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Exclusive application of tree-ring anatomy for reconstruction of past landslide behavior



Abstract Tree-ring-based analyses currently represent a modern, continuously evolving, and effective tool for the spatio-temporal reconstruction of past landslide movements. Although the use of standard macroscopic landslide signals is still more common, this classical approach has significant limitations. Recent research, however, shows that changes in the anatomical structure of tree rings can serve as a more efficient source of landslide signals. Thus, this unique pioneering study was conducted on two active landslides with the aim of reconstructing their spatio-temporal behavior using only anatomical responses, which are not accompanied by macroscopic manifestations. A total of 54 disturbed trees (*Fagus sylvatica* L. and *Acer pseudoplatanus* L.) were sampled. The only anatomical parameter examined was the change in vessel lumen area (VLA), which was analyzed to detect landslide signals. The results identified 17 and 12 landslide signals at the two sites, respectively, corresponding to four and three landslide events over the past several decades. The study found that anatomical changes in vessel lumen area effectively captured landslide events, offering advantages over traditional macroscopic approaches by minimizing noise and avoiding the masking of younger events by older ones. However, this methodology is most suitable for certain types of landslides, particularly flow-like and translational types with tension cracks that affect the root systems of trees. The results suggest that further refinement, including geophysical surveys to optimize sampling locations, could enhance the accuracy of this dendrogeomorphic approach. Thus, this study demonstrates the potential of using exclusively anatomical responses in tree rings for landslide reconstruction. While this method requires more resources than traditional approaches, it provides a clearer, less noisy record of landslide activity.

Keywords Landslide · Dendrogeomorphology · Chronology · Tree-ring anatomy

Introduction

Dendrogeomorphology is currently considered to be the most effective tool for spatio-temporal reconstruction of landslide movements (Stoffel et al. 2013) in climates where trees are able to form an annual increment in the form of a tree ring (Alestalo 1971). An approach based on the study of tree rings can analyze landslides hundreds of years old (Shroder 1978; Carrara and O'Neill 2003; Cockburn et al. 2016; Zhang et al. 2019) and achieve up to seasonal dating accuracy (Clague and Souther 1982; Fantucci and Sorriso-Valvo 1999; Stefanini 2004; Lopez Saez et al. 2012a). Moreover, the high adaptability of methodological approaches allows the analysis of different types of landslides including rotational (Astrade et al. 1998; Malik and Wistuba 2012; Savi et al. 2013), translational

(Wieczorek et al. 2006; Wistuba et al. 2018), and earthflows (Braam et al. 1987; Fantucci and McCord 1995; Klimeš et al. 2009).

The approach based on the study of the tree ring of disturbed trees allows not only to construct a chronological evolution of landslide activity (Fantucci and McCord 1995), but in combination with the position of these trees it is also possible to construct a spatio-temporal reconstruction of landslide movements (Lopez Saez et al. 2012b). It is the possibility of relatively accurate detection of spatial activity together with the low economic cost of dendrogeomorphic research that represent the main advantages over other methods of absolute dating of landslides (Lang et al. 1999). Conversely, limitations of the dendrogeomorphic approach include the ability to analyze only landslide events of limited size (Corona et al. 2014). Movements that are too large will destroy trees that subsequently cannot be used for dating, and movements that are too small may not affect tree growth. Another limitation is the inertial occurrence of growth disturbances in tree-ring series (Šilhán et al. 2024), which may cause obscuring of younger landslide events that subsequently cannot be dated.

These general limitations are related to classical macroscopic growth disturbances (Stoffel and Corona 2014), which are dominant in the study of landslide movements (Šilhán 2020). However, recent research clearly indicates that tree growth responses at the anatomical level can also be used very successfully in the study of landslides (Šilhán and Stoffel 2022). Anatomical responses associated with morphometric changes in wood cells (vessels, tracheids, resin ducts, rays) can be accompanied by macroscopically observable manifestations (e.g., brown-reddish color of compressive wood in conifers; Westing 1965), but they can also occur quite independently (Šilhán et al. 2023). In particular, anatomical responses independent of macroscopic expression offer a number of advantages over classical macroscopic growth responses.

The standard growth response of trees to landslide movement is tree-ring eccentricity (Braam et al. 1987). A limitation of this response is its high sensitivity to non-geomorphological influences, which induces a large amount of noise in the resulting chronology (Šilhán 2019). Another frequently exploited growth response is the formation of compression wood (the response of conifers to their tilting; Timell 1986). However, this reaction can occur with a lag of up to several years (Shroder 1978). An analogous reaction in deciduous tree species is the formation of tension wood, and its use yields very good dating results (Šilhán 2023), but its macroscopic identification is complicated and often requires time- and material-intensive preparation and analysis of microsections (Heinrich and Gärtner 2008). Some authors have used abrupt changes in tree-ring widths to detect landslide movements (Fantucci and Sorriso-Valvo 1999; Stefanini 2004; Guida et al. 2008). However, abrupt growth

release can have a large delay and must always be accompanied by another type of growth disturbance (Stoffel and Bollschweiler 2008). Conversely, abrupt growth suppression as a growth response to root damage may also have climatic causes (which can be eliminated by comparison with reference trees) and, moreover, it is not known exactly how large landslide movements will cause sufficient root damage to subsequently induce growth suppression.

In contrast, anatomical growth reactions not accompanied by macroscopic manifestations do not have most of the above limits. Their formation is not subject to delay and has minimal inertia (Šilhán et al. 2024). Nevertheless, there has been no research to date in which this type of anatomical reactions has been used exclusively for the analysis of landslide movements. The main reason seems to be the lack of a methodology that can successfully extract the landslide signal from interannual series of anatomical parameter values. A solution to this key aspect leading to a wider use of anatomical analyses in landslide research was only brought by Šilhán (2024), who defined the optimal approach for landslide signal extraction.

Thus, the aim of this study is to use for the first time only anatomical responses without their macroscopic accompanying manifestation for a comprehensive spatio-temporal reconstruction of landslide movements and to critically evaluate the obtained results for a possible future more frequent use of this specific dendrogeomorphic approach.

Study area

A unique dendrogeomorphic approach based exclusively on the detection of changes in morphometric parameters of vessels in the tree ring was applied to two active landslides located in the České středohoří Highland (Fig. 1). The broader region of the selected landslides is known for the abundance of landslides of different types (Raška et al. 2014b) including rotational, translational, and earthflows. The area is composed of neovolcanic rocks that overlie Mesozoic sediments of the Upper Cretaceous age (claystones and sandstones). The formation of the neovolcanic rocks (basalts, lavas, tuffs) is associated with the Saxon phase of Alpine orogeny (Rybář and Košťák 2003). The specific geological structure is characterized by mutual contacts of hard, rigid rocks with rocks that are soft, plastic, susceptible to weathering, and volumetrically unstable (Rybář and Košťák 2003). In particular, the presence of clay swelling minerals (dominantly smectite) can reduce slope stability and increase the risk of slope movements (Blahůt and Klimeš 2022). The entire volcanic mountain range is dissected by the deep incision of the Elbe River, which caused backward erosion of their side tributaries, resulting in the dissection of the volcanic table by deep and steep valleys. The climatic conditions of the study region can be characterized as moderate. At least 1 mm of precipitation falls on average during 100 to 120 days per year and total annual precipitation amounts to 650 to 750 mm. Precipitation can be very uneven in

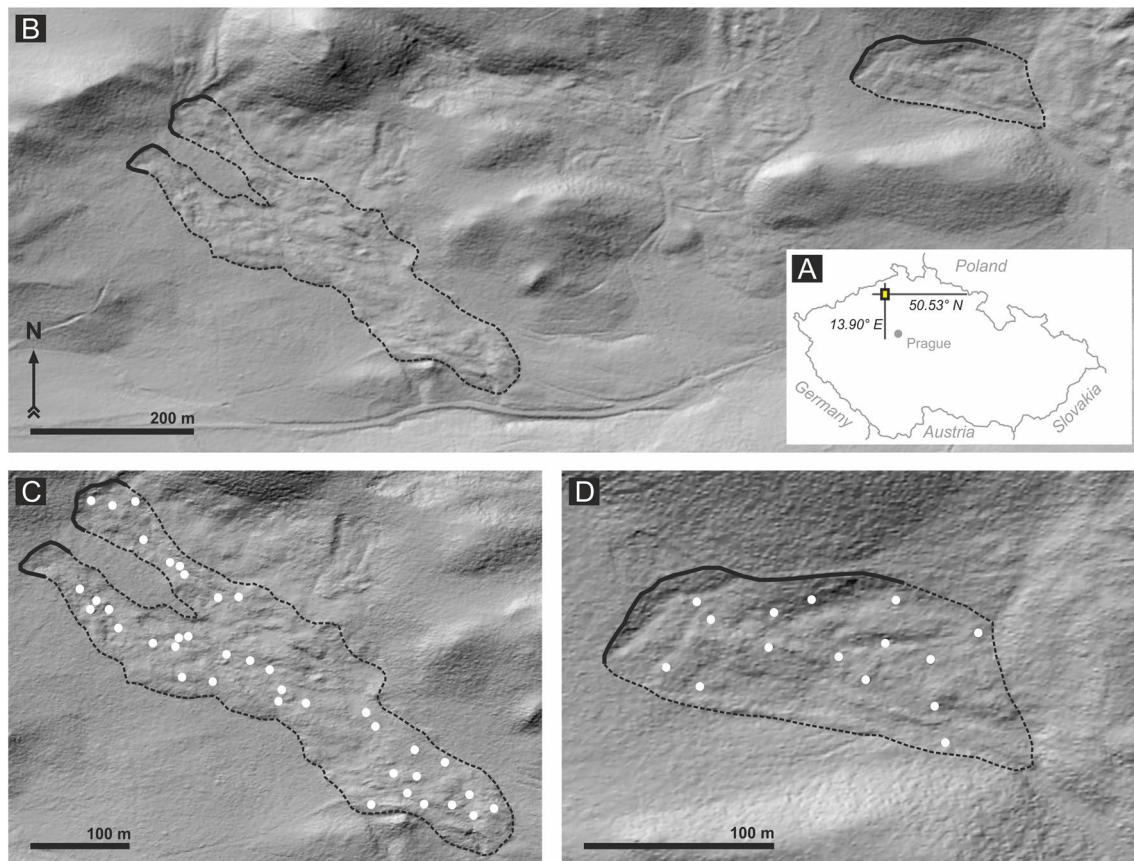


Fig. 1 The position of the area of interest within the Czech Republic (A) and the broader surroundings of the studied landslides (B) including a detailed view of landslide 1 (C) and landslide 2 (D) with the positions of the sampled trees (white dots)

time, with extreme amounts (up to tens of millimeters per several hours) occurring during summer thunderstorms with downpours. Snow cover during the winter season lasts up to 80 days. Average temperatures during the coldest month (January) are between -2 and -3 °C, while during the warmest month (July), they reach 16 to 17 °C (Tolasz et al. 2007). The vegetation cover of the mountains consists of discontinuous forest stands dominated by European beech (*Fagus sylvatica* L.), sycamore maple (*Acer pseudoplatanus* L.), and pendulate oak (*Quercus robur* L.). Of the coniferous species, common spruce (*Picea abies* (L.) Karst.), European larch (*Larix decidua* Mill.), and Scots pine (*Pinus sylvestris* L.) are present. Most of the area has been affected by forestry in the past and many trees have been planted or are colonizing individuals.

The first studied landslide (landslide 1; Fig. 1C; 50.530°N, 13.901°E) has a flow-like character with a total length of about 630 m and a maximum width of up to 100 m. In its upper part, it is a rotational type landslide with inclined platforms of individual blocks. The landslide source has a split character with two approximately 200-m-long branches. The source zone itself has a smooth character with an average slope of about 12°. The transport part of the landslide is less steep (approx. 8°) with obvious signs of landslide activity (undulating surface, waterlogged depressions, and the presence of tension cracks). The landslide activity in the past destroyed a road which had to be relocated about 80 m lower. However, it is now also partially damaged by the landslide. The second landslide studied (landslide 2; Fig. 1D; 50.535°N and 13.911°E) has an areal character with a length of about 260 m and an average width of 150 m. It is a translational landslide on a flat shear surface. The source zone of the landslide is morphologically very distinct with a step up to 5 m high. In the central part of the landslide, morphologically distinct lateral mounds are formed. The face of the landslide is also morphologically pronounced with up to 3-m-high thrust

mounds. Both studied landslides are covered with *F. sylvatica*, *A. pseudoplatanus*, *L. decidua*, and white birch (*Betula pendula* Roth.).

Methods

Both landslides were first mapped in detail geomorphically, focusing on the distribution of the main morphological features. For this purpose, LiDAR data-based DEM, orthophoto, and GNSS device were used. Trees on each landslide were then selected that were located in areas where the landslide could be expected to have a very strong effect on their root system, thus affecting their growth. These were positions near tension cracks or at the border of two approaching blocks/lobes where elevated pressure conditions could be expected (Fig. 2). In addition, such localized trees often showed leaning or bending of their trunks. Trees that had a damaged trunk with scars present or trees with significantly broken branches (e.g., due to falling nearby trees or wind) were not considered. The position of all selected trees was then recorded using a GNSS device and plotted on a map. Two increment cores were then taken from each selected tree using a Pressler increment borer (max. length: 50 cm; diameter: about 0.5 cm). The sampling position was at a height of about 50 cm above the ground, which according to the results presented by Šilhán et al. (2023) is the most suitable position for detecting anatomical changes in tree-ring series that are not accompanied by macroscopic manifestations. For leaning trunks, the sampling position was taken from the side of the tree. The considered anatomical reactions have a range in the whole circumference of the trunk (Šilhán et al. 2023) and there is no capture of tension wood with macroscopic manifestation. In addition to the disturbed trees, 20 individuals growing outside the landslide area but in similar microclimatic conditions were sampled to establish a reference chronology.



Fig. 2 Examples of disturbed analyzed trees on landslide bodies. **A** Leaning individuals of *F. sylvatica*, **B** leaning individuals of *A. pseudoplatanus* at the border of two landslide blocks, **C** bent trunks of *F. sylvatica*, **D** general view of a group of leaning trunks of different tree species

All samples were subsequently glued to woody supports in the laboratory and their surfaces were prepared using a core microtome (Gärtner and Nievergelt 2010). The first core of two from each tree was further treated with white chalk to increase the contrast between the vessels and the cell wall, and the surface so treated was scanned at 2400 dpi. Tree-ring widths were measured on this core to an accuracy of 0.01 mm using the CooRecorder program (Maxwell and Larsson 2021). Increment curves from these samples were then cross-dated against reference chronology in the program CDendro (Maxwell and Larsson 2021) to detect any false or missing rings. The accuracy of the cross-dating was verified in the Cofecha program (Holmes 1983). The tree-ring series thus correctly dated were used to accurately date tree rings on the second core from each tree. A microcut about 15 μm thick was subsequently taken from the second core using a core microtome. All microcuts were further chemically treated in a standard manner according to Schweingruber (1978). Microcuts were treated with sodium chlorite, stained with Safranin and Astra blue, and then dehydrated with an ascending alcohol series (50, 70, 96%). The final treatment consisted of application of Diasolv, gluing to a glass slide with Canada balsam, and heating in an oven at 60 $^{\circ}\text{C}$ for 12 h.

The resulting permanent slide was photographed at 50 $\times$ magnification and anatomical measurements were performed in the WinCELL software. Measurements were taken in a longitudinal strip along the entire tree-ring width (Arbellay et al. 2012; Diaconu et al. 2017; Mundo et al. 2019) and further processed in XCell. The only parameter studied was the size of the vessels, which is the dominant anatomical response of selected deciduous tree species to landslide movements, according to research by Šilhán et al. (2023). The detection of landslide signal from the interannual series of values of mean vessel lumen area (VLA) was performed according to the methodology by Šilhán (2024). The detection consisted of

calculating the average VLA value from all tree rings within the respective core. From this value, the standard deviation value was subtracted to obtain the VLA threshold value for landslide signal detection. Each tree analyzed thus had its own threshold value (Fig. 3). The dominant anatomical response is a critical decrease in the VLA value, and therefore, all years in which the VLA value was below the calculated threshold were considered to have a landslide signal.

The definition of the landslide event was then performed in a standard manner (Lopez Saez et al. 2012b). All landslide signals were separately chronologically summarized. To express landslide activity, a standard event-response (I_t) index (%) was calculated to express the percentage of trees containing a landslide signal in a given year out of all sampled trees that were alive in that year (Shroder 1978; Butler et al. 1987). Two thresholds were used to define the landslide event itself. The minimum value of the I_t index was set at 5% for landslide 1 and 7.5% for landslide 2. The values depended on the total number of trees analyzed at each landslide (Stoffel et al. 2013; Corona et al. 2014). The second threshold for defining a landslide event concerned the minimum number of trees that contained a landslide signal (significant anatomical response). For landslide 1, this was a minimum of three trees, and for landslide 2, it was a minimum of two trees. The spatial activity of landslide movements was expressed through event-response maps (Corominas and Moya 1999; Stefanini 2004).

The resulting chronologies were used as input data for the analysis of potential triggers of landslide movements. Due to general assumptions about the nature of triggers in the wider region (Raška et al. 2014a), the analysis focused on extreme rainfall events. Precipitation data were used from the Milešovka meteorological station (837 m a.s.l.; approximately 3 km to the NE). Maximum 1-day, 5-day, 10-day, and monthly precipitations for all years were

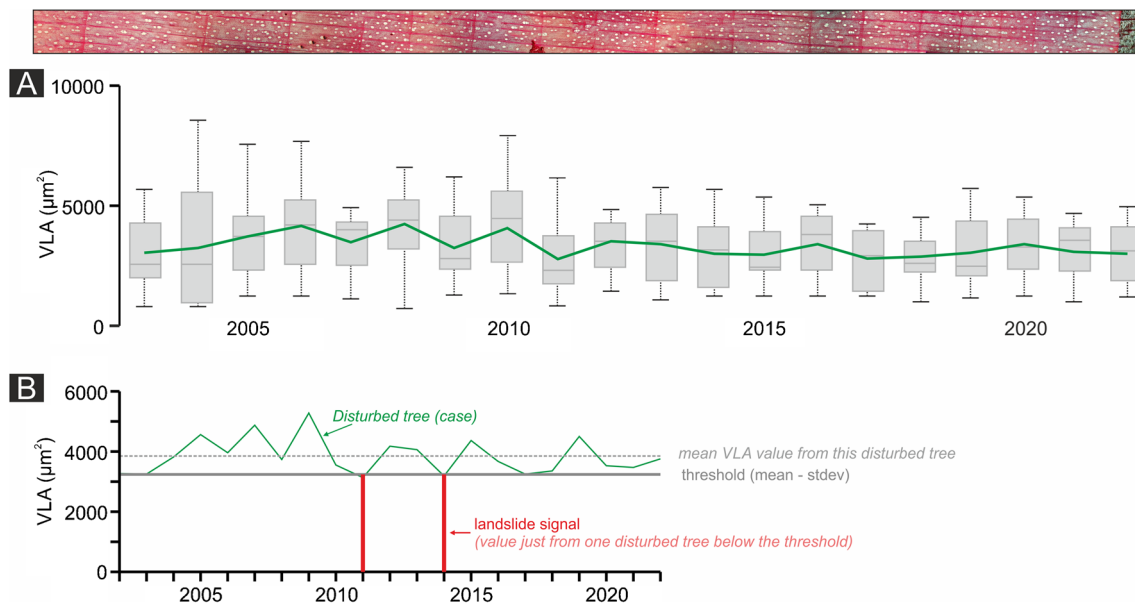


Fig. 3 Method used to detect landslide signal from a series of tree-ring anatomical parameter values (vessel lumen area (VLA)). **A** View of the core microtome including measured average VLA values for each tree ring, **B** method for extracting the landslide signal based on dropping VLA values below a threshold value, which was calculated as the average VLA value for the whole tree-ring series from one tree from which the standard deviation was subtracted (Šilhán 2024)

calculated. Subsequently, the differences between the values of these parameters between the group of years with the occurrence of a landslide event and other years were tested. Differences were tested using parametric *t*-test or non-parametric Mann–Whitney (M–W) test at $\alpha = 0.05$ level of significance. Normality of distribution was tested using the Shapiro–Wilk test. All statistical calculations were performed in the NCSS (NCSS 12 Statistical Software 2018) software environment.

Results

Sampled trees

A total of 54 trees were sampled on both landslides. Seventy-eight increment cores were sampled on landslide 1 and 30 increment cores were sampled on landslide 2. Only two tree species were sampled: *F. sylvatica* and *A. pseudoplatanus*. *A. pseudoplatanus* was the predominant species on both analyzed landslides (21 trees on landslide 1 and eight trees on landslide 2). On average, the trees on landslide 2 (49.3 years; stdev = 12.3 years) were older than those on landslide 1 (45.3 years; stdev = 8.9 years). The ages of the two tree species on the two landslides were very evenly matched (Table 1). The youngest tree was an individual of *F. sylvatica* at landslide 2 with an age of 29 years and the oldest tree was an individual of *A. pseudoplatanus* also at landslide 2 with an age of 69 years.

VLA values and number of growth disturbances

Mean VLA values including their standard deviations were calculated for each tree. For both landslides, higher mean VLA values

were found for *F. sylvatica* compared to *A. pseudoplatanus* (Table 2). The same finding was true for mean stdev values (Table 2). As a result, the threshold values for defining the landslide signal from the series of VLA values were 3073.8 μm^2 and 3041.4 μm^2 for *F. sylvatica* at landslides 1 and 2, respectively, and 3098.9 μm^2 and 3036 μm^2 for *A. pseudoplatanus* species also at the two landslides studied (Table 2). Based on the VLA thresholds thus determined, landslide signals were subsequently detected. A total of 17 landslide signals were detected on landslide 1, representing 0.4 signals per tree, and 12 landslide signals in a tree-ring series of 15 trees on landslide 2, representing an average of 0.8 landslide signals per tree.

Chronology of landslide events, their spatial occurrence, and possible triggers

The lengths of the landslide movement chronologies at both landslides were delineated in a standard manner, i.e., they were considered relevant if at least five trees entered from them. Thus, the total length of the landslide chronology at landslide 1 was 58 years (1966–2023), and at landslide 2, it was 56 years (1968–2023). From all the identified landslide signals (significant VLA values), three landslide events on landslide 1 were compiled according to the exceedance of the established thresholds, representing an average recurrence interval of 19.3 years. For landslide 2, four landslide events were defined, representing an average recurrence interval of 14.0 years (Table 3; Fig. 4). On average, higher values of the I_t index were found for landslide 2 (15.0%), while on landslide 1, the average values reached only 7.7%. The highest I_t index value was found for the 1982 landslide event at landslide 2 ($I_t = 20.0\%$).

Table 1 The number, species, and age of sampled trees on both analysed landslides

		Number	Mean age (stdev)	Minimal age	Maximal age
Landslide 1	<i>F. sylvatica</i>	18	45.3 (8.0)	35	63
	<i>A. pseudoplatanus</i>	21	45.2 (9.6)	30	67
	Total	39	45.3 (8.9)	30	67
Landslide 2	<i>F. sylvatica</i>	7	49.0 (13.6)	29	68
	<i>A. pseudoplatanus</i>	8	49.5 (11.1)	33	69
	Total	15	49.3 (12.3)	29	69

Table 2 The vessel lumen area (VLA) values (mean, stdev, signal threshold)

		Mean VLA (μm^2)	Mean stdev (μm^2)	Mean VLA threshold (μm^2)
Landslide 1	<i>F. sylvatica</i>	3559.7	485.9	3073.8
	<i>A. pseudoplatanus</i>	3331.2	232.3	3098.9
Landslide 2	<i>F. sylvatica</i>	3542.1	500.7	3041.4
	<i>A. pseudoplatanus</i>	3282.9	246.9	3036.0

Table 3 Growth disturbances (GD) and chronology of landslide events

	Chronology length (years)	Covered period	GDs	Event years	Recurrence (years)
Landslide 1	58	1966–2023	17	3	19.3
Landslide 2	56	1968–2023	12	4	14.0

For each landslide year detected, event-response maps were constructed to represent the spatial position of trees that contained a landslide signal in that year (Fig. 5). In essence, two recurring patterns of spatial distribution of landslide signals can be extracted on the two landslides studied. In the first case, landslide signals were spaced at greater distances apart. These were the years 1998 and 2001 at landslide 1 and the years 1995 and 2007 at landslide 2. In contrast, the second spatial pattern indicated clustering of landslide signals in a very limited space. This concerned the landslide

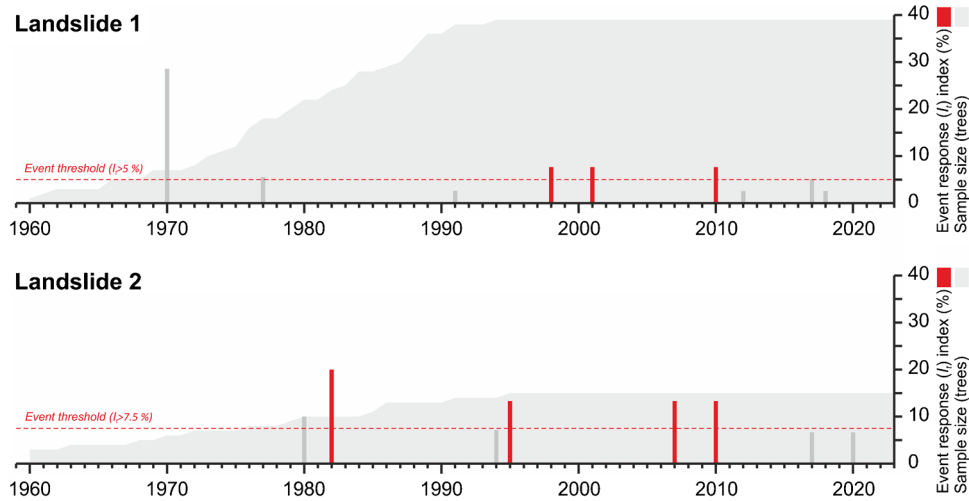


Fig. 4 Chronology of reconstructed landslide events on the two study landslides expressed using the event-response (I_r) index including the chronological evolution of sample size (number of living sampled trees)

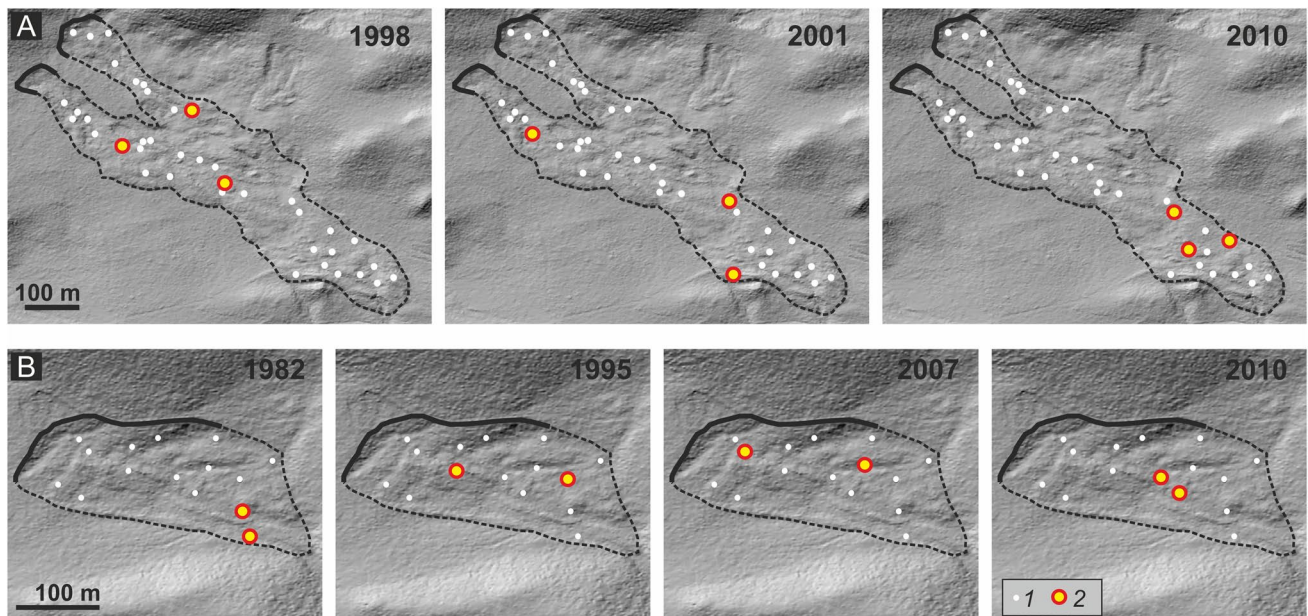


Fig. 5 Event-response maps for each dated landslide event on both study landslides (1 — positions of sampled trees, 2 — positions of trees showing landslide signal in a given year)

year 2010 on landslide 1 and the landslide years 1982 and 2010 on landslide 2.

The analysis of extreme rainfall events (maximum 1-day, 5-day, and 10-day rainfall in a year) showed that high rainfall can play a significant role in triggering landslide movements. For all the indicators analyzed, precipitation totals in event years (years with dated landslide movements) appear visually higher for both landslides studied compared to years with no dated landslide movement (other years). However, due to the very limited number of dated landslide events, the indicated difference is not statistically significant in any of the analyses performed (Fig. 6).

Discussion

This study was the first to use exclusively anatomical indicators in the tree ring of disturbed trees (changes in vessel size) for a comprehensive spatio-temporal reconstruction of landslide movements. For a pioneering case study, two active landslides in a neo-volcanic setting were selected, where 54 disturbed *F. sylvatica* and *A. pseudoplatanus* individuals were sampled and analyzed. Micro-cuts of whole increment cores were prepared from all trees and an average of 0.4 and 0.8 landslide signals per tree were identified.

A general characteristic of anatomical studies within the framework of dendrogeomorphic research is the generally low number of trees analyzed. However, these earlier studies were exclusively focused on characterizing the type of anatomical response to a single well-known geomorphic event; moreover, these anatomical responses were accompanied by a macroscopically identifiable

standard growth disturbance (e.g., trunk damage and callus tissue formation or traumatic resin ducts; Schneuwly et al. 2009; Arbellay et al. 2010, 2013, 2014; Ballesteros et al. 2010). However, in this study, previous knowledge of tree anatomical responses has already been used to effectively date previously unknown landslide events. In this case, however, the number of analyzed trees must already be higher to be able to use basic dendrogeomorphic procedures (e.g., determination of an optimal threshold value of the I_t index) in the construction of a spatio-temporal reconstruction of landslide movements (Corona et al. 2014). In this case, the numbers were 39 and 15 trees per landslide, respectively, but this already imposes a significantly higher time, material, and financial burden on the research. These are rather lower numbers of sampled trees, but still sufficient (especially in the case of 39 trees) to efficiently construct a chronology with a minimum amount of noise (Stoffel et al. 2013).

Two tree species (*F. sylvatica* and *A. pseudoplatanus*) were used for the study. In doing so, the methodology used to extract the landslide signal from the VLA series was developed using only data from the *F. sylvatica* species. However, based on the results, it seems that the methodological approach used is also suitable for the species *A. pseudoplatanus*, which may be due to the similar anatomical structure of the two tree species (both have a diffuse porous wood structure). However, the question is whether the methodology used would also be applicable in the case of ring-porous tree species, which are also often used in landslide studies (e.g., *Quercus* species; Fantucci and Sorriso-Valvo 1999; Stefanini 2004). Thus, further research should be aimed at detecting the nature of anatomical

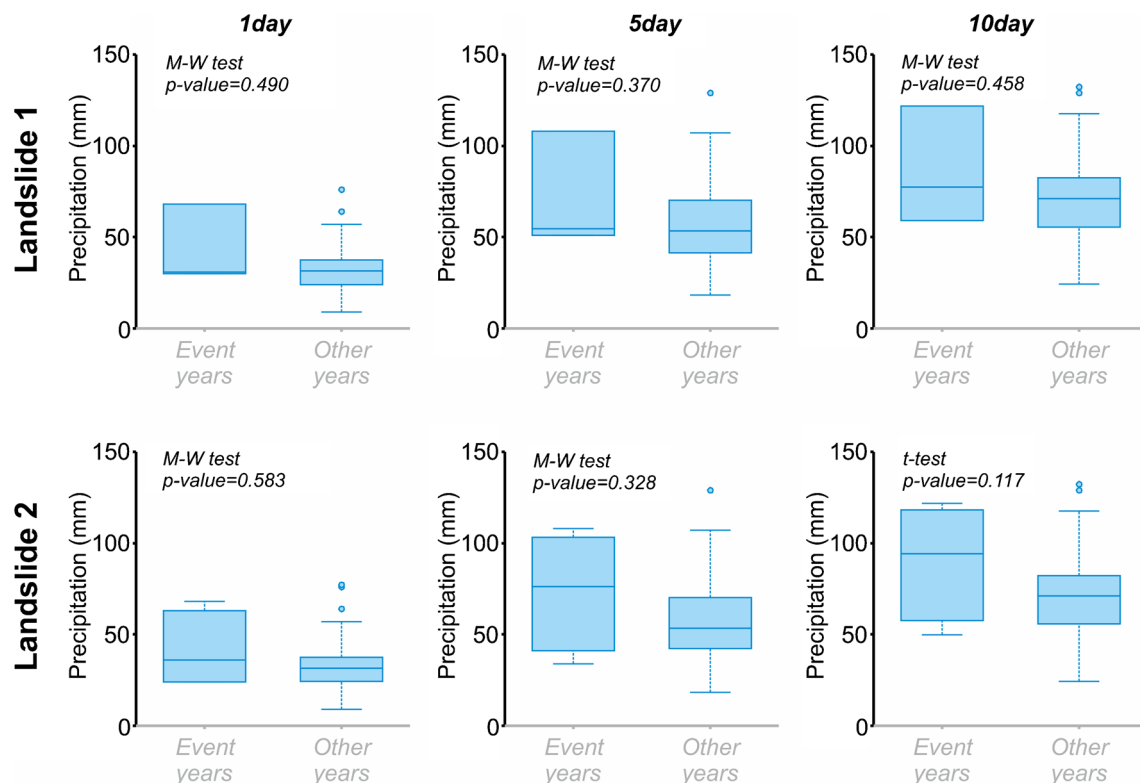


Fig. 6 Differences in values of maximum 1-day, 5-day, and 10-day precipitations in years with a dated landslide event (event years) and in years without a landslide event (other years). **A** Landslide 1, **B** Landslide 2

responses to landslide movements in selected ring-porous tree species and validating the effectiveness of the landslide signal extraction methodology used. However, it is possible that for ring-porous tree species, it will not be possible to apply the landslide signal extraction methodology used in this study and a new experimental study will be necessary to define optimal procedures for working with this group of trees.

The only type of anatomical growth response used was a change (significant decrease) in VLA. This anatomical response is assumed to be associated with damage to the root system of the affected trees due to either subsurface landslide movements or damage in tension cracks. Disruption of the dividing cambial layer in the roots subsequently blocks the standard basipetal flux of enzymes (especially the enzyme auxin) to more distant parts of the roots (Aloni and Zimmermann 1984; Kalev and Aloni 1999; Arbella et al. 2012). This enzyme (responsible for cell division) subsequently accumulates in excess in the zone above the root damage and intensively initiates further cell division. Thus, these cells are not sufficient to lighten to normal size and their limited size thus provides a signal useful for detecting a landslide event that has damaged the root system. However, according to the findings of Šilhán et al. (2023), this anatomical reaction can no longer be detected in higher parts of the stem. Thus, it can be expected that auxin accumulation above the damaged root system has a vertical limitation, to which the sampling height had to be adapted, thus differing from macroscopic investigations in which samples are taken at the point of maximum bending of tilted trunks (Stoffel and Bollschweiler 2008). However, the exclusive use of VLA changes induced by root damage for landslide signal detection is a completely new approach, and therefore, it was necessary to define a specific approach for identifying critical VLA thresholds that could be considered as the result of landslide movements. Nevertheless, the proposed approach could be further tested on other tree species in future studies. Furthermore, the time resolution of the approach used seems to be 1 year. From the results obtained and with respect to the methodology used, it seems that it is not yet possible to achieve seasonal dating accuracy as in the case of some macroscopic reactions (e.g., compression wood or callus tissue). On the other hand, the approach used does not seem to be limited by the age of the trees (although a potential age dependence would be worthy of future verification).

The methodological approach used is thus based on the assumption of damage to the root system due to landslide movements. However, this principle implies that this methodological approach is not suitable for all types of landslides. Considering the character of the movement mechanism of different types of landslides, the methodological approach from this study can be recommended for flow-like landslides with intense subsurface deformation or for translational landslides with the presence of tension cracks. On the other hand, it is questionable whether the above approach is applicable to the motion stage of rigid landslide blocks with rotational motion character. Indeed, in these cases, trees can be expected to be dominantly affected through the tilting of their trunks but without direct impact on the root system in the form of sufficient damage (Šilhán 2021). In these cases, it is instead sensible to orient research towards the detection of changes in tree-ring eccentricity or the detection of reaction wood. It can therefore be assumed that in the case of rotational or deep-seated landslides with deep shear surfaces, tree-ring-based research focusing on classical macroscopic

growth disturbances will be increasingly effective compared to the approach applied in this study.

The observed frequency of anatomical responses to landslide movements is generally lower compared to macroscopic responses, where their frequency can be up to several times that of anatomical responses (depending on the landslide activity, of course). However, in the case of macroscopic reactions, there is also a larger amount of noise (the ratio of missed growth reactions in the resulting chronology; Šilhán et al. 2022a, b). In the case of this study, however, the amount of growth reactions not used in the resulting chronology is significantly smaller (less than half in the cases of both landslides). Thus, it can be expected that the methodological approach used ensured a very good capture of landslide movements in the resulting chronology while minimizing the influence of creep, which is a common problem in tree-ring-based landslide analysis (Malik and Wistuba 2012; Fabiánová et al. 2021). Creep movements do not seem to be able to sufficiently damage the root system of trees so that anatomical growth responses can subsequently be detected.

The resulting chronology can thus be assumed to contain a smaller amount of noise induced by creep movements. Moreover, according to the observed absence of a series of several tree rings with significantly low VLA values, we can assume the absence of inertia of this type of anatomical reaction, which has a direct impact on the creep chronology, in which we can expect the presence of all events, since younger events cannot be masked by growth reactions to older events. However, due to the larger time intervals between dated landslide events, the inertia of the reactions would not be a serious problem in the case of this study. Conversely, it appears that this approach may have the advantage over macroscopic growth reactions of being well applicable in environments where landslide reactivations have a high frequency, as the anatomical approach used is able to record them.

The relatively limited number of sampled trees, combined with the low number of detected landslide signals, did not allow for the effective creation of a spatial distribution of recurrence interval landslide movements (Stoffel et al. 2005) or the modelling of future landslide activity through landslide hazard maps (Lopez Saez et al. 2012b). However, even event-response maps have highlighted the specificities of the anatomy-based approach used. Namely, trees could only respond at locations where their root system was damaged. Due to the heterogeneous nature of the landslide body, it is possible that in some locations (despite careful selection of sampling sites), only leaning of trunks occurred without root damage. This fact may explain the clustering of landslide signals in some years into a spatially constrained area. In contrast, the dispersion pattern of the signals may indeed reflect only local movement. Thus, for the future use of an anatomical approach for landslide motion detection, it may be recommended to complement the research with geophysical measurements (e.g., electrical resistivity tomography of ground penetrating radar) that could help to distinguish suitable sampling sites with highly expected bedrock heterogeneity (Šilhán et al. 2022b). Indeed, these approaches could help with the detection of subsurface structures associated with the presence of partial shallow shear surfaces or hidden tension cracks. The knowledge of landslide activity obtained using the approach could find future application in slope stability modelling or landslide risk assessment (Nikoobakht et al. 2022; Nanekaran et al. 2023). It could also be combined with remote sensing applications

in the future or used as input to deep/machine learning approaches in landslide modelling (Yimin et al. 2021; Nanehkaran et al. 2022).

Part of this study was to test the feasibility of using dated landslide chronology as an input dataset for the analysis of potential triggers. The results obtained confirm general assumptions about the control of landslide activity through high rainfall events within the study region (Raška et al. 2014a). However, the question is what is the potential influence of dry periods on slope stability. This aspect should be the subject of future research, particularly due to the declared presence of swelling minerals in landslide material in the wider region (Rybář et al. 2000). The presence of smectite in particular can create contraction cracks in landslide bodies during dry periods, which are then used as open pathways for faster infiltration of rainwater up to the shear surfaces (Tichavský et al. 2019). However, this effect has not yet been confirmed from the studied region although it can be theoretically assumed. The obtained tree-ring anatomy-based chronological data could be effectively used for this purpose.

Conclusions

In this study, for the first time, exclusively anatomical analyses were used to detect landslide signals from a tree-ring series to define past landslide events. Two active landslide sites were selected for this purpose, where a total of 54 individuals of *F. sylvatica* and *A. pseudoplatanus* were sampled. Using a methodology based on the detection of a significant decrease in vessel lumen area values, 29 anatomy-based landslide signals were identified, from which seven landslide events were constructed on both landslides.

The two tree species used showed virtually identical characteristics within the methodology used and it is possible to recommend their combination in future research. However, the question is what would be the usefulness of other tree species with different wood anatomy (i.e., ring-porous wood). This question should be resolved in future research. In view of the assumed principle of changes in the VLA due to landslide movements, the methodology used can only be recommended for selected types of landslides. Its use should be successful for flow-like landslides and translational landslides with the presence of tension cracks. On the contrary, the principle appears to be difficult to apply to rigid rotated landslide blocks. However, even with an appropriately chosen landslide type, careful selection of the sampling site is important so that damage to the root system can be expected. To this end, a geophysical survey may be recommended, which could greatly help with this aspect in future investigations. Further use of the optimized complex approach may find application in future slope stability modelling or landslide risk assessment. Although this is a more time-, material-, and cost-intensive tree-ring-based approach compared to working with classical macroscopic growth disturbances, this disadvantage is compensated by obtaining a very complete chronology (due to the absence of inertia of growth reactions) with a minimum of noise (the method seems to partially ignore creep type movements).

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Data Availability

Data will be made available on request.

Declarations

Conflict of interest The author declares no competing interests.

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References

- Alestalo J (1971) Dendrochronological interpretation of geomorphic processes. *Fennia* 105:1–139
- Aloni R, Zimmermann MH (1984) Length, width, and pattern of regenerative vessels along strips of vascular tissue. *Bot Gaz* 145:50–54. <https://doi.org/10.1086/337425>
- Arbellay E, Stoffel M, Bollschweiler M (2010) Wood anatomical analysis of *Alnus incana* and *Betula pendula* injured by a debris-flow event. *Tree Physiol* 30:1290–1298. <https://doi.org/10.1093/treephys/tpq065>
- Arbellay E, Fonti P, Stoffel M (2012) Duration and extension of anatomical changes in wood structure after cambial injury. *J Exp Bot* 63:3271–3277. <https://doi.org/10.1093/jxb/ers050>
- Arbellay E, Stoffel M, Decaulne A (2013) Dating of snow avalanches by means of wound-induced vessel anomalies in sub-arctic *Betula pubescens*. *Boreas* 42:568–574. <https://doi.org/10.1111/j.1502-3885.2012.00302.x>
- Arbellay E, Stoffel M, Sutherland EK et al (2014) Changes in tracheid and ray traits in fire scars of North American conifers and their ecophysiological implications. *Ann Bot* 114:223–232. <https://doi.org/10.1093/aob/mcu112>
- Astrade L, Bravard JP, Landon N (1998) Landslides and dynamics of an alpine geosystem: dendrogeomorphic study of two locations in the Boulc Valley (Diois, France). *Geogr Physique Quatern* 52:153–165. <https://doi.org/10.7202/004765ar>
- Ballesteros JA, Stoffel M, Bollschweiler M et al (2010) Flash-flood impacts cause changes in wood anatomy of *Alnus glutinosa*, *Fraxinus angustifolia* and *Quercus pyrenaica*. *Tree Physiol* 30:773–781
- Blahůt J, Klimeš J (2022) Causes and triggers of mass-movements: volcanic activity. In: *Treatise on Geomorphology*. Elsevier, pp 254–282
- Braam RR, Weiss EEJ, Burrough PA (1987) Spatial and temporal analysis of mass movement using dendrochronology. *Catena* 14:573–584
- Butler DR, Malanson GP, Oelfke JG (1987) Tree-ring analysis and natural hazard chronologies: minimum sample sizes and index values. *Prof Geogr* 39. <https://doi.org/10.1111/j.0033-0124.1987.00041.x>

- Carrara PE, O'Neill JM (2003) Tree-ring dated landslide movements and their relationship to seismic events in southwestern Montana, USA. *Quat Res* 59:25–35. [https://doi.org/10.1016/S0033-5894\(02\)00010-8](https://doi.org/10.1016/S0033-5894(02)00010-8)
- Clague JJ, Souther JG (1982) The Dusty Creek landslide on Mount Cayley, British Columbia. *Can J Earth Science* 19:524–539
- Cockburn JMH, Vetta M, Garver JI (2016) Tree-ring evidence linking late twentieth century changes in precipitation to slope instability, central New York state, USA. *Phys Geogr* 37:153–168. <https://doi.org/10.1080/02723646.2016.1157741>
- Corominas J, Moya J (1999) Reconstructing recent landslide activity in relation to rainfall in the Llobregat River basin, Eastern Pyrenees, Spain. *Geomorphology* 30:79–93. [https://doi.org/10.1016/S0169-555X\(99\)00046-X](https://doi.org/10.1016/S0169-555X(99)00046-X)
- Corona C, Lopez Saez J, Stoffel M (2014) Defining optimal sample size, sampling design and thresholds for dendrogeomorphic landslide reconstructions. *Quat Geochronol* 22:72–84. <https://doi.org/10.1016/j.quageo.2014.02.006>
- Diaconu D, Hackenberg J, Stangler DF et al (2017) Simulation study to determine necessary sample sizes for image analysis-based quantitative wood anatomy of vessels of beech (*Fagus sylvatica*). *Dendrochronologia* 45:35–38. <https://doi.org/10.1016/j.dendro.2017.07.002>
- Fabiánová A, Chalupa V, Šilhán K (2021) Dendrogeomorphic dating vs. low-magnitude landsliding. *Quat Geochronol* 62:101150. <https://doi.org/10.1016/j.quageo.2021.101150>
- Fantucci R, Sorriso-Valvo M (1999) Dendrogeomorphological analysis of a slope near Lago, Calabria (Italy). *Geomorphology* 30:65–174
- Fantucci R, McCord A (1995) Reconstruction of landslide dynamic with dendrochronological methods. *Dendrochronologia* 13:43–58
- Gärtner H, Nievergelt D (2010) The core-microtome: a new tool for surface preparation on cores and time series analysis of varying cell parameters. *Dendrochronologia* 28:85–92
- Guida D, Pelfini M, Santilli M (2008) Geomorphological and dendrochronological analyses of a complex landslide in the Southern Apennines. *Geografiska Annaler* 90:211–226
- Heinrich I, Gärtner H (2008) Variations in tension wood of two broad-leaved tree species in response to different mechanical treatments: Implications for dendrochronology and mass movement studies. *Int J Plant Sci* 169:928–936. <https://doi.org/10.1086/589695>
- Holmes R (1983) Computer-assisted quality control in tree-ring dating and measurement. *Tree-Ring Bull* 43:69–73
- Kalev N, Aloni R (1999) Role of ethylene and auxin in regenerative differentiation and orientation of tracheids in *Pinus pinea* seedlings. *New Phytol* 142. <https://doi.org/10.1046/j.1469-8137.1999.00398.x>
- Klimeš J, Baroň I, Pánek T et al (2009) Investigation of recent catastrophic landslides in the flysch belt of Outer Western Carpathians (Czech Republic): progress towards better hazard assessment. *Natl Hazards Earth Syst Sci* 9:119–128. <https://doi.org/10.5194/nhess-9-119-2009>
- Lang A, Moya J, Corominas J, Dikau R (1999) Classic and new dating methods for assessing the temporal occurrence of mass movements. *Geomorphology* 30:33–52
- Lopez Saez J, Corona C, Stoffel M et al (2012a) Dendrogeomorphic reconstruction of past landslide reactivation with seasonal precision: the Bois Noir landslide, southeast French Alps. *Landslides* 9:189–203. <https://doi.org/10.1007/s10346-011-0284-6>
- Lopez Saez J, Corona C, Stoffel M et al (2012b) Probability maps of landslide reactivation derived from tree-ring records: Pra Bellon landslide, southern French Alps. *Geomorphology* 138:189–202. <https://doi.org/10.1016/j.geomorph.2011.08.034>
- Malik I, Wistuba M (2012) Dendrochronological methods for reconstructing mass movements—an example of landslide activity analysis using tree-ring eccentricity. *Geochronometria* 39:180–196. <https://doi.org/10.2478/s13386-012-0005-5>
- Maxwell RS, Larsson L-A (2021) Measuring tree-ring widths using the CooRecorder software application. *Dendrochronologia* 67:125841. <https://doi.org/10.1016/j.dendro.2021.125841>
- Mundo IA, González CV, Stoffel M et al (2019) Fire damage to cambium affects localized xylem anatomy and hydraulics: the case of *Nothofagus pumilio* in Patagonia. *Am J Bot* 106:1536–1544. <https://doi.org/10.1002/ajb2.1395>
- Nanehkaran YA, Zhu L, Chen J et al (2022) Application of artificial neural networks and geographic information system to provide hazard susceptibility maps for rockfall failures. *Environ Earth Sci* 81:475
- Nanehkaran YA, Licai Z, Chengyong J et al (2023) Comparative analysis for slope stability by using machine learning methods. *Appl Sci* 13:1555. <https://doi.org/10.3390/app13031555>
- NCSS 12 Statistical Software (2018) NCSS, LLC. Kaysville, Utah, USA
- Nikoobakht S, Azarafza M, Akgun H et al (2022) Landslide susceptibility assessment by using convolutional neural network. *Appl Sci* 12:5992. <https://doi.org/10.3390/app12125992>
- Raška P, Zábanský V, Dubišar J et al (2014b) Documentary proxies and interdisciplinary research on historic geomorphologic hazards: a discussion of the current state from a central European perspective. *Nat Hazards* 70:705–732. <https://doi.org/10.1007/s11069-013-0839-z>
- Raška P, Hartvich F, Cajz V, Adamovič J (2014a) Structural setting of the Čertovka landslide (Ústí nad Labem, Czech Republic): morphostructural analysis and electrical resistivity tomography. *Geol Q* 58. <https://doi.org/10.7306/gq.1134>
- Rybář J, Košťák B (2003) Monitoring and physical model simulation of a complex slope deformation in neovolcanites. In: Natau O, Fecker E, Pimentel E (eds) *Geotechnical Measurements and Modelling*. Swets & Zeitlinger, Karlsruhe, pp 231–237
- Rybář J, Vilímek V, Čílek V et al (2000) Process analysis of deep slope failures in České Středohoří neovolcanites. *Acta Mont IRSM AS CR Ser AB* 115:39–46
- Savi S, Schneuwly-Bollschweiler M, Bommer-Denns B et al (2013) Geomorphologic coupling between hillslopes and channels in the Swiss Alps. *Earth Surf Process Landf* 38:959–969. <https://doi.org/10.1002/esp.3342>
- Schneuwly DM, Stoffel M, Bollschweiler M (2009) Formation and spread of callus tissue and tangential rows of resin ducts in *Larix decidua* and *Picea abies* following rockfall impacts. *Tree Physiol* 29:281–289. <https://doi.org/10.1093/treephys/tpn026>
- Schweingruber FH (1978) *Mikroskopische Holzanatomie*. Swiss Federal Institute of Forestry Research, Birmensdorf, Switzerland p 215
- Shroder JF (1978) Dendrogeomorphological analysis of mass movement on Table Cliffs Plateau, Utah. *Quat Res* 9:168–185. [https://doi.org/10.1016/0033-5894\(78\)90065-0](https://doi.org/10.1016/0033-5894(78)90065-0)
- Šilhán K (2019) Tree-ring eccentricity in the dendrogeomorphic analysis of landslides – A comparative study. *Catena* 174:1–10. <https://doi.org/10.1016/j.catena.2018.11.002>
- Šilhán K (2020) Dendrogeomorphology of landslides: principles, results and perspectives. *Landslides* 17:2421–2441. <https://doi.org/10.1007/s10346-020-01397-4>
- Šilhán K (2021) Dendrogeomorphology of different landslide types: a review. *Forests* 12:1–19
- Šilhán K (2023) Is tree-ring anatomy the key? searching for an optimal dendrogeomorphic approach to distinguish shallow creep and true slide movements. *Catena* 232:107466. <https://doi.org/10.1016/j.catena.2023.107466>
- Šilhán K (2024) Defining an optimal approach for landslide signal extraction from tree-ring anatomical parameter series: extending the application capabilities of dendrogeomorphology. *Catena* 243:108176. <https://doi.org/10.1016/j.catena.2024.108176>
- Šilhán K, Stoffel M (2022) Landslide-induced changes in tree-ring anatomy: a new dendrogeomorphic avenue? *Catena* 213:106144. <https://doi.org/10.1016/j.catena.2022.106144>
- Šilhán K, Pánek T, Škarpich V et al (2022a) Specifics of slope movements on slopes with contrasting structural conditions: Evidence from tree-ring records. *Geomorphology* 415:108425. <https://doi.org/10.1016/j.geomorph.2022.108425>
- Šilhán K, Pánek T, Škarpich V (2022b) Diversification of landslide areas as a means for reducing noise in dendrogeomorphic dating. *Quat Geochronol* 72:101362. <https://doi.org/10.1016/j.quageo.2022.101362>
- Šilhán K, Balek J, Hartvich F et al (2023) Anatomical growth response of *Fagus sylvatica* L. to landslide movements. *Sci Total Environ* 867:161554. <https://doi.org/10.1016/j.scitotenv.2023.161554>
- Šilhán K, Fabiánová A, Klimeš J et al (2024) The effect of tree growth disturbances inertia on dendrogeomorphic spatio-temporal analysis of

- landslides: a case study. *Catena* 235:107678. <https://doi.org/10.1016/j.catena.2023.107678>
- Stefanini MC (2004) Spatio-temporal analysis of a complex landslide in the Northern Apennines (Italy) by means of dendrochronology. *Geomorphology* 63:191–202. <https://doi.org/10.1016/j.geomorph.2004.04.003>
- Stoffel M, Bollschweiler M (2008) Tree-ring analysis in natural hazards research - an overview. *Nat Hazard* 8:187–202. <https://doi.org/10.5194/nhess-8-187-2008>
- Stoffel M, Corona C (2014) Dendroecological dating of geomorphic disturbance in trees. *Tree Ring Res* 70:3–20. <https://doi.org/10.3959/1536-1098-70.1.3>
- Stoffel M, Lièvre I, Monbaron M, Perret S (2005) Seasonal timing of rock-fall activity on a forested slope at Täschgufer (Swiss Alps) – a dendro-chronological approach. *Z Geomorphol* 49:89–106
- Stoffel M, Butler DR, Corona C (2013) Mass movements and tree rings: A guide to dendrogeomorphic field sampling and dating. *Geomorphology* 200:106–120. <https://doi.org/10.1016/j.geomorph.2012.12.017>
- Tichavský R, Ballesteros JA, Šilhán K, et al (2019) Dry spells and extreme precipitation are the main trigger of landslides in central Europe. *Sci Rep* 9. <https://doi.org/10.1038/s41598-019-51148-2>
- Timell TE (1986) *Compression wood in gymnosperms*, 1st edn. Springer Berlin Heidelberg, Berlin, p 2150
- Tolasz R, Míková T, Valeriánová A, Voženílek V (2007) *Climate atlas of Czechia*. Czech Hydrometeorological Institute, p 255
- Westing AH (1965) Formation and function of compression wood in gymnosperms II. *Bot Rev* 34:51–78
- Wieczorek GF, Eaton LS, Yanosky TM, Turner EJ (2006) Hurricane-induced landslide activity on an alluvial fan along Meadow Run, Shenandoah Valley, Virginia (eastern USA). *Landslides* 3:95–106
- Wistuba M, Malik I, Krzemień K et al (2018) Can low-magnitude earthquakes act as a triggering factor for landslide activity? Examples from the Western Carpathian Mts, Poland. *Catena* 171:359–375. <https://doi.org/10.1016/j.catena.2018.07.028>
- Yimin M, Yican L, Mwakepesa DS et al (2021) Innovative landslide susceptibility mapping portrayed by CA-AQD and K-Means clustering algorithms. *Adv Civ Engi* 8846779. <https://doi.org/10.1155/2021/8846779>
- Zhang Y, Stoffel M, Liang E et al (2019) Centennial-scale process activity in a complex landslide body in the Qilian Mountains, northeast Tibetan Plateau, China. *Catena* 179:29–38
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