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„Are hardwood species suited for reconstructing landslides?"

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Author's declaration

Hereby I confirm that the presented master's thesis is written by myself. Neither did I use other resources than the cited references, nor did I use illegitimate means of help. The master's thesis was not submitted as an examination paper in Austria or abroad. This thesis is identical with the version evaluated by the supervisor.

Vienna, July 2018
(Dorothée Post)

Pour

Maman,

Papa

et

Caroline

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Abstract

The kinetic energy of landslides highly influences the growth structure of tree stems and thus causes the development of reaction wood in the xylem. Most studies focus on assessing the reaction wood development in conifers. However, the response of hardwood species (e.g. beech - *Fagus sylvatica L.* and birch - *Betula pendula Roth.*) on external mechanical stresses caused by landslides was rarely addressed so far. In this study, the reaction wood development in (i) soft- and hardwood species and (ii) depending on the location and the specific mechanical influence causing deformation of the tree stems will be assessed. Therefore, 80 trees, consisting of beeches, birches, and Norway spruce (*Picea abies Karst.*) were sampled with an increment corer on three different positions in a landslide-prone area in the Walgau valley (Vorarlberg, Austria). Two positions were located on the area of a shallow landslide, whereas the third position lies on a stable slope, where the mechanical stresses are most likely caused by snow pressure. Cross-referencing was performed with 50 trees in CDendro-software. To identify reaction wood, thin sectioning and staining of the samples was conducted. The analyses showed that soft- and hardwood species develop comparable structures responding to mechanical stress. Nevertheless, the methods to reconstruct landslides on an annual basis do still have their weaknesses for slow moving, shallow landslides.

Kurzfassung

Gravitative Massenbewegungen üben mechanischen Stress auf den Untergrund und die darin verankerte Vegetation aus. Dieser mechanische Stress führt in Bäumen zur Bildung von Reaktionsholz und exzentrischem Wachstum. Je nach Spezies, die zu den Weich- oder Harthölzern gehören kann, bilden sich diese Merkmale unterschiedlich aus. Räumliche und zeitliche Rekonstruktion von gravitativen Massenbewegungen wurde mit Weichhölzern schon mehrfach durchgeführt, während Harthölzer noch nicht dafür genutzt wurden. Darum wurden Proben von 80 Bäumen der Spezies *Picea abies Karst.*, *Fagus sylvatica L.* und *Betula pendula Roth.* in Vorarlberg, Österreich genommen. Zwei der Standorte befinden sich auf flachgründigen Rutschungen, die im Rahmen des BioSlide Projektes kartiert wurden. Ein weiterer Hang zeigt gestörtes Baumwachstum ohne Anzeichen einer Rutschung. Eine Referenzchronologie wurde zur Datierung erstellt und die Proben vermessen. Weiters wurden Dünnschnitte der Harthölzer angefertigt, um das Reaktionsholz zu identifizieren. In den Analysen hat sich gezeigt, dass sowohl Weich- als auch Harthölzer ähnliche Reaktionen auf mechanischen Stress zeigen, die Methoden zur jährlichen Rekonstruktion einer gravitativen Massenbewegung jedoch noch nicht ausgefeilt genug sind, um sich langsam bewegende, flachgründige Rutschungen genau zu datieren.

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Chapter 1

Introduction

Mountainous regions of the world become more and more open for touristic infrastructure, human settlements and agriculture, which increases the damage potential of natural hazards (Baumann and Kaiser 1999, Montrasio and Valentino 2008, Haque et al. 2016). Especially gravitative mass movements, as landslides, are a concern to management in alpine regions, because they can cause loss of resources, affect infrastructure and pose a safety threat for human life (Braam et al. 1987*a*, Wistuba et al. 2013). For the development of management strategies, it is crucial to know about landslide activity and catalysts in the respective areas. Triggering conditions can be reconstructed with information on former activity of the slope. The further these records on activity go back in time, the more unmitigated the image of the slope and therefore the risk estimation gets. Therefore, methods that are able to add spatial and temporal information on the behavior of the slope are of great interest.

Trees are known to provide records of environmental changes and can therefore be included in the investigation of different aspects in their surroundings (Corominas and Moya 2010). Although tree rings were primarily used for the reconstruction of climate, which formed the scientific field of dendrochronology, they are currently used in various contexts. Some of the topics addressed are the hydrological properties of a site (Gholami et al. 2015), ecological processes like insect defoliation (Fan and Bräuning 2017), volcanic eruptions (Esper et al. 2017) or pollution (Čada et al. 2016). Dating of events plays an important role in these studies, as the trees provide the possibility to reconstruct a certain moment in time, where conditions changed and which was not recorded by other methods. This is one of the circumstances that made dendrochronology interesting for the use in geomorphological studies, which lead to the emerge of dendrogeomorphology.

The reconstruction of geomorphologic processes can be performed with macroscopic and microscopic investigations of the width of annual rings, the onset of changes in wood anatomy or the dating of scars (Gärtner 2007). Due to the impact of the environment on annual growth, the onset of these factors can mark the beginning change of growth controlling factors (Schweingruber 1983, Bräuning 1995, Carrara and O'Neill 2003, Cherubini et al. 2004, Cook and Kairiukstis 2013). Therefore, the start of stabilization of the stem with eccentric growth and occurrence of reaction wood can be interpreted as the onset of mechanical stress. A combination with geomorphological mapping of events and dating of mechanical stress proved to be a useful tool to investigate landslide activity, predict future behavior of the slope and event triggering conditions (Gärtner 2003*a*).

Nevertheless, a tree's growth is a complex process, that is related to many different factors, as the mentioned surrounding environmental conditions, but also to the genetic makeup. Every species reacts differently to the environment and has different growth rates and wood properties. Hence, the species used for dendrogeomorphological research determine, which growth changes can be used to detect mechanical stress induced by landslides. Softwood species, as Norway spruce (*Picea abies Karst.*) are known to be suited for the reconstruction of landslides and were frequently used in former studies. As hardwood species (e.g. beech - *Fagus sylvatica L.* and birch - *Betula pendula Roth.*) are well distributed over Europe, their use would open up new possibilities in the field of dendrogeomorphology, which was not yet performed (Tumajer and Treml 2013). Therefore, a main research question was formulated to identify the potential of hardwood species in dendrogeomorphic research:

"Are hardwood species sensitive for reconstructing landslide movements?"

The study is embedded in the work of Dr. Elmar Schmaltz within the BioSlide project. The BioSlide project aims to develop a multi-temporal landslide inventory for the Walgau region in Vorarlberg, Austria. As reliable inventories are scarce for woodland areas (Schmaltz et al. 2017), this study will evaluate the potential to use mixed stands and stands of hardwood species to add temporal information on landslides in an inventory. Within this study, dendrogeomorphological methods are applied on softwood and hardwood species to determine the landslide activity by dating of onset of eccentric growth and reaction wood. The dynamics of landslides are addressed in chapter 2.1 and the theoretical background on growth controlling factors in chapter 2.2. As the temporal reconstruction of landslides was performed

with conifer trees before (Wistuba et al. 2013) and hardwood trees are still underrepresented in dendrochronological studies, the goal is to examine if hardwood species are also suited for this specific approach. The representation of different species within former dendrogeomorphic studies is presented in detail in chapter 2.3. In the field, coring of *Picea abies Karst.*, *Fagus sylvatica L.* and *Betula pendula Roth.* was performed on three sites, where the trees showed externally visible growth changes related to mechanical stress. In addition, reference trees of each species were sampled to date the disturbed samples and to identify an average eccentricity value occurring on stable slope, which will be used as a threshold for interpretation of mechanical stress (Wistuba et al. 2013). The results for the reference chronology, reference threshold and the dating of mechanical stress in the three different sites will be presented in chapter 6. Regarding the formulated hypotheses (see chapter 3), these results will be discussed in the last section of this study to give an outlook for potential research in the future.

Chapter 2

Theoretical Approach and Research Gap

Conducting a dendrogeomorphological study implies that methodological approaches of geomorphology and dendroecology are combined. On the one hand, geomorphological processes must be understood to identify the type of mass movements and the dynamics within the study area. On the other hand, the relation between vegetation and geomorphology must be taken into account. Kinetics of mass movements, the motivation to create landslide inventories and the methods used to perform that are explained in chapter 2.1. Here, we focus on spatial and multi-temporal inventories of shallows landslides, where dendrochronology represents a tool to add temporal information. Further, the growth of trees is impacted by mechanical stress, which provides the possibility to use the growth pattern as a record of experienced pressure. To address this, the growth of a tree, its structure and the anatomical changes in growth when experiencing mechanical stress are explained in chapter 2.2. Dating mass movements with tree rings was conducted in many studies so far, but the processes examined and species used differ as can be seen in chapter 2.3.

2.1 Landslide Activity

The necessity of producing landslide inventories increased, as mass movements play a key role in forming landscapes in the eastern alps. Next to the threat for human life or infrastructure, ecosystems change due to geomorphic processes as gravitational mass movements affecting sediment fluxes, hydrology, connectivity and vegetation (Petschko et al. 2016). But not only

the effects of gravitational mass movements can be diverse. A geomorphic process is influenced by pre-disposing factors (e.g. composition of the material) and environmental conditions working as triggering factors, which cause varying types of movement. Various classifications of landslides exist and the types after Dikau (2004) are presented shortly to illustrate this aspect: lateral spreading is defined as the lateral extension of a mass that was initially held by cohesive forces. Often, the underlying material is softer and changes within this layer, what can be the reason for slope failure. The forward rotation of a mass like a rock, soil or debris is defined as toppling. If the material is falling freely, the process is called rock fall. The group of mass movements we focus on in this study, are landslide processes. Landslides in general are defined as a downward movement of material within a slope that moves under the influence of gravity. The definition of the term in this way can also refer to other gravitational mass movements called flows, but a landslide is further defined as material moving on a clearly distinguishable shear plane and is not forced to be attached to a transport medium as water. Does the movement occur with highly saturated conditions, where the particles move separately within the moving mass, it can be referred to as a debris or soil flow.

2.1.1 Driving Forces in Landslides

Despite not always being associated with high water content in the soil, landslides are often triggered by precipitation and their kinetic behavior is strongly related to water infiltration. There are also various other natural and anthropogenic triggering factors: natural factors as precipitation, earth shaking, temperature, humidity, solar radiation and wind impact the saturation of soil pores, weathering or erosion and consequently destabilize material (Schuster and Wieczorek 2002, Sorbino and Nicotera 2013). Human impact can also enhance processes, which decrease soil stability, such as deforestation, soil erosion due to land management or construction and mining. Due to these human actions, hydrology and soil geometry are changed, what might increase the risk of slope failure (Corominas and Moya 2008). If an environmental change occurs that destabilizes the soil, the composition of the material plays a major role. In this study we focus on precipitation induced events that can occur in soils composed of all kinds of grain sizes. However, the composition of the grain sizes affects the kinetics of the sliding process: in fine grained soil, a mass movement is more likely to move slowly, coarse grained material and more saturated soil potentially moves faster. In addition, slope geometry, vegetation, hydro-mechanical processes, boundary condi-

tions and the initial state of the slope play a key role (Sorbino and Nicotera 2013).

The BioSlide study area contains shallow landslides, which are known to cause heavy damages (Kesseli 1943, Caine 1980). They can vary in extent and dynamics, which stresses the importance of the mentioned factors controlling the movement. Their extent is defined with several centimeters to meters length and they mainly occur in regions with varied layers of substratum and a topsoil with a thickness of 1-2.5m (Montrasio and Valentino 2008). The driving forces can be seen in figure 2.1: the figure shows the geometry of a section from a shallow landslide in a substratum with varying layers. The length and depth affect the weight of the soil W, creating a downwards heading force. Moreover, the stabilizing and destabilizing factors are displayed in the figure. Changes in this system of resistance to downward driving forces shift the ratio within them and can induce movement (Montrasio and Valentino 2008). The forces that drive this ratio are the shear force t favoring the downward movement parallel to the slope and the shear strength S which works against t. The shear strength S can be enhanced due to roots, which explains the stabilizing effect of trees on slopes (Cohen and Schwarz 2017). Figure 2.1 also points out that the changing sediment planes increase the probability to work as a shear plane, especially when precipitation infiltrates between the layers. The increased water content of the soil weakens the shear forces and can induce the gravitational process.

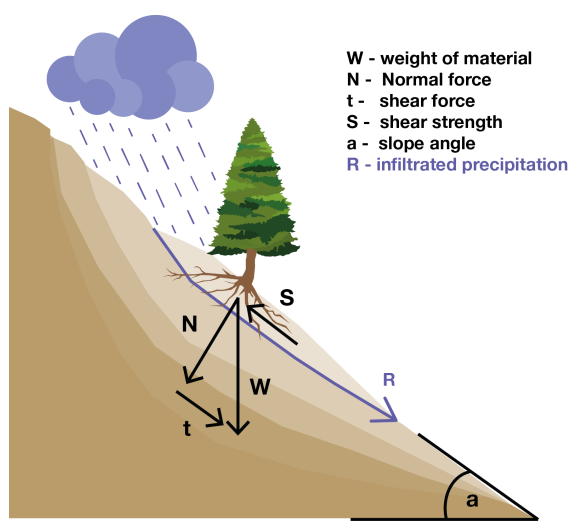

Figure 2.1: Driving forces controlling mass movements.

This explains why shallow landslides are mainly triggered by rainfalls of medium intensity that last for longer periods or extreme events after the soil is already saturated. Typically, there is a first triggering phase and a second evolving phase, so the response to a precipitation event might cause a lag in time (Montrasio and Valentino 2008).

2.1.2 Landslide Inventories

The facts above point out that shallow landslides are not moving in one single phase but can have several stages. This stresses the importance of monitoring the respective areas. The first step of comprehensive monitoring is a spatial landslide inventory that gives insight to the potential hazards in the investigated region and helps to develop management strategies. Knowledge on spatial distribution is important, as the density of landslide occurrences in an area can be combined with information as soil grain sizes, forest cover or hydrological properties to point out other endangered areas. The second step covers the temporal aspect, meaning that these analyses have to be performed repeatedly. Mapping in the field can be performed regularly to discover changes in the geomorphic system. However, studies showed that the identification of structures strongly depends on the knowledge and experience of the person mapping and can therefore be hardly reproduced (van den Eeckhaut et al. 2009, Guzzetti et al. 2012, Schlögel et al. 2015). With the development of modern techniques, detection of landslides got more precise and easier (Lang et al. 1999, Noferini et al. 2007). Methods used are satellite imagery (Peyret et al. 2008, Cascini et al. 2009, Herrera et al. 2013), laser scanning (Razak et al. 2011), geodetic survey (De Vita et al. 2013) and hydrogeological monitoring (Klimeš et al. 2012). Especially the possibility to produce detailed maps of spatial landslide distribution multiple times in an area was improved due to techniques as LIDAR (Light detection and range). Using LIDAR datasets, digital elevation models (DEMs) can be created. When DEMs of several points in time are available, differences in height can be calculated and point out areas, where the distribution of sediment changed (Guzzetti et al. 2012). Schmaltz et al. (2016) applied morphometric analyses to determine the types of landslides within an inventory with a quantifying method. Nevertheless, the temporal aspect is not included. However, a multitemporal inventory has key advantages: as geomorphic processes are not static and develop over time, their behavior is interesting to investigate. Schmaltz et al. (2016) recommend a combination of morphometric indices, field mapping and the use of available digital elevation data. In the respective publication it is also mentioned that the date of occurrence is

needed to reproduce the initial conditions before an event for morphometric analyses. As shallows landslides can be active for several decades or more, modern imagery datasets might not extend back far enough in time to record the initial date of a process. That is where dendrochronological information can fill a gap, as trees can reach ages of several centuries and record the environmental conditions in an area over time (Solomina 2002, Bollati et al. 2018).

2.2 Tree Rings

Trees are seed bearing plants (*Spermatophytae*) and subdivided into gymnosperms (*Gymnospermae*) and angiosperms (*Angiopermae*). Gymnosperm is Greek and stands for "naked seed", which relates to the production of seeds without any protection. In contrast, Angiosperms, which make up most (80%) of the plants, produce fruits enclosing their seeds. With some exceptions, as the species in the subfamily of *Laricoidae*, coniferous trees are gymnosperms and deciduous trees angiosperms. In this study coniferous species or softwood species are compared to hardwood species (angiosperms) (Sjöström et al. 1999). The distinction of trees by soft- and hardwood relates to the properties of the wood. Although the two types of trees differ in their properties, individuals of both types do form growth rings throughout the northern hemisphere, which makes them suitable for dendrochronological studies. As there are only ten softwood species in Europe, but 51 hardwood species, the use of hardwood species in dendrochronological research can open up many new research areas (Schweingruber 1983).

2.2.1 Stem Morphology

A tree consists of three organs: leaves, branches, the stem and roots. The leaves are the photosynthetic organs of higher plants, that are attached to the branches through a vascular system for the exchange of nutrients. The stem provides support, water and nutrient transport and the roots structural anchorage and provision of water (Schweingruber 1983).

In this study, we focus on the stem, which is increasing in diameter due to annual growth, and its morphology. The parts building up the stem are shown in figure 2.2. The outermost part is the bark, which protects the wood from injury and insects. The vascular or conducting tissue is the main component of the plant body and extends throughout the whole tree. This conducting tissue divides into two types: xylem and phloem. The xylem transports wa-

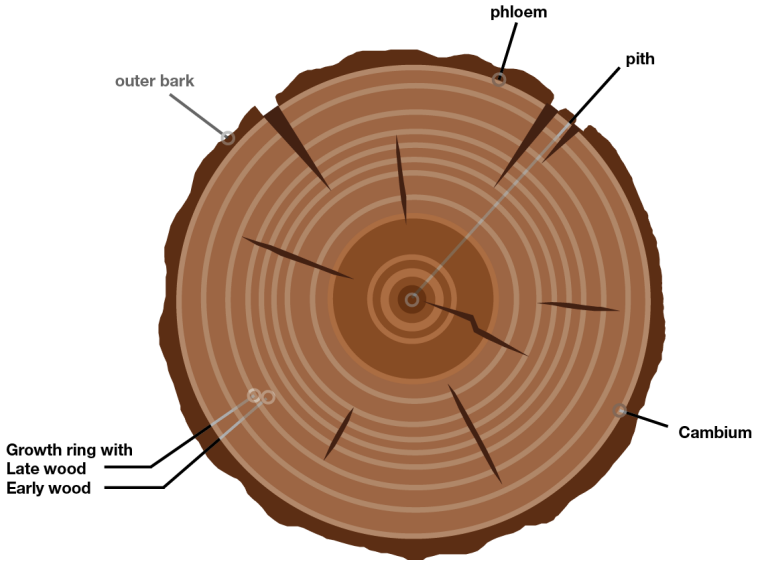

Figure 2.2: Schematic construction of conifer stem.

ter and minerals, as sugars, up to the leaves, whereas the phloem moves products of photosynthesis from the leaves to the branches, stem and roots. Growth takes place in the different organs of the tree in a tissue called the meristem. In the shoots and roots the apical meristem tissue is responsible for primary growth, which means the elongation of branches and roots. The vascular cambium, located between the phloem and the xylem, produces phloem cells towards the outer side of the stem and xylem cells towards the inner side (Begum et al. 2013). The thickening of the stem with the respective production of cells of the cambium on the inner side is called radial or secondary growth. The cell division in the cambial meristem and the following expansion and maturation of cambial derivatives form the tree rings (Pallardy 2010). The formation of tree rings depends to the annual rhythm of growing periods that is determined by changing conditions, which is addressed in the following section.

2.2.2 Growth controlling Factors

Growth patterns of tree rings can provide a record of the surrounding conditions of a tree reaching back to the last decades and centuries. Understanding how the growth of a tree is influenced by different endogenous and exogenous factors is crucial while determining changes in the wood that indicate mechanical stress (Brown 1996).

The growth of a tree depends on various factors. On the one hand, growth is dictated by the endogenous factors of the tree's genetic makeup that determines the longevity of a species' life and the wood properties (Schweingruber 1996). On the other hand, exogenous factors, as seasonal changes, control growth during a year. These factors represent an influence on growth at "any time, in any matter and intensity" (Schweingruber 1996, p. 26). The length of shoots and needles, the cell size, cell wall thickness and the width of annually formed tree rings is affected. Exogenous factors are, next to seasonal changes, extreme climatic conditions as drought or frost, insect outbreaks or the position of individuals within the stand, which influences the availability of resources needed (Stokes and Smiley 1968, Schweingruber 1996, Bräuning et al. 2016). Light as resource is needed for biomass production, but can also cause the decline of the same, when appearance of other individuals increases the concurrence within a timber stand. Temperature and water availability are two other strong growth controlling factors. Their impact on tree ring width is the reason for the possibility to reconstruct precipitation due the patterns formed. Two other climate related factors, which have to be taken into account while conducting a dendrogeomorphic study are wind and snow occurrence. Wind and snow pressure can cause eccentric growth and reaction wood, which are the same reactions that are related to mass movements. As many signals of growth influencing factors can overlay each other, a complete distinction of single factors poses a challenge (Schweingruber 1996). This shows, that knowledge on growth controlling factors in a specific site is important to prevent the misinterpretation of ring width patterns.

The annual growth cycle is driven by both, climatic conditions and genetics. Within the year, different stages of growth can be defined that follow the cycle of seasons for individuals located in the northern hemisphere: the dormancy period is characterized by the lack of cell production during unfavorable conditions in winter. After this phase, the cells respond again to hormones, that control tree growth as indole-3-acetic acid (IAA) (Little and Bonga 1974). IAA is produced in the meristem and influences the cell division and their elongation. The cambium is therefore able to produce xylem cells again if the conditions are favorable. During the activation of the cambium, new cells are formed and the primary growth takes place elongating the stem, branches and roots (Sjöström et al. 1999). The production of IAA also triggers the activity of the cambium to start xylogenesis (Tuominen et al. 1997), which depends on the concentration of IAA per area, the temperature in the stem and nutrient availability (Begum et al. 2013). During this phase, the production of earlywood takes place, which is one of the parts, that form a

tree ring. The earlywood can make up 40 to 80% of a tree ring and has lower density. The main task of this tissue is the transport of larger amounts of water to the other organs of the tree. The latewood, forming the second part of a tree ring, is produced, when climatic conditions change and the cambial cell division declines. This kind of wood has a higher density and larger cell wall thickness, which contributes to the stability of the stem. If these processes do not occur, or the conditions influencing hormone production are not favorable, the formation of the ring will not be completed, what can lead to the phenomenon of missing rings or other growth anomalies (Sjöström et al. 1999, Novak et al. 2016). When examining potential stresses that modify the growth pattern of a ring, it is important to know in which period of the year it occurred. If the stresses appear in the dormancy period, the reflection will be visible as soon as the tree starts producing cells in the next vegetative period with changed wood properties (Stefanini 2004). Anomalies can therefore be dated yearly (Schweingruber 1996) and seasonally (Stefanini and Schweingruber 2000, Lopez Saez et al. 2012).

The phenomenon of missing rings is important while dating the samples of a tree (Novak et al. 2011). Wilmking et al. (2012) define three different types of missing rings. Rings, that are not visible in only one part of the stem, are called locally missing rings. Totally missing rings will not appear in any part of the tree in a specific year and continuously missing rings are "missing rings at the stem base" (Wilmking et al. 2012, p. 213). The most common group are locally missing rings. Currently, it is not yet clear how the number of missing rings is related to a species, but they pose a problem in chronology building, as some chronologies had to be abandoned because too many rings were missing and others did not show any (Bräuning et al. 2016). This shows, that knowledge on missing rings is crucial, because they can mostly only be detected through crossdating (see chapter 5) (Leuschner and Schweingruber 1996). Other growth anomalies are density fluctuations, that appear to look like rings or years with narrow rings that can pose additional challenges for crossdating. If too many of these anomalies in an individual occur, samples have to be rejected (Bräuning et al. 2016). However, missing rings, density fluctuations and narrow rings can be a challenge but also useful for crossdating if they are occurring due to growth controlling factors affecting the whole timber stand. All growth patterns that are induced by environmental changes provide the chance to be used as markers during the dating process. In section 2.2.4, the impact that mechanical stress has on the formation and properties of tree rings will be explained in detail.

2.2.3 Softwood and Hardwood

The attribute soft- or hardwood addresses the properties of the wood in a tree. The schematic composition of the two wood types can be seen in figure 2.3. Softwood is often referred to as the wood from conifers, has a lower wood density and higher growth rates than hardwood species. However, not all softwood species do have softer wood, so the definition cannot be generally applied to conifers. Hardwood species, which are deciduous in most of the cases, have a higher density and stability of wood, but a lower growth rate (Schweingruber and Baas 2011). Another difference between the two wood types is the distribution of early- and latewood within a growth ring and their transition from one to another. The transition from earlywood to latewood in softwood species as *Picea abies Karst.* is for example gradual, whereas different patterns can be identified in hardwood species. Softwood does generally not have vessels, but tracheids for water and nutrient transport. Vessels serve the same purpose in hardwood and are also referred to as pores. Their appearance, size and distribution varies within the wood types and is responsible for the differing appearances of tree rings in hardwood species (Speer 2010).

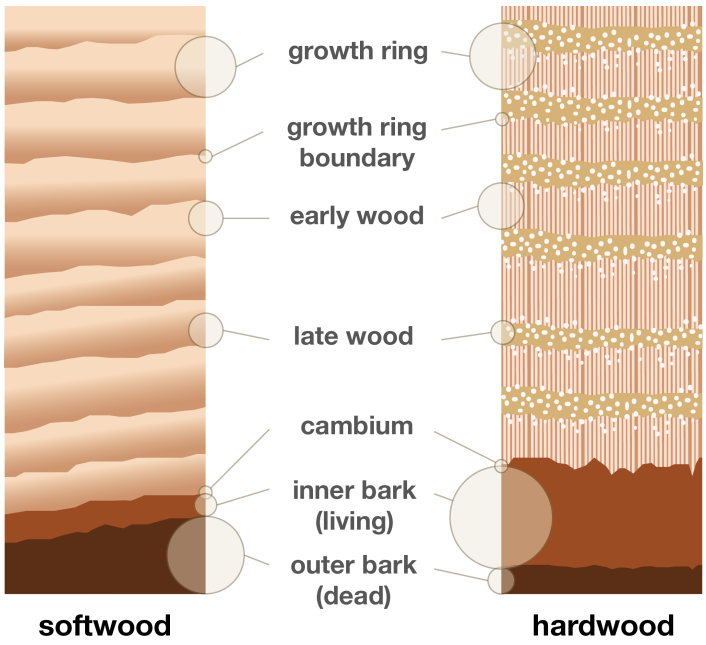

Figure 2.3: Tree rings in softwood and hardwood species (based on the illustrations of M.J. Favorite).

Ring porous species show the largest pores in the early wood getting gradually smaller towards the latewood, which forms a distinct border to the cells of the following year. In these species, the rings show distinct patterns that are well visible and easy to measure. Species with semi ring porous rings have pores that get smaller approaching the latewood, but do not show the same distinct zoning as ring porous species. The last group are diffuse porous rings, where the pores are distributed evenly but occur solitary throughout early and latewood. A species forming diffuse porous to semi-ring-porous annual rings is *Fagus sylvatica L.*. *Betula pendula Roth.* forms rather distinct ring boundaries that are marked with two to four radially flattened cells (Speer 2010).

2.2.4 Impact of mechanical Stress

Trees suffering from mechanical stress show different changes in shape, wood anatomy and growth rate. Externally visible consequences of mass movements are for example deformation, tilting of the stem, uprooting and scars on the bark caused by processes as rockfalls (Wiles et al. 1996, Carrara and O'Neill 2003). Within the stem, sudden growth reductions, reaction wood formation and eccentric growth of the annual rings are known aftereffects (Stefanini 2004).

Eccentric Growth

The irregular formation of wood in trees growing on unstable ground is referred to as eccentric growth of the stem. This growth eccentricity is described as "the tendency of a single tree to develop wider rings on one side of the stem." (Wistuba et al. 2013, p.42). The phenomenon of stem eccentricity was described by Parizek and Woodruff (1957), Braam et al. (1987*a*), Schweingruber (1996), Casteller et al. (2007) in relation to processes as mudflows and snow avalanches. Depending on the kinetics of the geomorphic processes, different forces can affect the tree and cause tilting. Figure 2.4 shows conifers in different tilting directions on an unstable and a stable slope. This illustrates, that eccentric growth does not only occur in downslope direction, but depends on the side that needs to develop wider rings to stabilize. Individuals growing on a stable slope, as on the right side in the respective figure, do not necessarily develop eccentric rings (Wistuba et al. 2013).

Several studies dated mechanical stress with occurrence of eccentricity (Malik and Wistuba 2012, Wistuba et al. 2013, Łuszczyńska et al. 2017). But there remains still a challenge: the quantification of eccentricity is still

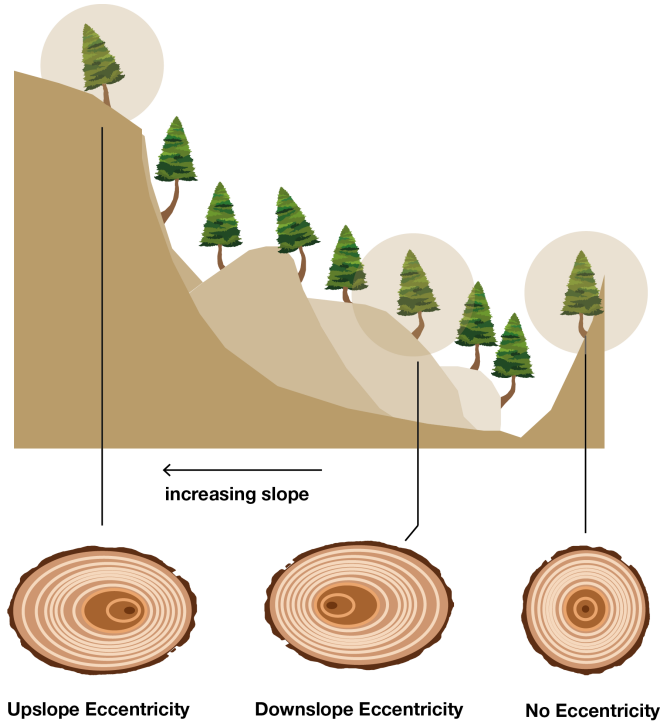

Figure 2.4: Differing directions of eccentric growth depending on the position of individuals on a sliding surface (after Wistuba et al. 2013).

discussed (Wistuba et al. 2013). Calculation of eccentricity indices was performed with dendrometrical data (van den Eeckhaut et al. 2009) or from ring width measurements (Casteller et al. 2007, Wistuba et al. 2013). Equations 2.1 to 2.5 show the different eccentricity indices, which were developed since the 1970ies. The approaches of Alestalo (1971) (see equation 2.1), Braam et al. (1987*a*) (see equation 2.2), Schweingruber (1996) (see equation 2.3) do all have the advantage of simplicity. Yet, the use of the complete radius, like in the approach of Alestalo (1971) does not provide any information on the exact year in which mechanical stress occurred and is therefore not suited to add temporal data to a landslide. Braam et al. (1987*a*) in turn recommend a different sampling strategy as Alestalo (1971). The samples should not be taken parallel to the slope but one on the lower side of the stem and the other one perpendicular to the stem. This strategy includes knowledge on the concentrically growing sides of the stem providing the possibility to compare it to the intensity of eccentric growth in the same individual, but still ignores possibly varying tilting directions. Casteller et al. (2007) (see equation 2.4) develop the index of Schweingruber (1996) for snow creep and calculates the

eccentricity for periods before and after a known event. This approach allows the comparison of eccentricity after the occurrence of mechanical stress, but also requires a known event. Consequently, it is suited for reconstruction of the intensity of known events, but cannot be applied if the events still have to be dated.

Wistuba et al. (2013) developed a new approach to date events on a landslide with unknown dates of occurrence. Wistuba et al. (2013) consider Braam's Index as the most advanced, but still mention, that the sampling perpendicular to the slope could miss upslope eccentricity or varying tilting directions. The index by Wistuba et al. (2013) follows a new strategy and calculates a value of eccentric growth for every year. Positive values of *Ex* calculated with equation 2.5 indicate an upslope eccentricity, a value equal zero no eccentricity and negative values downslope eccentricity. The results are then proceeded to a relative index in percent (*Eix[%]*) to achieve that the values are independent from the individual growth rates of a tree. The next step is to calculate the variability of the eccentricity in percent (*vEix[%]*) to determine the increase of eccentricity towards the previous year. An abrupt increase of eccentricity indicates the onset of stabilization measures of a tree. As this can also occur due to small movements in the ground, wind or wounding of stem or roots that disturb the balance of the tree, a reference threshold needs to be calculated from the reference trees. For every site, the range of eccentricity is determined due to the maximal and minimal variations of eccentricity within reference trees. Years that exceed this reference threshold are considered as events.

Alestalo (1971):

$$I_{ex} = \frac{R}{D} \cdot 100\% \qquad where \quad \begin{aligned} I_{ex} &= Eccentricity\ Index\ [\%] \\ R &= Radius\ up/downslope\ [cm] \\ D &= Stem\ diameter\ [cm] \end{aligned} \tag{2.1}$$

Braam et al. (1987):

$$I_{ex} = \frac{R_d - R_p}{R_d + R_p} \cdot 100\% \qquad where \quad \begin{aligned} I_{ex} &= Eccentricity\ Index\ [\%] \\ R_d &= Downslope\ radius\ [cm] \\ R_p &= Perpendicular\ radius\ [cm] \end{aligned} \tag{2.2}$$

Schweingruber (1996):

$$I_{ex} = \frac{R_d}{R_u} \qquad where \qquad R_u = Upsope\ radius\ [cm]$$
$$other : see\ equation\ 2.2 \tag{2.3}$$

Casteller (2008):

$$E_{i1995-1998} = \frac{\sum trw_{d1995-1998}}{\sum trw_{u1995-1998}} \qquad where \qquad E_i = Eccentricity\ [mm]$$
$$trw_{u/d} = ring\ width\ [mm]$$
$$E_{i1999-2002} = \frac{\sum trw_{d1999-2002}}{\sum trw_{u1999-2002}} \qquad u = upslope$$
$$d = downslope$$
$$E_i\% = \frac{E_{i1999-2002} - E_{i1995-1998}}{E_{i1995-1998}} \cdot 100\% \qquad E_i\% = Eccentricity\ Index\ [\%] \tag{2.4}$$

Wistuba et al. (2013):

$$\begin{aligned} Ex &= Ux - Dx && Ex = Eccentricity\ in\ year\ x\ [mm] \\ & && Dx = tree\ ring\ width\ downslope[mm] \\ & > 0 = (Ex/Dx)100\% && Ux = tree\ ring\ width\ upslope[mm] \\ Eix[\%] &= 0 = Ex && Eix[\%] = Eccentricity\ Index \\ & < 0 = (Ex/Ux)100\% && vEix[\%] = Variation\ of \\ & && Eccentricity\ Index \\ vEix[\%] &= Ei_x - Ei_{x-1} \end{aligned} \tag{2.5}$$

In this study the approach of Wistuba et al. (2013) is used. It is important to include complex patterns of tilting in different directions, as the kinetics of landslide movements can be complex. Furthermore, three species are examined that build up reaction wood in different parts of the stem (see the following section). Therefore, it is even more important to use an index that is independent from growth rates of different species, considering up- and downslope eccentricity and visualizes abrupt changes in growth.

Compression Wood and Tension Wood

Reaction wood is the wood produced in response to mechanical stress to keep the optimal growing direction of stem and branches (Carrara and O'Neill 2003, Schweingruber 2012, Gardiner et al. 2014). Depending on soft- or hardwood species, reaction wood is formed in different parts of the tree and has different properties. Regarding the stem, conifers produce compression wood on the lower side of the stem and hardwood trees tension wood on the upper side of the stem when tilted downslope (Sinnott 1952, Schweingruber 2012). Formation of reaction wood allows vertical growth, despite mechanical stress forcing against an upright position of the stem (Schweingruber 2012).

Compression wood can be found in every coniferous tree on the lower side of the branches and is most conspicuous in fast growing individuals (Sinnott 1952). In conifers, compression wood occurs moreover due to stabilization on the downslope side of the stem. However, a different tilting direction can induce the formation of compression wood in another direction of the slope, as explained for eccentric growth. In figure 2.5, a core of the upslope side of the stem of *Picea abies Karst.* can be seen on the left side, which shows no compression wood. On the right side of the picture, the downslope part of the stem shows reaction wood. The differing colors of the rings can be clearly seen in the detailed view. Compression wood can be identified macroscopically due to its red, yellowish and reddish brown color, that appears darker than the normally developed rings (Braam et al. 1987*b*, Sinnott 1952). Wood cell walls in common tree rings consist of cellulose, hemicellulose and lignin. Cellulose forms the skeleton and is surrounded by the other two ma-

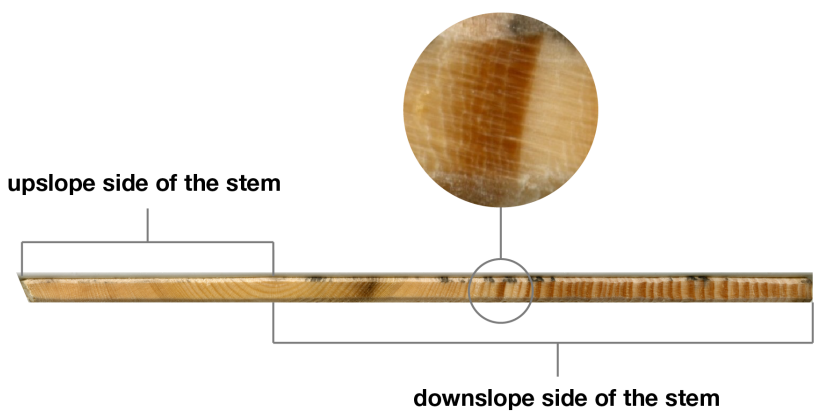

Figure 2.5: The upslope and downslope part of a conifer stem with darker rings showing reaction wood.

terials (Sjöström et al. 1999). The orientation of the cellulose microfibrils that build up the cell wall determines the direction of cell expansion and controls the shape of the cells. The orientation of the microfibrils influences the mechanical properties of the wood (Funada 2008). Microscopically, reaction wood shows a rounded shape of tracheids and thicker cell walls containing more lignin and less cellulose (Braam et al. 1987*b*, Du and Yamamoto 2007). The geometrics of the intracellular spaces due to rounded tracheids improve the physical properties of the wood. Other changes properties are the lack of the innermost S3 layer, an increased microfibril angle that facilitates longitudinal expansion of compression wood cells during the cell maturation process and pressing up the stem (Du and Yamamoto 2007).

Tension wood is not macroscopically visible and develops on the upper side of the downslope leaning stem (Shroder Jr 1980). It can have yellowish or gray color (Braam et al. 1987*a*) or a silvery sheen on the cross sections, but these features can be easily missed (Heinrich and Gärtner 2008). Consequently, the cell structure has to be examined macroscopically for tension wood. Tension wood fibers do have a thick, inner cell wall with a high amount of crystalline cellulose. The microfibril orientation within the layer is nearly parallel to the fiber axis. Moreover, it shows an almost unlignified gelatinous layer. When the cell experiences the maturation process, the fibers of the tension wood shrink and create a tensile stress, that pulls the branch or stem into an upright position (Du and Yamamoto 2007).

Staining of thin sections of the samples can show the tension wood as astra blue and safranin that stain lignin in red and cellulose in blue (Heinrich and Gärtner 2008). Two parts of thin sections of belonging to the same individual of *Fagus sylvatica L.* can be seen in figure 2.6. The downslope part of the stem shows no sign of differing colors, while the sample of the upslope part of the stem appears in blue. In this case the difference can clearly be seen. In other samples, the occurrence of tension wood might just occur in parts of a ring, which can give insight in which period of the growing season the stabilization of the stem took place.

The changes in the annuals rings due to reaction wood and eccentric growth allow the resistance to stem tilting and regulation of the tree's shape (Sinnott 1952, Du and Yamamoto 2007). The following studies dealt with the analysis of growth change and reaction wood: Terasmae (1975), Clague and Souther (1982), (Braam et al. 1987*a*), Braam et al. (1987*b*), Denneler and Schweingruber (1993), Wistuba et al. (2013). Koprowski et al. (2010) found that eccentricity develops a few years before reaction wood for *Pinus sylvestris*. However, the relation between reaction wood and eccentricity is not yet fully understood (Heinrich and Gärtner 2008), although they are

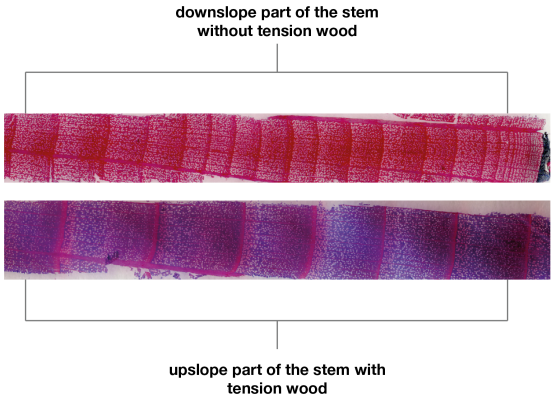

Figure 2.6: Up- and downslope part of *Fagus sylvatica L.* showing tension wood in the upper sample.

closely related to each other (Duncker and Spiecker 2008). It was mostly addressed for the need of forestry or wood anatomy. Duncker and Spiecker (2008) found positive correlations of compression wood and eccentric growth in *Picea abies Karst.*, but also one of each phenomenon occurring without the other one in tree rings. Nevertheless, both factors have been used for the dating of mass movements, as they do occur together and have to be examined in combination for a solid reconstruction of a landslide with tree ring properties.

2.3 Dendrogeomorphology

The term "Dendrogeomorphology" was first defined by Alestalo in the 1970ies as the "analysis of growth reaction of trees affected by geomorphological processes" (Strunk 1997, 138). Fantucci and McCord (1995) however, defined this term as the analysis of geomorphic processes through dendrochronological techniques. These two definitions reflect that the relation of vegetation and geomorphology cannot be viewed from one single perspective, as they represent two components in a system influencing each other. The field of dendrogeomorphology opened up new possibilities to date and reconstruct geomorphological events but also to see how trees react to mechanical stress (Alestalo 1971, Shroder Jr 1980, Schweingruber 1983, Butler 1987, Braam et al. 1987*a*, Williams et al. 1992).

The very first investigation of tilted trees was published by McGee in 1893. He discovered that the inspected trees showed different stem shapes

depending on their age, assuming a geomorphic process as the reason. In the early 19th century Fuller (1912) described different appearances of the trees near the Mississippi river after an earthquake, where younger trees grew upright and older ones where tilted. Further analyses were performed by Shroder (1978), examining tree rings of trees growing on a deposit, Reeder (1979), who correlated tree ring width with seismic data and Jensen (1983), who dated episodic movement on a landslide. More detailed studies were conducted in the 1980ies: Hupp (1984) determined the magnitude and frequency of debris flows and Braam et al. (1987*b*) created an automated method that poses the possibility of examining mass movement variability with ring width. Moreover, the research on tree rings was proceeded in the late 20th century through development of computer programs that provide the option to work with bigger datasets and complex statistical analyses (Braam et al. 1987*a*). This opens up the possibility to extent research on the interdisciplinary field of dendrogeomorphology, what lead to many different processes being covered by various studies until today.

In dendrogeomorphological research, different types of geomorphic processes were analyzed so far. Tumajer and Treml (2013) conducted a detailed meta-analysis of dendrogeomorphological case studies. Processes recorded were avalanches (Casteller et al. 2007, Corona and Stoffel 2010), rockfalls (Stoffel and Perret 2006, Stoffel and Hitz 2008), mudflows (Hupp 1984, Baumann and Kaiser 1999, Gärtner 2003*a*) and debris flows (Santilli and Pelfini 2002, Bollschweiler et al. 2007). Dating of landslides was for example performed by Filion et al. (1991), Jacoby et al. (1992), Denneler and Schweingruber (1993), Fantucci and McCord (1995), Schmid and Schweingruber (1995), Fantucci and Sorriso-Valvo (1999) and Gers et al. (2001). Figure 2.7 shows the distribution of geomorphic processes in dendrogeomorphological studies until 2013 (Tumajer and Treml 2013).

Out of 70 studies analyzed, ten studies were dealing with rockfalls, 21 with debris flows (including 2 about debris floods) and either 17 examining snow avalanches and landslides (including one study on a rockslide). Four of the studies dealt with combinations of processes or addressed various processes. Dating of landslide activity was performed with different methods as examination of burial dates of a tree by landslide masses (Filion et al. 1991), tree age dating of living trees on a landslide (Hupp 1984) or analysis of wood anatomy (Heinrich et al. 2007).

Next to the various geomorphic processes, different species can be used for dendrochronological studies on landslides. Conifers like *Picea abies Karst.* have a high sensitivity towards environmental changes and are widely spread over Europe. Schweingruber (1996) already stated in the 1990ies that all

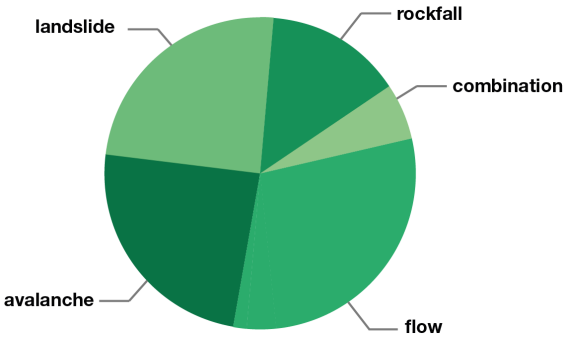

Figure 2.7: Representation of the different geomorphological processes in dendrogeomorphic studies (Tumajer and Treml 2013).

perennial woody plants should be considered for dendrochronological research. As can be seen in figure 2.8, softwood species are well represented in research on gravitative mas movements. *Picea abies Karst.* represents the mostly used species with appearing in 27 out of 69 studies. Looking at the angiosperms, there are more different species integrated, however the hardwood species used most is *Alnus sp.* occurring in seven studies followed by *Betula sp.*. and *Fagus sylvatica L.* with six studies. Within the publications addressing *Betula sp.*, a single study used *Betula pendula Roth.* growing on an avalanche (Casteller et al. 2007). Šilhán et al. (2012) published two studies using *Fagus sylvatica L.* to date rockfalls. The only study on landslides containing *Fagus sylvatica L.* was performed by van den Eeckhaut et al. (2009). It is known that *Fagus sylvatica L.* is suited for dendrochronological studies

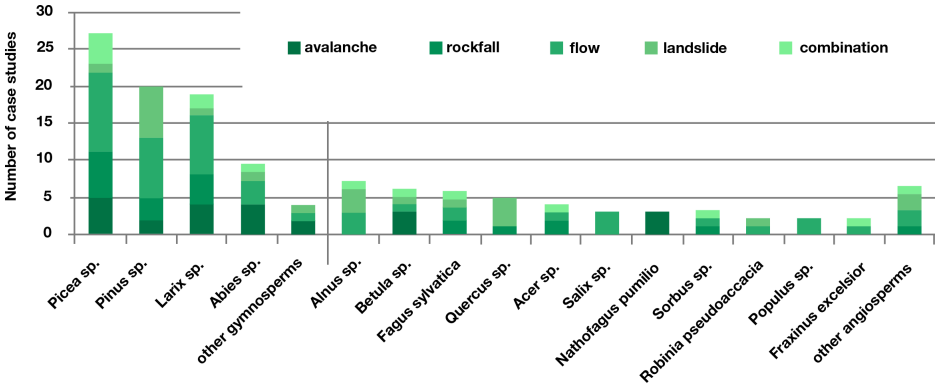

Figure 2.8: Former studies in dendrogeomorphology with species and processes examined (Tumajer and Treml 2013).

(Bonn 1998, Piovesan et al. 2003, Dittmar et al. 2003), even if not being easy crossdate (Biondi 1993, Gerecke 1988). Grundmann et al. (2008) showed, that crossdating is possible even with suppressed trees.

In addition to the challenges hardwood species pose while crossdating, other steps in methodology are more demanding to perform as in the use of softwood species. Gärtner (2007) states that there is a lack of studies dealing with tension wood and explains that the reason could be the difficulty with the identification of tension wood (see chapter 2.2.4). This leads to the need to produce microsections and coloring of the respective, which is a time-consuming process (Gärtner et al. 2015). Nevertheless, new techniques of cutting can provide the opportunity to perform studies on hardwood species with a reduced amount of time needed.

Various dendrogeomorphological studies exist addressing different geomorphic processes with different tree species. Self-evidently, the available tree species on a site determine which type of tree can be used. However, the studies reveal that a more systematic approach could be useful. Comparing the different species regarding their wood properties and reaction to mechanical stress could provide information on their suitability to be integrated in future dendrogeomorphic studies.

Chapter 3

Hypotheses

This study adds on to the aim of the BioSlide project to create a multitemporal landslide inventory for the study area in the Walgau, located in Vorarlberg, Austria. However, it does not only contribute local information to the three sites examined in the study area. The main point is to evaluate whether hardwood species are also suited for reconstructing landslides. Knowledge on the suitability for temporal landslide reconstruction of hardwood species is scarce, as the meta-analysis of Tumajer and Treml (2013) shows. Only two studies use the species *Fagus sylvatica L.* and *Betula pendula Roth.* on landslides and none of them used the more recently developed eccentricity indices of Wistuba et al. (2013). A general question was formulated to address this gap in dendrogeomorphic research:

"Are hardwood species sensitive for reconstructing landslide movements?"

To answer this question, three hypotheses were developed to subdivide the different aspects that are included in the research question. This study aims to reconstruct landslides, so the knowledge on the process is of major interest. In the "Dreiklang", which is the name of the study area, the landslides occurring are shallow mass movements with low velocities. Meaning that an abrupt event of slope failure is not necessarily the case. Former studies of Malik et al. (2016) or Łuszczyńska et al. (2017) showed that the eccentricity index of Wistuba et al. (2013) worked successfully for slow mass movements, deep seated movements and for the detection of activation zones within landslides. To ensure that a comparison between soft- and hardwood species on a shallow landslide is possible, the softwood species *Picea abies Karst.* is analyzed in the first place. Consequently, the first hypothesis was formulated:

I. The calculation of the eccentricity index for Picea abies Karst. identifies activation years on a shallow landslide.

This hypothesis contains several aspects that will be examined to verify or falsify the statement. The first aspect discussed will be whether the events are identified correctly or if they are over- or underestimated with the methods used. The second question emerges from the first one and asks, which factors influence the results. For the following interpretation of the hardwood species' results, it has to be clear if these aspects are affecting their results as well. The last aspect will be to determine, what can be improved in future research within the performed analyses.

As softwood species were already frequently used to reconstruct the temporal pattern of mechanical stress through the onset of eccentricity and reaction wood, the goal is to examine if hardwood species are suited for the reconstruction with the same methods. In chapter 2.2.3 we explained that the wood structure of soft- and hardwood species differs. Nevertheless, hardwood species are known to develop tension wood and consequently eccentric growth of the annual rings. One sampling site provides the possibility of a direct comparison between soft- and hardwood species, so both species will be analyzed with the same methods to see whether trees located next to each other show comparable reactions to mechanical stress in the same years. Therefore, a second hypothesis was developed to answer the main research question:

II. Softwood and hardwood species on the same shallow landslide do show signs of mechanical stress in the same years.

This implies, as in the first hypothesis, three aspects: First, it has to be verified if the hardwood species used, *Fagus sylvatica L.*, can successfully be crossdated (see chapter 5). This step is necessary to date the year of a possible event occurring. Secondly, the development of comparable reactions to mechanical stress, as they are known to occur in *Picea abies Karst.* have to be identified. Otherwise, the same method could not be applied to the different species. The last aspect clarifies if a reconstruction with annual resolution of a mass movement can be performed with the species used.

Furthermore, two locations containing individuals of *Betula pendula Roth.* were examined. One located on a shallow landslide, the other one on a slope, where no mechanical stress is known, but snow pressure. This provides the possibility to compare the reaction in the wood regarding differing external conditions. A major goal in this study, in addition to the evaluation of methods on a new type of landslide and the comparison between one softwood and

one hardwood species, is to examine another hardwood species to achieve more reliable results. As *Betula pendula Roth.* is known to be a pioneer species that is tolerant to extreme conditions (Arbellay et al. 2010), the wood properties and therefore the reaction to mechanical stress potentially differs from *Fagus sylvatica L.*. Eccentric growth and tension wood are known to appear in hardwood species, so *Betula pendula Roth.* will be examined in the same way as the other species to detect their reaction.

III. Betula pendula Roth. shows eccentric growth and tension wood due to mechanical stress induced by a shallow landslide.

To verify this hypothesis, the same three aspects will be discussed as in hypothesis II: The ability to crossdate the species, the occurrence of the expected reactions to mechanical stress and the possibility to reconstruct a mass movement temporally.

The three hypotheses help to cover the questions that arise from the main research aim. Summed up, the first will show if the species known to be suited for the reconstruction of landslides are also qualified to examine the shallow landslides in the "Dreiklang" area. In the second hypothesis, a first step to check the suitability of hardwood species for the tested method is conducted with the comparison of *Picea abies Karst.* and *Fagus sylvatica L.*. Finally, in the last hypothesis another hardwood species is added with *Betula pendula Roth.*, to be compared to the results of *Fagus sylvatica L.*. The sum of these aspects will answer, whether hardwood species are sensitive enough to reconstruct landslides.

Chapter 4

Study Area

The study area is located in Vorarlberg, the most western federal state of Austria. Vorarlberg is divided into four different districts: Bregenz, Dornbirn, Bludenz and Feldkirch. The cores were sampled near Feldkirch, between the communities of Düns, Röns and Schnifis at a latitude of 47.222401 and a longitude of 9.716068. These communities are part of the community districts Dünserberg (80403) and Düns (80402), which form the region Walgau. The area is also known as "Dreiklang" and is located at an altitude of 753m. The extent of the BioSlide study area, where landslides were mapped for the inventory, can be seen in figure 4.1. It extends from a height of 1586m down to 633m. The three sites, where the cores were sampled, lie within the study area and can also be seen in figure 4.1.

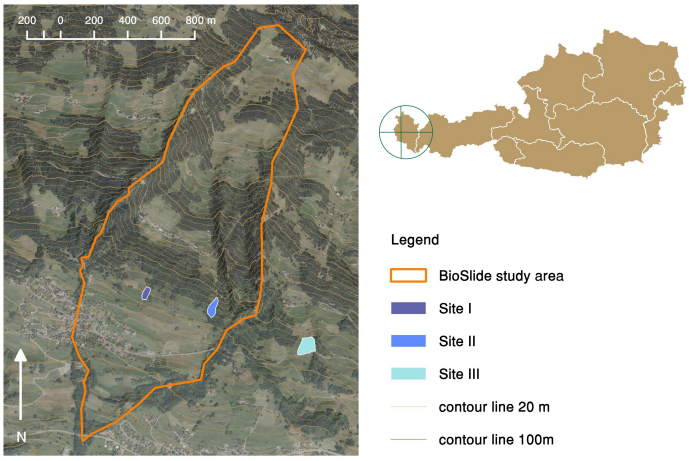

Figure 4.1: Map of the study area in Vorarlberg, Austria with sampling sites I, II and III.

The mean annual temperature in the period between 1961 and 1990 ranged between 8 and 10℃, whereas they are slightly lower in the upper parts of the study area with 7.8℃. Daily rainfall data was available for a period between January 1991 and December 2014. In figure 4.2, the monthly precipitation average can be seen. The most intensive rainfalls occur in the summer period in July with a mean of 200.6 mm. The months May, June, July and August show high means of precipitation as well. In winter, the precipitation average is lower than in summer, but the area experiences intensive snow falls and rain storms (Schmaltz et al. 2017). These climatic conditions contribute to high soil moisture after snow melt in spring and after the months with high precipitation rates in autumn, which favors the occurrence of landsliding processes. Several landslide-triggering rainstorms have been recorded in the area within this period: In Mai 1999 and August 2005, intensive precipitation events have been threatening infrastructure (Markart et al. 2005). Especially the year 1999 showed a short-term rainfall of 251mm and was followed by heavy snow falls in winter (Schmaltz et al. 2017).

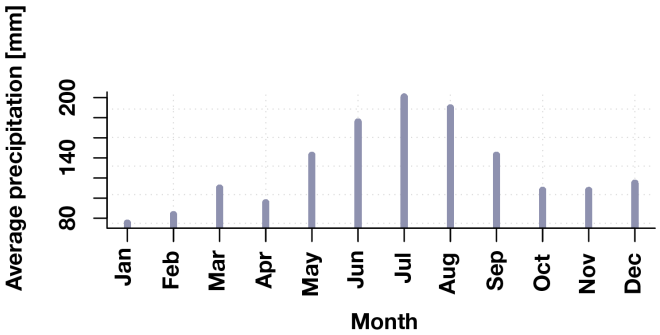

Figure 4.2: Monthly average of precipitation in the study area.

Vorarlberg is located on the geological border between the eastern and western alps. The study area itself lies in the Flysch zone that belongs to the western alps. The material of the Flysch in Vorarlberg are marine sediments that deposited around 200 million years ago. With changing conditions during the deposition processes, like stream velocity or combination of organisms, the composition of the layers in these sediments changes. In the Flysch zone in Vorarlberg, a sediment layer of 3000 m thickness build up, where solid layers of sandstones and softer layers of marl and clay alternate (Walach and Weber 1977, Ruff et al. 2002).

The study area is a south facing hillslope in the quaternary basin of the Walgau. It is formed through the activity of the Ill-glacier that transported gravels, alluvial sediments and morainic deposits towards the alluvial plain

and lower positions of the hillslope (Loacker 1971, De Graaff and Seijmonsbergen 1993, Ruff and Czurda 2008). The facies of the Reiselsberger sandstone, the sandstone of the Plancker Brücke series and the Piesenkopf limestone form the valley margins. The Reiselsberger sandstone contains brown sandstone layers that can reach a thickness of 5 meters and clay which forms hard layers of several centimeters. The sandstones of the Plancker Brücke series are gray sandstones, limestones and solid dark clay sediment stones with a depth of maximal one centimeter. The Piesenkopf series is formed by light colored limestones and dark clay sediment stones with layers of several centimeters. This limestone sequence has hydrophobic properties due to marls, which can lead to the development of creeks. The main creek in this valley developed on the Piesenkopf limestone (Montanastbach, Schluachtobel and Schnifnertobel). The soil in this area is as well influenced by hydrological conditions: the Federal Office for Calibration and Surveying in Austria classifies the soil in this area as Podsol and Semipodsol that shows gleyified units (Scherer and Buhmann 2013). This combination of highly saturated ground due to the complex geological setting and climatic conditions lead to a high potential of landslide activity in the area (Lateltin et al. 1997, Friebe 2004, Ruff and Czurda 2008).

The southern exposed hillslope provides good climatic conditions which allow a high biodiversity in the area. 3% of the area in the subalpine and montane range are covered with coniferous and mixed forests. The species that occur are spruces (*Picea abies Karst.*), firs (*Abies alba Mill.*), scots pines (*Pinus sylvestris L.*), oaks (*Quercus robur L.*) and European beeches (*Fagus sylvatica L.*). In addition, birches (*Betula pendula Roth.*) are mixed within many of the timber stands (Schmaltz et al. 2016).

Especially in the Dreiklang area, landslides where identified as threat for infrastructure (Markart et al. 2005). The population of Düns with 413 inhabitants on an area of 3,45km² (28 Inhabitants per km²) is higher than for Dünserberg with 155 inhabitants on 5,56 km². Even though these communities experienced a growth of population of 76 (Düns) and 27 (Dünserberg) inhabitants in the last decades, the community districts are among the four less populated areas in Vorarlberg (Statistik Austria 2011). The human impact on the landscape can nevertheless not be ignored as the area is used for forestry and agriculture. There are forest free areas that are used for pasture or hay production. In 2010, 14 agricultural or forest operations existed in Düns, from which 40% were executed as main operations. In Dünserberg the number lay at 20 operations from which 35% were carried out as main business showing that the area experienced changes of land use in the past centuries (Schmaltz et al. 2016). The meadows surrounding site I are used

for hay production and cut one to two times a year.

In the study area of the BioSlide project, nine viscous flows, 27 slides/flows and seven planar slides were found (the classification of Crozier (1989) was used in this study). Further, the study provided a detailed process-morphologic overview that contains two of the sites that were used as sampling sites in this study. Figure 4.3A shows the slope of the complete BioSlide study area. The sampling sites are all located in an altitude between 800 and 900m which is indicated with dashed lines in black.

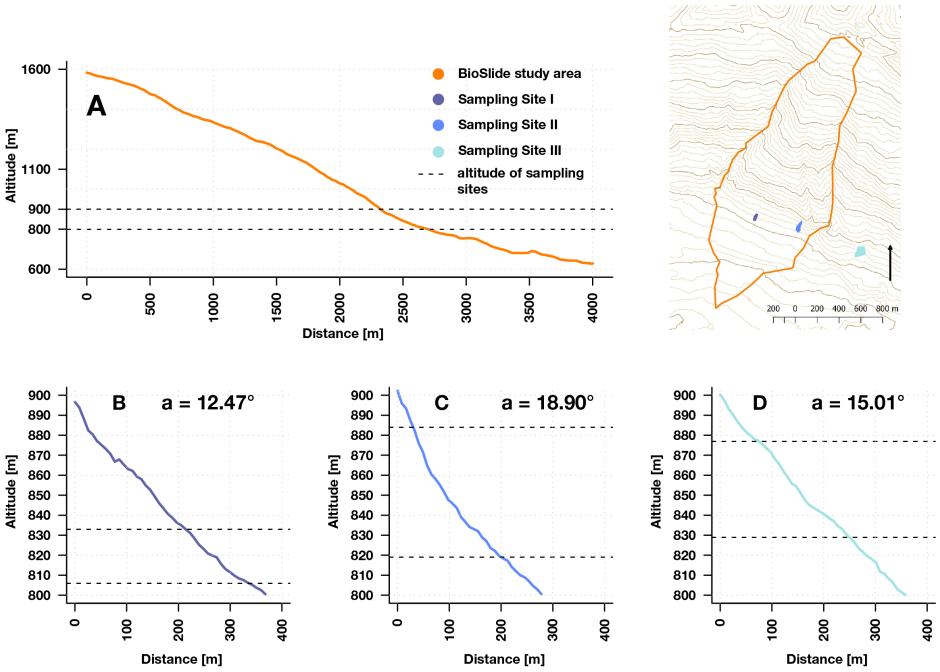

Figure 4.3: A) Profile of the relief in the BioSlide study area, with the altitude of the three sampling sites B) Profile of sampling Site I with an average slope a C) Profile of sampling Site II with an average slope a D) Profile of sampling Site III with an average slope a and the study area as overview with contour lines.

Sampling site I contains a stand of *Betula pendula Roth.* and is located on the mass accumulation zone of the landslide. Above the zone with the accumulated material, a surface flow can be found and, several meter further upslope, the head scarp of the landslide. The sliding process is influenced by the hydrological conditions in the upper part, where the soil is highly saturated with water. The mean slope in degrees is displayed in figure 4.3B with 12.47°. Also the sampling site of the second landslide is located on the

mass accumulation zone. The head scarp is lying 41m above the accumulation area. In this case, no creek was found, but the slope is steeper as in site I, what can be seen in 4.3C. Here, a maximum of 41° was recorded in the upper part of the sampling site. The third site (figure 4.3D) is not on the process-morphological map and also not recorded in the landslide inventory. It was included, because it contains not only trees that show bended stems, but also individuals tilted in different directions. In this location assuming a landslide has to be treated with caution, as bending of the stems could also occur due to snow pressure.

The slope profiles of the different sampling sites give insight to the pressure that the soil can have of the trees (see 2.1). All samples were collected in the lower parts of the sliding areas, as the maximum pressure is expected there. The detailed sampling positions with the number of every sample are presented in chapter 6.

Chapter 5

Methods

To evaluate, whether hardwood species are suited to reconstruct landslides and add temporal information to a spatial inventory, trees were sampled on the mass accumulation zone of two mapped landslides in the inventory created within the BioSlide project. Additional sampling was performed in one site, where tilted trees were found. In figure 5.1, the different steps can be seen in an overview. The sampling criteria was a deformed or tilted stem (a). Moreover, reference trees were collected on a stable slope taking samples on the right and left side of the trees (b). Disturbed trees showing eccentric growth were sampled on the upper and lower side of the slope (c). The cores were prepared (d) and curves created from the ring width for further analyses (e). The detailed description, which methods were used, follows in the sections below.

5.1 Sampling

Sampling of the cores took place during the growing season in March and August 2016. Three species were collected to compare their reaction to mechanical stress: *Picea abies Karst.*, *Fagus sylvatica L.* and *Betula pendula Roth.*. One part of the trees was collected in the three areas were the trees showed signs of experiencing mechanical stress and the other one in reference sites that do not have unstable slopes. These references were collected to reconstruct the growth signal in the study area, which is determined by the climatic conditions, like precipitation, and serves to date the tree rings (Gärtner et al. 2004).

Every tree was photographed and mapped with its location on the study site to compare the reaction of the trees considering their position. Two cores

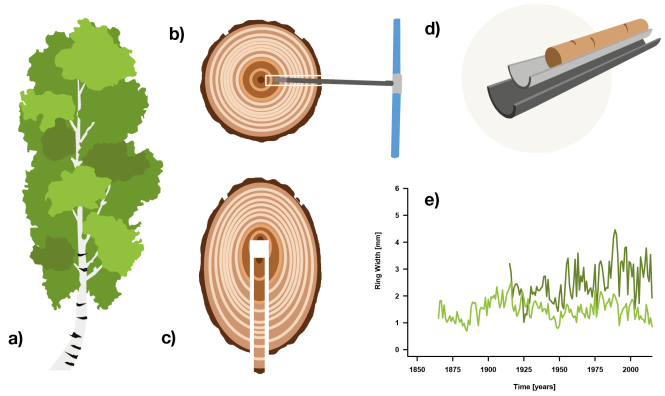

Figure 5.1: The different methodological steps in dendrochronology: a) sampling b) coring direction of the references and c) of the disturbed trees. d) retrieving the cores to measure the rings and e) measured ring width curve.

were taken from each tree with a borer of 5mm diameter. For reference trees on the left and right side parallel to the slope and on the upper and lower side of the slope for disturbed trees. The samples were taken at breast height in a right angle to the stem of the tree as described by Wilmking et al. (2012). In the case of the disturbed trees the height, where the eccentric growth of the stem could externally be seen strongest, was chosen for coring. Usually this part lay within the first meter of the stem above ground.

As mentioned above, reference trees were collected for each species that were growing in undisturbed places not far from the sites that will be examined. Criteria for these were a stable slope, enough space to grow and integrity. To define the needed amount of references, the amount of samples used in other studies was examined. Fantucci and McCord (1995) sampled 28 trees on their landslide site and twelve reference trees. In the study of Carrara and O'Neill (2003) 32 trees were used and Wistuba et al. (2013) collected 36 to 40 trees on their disturbed sites and ten to twelve trees on every reference site. Malik et al. (2016) sampled 70 trees on three landslides and ten references per site, Fantucci and Sorriso-Valvo (1999) collected 14 references. In this study for *Picea abies Karst.* 20 reference trees, for *Fagus sylvatica L.* 15 and *Betula pendula Roth.* 14 trees were sampled, what can be seen in figure 5.2. The number was depended on the availability of suited trees in the area.

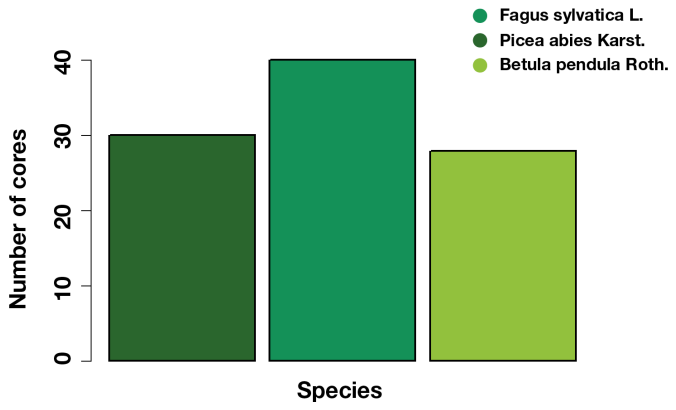

Figure 5.2: Number of reference cores for every sampled species.

Figure 5.3 shows the amount of samples collected in Site I, II and III. In Site I, nine trees of *Betula pendula Roth.* were collected. Site II contained two species, *Picea abies Karst.* and *Fagus sylvatica L.*. Eleven individuals were cored of *Fagus sylvatica L.* and seven of *Picea abies Karst.*. Not all trees of *Picea abies Karst.* available on the site were collected as they were not old enough. In Site III, four cores of *Betula pendula Roth.* were sampled. The detailed spatial distribution of the sampled trees can be seen in chapter 6. After sampling, the cores were stored for further treatment, before being measured.

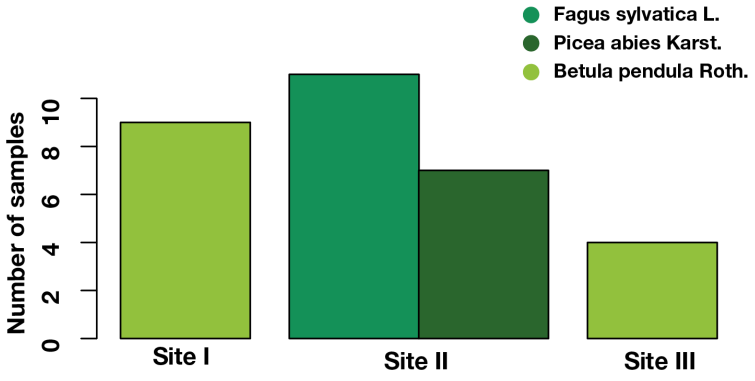

Figure 5.3: Number of disturbed trees sampled in the different sites.

5.2 Preparing the Cores for Analysis

The samples have to be treated for measurement and visual inspection: the reference samples were mounted on wooden holders to stabilize them, whereas the disturbed samples were still left in special boxes to keep opportunity for thin sectioning, if required. As explained in Gärtner (2003*a*), production of thin sections from the samples is not possible anymore after drying, gluing and mounting the cores on wooden holders without breaking. To prepare the surface for better visibility of the rings, the core is moistened in order to avoid breaking and cut with a lab microtome. The orientation of tracheids or vessels has to be upward for this step to achieve best visibility of the cells (Gärtner et al. 2015).

Thin sectioning was performed for the disturbed hardwood trees to identify tension wood as it is not evident through visual inspection of a core (Stefanini 2004). Thin sections of the cores do have several advantages compared to the cores: it is easier to identify narrow rings or anomalies in growth as density fluctuations, due to the more detailed visibility of the cells (Gärtner et al. 2015). Studies on improvement of micro sections have been performed by Gärtner et al. (2015). In Gärtner et al. (2014) it is explained how thin sections from 40 cm length can be produced. In this study both, long and short ($\sim$ 6cm) sections where used, depending on the possibility to produce longer samples. The achievement of producing longer cores improves the process due to easier and secure measurement of the ring width and therefore more reliable results while crossdating. As the amount of work is higher when making thin sections (Gärtner et al. 2015), only the hardwood cores were chosen.

The sections are cut with a microtome in the laboratory (see Gärtner and Nievergelt (2010)). After cutting, the sample has a thickness of 15-20 µm, can easily break into pieces and has therefore to be treated carefully. These sections are then stabilized, moisturized and stained. Staining is performed with Safranin, Astra blue and Ethanol for the dehydration of the sample. Canada balsam and Xylol are used for embedding the sample within two microscope slides (Gärtner et al. 2015).

Common problems detected are a missing core of the sample, bad cutting quality, the low resistance of the tissue to strain, appearance of fissures and cracks or fibers changing orientation. The rings can separate after cutting, sections can be too thick or rings can partly miss. At best, long sections can be produced. When problems occur, shorter sections should be provided. However, the loss of samples is a risk that is included within the production of thin sections.

5.3 Measuring Procedure

Measuring was conducted with two methods for all cores. First, all samples were scanned with a resolution of 2400 dpi and measured with the software CooRecorder. This provides the opportunity to inspect the measurement again and find potential errors while crossdating. Furthermore, the scans serve to examine where reaction wood in conifers appears and provide potential of reanalysis at any time. Yet, this maximum scan resolution could not provide satisfying results for rings smaller than 0.1mm. Especially in sections with heavily reduced growth rates, measurements using the LINTAB™ measuring table and TSAP-Win™ software had to be performed in addition to the ones with the scans. Using both methods ensures the correctness of the measurements, as mistakes can be crucial for further analysis.

5.4 Crossdating

When performing a dendrochronological analysis, a year is linked to every ring. Due to missing rings, very narrow rings or cracks, the ring width curve can, in some cases, be shifted for a year. In addition, competition within the stand or disturbing factors that affect tree growth can cause narrow or wider rings in a single tree. The procedure to check the growth curve for matching periods is called crossdating and has to be performed for every ring width curve of a tree. It was first performed by A.E. Douglass on timbers from archaeological sites and remains a part of every dendrochronological study (Webb 1983). Douglass managed to match the curves from trees that were about 100 miles away from each other and could therefore show that tree growth is related to climatic conditions (Cook and Kairiukstis 2013). Today, several programs can be used to support visual crossdating with statistical methods (CDendro TSAP-Win, COFECHA a.o.) (Holmes 1983, Grissino-Mayer 2001, Maxwell et al. 2011). Nevertheless, the visual inspection of the curve is necessary, as not all statistical tools can identify matching curves without errors in the offset. The first step is to compare the two samples of one tree. If these curves match, they can be compared to other the curves of other trees, to calculate a mean value curve (MVC) for the site. The more correctly dated samples the MVC contains, the stronger the reliability of the dating (Graybill et al. 1982).

Different species have different properties of growth as explained in chapter 2.2, which is also the case for their ability to be crossdated. Grissino-Mayer (1993) developed an crossdating index (CDI) to standardize the po-

tential of different species to be crossdated. This allows to specify whether a species can be crossdated within a site (CDI = 1) or within a whole region (CDI = 2). *Picea abies Karst.* and *Fagus sylvatica L.* are marked with an CDI of 2, but *Betula pendula Roth.* shows a CDI of 1, what can pose a challenge while dating. To ensure that crossdating was performed correctly, the statistical analyses explained in the following section were applied.

5.5 Statistical Analysis

Statistical analysis of the measured curves is an important addition to visual inspection to see, whether the core contains missing rings or mistakes in the measurement. These tools can also help to identify disturbed samples in the reference chronology with growth rates not reflecting the climatic signal of the area. There are many different parameters to check the quality of the chronologies. In this study, three parameters were calculated: The Pearson correlation coefficient as recommended by Baillie and Pilcher (1973), the ttest which is also proposed in the same publication and the "Gleichläufigkeit", which is the percentage of synchrony between the curves.

5.5.1 Correlation

To test if the samples were correctly crossdated, correlation and ttest are analyzed for the chronologies. As missing or partly missing rings can occur and manipulate the growth pattern, these analyses are important to help obtaining the right results for the ring width sequence. The results have to be checked carefully, as there is just one correct pattern of the ring width to measure. Programs as CDendro support the analysis with the correlation of manually defined blocks, but in the end the correlation of the whole sample will be calculated as quality check for the chronology. Baillie and Pilcher (1973) propose Pearsons product-moment correlation coefficient, as do programs like CDendro and the dplR package for dendrochronological analyses in R. Formula 5.1 shows the coefficient which is calculated. A value of +1 signalizes a very high correlation, whereas 0 represents no correlation and -1 perfect negative correlation. The correlation between two samples growing under the same conditions should be positively high (Baillie and Pilcher 1973). In addition, the Student's ttest should be calculated with the number of years that overlap. The calculation of the ttest is shown in formula 5.2. For the application of the product-moment-correlation coefficient the data has to be checked for normal distribution, which was conducted with the Shapiro-

Wilk-test. In this case, the regional curve standardization was applied with CDendro, which is proposed by Biondi and Qeadan (2008) and Bunn et al. (2017).

Pearson correlation coefficient:

$$r = \frac{cov(X,Y)}{\sigma_x \sigma_y} \qquad \begin{aligned} r &= correlation\ coefficient \\ cov &= covariance \\ \sigma_x &= standard\ deviation\ of\ x \\ \sigma_y &= standard\ deviation\ of\ y \end{aligned} \tag{5.1}$$

ttest:

$$t = \frac{r\sqrt{N-2}}{\sqrt{1-r^2}} \qquad N = overlap\ between\ the\ samples\ [years] \tag{5.2}$$

Depending on the length of the sample, the exclusive use of correlation values can have its weaknesses. If the CDI for a species is higher than one, crossdating should be possible. As then the trees follow the same growth trends, increasing and decreasing ring width of different trees form the same pattern. To have an additional statistical analysis of the synchrony of two curves, the Gleichläufigkeit was calculated.

5.5.2 Gleichläufigkeit

For the analysis of a dendrochronological time series the trend of every year is important for crossdating and for the identification of eccentric growth. Therefore, the Gleichläufigkeit (GLK) represents a useful tool. Does the ring width of two samples or trees increase or decrease in the same year, the growth curve is synchronous. Years showing the same growth trend will be marked with a positive value, the ones that do not have the same trend, with a negative one. From the amount of years that show synchronous trends, a percentage is calculated (Bunn 2010). An example is given in 5.4. Two curves of a *Picea abies Karst.* reference can be seen that show a GLK of 0.80. With few exceptions, the curves are following the same growth pattern.

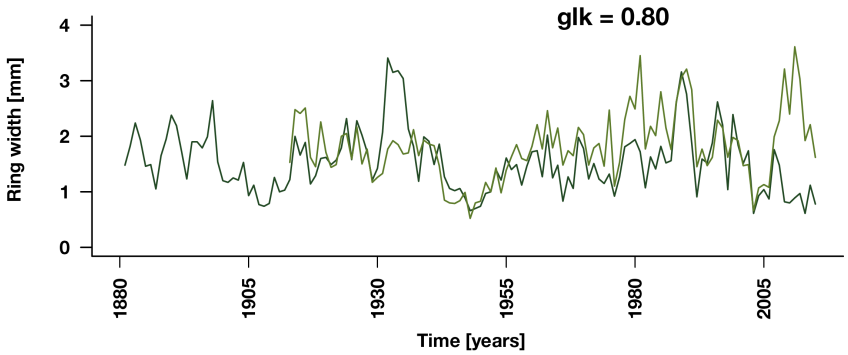

Figure 5.4: High value of Gleichläufigkeit for a *Picea abies Karst.*sample.

5.6 Temporal Reconstruction of Mechanical Stress

The reconstruction of mechanical stress in trees takes place with the evaluation of growth patterns and the identification of reaction wood. A time series can be created from a site, that cumulates all events dated to identify periods of activity within the gravitative mass movement.

5.6.1 Event Identification

Several studies reconstructed landslides with retrieving years that indicate an onset of mechanical stress. Spatial or temporal patterns were reconstructed (Šilhán et al. 2016, Łuszczyńska et al. 2017) using the appearance of properties that change (Šilhán 2017). In this study, two approaches will be used to determine onsets of mechanical stress in the trees. First, the onset of eccentric growth will be identified visually and marked. This approach, where an event is marked by differing growth trends of the up- and downslope ring width, was used in former studies (Wiktorowski et al. 2017). The specific years will be checked within the wood samples, as local growth anomalies like scars or branches can also cause eccentric growth. If the year was confirmed for eccentric growth with no anomalies, it will be checked for reaction wood. Experiments conducted by Heinrich et al. (2007) showed, that wood anatomical information should be included in modern dendrochronological analyses next to tree ring analysis. As these results in this study follow a rather qualitative approach, additional quantification will be achieved with the calculation of the eccentricity index after Wistuba et al. (2013) presented in chapter 2.2.4. The visual identification of onset of eccentricity is here used as a quality check for the eccentricity index.

5.6.2 Verification of Events

As one goal is to examine whether soft- and hardwood species are both suited for the reconstruction of mass movements, the identified events have to be certain. Therefore, not only the application of the two methods for event identification are compared, but also the record of events of both methods with the precipitation data that is available from January 1991 to January 2015. As shallow landslides are likely to be triggered by longer periods of precipitation or extreme events, the records with events can be compared. Daily data of four weather stations in Frastanz, Thüringen, Thüringerberg and Laterns was available. The daily data is summed up to monthly data to determine and classify months with outliers in precipitation in mm. The threshold for outliers was defined as the 3rd quantile times 1.5 as it is used in standard boxplots. As the data is available monthly, it has to be processed before being compared to the events shown by the two methods in the trees. Landslide events that occur during the growth season are recorded immediately in the wood, but if the stress occurs while the tree is in the dormant period, the reaction will be visible in the year after. Therefore, extreme rainfall events that are recorded between March and September are added to the current year and events between October and February will be added to the following year.

Chapter 6

Results

Three species were sampled to compare the suitability of soft- and hardwood species for reconstructing landslides. Next to the samples on the disturbed sites, references are analyzed for proper dating. Afterwards, potential events will be identified within the trees growing on instable slopes. The structure of this chapter on the results of the study is given by the hypotheses formulated in chapter 3. Therefore, the sampled trees of *Picea abies Karst.* on site II are checked for consistency with the used methods after the analysis of the references. We consequently proceed to the results that will answer hypothesis II, where *Picea abies Karst.* and *Fagus sylvatica L.* will be compared. Afterwards, the information retrieved from the two sites of *Betula pendula Roth.* will be analyzed and in the end the extreme events of precipitation are presented. The identification of years with extreme precipitation events serves to validate if the mass movement periods shown by the trees are reasonable in chapter 7.

6.1 Reference Chronologies

The first step in dendrochronological studies is the creation of a reliable reference chronology for every species to date the disturbed trees and thereby the events. Further, reference thresholds determined from the yearly variation from the eccentricity index in percent (in the following: reference threshold) were calculated to identify rings that show remarkable eccentricity. In this section, the results of these analyses are presented.

6.1.1 *Picea abies Karst.*

In total, 40 samples of *Picea abies Karst.* were collected in two different sites on a stable slope. The samples were crossdated, meaning that potential offsets or missing rings were identified and inserted. Anomalies in growth, as rotten wood or sequences of very narrow rings were found in the reference samples, so measurements were conducted twice, with CooRecorder and TSAP-Win™. Both methods showed advantages: The datasets of the scans could be saved and checked afterwards, but the resolution of 2400dpi was still not high enough for rings smaller than 0.1mm, that occurred in the samples. In this case, the use of the binocular to compare the measurements and to check rings for potential density fluctuations proved to be useful.

The measurements (see figure 6.1) show that the age of the *Picea abies Karst.* trees in the two reference sites differs: the maximum age for the first site shows a range between 20 and 35 years, whereas the trees in the second site turn out to be older with sample lengths between 101 and 168 years. This can be seen in the jump at the sample depth, displayed in figure 6.1, between 1980 and 1990. Missing rings had to be inserted in six trees, especially in the sequences with narrow rings. After crossdating, correlations of all trees were calculated and trees that did not show satisfying results were removed from the chronology. Due to the disturbed patterns, some of the trees show, a threshold for elimination of $r < 0.3$ and a ttest < 2.0 was defined. As a consequence of this analysis, four samples of *Picea abies Karst.* had to be removed, because they were not old enough (< 20 years) and additional two samples could not be crossdated properly. The maximum result for correlation towards the rest of the chronology is 0.73 and the maximum ttest value 11.4. Minimum values lay at the chosen threshold of correlation coefficient and ttest. After the elimination of these samples, an inter series correlation of 0.49 could be achieved.

From the ring width data of every series a mean value chronology (MVC) was calculated. It represents the growth trends in the study area for the concerning species and is important for the dating of trees showing mechanical stress. During a trees life, the growth of a tree decreases gradually, which can be seen in figure 6.1 a) from 1850 until 1975. The curve increases again from 1975, which is related to the increased sample depth in this period. As the trees from the first reference site are younger, they develop wider rings and influence the mean ring width in the reference curve. To deal with this issue, the raw tree ring width data is detrended. For the growth trend, a linear function could be sufficient, but a spline was used here to deal with the increased sample depth. The result of the detrended series can be seen in

Figure 6.1 part b). The trend is removed, which provides the opportunity to crossdate the disturbed samples.

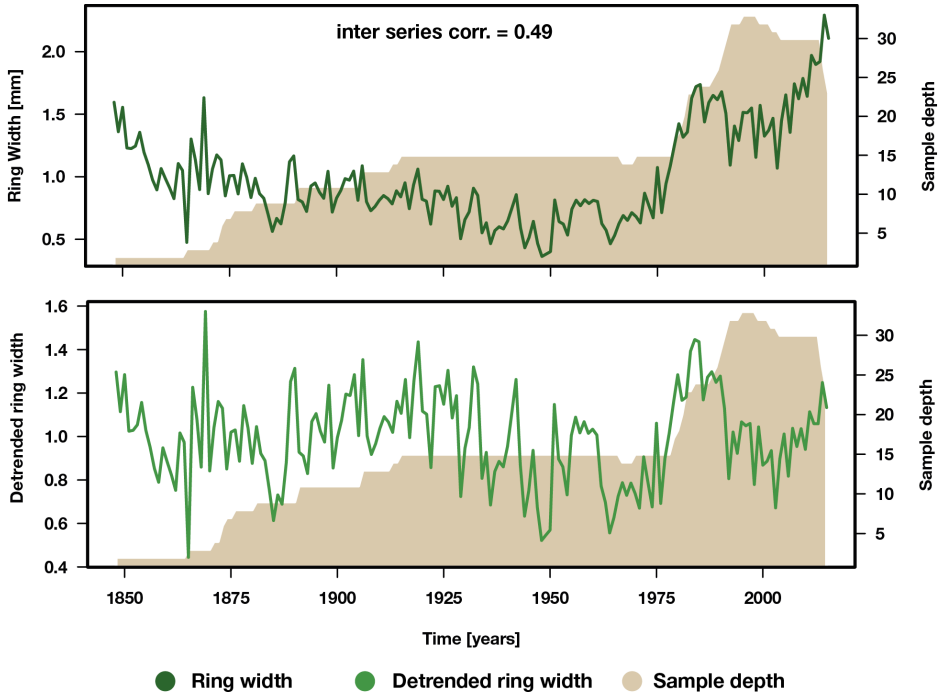

Figure 6.1: Sample depth and mean value chronology before (a) and after (b) detrending of the *Picea abies Karst.* references.

6.1.2 *Fagus sylvatica L.*

30 samples of *Fagus sylvatica L.* were collected in one reference site. As for *Picea abies Karst.*, the samples were measured and crossdated. Eight samples showed missing rings with a maximum of five in one tree, but could still be crossdated to calculate a MVC, which is displayed in figure 6.2 a). Also in this species and site, sequences of narrow rings occurred. The quality control of crossdating was carried out with the Pearson correlation coefficient, ttest and Gleichläufigkeit with the same criteria for the removal of samples as in *Picea abies Karst.*.

Correlations reached from 0,27 to 0,63 and ttest results from 2.0 to 7.5. One sample could not be crossdated and was removed. After the data cleansing, an inter series correlation of 0.46 was achieved.

In Figure 6.2, the raw ring width chronology can be seen in part a) and

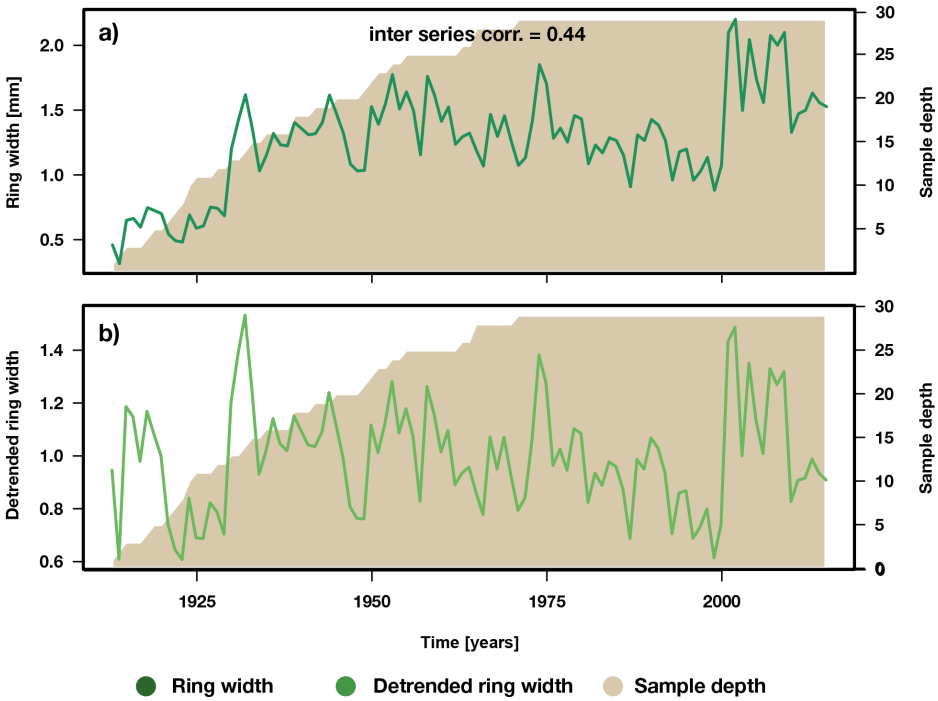

Figure 6.2: Sample depth and mean value chronology before (a) and after (b) detrending of the *Fagus sylvatica L.* reference

the detrended one in part b). Looking at the MVC that is not yet detrended, sudden growth increases can be seen in 1931, 1974 and 2001. Five samples showed the increase both in 1932 and 1974. In 2001, 13 individuals displayed abruptly increasing growth rates. The chronology was detrended for the crossdating of disturbed samples, nevertheless attention must be payed to growth increases, as pointer years can be a useful addition to date a tree ring series or to interpret growth increases in disturbed samples that are not related to the stabilization of the individual.

6.1.3 *Betula pendula Roth.*

In total, another 30 samples were collected for the reference chronology of *Betula pendula Roth.*. The age of the samples turned out to range between 16 and 70 years. Before dating, six samples had to be removed, because they did not have enough rings to be properly crossdated. After crossdating, four more samples had to be removed due to bad correlation values. This sorting process lead to a total of 20 samples building up the final reference

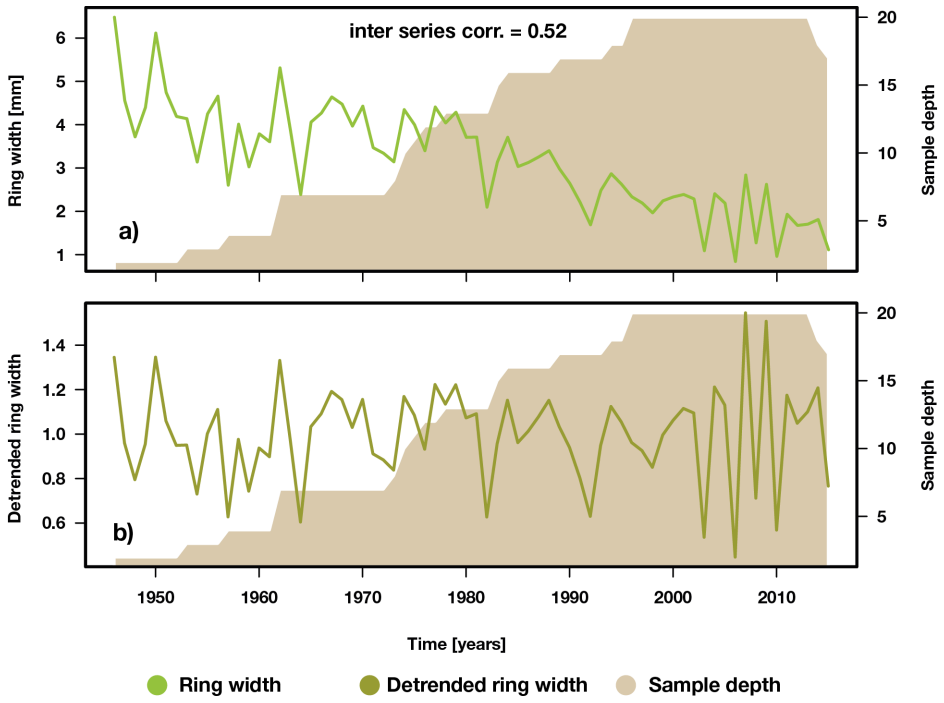

Figure 6.3: Sample depth and mean value chronology before (a) and after (b) detrending of the *Betula pendula Roth.*reference.

chronology. In five trees missing rings occurred that had to be added. After this procedure, correlation values between 0.29 and 0.74 and ttest values between 2.0 and 7.5 were achieved. The mean inter series correlation is higher than for *Picea abies Karst.* and *Fagus sylvatica L.* with a value of 0.52.

As can be seen in figure 6.3, the chronology shows a decreasing growth trend with increasing age. It was removed with a spline as in the other chronologies.

The three chronologies differ in length and sample depth. The reference chronology of *Picea abies Karst.* goes back to 1849 and is the longest one, followed by *Fagus sylvatica L.* that extents back to 1913. The reference chronology of *Betula pendula Roth.* is the shortest and goes back to 1946. Also, the sample depth differs: most samples could be used for *Picea abies Karst.* (34 samples) and *Fagus sylvatica L.* (29 samples). The highest number of samples had to be sorted out for *Betula pendula Roth.*, what lead to a decreased sample depth of maximum 20 trees in one part of the chronology. To compare the reaction of the disturbed trees, the mean ring width was calculated from the references, which are shown in table 6.1. *Betula pendula*

Roth. shows the widest rings with a mean of 2.85mm. *Picea abies Karst.* displays a mean ring width of 1.60 and a high variance of 0.76mm, while *Fagus sylvatica L.* has the lowest mean ring width and the lowest variance.

Table 6.1: Mean ring width and variance of the reference samples

	Picea abies Karst.	*Fagus sylvatica L.*	*Betula pendula Roth.*
Mean ring width [mm]	1.60	1.42	2.85
Variance [mm]	0.76	0.26	0.63

6.2 Reference Threshold

For the analysis of the disturbed samples, the threshold of eccentricity for the references was analyzed in advance. The rings showing values above or below the positive or negative reference threshold in the disturbed trees will be considered as events. For every reference tree, in which both samples could be crossdated successfully, the indices were calculated.

The calculated difference of the upslope and downslope sample shows the side of tilting within a tree. To examine how the reaction of soft- and hardwood species differs, the percentage of rings dominant on the upper and lower side of the slope will be calculated for the disturbed samples. The same procedure is performed for the reference trees, to avoid misinterpretation. The results can be seen in table 6.2. Eccentric growth is evenly distributed in *Picea abies Karst.* and *Fagus sylvatica L.* on both sides in the reference sites. The results show further, that concentric growth in tree rings is extremely rare. For *Betula pendula Roth.* the distribution is slightly different with a ratio of 39.76 to 60.23%.

Table 6.2: Percentage of rings showing eccentricity on the left/right side of the stem or concentric growth of the reference trees

	Picea abies Karst. [%]	*Fagus sylvatica L.* [%]	*Betula pendula Roth.* [%]
Right	51.45	47.76	39.76
Concentric	1.10	1.39	0
Left	47.44	50.84	60.23

The figures 6.4, 6.5 and 6.6 show the range of the variability of eccentricity in percent (vEix[%]). As can be seen in figure 6.4, sample RP16 (Reference *Picea abies Karst.* number 16) has outliers in both directions, that exceed the outliers of the other samples substantially (maximum range between outliers in other trees: 100-100% and in RF16 200 to - 142.2%). Therefore, the sample was not used for the calculation of the reference threshold as its calculation is strongly affected by outliers. After the data cleansing, the threshold was calculated from 14 trees with a maximum of 57.74 % and a minimum of -55.65%.

The threshold for *Fagus sylvatica L.* could be calculated out of 14 sample pairs. Three trees showed values that exceed 100% or -100% but were not removed, as there was more than one tree that showed these outliers. The median varies around zero and the upper and lower Whisker from 25 to -20%. Compared to *Picea abies Karst.*, the variation of vEix[%] shows more outliers above 50% and below -50%. The mean was calculated and reached 70.79% to -71.87% which is a larger range than in *Picea abies Karst.*.

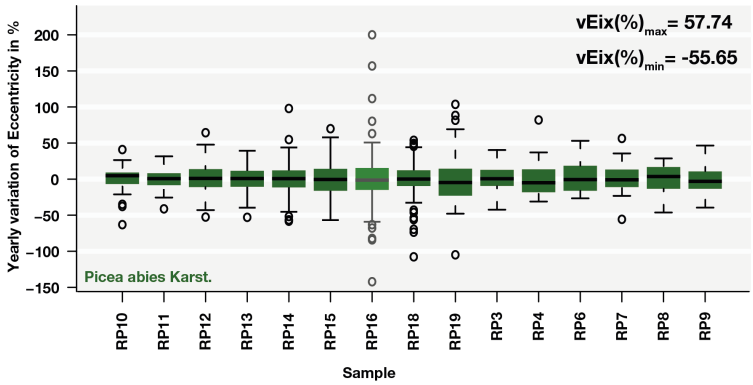

Figure 6.4: Boxplot with the calculated reference threshold from the variation of eccentricity in percent for *Picea abies Karst.*.

The sample number of *Betula pendula Roth.* was lower with 20 samples suited for crossdating than for the other two species and only seven pairs could be used for the calculation of the eccentricity. Two trees showed outliers above 150% and two other ones below -100%. Nevertheless, they were used, as the sample depth would not be sufficient to obtain a representative threshold. As for the other species, the median is at zero (+-3%). Upper and lower Whisker lies within the range of 100 and -100% for all samples. Compared to the other two species, the range of mean variation of eccentricity is high: The positive value indicating upslope eccentricity lies at 112.30% and the negative value at -98.13.

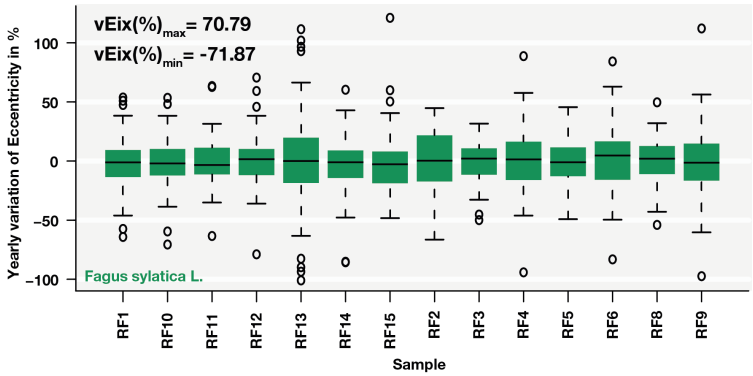

Figure 6.5: Boxplot with the calculated reference threshold from the variation of eccentricity in percent for *Fagus sylvatica L.*.

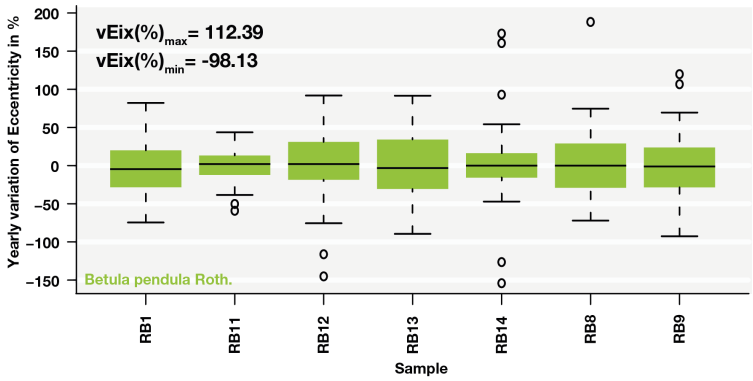

Figure 6.6: Boxplot with the calculated reference threshold from the variation of eccentricity in percent for *Betula pendula Roth.*.

The calculation of the reference threshold displays different results for the species. *Picea abies Karst.* showed the smallest range with values from 57.74 to -55.65%. Higher values were calculated for *Fagus sylvatica L.* with a range of 70.79 to -71.87%. The largest range was calculated for *Betula pendula Roth.* with 112.39 to -71.13%. Equivalent to the reference chronologies, the sample depth differs. As only the trees that could be crossdated are used and for the calculation of vEix[%] two samples of a tree have to be available, the amount of samples decreased. The influence of this factor will be discussed in chapter 7. To avoid that the decreased amount of samples causes a higher range of reference threshold and therefore underestimates the number of events, another threshold of 50 to -50% was used for every species. These variations are therefore also marked and will be discussed.

6.3 Event Identification

The identification of events takes place with a combination of different methods. A first step is the visual examination of the curves: The upslope and downslope samples are crossdated, first within themselves and then with the reference chronology. This can be a difficult task, as the trees are disturbed and the signal of the geomorphic events can overlie the climatic signal used for crossdating. Dating can be performed with segments of the sample that show no disturbances. As a consequence, the correlation values of the whole samples are not used in this section to describe crossdating.

The onset of an event can be identified by eccentric growth. When mechanical stress occurs, the tree will stabilize and thicker rings containing reaction wood form on one side of the tree, depending on tilting direction and species. As this reaction takes place immediately, the onset of eccentricity is dated as the event. In the following figures, these visually identified events are marked in section A of the figure with red circles and the year of occurrence. In section B, the eccentricity index calculated from the difference between the upslope and downslope sample is displayed and in section C the same in percentage. In the last section (marked with D), the variation of the eccentricity index in percent compared to the previous year is displayed in a barplot. If the variation exceeds the eccentricity threshold of the corresponding species, the bars appear in dark red for upslope eccentricity and in dark blue for downslope eccentricity. In the same colors, but lighter, the variation exceeding 50% or -50% is added, as the threshold of *Fagus sylvatica L.* and *Betula pendula Roth.* is high compared to values found in former studies. Still, the calculated threshold is used, as hardwood species were not examined in former studies. The occurrence of reaction wood was checked visually for the years that show eccentricity or anomalies, as they can give insight whether the onset of eccentricity can be related to mechanical stress or other factors as scars.

6.3.1 Site II - *Picea abies Karst.*

Site II is a mixed stand of *Picea abies Karst.* and *Fagus sylvatica L.*. The exact location of the individuals on the landslide body can be seen in figure 6.7. The tree species are evenly distributed, which provides the possibility of examination whether soft- and hardwood species show the same events. First, four trees of *Picea abies Karst.* and two trees of *Fagus sylvatica L.* are described in detail, then the events that were calculated with the variation of the eccentricity index in percent (vEix[%]) are compared to the visual

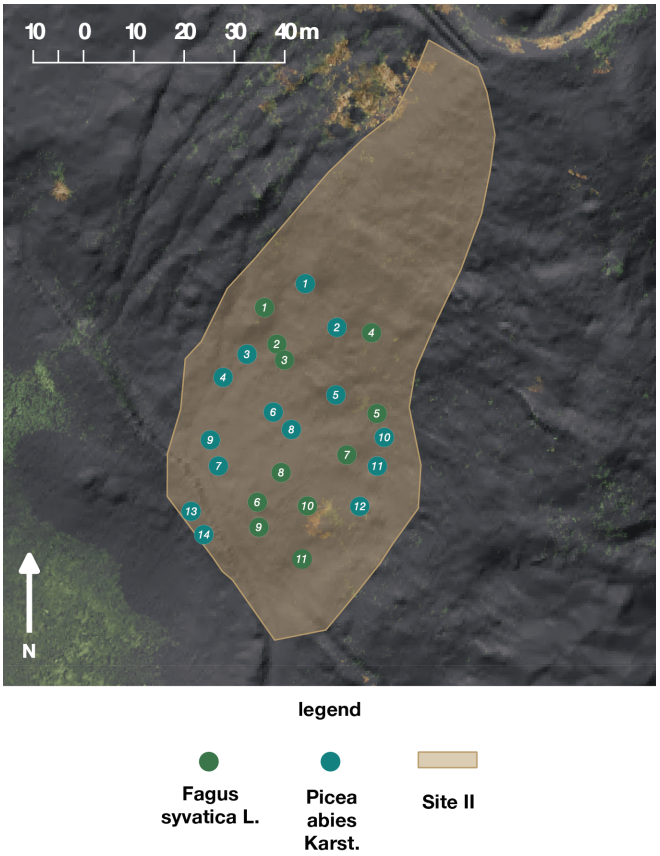

Figure 6.7: Location of sampled *Picea abies Karst.* and *Fagus sylvatica L.* individuals in site II.

examination of the events. That takes into account the properties of the sample as very narrow rings or reaction wood. Then, every species is checked for the consistency of results in the same years before comparing the two species and answering the hypotheses. From eleven individuals of *Picea abies Karst.*, eight could be used for the analysis of the events. For *Fagus sylvatica L.* eleven trees were sampled and seven could be used. Thin sections of three of them were available for the examination of tension wood. Cores that were not long enough or too disturbed to be crossdated could not be included in further analyses. With the intention to still see the location of the specific tree and their distribution on the landslide, the sample numbers were not changed.

***Picea abies Karst.* 02** Located in the upper part of the sampling area, the two samples have an overlap of 70 years, from 1945 to 2015. The Pearson correlation coefficient between the two samples is 0.51 with a ttest value of 4.8. The samples could be crossdated through good correlation values in the beginning and end of the curves (e.g. period 2015-1980 - CorrC 0.70).
The ring width curves (see figure 6.8) show increased growth of rings on the downslope side in almost every year. The only exception is also the first onset of eccentric growth in the year 1957, where the width of the upper ring is abruptly increasing. The stronger growth of the upslope ring does not last for more than one year and the downslope ring width is wider than downslope for the rest of the core. The detailed view on the downslope sample below the ring width curve shows reaction wood in the year 1956 and a canal of resin ducts in the beginning of the early wood of the year 1957. The same ring of the upslope core shows no anomalies. The difference in width is high with 2.3 mm (upslope) and 1.7 mm (downslope).
Three more rings do show eccentric growth: 1968, 1976 and 1995. In 1968, the downslope sample contains reaction wood and is followed by another ring with strong annual growth. The rings of 1976 and 1977 of the same sample show sudden growth decreases and no reaction wood, which can also be seen in the years 1995 and 1996. Before, a period of strong reaction wood can be found from 1988 until 1994.

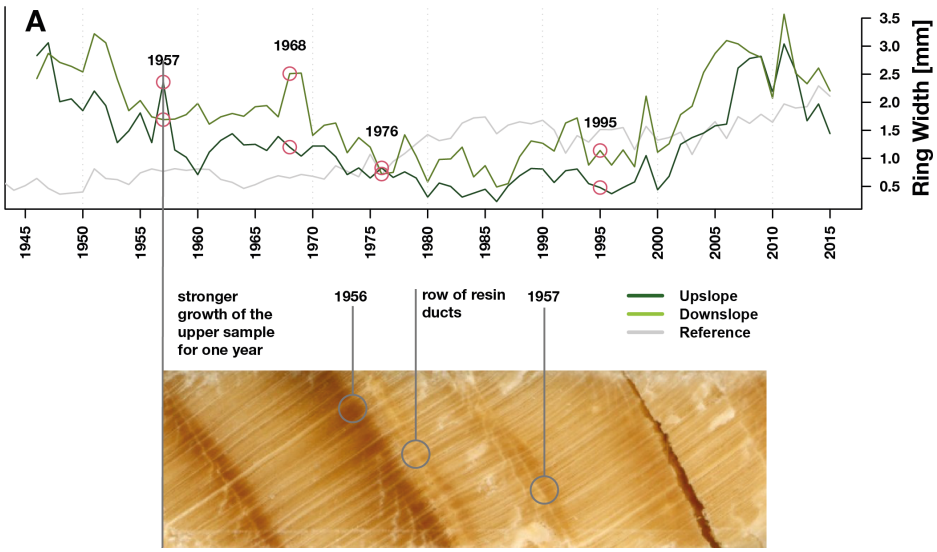

Figure 6.8: *Picea abies Karst.* 02 - ring width and detailed view on the year 1957.

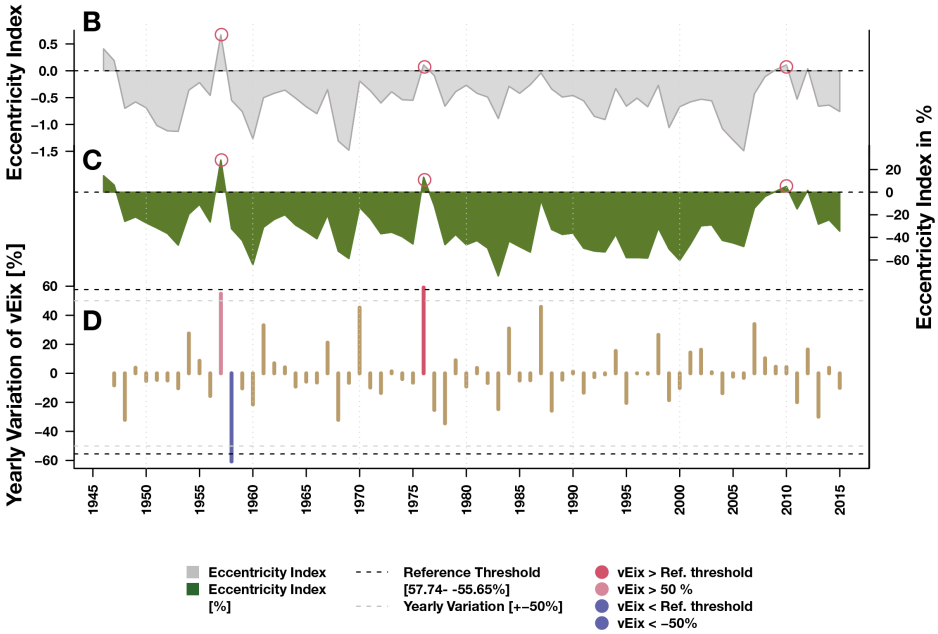

Figure 6.9: *Picea abies Karst.* 02 - eccentricity index (B), eccentricity index in percent (C) and yearly variation of the eccentricity index in percent vEix[%] (D).

Figure 6.9 shows the three different indices calculated. Section B and C show eccentric growth on the downslope side of the stem in most years. In 1957, 1976 and 2010 the tree is slightly tilted on the upslope side. Looking at the variation of eccentricity in percent, the years of 1968 and 1995 (marked in the raw ring width) do not exceed the reference threshold and are therefore not automatically marked as events.

In addition to the analysis of potential events, the general form of the growth curve has to be taken into account. Growth decreases as expected with increasing age, but then increases again from the year 2000 for both sides of the tree. The width of the rings in this stadium do even exceed the ones in the beginning of the trees life.

***Picea abies Karst.* 03** Crossdating for trees that show disturbances as this individual remains a challenge. Still, the tree could be dated to 2015 due to its less disturbed periods. Downslope eccentricity is dominating through most of the period that was recorded by these samples. Both samples go

back until 1882 but differ in length as can be seen in figure 6.10 a) and b) that show the core of *Picea abies Karst.* 03. As can be seen in section A and in the calculation of the eccentricity index in section B of figure 6.11, the rings on the downslope side are wider in almost every year. This causes the different lengths of the upslope and downslope sample. Several onsets of eccentricity can be identified in the curves of the two samples. The first one occurs in 1906, where preceding years show already a slight increase of growth in the downslope sample, but increment increases abruptly in the following year. In 1907, a growth difference of 2.57 mm can be recorded. The strong difference between the two samples varies, but lasts until 1932. In this year, both sides of the tree form almost the same ring widths again, but in 1933 and 1935 eccentric growth marks the beginning of stronger growth of the downslope part of the stem. Looking at the sample of the downslope part of the tree, an onset of compression wood can be seen. Two years later, in 1935, the reaction wood occurs more intense. The same can be seen for the year 1951. The downslope rings grow wider than the opposite ones from 1948, but eccentricity starts in 1951. Compression wood can be seen after the year 1951. The same phenomenon occurs in 1967. 1977, on the other hand, shows another case: s zoomed view (figure 6.10 c)) was used here to visualize the structure showing increased growth on the upslope part of the stem. Here, the rings show deformation and sudden increased width. The rings following these structures are still compressed, but no reaction wood can be seen. Years that shows anomalies like this, were not taken into account for events, as more samples would have been needed to identify the reason for this growth pattern. In 1994, a series of narrow rings appears, reaction can be seen, but not more intense than in the years before. After 1994, the stronger growth of the downslope part increases gradually again.

The eccentricity index shows stronger growth of the downslope side and periods, where this circumstance is not that intense. The variation of the eccentricity in percent shows years that exceed the reference threshold in 1909. In this year eccentricity occurs, but it is not the onset of eccentric growth, which occurs three years before in 1906. 1906 can be seen in vEix[%], but does not exceed the reference threshold. Further, 1934 and 1935 are years that are marked in section D of figure 6.11. As in the previous case, onset of eccentricity can be seen in 1933 in section A, but the threshold is only exceeded by the following years. Compression wood can already be seen in 1933, but it appears more intense in 1935. The years 1951 and 1967 do not appear as events in vEix[%]. In contrary 1977 can be found, same as years of eccentric growth in 1994 and 1999.

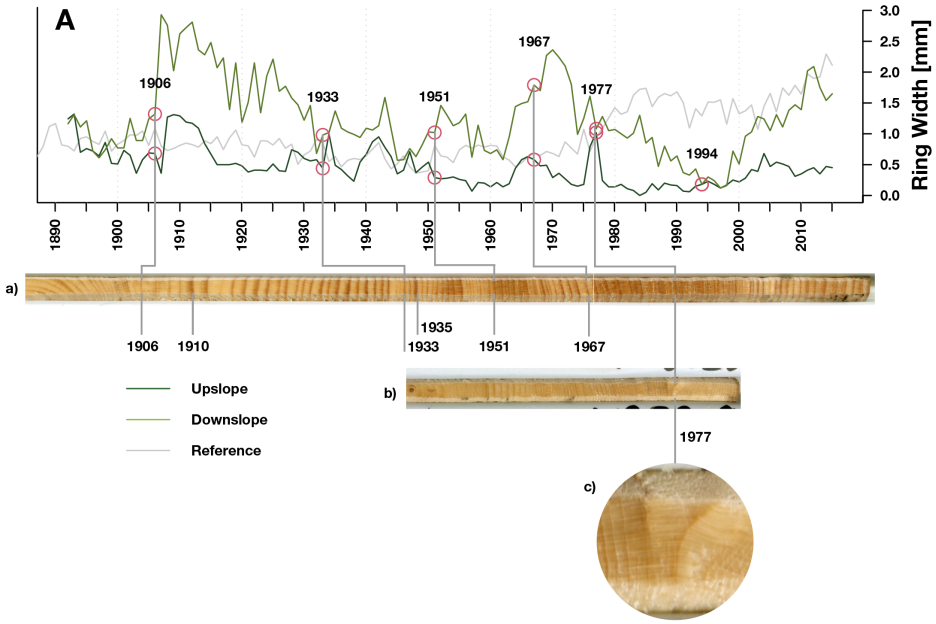

Figure 6.10: *Picea abies Karst.* 03 - ring width and sample details.

This tree shows signs of mechanical stress in several periods. The wider width of the rings on the downslope side indicates, that the tree stabilized since the early 20th century. Reaction wood can be found that matches periods after the onset of eccentricity, but does not occur in the same year. Onsets of eccentricity and calculation of vEix[%] do not show exactly the same results, but indicate approximately the right years. Two onsets of eccentricity are not displayed (1951 and 1967) and one has to be rejected, as the anomaly in the wood cannot be interpreted correctly (1977).

***Picea abies Karst.* 07** This tree, located in the mid part of the sampling area (see figure 6.7) shows a correlation value of 0,66 and a ttest value of 8,6 within its two samples. It could be crossdated towards the reference chronology successfully. The two samples have an overlap of 97 years, starting in 1918 and ending in 2015. The growth pattern of the two samples can be seen in figure 6.12. Three different stages can be defined: In the first period from 1919 to 1934, three rings show eccentricity in the years 1925, 1931 and 1934. In 1925, the width of the downslope sample increases, what indicates a downslope tilting of the tree. In 1931 the direction changes, as it does in 1934. Then a period from 1935 to 1967 follows, where ring width decreases on both sides of the stem and follows the same trends. From 1968 until the

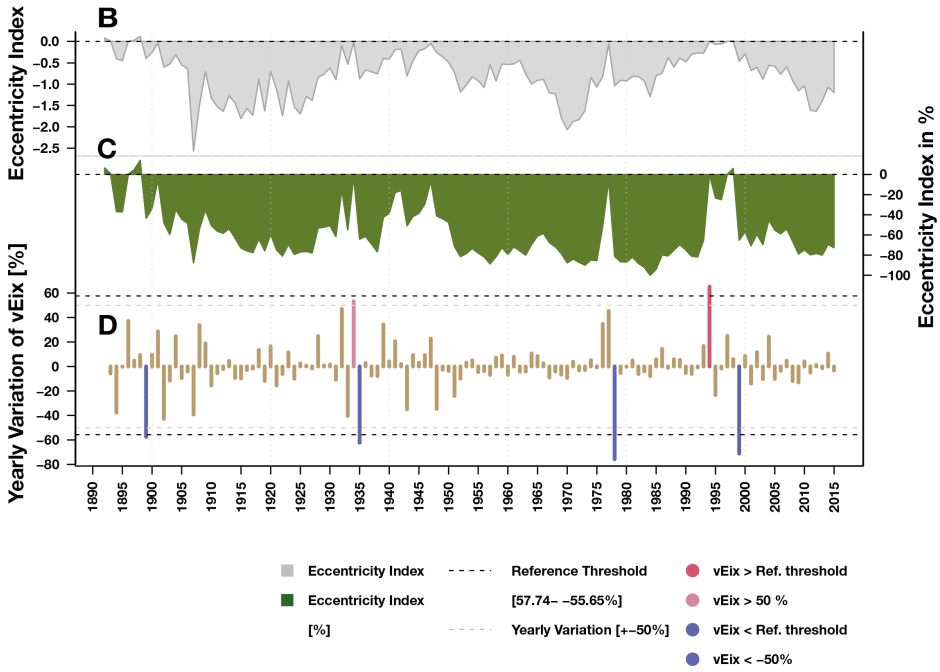

Figure 6.11: *Picea abies Karst.* 03 - eccentricity index from raw ring width and in percent in section B and C. D shows vEix[%].

end of the samples the ring width of the upper and lower side of the stem shows stronger growth on the downslope side. After the onset of eccentricity in 1968 the samples follow the same trends again. Exceptions can be seen in the years 1980 and 1995.

In addition to eccentric growth, the examination of the downslope sample shows reaction wood in parts of the sample. Looking at the first three onsets of eccentricity, no reaction wood can be found. Further examination draws attention to the year 1980, as the rings before and after do show no or very light reaction wood. Compression wood starts three years later with the same intensity as in 1980, in 1983, and appears in every ring until 2015 as can be seen in figure 6.12 a).

The calculation of the eccentricity index reflects the division of the samples into the mentioned three parts. Due to the eccentricity index, the direction of tilting gets more clearly: section B shows the calculated eccentricity index from the raw ring width and section C the index in percent. In the period from 1919 to 1945, the annual increment of the upper and lower sample changes dominating side every two to five years. Afterwards, a period from 1946 to 1966 shows clearly upslope eccentricity. This changes in the period

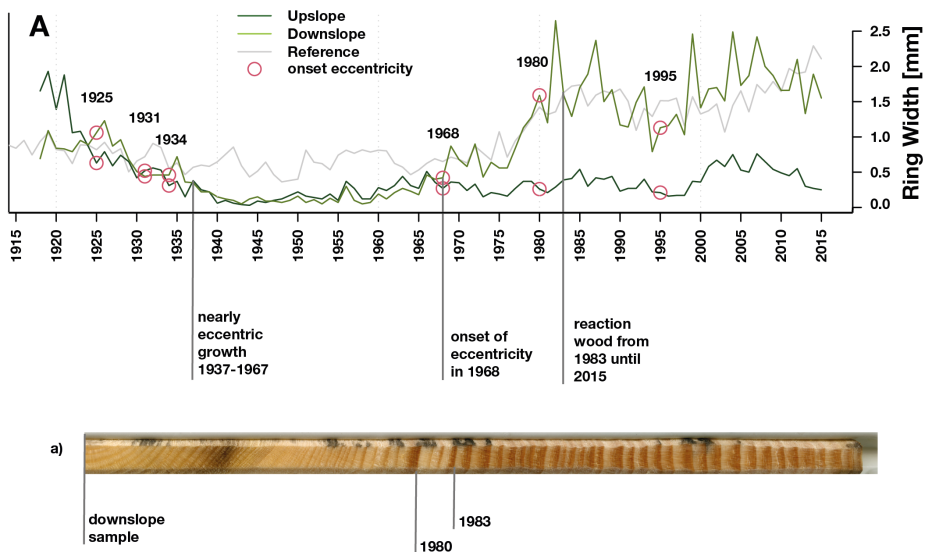

Figure 6.12: *Picea abies Karst.* 07 - detailed view of ring width of the upper and lower sample with reference curve, onsets of eccentricity and scan of lower sample.

from 1967 to 2015, where downslope eccentricity dominates. The eccentricity index in percent shows the same tendencies, but the intensity of the events appears stronger, what simplifies the interpretation of the direction of eccentricity. For example, it can be seen that in the second period the values appear nearly as intense as in the third period even though the difference in the raw ring width is minimal.

Looking at the barplot in section D (figure 6.14), the yearly variance of the calculated percentage of the eccentricity is displayed. Taking a percentage above or beneath the respective reference threshold as an event, it shows a strong upslope event in 1937 and strong downslope event in 1940. A less intensive variation of the index takes place in 1944. After the year 1944, more intense variations are recorded until 1969. The period afterwards does show only small variations that do not exceed a range of 20%.

The different methods show different years and periods that could be identified as events. Potential events that where identified through visual inspection show onsets of eccentricity in the years 1968, 1980 and 1995. Reaction wood occurs in 1980 and from 1983 to 2015 and supports these analyses. The vEix[%] however, shows an upslope tilting in 1937 and two downslope tilting events in 1940 and 1944.

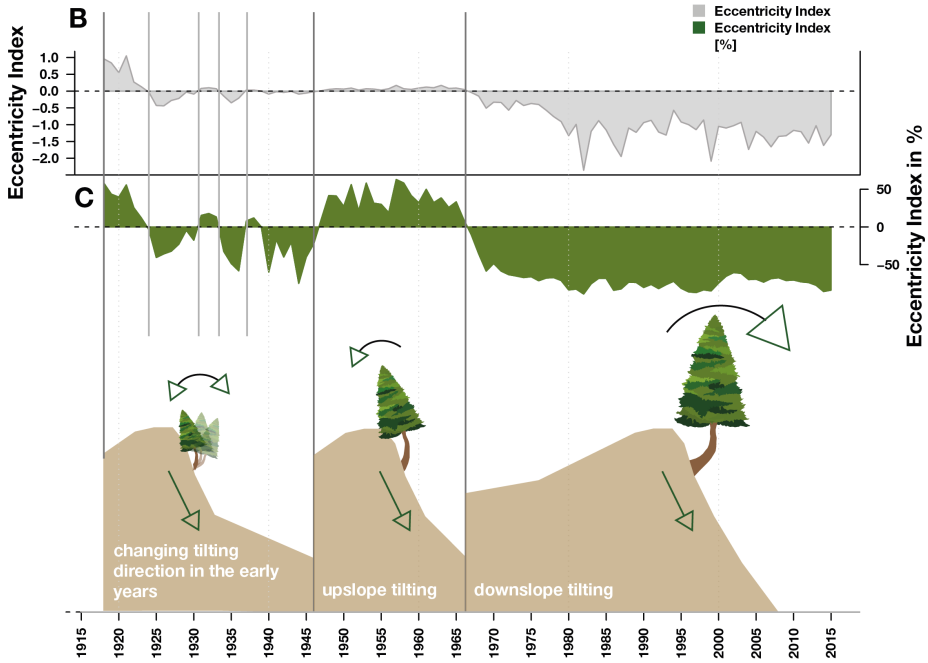

Figure 6.13: *Picea abies Karst.* 07 - the calculated eccentricity index shows the tilting direction of the stem.

***Picea abies Karst.* 08** With a correlation coefficient of 0.82 and ttest value of 11.6 the upper and lower sample show very good statistical parameters towards each other. The core of the upper side goes back to 1932 and the one of the lower side to 1947. Ring width increases during the life of the tree. As in sample 07, the rings are narrow until the 1960ies and get wider towards present times. In the period before 1960, nearly concentric growth can be seen. Then the lower part develops slightly wider rings between 1959 and 1965, which can be related to mechanical stress. Between 1966 and 1979, the upper part develops wider rings, so the tree was tilted upslope. This changes between 1980 and 1983 until the lower part develops wider rings again from 1988. Eccentricity onset occurs in the years 1960, 1971, 1978 and 1992. The onset in 1960 and 1969 is very weak compared to the two other years. The results of the index calculation show these events more clearly. All in all, the calculation of vEix[%] shows four events that exceed the reference threshold and one event that exceeds 50% in the year 1958, 1968, 1969, 1970 and 1980. In the years before 1968, ten rings can be identified that show compression wood. Looking at year 1978, reaction wood occurs less intense but is still recognizable. A sequence of strong reaction wood

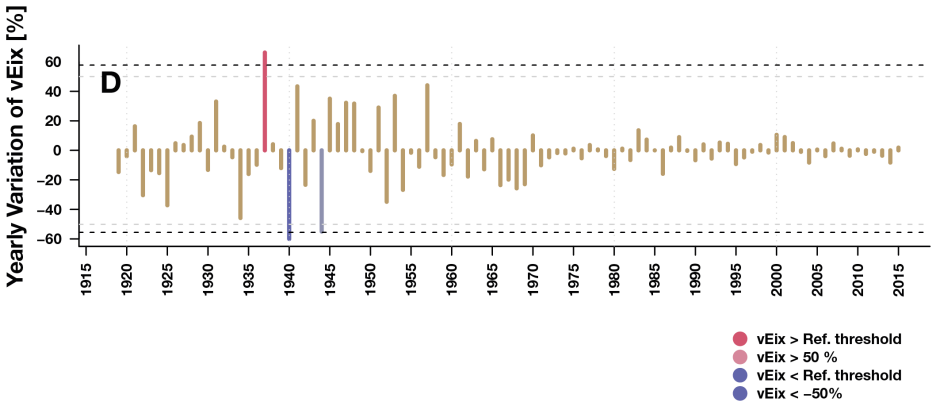

Figure 6.14: *Picea abies Karst.* 07 - the yearly variation of vEix[%] with highlighted events on the upper and lower side of the slope.

can be seen during 1989 and 1993. As in *Picea abies Karst.* 07, the results of the identification of events with the two methods differ. Both show events between 1968 and 1971. Compression wood occurs before and after. In the year of 1978 eccentric growth occurs, but vEix[%] shows an event two years after. Inspection of the sample shows weak reaction wood within the correspondent rings.

Next to the detailed explanations of the trees *Picea abies Karst.* 02, 03, 07 and 08, four more trees were sampled and examined. The results can be found in the appendix. *Picea abies Karst.* 04, with a length of both samples of 91 years, shows downslope eccentricity throughout the whole sample. Only in the year 1957, an increase of the ring in the upslope sample can be seen. The restoration of the wider width of the lower sample leads to an onset of eccentricity in 1959. This is also recorded by the calculation of the eccentricity indices. The visually defined events do match with vEix[%]. Reaction wood can be found in every ring of the lower sample. *Picea abies Karst.* 09, reaching back to 1953, shows a correlation of 0.80 and a ttest of 10.3 towards each other. These values already indicate, that the is almost no year with eccentric growth in the sample. The only exceptions occur in the year 1957, 1992 and 1998 as the width of the downslope sample decreases slightly. These changes of growth direction do not exceed the calculated reference threshold. In the years 1989 and 1990 the sample shows an above normal increase of increment of 7.17 and 11.12 mm. vEix[%] shows no variations in eccentricity that exceed the reference threshold, which would indicate no relevant activity of the slope. Both samples not showing abrupt onsets of eccentricity are located on the outer margins of the landslide area.

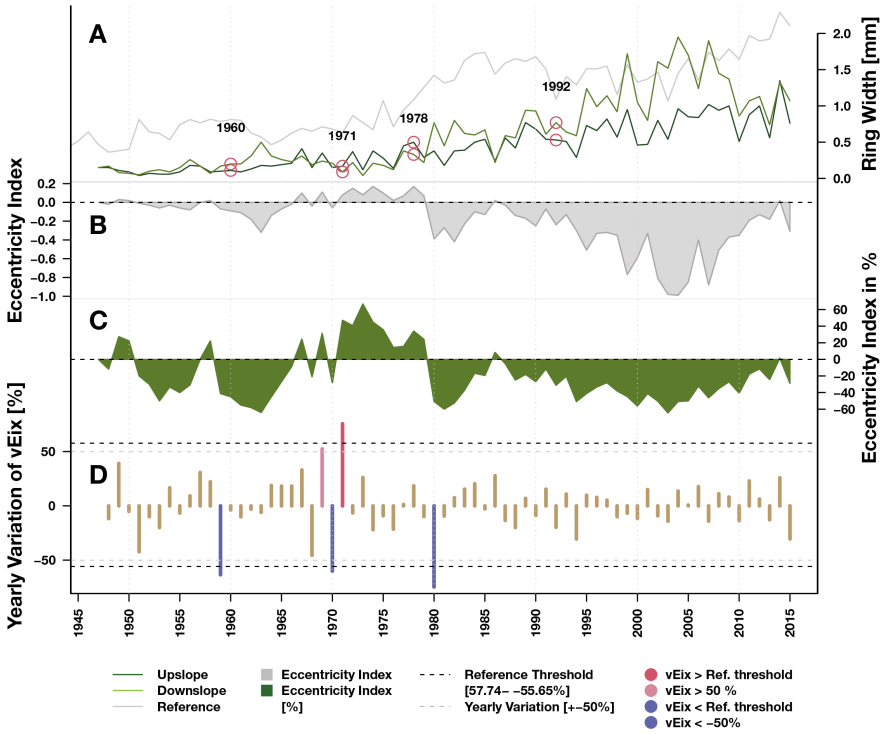

Figure 6.15: *Picea abies Karst.* 08 - ring width of the upslope and downslope sample in section A and calculated eccentricity indices in section B, C and D.

The two other trees, *Picea abies Karst.* 11 and 12 are located opposite to No. 04 and 09 in the eastern part of the landslide area. The sample of number 11 shows a highly disturbed growth curve. Both samples were not easy to crossdate, as there was nearly no undisturbed period. Still, it could be dated with the last 20 years of the sample. It shows a length of 59 years and onsets of eccentricity in the years 1967, 1986, 1992, 1998 and 2003. vEix[%] shows additional downslope onsets of eccentricity in the years 1984, 1994 and seven more after the year 2000. As crossdating cannot be fully secured and missing rings could occur in this part, these events were not taken into account for further analysis. The samples of tree 12 posed similar challenges while determining events. It showed one missing ring in the year 1966. Still, eccentric growth in the years 1968, 1981 and 1988 could be detected. Moreover, the period between 1994 and 2000 shows multiple changes of tilting direction. These two samples have in common that they

show eccentric growth in the same periods: The years 1967 and 1968 show disturbances, as do the years 1987 and 1988. In both samples, the period from 1994 shows eccentric growth.

The sampled individuals of *Picea abies Karst.* can therefore be grouped by their location on the landslide: Trees 04 and 09 show signs of ongoing stabilization throughout the whole curve, with slight eccentric growth in the year 1957. The trees 02 and 03 in the upper part show disturbed growth in different years, as do the samples 07 and 08. Throughout all samples a stronger growth on the lower side of the stem could be detected, with only few exceptions. Moreover, in all of the samples reaction wood could be identified in the lower side of the stem. These results are summed up in table 6.3. For every ring, the direction of eccentricity was calculated and displayed. In total, 65.06% of the trees show downslope eccentricity, while only 34.00% show upslope eccentricity.

Table 6.3: Percentage of rings showing upslope eccentricity, downslope eccentricity or concentric growth of *Picea abies Karst.*

	Picea 02	Picea 03	Picea 04	Picea 07	Picea 08	Picea 09	Picea 11	Picea 12	Total [%]
Dowslope	63	116	0	66	51	60	34	29	65.06
Concentric	0	3	0	1	2	0	0	0	00.94
Upslope	7	5	92	31	16	3	26	39	34.00

Table 6.4: Mean ring width (MRW) and range of the upslope and downslope ring width (RW) of *Picea abies Karst.* in site II

	Picea 02	Picea 03	Picea 04	Picea 07	Picea 08	Picea 09	Picea 11	Picea 12	Mean
MRW upslope	1.29	0.46	0.6	0.4	0.43	2.88	0.97	2.77	1.23
MRW downslope	1.77	1.26	1.89	0.89	0.62	4.06	0.99	2.54	1.75
range RW upslope	2.83	1.32	1.72	1.9	1.31	7.73	2.72	6.11	
range RW downslope	3.08	2.81	3.00	2.6	1.91	10.05	3.23	4.21	

Furthermore, the mean ring width was calculated to compare it to the mean ring width of the reference trees of the species. Table 6.4 shows the values for every sample on the upslope and downslope side. In addition, the mean ring width of the whole site was calculated for the upslope and

downslope samples. It shows, that the downslope ring widths exceed the mean ring widths of the reference samples.

Comparison of methods within *Picea abies Karst.* on Site II Before the species can be compared, the events within a species have to be defined. This was performed with the calculation of vEix[%] and the determination of onset of eccentricity with the occurrence of reaction wood. All samples show signs of mechanical stress as they develop wider rings on the downslope side of the stem and show reaction wood. Comparing the visual determination of events and the events defined by vEix[%] that exceed the reference threshold, the results differ. In Figure 6.16 the events that were identified in section A of the plots from all trees are collected. Onsets of eccentricity that show growth anomalies, which are not related to mechanical stress were not taken into account. The lower histogram in the same figure displays the sum of events that exceed the reference threshold. From the visual event determination, events were defined in 22 out of 123 years. In seven years, more than one tree showed the same event. The maximum amount of trees showing indicators for the onset of mechanical stress is three individuals in the years 1957 and 1968. 35 events were defined by the calculation of vEix[%], but only four were shown by more than one tree. In 1994, three trees display events.

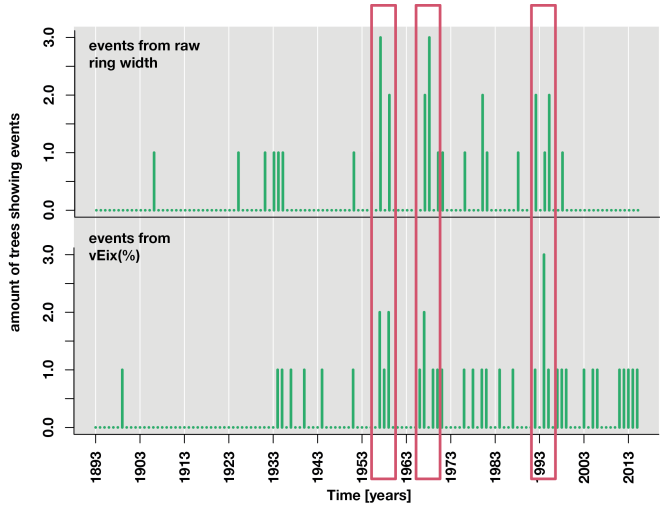

Figure 6.16: The determination of events through onset of eccentricity and reaction wood compared to the events calculated with vEix[%] in percent of *Picea abies Karst.* in site II.

Several periods can be seen in Figure 6.16 that show a higher occurrence of possible events. Both methods show more than one tree with mechanical stress between 1957 and 1959. The same can be seen in 1967/1968 and in the period between 1992 and 1994. In 12.2% of the years only one method showed an event. In 21.9% both methods showed events. Within the years that show events, 35.7 % are shown by both methods and 64.2% by only one method.

6.3.2 Site II - *Fagus sylvatica L.*

In the same area as the *Picea abies Karst.* individuals on the mass accumulation zone of the landslide in site II, trees of the species *Fagus sylvatica L.* are growing. This provides the possibility to analyze a mixed timber stand and to evaluate the suitability of hardwood species to reconstruct the landslide. As in chapter 6.3.1, two trees are described in detail to examine the methods used. The same procedure as for *Picea abies Karst.* is conducted and the results are compared in the next section. All trees are addressed shortly and the detailed figures showing all calculations and curves can be found in the appendix.

***Fagus sylvatica L.* 02** This individual, located in the near environment of *Picea abies Karst.* 04, lies in the upper part of the sampling area, in the middle of the landslide body. The overlap between the two samples covers 74 years ending in 2015. The upslope rings are wider than the downslope rings throughout most parts of the chronology (see section B of figure 6.17). Signs of disturbed growth due to mechanical stress can be seen in section A as the upslope side develops wider rings between 1953 and 1974, 1984 and 1999 and from 2001 to 2015. The correlations between the two samples are rather low with the best option of a correlation coefficient of 0.22 and a ttest of 1.9.

In 1943, the first onset of eccentricity can be seen, which was not used for further analyses, as there is no information on the ring width before these years. The first onset that is used, is marked in 1953 and initiates a period of stronger growth of the upslope sample until 1972. In 1973, the downslope sample shows a wider ring and eccentric growth. Between 1976 and 1983 the rings on both sides of the stem get narrower. Another onset of eccentricity, followed by 15 years of wider rings on the upslope site, can be seen following 1984. Until the year 1999, the ring width on in this sample decreases, but in 2001 eccentric growth starts again.

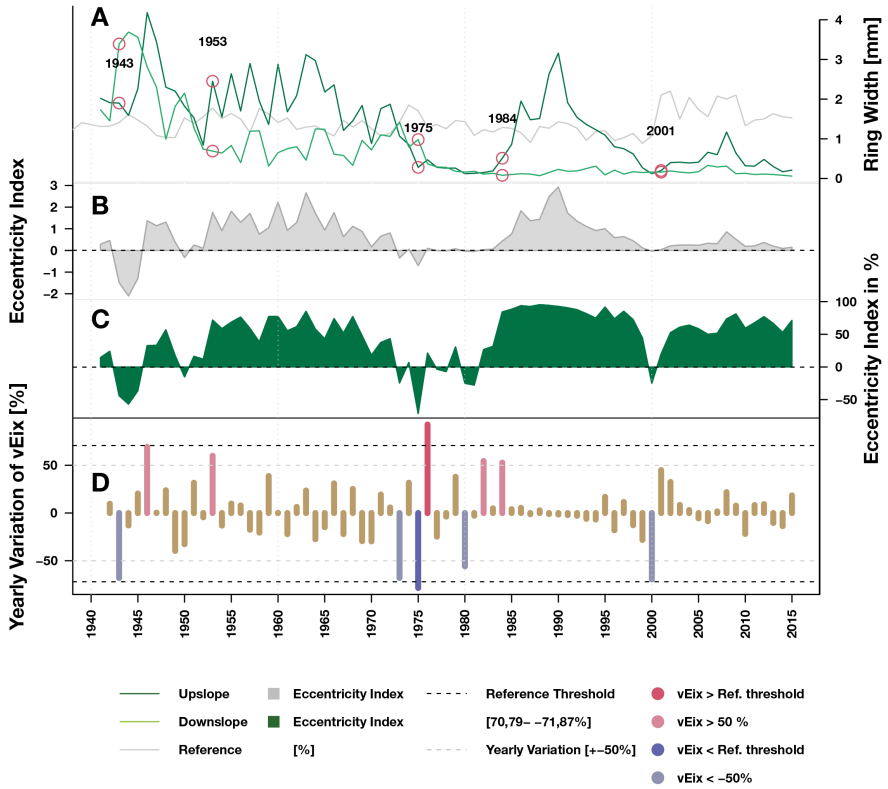

Figure 6.17: *Fagus sylvatica L.* 02 - ring width of the upslope and downslope sample in section A and calculated eccentricity indices in section B, C and D.

Three dominant periods of eccentric growth are displayed in the sections B and C of figure 6.17: 1953-1972, 1984-1999 and 2001-2015. The calculation of vEix[%] shows four upslope variations in eccentricity that exceed 50% (1946, 1954, 1982 and 1984) and one that exceeds the reference threshold in 1976. On the downslope side years reaching below -50% occur in 1943, 1973, 1980 and 2000. One event exceeds the negative reference threshold in 1975. The tree shows strong signs of disturbances due to stronger growth on the upslope side. The results between the onset of eccentricity and the calculation of vEix[%] differ, as vEix[%] shows more events as the analysis of the raw ring width. All events that are visually identified are displayed in the calculation of the index, but not necessarily exceeding the reference threshold: 1953 and 1984 stay below the 50% threshold and would not automatically be detected by vEix[%].

***Fagus sylvatica L.* 07** The Beech tree *Fagus sylvatica L.* 07 is located next to *Picea abies Karst.* 11 and 12 in the eastern part of the landslide area. The samples go back to 1944 and could be crossdated within themselves with a correlation coefficient of 0.68 and a ttest of 7.5. The Gleichläufigkeit within the samples reaches 0.70. Towards the reference chronology a value of 0.60 was achieved. Although the two curves of the upslope and downslope side of the stem show high values of Gleichläufigkeit, eight onsets of eccentricity can be seen (see figure 6.18 section A). They last for one year and initiate a change of the dominant side of growth between the upslope and downslope part (figure 6.18 section B). Looking at the calculation of eccentricity, the direction of eccentric growth changes nine times between upslope and downslope. The calculation of vEix[%] showed that none of the onsets of eccentricity exceeds the reference threshold (figure 6.18 section D). The

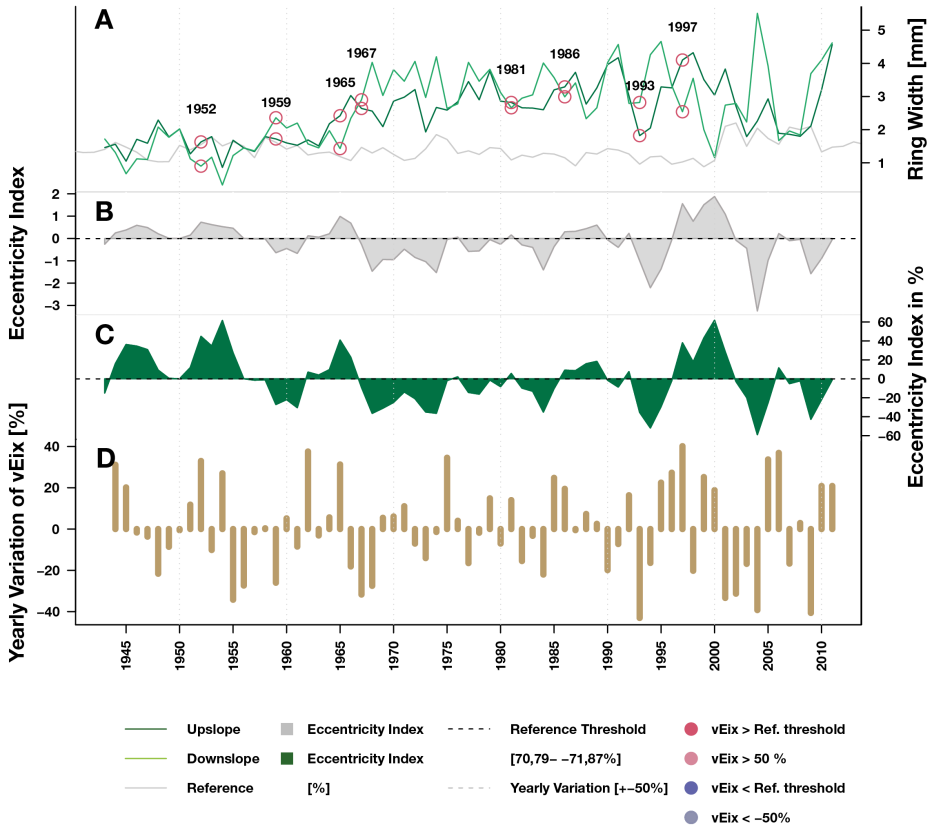

Figure 6.18: *Fagus sylvatica L.* 07 - ring width of the upslope and downslope sample in section A and calculated eccentricity indices in section B, C and D.

maximum positive value lies at 40.15% and the minimum value at -43.07%. With the reference threshold at and 70.79 and -71.87%, the variation in eccentricity is far below the thresholds for *Fagus sylvatica L.*. For this sample a complete thin section of the sample was available to examine it for the occurrence of tension wood, which is displayed in figure 6.19. Tension wood can be found in the following periods of the upslope sample: 1942-1948, 1950-1954, 1956-2015. A period of strong reaction wood occurrence can be seen from 1968-1991. Comparing these informations with the original ring width curve, an increased increment of both samples begins in 1967, what matches with increased tension wood occurrence.

Figure 6.19: *Fagus sylvatica L.* 07 - periods with reaction wood within the sample.

Five more trees were used from this site to examine *Fagus sylvatica L.*. For three of them, 03, 04 and 10, no thin sections where available, nevertheless, the results for eccentricity were used for comparison. Their detailed figures are displayed in the appendix. The cores of *Fagus sylvatica L.* 03 go back to 1938. Eccentric growth can be recorded in the beginning, but was not taken into account as the previous ring widths are unknown. A first onset of eccentric growth can be seen in the year 1945. It lasts for one year, and the ring width continues then not only to be concentric but also showing almost the same width on the upper and lower side for six years. A small change of tilting direction can be seen in 1963, followed by eccentric growth in 1966. In the following period until 1987, the upslope sample shows wider rings than the downslope sample, which is turned for a short period after eccentric growth in 1988. The eccentricity index shows changing directions of stronger growth between upslope and downslope sample in the early stage of the trees' life. A stronger downwards growth appears until 1966 and a dominance of the upslope side of the stem until 2015 (exceptions in 1988 and 1989). In contrary to the previous results, the calculation of vEix[%] shows less years exceeding the reference threshold or even the threshold of 50–50%. The only cases are 1939 and 1940, that had to be excluded as they appear in the early life of the tree and 1963 with eccentric growth but no growth increase on the upper part of the stem.

Also *Fagus sylvatica L.* 04 goes back to the 1930ies. The earliest measured year is in 1928. Onsets of eccentricity introduce longer periods, where the one part of the stem shows wider rings. After the eccentric growth in 1931, the upslope side of the stem develops wider rings, which changes after eccentric growth in 1951. The next period starts in 1966. This period shows an onset of eccentricity in 1982, but not a change of wider rings to the downslope side. After a sudden growth increase of the downslope sample in the year 2000, this circumstance changes. In this sample all onsets of eccentricity are also recorded by the calculation of vEix[%]. However, what can be seen is, that in the cases 1931/2 and 1981/82 not one year is marked, but also the following year with a indication of tilting into the opposite direction. Furthermore, the analysis of this tree shows that in some cases eccentric growth sets on, but the year afterwards is probably the event, when the difference of growth and increases in the year later (see 2000/01).

An interesting growth curve can be seen in the samples of the tree with the number 10. It is located in the lower part of the landslide body. The ring width of the upper and lower sample varies around the values 2.08 and 0.1mm in the period between 1945 and 1998. In 1999, a growth increase occurs peaking with a maximum value of the upslope sample reaching 4.45 mm and 6.08mm in the downslope sample. The mean ring width of the upper sample lies at 1.8mm, the mean of the lower sample at 1.55mm and the mean of the reference chronology at 1.39mm. These sudden increases of growth were already recorded in some *Fagus sylvatica L.* individuals of the reference chronology and have to be taken into account.

Thin sections that were examined for reaction wood were available for two more trees: The tree 01 in the upper part of the landslide is rather young compared to the other ones and located in the upper part of the sampling area. It shows eccentric growth in e.g. 1992, which is not exceeding reference thresholds and in 2010, which can be seen in vEix[%]. The upslope sample shows reaction wood throughout the whole core. In some years, it is harder to detect as minimal changes in thickness of the section already influence the visibility. An available short section shows definitely reaction wood (see figure 6.20), but was too short to be crossdated. Despite of the short sample, it could still be shown that the tree forms reaction wood to stabilize itself in this upper part of the sampling area. *Fagus sylvatica L.* 09 was dated back to 2011 as the first part of one of the sample was missing. It shows wider rings on the downslope side of the stem from 1968 to 1977, but then the upslope part increases in ring width. This is again enforced in the year 1994. Unfortunately, the thin section in this case was too thick to examine it for reaction wood.

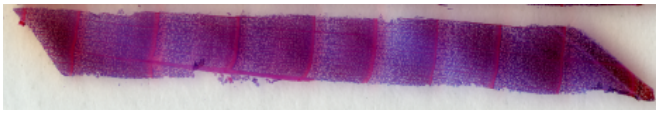

Figure 6.20: *Fagus sylvatica L.* 01 - tension wood.

All trees examined of the species *Fagus sylvatica L.* in site II show signs of mechanical stress. Increased growth on the upslope side, as expected for hardwood species, occurs in all trees. One exception is *Fagus sylvatica L.* 07, which shows changes in the direction of eccentric growth throughout the whole covered period. Even though the dominant ring width in the other trees is upslope, six of the total seven sampled trees show changes in the direction of eccentric growth during their life. The detailed amount of years showing up- or downslope eccentricity is displayed in table 6.5. Looking at these values, the dominance of eccentric growth on the upslope side becomes visible. 30.82% of the rings show downslope eccentricity, while 68.23% display stronger increment on the upslope side of the stem. As it could already be seen in the equivalent table for *Picea abies Karst.*, concentric growth does nearly not occur. In the three individuals, where thin sections were available, tension wood could be found in the upper samples.

Table 6.5: Percentage of rings showing upslope eccentricity, downslope eccentricity or concentric growth of *Fagus sylvatica L.*

	Fagus 01	Fagus 02	Fagus 03	Fagus 04	Fagus 07	Fagus 09	Fagus 10	Total [%]
Dowslope	0	11	21	24	38	17	20	30.82
Concentric	0	0	0	1	2	0	1	0.94
Upslope	28	64	57	63	63	28	49	68.23

In addition, the ring width of every tree was analyzed, what can be seen in table 6.6. While the mean downslope ring width is very similar to the mean ring width of the reference samples (1.47mm), the mean of upslope ring width is significantly higher with 2.15mm. In trees that show more rings with upslope eccentricity, the range of the upslope samples are correspondingly higher.

Table 6.6: Mean ring width (MRW) and range of the upslope and downslope ring width (RW) of *Fagus sylvatica L.* in site II

	Fagus 01	Fagus 02	Fagus 03	Fagus 04	Fagus 07	Fagus 09	Fagus 10	Mean
MRW upslope	3.96	1.32	1.95	1.45	2.50	2.09	1.8	2.15
MRW downslope	2.00	0.68	1.31	1.04	2.65	1.25	1.55	1.50
range RW upslope	4.02	4.06	3.94	2.93	3.71	4.01	3.91	
range RW downslope	1.88	3.63	4.21	2.77	5.18	2.98	5.95	

Comparison of methods in *Fagus sylvatica L.* on Site II The analyzed trees cover a period of 87 years going back to 1929. The two methods showed different years with events. From the visual identification of years that show onsets of eccentricity, 30 individuals show events and of the calculation of vEix[%] also 30 individuals display events. However, as can be seen in figure 6.21, the 30 event years found with the methods are not identical. Counting both methods, in 31 years only one method displays events and in ten years each, both methods show events. Within these ten years that are indicated by both methods, a maximum of two trees displays mechanical stress in the same year. Looking at the time series of both methods in figure 6.21, the periods that do show no signs can give more indications. Both methods do not show any trees with mechanical stress in 1933-1943, 1989-1991, 1995-1996. Further, no events are shown from the year 2002 until present with the exception of 2011/2012. Differing from the results of *Picea abies Karst.*, no distinct periods of mechanical stress that are shown reliably by both methods could be found here.

6.3.3 Site II - Temporal Reconstruction of mechanical Stress

As the results of the two methods used for event identification differ, both were used for the comparison of *Picea abies Karst.* and *Fagus sylvatica L.* to open up the outcome for discussion. First, the analysis of the visual identification of the events will be presented and afterwards the results for the eccentricity index.

The detailed presentation of the amount of trees of both species that show events after visual interpretation can be seen in figure 6.16 and 6.21. Both time series were compared and years that showed values above 0 for

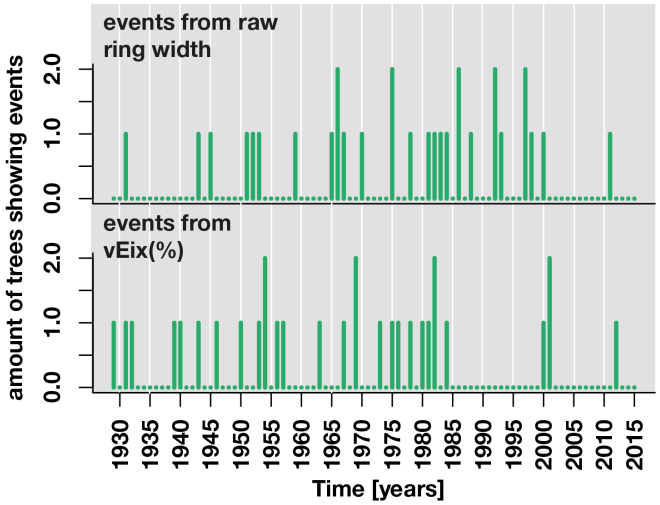

Figure 6.21: The determination of events through onset of eccentricity and reaction wood compared to the events calculated with vEix[%] in percent of *Fagus sylvatica L.* in site II.

both species printed in table 6.7. The years 1931, 1951, 1970, 1981, 1988 and 1998 showed one tree of every species reacting to mechanical stress. In 1959, two trees of *Picea abies Karst.* and *Fagus sylvatica L.* showed a reaction. The trees *Picea abies Karst.* 04, *Picea abies Karst.* 08 and *Fagus sylvatica L.* 07 are all located on an transect in the same height of the mass accumulation zone. In the year 1967 also three trees show reactions: *Picea abies Karst.* 03, *Picea abies Karst.* 11 and again *Fagus sylvatica L.* 07. These trees are not located in a place on the sampling area related to each other. In 1992, reactions were displayed by a maximum of four trees. Two of them belong to *Picea abies Karst.* (08 and 11) and another two to *Fagus sylvatica L.* (01 and 03). All of these individuals are located in the upper half of the sampling area.

The results of the quantification of the eccentricity through vEix[%] differ from the visual identification of reactions. Common years of one tree of each species were found in 10 years and are also displayed in table 6.7: 1940, 1976, 1978, 1980, 1981, 1984 and 2012 with one tree of each species and maximum of 3 trees showing events were displayed in 1957, 1967, 1969.

Comparing the two methods stresses again, what could already be seen in chapter 6.3.1 and 6.3.2: the results differ. The visual identification of reactions to mechanical stress showed eleven events that were displayed by both species. The calculation of vEix[%] showed 10 years that exceeded

Table 6.7: Amount of individuals showing reactions due to visual event determination (sum visual) or from the calculation of vEix(%) in both species used

	1931	1940	1951	1957	1959	1967	1969	1970	1976	1978	1980	1981	1984	1988	1992	1998	2012
sum visual	-	2	-	3	-	3	3	-	2	2	2	2	2	-	-	2	2
sum vEix [%]	2	-	2	-	3	3	-	2	-	-	-	2	-	3	4	-	-

the reference threshold of the corresponding species and were displayed by both species. Although the amount is almost the same, only two years were displayed by both methods: 1967 and 1981.

Even though these differences, which will be discussed in chapter 7, have to be taken into account, a temporal reconstruction of mechanical stress was performed with the calculation of the variation in eccentric growth after Wistuba et al. (2013). For both species, the results were cumulated and plotted in figure 6.22. In part A, the cumulated results of *Picea abies Karst.* can be seen. No relevant activity can be seen until 1935. Then, the trees start to stabilize in some single years. Starting in 1957, three years show activity. In the following period, eccentric growth varies and exceeds the reference threshold more regularly. Most intensive variations in eccentricity can be seen starting from 1993. The outcome of *Fagus sylvatica L.* can be seen in part B of the same figure and displays regular variations in eccentricity occurring from 1930 to 1984. In the period following 1984 until present, only two more years show variations that exceed the threshold, what is contrary to the results of *Picea abies Karst.*. The combined plot of both species can be seen in section C of 6.22. No distinct pattern can be identified anymore, as variations in eccentricity occur during most of the recorded years.

6.3.4 Site I - *Betula pendula Roth.*

The first sampling site contains trees of the species *Betula pendula Roth.* distributed in the lower part of mass accumulation zone on a landslide. The area showing signs for mass movement is not fully covered with trees, as can be seen in figure 6.23. The upper part is covered with reed vegetation with a high water saturation in the surface near soil. There is no date of activity available of other sources (Schmaltz et al. 2017). The landslide inventory of Schmaltz et al. (2017) of the region shows that this area is one of eight moving masses in the same altitude. The date is unknown, so the

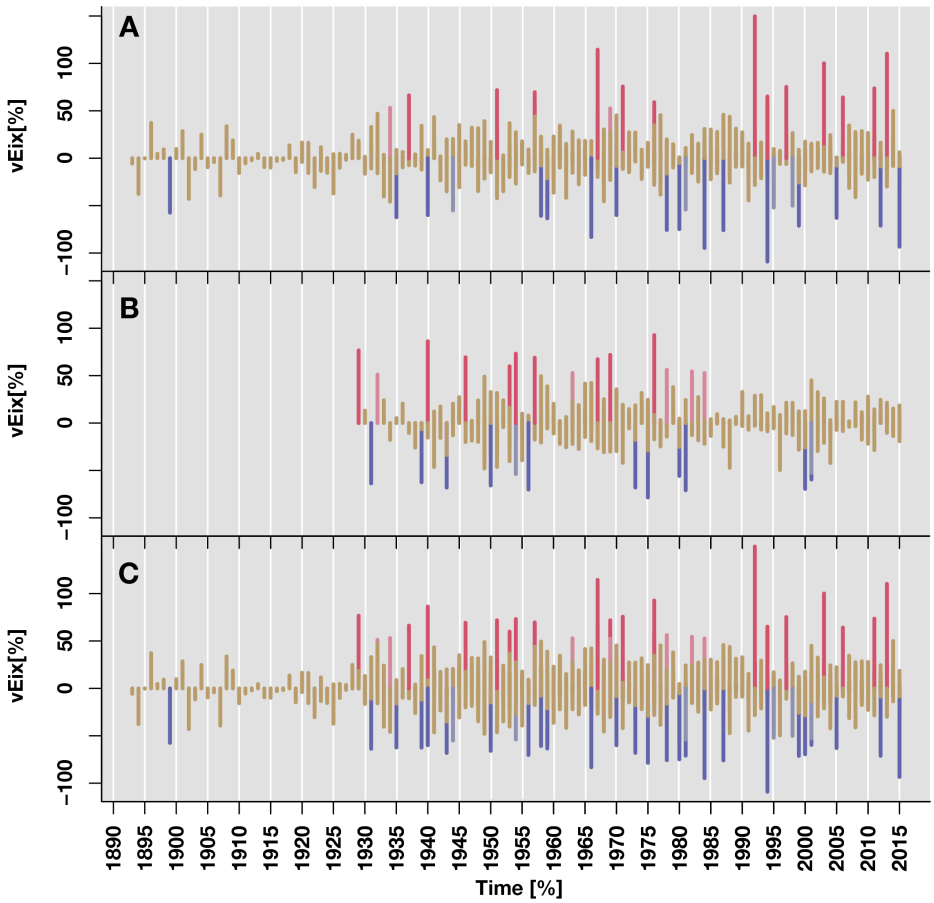

Figure 6.22: Cumulative results of vEix[%] from *Picea abies Karst.* (A), *Fagus sylvatica L.* (B) and both (C).

information the trees provide would give the opportunity to increase knowledge on the events in the area. Nine trees were sampled in the lower part of the landslide body. For five of the trees, it was possible to produce long thin sections of the upper and lower side of the stem. In four other cases, shorter sections were available, as the complete section had to be cut into pieces. The reason is the fragility of the thin sections that makes it hard to produce long sections without breaking. Consequently, in these cases the shorter ones were produced. However, the rings of *Betula pendula Roth.* are (with an average of 2.85mm) rather wide and it is not possible to crossdate these sections properly, as they contain six to ten rings. From the five trees used, long thin sections were available. These five trees are all located in the eastern part of the sampling area: *Betula pendula Roth.* 01 and 02 in the

upper part, and 05, 06 and 07 in the lower part.

Figure 6.23: Location of sampled *Betula pendula Roth.* trees in Site I.

The trees on site I were all relatively young compared to the trees available for *Picea abies Karst.* and *Fagus sylvatica L.*, with a maximum age of 30 years and a minimum age of 19 years. Still, they could be crossdated with the reference chronology with reasonable values. As the samples are short, the values have to be treated with caution what is discussed in chapter 7.

Individuals 01 and 03 are located next to each other. The samples are not all going back to 2015, so the period they show starts in 2013 (for sample 01) and 2014 (for sample 03). Both trees are very young with an age of 21 and 25 years. Figure 6.24 sums up the detailed view of the results from *Betula pendula Roth.* 01. Tree 01 shows wider rings on the upper side of the stem from the beginning until 2003, with an exception in the year 2000. Then a period with eccentric growth starts, where almost every year shows eccentricity and therefore varying sides of dominant ring width between the upper and lower sample. To exclude that this is due to bad crossdating, it was made sure that the dating is correct: The upslope sample could be crossdated with a correlation value of 0.83 and a ttest of 8.3 to the reference. The lower sample showed weaker values, but a positive correlation of 0.39

to the partner sample, which was the best option. Sample 01 points out two downslope tilting events that exceed the reference threshold in 2003 and 2008 and one upslope tilting in 2009. In the period after 2009, no eccentric growth was recorded and the upslope sample shows wider rings than the downslope sample again. The examination of the thin section shows reaction wood starting in the year 1999. In addition the upslope sample shows density fluctuations in every year starting in 1999 (see Figure 6.25).

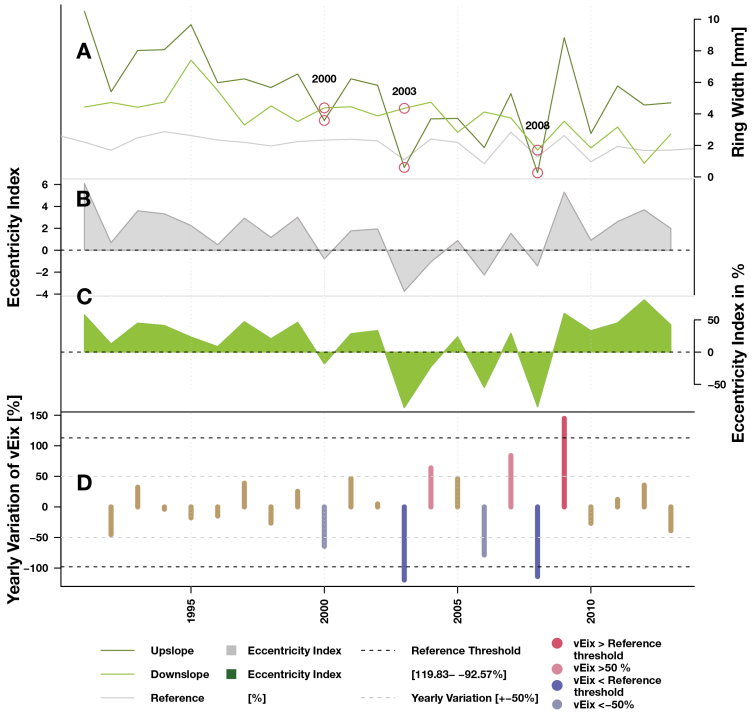

Figure 6.24: *Betula pendula Roth.* 01 - ring width of the upslope and downslope sample in section A and calculated eccentricity indices in section B, C and D.

The detailed figures for the other sampled trees can be seen in the appendix. For Tree 03, only one year develops eccentric growth in 2004. Calculating vEix[%] shows that the event stays below 50% and is therefore not recorded with this method. Only slight signs of tension wood can be detected, that were hard to identify as the thin section is fine and the colors of staining did not appear clearly. Tension wood could be found in the early years of the trees life until 1996. Comparing the trees 01 and 03, considering their location, the year 2004 could mark the onset of mechanical stress in this lo-

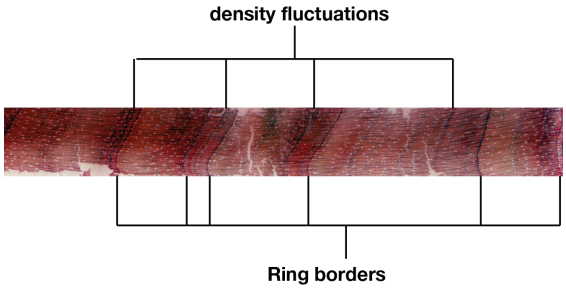

Figure 6.25: *Betula pendula Roth.* 01 - density fluctuations.

cation. Tree 01 is located in the mid part of the landslide body, so the stress could have been more intense and stabilization took several years. Tree 03 is located on the outer margins and shows less signs of eccentricity.

Betula pendula Roth. 05, located next to *Betula pendula Roth.* 06 in the lowest part of the sampling area shows slightly wider rings in the upper part of the stem, which changes in the period, where also an onset of eccentricity takes place in 1993. The ring width differs already in the two years before, but is still concentric. After 1994, the two sides of the stem grow eccentric again. The direction of wider rings varies from year to year in this period. Eccentricity occurs again in the years 2003 and 2006. The calculation of vEix[%] shows variation of the eccentricity that exceeds the eccentricity threshold in 1990, 2004 and 2004 and in 2012. No reaction wood was found in this sample. *Betula pendula Roth.* 06 shows concentric growth until the year 2009. Afterwards the curves differ, what also leads to the same question, as in tree 01 if there is a missing ring in the particular year on the upslope side. Comparing the curve with the reference, the upslope sample does not show a missing ring. Therefore, the downslope sample was checked again for density fluctuations and the ring in 2009 was clearly visible under the binocular. The last tree on this site is *Betula pendula Roth.* 07. It goes back until 1990 and grows nearly eccentric. Years with eccentricity are 1995 and 2005, whereas the calculation of vEix[%] shows a variation of eccentricity in percent exceeding the threshold in the 2006. The onset of eccentricity of 2005 becomes more intense in the following year, so that 2006 shows a stronger variation compared to 2005.

When checking the raw ring width for onsets of eccentric growth between the upslope and downslope sample, several years could be found. The years are displayed in figure 6.26. Events were found in 1993, 2001, 2004, 2006 and 2009. The year of 2009 was the only year that points out onsets of eccentricity in two trees (*Betula pendula Roth.* 06 and 07). Comparing the results

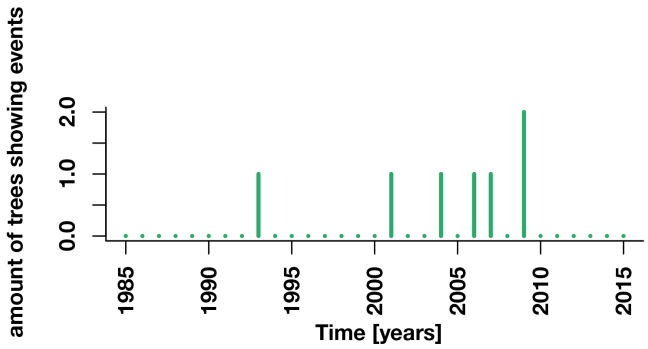

Figure 6.26: The defined onsets of eccentricity (detailed in the appendix) of *Betula pendula Roth.* on site I.

with the indicated events of the calculation from vEix[%], more years are displayed by the latter. In figure 6.27, all results of the calculation of vEix [%] are plotted over each other to visualize the changes in eccentricity over the whole site. Before the year 2000 only one year shows eccentric growth exceeding the reference threshold in 1991. The occurrence of variations in eccentricity that exceed the threshold increases from the year 2004. Still, the maximum of trees that indicate mechanical stress due to variation in eccentricity are two trees in the years 2004/5, 2009/10 and 2013.

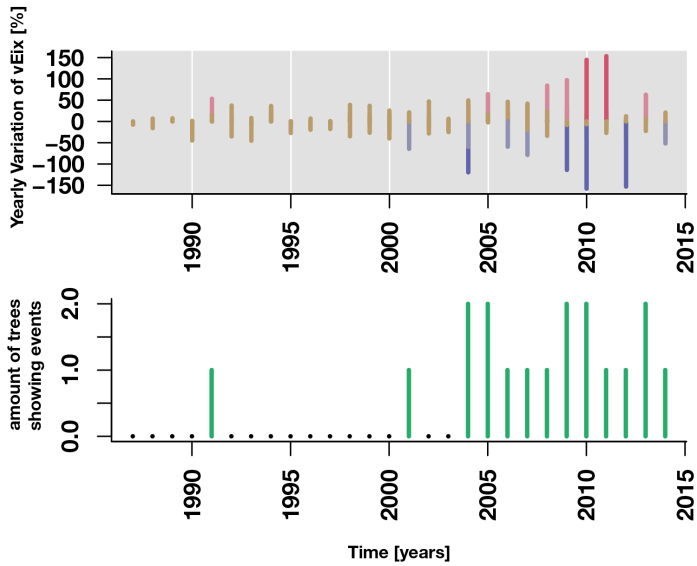

Figure 6.27: Cumulated events indicated from vEix[%] on site I.

The amount of trees that could be used for analysis was decimated due to difficulties to produce long thin sections that can be crossdated. Shorter sections could not be dated, as the ring width was to wide to have more than ten years in one sample. Therefore, only five trees could be used. They show onsets of eccentricity as an indicator for mechanical stress. The results for the onset of eccentricity from the raw ring width and the calculation of vEix showed that more events are indicated by the second method. Both methods show an increased occurrence of striking values from 2004.

To sum up the results of eccentric growth for *Betula pendula Roth.*, table 6.8 displays the percentage of upslope and downslope eccentricity in site I. In the trees 01, 03 and 07, the dominance of the upslope rings can clearly be seen. Less obvious is the ratio in tree number 05, whereas the individual with number 06 shows an even distribution between eccentric growth in both directions. All in all, 75.04% of the rings grow eccentric in the upslope part of the stem.

Table 6.8: Percentage of rings showing upslope eccentricity, downslope eccentricity or concentric growth of *Betula pendula Roth.* site I

	Betula 01	Betula 03	Betula 05	Betula 06	Betula 07	Total [%]
Dowslope	3	5	7	15	3	25.19
Concentric	0	0	1	0	0	0.76
Upslope	23	18	20	13	23	74.04

Table 6.9 shows the mean ring widths of the sampled trees in site I. Both, the mean upper and lower ring width exceed the mean ring width of the references. The sample 06, which shows an even distribution of up- and downslope eccentricity, has a low difference between the mean ring width of both sides of the stem. In the samples that display these difference more clearly, the mean rings differs significantly, as can be seen in sample 03. Furthermore, the table displays that the range of the rings can be extremely high with a maximum of 10.25.mm between the narrowest and widest ring, as in sample 01. This value is specifically interesting compared to the ranges in tree ring width of the other examined species.

Table 6.9: Mean ring width (MRW) and range of the upslope and downslope ring width (RW) of *Betula pendula Roth.* site I

	Betula 01	Betula 03	Betula 05	Betula 06	Betula 07	Mean
MRW upslope	5.37	7.60	3.04	3.23	5.01	4.92
MRW downslope	3.86	3.04	2.85	3.42	3.52	3.34
range RW upslope	10.25	10.58	6.49	6.23	6.11	
range RW downslope	6.54	6,76	7.14	6.99	4.9	

6.3.5 Site III - *Betula pendula Roth.*

Site III was included in this study as the individuals show tilted and bended stems and can be seen in figure 6.28. Four trees were sampled in the middle part of the area to determine if the show signs of mechanical stress. The area is not mapped as a landslide by Schmaltz et al. (2017). As in site I, production of thin section posed a challenge. In this case, no long sections could be produced, but the ring were not as wide as in the samples of site I, so crossdating for three trees was possible.

Figure 6.28: Location of sampled *Betula pendula Roth.* trees in Site III.

The three samples have a length of 18 years (sample 01), 26 years (sample 02) and 21 years (sample 04). The length of the samples poses limitations for the analysis, as crossdating is questionable and development of eccentric growth could be age related. Nevertheless, an example is displayed in figure 6.29. For the interested reader, the detailed view of the other two samples can be seen in the appendix. *Betula pendula Roth.* 04 shows variations between the direction of ring width throughout the whole sample. Real eccentric growth can be seen in the year 2002. The calculation of vEix[%], also shows variation in eccentricity beginning from the year 2002. Tension wood was found in single rings, that did not match the years of eccentric growth. Similar patterns can be seen in the other two samples of this site. Also *Betula pendula Roth.* 01 and 02 show eccentric growth in 2002, what could be an indicator for increased mechanical stress on the stems.

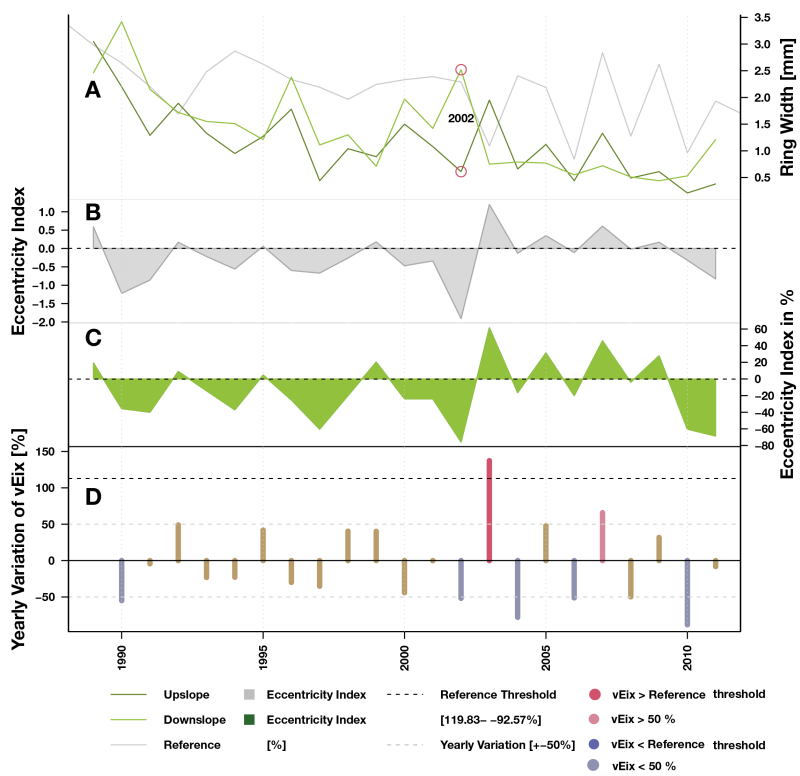

Figure 6.29: *Betula pendula Roth.* 04 - ring width of the upslope and downslope sample in section A and calculated eccentricity indices in section B, C and D.

Also the percentage of eccentric rings concerning their direction was calculated for the trees here. Years showing a downslope eccentricity showed a slight majority with 55.71%, whereas upslope eccentricity can be seen in 44.28% in total. This ratio does, in comparison to the individuals of site I indicate, that the trees did not experience mechanical stress. Moreover, the amount of years showing eccentric growth on the upslope side as it would be expected due to reaction wood formation, is less than in the reference trees.

Table 6.10: Percentage of rings showing upslope eccentricity, downslope eccentricity or concentric growth of *Betula pendula Roth.* site III

	Betula 01	Betula 02	Betula 04	Total [%]
Downslope	3	21	15	55.71
Concentric	0	0	0	0
Upslope	17	6	8	44.28

To obtain further information if the individuals in site III experience mechanical stress, their ring widths were analyzed. The results can be seen in table 6.11. The mean ring width of every tree in this site lies below the mean ring width of the references. Also the ranges of width of the upslope and downslope cores do not show differences as high as in site I.

Table 6.11: Mean ring width (MRW) and range of the upslope and downslope ring width (RW) of *Betula pendula Roth.* site III

	Betula 01	Betula 02	Betula 04	Mean
MRW upslope	2.84	0.97	1.15	1.65
MRW downslope	1,99	1.22	1.37	1.37
range RW upslope	4.25	3.31	2.84	
range RW downslope	4.65	3.29	2.98	

Individuals of the species *Betula pendula Roth.*were analyzed in two sites to examine their suitability for the temporal reconstruction of mechanical stress. Eccentric growth and tension wood was found in the trees of site I. In site III the trees do also show eccentric growth in some years, but the age of the trees is a limiting factor for the analysis. The consequences for

the interpretation of the results will be discussed in chapter 7. To interpret the information provided by the growth curves of the different species, further information of the potential activity of the slope is required. Therefore the results of the analysis of extreme precipitation events is presented in the following section.

6.4 Extreme Precipitation Events

Precipitation data from January 1991 to December 2014 was available. An average of the climate stations Frastanz, Thüringerberg, Thüringen and Laterns was calculated. The time series of rainfall can be seen in figure 6.30. A mean annual precipitation of 128.00 mm a month was calculated. As extreme precipitation events can induce slope failure, outliers were identified. The 3rd quantile times 1.5 was used for that, which defined a threshold of 253.05 mm. In total, 18 months out of 289 showed rainfall events that exceeded the defined threshold for outliers. That makes up 6.22 %. But in 15 out of 24 years extreme events occurred, meaning that 62.5% of the years show extreme events in this period. This fact makes it difficult to distinguish years that might be more likely to induce slope failure. However, the years 1991 showed three months with extreme events in February, May and June. In the Year 2001 extreme events occurred in June and September. In addition, the periods that show no extremes can also be of interest. Less events occur in the period from 1991 to 1997 and from 2006 to 2010.

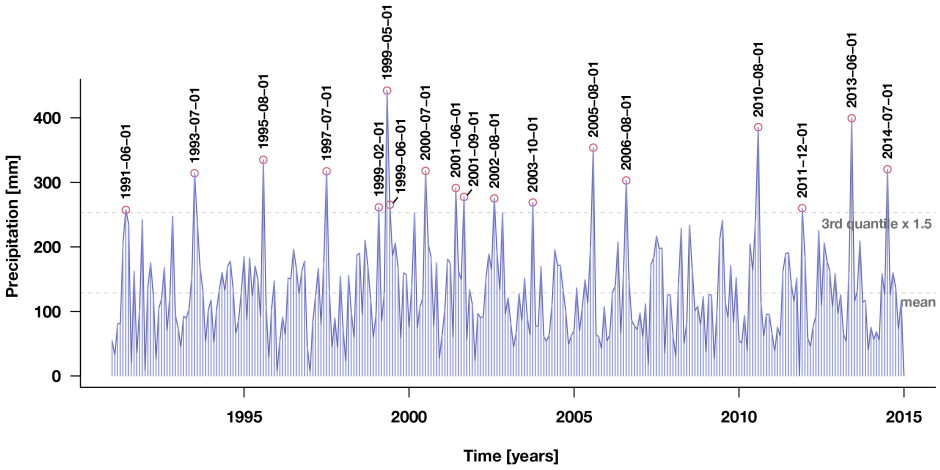

Figure 6.30: Precipitation from January 1991 to January 2015 and months with extreme rainfall events.

Chapter 7

Discussion

An analysis to determine years showing events on shallow landslides in the Dreiklang area in Vorarlberg was performed with three species - *Picea abies Karst.*, *Fagus sylvatica L.* and *Betula pendula Roth.*. In addition, a reference chronology of trees growing on a stable slope was created for each of these species. To determine events with the eccentricity index after Wistuba et al. (2013), a reference threshold was calculated. Afterwards, the analysis of *Picea abies Karst.* was conducted to verify the first hypothesis that aimed to answer if the eccentricity threshold identifies years of activation on the sliding surface with annual resolution. The same procedure was performed for *Fagus sylvatica L.* to address the second hypothesis, whether *Fagus sylvatica L.* shows the identical reactions as *Picea abies Karst.* in the same site. Individuals of *Betula pendula Roth.* were analyzed additionally to see how their reaction to stress can be compared to *Fagus sylvatica L.* in order to verify or falsify hypothesis III.

7.1 Reference Chronology

A reference chronology is essential in every dendrogeomorphological study to date the disturbed trees and is a common technique since the early beginnings of research in this field (Alestalo 1971). The reference chronology serves to crossdate the disturbed samples and to find the correct year for every tree ring. The results of the reference chronology will be discussed here, as it is important to reveal chronology quality for further dating of the potential years revealing landslide activation.

The three chosen species for this study were checked in advance with results of former studies for their ability to be crossdated. The CDI marks a

value of 2 for *Picea abies Karst.* and *Fagus sylvatica L.*, which means that it is possible to crossdate individuals spread over a region. *Picea abies Karst.* was used in many dendrogeomorphic studies before and proved to be a species that can be crossdated easily (Tumajer and Treml 2013). Still, many samples showed series of narrow rings or density fluctuations, what can be related to intra annual climatic changes or changes in soil water reserve (Bouriaud et al. 2005). Studies showed that *Fagus sylvatica L.* can be crossdated even when suppressed (Grundmann et al. 2008), but the climatic signal is rather weak (Dittmar et al. 2003). Literature about the potential of *Betula pendula Roth.* for crossdating is scarce, but some studies addressed this species: *Betula pendula Roth.* can also be crossdated but is marked with a CDI of 1, which indicates that the trees of a site can be crossdated within a site (Grissino-Mayer 1993). Therefore, close by reference trees to the site of the disturbed trees were chosen to increase the quality of the chronology.

In former dendrogeomorphological studies the amount of samples used differs: The number of individuals in reference chronologies varies with 12 (Wistuba et al. 2013), 20 (Šilhán et al. 2016), 22 (Grundmann et al. 2008) or 32 trees (van den Eeckhaut et al. 2009). In this study 15 trees were collected for *Fagus sylvatica L.* and *Betula pendula Roth.*, whereas 20 trees where sampled for *Picea abies Karst.*. This amount lies within the number of collected samples from former studies. The lower amount of individuals of the two hardwood species was determined by the availability of trees on a stable slope. Especially for *Betula pendula Roth.*, the coring of trees that are old enough for crossdating turned out to be a challenge. As already mentioned by Schmaltz et al. (2017), single *Betula pendula Roth.* trees are mixed within timber stands of other species and no site of this species growing on a stable slope could be detected. In addition, the CDI of *Betula pendula Roth.* indicates that the trees can be crossdated in one site, but poses challenges when they are in the same region. Hence, additional sampling in the other parts of the valley was not performed. It would be desirable to use an amount of at least 20 individuals of every species for the calculation of a reference chronology.

The measurement of the samples was conducted with two methods. First, the samples were scanned with a resolution of 2400 dpi to measure them with CooRecorder. As series of narrow rings occurred in these samples, the resolution was in some places not high enough to determine every ring. In addition they were measured with the TSAP-Win™ measuring table. A convenient consequence was the secure measurement of narrow rings. However, the scans had the advantage, that the data could be accessed and checked again for comparison. This provided the opportunity to identify sec-

tions with growth anomalies and to add comments. The reproductivity of the measurements was provided due to this possibility. For future applications, a combination of the two methods or an increased resolution of the scans is recommended. High resolution photography could therefore be a technique to improve the measurement procedure.

The age of the sampled trees is also affecting the quality of the chronology. In an area like the Dreiklang, the forests are managed, so the maximum age of trees decreases. Casteller et al. (2007) already stated that the average age in a timber stand decreases due to forest management. Age and stem diameter are not forced to be related, but still the trees with the largest diameter should be sampled to be used as a reference. In this study, the trees of *Picea abies Karst.* were cored in two different sites that showed differing ages: in the first site, the age ranged between 20 and 35 years and in the second between 101 and 168 years. This difference in age causes a jump in mean ring width of the reference curve from the 1970ies on. The annual rings in younger trees are wider than the ones developed with increasing age, so the mean ring width in the younger samples is higher and manipulates the mean ring width in the chronology. As the climatic signal has to be recorded to exclude jumps in growth caused by good conditions and their misinterpretation as an event, this has to be taken into account. In order to avoid this issue, the chronology was detrended with a spline for crossdating. For *Fagus sylvatica L.* and *Betula pendula Roth.* the jump in age was not an issue, but the trees of *Betula pendula Roth.* also showed challenges due to their age. Despite sampling trees with large stem diameter, the trees turned out to be relatively young. Correlation of segments can only be conducted with an minimum age of 20 years (Grissino-Mayer 2001). In addition, several studies exclude the first 30 years from a chronology as the early growth is often differing from the climatic signal (Schweingruber 2012). Some trees had to be removed because of this issue, what leads to an decreasing amount of samples and poses a threat for the quality of the chronology. Ultimately, additional samples have to be collected if possible, as not every sample is suited for crossdating.

Growth anomalies as scars or missing rings are known to pose problems for crossdating. Missing rings were identified in every of the three species used. Carrara and O'Neill (2003) identified missing rings in *Picea abies Karst.* and Grundmann et al. (2008) detected a maximum of 36 missing rings in *Fagus sylvatica L.* in one tree. Other authors found up to 15 (Rozas 2003) or 16 missing rings (Bonn 1998). Grundmann et al. (2008) in turn, argue that an amount up to 25 missing rings can be plausible. They further add that these values have to be seen in relation to the age and environment of the

trees, as industrial smoke, defoliation, summer drought or spring frost can cause missing rings. In this study, a maximum of 5 rings was found in a tree of 91 years, which was assumed as a reasonable value compared to former studies and the managed environment.

Besides missing rings, other growth anomalies such as abrupt increases of annual increment have to be taken into account. These changes in the reference chronology have to be noted and checked for the event identification later. When growth increase represents favorable conditions due to climate or reduction of concurrence, it should not be misinterpreted as an onset of growth due to stabilization. In the results of the chronology of *Fagus sylvatica L.*, jumps in growth can be seen in 1931, 1974 and 2001. As the area is used for forestry, clear cutting in the direct environment of the trees can be assumed. This indicates that the analysis of trees in managed areas has to be performed with caution as local factors influence tree growth.

It was possible to crossdate most of the samples of all three species, but missing rings and growth anomalies occurred in all of them. Samples that could not be dated were either too young or too disturbed. It can be assumed that the loss of samples while crossdating is lower when the tree's age exceeds 50 years. The last step was the calculation of a mean value curve. To check its quality, a mean series intercorrelation was calculated. A value of 0.49 for *Picea abies Karst.*, 0.44 for *Fagus sylvatica L.* and 0.52 for *Betula pendula Roth.* could be achieved. Also in this case, the values were compared to other studies to see whether the chronologies are suited for further dating of disturbed trees. For *Picea abies Karst.*, a value of 0.41 was presented by Lévesque et al. (2013). With a value of 0.49, the mean correlation in this study is slightly higher, though it remains under the desired value of 0.5. For *Fagus sylvatica L.* former studies presented following values: 0.37-0.59 (Roibu et al. 2017), 0.67-0.83 (Van der Maaten 2012), 0.16-0.69 (Hartl-Meier et al. 2014). They show that high correlations can be achieved with *Fagus sylvatica L.*. The results for the interseries correlation in this study are within the range of other studies, though it would be desirable to have a higher amount of samples, in order to achieve more stable results.

7.2 Reference Threshold

The reference thresholds for the three species vary from each other. *Picea abies Karst.* shows the smallest range with 54,74% to -55,65% and has the highest sample depth. *Fagus sylvatica L.* shows a range from 70,79 to -71,87% and *Betula pendula Roth.* from 112,39 to -98,13%. All three species

do show outliers. As there was just one tree in *Picea abies Karst.* that showed extreme outliers, it could be removed. The other two species showed too many trees with outliers to ensure that they were exceptions. The threshold of *Picea abies Karst.* lies within the range of the ones published in other studies: Wistuba et al. (2013) calculated a threshold of 59.39% and -63.04%, Malik and Wistuba (2012) presented a span between 56.38 and -59.54% and Łuszczyńska et al. (2017) values ranging between 32.79% and -38.81%. *Fagus sylvatica L.* shows values slightly exceeding these numbers, but there is still no published research on the intensity of eccentric growth in *Fagus sylvatica L.* on stable slopes to compare them. For *Betula pendula Roth.*, the values lie clearly above the percentages of the other species. This can be related to several reasons: On the one hand, the sample depth from trees that could be crossdated and where still both samples could be used is very low. On the other hand, the trees were younger than the ones of the other two species. The age of the species influences the eccentricity as a young tree is more prone to mechanical stress from wind or other sources than landsliding, what could lead to a higher sensitivity. Further, the rings of *Betula pendula Roth.* can be very wide as the mean ring width shows. So the value's variance can increase and cause high values for the intensity of eccentric growth. Corona et al. (2014) stated that sample size is crucial for the determination of thresholds. As already explained in the preceding section, we strongly recommend to increase sample depth and age for further research on the eccentricity of this species.

7.3 Event Identification within *Picea abies Karst.*

The calculation of the eccentricity index for *Picea abies Karst.* identifies activation years on a shallow landslide in site II. In former studies *Picea abies Karst.* was used to reconstruct landslides of different types (Bollschweiler et al. 2007, Malik et al. 2016, Šilhán 2017). They all concluded, that *Picea abies Karst.* is suited to reconstruct spatial and temporal patterns in mass movements. In this study, the method was not only applied to *Picea abies Karst.*, but also to *Fagus sylvatica L.* and *Betula pendula Roth.*. However, the first step is to show if the eccentricity index is suited to reconstruct the patterns of movement on landslides in this specific site. Therefore, events were defined visually through the onset of eccentricity and the properties of the wood. Afterwards the eccentricity index after Wistuba et al. (2013) was calculated to compare the results. Four trees of *Picea abies Karst.* were described in detail in chapter 6.3.1. The results are discussed in the first section of this chapter, before hypothesis I is answered, as it is relevant to understand

possible weaknesses of the methods used.

The tree *Picea abies Karst.* 02 shows four onsets of eccentricity in the raw ring width, but only three are displayed by vEix[%]. In 1957, the upslope sample shows a higher growth rate in comparison to the same ring in the downslope sample. The calculated indices show events due to a variation in the eccentricity compared to the previous year. Looking closer at this specific pair of growth rings, a resin duct canal can be seen in one of the samples that is responsible for the differing ring widths. Resin ducts can occur because of geomorphic events such as rockfalls, avalanches or debris flows (Stoffel 2008, Schneuwly et al. 2009, Gärtner and Heinrich 2009). However, in this case no core was taken in another height of the same side of the stem, so an event cannot be certainly defined in this year. 1968 shows a clear onset of eccentricity that does not exceed the threshold of vEix[%]. This can occur, because the stronger growth in the downslope sample is already appearing in the years before, so the variation in comparison to the previous year is not high enough to exceed the threshold. Comparing 1968 and 1976, the difference in ring width is much lower in 1976 than in the former. Still it is reflected in vEix[%]. The onset of eccentricity in 1995 is also not intense in comparison to the year before, which is the reason that it does not appear in vEix[%]. These examples show, that it is not easy to define events only due to one method. Visual examination of the onset of eccentricity shows other results than the calculation of vEix[%]. In addition, compression wood occurs in more years than the ones marked in figure 6.9. Moreover, the tree shows a growth curve similar to the reference curve. These do also display an increase of annual growth beginning in the year 2000. Besides climatic conditions, which can explain that this signal can be found again in a tree further away from the reference site, the human impact has to be taken into account. Clearing of forests can lead to increases in the growth rates due to a decrease of concurrence in the site (Briceño-Elizondo et al. 2006). Both areas, the reference sites and the landslide area are managed. Several trees were cut in this area, which can lead to less competition for sunlight and nutrition and hence induce an increase in growth rate.

In the tree *Picea abies Karst.* 03, the results of the visual detection of the onset of eccentricity and the calculation of vEix[%] are nearly consistent. The first striking onset of eccentricity can be seen in 1907, where the downslope side of the tree experienced a large growth increase. After this event, both sides of the tree grow eccentric again over time. Consistent periods of mechanical stress with both methods can be dated from 1933 to 1936. An onset not recorded by vEix[%] can be seen in 1951 and 1967. In the years 1994, a year of onset of mechanical stress is recorded by both methods. Even though

the onset of eccentricity in 1999 is minimal in the raw ring width, the calculation of vEix[%] points it out intensely. This does also stress an advantage of the use of an index, as it does not miss these changes. For all identified events in this sample reaction wood was detected. However, reaction wood can again be identified in more periods than the ones indicated. This shows that eccentricity and reaction wood have to be inspected in combination to achieve reliable results. The occurrence of reaction wood without eccentric growth was also observed by other studies. Duncker and Spiecker (2008) reviewed the statistical relation between eccentricity and compression wood in *Picea abies Karst.* and observed positive correlations between these two reactions, but sections can be found that show compression wood without eccentric growth and vice versa.

The examination of the results for *Picea abies Karst.* 07 shows that visual identification of the onset of eccentricity, reaction wood occurrence and the analysis of vEix[%] can differ. The first three rings displaying eccentricity in the beginning of the core lie within the first 25 years of the tree's life. As trees with less stem diameter could potentially compensate mechanical stresses not induced by landsliding, such as wind, with eccentric growth, these years should not be considered for further analyses. Looking at the ring width curve, the onset of an event takes place in 1968. Nevertheless, reaction wood occurs from 1980 on and continues appearing throughout the whole sample. A more detailed view on the sample shows a series of very narrow rings before 1968. Consequently, the onset of eccentricity could also be an indicator for the release of growth suppression. The fact of the three methods showing different years for the occurrence of events, points out the complexity of landslide reconstruction with the properties of tree rings.

As in Tree 07, tree *Picea abies Karst.* 08 also shows different results for the analysis of eccentricity and reaction wood. One year has to be inspected more detailed to understand the relation between the raw ring width and vEix[%]: An onset of eccentricity takes place in 1978, but the index records an onset of eccentricity in the opposite direction in the year 1980. It is not clear, whether 1978, 1980 or both represent an event. When calculating the variation of the eccentricity Index, the difference to the year before is taken into account. Subsequently, an onset of eccentricity in one year being less intensive will not be recorded as an event as in 1978. Therefore the calculation of vEix[%] does provide a useful tool for intensive eccentric growth, but not for a gradual onset of it. This has to be considered when examining slow landslides that move over several years.

Picea abies Karst. 04 shows indications of stabilization throughout the whole curve. The downslope sample shows permanently larger rings than

the upper one and reaction wood can be identified in every ring. The event dated in 1957, shows an increase of the upslope ring. This could take place due to ground movement that tilts the tree in upslope direction, but could also be a growth increase related to another growth controlling factor. Still, the growth of the upslope sample drops again in year 1959, which increases the probability of mechanical stress. Due to this sample no distinct event can be identified, but it clearly indicates, that the tree is experiencing mechanical stress. This example illustrates again the necessity of a reasonable amount of samples, since a tree showing reaction wood in every year could also have experienced snow pressure. Although tree 09 is located next to tree 07, which shows eccentric growth, it does not display a particular reaction to mechanical stress. *Picea abies Karst.* 11 stresses that sample depth of a dendrogeomorphological study has to be high enough, because the possibility remains that mechanical stress is so intense or overlaid by other factors, that crossdating is not possible anymore, as missing rings can occur. Without identification of particular years, no exact date of the landslide activity can be found and therefore the onset of activity not be dated. In this case the tree experienced mechanical stress that lead to tilting in different directions. Also for *Picea abies Karst.* 12, the development of eccentric rings changes from the upslope to the downslope side of the stem. In summary, *Picea abies Karst.* in this location shows changes of eccentricity from up and downslope and reaction wood. Every individual analyzed displays different years and patterns of reactions. This can be seen as an indicator for changing dynamics of the landslide in the different locations.

In the visual determination of the events, several circumstances can lead to misinterpretation, making the checking of samples individually essential. When growth anomalies occur, the rings can be wider in one part of the stem and therefore mistakenly interpreted as events. Rings can be wider due to a row of resin ducts (*Picea abies Karst.* 02) but also due to formation of scars. Both can be related to mechanical stress, but a certain event cannot be recorded without further information. The results showed that forestry can lead to an increase of growth due to declining competition within the timber stand, so growth increase has to be carefully checked on both sides of the stem. Further, the tilting direction can vary during the early life of a tree because of other factors than mechanical stress, e.g. low resistance to wind. Therefore, events in the early life of a tree have to be treated with caution. However, events can also be missed, as they can be overlaid by former reactions to mechanical stress. An example can be seen in *Picea abies Karst.* 03, where eccentric growth sets in within 1933, but the actual event probably occurred in 1935, where reaction wood occurrence begins. The analysis of the

eccentricity index can also lead to underestimation: Events can be missed if the growth of the annual rings follows the same trend, but one side develops wider rings gradually. This slow increase of ring width can be seen in *Picea abies Karst.* 02 or *Picea abies Karst.* 07, where no events that exceed the threshold are marked. Often, the variation of the index does also show two years in a row exceeding the threshold. The first year marks the actual year of the event and the next one indicates the return to former growth directions. Due to these factors influencing the interpretation of the data, the results displayed by the methods used are compared within the following section.

7.4 Comparison of visual Event Definition and vEix[%] in *Picea abies Karst.*

In figure 6.16, the events recorded by both methods are compared. Only 35.7% of the events were detected both, visual event identification and the calculation of the eccentricity index. Sections showing more than one event in the same period were found between 1955 and 1960, 1965 and 1970 and in 1990-1995. These results show no distinct years indicating an abrupt failure of the slope, but periods where more trees show reactions to mechanical stress. Regarding this circumstance, Malik and Wistuba (2012) mention in their study, that one year was indicated by various trees, but some individuals showed the signals in the two years before. This can already mark the beginning of the movement, which can also be the case in the site of this study. Malik et al. (2016) found that eccentric growth shown by only few trees can be indicators for low displacement rates that indicate the failure of the slope in the future. Furthermore, they found that due to the morphology of the slope examined, trees showed reactions in almost every year what is also the case in this site. Small displacement can precede larger events, what can be interesting for the management of the area. Therefore, reasons for the diffuse distribution of mechanical stress detected by both methods can be related to the dynamics of the shallow landslide. These landslides can be slow and only being moved partially, subsequently explaining the minor amount of trees per year showing mechanical stress.

Nevertheless, the methods applied have to be accurate to achieve solid results. Hypothesis I aimed to answer, whether the known methods are suited for the temporal reconstruction of the shallow landslide in site II:

> *I. The calculation of the eccentricity index for Picea abies Karst. identifies activation years on a shallow landslide.*

Wistuba et al. (2013) developed the eccentricity index used in this study and argued that it has advantages in comparison to former developed indices: It provides the possibility to take differing tilting directions within the slope into account and displays the first year showing eccentric growth which can date an event. Further, the intensity of eccentricity is displayed and the method was successfully applied on more than one location, which stresses the applicability of the method in other regions. However, it is further stated that an annual resolution is possible for the reconstruction, which could not be confirmed in this very study as the results with the manual identification of events differ and the landslide is not monitored so the exact spatial distribution of mechanical stress cannot be verified. The aspects discussed in the event determination show the following point concerning the aspects addressed within hypothesis I:

- With both methods all three cases can occur: correct identification of events, but also under- and overestimation
- Growth anomalies can lead to an overestimation of events
- Events can be masked by former onset of eccentric growth
- Growth increases due to forest management potentially overlying the signal of mechanical stress
- Abrupt increase of the rings without eccentric growth are not recorded as an event
- Reaction wood occurs in most of the samples, but can occur without eccentric growth and vice versa
- The reference threshold could in some cases be too high and underestimate the years with events

These details still pose challenges for the reconstruction of the landslide on an annual resolution. Therefore, the hypothesis cannot fully be verified. Site specific conditions can pose challenges in the reconstruction of landslides with the eccentricity index used do only allow the definition of periods of activation. However, the results of the analysis of the methods show that it is essential to discuss opportunities and challenges to define events. Without the knowledge on the cases that can lead to misinterpretation of the growth curves, a comparison between soft- and hardwood species would not be applicable. In the following section, the results of the comparison between *Picea abies Karst.* and *Fagus sylvatica L.* will be discussed regarding the results of the analysis in this chapter.

7.5 Event Identification within *Fagus sylvatica L.*

The distribution of trees on site II provided the possibility to compare the reaction to mechanical stress of two species. *Picea abies Karst.* and *Fagus sylvatica L.* are evenly distributed on the mass accumulation zone of a landslide in the BioSlide study area. The species were analyzed separately to evaluate the methods used before the comparison of their reaction. In the preceding chapter, the implemented methods showed challenges while defining exact years that show signs of mechanical stress in *Picea abies Karst.*. Still, both methods were applied to the trees of *Fagus sylvatica L.*, to see whether they show the same challenges within the method. Two individuals showing differing results were presented in detail in chapter 6.3.2.

Fagus sylvatica L. 02 is located in the upper part of the sampling area and develops stronger rings throughout most parts of the sample. Former studies showed, that tension wood in hardwood species develops in the upslope part of the tree (Gärtner 2003*b*). Therefore, it was expected that wider rings would be discovered in the upslope part of the stem, when the individual is exposed to mechanical stress. The results of the trees for *Picea abies Karst.* already showed, that the trees do clearly show signs of mechanical stress in the site. Yet though, the detailed reaction of the hardwood individuals is of interest. In this case, five periods of potential mechanical stress could be determined. The first period had to be rejected, because it occurs in the very beginning of the tree's life, as performed in the analysis of *Picea abies Karst.*. Further, the tree shows the onset of a reaction in 1953 and the development of wider rings lasts for the following 22 years. This change of growth direction is also recorded by the calculation of the eccentricity index, which is also the case in 1984 and 2000. Nevertheless, the tree also shows a period, where the variation of eccentricity shows its weaknesses: In the period between 1975 and 1984, the rings in both sides decrease and start nearly growing concentric. The ring width values are so similar that even small differences in dominating growth direction are recorded as events by the eccentricity indices. This shows, that also in this case, the inspection of the raw ring width cannot be ignored and quantification of the changes eccentric growth cannot be interpreted correctly without the corresponding raw ring widths.

A second tree (*Fagus sylvatica L.* 07), was described in detail, that is located on the margins of the sampling area. Good correlation values and a high Gleichläufigkeit could be identified here, which shows, that crossdating is possible, even with disturbed individuals of this species as assumed by Grundmann et al. (2008). This individual shows a different growth curve com-

pared to the previously discussed sample. No periods of significantly wider ring widths of the upslope sample can be identified, but the curve itself shows nine variations in the side with dominating ring width. Further, the curve does not follow the typical growth curve of trees, that show decreasing ring widths with increasing age (Rybnicek et al. 2010). Even though the side of eccentric growth changes that often, no year is shown that exceeds the eccentricity index. This can be explained with the gradual changes in ring width. The variation in eccentricity is calculated by the difference of the eccentricity in percent from a year to the preceding year. Therefore, the change has to be abrupt to be recorded. In this case, no event exceeds the threshold, so no event would be recorded. Looking at the thin section, a different image is presented. The tree shows tension wood in the upslope sample throughout most of the years (from 1942 on with only two years without tension wood). Therefore, the tree did react to mechanical stress and stabilized, but not with eccentric growth for longer periods as did *Fagus sylvatica L.* 02.

Both trees show a similar age and length of samples, still the results display highly different patterns. This can be related to the different location of the individuals: *Fagus sylvatica L.* 02 is located in the upper part of the sampling area and might experience stronger mechanical stress than *Fagus sylvatica L.* 07 that is located closer to the margins of the landslide. Shallow landslides can be complex in distribution and intensity of movement, but it can be assumed, that kinetic energy is stronger in the mid part than on the outer margins (Montrasio and Valentino 2008). The differing reaction of the two trees can be an indicator for that. In the close by environment of *Fagus sylvatica L.* 07 more trees are growing than in the environment of *Fagus sylvatica L.* 02. Tree roots of neighboring individuals can stabilize the ground and absorb mechanical stress (Gärtner 2003*a*), what can be another explanation for the less disturbed growth curve of *Fagus sylvatica L.* 07.

Also the other trees in the location show signs of mechanical stress. Sudden growth increases that last for longer periods can be found in *Fagus sylvatica L.* 04 and 09. They also show changes in tilting direction that were reflected by the eccentricity index. As in *Picea abies Karst.*, the variation of eccentricity showed two years in a row exceeding the reference threshold when the growth returned to former conditions after one year. This stresses again that the overestimation of events has to be taken into account when applying this method. *Fagus sylvatica L.* 10 points out the occurrence of another phenomenon already addressed within *Picea abies Karst.* 02. It shows an increase of ring width in both sides of the stem in the year 2000, which is also displayed as an potential event in vEix[%]. A possibility is the decrease of concurrence due to forest management. Another cause could be landslide

related uprooting of a tree in the near environment of this individual. These analyses show, that every tree has a very individual story, that is potentially influenced by multiple factors. Forest management, death of surrounding individuals or the complex structure of the slope can result in various patterns of tree growth curves. This makes the analysis very complex, what stresses the importance of a clear method to determine mechanical stress.

Therefore, the comparison between the visual onset of eccentricity and the years indicated by the variation in eccentricity in percent took place in the same way, as performed before in *Picea abies Karst.*. In this case, vEix[%] does not significantly overestimate years with mechanical stress, as the amount of trees indicating mechanical stress was the same. Figure 6.21 shows clearly, that the temporal distribution differs. While the visual identification of events shows less events in the first third of the analyzed period, vEix[%] shows a denser pattern of years that display mechanical stress in the individuals. The explanation of this circumstance lies within the strategy to manually exclude events in the early period of the trees life with visual event estimation. In the mid part of the examined period, both methods detect events, but in the last section the results differ again. Here, the visual estimation counts more years with events. A possible explanation can be that the calculation of vEix[%] does not count events that are displayed with gradual change in ring width or already overlay by the signal of a former event. Moreover, as it could already be seen in *Picea abies Karst.*, a maximum of two trees is recorded by both methods in the same year. This leads to the conclusion, that the diffuse temporal distribution of the onset of reactions to mechanical stress in site II is induced by the complex patterns of the landslide, because it could already be found in *Picea abies Karst.*.

The results of the two methods differ in both species, *Picea abies Karst.* and *Fagus sylvatica L.*. For a clear annual resolution, consistent, quantified results would be an aim to reconstruct the temporal and spatial pattern of the landslide. In cases of changes in tilting directions, two years are marked, leading to an overestimation of these events. Some other events are missed due to gradual increase of growth and events overlaid by former onsets of eccentricity cannot be recorded. Furthermore, the results seem to be age dependent. In the early life of a tree, eccentric growth can occur due to many factors as the stem does not yet have the properties to resist pressure. Later in the tree's life, the intensity of a reaction will be affected by the same properties, as a wider stem diameter could provide stabilization. However, the use of indices is important for the quantification of the results, as manually detected events can be missed and would be outpointed by calculated results.

7.6 Temporal Patterns of mechanical Stress in Site II

Within this section, the reaction of the two species to mechanical stress will be discussed. On the one side the mean ring width of the two species was calculated within chapter 7.1 and shows values of 1.60mm for *Picea abies Karst.* and 1.42mm for *Fagus sylvatica L.*. Softwood species develop wider rings on the downslope side of the stem, when they need to stabilize (Gärtner 2003*b*). This could be confirmed by calculating the percentage of rings showing downslope eccentricity in site II, which was shown by 65.06% of the trees. Moreover, the mean ring width of the downslope rings in site II of *Picea abies Karst.* showed a value of 1.75, which lies above the reference value. This indicates that the trees of this species do stabilize as expected with the formation of wider rings containing reaction wood. The same analysis was conducted for *Fagus sylvatica L.*. Hardwood species are known to stabilize upslope with the development of tension wood (Du and Yamamoto 2007). As 68.23% of the rings showed upslope eccentricity and tension wood was found, the general occurrence of mechanical stress can be confirmed. Further, the mean ring width of the upslope samples is with 2.15mm significantly higher than the mean ring width. This analysis shows that *Fagus sylvatica L.* develops the expected properties in response to mechanical stress previously used to reconstruct landslides with softwood species.

The goal, however, is to create a temporal reconstruction of the landslide with two species and not only the determination of mechanical stress in general. The cumulated comparison both species indicating events with both methods displayed two years of events, 1967 and 1981 showing the most consistent results. Many more individuals show single years with reactions to mechanical stress. Figure 6.22 shows the cumulated results of the eccentricity index. Even though the method has its weaknesses, as discussed above, it can give an idea of the temporal patterns of movement. It was renounced to display the same results of the visual event determination, as the quantification of the results should be a major goal in landslide reconstruction. The sample depth is not high enough throughout the whole period to reconstruct all areas of the sampling site. However, according to the results, the slope has been in movement for all the recorded period. Several periods of stable years can be seen, e.g. 1960 to 1965 or 2007 to 2010. Considering the type of landslide, these results could be taken as correct. Considering the differences between visual event identification and the index, the reconstruction is not displaying the exact temporal pattern of the landslide. Other studies showed the same problem of constant signal of mechanical stress that did not allow a clean annual reconstruction of the landslide (Gussenstätter and

Bräuning 2004).

To validate the results, rainfall data was analyzed for the occurrence of extreme events. As shallow landslides can be triggered by long rainfall periods or extreme precipitation within a few days (Corominas and Moya 1999, Guida et al. 2016, Kashiwaya et al. 1989), the data gives additional insight in the temporal patterns. Figure 6.30 shows the months that exceeded precipitation sums of 253.05 mm. Events with intense precipitation occur regularly every two years. The only exception is the period from August 2006 and June 2010. Comparing this to the results presented before, one period without any reaction in trees have been the years 2007 to 2010. This shows, that the method does still, even when having weaknesses show correct results for the reconstruction of landslides with soft- and hardwood species.

Hypothesis II targets to evaluate the suitability of *Fagus sylvatica L.* in comparison to *Picea abies Karst.* for the reconstruction of landslides:

> *II. Softwood and hardwood species on the same shallow landslide do show signs of mechanical stress in the same years.*

The first aspect of the hypothesis can be verified, as soft- and hardwood species do show sings of mechanical stress, as expected.

- *Fagus sylvatica L.* turned out to be suited for crossdating, also if disturbed by mechanical stress
- In *Picea abies Karst.* a dominance of downslope ring and compression wood was found. Also in *Fagus sylvatica L.* the occurrence of eccentric growth in the upslope parts of the stems was found in the major amount of the samples
- Tension wood could be detected
- Further processing of the eccentricity index is needed to obtain exact, quantified results on the temporal pattern of mechanical stress

These aspects make *Fagus sylvatica L.* suited for the detection of mechanical stress. However, the second aspect addressed in hypothesis II cannot be verified. An secure annual identification of events was not possible with the quantifying method used in this study. This circumstance is not species related, as the same issues in the dating of events occurred already in *Picea abies Karst.* and are therefore related to the methodological approach.

7.7 Event Identification within *Betula pendula Roth.*

Next to *Fagus sylvatica L.*, the growth changes due to mechanical stress within another hardwood species were examined: for *Betula pendula Roth.*, onsets of eccentric growth and occurrence of tension wood were detected. Furthermore, the development of the ring width within this species was inspected and compared to the other two species.

The first sampling site is a stand of *Betula pendula Roth.* in the lower part of a landslide mass, were no further date is available on the activity. The dating of the trees in this location posed some challenges: First, the trees are not evenly distributed on the sampling area. When dating mechanical stress in an area, the goal should be to have a raster of evenly distributed trees. In this case, nine trees were sampled in the lower part of the landslide, as no more trees were available (see figure 6.23). The next fact, that poses difficulties for event dating in this site, is the age of the trees. In dendrochronology, a minimum age of 50 years (Schweingruber 2012) is recommended for the achievement of meaningful results. On the one hand, correlations that are used for crossdating of trees are not significant below a length of 30 years and on the other hand, the growth of a tree in its early life is not following the same growth trends as afterwards, and the rings widths are wider. Another challenge while dating events, is the preparation of thin sections. In this case, for five out of nine sampled trees, thin sections were available that covered the whole sample. For the other trees, the sections could be produced partly, but not crossdated as they were too short. This reduced the amount of samples drastically, so that dating of the events on this site could not be performed in detail. The procedure was still performed to examine what signs *Betula pendula Roth.* can provide for the dating of mechanical stress.

The visual determination of events revealed onsets of eccentricity in six years. Tension wood was not found in all the samples, so it is questionable if the eccentricity is related to mechanical stress. The calculation of vEix[%] showed onsets of eccentricity in 13 years, which doubles the amount of years detected by the first method. Still, it has to be mentioned that both methods detect an increased amount of events starting from the years 2004 to the year 2011. Due to the same challenges discussed in the precious sections, the exact onset of mechanical stress cannot be determined on this site. The results do indicate an onset of mechanical stress in the mentioned period, but as the trees are only distributed in one part of the landslide body, the amount of samples is not sufficient and the age of the trees does not exceed 30 years. An interpretation has therefore to be treated with caution.

A goal of the study was to determine if the indicators of mechanical

stress do also occur in *Betula pendula Roth.* and how they appear in comparison to the other examined species *Fagus sylvatica L.*. In Site I, 74.04% of the rings of all trees showed upslope eccentricity, whereas 25.19% show downslope eccentricity. Generally assuming that upslope tilting results in upslope eccentricity as tension wood occurs upslope in hardwood species, they are suited to be used for reconstruction. However, growth is genetically driven (Schweingruber 1996) and has therefore to be examined for every species individually. The reference trees of *Betula pendula Roth.* showed the largest mean ring width with 2.85mm compared to the two other species. The mean ring width of the upper and lower samples is exceeding the reference ring width. Furthermore, the upslope rings are wider than the downslope rings. The increased ring width can be related to site specific factors, as the area is not densely populated with individuals. Still, the dominance of upslope rings shows, that the species is suited to reconstruct mechanical stress.

Further, three individuals were examined that were growing in a site showing tilted stems, which is not mapped as a landslide in the inventory. Also these trees posed the problem to be very young. Consistent eccentric growth was found in the year 2002, but the detailed approach to identify single years with indication of mechanical stress is questionable because of the young age. Still, the occurrence of eccentric growth was checked to compare it to the results of site I. In this case up- and downslope eccentricity is almost evenly distributed with 55.71% of the rings showing downslope eccentricity and 44.28% showing upslope eccentricity. The mean ring width in this location is below the average of the references. The upslope rings are slightly stronger developed as the downslope rings. Regarding these results, no clear signs of mechanical stress due to landsliding can be found in this site. The occurrence of growth changes in the trees of site I stresses this conclusion.

To examine whether hardwood species are suited for the reconstruction of landslides, *Betula pendula Roth.* was analyzed as a second species next to *Fagus sylvatica L.*. Therefore hypothesis III was formulated:

> *III. Betula pendula Roth. shows eccentric growth and tension wood due to mechanical stress induced by a shallow landslide.*

Also for this species, the following points could be stated:

- Trees of *Betula pendula Roth.* can be crossdated, even when disturbed
- *Betula pendula Roth.* shows increased ring width on the upslope site when experiencing mechanical stress
- Tension wood can be found with the production of thin sections
- The analysis should be performed in further studies with older individuals

This species proved to be suited for the reconstruction of landslides as well. However, the discussion of the results showed several challenges within this species. As a first aspect, *Betula pendula Roth.* is less easy to crossdate as *Picea abies Karst.* and *Fagus sylvatica L.*. This can lead to a temporal misinterpretation of the dating, when performed on an annual basis. Further, the annual increment of *Betula pendula Roth.* is higher than of the other two species. This can lead to the sampling of young trees, where signals have to be interpreted with caution. *Fagus sylvatica L.* turns out to be more suited for the analysis of landsliding. Nevertheless, *Betula pendula Roth.* is known to be a pioneer species (Zhantlessova and Zhumadina 2015). Therefore it can populate areas, that have complex hydrological conditions or experience regular slope failure. Regarding these aspects, it would be highly interesting to learn more about the responses of *Betula pendula Roth.* to mechanical stress.

7.8 Conclusion

A dendrogeomorphological analysis was conducted on three different sites, containing three different species. In two sites, mechanical stress could be detected. In these sites, trees of the species *Picea abies Karst.*, *Fagus sylvatica L.* or *Betula pendula Roth.* occurred. A goal of this study was to examine the suitability of hardwood species to detect mechanical stress. Therefore three hypotheses were formulated to answer the main research question:

Are hardwood species sensitive for reconstructing landslide movements?

The first hypothesis evaluated if a temporal reconstruction of the landslides was possible with the latest developed eccentricity indices. It showed that the index has advantages, as it considers different tilting directions of the tree, but still there are some challenges. Growth anomalies, masking of signals due to former signals, growth increases due to forest management and the slow, continuous movement of the shallow landslide posed problems in determining single years for events. Both, overestimation and underestimation of the occurrence of mechanical stress took place through the calculation of the variability of eccentricity. Therefore, no detailed spatial reconstruction of the landslide was performed here, as only periods of movement could be assumed.

As a consequence of the fact that single years could not be compared in the different species, their general behavior was examined to answer the second hypothesis. It aimed to answer if the same years of mechanical stress could be identified in *Fagus sylvatica L.* that was growing in the identical site as *Picea abies Karst.*. Analysis of eccentric growth showed a clear dominance of upslope eccentricity and the occurrence of tension wood. Also, the detailed analysis with the eccentricity index was conducted, but posed the same challenges as in *Picea abies Karst.*.

One species would not be sufficient to evaluate the suitability of hardwood species for dendrogeomorphic studies. Therefore, *Betula pendula Roth.* was used as a third species. A site containing *Betula pendula Roth.* next to the site of *Picea abies Karst.* and *Fagus sylvatica L.* was available and analyzed. The trees here showed upslope dominance of ring width and the occurrence of reaction wood. Issues for a detailed analysis turned out to be the young age of the trees.

Despite challenges within the methods used, it can be stated that hardwood species are suited for reconstructing landslides. They develop the same reactions as softwood species, that were used in former studies to

reconstruct mechanical stress. This aspect opens up many methodological possibilities in the field of dendrogeomorphology and potential study areas for future research.

Chapter 8

Outlook

This study on the suitability of hardwood species for reconstructing landslides gave not only insight on the reaction of hardwood species to mechanical stress, but also on some methodological aspects that can be included in future research.

On one hand, it could be demonstrated that hardwood species show similar reactions as softwood species to mechanical stress and can therefore be used for dendrogeomorphogical studies. *Fagus sylvatica L.* can be crossdated, even when growing on disturbed sites and shows upslope eccentricity and tension wood. For *Betula pendula Roth.* the examination displayed also the same results, but more research is needed with older trees to inspect whether the results of this study are generally applicable. Furthermore, *Betula pendula Roth.* is harder to crossdate, as shown in former studies (Grissino-Mayer 1993). This points out that the study gives information on the suitability of hardwood species in dendrogeomorphology, but every species has to be treated individually. Evaluation of other species would be desirable to answer the main research question on this topic to its full extent, before being able to develop a standardized threshold as recommended by Corona et al. (2014) for hardwood species.

The results of *Fagus sylvatica L.* and *Betula pendula Roth.* showed that species have different wood properties, what results in differing patterns in formation of reaction wood, eccentric growth or periodic decrease of growth. The relationship of eccentric growth and reaction wood within a species does still need more research. Experiments have been conducted to examine the mechanical reaction of different species to mechanical treatment (Peltola et al. 2000, Heinrich and Gärtner 2008, Nugroho et al. 2018, Roignant et al. 2018). This gave interesting insights into a tree's reactions and stabil-

ity when exposed controlled mechanical stress. Including this information on wood properties into dendrogeomorphological studies on landslides would be interesting, as it could provide kinetic details on landslides, which are only recorded passively (Pawlik and Šamonil 2018).

In addition to the detailed properties of wood in the species and their reactions, a verification with already examined landslides would be of interest when using new species. In this case, the pattern of reactions fitted to the properties of a shallow, slowly moving landslide and the precipitation record, but real verification of the method with a monitored landslide was not yet performed. For unequivocal testing of new species, we recommend sites with abruptly moving slopes, as some of the challenges within the use of the eccentricity index results from slow movement and gradual increase of mechanical stress.

Next to the results on reaction to mechanical stress in hardwood species this work also showed some methodological challenges in this field. For some issues such as the length of thin sections, research has already developed new techniques for the production of complete core sections (Gärtner et al. 2015). Challenges like the age of the trees, an increased sample depth needed, or the production of long thin sections can therefore be overcome with sufficient resources. Still, former studies stated that an annual resolution can be achieved with the calculation of the variability of eccentricity indices (Malik et al. 2016). The results on the eccentricity analysis in *Picea abies Karst.* in the site examined in this study showed several issues for the annual reconstruction. Therefore, it should be considered to add additional aspects to the calculation of eccentric growth. Growth anomalies that are not induced by mechanical stress have to be included in the dataset from the beginning, as they manipulate the results of the index. Further, years of clearing due to forest management should be added. Another aspect has been the differing age of the samples. Even if it is desirable to perform studies in sites with trees of equal ages, these will be scarce in reality. Tilting directions in the early age of a tree can be varying due to other factors as landsliding and manipulate the frequency of events. Studies showed that the ability of trees to record mechanical stress is age and stem diameter dependent (Šilhán and Stoffel 2015). This means that the above mentioned experiments could give insight on the impact of stem diameter on the development of eccentric growth or reaction wood formation, as it is likely that these factors influence the resistance to mechanical stress. Moreover, stand density and therefore the root network absorbing kinetic energy could be another factor influencing these reactions (Gärtner 2003*a*). Due to this, the density of the population might be another interesting aspect to include into the analysis. To insert quantified

data of the reaction wood occurrence would be an additional point. These aspects show, that various factors could be added to create more reliable results. They could be included to calculate the probability of a signal in a tree being induced by mechanical stress. Only, if the temporal reconstruction of mechanical stress on a landslide is completely certain, it can be a profit for future landslide inventories.

All in all, the opportunity to use different species to reconstruct landslides opens up many possibilities, as hardwood species are widely spread over Europe (Schweingruber 1983). Still, reactions to mechanical stresses of the different species are influenced by various factors, that could if integrated into the current approaches, give a more distinct image. The growth patterns of trees do record all these factors and provide therefore the possibility to learn much about their environment and the different driving forces within a system (Bollati et al. 2018). Although dendrogeomorphological research has been very active in the last decades, many aspects remain to examine, what makes the work with growth patterns of trees and their anatomical properties an interesting field in science for the future.

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Appendices

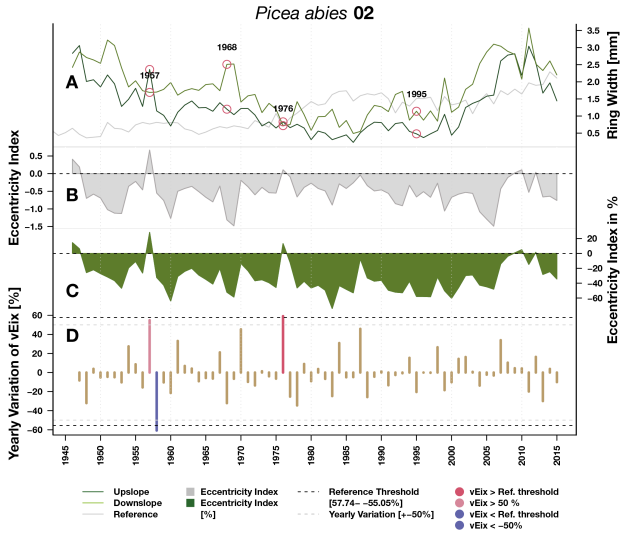
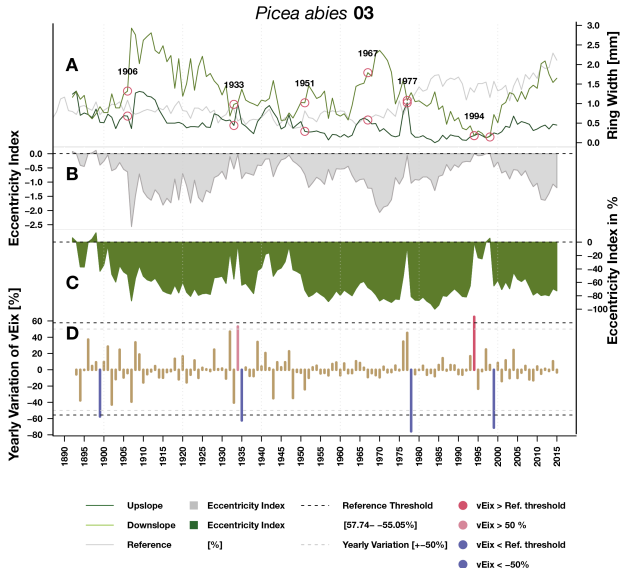


Figure 1: *Picea abies Karst.* 02 in site II



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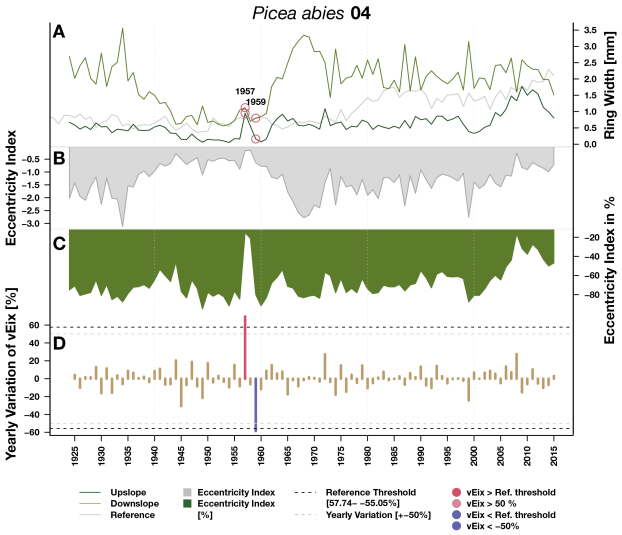

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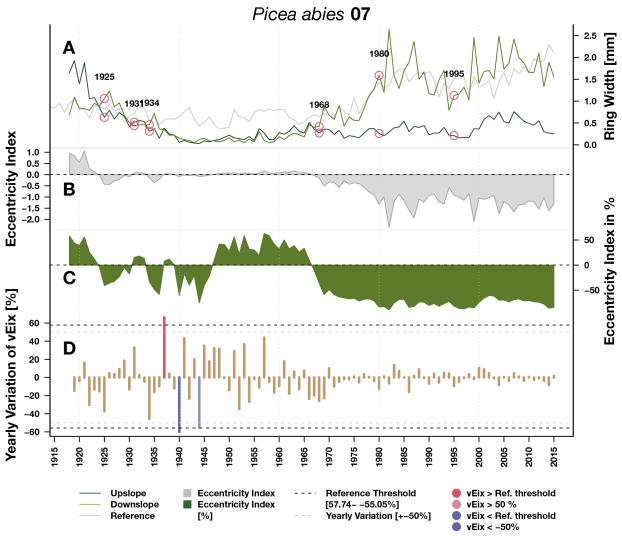
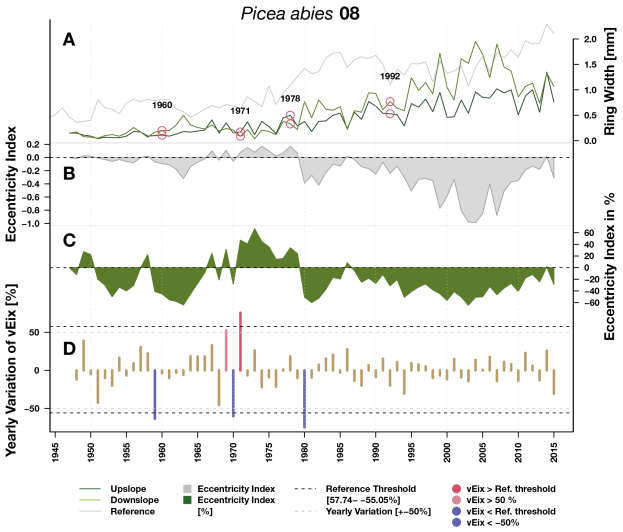


Figure 4: *Picea abies Karst.* 07 in site II



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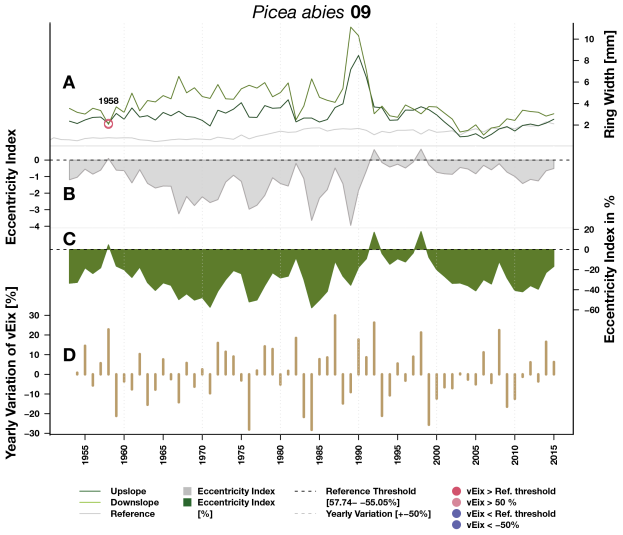

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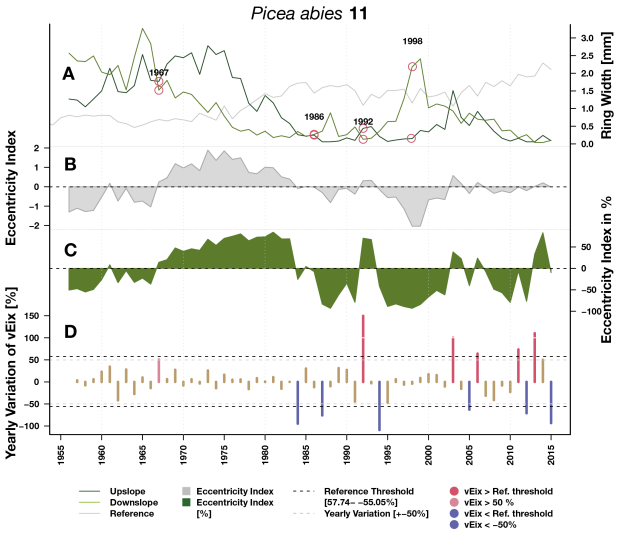
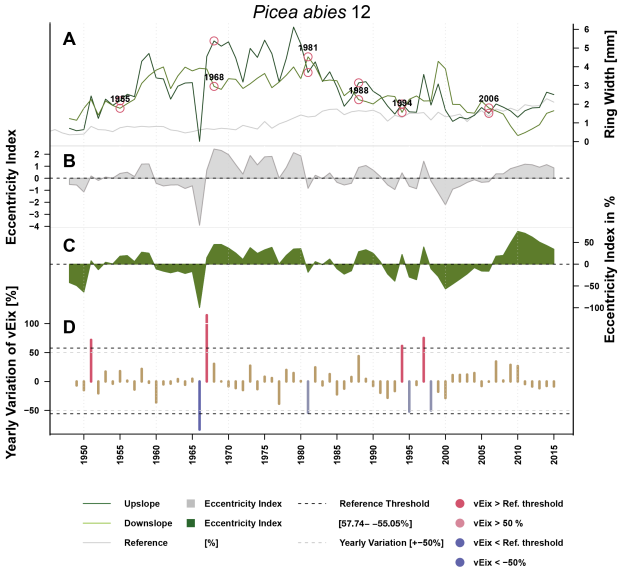


Figure 7: *Picea abies Karst.* 11 in site II



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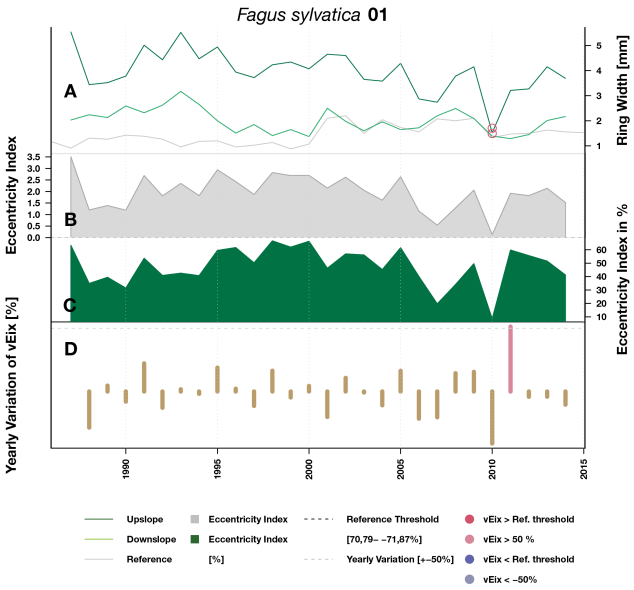
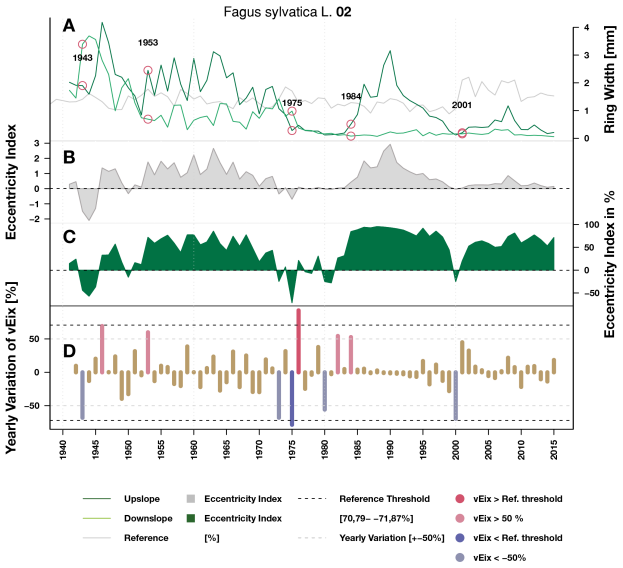


Figure 9: *Fagus sylvatica L.* 01 in site II



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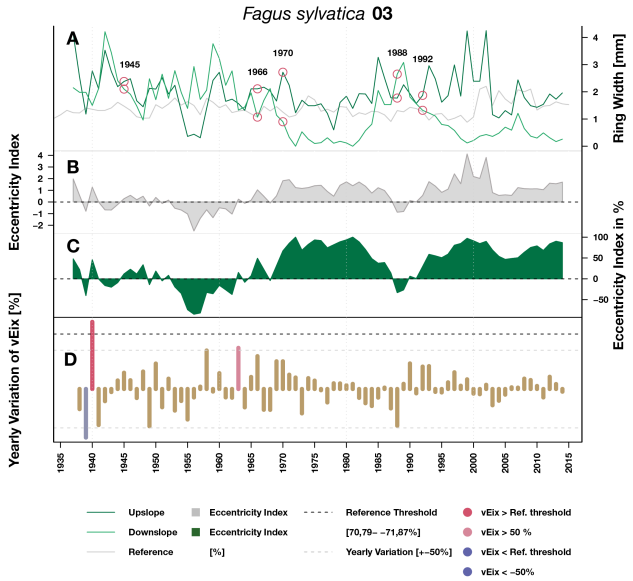

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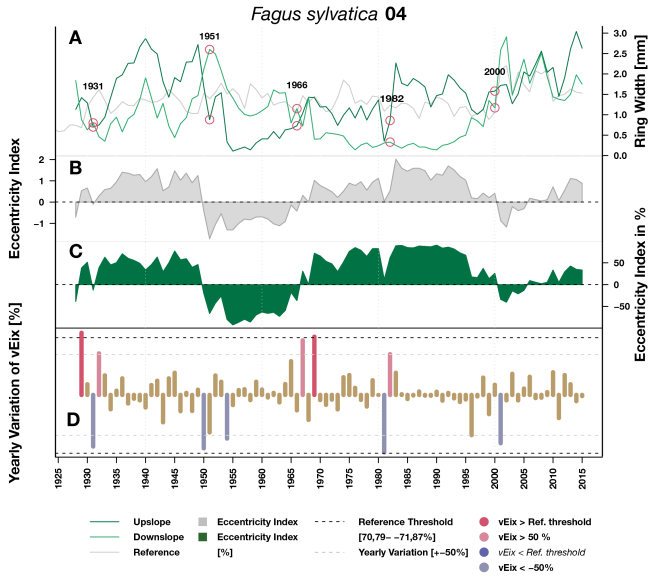

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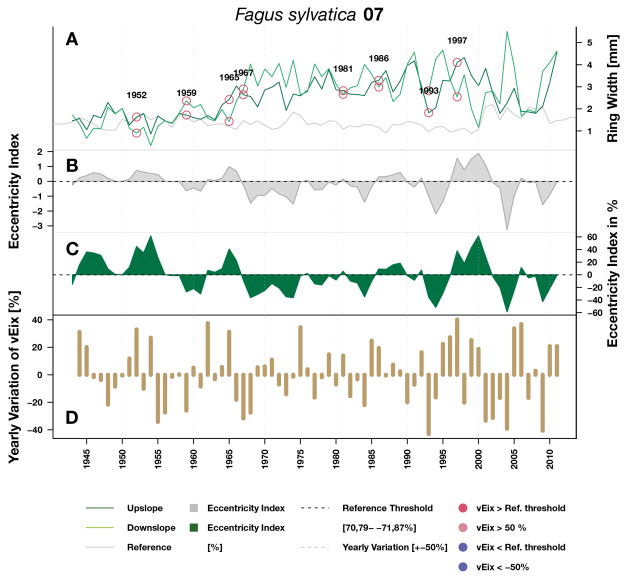

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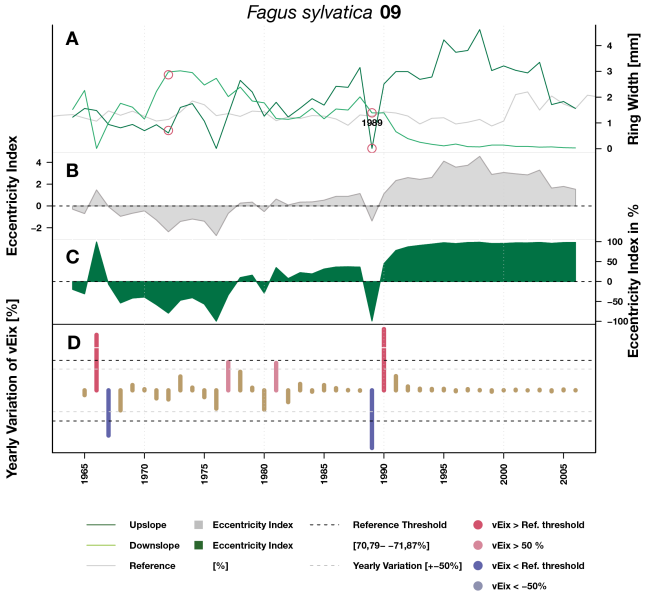

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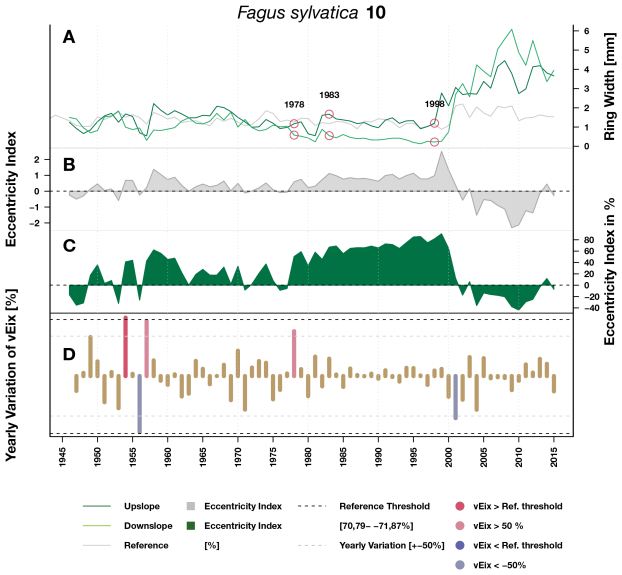

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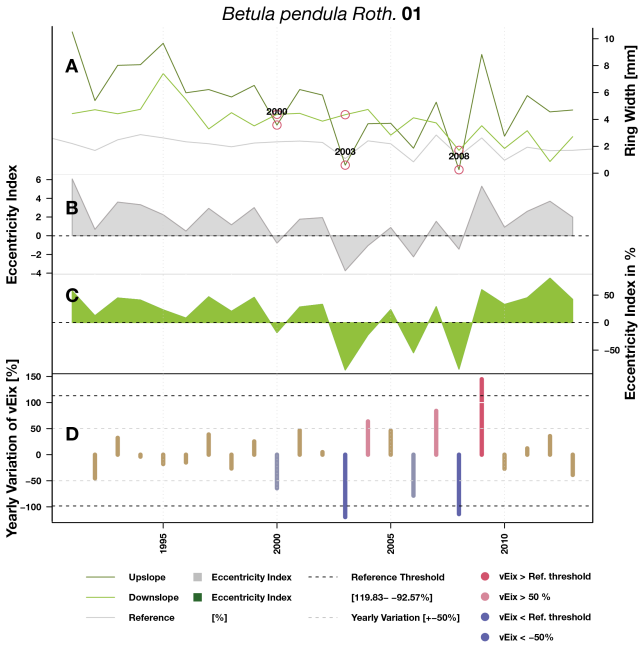


Figure 16: *Betula pendula Roth.* 01 in site I

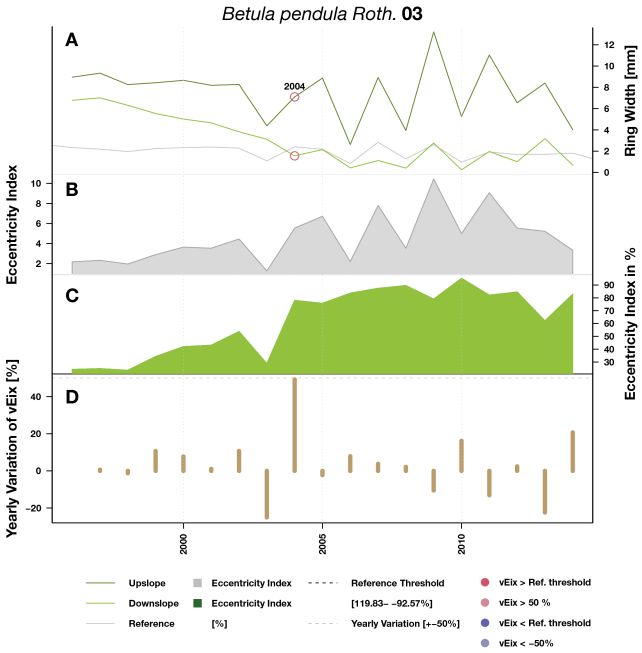
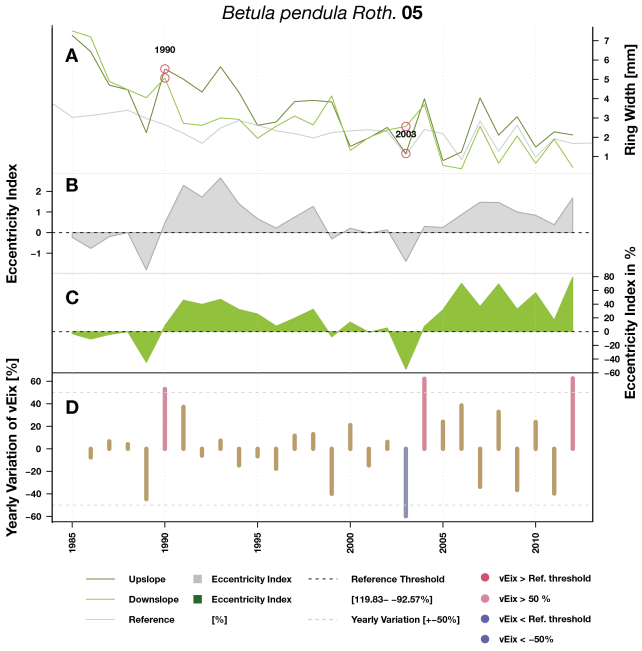


Figure 17: *Betula pendula Roth.* 03 in site I



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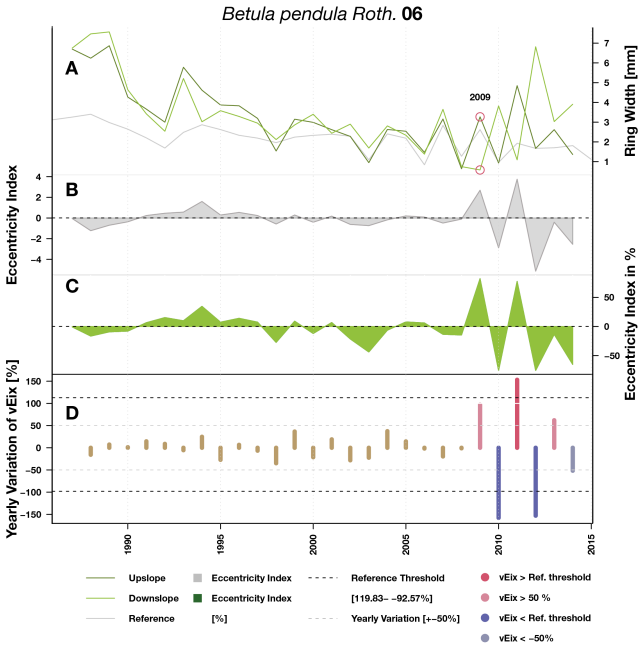

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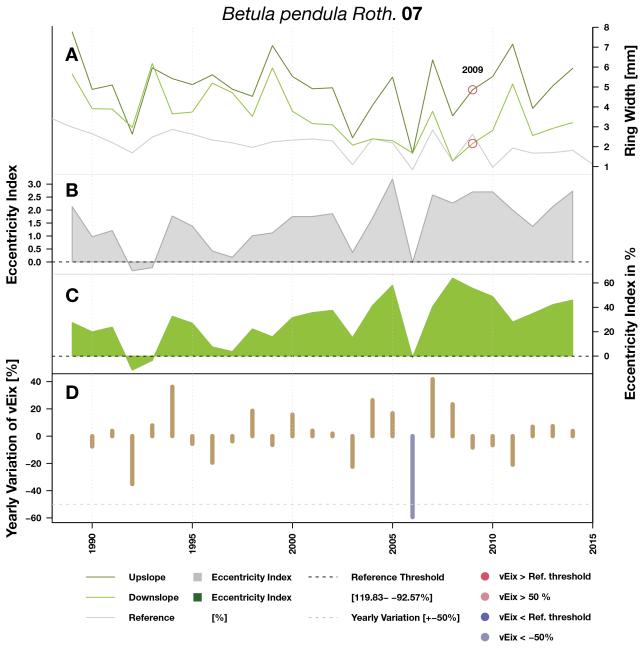

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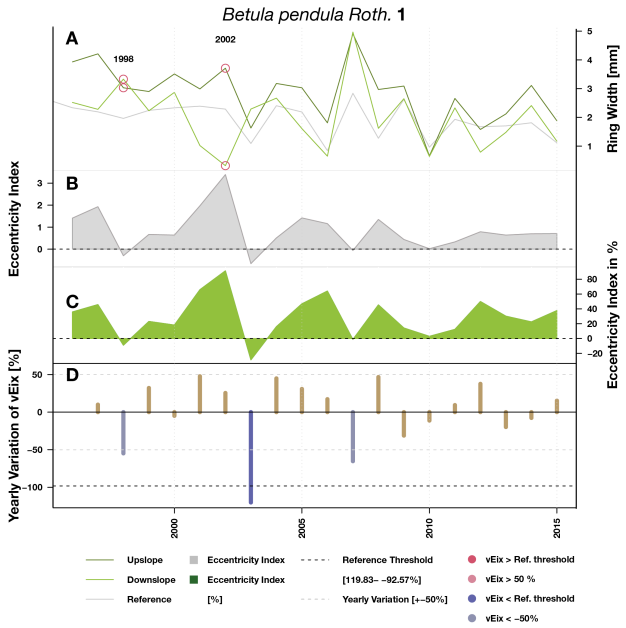

Figure 21: *Betula pendula Roth.* 01 in site III

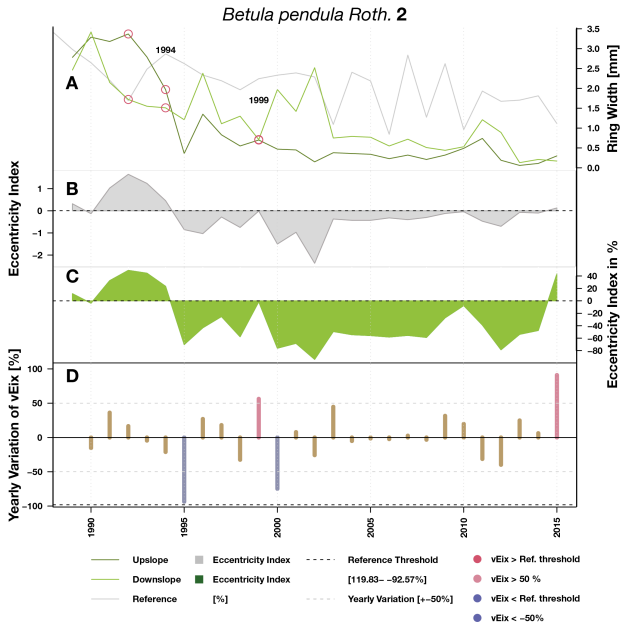

Figure 22: *Betula pendula Roth.* 02 in site III

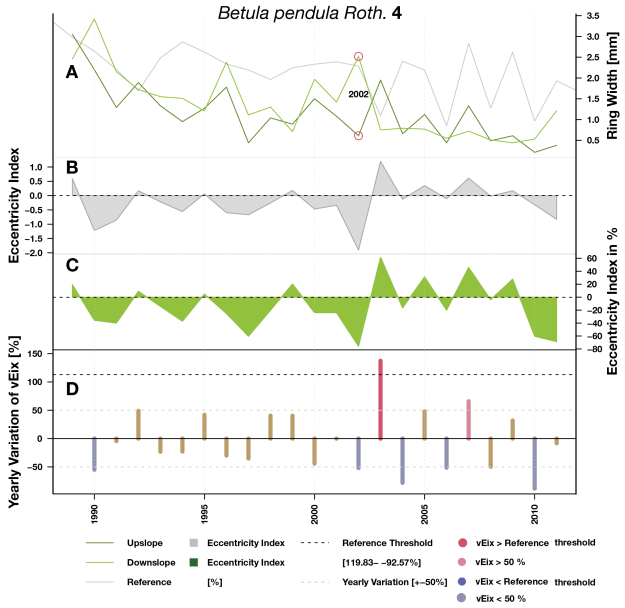

Figure 23: *Betula pendula Roth.* 04 in site III