forests

MDPI

Review

Dendrogeomorphology of Different Landslide Types: A Review

Karel Šilhán

Department of Physical Geography and Geoecology, University of Ostrava, Chittussiho 10, 710 00 Ostrava, Czech Republic; karel.silhan@osu.cz; Tel.: +420-597-092-358

Abstract: The dating of past landslide events is one of the most crucial aspects of landslide research, leading to a better understanding of past landslide activity. Landslides can be extremely dangerous natural hazards, and thus, solving the relationships between their activity and climate variations is of high importance. For these purposes, data about past landslide activity are fundamental for such analyses. Various methods of landslide absolute dating exist, but the most precise approach that dates back several centuries is based on tree-ring analysis (dendrogeomorphology). Landslide movements can affect the growth of trees in response to specific growth disturbances. Although dendrogeomorphic methods are successfully used for dating other geomorphic processes, their use in landslide research is actually the most frequent. Dendrogeomorphic research on landslides is strongly influenced by general approaches of landslide signal extraction from tree-ring series of disturbed trees and by the type of landslide (varying by morphology, material and mechanism of movement). This study provides an overview of basic aspects of dendrogeomorphic research on landslides, and more specifically, it reviews basic tree-ring-based approaches of landslide dating. Presented review focuses on various landslide types and their effect on dendrogeomorphic dating. This review is built from the extensive database of all accessible dendrogeomorphic studies of landslides from 1893 to 2020. Moreover, recommendations for specific sampling and approach choice in individual landslide types are presented. Finally, limits of tree-ring-based approaches are presented, including provided proposals for further research.

Keywords: dendrogeomorphology; landslides; tree-ring; methods; review

check for updates

Citation: Šilhán, K. Dendrogeomorphology of Different Landslide Types: A Review. *Forests* **2021**, *12*, 261. https://doi.org/10.3390/f12030261

Academic Editor: Filippo Giadrossich

Received: 7 February 2021
Accepted: 19 February 2021
Published: 25 February 2021

1. Introduction

Landslides are frequent forms of relief and dangerous natural hazards [1]. Negative effects of landslide movement may be visible, e.g., in damage to roads (e.g., in 2013, a large landslide disturbed the construction of a key highway connection in the northern Czech Republic [2]), forests, buildings or even fatalities [3]. Under certain conditions, landslides can cause damming of streams. Longitudinal profiles of affected streams are significantly modified, and accelerated erosion is a frequent response. A wide spectrum of landslide types exists [4–6], and they differ in morphology, inner structure, development velocity and movement mechanism. Moreover, landslide types differ in their predisposition and triggering factors. Landslide triggers are usually specific to the landslide type, e.g., high-magnitude and short-duration rainfalls play a crucial role in the triggering of shallow landslides, earth flows or debris slides [7,8]. Conversely, medium-magnitude and long-duration rainfalls are significant triggers of deep-seated landslides (DSLs) and deep-seated gravitational slope deformations (DSGSDs) [9,10]. Flood events can generate landslide movements on undercut riverbanks [11,12]. In addition to hydrometeorological triggers, seismic activity during earthquake events plays a crucial role in the activation of several thousand landslides in affected regions (e.g., landslide calamity following the 2008 Wenchuan earthquake in China; [13,14]). According to [15], an M < 5 earthquake is able to trigger landslides at an epicentral distance <1 km under suitable geological conditions. In addition to natural triggers (various precipitation patterns or seismicity), significant damage can be caused due to landslides induced by anthropogenic activities that are connected with artificial shaking (usually small size landslides) and slope undercutting during road building [16] or increasing water pore pressure during artificial dam soaking (e.g., the Vajont landslide in 1963; [17]).

As landslide activity is closely related to hydroclimatic conditions, a detailed understanding of the climate-landslide relationship is of particular importance, as climate changes are expected to occur in the future [18]. Nevertheless, for these purposes, knowledge of past landslide activity is crucial. Unfortunately, such data are usually very rare or completely missing. [19] noted the limitations of archival data (difficult comparison of data from different sources or impossible determination of exact locality). In such cases, methods of absolute dating can provide useful insight into past landslide activity. The use of radiocarbon dating methods is very frequent in landslide research; radiocarbon dating methods use organic material incorporated in a body of old deep seated landslide or accumulated in landslide-related depressions (near-scarp or inter-colluvial depressions or landslide-dammed lakes) [20]. The U/Th dating approach is more robust in dating speleothems (compared with ^{14}C) on exposed carbonate walls [21]. Moreover, the moment when fine sediment is buried by landslide material in a landslide event can be determined using optically stimulated luminescence. Methods using cosmogenic radionuclides are suitable for dating the moment of rock wall exposure due to landslide movements [22]. Unfortunately, these methods are often high-cost and require a large number of samples to obtain meaningful results, and some landslides are not suitable for their application.

In contrast, methods based on the dating of tree rings (dendrogeomorphology; [23]) are very cheap, and many samples can be processed in a relatively short time. These methods are applicable in locations where trees occupying landslide surfaces form annual increments in the form of tree rings. Dendrogeomorphic methods can provide data of past landslide activity ranging several hundred years in the past [24] with seasonal precision [25]. Their principle is based on the ability of trees to record external disturbances in tree-ring series. Landslide movements can induce various types of external disturbances (e.g., tree tilting) depending on the landslide type. Trees subsequently respond to such external impacts by specific growth disturbances that are recorded in the tree-ring series of affected trees [26]. Landslide properties (velocity, depth of shear zone, movement mechanism, magnitude of surface deformation) seem to be crucial factors influencing the type and intensity of growth disturbances. As dendrogeomorphic methods are dependent on the presence of growth disturbances in tree-ring series, various landslide types can be dated using a tree-ring approach with varying precision and success. Some landslide types may not be datable. The success of landslide dating depends on the method used for landslide signal extraction from tree-ring series. Again, various approaches to signal extraction exist. Their application is not only dependent on the landslide type and induced disturbance, but tree species also play an important role. Results obtained using dendrogeomorphic methods can be useful for urban planners of insurance companies because the research can provide data about the most dangerous parts of landslide areas or the recurrence intervals of landslide events. Although dendrogeomorphic methods are generally meaningful and useful approaches for landslide dating, several limitations still exist that should be minimized during future research (e.g., defining of optimal age structure of sampled trees, filtering of tree-ring signals coming from various landslide types, or defining the general sensitivity of trees to landslide movements).

Based on the abovementioned aspects of dendrogeomorphic landslide dating, the aims of this paper are (i) to provide an overview of tree-ring-based methods for past landslide event dating, (ii) to review the effect of various methodical approaches on the results of landslide dating, (iii) to review the specific effects of various landslide types on tree-ring-based dating, and (iv) to provide an overview of limitations and research gaps and provide suggestions for solving these problems in future dendrogeomorphic research.

2. Methodical Overview

2.1. Principle of Tree Growth Responses to Landslide Movements

The general principle of tree growth vs. geomorphic process interactions (on the basis of dendrogeomorphology; Figure 1) was described already by [26]. However, the basic principles are applicable to the problem of landslides, as introduced by [27]. Landslides affect tree growth in several ways. Hidden subsurface movements can cause damage to root systems. Undulation of landslide surfaces during movement can cause destabilization of tree stems and their tilting. Intensive tilting can cause the contact of neighbouring stems and mutual wounding or decapitation. Each of these external disturbances induces a specific tree growth disturbance response [28].

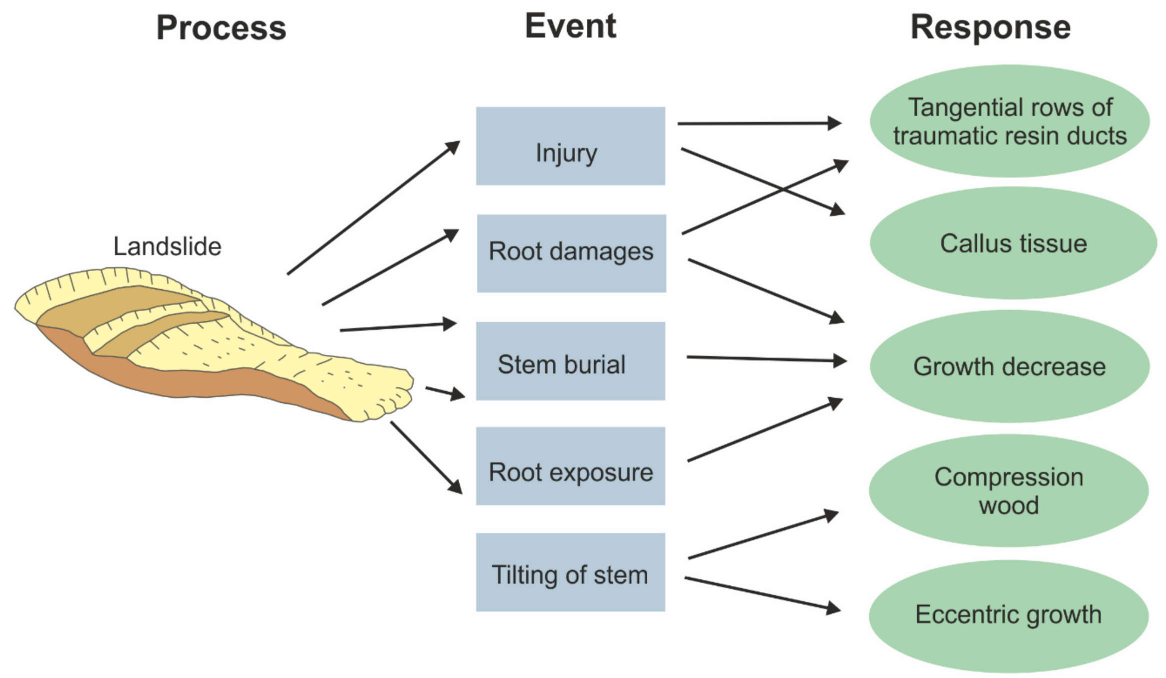

Figure 1. The principle of landslide vs. tree growth interaction (adapted after [26]).

The most common external disturbance induced by landslide movements is tilting of tree stems [29]. Trees subsequently try to recover to their original vertical geotropic growth by two basic growth responses. Coniferous tree species start to produce a so-called compression form of reaction wood. It is a specific wood structure with a high density and darker colour formed on the lower side of tilted stems [30]. In contrast, broad-leaved trees create a tension form of reaction wood on the upper side of tilted stems [31]. This wood structure has only slightly different colours compared to normal wood; thus, tension wood is hardly macroscopically distinguishable (but nevertheless observable; [32,33]). Tree rings composed of reaction wood are usually wider than normal tree rings. This increased tree-ring width on one side of the stem is compensated by distinct tree-ring narrowing on the opposite stem side [34]. The effect of this asymmetric growth is tree-ring eccentricity [35].

Some plastic landslides with low-viscosity material can cause the burial of tree stems. If trees survive such events, they usually suffer from increased edaphic pressure on roots or limited water and nutrition supplies [36]. This growth discomfort usually results in decreasing annual increments and abrupt growth suppression [37,38]. The same growth response can occur under different circumstances (abrupt growth suppression can even be induced by subsurface damage to the root system). In contrast, in some cases, trees can profit from the supply of buried material. This state can occur when the material is rich in water and nutrients, as demonstrated, e.g., by [39], for fine-grained limestone debris. In such cases, trees respond by growth release [40]. Landslide-induced scars can have a very prolonged shape when they originate due to a falling neighbouring tree [41,42]. Generally, smaller scars originate via the impact of falling rock from landslide rocky scarp. [25] dated one phase of landslide reactivation based on tree scars with the aforementioned origins.

Exposed tree roots in tension cracks (if the trees survive) usually respond to new atmospheric conditions at the anatomical level [43]. The use of exposed tree roots in dendrogeomorphic research is very rare [44], but [19] demonstrated good synchronicity between tree root data and tree stem data. Moreover, [45] tried to estimate the rate of landslide movements based on tree root exposure data. Tree growth responses to landslide-induced external disturbances are rarely single and occur simultaneously. This finding particularly applies to reaction wood and tree ring eccentricity; however, reaction wood can also be accompanied by abrupt growth suppression [42]. The modification of primary growth responses by other factors can generate similar growth disturbances recorded in trees but induced by different processes. [32] expected the same tree growth responses induced by creep movements (slow movements of shallow slope weathering mantle; [4] as by large deep-seated landslides).

2.2. General Dendrogeomorphic Procedure

The first step in dendrogeomorphic research is choosing a suitable study site. The key aspects of this choice are the recent activity of landslides, the presence of living trees on the landslide surface and the geographical position of landslides, all of which ensure radial tree increments with annual frequency. It is very useful to use orthophotos for remote areas for this purpose [46]. Infrared satellite images can help distinguish coniferous and broad-leaved trees or living and dead trees. Subsequently, the landslide activity and vegetation suitability are verified in the field. The landslide should be geomorphically mapped at a detailed scale of approximately 1:500. LiDAR-based DEMs (Digital Elevation Model), orthophotos and GNSS (Global Navigation Satellite System) devices are helpful materials and tools for this step. During mapping, basic morphological landslide features are recorded (tension cracks, head and minor scarps, individual landslide blocks, lateral and frontal lobes, inter-colluvial and near-scarp depressions, etc.). Simultaneously with this step, the positions of suitable trees for sampling are recorded. Choosing the final trees for sampling is based on the position of trees on the geomorphic map (i.e., considering the local landslide morphology) and the intensity of landslide movement on tree growth. Before the tree is sampled, an inventory of basic tree characteristics is necessary (tree species, diameter at breast height, tree height, direction and intensity of possible stem tilting, and social status of the tree [46]).

Sampling can be performed in several ways. Cutting down the tree and cutting off the cross-section can provide excellent samples where all growth disturbances are visible. Unfortunately, it is usually not possible to cut such samples, and landslide studies that use them are very rare [47–49]. Dominantly, studies use non-destructive extraction of increment cores. Usually, two to four increment cores are extracted using a Pressler increment borer of various lengths and diameters (most frequently 40×0.5 cm). The height of sampling should be at the position of maximal stem bending [28]. Increment cores are usually extracted from the lower and upper sides of tilted stems. Additional cores (if necessary) are extracted from perpendicular directions. Extracted cores are placed into suitable shelters and transported to the lab [50]. Sampled trees should be located at a regular interval across the entire landslide, omitting sampling in clusters [51]. Moreover, locations on sub-horizontal landslide blocks should be preferred to steep parts of landslides and head scarps [52]. To model climatic variation and detect non-geomorphic influences on tree growth at the study site, reference trees should be sampled. Reference trees should be located under microclimatic conditions similar to those of trees on the landslide, and they should be the oldest trees and absent of any visible external disturbances [53]. Usually, two increment cores perpendicular to the relief slope are extracted per reference tree.

The laboratory procedure of sample processing has already been described by [27,29,40,50,54,55]. Individual technical steps include sample air drying, gluing into wood supports, and sanding by descending sandpaper grits. After samples are prepared, dendrochronological processing starts with tree ring counting and marking, realization of skeleton plots and cross-dating against the reference chronology. The reference chronology is usually created using ARSTAN software [56]. Cross-dating enables the detection of possible dating errors caused by the presence of false missing wedging rings. Moreover, a reference chronology is necessary for filtering landslide-induced and non-landslide-induced (e.g., due to climate variations or insect attacks) growth disturbances. The cross-dating accuracy is usually checked using COFECHA software [57]. When tree ring series are checked and corrected, the identification of growth disturbances follows. Growth disturbances can be identified directly on the prepared surface of increment cores in the case of anatomical growth responses (e.g., compression wood) or using increment curves in the case of increment disturbances (e.g., abrupt growth changes). Various approaches for the detection of landslide signals in growth disturbances exist, but three of them are dominant: analysis of abrupt growth changes, detection of reaction wood, and analysis of tree-ring eccentricity. After all landslide-induced growth disturbances are identified and dated, the chronology of landslide events can usually be compiled using the event-response index (the proportion of trees with landslide signals from all sampled trees alive in a given year; [26]). The spatial distribution of landslide activity can be reconstructed using the recorded positions of analysed trees [25,27,51].

2.3. Dendrometry

Trees not only serve as a source of tree rings for dating, but the general morphology of tree stems can also provide important information regarding landslide behaviour [41]. Moreover, dendrometric analysis is often a necessary step preceding tree sampling. Dendrometry involves the measurements of various tree parameters (diameter, size, volume, etc.). From a dendrogeomorphic point of view, the most interesting parameters are the degree and direction of stem tilting. The landslide movement mechanism and the corresponding inner structure can be estimated based on the intensity and direction of tree stem tilting [58]. The tilting of tree stems is usually used as evidence of landslide activity; nevertheless, detailed analysis of tree tilting data with a large sample size can provide more detailed information. [59] used tree tilting data from approximately 1800 individuals of *Picea abies* (L.) Karst. to estimate the landslide movement mechanism. [60] analysed the orientation of reaction wood as an indirect indicator of the landslide movement direction. [23,34] described tree tilting aspects in detail. This approach is referred to as dendrometry, but [61,62] use the term dendroinclinometry. Large landslide areas often have complex morphologies with different activities and movement mechanisms in different parts [63,64]. Detailed analysis of tree stem tilting enables the estimation of parts of landslides with rotational or translational movements; however, additional research is needed because contrasting observations have been obtained. In general, trees that grow on rotational landslides are tilted upslope [65]; however, [66] assume a bimodal differentiation of the tree tilting direction. Conversely, [65,67] assume a monomodal stem inclination in the case of trees that grow on translational landslides. However, [68] assume only a weak stem inclination for this type of landslide movement. Chaotic tilting orientations were observed by [69] in the case of earth flows and by [61,62] in the case of trees that grow on pressure folds. In addition to the tilting direction, even the tilting intensity can provide data about landslide aspects. Based on the tree tilting intensity, [59] detected the presence of an active fault that crosses a landslide area and locally accelerates landslide block movements. Interestingly, [70] used tree tilting as an indirect indicator of the A.D. 1812 earthquake-induced landslide. He applied the principle of relative dating when discovering that old trees (older than 1812) expressed distinct stem tilting and younger trees (younger than 1812) expressed straight growth.

3. Principles and Effectiveness of Landslide Signal Extraction Methods

Various approaches to extracting the landslide signal from tree-ring series of disturbed trees exist [27]. Some of them have only been used in specific studies (e.g., anatomical changes in tree roots—[44,45]—or the presence of scars—[41,47,71]), but a generally dominant number of studies have used three basic approaches: (i) abrupt growth changes, (ii) reaction wood, and (iii) tree-ring eccentricity. Each of these approaches has different principles and focuses on different event-response patterns and tree growth response mechanisms. Thus, the results of all approaches can distinctly differ, and each of them is suitable for different tree species, landslide types and mechanisms. Individual approaches are very often combined and mutually supplemented to reach more credible and robust results. Basic aspects of the use of the three mentioned dating approaches from all accessible dendrogeomorphic studies of landslides between 1893 and 2020 (89 papers, 184 landslides, 9434 analysed trees, and 1632 dated landslide events) are reviewed below.

3.1. Abrupt Growth Changes

Plastic landslide masses with decreased viscosity can cause burial of the stem base [27]. They can also cause increased edaphic pressure on the root system in combination with isolation of roots from water and nutrition [37,72]. Trees growing under stress conditions usually experience a decrease in annual increments and abrupt growth suppression. The same growth response can be induced by invisible damage to the root system due to subsurface landslide movements. In contrast, trees can occasionally profit from burial by new material when it is rich in water and nutrition [39]. Under such conditions, trees respond to burial by growth release. Some landslides can be destructive enough to damage the forest stand occupying it. In such cases, trees surviving in stable positions neighbouring landslides can profit from a reduction in competitors and can release their growth [73]. Unfortunately, such a response can be delayed and should not be used as the only evidence of landslide events [40].

The basic and dominantly used principle of detecting abrupt growth change was published by [74]. The principle mathematically compares tree ring width to the mean widths of four preceding tree rings (Figure 2). The difference is expressed in a percentage. The intensity of growth suppression and release can be classified further according to its intensity into categories of slight, moderate and strong [74]. One of the first uses of this approach (although in a modified manner) occurred during the 1970s [26,75]. Since this time, this approach has been used as the singular method in ten percent of all studies. In combination with other approaches, it has been used in 45% of all studies. Most frequently, this approach is combined with the detection of reaction wood (26% of all studies; e.g., [11,76]). This approach is dominantly used to analyse tree-ring series of broad-leaved trees (78%; e.g., [67]) rather than coniferous trees (22%; e.g., [73]). This difference is caused by the limited ability of broad-leaved trees to create macroscopically visible reaction wood. Similarly, it is most frequently used in European studies (78%; e.g., [77]) in comparison to its lesser use in American studies (22%; e.g., [48]). This approach has been previously used with a relatively low number of trees (37 analysed individuals per landslide on average). [77] applied the principles of abrupt growth changes to only 17 sampled trees. The mean number of detected growth suppressions or releases per tree in studies using exclusively this approach was 1.6, and the mean recurrence of reconstructed landslide events was 6.1 years. Based on the abovementioned statistics, this approach seems to be relatively sensitive to landslide movements. Nevertheless, [78] did not find any agreement between the results obtained by this approach and data from field landslide monitoring. The inconsistency of results can be explained by different depths of detected movements using both approaches. Finally, both growth changes can occur subsequently, as demonstrated [63].

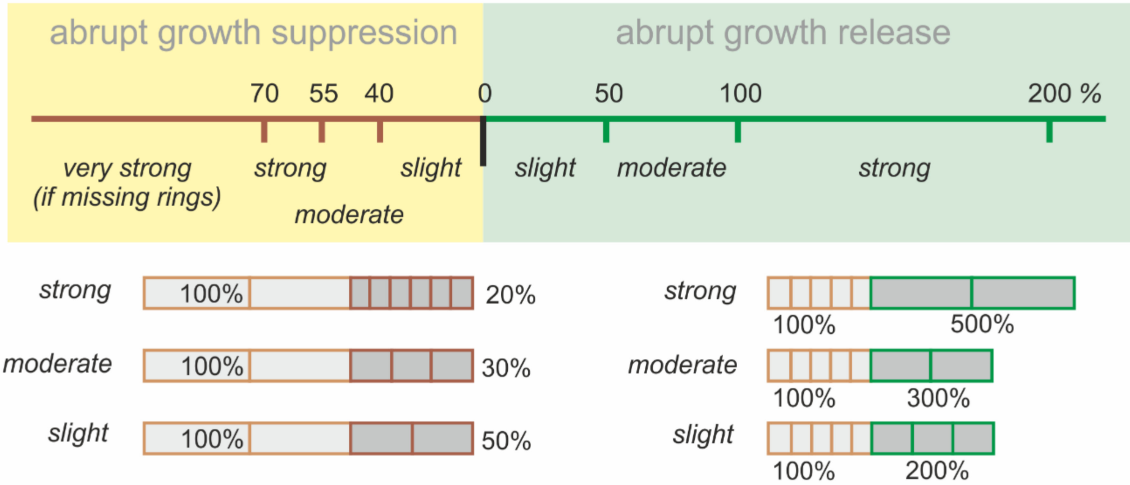

Figure 2. The principle of abrupt growth changes (suppression or release) detection in tree-ring series as a landslide dating approach (adapted after [74]).

3.2. Reaction Wood

Destabilization of the stem base due to landslide movements and associated changes in landslide surface morphology usually leads to tilting of the tree stem. The anatomical growth response to stem tilting differs between coniferous and broad-leaved trees. Coniferous tree compression wood is formed by special cells with rounded shapes, thickened cell walls and the presence of inter-cellular spaces [30,79]. Compression wood is formed on the lower sides of tilted stems and is clearly macroscopically visible (Figure 3). In contrast, tension wood of broad-leaved trees is formed by elongated woody cells with the presence of gelatinous layers in fibres [80] on the upper sides of tilted stems. Unfortunately, its macroscopic visibility is very limited [31], and it is usually identified by time-consuming microscopic analysis [81].

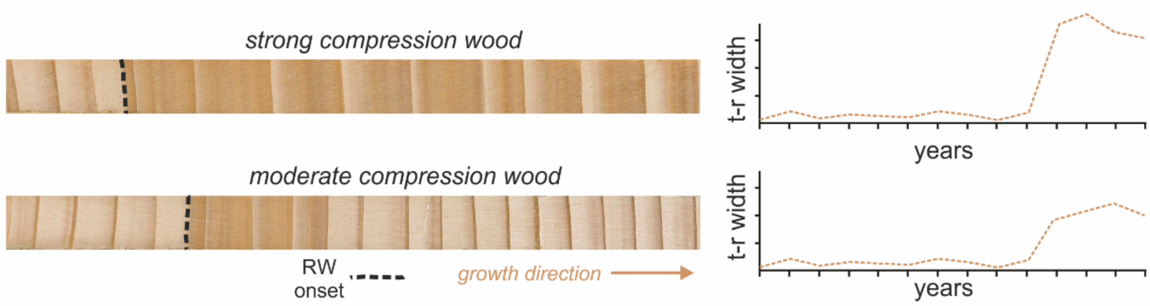

Figure 3. The view of compression wood in tree-ring series of coniferous trees including the increment curves with visible associated growth release.

Anatomical properties and their macroscopic impacts directly affect the method of detecting both reaction wood types. Compression wood is standardly macroscopically identifiable and even categorized according to its intensity [28]. The minimal condition for considering compression wood to be the result of a landslide event is the presence of reaction wood cells in at least 50% of tree-ring widths and in three consecutive tree rings [28]. In contrast, tension wood is hardly macroscopically visible, and difficult microscopic analysis must be undertaken. Thus, this type of reaction wood is much less frequently used in landslide research. Out of the experimental studies of [31] or [82], the only exceptions are the studies of [33,81].

Similar to the analysis of abrupt growth changes, the detection of compression wood was introduced in the landslide literature during the 1970s [26,75]. Only 3% of all landslide studies use this growth disturbance detection as the sole dating approach [83,84].

Nevertheless, this approach is very often combined with other approaches, and in combination, it occurs in 44% of all studies. It is most frequently combined with the analysis of abrupt growth changes (26% of all studies, e.g., [46,85]). Unsurprisingly, all studies dealing with compression wood use tree-ring series of coniferous trees. Studies from North America dominate (67%; [83]) over European studies [86]. In studies working with compression wood, the mean number of trees per landslide was 32, the mean number of detected occurrences of compression wood per tree was 2.1, and the mean reconstructed recurrence interval between the following landslide events was 16.8 years. The impact on this statistic have probably studies using long-lived trees in North America (e.g., [41] analysed 400-year-old individuals of *Pseudotsuga menziesii* (Mirb.) Franco) and Asia (e.g., [24] analysed a millennium-old *Sabina przevalskii* Kom.). Nevertheless, as demonstrated by [87], compression wood is a very sensitive indicator of landslide movements, even on the order of mm. The systematic use of tension wood as the sole and independent indicator of past landslide activity is still not realized.

3.3. Tree-Ring Eccentricity

Landslide-induced tree tilting can cause the formation of reaction wood, but this growth response is often accompanied by asymmetric tree-ring growth. Moreover, tree-ring eccentricity can occur even without the formation of reaction wood [88], and thus, several authors suggest it to be a very sensitive approach to past landslide movement detection [35,89–91]. The calculation of tree-ring eccentricity was introduced by [23], and the approach was extended by [34]. The eccentricity calculation is a relatively fast and easy approach, and many authors use it (Figure 4). Its first use for landslide dating was introduced in the 1980s by [34]. Since that time, many authors have used eccentricity calculations, but the key question of landslide signal extraction from rows of tree-ring eccentricity values has been presented only in tree cases. The oldest approach was introduced by [34], and the signal extraction is based on the filtering of eccentricity values by two moving windows and statistical testing of differences. The second approach was introduced by [35]. Their approach is based on the comparison of eccentricity values with data from reference trees. The most recent tree-ring eccentricity-based method of landslide dating was introduced by [12]. Their approach is based on the detection of abrupt changes in tree-ring eccentricity.

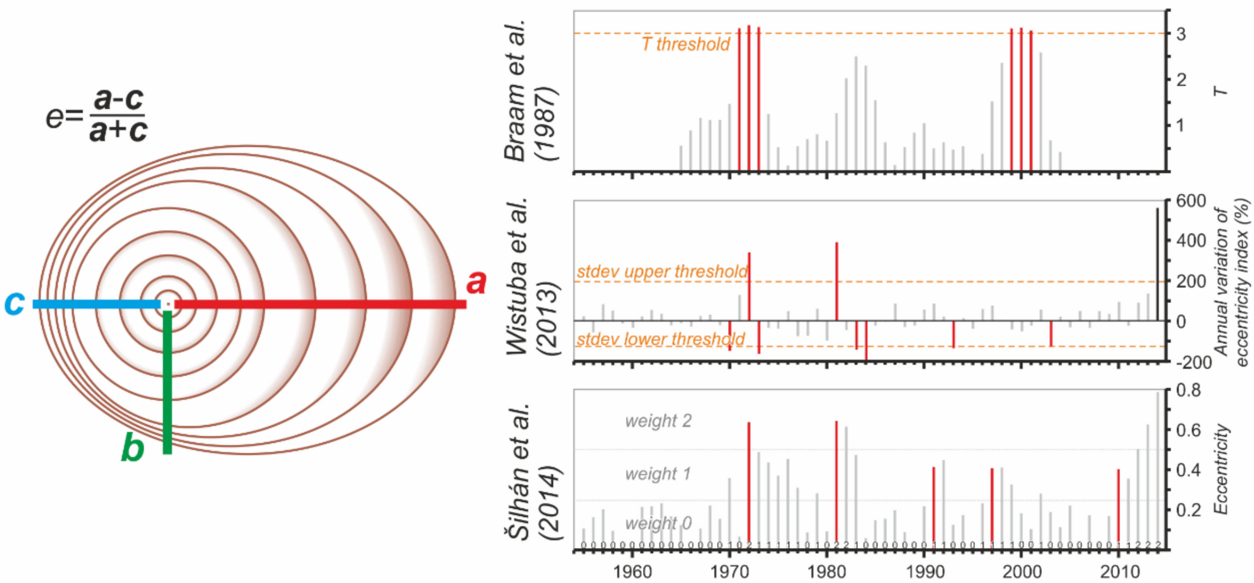

Figure 4. The scheme of tree-ring eccentricity including three types basic approaches of signal detection from rows of tree-ring eccentricity.

Tree-ring eccentricity-based approaches as the sole method are most frequently used in landslide research (24% of all studies). Similar to previously mentioned approaches, it is often combined with other methods (43% of all studies). Studies dealing exclusively with tree-ring eccentricity generally use the highest number of trees per landslide (90 trees on average). This approach is dominantly used for coniferous trees (82%) compared to broad-leaved trees [12] and in Europe (92%; [92,93]) compared to in America [91,94]. From all previously mentioned approaches, the tree-ring eccentricity-based approach provides evidence of the highest mean number of landslide signals per tree (5.5). The mean recurrence interval of two following dated landslide events is 6.9 years. The mentioned statistics support the assumption of very high sensitivity of this approach [95,96].

4. Dendrogeomorphic Aspects of Various Landslide Types

Landslide types are usually classified based on the movement mechanism and the character of moved material [6]. Of course, differences in the depth and character (i.e., viscosity) of moved material and movement mechanism can play an important role in the character of induced external disturbance and intensity of corresponding growth disturbance. To distinguish the influence of individual landslide types on tree growth, they were classified according to the modified classification of landslides by [4] provided by [6]. Only those landslide types that were studied in at least three case studies were analysed. The others were grouped into a standalone mixed group. The oldest dendrogeomorphic studies of landslides were from 1893 [70], but the first categorization of landslide types was provided in 1987 by [34]. The most tree-ring-based analyses of landslides that distinguished individual landslide types has been clearly observable during the last decade (Figure 5). The number of analysed landslides per type has differed. Although no statistically significant differences were detected among individual landslide types (with the exception of the mean number of analysed trees per landslide), some differences occurred (Figure 6).

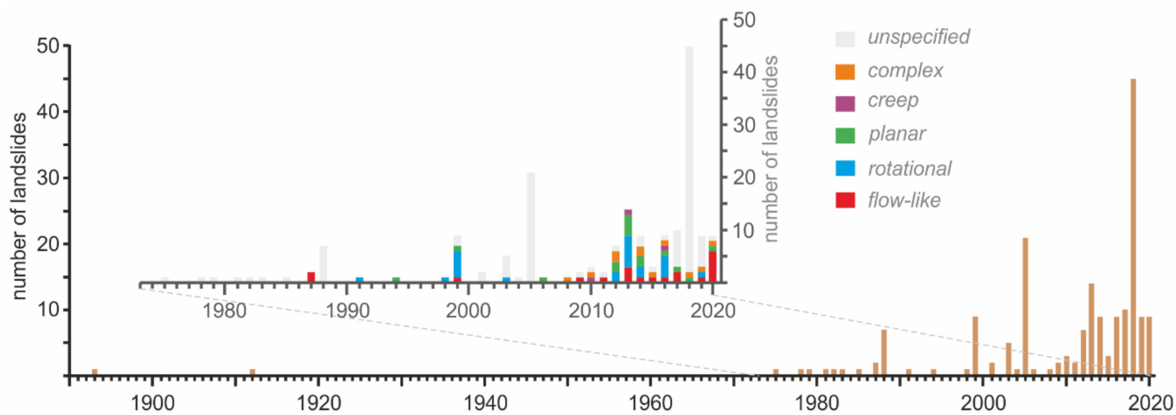

Figure 5. The chronological number of landslides analysed by dendrogeomorphic methods including the type of studied landslide.

4.1. Flow-Like Landslides

The flow-like landslides group (according to [6]) contains a wide spectrum of various landslide subtypes with generally moderate to high velocities. For this review (and considering the various authors' definitions), only debris slides, mudflows and earthflows have been considered. The common features of these landslides are plastic movements with rather moderate velocity and intensive deformation of their surfaces during movement. Nevertheless, these landslides can change slow movement phases when material deformations are generally concentrated in the main shear zone, and they can change the acceleration phase when many partial shear zones occur and deformations affect the whole mass of the landslide [7].

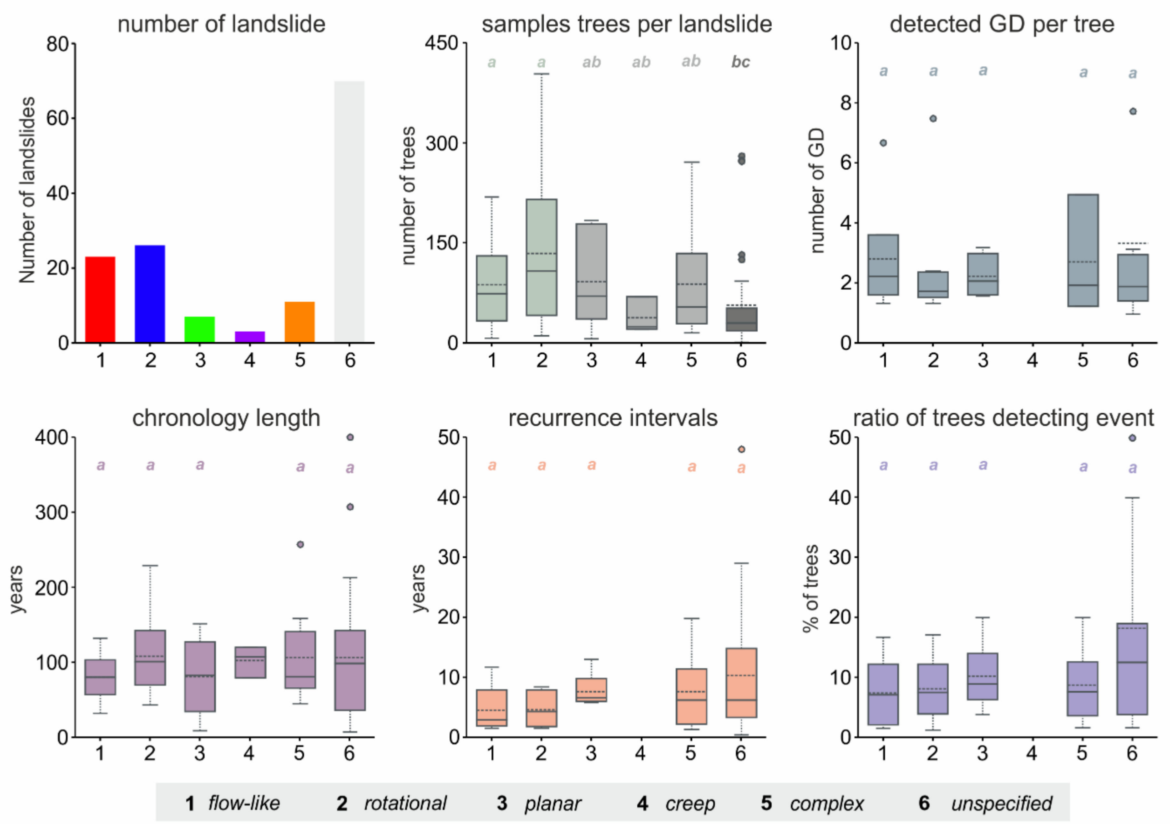

Figure 6. Comparison of basic dendrogeomorphic aspects in landslides of various types.

This behaviour has a direct impact on trees occupying the landslide surface (Figure 7). The dominant effect on tree growth occurs during the acceleration phase. In this phase, trees are affected not only by destabilization of their stems due to surface deformations but also by very intensive damage to their root systems due to the occurrence of multiple shear zones at various depths. Although several authors have demonstrated the clear dominance of abrupt growth suppression above the reaction wood (proportion higher than 60%; [46,85,97]) corresponding to the dominance of root damages due to stem tilting, these landslide types have been dated mostly by tree-ring eccentricity evidence in the past (42% of all studies; e.g., [91,98]). The effect of root damage is probably more pronounced and is able to mask and inhibit the response of trees to stem tilting. Thus, to obtain the most valuable result during dating of this landslide type, the focus should be on abrupt growth suppression. Moreover, the most recent study by [52] demonstrates that with this type of mechanism, there is minimal noise in tree-ring signals resulting from landslides.

4.2. Rotational Landslides

Rotational landslides (in rocks or clay/silt material) have slow to moderate velocities and dominantly affect weak material. They are the most frequently studied landslide type using tree-ring-based methods. Studies analyzing them use the highest number of trees per landslide on average. In some cases, rotated blocks can be built by rigid rock moving on weak subsoil [99]. No structural controls are observed (isotropic behaviour). The typical morphology of such landslides comprises a steep main scarp below a back-tilted main block [100]. Tension cracks can occur above the main scarp. The morphology of the main rotated block usually does not have distinct inner surface deformations. Rotational landslides are very dangerous and the affected area can be often fully destroyed.

Figure 7. The effect of flow-like landslide movements to tree growth.

The effect of this type of landslide on tree growth is simpler than that of flow-like landslides (Figure 8). The limited presence of internal cracks and plastic deformation prevent damage to the root systems of trees. This type of landslide damage can be expected only in the zone of tension cracks, at the border of the moved block, or above the main scarp. The root damage in these locations is clearly visible. The stretched roots of trees with shallow root crowns (e.g., *Picea abies* (L.) H. Karst.) frequently occur on main scarps. Nevertheless, root damage usually does not affect the structure of detected growth disturbances, among which the occurrence of reaction wood or tree-ring eccentricity fully dominates, as demonstrated, e.g., by [59]. This clearly suggests the supposed dominant effect of rotational landslide movement on the tilting of tree stems. As damage to the root system is limited, abrupt growth suppression cannot inhibit reaction wood creation. The dominant responses of trees to stem tilting has been observed by [64,101] in the form of tree-ring eccentricity and reaction wood. Thus, rotated blocks cause only stem tilting without any additional external disturbances [52]. The mechanism of the rotated landslide effect on tree growth is well known because 31% of all studies use tree-ring eccentricity as the sole dating approach, and reaction wood in combination with another approach is used in 41% of all studies.

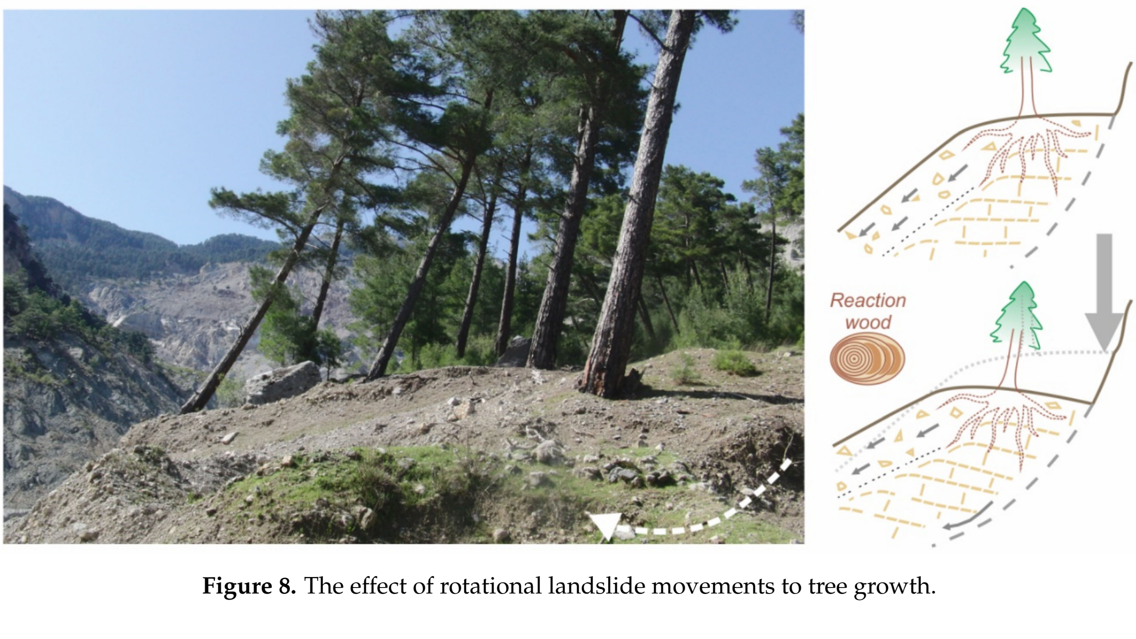

Figure 8. The effect of rotational landslide movements to tree growth.

4.3. Planar Landslides

Planar landslides in rocks or clay/silt material are relatively less frequently studied landslide types compared to the previous two types (there are only six distinct case studies). They can move very fast in comparison to rotational landslides because of the absence of self-stabilizing factors [6]. From a dendrogeomorphic point of view, the minimal internal deformations in the sliding mass and the possible presence of deep tension cracks at the slide head are important (Figure 9). The material is moved along a structurally predisposed shear zone that is often parallel to the surface slope.

Figure 9. The effect of planar landslide movements to tree growth.

The combination of reaction wood and abrupt growth changes is the most frequently (67%) used approach of landslide type event dating. Tree-ring eccentricity was used only in one case study. Most likely, the mechanism of landslide movement and limited possibilities of internal deformations cause similar structures of detected growth disturbances in rotational landslides. Refs. [59,102] detected more than 75% of all growth disturbances induced by planar landslides in the form of reaction wood. Similarly, [103] detected landslide events based on the presence of reaction wood and tree-ring eccentricity. Nevertheless, in some cases, the higher proportion of abrupt growth suppression due to the presence of tension cracks is not excluded. For example, [19] observed that almost half of dated growth disturbances occur in the form of abrupt growth suppressions. Even in the case of planar landslides, it seems that authors are aware of how this landslide type affects tree growth and adequately combine dating approaches to obtain optimal results. Thus, due to generally expected landslide surface deformations and possible root damage in tension cracks, the combination of reaction wood and abrupt growth suppression analysis can be recommended for future research.

4.4. Soil Creep

Creep movement is very slow (several mm per year) and affects the soil and weathered rock mantle to a maximal depth of one metre [104]. The movement is usually caused by climatic variations that cause wetting and drying of the surface material. Soil creep can occur in extensive parts of slopes, but only local occurrence along stable slopes is possible. Regarding movement, soil creep exists in a continuous form and a seasonal form. In particular, the second can be locally accelerated [6]. Moreover, shallow creep movements can occur on slopes affected by catastrophic landslide activation several decades prior [105–107].

Trees growing on slopes affected by continuous creep movements must gradually compensate for the continuous tilting of their stems (Figure 10). This process results in a typical pistol-butted tree form [34,58,66]. During seasonal acceleration of movements, more intensive stem tilting can be expected, and damage to the root system cannot be excluded. In such cases, the presence of reaction wood, tree-ring eccentricity and abrupt growth suppression can be expected. Generally, soil creep can cause problems with dating other slope movements because it can occur on slopes with the presence of other landslide types. In such cases, soil creep can simulate the same growth responses as would, e.g., rotational landslide induction [32]. The quantification and filtering of creep-induced noise from chronologies of roto-translational landslides was performed by [96,108]. They concluded by recommending tree sampling on sub-horizontal landslide blocks to eliminate the effect of creep on the resulting landslide chronologies. Dendrogeomorphic studies of soil creep as the sole process are very rare, with only four cases. Three of them [32,109,110] used tree-ring eccentricity as a signal of past creep accelerations. Specifically, [111] used the maximal tree age in combination with stem dendrometry to estimate the creep rate. The use of tree-ring eccentricity seems to be a suitable approach for soil creep analysis due to its high sensitivity, as expected by [91] or [89]. Interestingly, according to the findings of [96], soil creep movements did not induce any distinct reaction wood responses.

Figure 10. The effect of creep movements to tree growth.

4.5. Complex Landslides

According to the classification by [6], the standalone category of complex landslides has not been introduced. Nevertheless, the same authors suppose that all landslides are complex landslides with a combination of several landslide types. Moreover, the original classification by [4] contains such category. In total, 11% of all dendrogeomorphic studies of landslides indicated that their studied landslides were complex. Landslides from this category express heterogeneous morphology, inner structures, and a combination of various movement mechanisms. Such conditions necessitate a very complex landslide influence on tree growth. Thus, tree-ring series of trees affected by complex landslides contain all basic growth disturbances (reaction wood, abrupt growth changes, and tree-ring eccentricity). Data from all studies working with this type of landslide confirm the aforementioned assumptions because they use all three approaches in a fully balanced ratio (33.3%). Subsequently, individual-specific studies provide evidence of a wide and often contrasting variety of the proportions of individual growth disturbance types. For example, [46] detected the dominant occurrence of reaction wood comparing the abrupt growth suppression on studied complex landslides in the French Alps. In contrast, [112] found the opposite ratio of both growth disturbances on a complex landslide in the Outer Western Carpathians. The ratio of growth disturbances contained in the tree-ring series of analysed trees probably depends on the specific character of complex landslides, i.e., which type of landslide dominates (rotational, flow-like, etc.). Thus, the recommendation for the choice of approach in the case of complex landslides is to base the final decision on detailed geomorphic mapping of the studied landslide and consider the dominant movement mechanism.

Unfortunately, a high proportion (52%) of all analysed studies (89) did not specify the landslide type they studied; thus, their statistics would contain noise from the combination of data from various landslide types.

5. Challenges and Opportunities of the Next Research

Although dendrogeomorphic methods are generally supposed to be useful tools for dating past landslide events [27,113,114], some limitations exist, which are necessary to mention here. Some trees express a low correlation with the reference chronology and must be excluded from the sample size that can decrease below some critical level (e.g., 13% of trees in the case of [46]). Next, the use of some tree species is limited due to the creation of indistinct tree-ring boundaries or too many missing rings (e.g., according to [115], this problem is prevalent after the tree age of 100 years in the case of *Tilia cordata* Mill.). The maximum precision of tree-ring-based dating is seasonal, which is sufficient for the calculation of landslide frequency but may be insufficient for detailed identification of a concrete triggering event [116]. The precision of seasonal dating depends on the physiographical conditions of the site, the length of the vegetation season and the tree-ring width. Thus, the best results are possible to expect when the event is dated during early or late wood formation in the case of a very short vegetation season (only weeks or a few months).

The method employed for landslide signal extraction from the tree ring series can be another limitation. [46,97] discussed the magnitude of a landslide event that is detectable by dendrogeomorphic methods. Only events with moderate magnitudes seem to be recordable. Solving this question is possible by comparing tree-ring-based data with data from long-term field monitoring of landslides. The comparison enables the maximal and minimal magnitudes of landslide movements detectable by trees to be defined. Some attempts have already been made. Nevertheless, [94] did not find any significant relationship between tree ring-based data and monitoring-based data. Next, [85] tested the effectiveness of spatial reconstruction and found only low to moderate agreement. The most promising findings were provided by [87], who evidenced the ability of trees to record landslide movements on the order of several millimetres. On the other hand, landslide events that have magnitudes that are too high can destroy all trees growing on it. Nevertheless, [73] confirmed the assumption of such a landslide dating possibility using the detection of growth release in a tree-ring series of surviving trees located in positions neighbouring landslide bodies. Thus, dendrogeomorphic dating is not strictly limited to only moderate magnitude landslide events, but the spectrum is much wider from movements of millimetres to fully destructive events.

Retrospective analysis of landslide movements cannot solve the question of relief changes during sliding events (i.e., landslides change their morphology and morphometry during movement). Unfortunately, this aspect can play a crucial role in the selection of trees for sampling, as actual affected trees can grow in stable positions in the past, and vice versa [25,85]. Moreover, some areas of current tree positions (that are evidently stable) can be affected by other types of slope movements, such as creep (causing the input of noise into landslide chronology), when the landslide morphology was different in the past. At least for a detailed description of current landslide morphology, more intensive work with laser scanning-based DEM can provide detailed insight into this problem and into specific tree growth responses in various landslide parts dominated by different movement mechanisms.

Low number of regional reconstructions of landslide activity is the additional limitation. They can provide a more complex view of landslide behaviour compared with a single case study; nevertheless, with the exceptions of [68,117,118], such studies are missing. The next opportunity to increase the usability of tree-ring data in landslide research is the use of long-lived North American or Asian conifers for the creation of chronologies of several thousand years long [24]. Landslide chronologies with these lengths can more effectively bridge the gap between high-resolution dating methods (dendrogeomorphology) and radiometric absolute dating approaches (^{14}C). The use of shrubs for landslide dating is rare, with the exception of only one case [60]. While using is in reconstruction of past landslide activity would distinctly extend the usability of dendrogeomorphic methods into regions with an absence of trees and the presence of only shrubs. Although dendrogeomorphic research is concentrated in two major centers in the World, some neglected regions can provide very suitable conditions for its implementation (e.g., South America or forested regions of central Asia). Trees covering landslides in these regions should be suitable enough for dendrogeomorphic analysis if create annual increment in the form of tree rings. Considering the spectrum of dated landslide types, some sackung-type slope deformations are practically neglected. Only [67] vicariously investigated this phenomenon through shallow surface movements. Again, this gap represents an opportunity for future dendrogeomorphic research. In addition, although tree-ring-based data of past landslide activity serve as a foundation for the analysis of triggers, detailed determination of rainfall triggering thresholds is rare, with only some exceptions [68]. Finally, tree sampling using an increment borer is physically very strenuous. The development of accumulator-based devices for coring would significantly aid in fieldwork and provide more samples in the same amount of time.

6. Conclusions

Dendrogeomorphic (tree-ring-based) methods have been frequently used for landslide research for more than a century, with a dynamic increase in the interest in these approaches during the last decade. The review of all accessible studies dealing with this problem discovered a surprising gap in the considering of specific landslide movement mechanism to character and intensity of tree growth responses. Thus, in addition to providing an overview of the basic principles used in the tree-ring analysis of landslides, this paper evaluates the effect of different landslide mechanisms to tree growth responses and discuss the effectiveness of used methods of analysis. Three basic principles of landslide signal extraction from tree-ring series exist. Their use is reviewed using a wide database of landslide studies. Moreover, within the variety of methods used, the different types of landslides (regarding the morphology, material and mechanism of movements) are studied. This study reviews the approaches used to analyse individual landslide types and the detected structure of growth disturbances in sampled trees. Generally, landslides with limited inner deformation abilities dominantly cause the induction of reaction wood and tree-ring eccentricity. In contrast, plastic landslides with intensive inner deformations are evident in tree-ring series as abrupt growth suppressions. The detailed analysis of landslide morphology and assessment of landslide mechanisms should precede the sampling and choice of analysis method. Although various limitations of dendrogeomorphic methods in landslide research exist, many of them can be reduced by solving specific problems or using new modern supporting data (e.g., laser scanning-based DEM) in future tree-ring-based research.

Author Contributions: K.Š.: conceptualization, methodology, formal analysis, investigation, writing—original draft, writing—review and editing, visualization, funding acquisition.

Funding: This research was funded by Czech Science Foundation, grant number 19-01866S and University of Ostrava, grant number sgs05/PřF/2019–2020.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data available on request.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Guzzetti, F. Landslide fatalities and the evaluation of landslide risk in Italy. *Eng. Geol.* **2000**, *58*, 89–107. [CrossRef]
2. Pospisil, P.; Rapantova, N.; Kycl, P.; Novotny, J. Pitfalls in Generating an Engineering Geological Model, Using a Landslide on the D8 Motorway near Dobkovičky, Czech Republic, as an Example. *IAG/AEG Annu. Meet. Proc.* **2018**, *6*, 269–276.
3. Grahne, T.; Jaldell, H. Assessment of data availability for the development of landslide fatality curves. *Landslides* **2017**, *14*, 1113–1126. [CrossRef]
4. Cruden, D.M.; Varnes, D.J. Landslide types and processes. In *Landslides, Investigation and Mitigation, Special Report 247*; Turner, A.K., Schuster, R.L., Eds.; Transportation Research Board: Washington, DC, USA, 1996; pp. 36–75.
5. Dikau, R.; Brunsden, D.; Schrott, L.; Ibsen, M.L. *Landslide Recognition, Identification, Movements, and Causes*; John Wiley and Sons: Chichester, UK, 1996; p. 251.
6. Hungr, O.; Leroueil, S.; Picarelli, L. The Varnes classification of landslide types, an update. *Landslides* **2014**, *11*, 167–194. [CrossRef]
7. Rianna, G.; Pagano, L.; Urciuoli, G. Rainfall patterns triggering shallow flowslides in pyroclastic soils. *Eng. Geol.* **2014**, *174*, 22–35. [CrossRef]
8. Palladino, M.R.; Viero, A.; Turconi, L.; Brunetti, M.T.; Peruccacci, S.; Melillo, M.; Luino, F.; Deganutti, A.M.; Guzzetti, F. Deep seated gravitational slope deformations in the European Alps Rainfall thresholds for the activation of shallow landslides in the Italian Alps: The role of environmental conditioning factors. *Geomorphology* **2018**, *303*, 53–63. [CrossRef]
9. Crosta, G.B.; Frattini, P.; Agliardi, F. Deep seated gravitational slope deformations in the European Alps. *Tectonophysics* **2013**, *605*, 13–33. [CrossRef]
10. Pánek, T.; Klimeš, J. Temporal behavior of deep-seated gravitational slope deformations: A review. *Earth-Sci. Rev.* **2016**, *156*, 14–38. [CrossRef]
11. Wieczorek, G.F.; Eaton, L.S.; Yanosky, T.M.; Turner, E.J. Hurricane-induced landslide activity on an alluvial fan along Meadow Run, Shenandoah Valley, Virginia (eastern USA). *Landslides* **2006**, *3*, 95–106. [CrossRef]
12. Šilhán, K.; Pánek, T.; Turský, O.; Brázdil, R.; Klimeš, J.; Kašičková, L. Spatio-temporal patterns of recurrent slope instabilities affecting undercut slopes in flysch: A dendrogeomorphic approach using broad-leaved trees. *Geomorphology* **2014**, *213*, 240–254. [CrossRef]
13. Chigira, M.; Wu, X.; Inokuchi, T.; Wang, G. Landslides induced by the 2008 Wenchuan earthquake, Sichuan, China. *Geomorphology* **2010**, *118*, 225–238. [CrossRef]
14. Qi, S.; Xu, Q.; Lan, H.; Zhang, B.; Liu, J. Spatial distribution analysis of landslides triggered by 2008.5.12 Wenchuan Earthquake, China. *Eng. Geol.* **2010**, *116*, 95–108. [CrossRef]
15. Keefer, D.K. Landslides caused by earthquakes. *Geol. Soc. Am. Bull.* **1984**, *95*, 406–421. [CrossRef]
16. Laimer, H.J. Anthropogenically induced landslides—A challenge for railway infrastructure in mountainous regions. *Eng. Geol.* **2017**, *222*, 92–101. [CrossRef]
17. Kilburn, C.R.J.; Petley, D.N. Forecasting giant, catastrophic slope collapse: Lessons from Vajont, Northern Italy. *Geomorphology* **2003**, *54*, 21–32. [CrossRef]
18. IPCC. *Climate Change 2014: Synthesis Report*; Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; IPCC: Geneva, Switzerland, 2014; 151p.
19. Lopez-Saez, J.; Morel, P.; Corona, C.; Bommer-Denns, B.; Schlunegger, F.; Berger, F.; Stoffel, M. Tree-ring reconstruction of reactivation phases of the Schimbrig landslide (Swiss Alps). *Géomorphol. Relief Process. Environ.* **2017**, *23*, 265–276. [CrossRef]
20. Margielewski, W. Records of the Late Glacial–Holocene palaeoenvironmental changes in landslide forms and deposits of the Beskid Makowski and Beskid Wyspowy Mts. Area (Polish Outer Carpathians). *Folia Quat.* **2006**, *76*, 1–149.
21. Prager, C.; Ivy-Ochs, S.; Ostermann, M.; Synal, H.A.; Patzelt, G. Geology and radiometric 14C-, 36Cl- and Th-/U-dating of the Fernpass rockslide (Tyrol, Austria). *Geomorphology* **2009**, *103*, 93–103. [CrossRef]
22. Zerathe, S.; Lebourg, T.; Braucher, R.; Bourlés, D. Mid-Holocene cluster of large-scale landslides revealed in the Southwestern Alps by 36Cl dating. Insight on an Alpine-scale landslide activity. *Quat. Sci. Rev.* **2014**, *90*, 106–127. [CrossRef]
23. Alestalo, J. Dendrochronological interpretation of geomorphic processes. *Fennia* **1971**, *105*, 1–139.
24. Zhang, Y.; Stoffel, M.; Liang, E.; Guillet, S.; Shao, X. Centennial-scale process activity in a complex landslide body in the Qilian Mountains, northeast Tibetan Plateau, China. *Catena* **2019**, *179*, 29–38. [CrossRef]
25. Stefanini, M.C. Spatio-temporal analysis of a complex landslide in the Northern Apennines (Italy) by means of dendrochronology. *Geomorphology* **2004**, *63*, 191–202. [CrossRef]
26. Shroder, J.F. Dendrogeomorphological analysis of mass movement on Table Cliffs Plateau, Utah. *Quat. Res.* **1978**, *9*, 168–185. [CrossRef]
27. Šilhán, K. Dendrogeomorphology of landslides: Principles, results and perspectives. *Landslides* **2020**, *17*, 2421–2441. [CrossRef]
28. Stoffel, M.; Corona, C. Dendroecological dating of geomorphic disturbance in trees. *Tree-Ring Res.* **2014**, *70*, 3–20. [CrossRef]
29. Tumajer, J.; Treml, V. Meta-analysis of dendrochronological dating of mass movements. *Geochronometria* **2013**, *40*, 59–76. [CrossRef]

30. Westing, A.H. Formation and function of compression wood in gymnosperms. *Botanic. Rev.* **1965**, *31*, 381–480. [CrossRef]
31. Heinrich, I.; Gärtner, H.; Monbaron, M. Tension wood formed in Fagus Sylvatica and Alnus Glutinosa after simulated mass movement events. *IAWA J.* **2007**, *28*, 39–48. [CrossRef]
32. Pawlik, L.; Migoń, P.; Owczarek, P.; Kacprzak, A. Surface processes and interactions with forest vegetation on a steep mudstone slope, Stołowe Mountains, SW Poland. *Catena* **2013**, *109*, 203–216. [CrossRef]
33. Šilhán, K. Assessment of spoil heap landslide development using anatomical tree growth responses. *Eng. Geol.* **2021**, *281*, 105988. [CrossRef]
34. Braam, R.R.; Weiss, E.E.J.; Burrough, P.A. Spatial and temporal analysis of mass movement using dendrochronology. *Catena* **1987**, *14*, 573–584. [CrossRef]
35. Wistuba, M.; Malik, I.; Gärtner, H.; Kojs, P.; Owczarek, P. Application of eccentric growth as a tool for landslide analyses: The example of Picea abies Karst. in the Carpathian and Sudeten Mountains (Central Europe). *Catena* **2013**, *111*, 41–55. [CrossRef]
36. Kogelnig-Mayer, B.; Stoffel, M.; Schneuwly-Bollschweiler, M. Four-dimensional growth response of mature Larix decidua to stem burial under natural conditions. *Trees* **2013**, *27*, 1217–1223. [CrossRef]
37. Marin, P.; Filion, L. Recent dynamics of subarctic dunes as determined by the tree-ring analysis of white spruce, Hudson Bay (Quebec). *Quat. Res.* **1992**, *38*, 316–330. [CrossRef]
38. Strunk, H. Dating of geomorphological processes using dendrogeomorphological methods. *Catena* **1997**, *31*, 137–151. [CrossRef]
39. Procter, E.; Bollschweiler, M.; Stoffel, M.; Neumann, M. A regional reconstruction of debris-flow activity in the Northern Calcareous Alps, Austria. *Geomorphology* **2012**, *132*, 41–50. [CrossRef]
40. Stoffel, M.; Bollschweiler, M. Tree-ring analysis in natural hazards research—An overview. *Nat. Hazards Earth Syst. Sci.* **2008**, *8*, 187–202. [CrossRef]
41. Carrara, P.E.; O'Neill, J.M. Tree-ring dated landslide movements and their relationship to seismic events in southwestern Montana, USA. *Quat. Res.* **2003**, *59*, 25–35. [CrossRef]
42. Šilhán, K. Evaluation of growth disturbances of Picea abies (L.) Karst. to disturbances caused by landslide movements. *Geomorphology* **2017**, *276*, 51–58. [CrossRef]
43. Ballesteros-Cánovas, J.A.; Bodoque, J.M.; Lucía, A.; Martín-Duque, J.F.; Díez-Herrero, A.; Ruiz-Villanueva, V.; Rubiales, J.M.; Genova, M. Dendrogeomorphology in badlands: Methods, case studies and prospects. *Catena* **2013**, *106*, 113–122. [CrossRef]
44. Wrońska-Wałach, D.; Zielonka, A.; Sobucki, M.; Oleszko, B. Longitudinal and cross-sectional wood anatomy variability of vertical fir roots (Abies alba Mill.) as a record of landslide processes—An example from the Carpathian foothills. *Sci. Tech. Rep.* **2015**, *13*, 102–109.
45. Přecechtělová, H.; Šilhán, K. Tree ring based estimation of the landslide movement velocity: Evaluation of new experimental approach. *Geomorphology* **2019**, *339*, 104–113. [CrossRef]
46. Lopez-Saez, J.; Corona, C.; Stoffel, M.; Schoeneich, P.; Berger, F. Probability maps of landslide reactivation derived from tree-ring records: Pra Bellon landslide, southern French Alps. *Geomorphology* **2012**, *138*, 189–202. [CrossRef]
47. Clague, J.J.; Souther, J.G. The Dusty Creek landslide on Mount Cayley, British Columbia. *Can. J. Earth Sci.* **1982**, *19*, 524–539. [CrossRef]
48. Paolini, L.; Villalba, R.; Grau, H.R. Precipitation variability and landslide occurrence in a subtropical mountain ecosystem of NW Argentina. *Dendrochronologia* **2005**, *22*, 175–180. [CrossRef]
49. Šilhán, K. Dendrogeomorphological analysis of evolution of slope processes on flysch rocks (the Vsetínské vrchy Mts; Czech Republic). *Carpathian J. Earth Environ. Sci.* **2012**, *7*, 39–49.
50. Speer, J.H. *Fundamentals of Tree Ring Research*; University of Arizona Press: Tucson, AZ, USA, 2010.
51. Corona, C.; Lopez Saez, J.; Stoffel, M. Defining optimal sample size, sampling design and thresholds for dendrogeomophic landslide sampling. *Quat. Geochronol.* **2014**, *22*, 72–84. [CrossRef]
52. Šilhán, K. Spatial dendrogeomorphic sampling based on the specific tree growth responses induced by the landslide mechanism. *Quat. Geochronol.* **2021**, *61*, 101132. [CrossRef]
53. Cook, E.R.; Kairiukstis, L.A. *Methods of Dendrochronology: Applications in the Environmental Sciences*; Springer: Dordrecht, The Netherlands, 1990; 394p.
54. Stokes, M.A.; Smiley, T.L. *An Introduction to Tree-Ring Dating*; University of Chicago Press: Chicago, IL, USA, 1968.
55. Bräker, O.U. Measuring and data processing in tree-ring research—A methodological introduction. *Dendrochronologia* **2002**, *20*, 203–216. [CrossRef]
56. Holmes, R. *Dendrochronology Program Library—User Manual*; Laboratory of Tree-Ring Research: Tucson, AZ, USA, 1994.
57. Holmes, R. Computer-assisted quality control in tree-ring dating and measurement. *Tree-Ring Bull.* **1983**, *43*, 69–78.
58. Šilhán, K. Can tree tilting indicate mechamisms of slope movement? *Eng. Geol.* **2015**, *199*, 157–164. [CrossRef]
59. Šilhán, K.; Pánek, T.; Dušek, R.; Havlů, D.; Brázdil, R.; Kašičková, L.; Hradecký, J. The dating of bedrock landslide reactivations using dendrogeomorphic techniques: The Mazák landslide, Outer Western Carpathians (Czech Republic). *Catena* **2013**, *104*, 1–13. [CrossRef]
60. Gers, E.; Florin, N.; Gartner, H.; Glade, T.; Dikau, R.; Schweingruber, F.H. Application of shrubs for dendrogeomorphological analysis to reconstruct spatial and temporal landslide movement patterns. A preliminary study. *Z. Geomorph.* **2001**, *125*, 163–175.
61. Baroň, I.; Cílek, V.; Krejčí, O.; Melichar, R.; Hubatka, R. Structure and dynamics of deep-seated slope failures in the Magura Flysch Nappe, outer Western Carpathians (Czech Republic). *Nat. Hazards Earth Syst. Sci.* **2004**, *4*, 549–562. [CrossRef]

62. Yamada, Y.; Ueda, S.; Kaneda, K.; Baba, K.; Matsuoka, T. Analogue and Digital modelling of Accretionary Wedges. In Proceedings of the Abstracts of 32nd International Geological Congress, Florence, Italy, 20–28 August 2004.
63. Fantucci, R.; McCord, A. Reconstruction of landslide dynamic with dendrochronological methods. *Dendrochronologia* **1995**, *13*, 43–58.
64. Malik, I.; Wistuba, M.; Migoń, P.; Fajer, M. Activity of slow-moving landslides recorded in eccentric tree rings of Norway spruce trees (Picea abies Karst.)—An example from the Kamienne Mts. (sudetes Mts., central Europe). *Geochronometria* **2016**, *43*, 24–37. [CrossRef]
65. Razak, K.A.; Straatsma, M.W.; van Westen, C.J.; Malet, J.P.; de Jong, S.M. Airborne laser scanning of forested landslides characterization: Terrain model quality and visualization. *Geomorphology* **2011**, *126*, 186–200. [CrossRef]
66. Van Den Eeckhaut, M.; Muys, B.; Van Loy, K.; Poesen, J.; Beeckman, H. Evidence for repeated re-activation of old landslides under forest. *Earth Surf. Process. Landf.* **2009**, *34*, 352–365. [CrossRef]
67. Fantucci, R.; Sorriso-Valvo, M. Dendrogeomorphological analysis of a slope near Lago, Calabria (Italy). *Geomorphology* **1999**, *30*, 165–174. [CrossRef]
68. Corominas, J.; Moya, J. Reconstructing recent landslide activity in relation to rainfall in the Llobregat River basin, Eastern Pyrenees, Spain. *Geomorphology* **1999**, *30*, 79–93. [CrossRef]
69. Klimeš, J.; Baroň, I.; Pánek, T.; Kosačík, T.; Burda, J.; Kresta, F.; Hradecký, J. Investigation of recent catastrophic landslides in the flysch belt of Outer Western Carpathians (Czech Republic): Progress towards better hazard assessment. *Nat. Hazards Earth Sys. Sci.* **2009**, *9*, 119–128. [CrossRef]
70. McGee, W.J. A fossil earthquake. *Geol. Soc. Am. Bull.* **1893**, *4*, 411–414.
71. Šilhán, K.; Pánek, T. Registration of rock block movements using dendrogeomorphic methods: New methodical approach in a case of localities in the Moravskoslezské Beskydy Mts. *Geografie* **2014**, *119*, 50–66. [CrossRef]
72. Friedman, J.M.; Vincent, K.R.; Shafroth, P.B. Dating floodplain sediments using tree-ring response to burial. *Earth Surf. Process. Landf.* **2005**, *30*, 1077–1091. [CrossRef]
73. Chalupová, O.; Šilhán, K.; Kapustová, V.; Chalupa, V. Spatiotemporal distribution of growth releases and suppressions along a landslide body. *Dendrochronologia* **2020**, *60*, 125676. [CrossRef]
74. Schweingruber, F.H.; Eckstein, D.; Serre-Bachet, F.; Braker, O.U. Identification, presentation and interpretation of event years and pointer years in dendrochronology. *Dendrochronologia* **1990**, *8*, 9–38.
75. Terasme, J. Dating of landslide in the Ottawa river valley by dendrochronology—A brief comment. In *Mass Wasting Proceedings, 4th Guelph Symposium on Geomorphology*; Geo Abstracts Ltd.: Norwich, England, 1975; pp. 153–158.
76. Savi, S.; Schneuwly-Bollschweiler, M.; Bommer-Denns, B.; Stoffel, M.; Schlunegger, F. Geomorphic coupling between hillslopes and channels in the Swiss Alps. *Earth Surf. Process. Landf.* **2013**, *38*, 959–969. [CrossRef]
77. Papadopoulos, A.M.; Mertzanis, A.; Pantera, A. Dendrogeomorphological observations in a landslide Tymfristos mountain in Central Greece. In *Eco- and Ground Bio-Engineering: The Use of Vegetation to Improve Slope Stability*; Cammeraat, E., Stokes, A., Norris, J.E., Spanos, L., Eds.; Springer: Berlin/Heidelberg, Germany, 2007; pp. 223–230.
78. Guida, D.; Pelfini, M.; Santilli, M. Geomorphological and dendrochronological analyses of a complex landslide in the southern Apennines. *Geogr. Ann. Ser. A* **2008**, *90*, 211–226. [CrossRef]
79. Yumoto, M.; Ishida, S.; Fukazawa, K. Studies on the formation and structure of the compression wood cells induced by artificial inclination in young trees of *Picea glauca*. IV. Gradation of the severity of compression wood tracheids. *Res. Bull. Coll. Exp. For. Hokkaido Univ.* **1983**, *40*, 409–454.
80. Dassot, M.; Fournier, M.; Ningre, F.; Constant, T. Effect of tree size and competition on tension wood production over time in beech plantations and assessing relative gravitropic response with a biomechanical model. *Am. J. Bot.* **2012**, *99*, 1427–1435. [CrossRef] [PubMed]
81. Burkhalter, P.; Egli, M.; Gärtner, H. Reconstruction and actual trends of landslide activities in Bruust–Haltiwald, Horw, canton of Lucerne, Switzerland. *Geogr. Helv.* **2019**, *74*, 93–103. [CrossRef]
82. Tumajer, J.; Burda, J. Landslide-induced changes of vessel shape in Betula pendula Roth—A preliminary study. *AUC Geogr.* **2013**, *48*, 59–68. [CrossRef]
83. Kappel, M. Dating Hydrologic and Geomorphic Change Using Dendrochronology in Tully Valley, Central New York: A Summary. *Tree-Ring Res.* **2014**, *70*, 91–99. [CrossRef]
84. Stewart, A.K.; Heinrich, C.E.; Hubbart, T.D. *Dendrogeomorphic Evidence of Frequent Mass Movement Using Reaction Wood in Black Spruce: Alaska Highway Milepost 1267*; Alaska Division of Geological & Geophysical Surveys Report of Investigation: Northway Junction, AK, USA, 2017; p. 18.
85. Šilhán, K.; Prokešová, R.; Medve'ová, A.; Tichavský, R. The effectiveness of dendrogeomorphic methods for reconstruction of past spatio-temporal landslide behaviour. *Catena* **2016**, *147*, 325–333. [CrossRef]
86. Šilhán, K.; Pánek, T.; Hradecký, J. Tree-ring analysis in the reconstruction of slope instabilities associated with earthquakes and precipitation (the Crimean Mountains, Ukraine). *Geomorphology* **2012**, *173–174*, 174–184. [CrossRef]
87. Šilhán, K.; Klimeš, J.; Tichavský, R. The sensitivity of dendrogeomorphic approaches to assessing landslide movements. *Geomorphology* **2019**, *347*, 106869. [CrossRef]
88. Fisher, J.B.; Marler, T.E. Eccentric growth but no compression wood in a horizontal stem of cycas micronesica (cycadales). *IAWA J.* **2006**, *27*, 377–382. [CrossRef]

89. Šilhán, K.; Stoffel, M. Impacts of age-dependent tree sensitivity and dating approaches on dendrogeomorphic time series of landslides. *Geomorphology* **2015**, *236*, 34–43. [CrossRef]
90. Šilhán, K. How different are the results acquired from mathematical and subjective methods in dendrogeomorphology? Insights from landslide movements. *Geomorphology* **2016**, *253*, 189–198. [CrossRef]
91. Migoń, P.; Kacprzak, A.; Malik, I.; Kasprzak, M.; Owczarek, P.; Wistuba, M.; Pánek, T. Geomorphological, pedological and dendrochronological signatures of a relict landslide terrain, Mt Garbatka (Kamienne Mts), SW Poland. *Geomorphology* **2014**, *219*, 213–231. [CrossRef]
92. Van Asch, T.W.J.; Van Steijn, H. Temporal patterns of mass movements in the French Alps. *Catena* **1991**, *18*, 515–527. [CrossRef]
93. Malik, I.; Wistuba, M. Dendrochronological methods for reconstructing mass movements—An example of landslide activity analysis using tree-ring eccentricity. *Geochronometria* **2012**, *39*, 180–196. [CrossRef]
94. Fleming, R.W.; Johnson, A.M. Landslide in colluvium. *U.S. Geol. Surv. Bull. 2059-B* **1994**, 1–24. Available online: https://pubs.usgs.gov/bul/2059b/report.pdf (accessed on 20 September 2010).
95. Šilhán, K. Tree ring eccentricity in the dendrogeomorphic analysis of landslides—A comparative study. *Catena* **2019**, *174*, 1–10. [CrossRef]
96. Fabiánová, A.; Chalupa, V.; Šilhán, K. Dendrogeomorphic dating vs. low-magnitude landsliding. *Quat. Geochronol.* **2021**, *62*, 101150. [CrossRef]
97. Lopez-Saez, J.; Corona, C.; Stoffel, M.; Berger, F. High-resolution fingerprints of past landsliding and spatially explicit, probabilistic assessment of future activations: Aiguettes landslide, Southeastern French Alps. *Tectonophysics* **2013**, *602*, 355–369. [CrossRef]
98. Papciak, T.; Malik, I.; Krzemień, K.; Wistuba, M.; Gorczyca, E.; Wrońska-Wałach, D.; Sobucki, M. Precipitation as a factor triggering landslide activity in the Kamień massif (Beskid Niski Mts, Western Carpathians). *Bull. Geog. Phys. Geog. Ser.* **2015**, *8*, 5–17. [CrossRef]
99. Hutchinson, J.N.; Bromhead, E.N.; Lupini, J.F. Additional observations on the Folkestone Warren landslides. *Q. J. Eng. Geol. Lond.* **1980**, *13*, 1–31. [CrossRef]
100. Hungr, O.; Evans, S.G. The occurrence and classification of massive rock slope failure. *Felsbau Vienna Austria* **2004**, *22*, 16–23.
101. Cockburn, J.M.H.; Vetta, M.; Garver, J.I. Tree-ring evidence linking late twentieth century changes in precipitation to slope instability, central New York state, USA. *Phys. Geog.* **2016**, *37*, 153–168. [CrossRef]
102. Lopez-Saez, J.; Corona, C.; Stoffel, M.; Berger, F. Assessment of forested shallow landslide movements coupling tree ring records from stems and exposed roots. *Geomorph. Relief. Process. Environ.* **2014**, *2*, 159–174. [CrossRef]
103. Wistuba, M.; Malik, I.; Krąpiec, M. Can we distinguish between tree-ring eccentricity developed as a result of landsliding and prevailing winds? Consequences for dendrochronological dating. *Geochronometria* **2018**, *45*, 223–234. [CrossRef]
104. Saunders, I.; Young, A. Rates of surface processes on slopes, slope retreat and denudation. *Earth Surf. Process. Landf.* **1983**, *8*, 473–501. [CrossRef]
105. Petley, D.N.; Allison, R.J. The mechanics of deep-seated landslides. *Earth Surf. Process. Landf.* **1997**, *22*, 747–758. [CrossRef]
106. Pánek, T.; Šilhán, K.; Tábořík, P.; Hradecký, J.; Smolková, V.; Lenárt, J.; Brázdil, R.; Kašičková, L.; Pazdur, A. Catastrophic slope failure and its precedings: Case of the May 2010 Girová Mountain long-runout rockslide (Czech Republic). *Geomorphology* **2011**, *130*, 352–364. [CrossRef]
107. Šilhán, K. Tree ring evidence of slope movements preceding catastrophic landslides. *Landslides* **2020**, *17*, 615–626. [CrossRef]
108. Šilhán, K. Dendrogeomorphic chronologies of landslides: Dating of true landslide movements? *Earth Surf. Process. Landf.* **2017**, *42*, 2109–2118. [CrossRef]
109. Žížala, D.; Zvelebil, J.; Vilímek, V. Using dendrogeomorphology in research on a slope deformation in Běleč, Czech-Moravian Highland (Czech Republic). *Acta Geogr. Carol.* **2010**, *2*, 73–88.
110. Burda, J. Spatio-temporal activity of mass movements in the Krušné hory Mountains (Czech Republic): Dendrogeomorphic case study. *AUC Geogr.* **2011**, *46*, 15–30. [CrossRef]
111. Sabir, M.A.; Umar, M.; Farooq, M.; Faridullah, F. Computing soil creep velocity using dendrochronology. *Bull. Eng. Geol. Environ.* **2016**, *75*, 1761–1768. [CrossRef]
112. Šilhán, K.; Tichavský, R.; Fabiánová, A.; Chalupa, V.; Chalupová, O.; Škarpich, V.; Tolasz, R. Understanding complex slope deformation through tree-ring analyses. *Sci. Total Environ.* **2019**, *665*, 1083–1094. [CrossRef] [PubMed]
113. Butler, D.; Malanson, G.; Oelfke, J. Tree-ring analysis and natural hazard chronologies: Minimum sample sizes and index values. *Prof. Geogr.* **1987**, *39*, 41–47. [CrossRef]
114. Stoffel, M.; Butler, D.R.; Corona, C. Mass movements and tree rings: A guide to dendrogeomorphic field sampling and dating. *Geomorphology* **2013**, *200*, 106–120. [CrossRef]
115. Moir, A.K.; Leroy, S. The dendrochronological potential of lime (Tilia spp.) from trees at Hampton Court Palace, UK. *Agric. J.* **2013**, *35*, 7–17.
116. Lopez-Saez, J.; Corona, C.; Stoffel, M.; Astrade, L.; Berger, F.; Malet, J.P. Dendrogeomorphic reconstruction of past landslide reactivation with seasonal precision: The Bois Noir landslide, southeast French Alps. *Landslides* **2012**, *9*, 189–203. [CrossRef]
117. Lopez-Saez, J.; Corona, C.; Stoffel, M.; Berger, F. Climate change increases frequency of shallow spring landslides in the French Alps. *Geology* **2013**, *4*, 619–622. [CrossRef]
118. Šilhán, K.; Tichavský, R.; Škarpich, V.; Břežný, M.; Stoffel, M. Regional, tree-ring based chronology of landslides in the Outer Western Carpathians. *Geomorphology* **2018**, *321*, 33–44. [CrossRef]