.7	0.9
Weak	3.7	1.6	3.5	1.3
Strong	5.8	3.7	5.3	1.9
Very strong	11.9	7.9	8.3	6.0

trees were 22 and 125 years old, respectively, and only 6 trees (5%) exhibited more than 100 growth rings.

4.2. Chronology of landslide movements

Eccentricity analysis of *P. nigra* sampled at Taraktash landslide reveals 463 landslide signals covering the past 258 years (1752–2009), most of them in the form of very weak (43%) and weak (21%) reactions, and smaller amounts of strong (19%) and very strong signals (17%; Fig. 4). A total of 34 landslide events can be dated in this case with thresholds of $It \geq 10\%$ and $GD \geq 5\%$, with the oldest event occurring in A.D. 1790. The frequency of landslide events is 7.6 years, and the mean decadal frequency is 1.3 events. The highest *It* index value is observed in 1927 with 41%, whereas the mean *It* index value during landslide years was 20.2% (SD: 7.1%). The GDs in all event years were composed of (very) weak and (very) strong signals, and none of the events only contained intense reactions. In case that only strong or very strong reactions are taken into account, 13 landslide events can be reconstructed, resulting in a mean recurrence of 19.8 years and a mean decadal frequency of 0.5 events. Table 2 illustrates the link between the intensity of eccentricity and the duration of eccentricity for both landslides and tree species. We can see quite clearly that stronger landslide signals typically also resulted in longer lasting reactions.

The analysis of tree-ring eccentricity in the *F. sylvatica* trees sampled at Vidče revealed 319 potential landslide signals. A majority of the signals were very weak (41%) or weak (26%), whereas strong and very strong eccentricity signals were only identified in 15% and 18% of the cases, respectively. The reconstructed chronology covers the period 1911–2011 for which the sample size was >5. The analysis of tree-ring eccentricity (including very strong, strong, weak, and very weak landslide signals) reveals a total of 15 landslide events for which $It \geq 10\%$ and $GD \geq 5$ (Fig. 3), pointing to an average interval of 6.7 years between two events and a mean decadal frequency of 1.5 events. The highest *It* index was recorded in 1971 (18.9%), whereas the mean *It* index for years with landslide activity was 14.2% (SD: 2.9%). The GDs in event years spanned all categories of signals (from very weak to very strong). If only (very) strong signals would have been considered, none of the landslides provided in Fig. 3 would have been detected with an $It \geq 10\%$ threshold. If the *It* threshold is lowered to 5%, five years will show a sufficient number of (very) strong landslide signals and would yield a mean recurrence of landslide activity of 20.2 years and a mean decadal frequency of 0.5 events. If the same $It \geq 5\%$ threshold is applied to the entire data set of eccentricity, the landslide chronology will remain unchanged, meaning that the very same (number of) years will appear in Fig. 3.

When analyzed with classic dendrogeomorphic approaches (focused on the onset of compression wood), the 39 *P. nigra* trees sampled at Taraktash reveal 162 occurrences or reaction wood as a consequence of landsliding. Here, 16 landslide events can be identified (Fig. 5) with the oldest event being dated to A.D. 1839. The resulting return period is 16.1 years and decadal frequency 0.6 events. The highest *It* value was

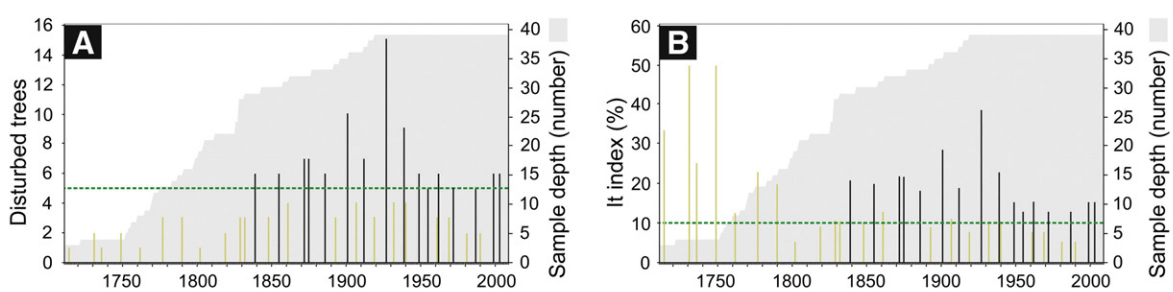

Fig. 5. Chronology of landslide activity at Taraktash based on the occurrence of reaction wood in *Pinus nigra*: (A) number of disturbed trees showing landslide signals in individual years; (B) *It* values in individual years.

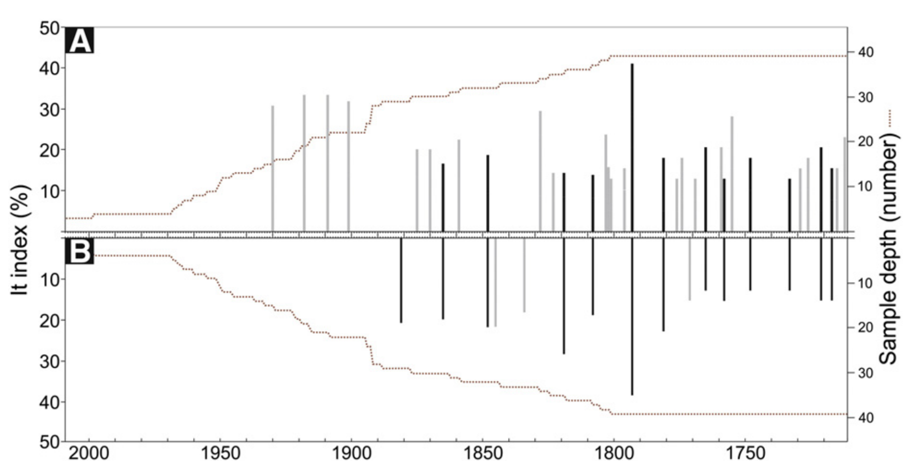

Fig. 6. Comparison of landslide time series based on different dating approaches at Taraktash: (A) chronology obtained by means of tree-ring eccentricity analysis; (B) chronology derived from reaction wood analysis. Black columns indicate years which have been confirmed by both approaches; years represented with gray columns have been confirmed by only one of the methods.

Table 3
Agreement of landslides dated with eccentricity signals and reaction wood occurrence in *Pinus nigra*.

Taraktash	Landslide signal			
%	Very weak	Weak	Strong	Very strong
With reaction wood	15	44	68	79
Without reaction wood	85	56	33	21

recorded in 1927 (28.5%), whereas the mean *It* index value during landslide years was 19.5% (SD: 6.7%). From all the landslide events dated with reaction wood formation, 13 (81.3%) could be confirmed by the eccentricity analysis (Fig. 6). Reaction wood was, by contrast, absent in 22 landslide years dated via the presence of eccentricity in the tree-ring series. The *It* values in landslide years observed in both data sets were, however, not significantly different between the two data sets (p-value from t-test = 0.121). Moreover, when reaction wood years are compared with individual categories of eccentricity signals (Table 3), one realized that (very) strong eccentricity is much more likely to coincide with reaction wood formation.

4.3. Age and size dependent ability of trees to record landslide event

In addition to the analysis of reaction wood in *P. nigra* and eccentricity in *F. sylvatica*, we also assessed tree age and diameter so as to see whether the probability (and the intensity) for reaction being formed was changing over the life cycle of a tree.

In the case of the eccentric rings in *F. sylvatica*, reactions are most frequent in trees being between 50 and 60 years old (0.44 events.tree^{-1}; Fig. 7) when tree diameters at breast height were 33.1 cm on average (SD: 3.4 cm). This period also represents the age window during which reactions identified in *F. sylvatica* were strongest and usually belonged to the categories *strong* and *very strong* (Fig. 7C).

In the case of *P. nigra*, trees recorded most landslide signals at tree ages comprised between 40 and 60 years (Fig. 8B), with a maximum being observed between 50 and 60 years (0.52 events.tree^{-1}). In addition to showing the largest number of eccentric rings, we note that reactions during this period were generally strongest as well (Fig. 8C). A high proportion of strong and very strong signals was also recorded at ages ranging between 100 and 140 years, which corresponds to tree diameters at breast height of 28.1 cm (SD: 1.0 cm). However, the number of reactions during this second window did not usually occur in sufficient numbers (in terms of *It* and GD thresholds) to result in landslide events in the chronology.

The occurrence of reaction wood in *P. nigra* shows a bimodal distribution of highest signal frequency as well. As could be expected, most GD are formed at tree ages ranging from 40 to 60 year and at ages comprised between 110 and 130 year (up to 0.36 events.tree^{-1}; Fig. 9B), i.e., generally at the same time as eccentricity signals were most frequent. During these periods, the number of consecutive years of reaction wood formation was also largest (Fig. 10).

5. Discussion

In this study we compare different dendrogeomorphic approaches to date landslide movements and test the capability of tree-ring eccentricity in providing reliable time series of past landslides. In addition, the ability of trees to record past landsliding is challenged and related to tree age and diameter. Experimental work has been performed at two locations with different physical geographic conditions and different tree species. A total of 119 *F. sylvatica* and 39 *P. nigra* tree have been sampled with two increment cores per tree for the purpose of the study at the Vidče (Czech Republic) and Taraktash (Ukraine) landslides.

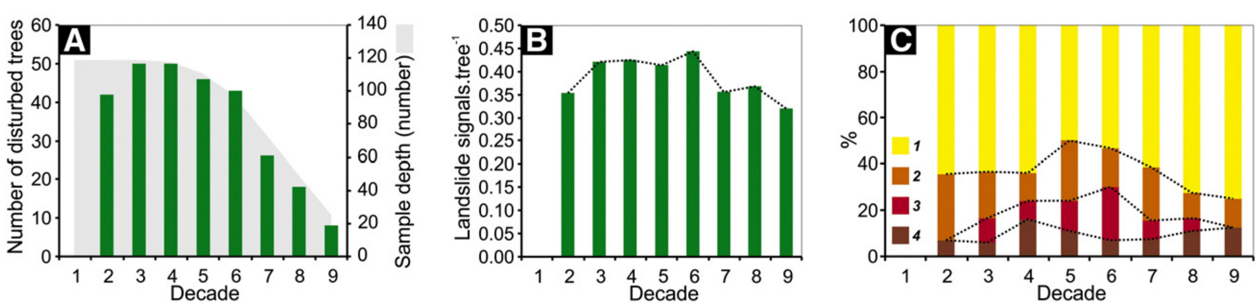

Fig. 7. Analysis of changes in tree sensitivity depending on age at Vidče locality: (A) number of disturbed trees showing landslide signal (based on ring eccentricity) in individual decades of tree age; (B) number of landslide signals (based on ring eccentricity) per tree in individual decades of tree age; (C) proportion of landslide signal intensities in individual decades of tree age (1 — very weak landslide signal, 2 — weak landslide signal, 3 — strong landslide signal, 4 — very strong landslide signal).

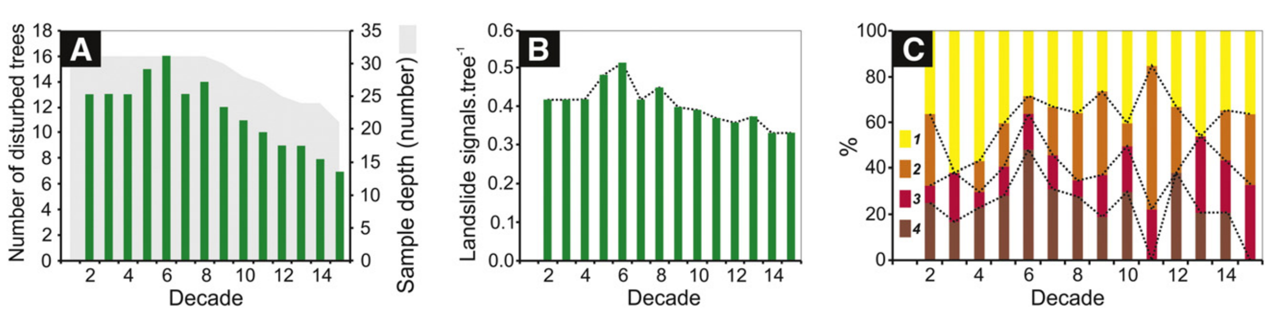

Fig. 8. Analysis of changes in tree sensitivity toward landslide movements at Taraktash: (A) number of disturbed trees showing landslide signal (based on ring eccentricity) in individual decades of tree age; (B) number of landslide signals (based on ring eccentricity) per tree in individual decades of tree age; (C) proportion of landslide signal intensities in individual decades of tree age (1 — very weak landslide signal, 2 — weak landslide signal, 3 — strong landslide signal, 4 — very strong landslide signal).

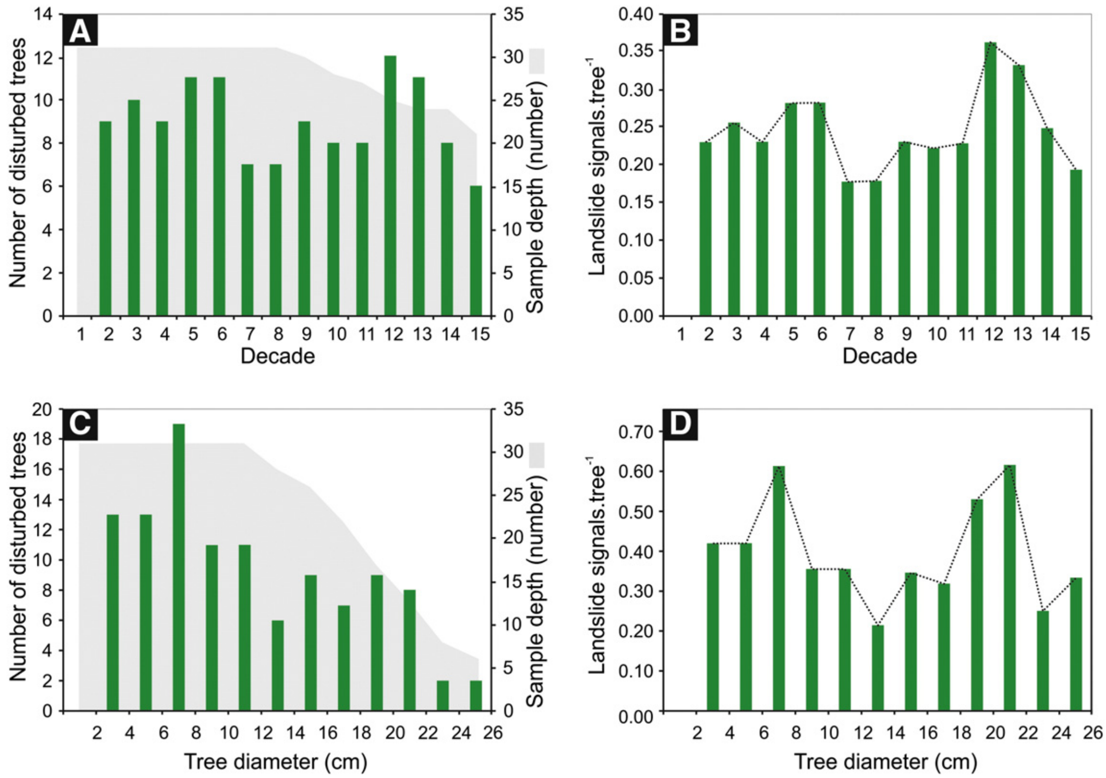

Fig. 9. Changes in the ability of trees to record a landslide event through the formation of reaction wood as a function of tree age and tree trunk diameter: (A) number of disturbed trees showing landslide signal (based on reaction wood) in individual decades of tree age; (B) number of landslide signals (based on reaction wood) per tree in individual decades of tree age; (C) number of disturbed trees showing landslide signal (based on reaction wood) in individual intervals of stem diameter; (D) number of landslide signals (based on reaction wood) per tree in individual intervals of stem diameter.

5.1. Evaluation of different approaches to record landslides

In the past, landslide activity has most frequently been dated via the assessment of reaction wood formation in conifers. Work typically consisted in a simple macroscopic analysis of rounded, thick wall cells (so-called compression wood tracheid) that form in conifers as a response to landslide movement (Shroder, 1978). In mid-elevation mountain ranges comprised within temperate climate zones, however, landslide bodies are often covered with deciduous forest stands (Van Den Eeckhaut et al., 2009). The analysis of deciduous trees has been much scarcer in the past, and analysis primarily focused on tree-ring eccentricity. Most frequently, work was based on the analysis of cumulative eccentricity values (Fantucci and Sorriso-Valvo, 1999; Klimeš et al., 2009; Pánek et al., 2011). As eccentricity can be induced by processes other than geomorphic, its analysis has been affected by noisy reconstructions, also because tree-ring eccentricity can appear in the tree-ring record with certain inertia, i.e., up to several years after the actual landslide event actually occurred (Šilhán, 2012). The methodological approach presented in this paper is based on the extraction of landslide signals from a range of tree-ring eccentricity values and is able to identify initial eccentricity so that noise can be largely eliminated from the reconstruction. As the strongest eccentricity values do not necessarily occur in the very first year after tree tilting (Burda, 2010), we have categorized landslide signals in a way to overcome this tree physiological phenomenon by which the highest eccentricity values often become visible in the second year after the actual landslide event (see the structure of very weak signals where the highest eccentricity occurs in the second year after tilting). Similar to other

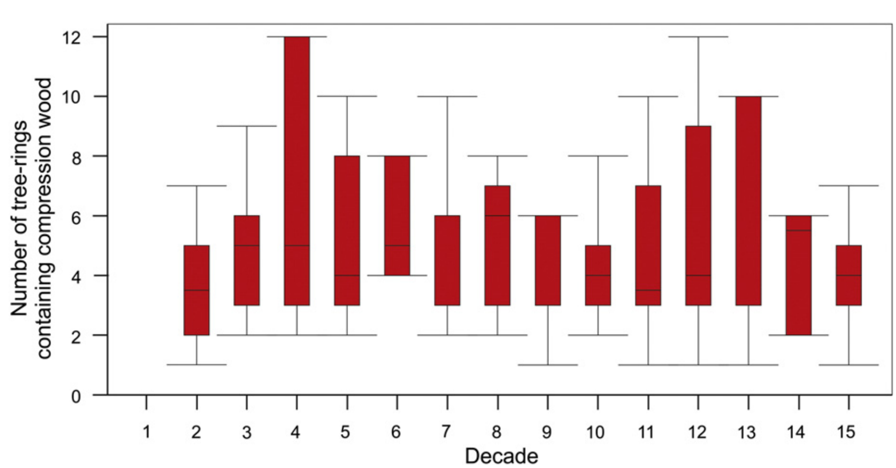

Fig. 10. Number of subsequent tree rings showing reaction wood (*P. nigra*) as a response to landsliding for individual decades of tree life in the Taraktash landslide.

dendrogeomorphic approaches (Stoffel and Bollschweiler, 2008; Stoffel and Corona, 2014), time series of landslides have to be seen as minimum numbers of events (Stoffel and Bollschweiler, 2008; Stoffel and Corona, 2014) as an initial reaction still may be ongoing while the tree is affected by a subsequent event. The latter may thus be overlooked (or blurred), and we thus suggest to limit eccentricity analyses to locations with moderate landslide activity.

The validity of tree-ring eccentricity for landslide analysis, which was used primarily for the assessment of landslide time series in deciduous trees so far, has been applied in the conifer species *P. nigra* for which reaction wood data can be retrieved as well. The agreement in more than 80% of all dated landslides shows the potential of tree-ring eccentricity for landslide reconstructions but also points to some limitations inherent to the use of reaction wood alone. Depending on the *It* and GD thresholds used as well as the intensity of eccentricity values (e) included in analyses, the use of eccentricity can also help the detection of weak landsliding events that would remain undetected if only reaction wood had been taken into account. This finding is in agreement with Schweingruber (1996) who state that coniferous trees may react to trunk tilting by eccentric growth without forming visible reaction wood. A verification of landslide events reconstructed with tree-ring eccentricity with the landslide chronology reconstructed using the formation of tension wood was not possible for *F. sylvatica*, as tension wood can only be detected via microscopic analyses. However, data on the regional occurrence of slope deformations induced by extreme hydrometeorological conditions in 1939, 1971, 1996, 1997, 2002, 2006, and 2010 (e.g., Bíl and Müller, 2008; Kirchner and Krejčí, 1998; Pánek et al., 2011; Šilhán and Pánek, 2010; Šilhán et al., 2013b) agrees with years of reconstructed landsliding at the study site and thereby confirm the validity of tree-ring eccentricity as a valuable and precise tree-ring proxy of landsliding.

At the same time, (very) weak eccentricity signals probably point to moderate tree tilting and thus preferably to more subtle (or more deep-seated) landslide movements for which reaction wood is unlikely to form (Table 3). Eccentric growth can thus be seen as a more sensitive recorder of landslide activity and is likely to yield more data on past events than the commonly used macroscopic analysis of reaction wood will do. Moreover, the combination of both approaches might possibly help to distinguish more intense from weaker landslide episodes in the future, as long as thresholds for the acceptance of events is kept at a level that will limit the inclusion of noise in landslide time series (Corona et al., 2014; Stoffel et al., 2013).

5.2. Sensitivity of trees toward landslide events

Several authors have questioned the ability of trees to record signs of geomorphic process activity in their growth-ring series in a similar way across their lifespan (e.g., Bollschweiler and Stoffel, 2010; Šilhán et al., 2013a), without however having tested the hypothesis and/or quantified these changes. General agreement exists that trees are very sensitive recorders of disturbance during juvenile growth (i.e., during the first decade(s) of their life, depending on growth conditions and forest stand dynamics; Stoffel and Bollschweiler, 2008). At the same time, however, juvenile trees will also tend to react more easily to nongeomorphic disturbances (e.g., internal stand dynamics, snow pressure, browsing and fraying by ungulates), and GD occurring in the first decade(s) of a tree's life should thus be neglected.

The two species analyzed in this study, *P. nigra* and *F. sylvatica*, confirm the sensitivity of juvenile trees to disturbance, but also exhibit similar features in their ability to record landslide events. In this sense, both species are characterized by a general decrease in their ability to record landslides when they have reached ~60 years, presumably as a result of the thickening stem which becomes increasingly stiffer so that the tree will lose part of its flexibility. This means that, depending on the nature of the mechanical disturbance, trunks of increasingly older trees will either break in the case of very abrupt and heavy impact (e.g., rockfall, snow avalanche, debris flow; Schneuwly et al., 2009a,b) or regain the original vertical position more slowly. Moreover, changes in tree elasticity will be reflected in the nature of tree tilting itself. Trunks of young, flexible trees will tend to deform to knee-like shapes close to the ground (so-called drunken forest; Agafonov et al., 2004), whereas the trunks of older, less flexible trees will tend to bend fully and throughout the length of their trunk. In addition, increasingly aging trees also exhibit a gradual decrease in average yearly increments (i.e. ring width) as they have to allocate their resources to a steadily growing trunk and branch surface (Stoffel et al., 2013), and may thus be another explanation for the weakening or missing eccentricity reaction.

The formation of reaction wood in *P. nigra*, however, points to a somewhat different behavior. The gradual decrease in reaction wood formation up to an age of 60 to 70 years is followed by an increase in the ability of trees to form reaction wood, as well as in more intense reactions at tree ages ranging from 110 to 130 years. This observation points to the fact that reaction wood formation is neither exclusively related nor fully restricted to the coexistence of tree-ring eccentricity (Schweingruber, 1996; Šilhán, 2012; Table 3). We conclude that the limitation of resources and the reduction in annual increment does not seem to have the same limiting, negative impact on reaction wood and that this feature may still form at tree ages where tree-ring eccentricity may no longer be seen in the growth-ring record as a result of very narrow rings. The presence of reaction wood in younger trees seems to be important to bend the tree trunk back to its original vertical position. But the reaction wood in older trees (110–130 years) will most probably serve the stabilization of the tree trunk as its straightening to the original vertical positions will no longer be possible as a result of the weak eccentricity.

6. Conclusion

In this study landslide signals are identified through the analysis of tree ring eccentricity values and events dated at two dissimilar landslide localities. The study also tested the ability of trees to record landslide signals with increasing age and size using 39 *P. nigra* and 119 *F. sylvatica* trees.

We confirm the accuracy and value of tree-ring eccentricity in detecting landslide signals in trees, but also realize that trees are more likely to record eccentricity than reaction wood. This will on one hand lead to more events being recorded, but can also point to more frequent sliding activity than other techniques would do. Limiting analyses to (very) strong eccentricity reactions alone provides results that are more comparable to what classical tree-ring records would yield. This fact again opens the possibility of using weaker eccentricity in trees for the detection of less severe ground movements which remained unnoticed in tree-ring records focusing on reaction wood alone. We also call for the inclusion of eccentricity in older trees that have been shown to become less sensitive recorders of reaction wood but that will still form eccentric rings. The sensitivity of trees to record geomorphic disturbance with increasing age and size also calls for a careful selection and mix of tree samples belonging to different age classes to avoid the lack of reacting trees for specific times of the past.

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