Root Tensile Strength Related to Wood Anatomical Features

Master Thesis GEO 511

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Abstract

Planting trees and shrubs is part of various ecological engineering measures which aim at stabilizing steep vegetation free slopes. Root tensile strength is an important parameter in characterizing the soil stabilization potential of trees and shrubs. It is known that tree roots show a high variability in their anatomical structure depending on their depth below soil surface as well as their distance to the main stem. Therefore, it is assumed that these structural changes affect the tensile strength of roots.

In order test this hypothesis, the root systems of seven trees (4 *Acer pseudoplatanus* L. and 3 *Alnus incana* (L.) MOENCH) were excavated and analyzed. The examined trees were part of ecological engineering measures which were taken in the Prättigau valley in the Eastern Swiss Alps in 1997. The substrate is coarse grained morainic material, mean annual air temperature reaches 4.64 °C, average precipitation is 1170 mm, and the altitude of the study site is about 1000 m a.s.l..

The tensile strength of almost 400 samples was determined. Of all analyzed samples 41% of the tensile tests were considered to be successful and samples were further processed. Various wood anatomical parameters, such as number and lumen area of vessels were determined.

The results showed that tensile strength of roots of the two tree groups increaseed with decreasing diameter. Tensile strength of roots was higher for *Acer pseudoplatanus* L. than for *Alnus incana* (L.) MOENCH. The roots of *Acer pseudoplatanus* L. showed the highest tensile strength in diameter classes < 2 mm. The tensile strength and the wood anatomical structure differed between the two tree groups. It was found that the wood anatomy most likely influenced the root tensile strength.

Furthermore root age had a negative effect on tensile strength in both tree groups. After the roots reached a certain age (7 years in the case of the Acer tree groups and 4 years in the case of the three Alnus trees) the tensile strength remained on a constant level. The number of samples of the three evaluated Alnus trees was not sufficient to allow a conclusion regarding the influence of the distance of a root to the stem on tensile strength. For the group of Acer trees it can be stated that tensile strength increased with increasing distance to the stem base.

Contents

Figures

Tables

Abbreviations

CSA	Cross sectional area
CV ratio abundance	Ratio of number of fiber cells and number of vessels
CV ratio area	Ratio of total fiber cell lumen area and total vessel lumen area
dbh	Diameter at breast height
e. g.	For example
ETH	Swiss Federal Institute of Technology
FBM	Fiber Bundle Model
i. e.	Id est
LOWESS	Locally weighted scatterplot smoother
MAD	Median absolute deviation
n	Number of samples
Rel. hum.	Relative humidity
SVLA	Standardized vessel lumen area
VPUA	Vessels per unit of area
WSL	Swiss Federal Institute for Forest, Snow, and Landscape Research
WWM	Wu and Waldron's Model

1. Introduction

1.1 Motivation

Slopes are a common feature of alpine areas (Bast et al., 2014). They are either of a natural or an anthropogenic origin and many of them are naturally unstable (Norris and Greenwood, 2008). Especially steep, vegetation free slopes are prone to erosion (Bast et al., 2014; van Beek et al., 2008). On steep slopes, small scale shallow landslides cannot only be commonly observed, but are also likely to develop into large scale debris flows (Roering et al., 2003).

Slope instabilities have numerous socio-economic impacts throughout the world. Despite the direct costs (e.g., replacement of infrastructure) indirect costs have to be taken into account. These can be loss of industrial, agricultural and forest productivity, or reduced tourist revenues, real estate values and water quality, as well as the loss of human or animal productivity because of psychological trauma, injury or even death (Kjekstad and Highland, 2009).

Potentially fatal mass movements are primarily caused by environmental factors, such as precipitation, wind or snow melt. However, it is the hillslopes which provide the gradient necessary to transport material by gravity. If the gradient is insufficient to mobilize loose material, or the cohesion of soil particles is high enough to resist the gravitational force, water and wind flowing along the surface are able to entrain material and thus initiate mass movements (van Beek et al., 2008). It can be said that climate is capable of accelerating the numerous processes of landscape formatting (Satkunas et al., 2006).

In 2007 the Intergovernmental Panel on Climate Change (IPCC) stated that global temperatures are increasing (Parry et al., 2007). This change in temperature also results in a projected increase of mean annul precipitation in the North of Europe. Also Climate Change is likely to alter the seasonality of precipitation. It is assumed that the frequency of intense short duration precipitation events will increase, especially in winter, whilst summer precipitation is likely to decrease (Alcamo et al., 2007).

Climate Change already caused an acceleration and intensification of some geomorphic processes in high mountain areas in Switzerland. The increase of temperatures during the 20th century caused a rapid glacial retreat and thaw of alpine permafrost. It is likely that this change in climate is responsible for the increased magnitude and frequency of various kinds of mass movements (Clague, 2009; Curtaz et al., 2014).

Since soil moisture conditions have a significant influence on mass movements on hill slopes, the changes in the precipitation regime are expected to cause an increase in the magnitude and frequency of landslides and other kinds of mass movements (Delmonaco and Margottini, 2004; Stokes et al., 2008). Therefore, unstable slopes create a variety of issues concerning the prevention of slope failures, respectively the minimization of slope failure induced damage (Norris and Greenwood, 2008). Anthropogenic measures can be taken in order to influence rates of occurrences (Hu et al., 2013).

Ecological engineering, which has developed rapidly over the last decade, is a promising approach in order to deal with slope failure. It aims to design sustainable ecosystems that not only enrich human society, but also the natural environment (Mitsch, 2012).

Vegetation has been known for centuries to prevent and control the negative effects of landslides and other forms of mass movements (Ali et al., 2012; Andreu et al., 2008). Due to the soil-root interaction, the stability of slopes can be significantly increased with a well established vegetation cover (Fan and Lai, 2013). Different kinds of plants can be used to reinforce unstable slopes and hence reduce the occurrence of potentially dangerous mass movements (De Baets et al., 2006; Hu et al., 2013; Norris and Greenwood, 2008; Stokes et al., 2008).

Even though it is clear that root systems enhance soil stabilization, the details of the different processes are yet unknown (Bischetti et al., 2007; Ghestem et al., 2013; Hales et al., 2013; Reubens et al., 2007). It is assumed that the use of vegetation can be an asset in order to stabilize inclined soils (Hu et al., 2013; Mao et al., 2012; Norris and Greenwood, 2008). Therefore it is of importance to specify the impact of certain plant characteristics on slope stabilization, in order to facilitate the identification of suitable species (Genet et al., 2005).

In recent years the anatomy of tree roots has been the subject of interest of many studies (e.g., Gärtner et al. 2001; Gärtner 2003, 2007; Hitz et al. 2008; Sun et al. 2014; Wrońska-Wałach 2014). However, the focus of these studies lay on dating the time a root was uncovered and thus calculating erosion rates. It is known, that the cellular structure within a single root can be of high variability (Gärtner, 2007). This is due to locally different environmental conditions, such as depth or exposure of a root (Gärtner, 2003).

1.2 Hypotheses & Research Questions

It would appear to be evident that the anatomical structure of roots affects their tensile strength. No study aiming at finding a relation between root tensile strength and the wood anatomical structure of the roots has been conducted. Thus, the hypotheses of this Master Thesis are:

1) The root tensile strength of *Acer pseudoplatanus* L. and *Alnus incana* (L.) MOENCH differs between the two groups of trees.
2) Furthermore, root tensile strength is not only influenced by root diameter, but also by wood anatomical parameters.
3) Additionally it is assumed that other architectural traits of the roots (i. e., age and distance of a root to the stem) influence root tensile strength of the two tree groups as well.

In order to judge these three hypotheses the following research questions arise

a) What is the root tensile strength of the two groups of trees in relation to their diameter and how does this relation differ between the two tree groups?
b) Is there a difference in the structure of the wood anatomy between the two evaluated tree groups?
c) Does the wood anatomical structure, the age of a root and the distance to the stem influence the root tensile strength of the two groups of trees?

1.3 Outline

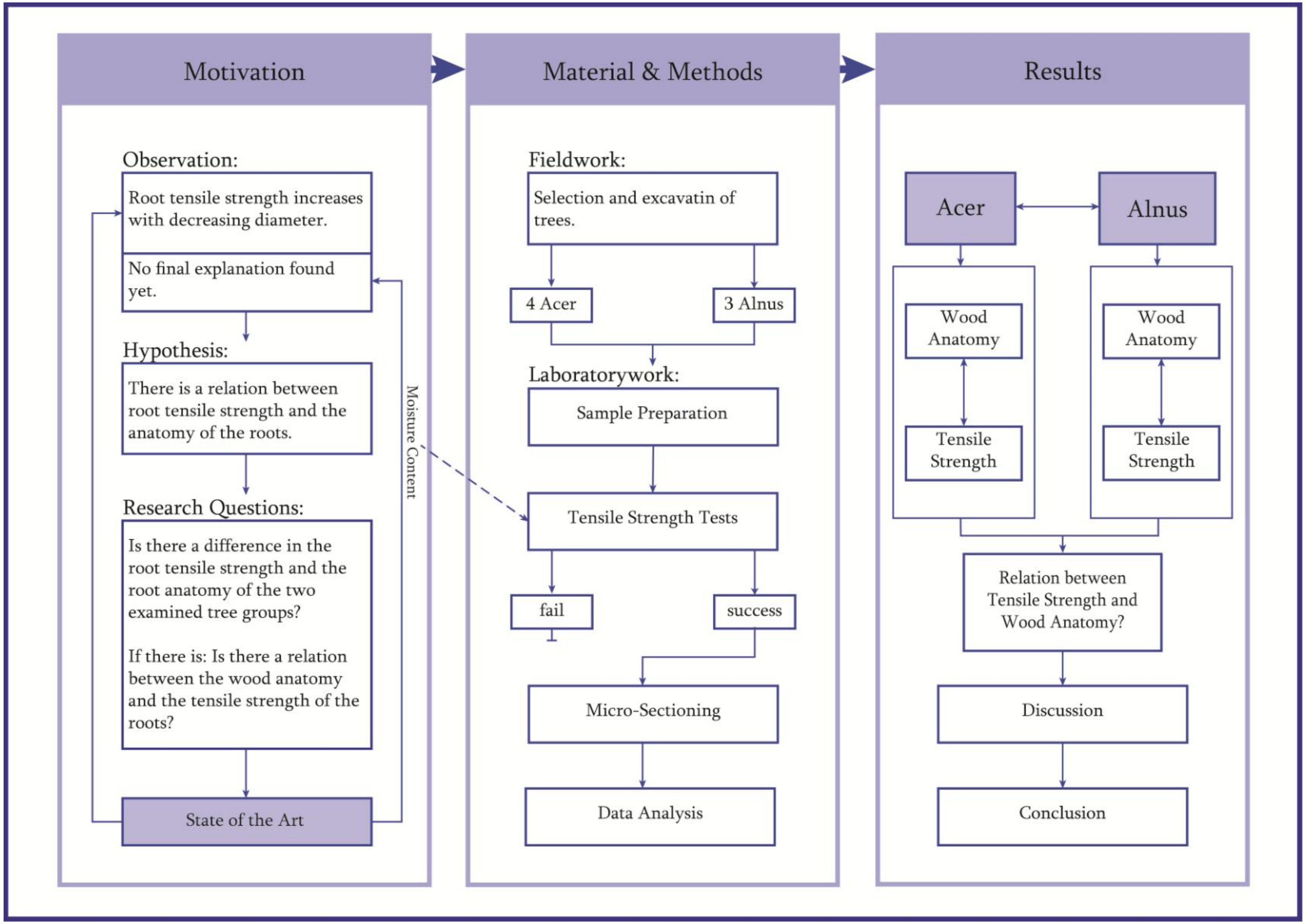

Fig. 1.1: Outline of this Master Thesis.

1.4 State of the Art

1.4.1 Root Tensile Strength

So far knowledge of the growth and development of tree roots and the environmental factors influencing these processes is limited. However, it is of fundamental importance for various fields of application (Ahlström et al., 1988). Tree root systems enhance soil stability by binding loose soil particles and thus increasing shear strength soil and thereby, to some degree, prevent shallow landslides and other kinds of erosion (Abdi et al., 2010; Ziemer, 1981).

Soil has a much higher compression strength, than tensile strength (Pollen, 2007). In contrast to that, the wood of roots shows a higher tensile than compression strength (Ammann 2006). The compression strength of wood is positively correlated with the altitude of a tree stand (Barij et al., 2007). It was estimated that the tensile strength of soil is 3 – 5 orders of magnitude weaker than that of roots (Coutts, 1983a). Regarding elasticity and durability, soil-root systems can be compared with armored concrete. The concrete has a high compressive strength, but tends to break when bent, similar to soil. The armoring irons add elasticity to the system, which can be compared with roots growing in soil (Ammann, 2006).

Since roots provide anchorage, Stokes et al. (2008) name them first when listing the elements of plants which are likely to be useful in an attempt to keep an unstable slope from failing. Above ground parts of the plants, the stem, branches and leaves are also important for slope stabilization because of their ability to intercept precipitation and initiate evapotranspiration, which finally depletes soil moisture (Stokes et al., 2008). On top of that, the diversity of the plants growing on a slope as well has an impact on its stability (Genet et al., 2010).

Roots have an influence on different soil properties, which control soil erosion and hydrologic conditions in various degrees. Examples for these characteristics are the infiltration rate, aggregate stability or shear strength (Bischetti et al., 2007; Cammeraat et al., 2007; De Baets et al., 2008). De Baets et al. (2014) specify the assets of tree roots to slope stabilization by distinguishing between mechanical and hydrological functions. The provision of tensile strength to the soil and the binding of surface particles can be regarded as mechanical advantages of roots. Hydrological improvements to the soil induced by tree roots are the increased roughness, which promotes infiltration and thereby decreases the surface runoff, as well as the consumption of water, which lowers the water pore pressure and therefore increases soil cohesion (De Baets et al., 2014). Osman

& Barakbah (2006) agree with De Baets et al. (2014) by stating that the two major aspects of the contribution of vegetation towards slope stability are soil reinforcement by the root system and the regulation of soil hydrology.

Johnson & Wilcock (1998) found that, depending on the site, root cohesion has a greater effect on slope stability than pore pressure. The aboveground part of vegetation also reduces the impact energy of raindrops. This also potentially reduces soil erosion (Operstein and Frydman, 2000).

Rooting depth is of great importance for soil shear strength. Cammeraat et al. (2007) found that on the slopes of steep ravines in Southeast Spain, roots only contribute to soil strength in the upper 0.4 m of the soil. Most failures occurred between 1.0 – 1.2 m, where root anchorage was insufficient or absent. Where rooting depth is low, the morphology of the root systems becomes more important. Asymmetric root systems are less stable, because, where main roots are poorly developed or non existing, stability will be reduced (Coutts et al., 1999; Coutts, 1983b).

Root morphology and slope stability interact with each other (Di Iorio et al., 2005). The architecture of root systems as well as different soil properties affect not only the shape of a root system but also its stability and the tree anchorage. It is known that roots contribute to soil reinforcement, however their biomechanical properties are not fully understood yet (Comino and Marengo, 2010). The ideal architecture of a root system, considering tree anchorage, is the one that provides a given degree of anchorage, for a minimum investment of material (Ennos, 1993).

There is a spatial variation of soil reinforcement by roots, which impacts slope stability (Ji et al., 2012) Danjon et al. (1999) used a low-magnetic-field digitizing device in combination with software, designed to evaluate plant architecture, and found it to be an efficient approach to analyze the geometry and topology of tree roots.

Di Iorio et al. (2005) used a less complex approach to estimate the root volume. They found that the diameter at breast height (dbh) was the best indicator of this parameter. However, other architectural properties, such as length, number of roots, or their distribution, could not be assessed. Nevertheless, the estimation of the dbh gives a rough idea of the root volume that can be expected.

Even though Lindström & Rune (1999) did not examine the effect of slopes on root growth, it is worth mentioning that they found that older trees generally showed a better root distribution than younger ones.

The root system architecture which is best suited to enhance tree anchorage has not yet been identified. Khuder et al. (2007) found that plant growth and development can be influenced by using different nursery techniques. However there are still a lot of unanswered questions regarding detailed long-term consequences of such techniques on tree anchorage.

An important factor influencing the benefit of a certain plant to stabilize and fixate soil is the tensile strength of its roots (Genet et al., 2005; Zhang et al., 2012). Roots add strength to the soil not only by vertically penetrating possible shear horizons and anchoring into fractures in the bedrock, but also by laterally binding the slope together over zones of weakness (Ziemer and Swanston, 1977). They are able to penetrate lower soil horizons, interlocking these with each other, and eventually stabilizing soils by forming soil-root system (Andreu et al., 2008).

Numerical modeling appears to be a promising way to estimate the role each root plays in anchoring a tree (Khuder et al., 2007). In order to solve problems dealing with unstable slopes, field studies need to be combined with numerical modeling. This is especially true for issues concerning large scale slope instabilities (Stokes, 2008).

There are numerous models to estimate the cohesion that roots add to soil. The most widely used are the Wu and Waldron's Model (WWM, Wu 1976; Waldron 1977; Wu et al. 1979) and the Fiber Bundle Model (FBM, Pollen & Simon 2005; Mao et al., 2012). Many studies model different kinds and aspects of slope failure processes (e.g., Dupuy et al. 2005; Mao et al. 2012, 2013; Mickovski et al. 2009; Nakamura et al. 2007; Pollen & Simon 2005; Schwarz et al. 2010; Thomas & Pollen-Bankhead 2010; Wu 2007). However, the implementation of complex factors, such as vegetation, in such models is traditionally simplified. Depending on the complexity of a model used, some important factors might not be considered. Therefore it is important to improve our knowledge of vegetation factors to enhance existing models (Stokes et al., 2009).

Gyssels & Poesen (2003) argue that the temporal character of roots should also be considered when modeling long periods of time. Not only live roots have to be taken into consideration when estimating the slope stabilization ability of vegetation. Dead roots are still able to stabilize the soil to some degree, depending on the rate of decay and the time a root died (Ammann, 2006; Watson et al., 1999).

FBMs as well as the WWM require similar input data. These are root density, a root orientation factor in regard to the shear plane and root tensile strength (Mao et al., 2012). Root tensile strength has been investigated in a number of studies. There are different approaches to estimate this parameter. Some studies dealt with in situ tests, where the force needed to pull roots out of the soil was measured. Others carried out laboratory tests, where the maximum tensile strength of root samples was measured using a testing machine in a controlled environment. Some studies combined these two approaches mostly aiming at the verification of laboratory tests using in situ tests or vice versa (e.g., Ammann 2006; Burylo et al. 2011; Docker & Hubble 2008; Genet et al. 2005; Hales et al. 2013; Mattia et al. 2005; Norris 2007; Schmidt et al. 2001; Tosi 2007; Zhang et al. 2012). Soil shear strength, which is correlated with root tensile strength, has also been investigated by various researchers (e.g., Fan & Su 2008; Loades et al. 2010; Wu et al. 1979).

The idea to relate root tensile strength to wood anatomical features is not new. In 1975 Hathaway & Penny investigated root tensile strength in relation to the anatomy of the roots and their chemical composition. They found that the diameter was negatively correlated to the tensile strength.

Soukup et al. (2004) and Zhang et al. (2014) both concentrated on biochemical analysis of roots, with a focus on lignin content. In addition to the lignin content, Zhang et al. (2014) also evaluated the cellulose content of roots, as well as their tensile strength. Genet et al. (2005) estimated the influence of the cellulose content on root tensile strength.

The analysis of the chemical composition of roots is able to explain the variations in tensile strength in different diameters to some degree. This work tries to evaluate a different aspect of root anatomical analysis, not by conducting chemical test, but by examining the cellular structure of roots.

1.4.2 Ecological Engineering

The first textbook on ecological engineering was published in 1989 by Mitsch & Jørgensen. Making this field still young and in a stage of development. As already mentioned, the goal of ecological engineering is to develop and design healthy, secure, and sustainable ecosystems, which can be natural or artificial. These ecosystems are supposed to be sustainable and enrich human society as well as the natural environment (Jørgensen, 2008; Mitsch, 2012).

The aim is to manage nature in a way, that a connection between a society and the environment is created (Odum and Odum, 2003; Painter, 2003). However, the focus does not only lie on the technological aspect. A crucial component of ecological engineering is not provided by humans but by ecosystems. Their ability to self-organize and adapt to special circumstances and conditions, is used by ecological engineers to design new ecological communities and habitats (Odum and Odum, 2003). This requires a well-founded understanding of nature, the processes taking place in the different ecosystems and the connections between the diverse ecosystems. If these requirements are met, it is possible for human society not to abuse the natural environment, but to responsibly handle its resources in a sustainable way, which ultimately acts in benefit for both (Jørgensen, 2008; Mitsch and Jørgensen, 2003).

Throughout the world various aspects of ecological engineering are being implemented. Examples for ecological engineering measures are the restoration of rivers in the Everglades in Florida and in Maryland in the USA (Mitsch and Jørgensen, 2003; Palmer et al., 2013), or soil and water conservation in Taiwan in order to dampen the devastating impacts of floods and storms (Wu and Feng, 2006). Stabilizing erosion prone slopes is not only the focus of many other studies working with ecological engineering measures (e.g., Loades et al. 2010; Mao et al. 2012; Stokes 1999), but also the integral part of this work.

1.4.3 Wood Anatomy

Wood anatomy deals with the description of wood features on a microscopic scale. In order to prepare the wood samples for the microscopic analysis, the wood has to be cut into micro-sections with an ideal thickness of 12 - 15 µm. A sliding microtome is used to prepare such micro-sections. These instruments have proven to be well suited for many different kinds of wood and are believed to remain the state of the art for many years to come (Carlquist, 1988).

Due to their different purposes, roots and shoots exhibit different anatomical structures. Roots show a higher frequency and greater size of vessels, along with larger diameters of fiber cells than shoots. (Schweingruber et al., 2006).

The two cell types analyzed in this work are vessels and fiber cells. Vessels are tube like series of cells. The purpose of vessels is to transport water and therein contained nutrients (Schoch et al., 2004) Vessels can occur solitarily or in different kinds of groups, such as clusters or radial multiples (Carlquist, 1988).

Fiber cells are often unlignified (Schweingruber et al., 2011). They are often present in tension wood of roots and show a characteristically high cellulose content (Schweingruber et al., 2006). Fiber cells are of importance in regard of the resistance of roots to tension, because cellulose is responsible for the tensile strength of roots, due to its microfibrillar structure (Genet et al., 2005).

The transversal sections of *Acer pseudoplatanus* L. are described as diffuse-porous, where the solitary vessels, or pores, are widely spaced in multiples of two to four, sometimes even six. The growth ring is determined by a few rows of radially flattened fibers, the walls of which often vary in thickness (Schoch et al., 2004).

The same sections of the diffuse- and semi-ring-porous *Alnus incana* (L.) MOENCH are characterized by more or less densely packed vessels which are often clustered in the earlywood. The growth ring boundaries are more or less undulating (Schoch et al., 2004).

2. Study Site

The study site is located in the Arieschbach catchment (46°53’43.41 N, 9°44’30 E), near the village of Fideris, which is situated in the Prättigau valley in the Eastern Swiss Alps (Fig 2.1) (Bast et al., 2014). The catchment includes an area of roughly 20 km^2 and is dominated by different erosional processes (Graf, 2009). The sub-oceanic climate with mild winters and temperate summers, leads to a mean annual air temperature of 4.64 °C and an average annual precipitation of 1170 mm (Bast et al., 2014).

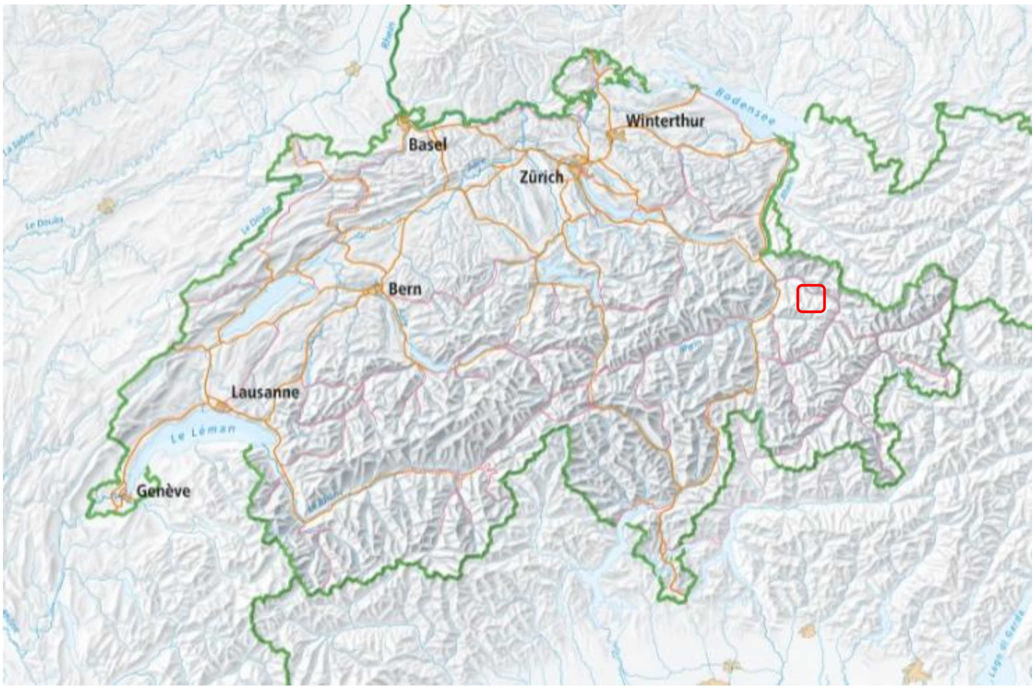

Fig. 2.1: Location of the study site. Source: Swisstopo 2014.

Due to reoccurring intensive precipitation events, especially in August 1987, which triggered large mass movements, such as landslides and debris flows, it was decided to take various technical and ecological engineering measures (Bast et al., 2014; Graf, 2009). These were carried out between 1970 and 2006. One of which was the Patjänja area in 1997 (Fig. 2.2). The Patjänja is the area of interest of this thesis (Graf, 2009).

Figure 2.2 indicates a high geomorphic activity in the Arieschbach catchment. Concrete check dams were installed in the upper part of the ravine. There are vegetation free slopes, which are prone to erosion and therefore shallow landslides, debris flows and rock falls are of common occurrence. At the exit of the valley, where the Arieschbach discharges into the river Landquart, a gravel plant was established, which implies a high traction load of the torrent (Bast et al., 2014).

The bedrock, which is mainly made up of Prättigau flysch, is covered with quaternary sediments. Most of these sediments are of a morainic origin. Typically occurring soils are Cambisols, Luvisols, Regosols, and Leptosols (Ott et al., 1997).

Fig. 2.2: Aerial view of the Arieschbach catchment, the Patjänja 97 area (1) and concrete check dams (2). Source: Swisstopo 2014.

The substrate of the Patjänja area is coarse grained (Fig. 2.3). The grain size analysis of Weisser (2013) yielded a gravel percentage of 60 – 65%. The sandy fraction of the substrate makes up 20 – 25%, the rest is finer material of the silt (5 – 10%) and clay (0 – 5%) fraction.

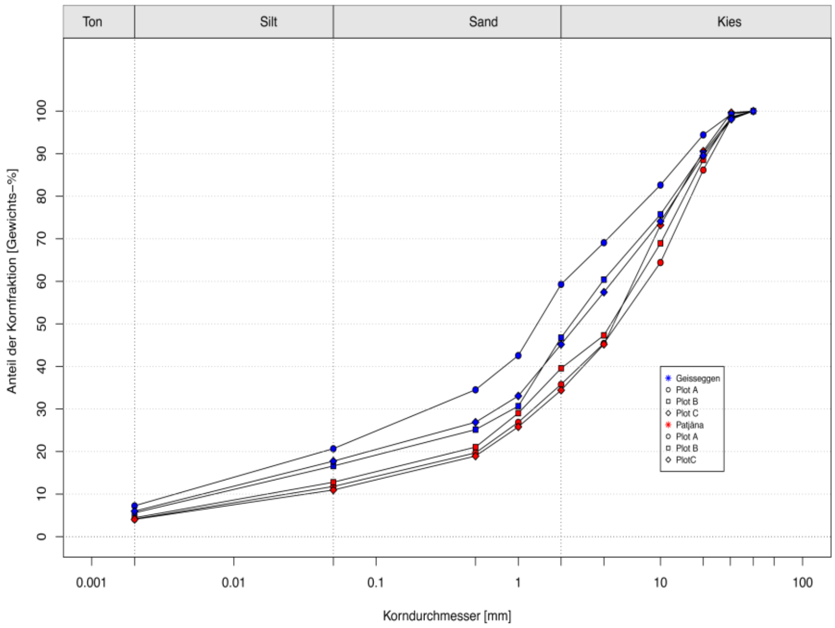

Fig. 2.3: Grain size distribution diagram of the Patjänja (red) and the Geisseggen (blue) area. Source: Weisser 2013.

Fig. 2.4: View of the study area from the valley bottom. Photo: D. Kink, September 2013.

Figure 2.4 shows a view of the study area as seen from the bottom of the valley. On the left side of the image, the so called Patjänja Rüfe can be seen, a geomorphologically highly active area, dominated by near subsurface erosion. The study site of this thesis is located next to it on the right. Two lines of log cribwalls were installed and afforestated one year later. The vegetation cover on the left side adjacent to the Patjänja Rüfe is well established. In the center there is little to no vegetation. This part of the area showed higher soil moisture content compared to the where the trees were taken from. No soil moisture measurements were conducted, but water runoff was observed close to the surface. This was not the case for the areas with a better developed vegetation cover. The exact locations of the trees, which were taken from this site, can be seen in the following chapter (Fig. 3.1).

3. Material and Methods

3.1 Field Work

In total seven trees, four *Acer pseudoplatanus* L. (in this work also referred to as Acer) and three *Alnus incana* (L.) MOENCH (in this work also referred to as Alnus) were excavated and taken from the study site (Fig. 3.1). The aim was to examine two species which typically find application in ecological engineering. *Acer pseudoplatanus* L. and *Alnus incana* (L.) MOENCH happened to be two species which were planted on the study site in 1997, which is why they were chosen for this study. Before starting to excavate the root systems, the trees were cut in order to facilitate the excavation work and tree handling. Except for Acer 01 and Alnus 01, which originally were thought to be test trees, tree properties were determined from the sampled trees. These properties are summarized in Table 3.1.

Care was taken not to damage any roots while uncovering the root systems as completely as possible. After the root systems were documented in situ, they were removed and brought to the Swiss Federal Institute for Forest, Snow, and Landscape Research (WSL) in Birmensdorf. Until the root systems were cut apart into single root samples, they were stored at 4 °C, to keep the roots from decomposing. It was attempted to process the root systems quickly in order to ensure the samples were as fresh as possible.

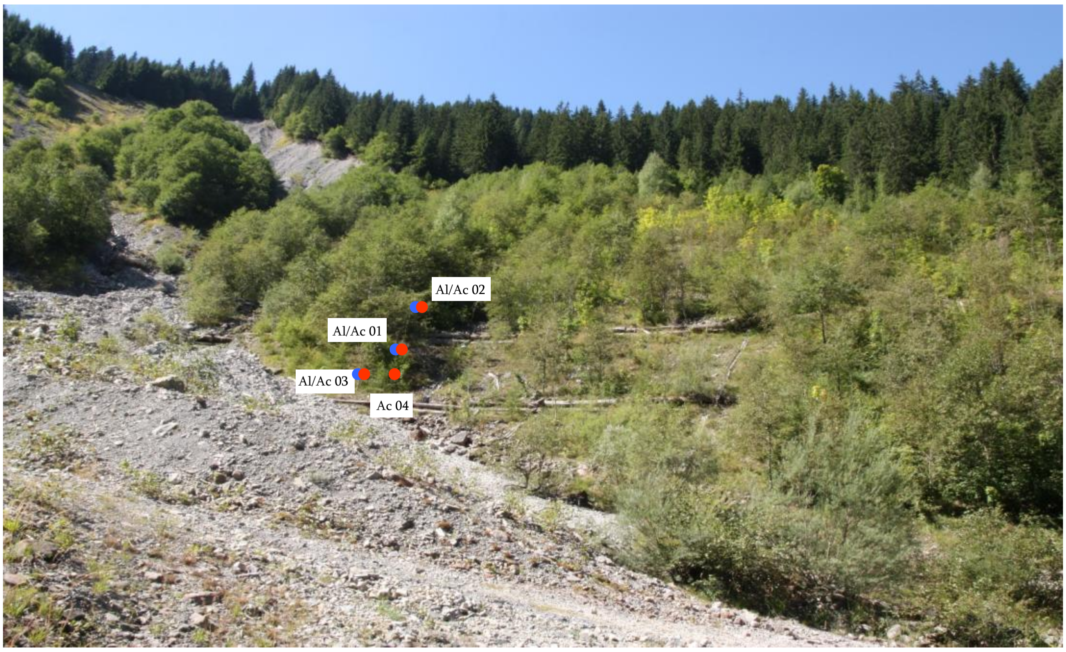

Fig. 3.1: The study site as seen from the valley bottom. The blue dots indicate the positions where the three Alnus (Al) were taken. The red dots show the location of the four Acer (Ac) which were removed from the site. Photo: D. Kink, September 2013.

Tab. 3.1: Properties of the sampled trees. The properties of Acer 01 and Alnus 01 were not assessed.

	Height [m]	Height of knotless trunk [m]	Crown diameter [m]	Mainstem (1/0)	Secondary stem(s)	Mainstem diameter [cm]	Age [y]
Acer 01	-	-	-	-	-	-	15
Acer 02	3.3	0.2	1.4	1	4	2.5	12
Acer 03	4.5	0.5	0.8	1	1	2	15
Acer 04	2.2	0.5	0.7	1	1	2	9
Alnus 01	-	-	-	-	-	-	18
Alnus 02	5	0.55	1.5	1	3	6	17
Alnus 03	4.5	0.9	1.4	1	1	5	17

3.2 Laboratory Work

Once the root systems were retrieved from the field they had to be further processed. This happened in the following steps.

3.2.1 Sample Preparation

Before cutting the root systems apart, they were photographed on a grid with 5 cm spacing. While cutting the root systems into single root samples, their exact position was marked on a hardcopy of the photograph in order to be able to recreate the exact location of every root sample later on (Fig. 3.2). Due to the grid, it was possible to estimate the distance of a sample to the tree stem as well as whether the sample was on the uphill or downhill side of the tree. Before discarding the left over stem, three discs were taken from 10, 30 and 50 cm above the ground.

The samples were then put into resealable plastic bags, which were labeled individually. Tissues were soaked in a mixture of water and alcohol, where 30% of the volume was alcohol. These tissues were put into the bags along with the samples, in order to keep them moist and to prevent fungi from spreading. Until being further processed, the samples were again stored at 4 °C.

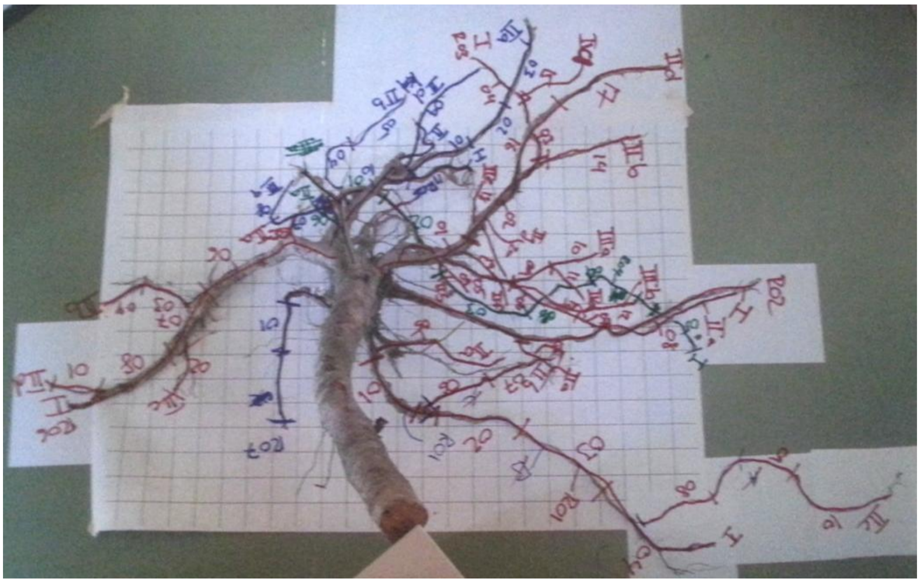

Fig. 3.2: The second photograph of the root system on a 5 cm grid was used to precisely mark the position of the root samples. Photo: A. Bast, September 2013.

Before the samples were prepared for the tensile tests, about 3 cm were cut off of each sample side and put aside for the preparation of micro-sections in a later step. Other studies dealing with root tensile strength (e.g., Ammann 2006; Hales et al. 2013; Marcandella 2010; Genet et al. 2005; Genet et al. 2008; Nilaweera & Nutalaya 1999), approached the problem of how to place and fasten the root samples in the testing machine in various ways. Genet et al. (2005) tested their samples using cork spacers between the roots and the jaws of the testing machine. According to Hales et al. (2013) this method minimizes the number of samples needed to produce recordable results. Ammann (2006) enhanced the method described by Nilaweera & Nutalaya (1999) by moulding the root samples into cubic wooden blocks with epoxy resin.

The approach of Ammann (2006), which was also used by Marcandella (2010), appeared to be the most promising. The samples were placed in aluminum U-profiles, taped to a board and vertically put against a wall. After filling the lower U-profile with epoxy resin, the sample was put into an oven at 70 °C for an hour. Then the sample was turned 180° and the second U-profile was filled with resin and again put into an oven. This procedure is not only time-consuming, but after two hours at 70 °C the roots have started to dry out and can therefore not be considered fresh anymore. Thus, a more effective and faster method, which is less compromising to the root's freshness, was to be developed.

In addition to epoxy, a resin on a polyester basis was tested. It was not only too expensive to find reasonable application for a high number of samples, but also laborious to work with, due to its fumes and toxicity. Hence, a commercial epoxy resin (Harz L and Härter L, suter-kunststoffe ag, Fraubrunnen, Schweiz) was used at a weight ratio of 40:100 (hardener:resin).

Different experiments with plastic molds and self assembled wooden boxes were not very promising (Fig. 3.3). The idea of creating adjustable silicon molds was not realized, due to the pricey material and lack of time. In the end, oak cuboids (edge length: 2 x 4 x 5 cm) proved to be the best solution.

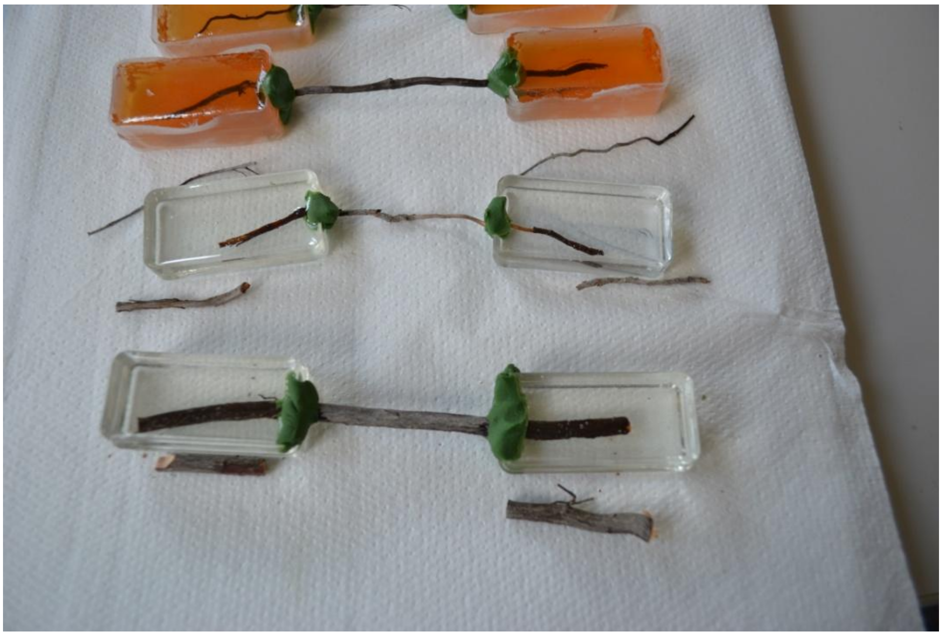

Fig. 3.3: First experiments using plastic molds and different resins, before it was realized that the bark would need to be removed. Photo: D. Kink, October 2013.

In order to accelerate the resin pouring process, holes were drilled into two sides (a 4 x 5cm, and a 3 x 4 cm side) of the cuboids. A cuboid was placed on each end of a root sample and the gaps between root and wood were plugged up with commercial putty (Play-Doh, Hasbro (Schweiz) AG, Luzern, Switzerland). This setup allowed pouring the resin into both cuboids at the same time. After 12 – 24 hours more resin had to be added, because the oak cuboids would saok up some of it.

First tensile tests showed that the roots were prone to slipping out of the bark, as the bark bonded very well with the epoxy resin. However, it would not withstand the tension, which would cause the root to slip out of the clamps before failing from tension. From this point on, the roots were carefully pealed before they were fixated in the cuboids. Especially roots with a large diameter would still occasionally slip out of the resin. In an attempt to solve this problem, the ends of larger roots were reinforced with wire. It was important to ensure that only the part of the root which was in the resin would be reinforced. Care was taken that the part of the sample between the cuboids, which was to be tested, was not affected by the reinforcement.

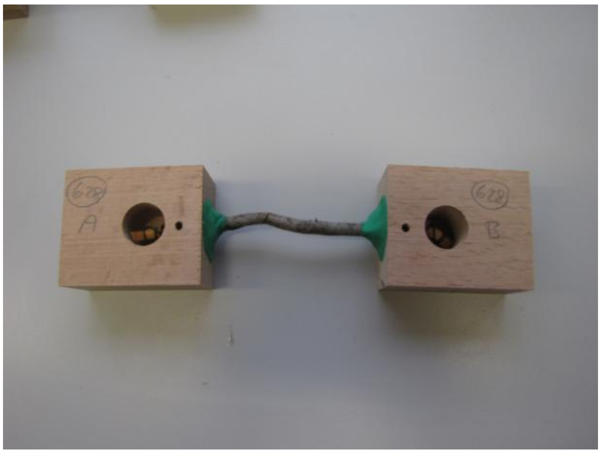

Fig. 3.4: Samples before pouring. Photo: D. Kink, November 2013.

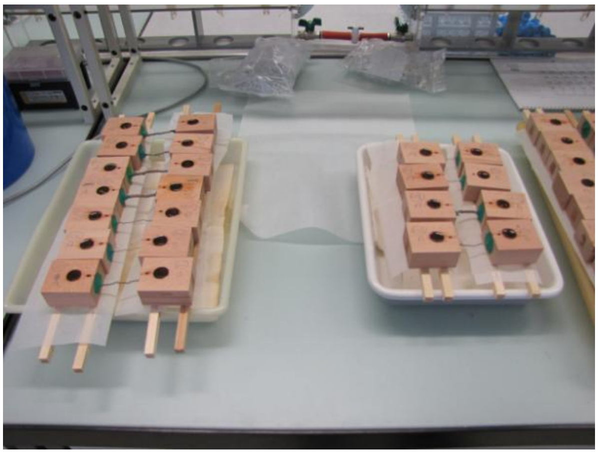

Fig. 3.5: Samples after pouring. Photo: D. Kink, November 2013.

During this preparation process the samples would lie around in the laboratory openly, and thus lose moisture. Since it was the goal to simulate as realistic conditions as possible, the samples were put in a climate room (20 °C and 95% relative humidity (rel. hum.)) for seven days prior to the tensile strength tests.

It was assumed that seven days would be enough time for the samples to be re-moisturized. It might have been preferable to store the roots for more than seven days at 20 °C/95% rel. hum., however there were other samples stored in the same room, which were showing various fungi. Keeping the samples in this room for longer, would have meant to risk decay of the root structure, which would have distorted the measurements.

3.2.2 Tensile Strength Tests

For the tensile tests a Zwick/Roell Z100 (Zwick GmbH & Co. KG, Ulm, Germany) universal testing machine of the Institute for Building Materials at the Swiss Federal Institue of Technology (ETH) Hönggerberg in Zürich was used (Fig. 3.6). This machine had self-clamping jaws, in which the root samples had to be placed and fastened in order to be tested. During the tests the machine's crosshead speed was kept constant at 5mm/min. A load cell with a nominal strength of 100 kN and an accuracy of 1% of the measured value was used. The software used in order to conduct the tests was testXpert II, version 3.0, which was developed by Zwick/Roell. In 2012 the load cell was calibrated and tested. It was found that all the requirements were fully met at that time.

The vertical force exerted by the machine was transferred by the clamps into a horizontal direction and was hence applied to the samples directly. If the roots would have been fastened to the clamps without any kind of buffering material (i.e., the used oak cuboids), most of the samples would have been crushed before the test would have been finished and thus voided the measurement.

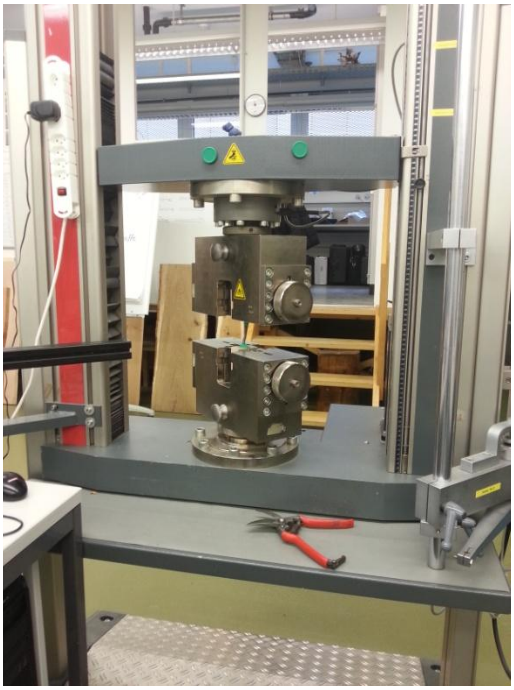

Fig. 3.6: The Zwick/Roell 100 univesal testing machine at the ETH Hönggerberg. Photo: D. Kink, November 2013.

Even though the climate room was close to the testing room, not more than eight samples were removed from the climate room at once, to ensure their freshness. Between the removal of the samples from the climate room and the actual test, the samples were kept in a plastic bag. A testing session would take several hours, during which the samples were not wanted to dry out again.

A test was considered successful, when the root was torn apart between the two oak cuboids in the part that was visible during the test. Often the sample would fail inside a cuboid or right at the edge of the epoxy resin. If this happened, the test was voided. Five locations of breakage were defined (Fig. 3.7); 1 and 5 would mean a test was void, 2 – 4 indicate a successful test. Only the data from the successfully tested root is taken into account for the evaluation.

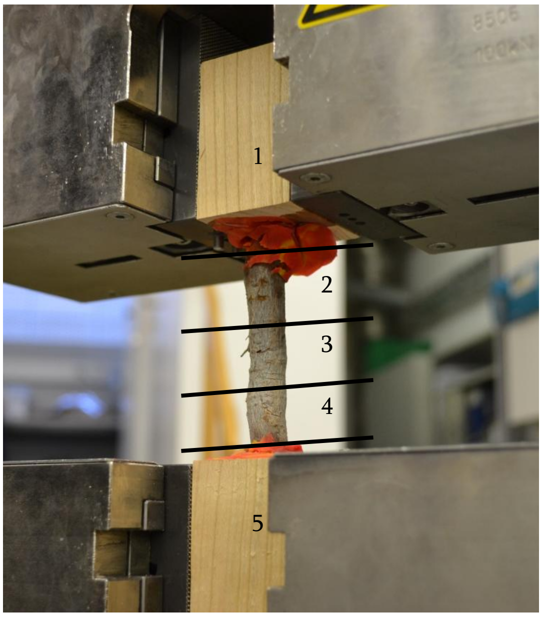

Fig. 3.7: A sample in the testing machine, before examination. The numbers mark the zones in which failure had to occur in order for the sample to have been tested successfully (2 – 4) or not (1, 5). Photo: D. Kink , November 2013.

After a successful test, roots were cut off the two cuboids using secateurs. The sample was then weighted at the ETH on a scale with an accuracy of 1 mg. This way the initial weight of a sample was determined without losing moisture to evaporation. The samples were then taken to the WSL, dried in an oven (60 hours at 60 °C), and weighed again, this time with a scale at the WSL, which had an accuracy of 0.01 mg.

Although the output of the tensile tests included a value for the relative tensile strength, it was recalculated because the automatically generated value was not reproducible. Similar to Genet et al. (2008) the tensile strength of a root sample was calculated by dividing the maximal force applied to the root before the sample failed by the cross-sectional area (CSA). The CSA was calculated using the average diameter, which was generated using six measurements of the over-bark diameter applying an electronic slide gauge.

3.2.3 Wood Anatomical Analysis

In a next step two micro-sections were prepared from every successfully tested sample, using the material that was put aside earlier. It was the aim to achieve a thickness of 15 µm. A WSL-lab microtome and the methods described by Gärtner & Schweingruber (2013) were used to prepare the samples (Fig. 3.8). After staining and embedding the samples in Canada balsam, they were photographed using a Canon EOS 650D in tethering mode and mounted on a microscope along with the EOS Utility software (Canon Inc., Tokyo, Japan).

Since the bark was removed prior to fixating the root samples in the wooden cuboids, it did not have an influence on the measured tensile strength. Therefore it had to be excluded in the wood anatomical analysis. The micro-sections were analyzed using the image analysis software WinCELL (Regent Instruments Inc., Québec, Canada). Before loading an image into the software, the bark was removed using Adobe Photoshop CS4 (Adobe Systems Inc., San Jose, CA, USA).

WinCELL is able to distinguish between vessel and fiber cells, using a threshold which can be adjusted by the user. Various parameters such as cell type, lumen area, lumen length and height, cell wall thickness, total lumen area and many more were evaluated by the software. For every analyzed micros-section a .txt data file was created listing every single cell measured.

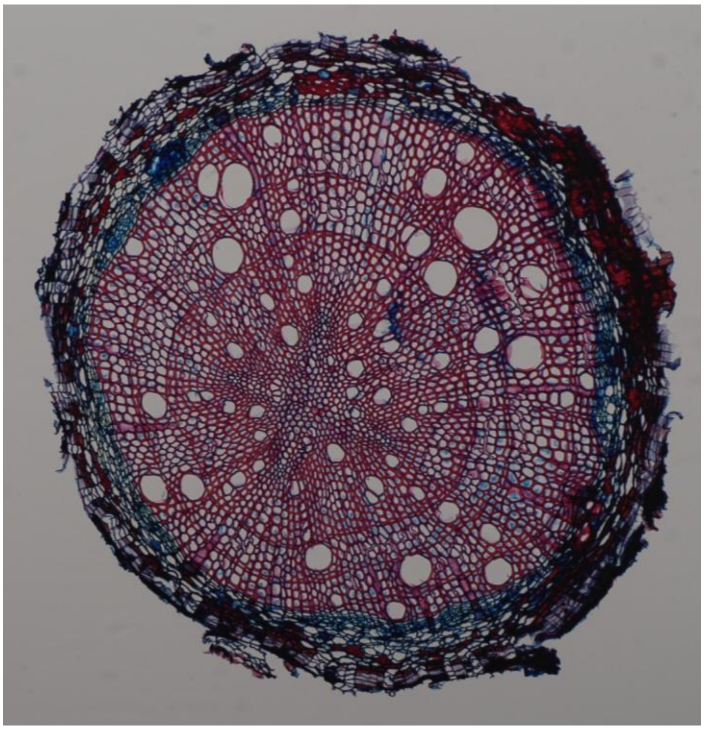

Fig. 3.8: Micro-section after staining and embedding. After removing the bark in Photoshop, it would be prepared to be analyzed in WinCELL. Photo: D. Kink, February 2014.

3.3 Data Analysis

41% of the tensile tests were successful (Tab. 3.2). In total the properties of over 6’000’000 cells were recorded using WinCELL. In order to be able to analyze the data, a file had to be created, including all assessed parameters from the tensile test and the micro-sectioning. This was done, by combining the various output files from the tensile tests (Excel file) with the WinCELL output (text file) using R, version 3.0.1(R Development Core Team, 2011). The assessment of the data was also performed in R.

Tab. 3.2: Summary of the tested samples.

	Alnus 01 - 03		Acer 01 - 04		Total	
	No.	%	No.	%	No.	%
Total of tested samples	199	100	190	100	389	100
Successfully tested	76	38.2	82	43.2	158	40.6
Failed	123	61.8	108	56.8	231	59.4

After a first assessment of the data, it was decided that the data of Acer 04 was not going to be considered in the further evaluation. The variation of several parameters of the individual trees within their group was large. Only 3 samples (13% rate of success) of Acer 04 were tested successfully, which was not considered to be enough in order to be representative. The numbers of successful samples of the other trees were (number of samples (success rate)); Acer 01: 15 (48.4%), Acer 02: 51(57.8%), Acer 03: 13 (36.1%), Alnus 01: 12 (40%), Alnus 02: 43 (37.1%), Alnus 03: 21(39.6%).

Due to the nested nature of the data, which would have made mixed effects models as described by Zuur et al. (2009) necessary, it was chosen to pursue a descriptive approach for the evaluation of the presented data. Two different kinds of diagrams are used to present the data in Section 4; scatterplots and boxplots.

In order to detect trends in the scatterplots, which display the values of two parameters, LOWESS smoothers were added. LOWESS stands for LOcally WEighted Scatterplot Smoother. LOWESS smoothers were developed by Cleveland (1979). The values of a scatterplot are fitted to a line using weighted least squares. The closer a data point is, the higher its weight becomes. It is a robust fitting procedure which enhances the visual information of a scatterplot (Cleveland, 1979). LOWESS lines should not be mistaken as regression curves.

Boxplots are suited to visualize categorical data (Ammann, 2006). The different elements are specified in Figure 3.9. All the boxplots presented in section 4 show notches. These indicate the 95% confidence interval of the median. An overlap of the notches strongly indicates that the medians do not differ significantly. However, this is just an indication and not a formal test (Craig and Wood, 1991). In two (Fig. 4.5 & 4.6) of the three boxplots presented in Section 4 the outliers had to be removed. If they would have been displayed, the boxes would have turned out to be too small for an adequate interpretation, because the values of the outliers were very high. These missing values are described in the text of Section 4.

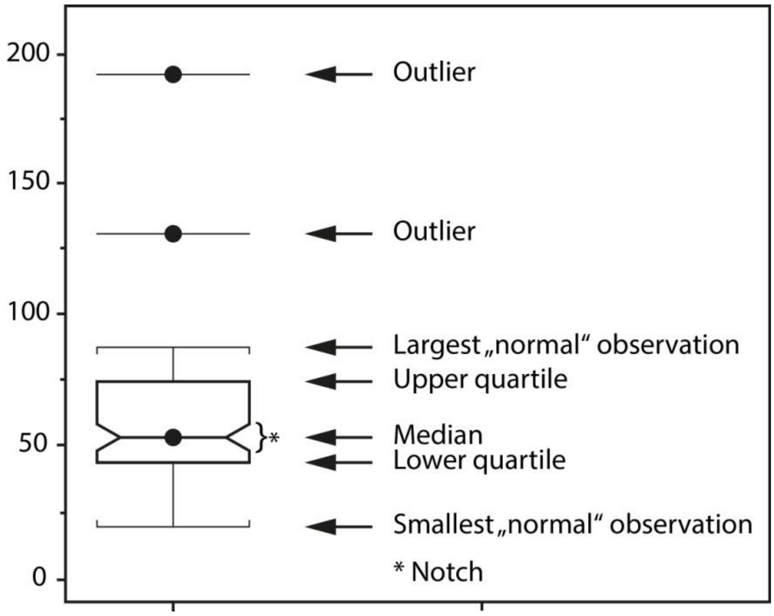

Fig. 3.9: Specification of the elements of a boxplot. Modified after Stahel (2000).

In total 8 wood anatomical parameters were evaluated. It was chosen to only present and discuss 2 of these parameters (standardized number of vessels & standardized vessel lumen area) in the following sections. The different figures of the other six wood anatomical parameters can be found in the Appendix.

4. Results

4.1 Root Tensile Strength

4.1.1 Distribution of the Data

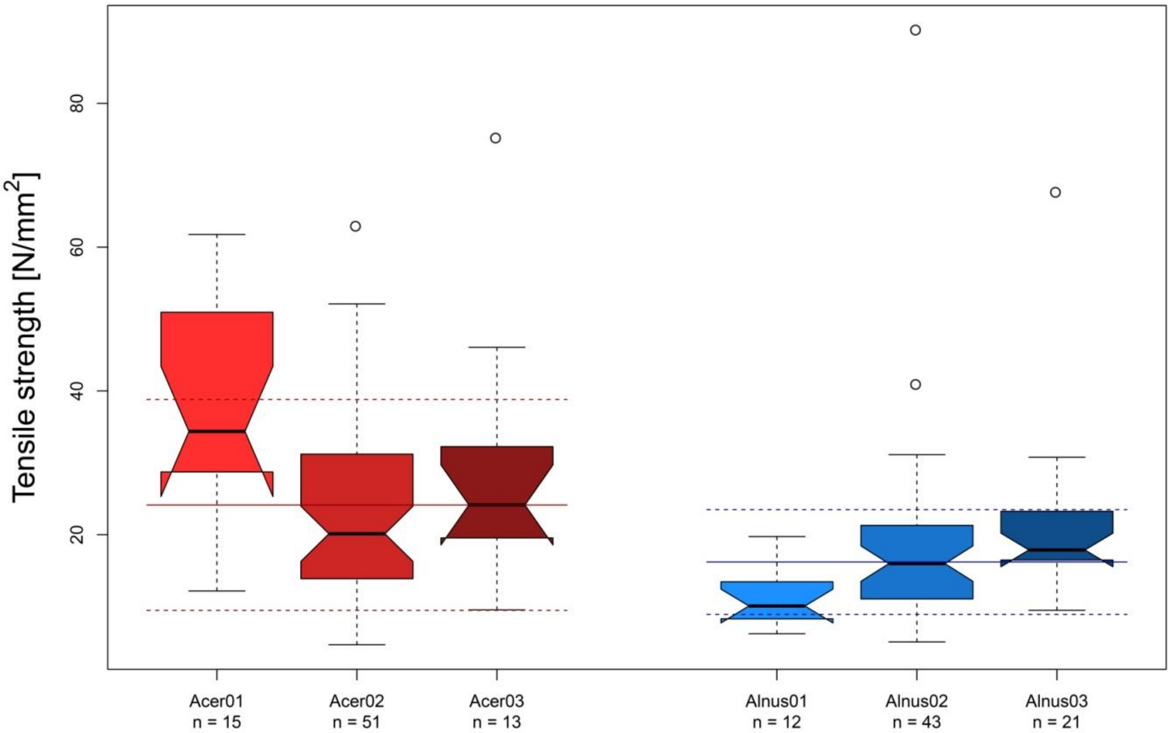

Fig. 4.1: Tensile strength values of Acer 01 – 03 and Alnus 01 – 03. The solid lines represent the overall median values within the respective group of trees. The dashed lines indicate the median absolute deviation.

Figure 4.1 does not only display the variation of tensile strength between the two evaluated groups of trees, but also the different numbers of samples as well as the differences in tensile strength within the two tree groups.

The root tensile strength of the three analyzed Acer trees ranged from 4.7 N/mm^2 to 75.2 N/mm^2 (Fig.4.1). The Alnus trees 01 – 03 showed root tensile strength values ranging from 5.1 N/mm^2 to 90.2 N/mm^2. If the three outliers of Alnus 01 – 03 were not taken into account, the highest tensile strength of this tree group would have been 31.1 N/mm^2. The highest tensile strength of the three Acer trees, if the two outliers were to be ignored, was 61.8 N/mm^2.

The overall median of the three Acer trees was 24.1 N/mm^2 (± 14.7 N/mm^2). The corresponding value of the Alnus trees 01 – 03 was 16.2 N/mm^2 (± 7.3 N/mm^2). Hence, the overall median of the Acer trees 01 – 03 was 1.5 times higher than the overall median of the three Alnus trees.

More samples were successfully tested of Acer 02 (51), than of Acer 01 (15) and Acer 03 (13) combined. Nevertheless, the notches of Acer 02 and Acer 03 suggested the medians of the tensile strength of these two trees to be similar. Acer 01 showed the highest median (34.4 N/mm^2) of the three Acer trees (median of Acer 02: 20.1 N/mm^2, median of Acer 03: 24 N/mm^2). However, it still lay within the MAD distance of the overall median. The notches of Acer 01 indicated that its median was likely to be similar to the one of Acer 03, but not to the one of Acer 02. Unlike Acer 01, the tensile strength values of Acer 02 and 03 appeared to be similar to each other.

Of the three Alnus trees, Alnus 02 was the one with the most successful samples (43). 12 samples of Alnus 01 and 21 samples of Alnus 03 were considered to be successful. The median of Alnus 02 (16 N/mm^2) was the one closest to the overall value of this tree group. The median value of Alnus 01 showed the largest deviation from the overall median, with an equivalent of 10.1 N/mm^2. Even though this value was close to the lower MAD distance, it still lay within this range. The median of Alnus 03 was 17.9 N/mm^2. The notches indicated that the medians of Alnus 01 and 02 did not differ significantly from each other. This was not the case for Alnus 01, for which no overlapping area with the two other trees could be seen.

Overall it can be said that the Acer trees showed a higher tensile strength than the Alnus trees. However, Acers 01 – 03 showed a larger variation than Alnus trees 01 – 03, especially in regard of the MAD. For both groups of trees it can be said that the first individual (Acer 01/Alnus 01) showed the largest variation within their groups. Acer 02 and 03 as well as Alnus 02 and 03 seemed to be relatively similar to each other, despite the large discrepancy in the number of samples.

4.1.2 Relation to Diameter

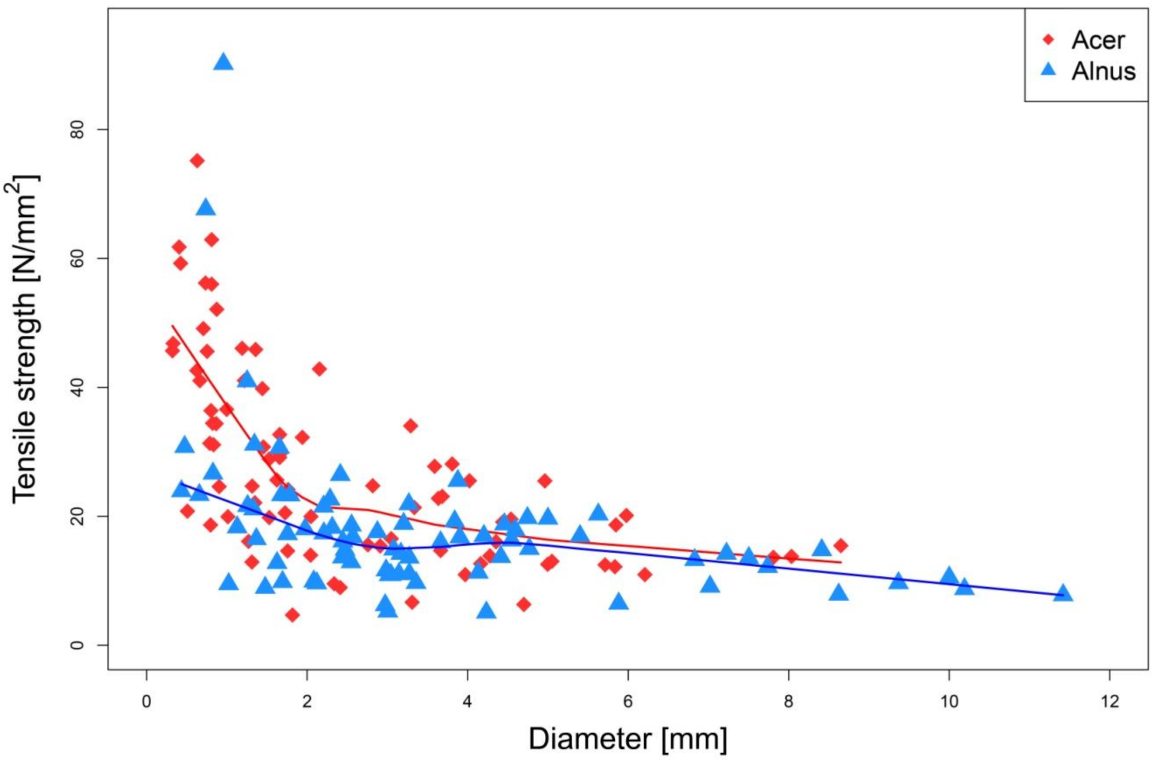

Fig. 4.2: Tensile strength in relation to the root diameter. The lines represent LOWESS smoothers; red: Acer 01 – 03 (n = 79); blue: Alnus 01 – 03 (n = 76).

In addition to the relation between root diameter and root tensile strength, Figure 4.2 also gives an idea of the diameter distribution of the successfully tested samples. The range of diameter of Acer trees 01 – 03 lay between 0.3 mm and 8.7 mm. The roots of Alnus trees 01 - 03 showed a marginally larger diameter range than the three Acer trees, namely from 0.4 mm – 11.4 mm. The numbers of samples of the two tree groups were comparable to each other (Acer 01 – 03: 79 samples, Alnus 01 – 03: 76 samples).

Small diameters were stronger represented than larger ones. This was especially the case for Acer trees 01 – 03. The three Alnus trees showed the most samples between 2 mm and 4 mm. There were 43 samples of the three Acer trees between 0 mm and 2 mm (22 samples between 0 mm and 1 mm), whereas Alnus trees 01 – 03 had less than half as many samples (21, 6 of which between 0 mm and 1 mm) in this range. Acer trees 01 – 03 had 18 samples of which a diameter between 2 mm and 4 mm was measured (8 samples between 2 mm and 3 mm). The corresponding diameter range of the three Alnus trees contained 31 samples (16 between 2 mm and 3 mm). Between 4 mm and 6 mm there were 14 samples (9 of which between 4 mm and 5 mm) of Acer trees 01 – 03, and

13 samples (9 if which between 4 mm and 5 mm) of the three Alnus trees. There were no samples of Acer trees 01 – 03 which had a diameter larger than 9 mm. Four samples of the three Acer trees lay between 6 mm and 9 mm. The three Alnus trees showed 11 samples which were distributed between 6 mm and 12 mm.

The smoothers suggested that the tensile strength of Acer trees 01 – 03 was higher than for Alnus trees 01 – 03. This was true for all measured diameters. The trend lines of the two tree groups showed differences, especially in small diameters, where the number of samples also strongly differed between the two groups of trees.

The LOWESS smoother of Acer trees 01 – 03 showed the lowest value where the diameter was greatest. Between 8.7 mm and 2.5 mm this red line increased constantly. There was a small decrease between 2.5 mm and 2 mm. From 2 mm to 0.3 mm the smoother showed a strong increase, especially when compared to the slope between 8.7 mm and 2.5 mm.

The LOWESS line of the three Alnus trees also showed the lowest value where the diameter was greatest. The smoother of Alnus trees 01 – 03 was similar to the one of the three Acer trees. However, the trend of the blue line was not as distinct as the red one. There was a slight increase between 11.4 mm and 4.5 mm, after which the line decreased until it reached 3 mm. Following this decrease, the trend started to increase again, and did so until it reached its minimum diameter of 0.4 mm.

The smaller the diameters of the samples got, the greater the difference between these two LOWESS lines became. Between diameters of 2 mm – 8.7 mm the trend line of Acer trees 01 – 03 was higher than the one of Alnus trees 01 – 03, the difference however was not greater than 10 N/mm^2. There was a sharp increase in the LOWESS line of Acer trees 01 – 03, around a diameter of 2 mm. The smoother of the three Alnus trees increased steadily, which led to a larger difference between the two lines in diameters < 2 mm. The maximum value of the smoother of Alnus 01 – 03 was 25 N/mm^2, which was half the value of Acer 01 – 03 (50 N/mm^2).

Altogether it can be said that that tensile strength increased with decreasing diameter. It can be seen that Acer trees 01 – 03 showed higher tensile strength than Alnus trees 01 – 03. This was especially the case for small diameters (< 2 mm), which in the group of the three Acer trees were stronger represented. The larger the diameters got, the more similar the values of tensile strength of the evaluated tree groups became, along with a decreasing number of samples.

4.1.3 Relation to Age & Distance to Stem

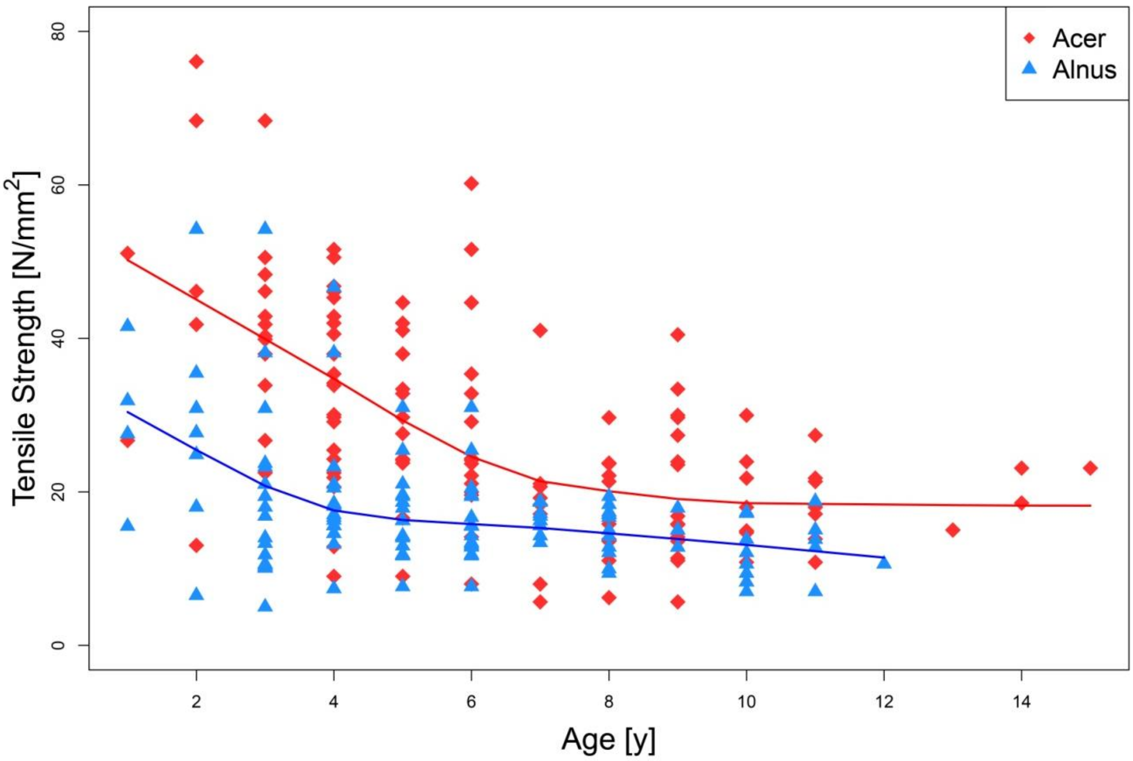

Fig. 4.3: Root tensile strength in relation to the root age. The lines represents LOWESS smoothers; red: Acer 01 – 03 (n = 141); blue: 01 – 03 (n = 138).

Figure 4.3 presents the relation between tensile strength and age, as well as the age distribution of the different samples. It has to be kept in mind that for every tensile strength value, two different ages were determined, since from every sample two micro-sections were prepared and analyzed. This led to a higher number of data points, but also to a certain degree of redundancy. It was not possible to estimate the exact number of year rings at the point of failure.

With 28 samples, 4 years was the most frequent age of Acer trees 01 – 03 followed by 6 years (18 samples) and 3, 5, and 9 years (all three had 15 samples). The majority (64.5%) of the samples of the three Acers were either between 3 and 6, or 9 years old. There were 8 samples of this tree group which were younger than 3; 2 samples with an age of 1 year and 6 which were 2 years old. Due to the overlap of points described above, only 5 of the 6 data points of Acer trees 01 – 03 are visible for the age of 2 years. The number of samples of the other age classes were (age: number of samples): 7: 9, 8: 11, 10: 9, 11: 7, 12: 0, 13: 2, 14: 3, 15: 1.

57.3% of the samples of Alnus trees 01 – 03 were between 3 and 6 years old; 25 samples were 3 years old, 21 samples were 4 years old, 17 samples were 5 years old, and 16 samples were 6 years old. More samples which were younger than 3 years were found for Alnus trees 01 – 03 than for the three Acers; 9 samples had an age of 1 and 11 samples were 2 years old. The number of samples of the other age classes of Alnus trees 01 – 03 were (age: number of samples): 7: 8, 8: 11, 9: 5, 10: 9, 11: 5, 12: 1. For the three evaluated Alnus trees no sample was found which was older than 12 years.

Similar to the trend lines in Figure 4.2, the LOWESS smoothers of Figure 4.3 suggested Acer trees 01 – 03 to have a higher tensile strength than Alnus trees 01 – 03. For both trend lines it appeared as if the younger a root sample was, the higher tensile strength was measured. For Acer trees 01 – 03 there was a negative trend in tensile strength between the ages 1 and 7. This trend stagnated at the age of 7 and was more or less constant for the other ages. The three Alnus trees showed a similar trend. However, the LOWESS line of Alnus trees 01 – 03 stagnateed earlier; at the age of 4.

The majority of the data of both tree groups lay between 1 and 11 years. Between ages 3 and 11 the number of samples in for each age class was ≥ 5. If the focus would lay on the roots which were between 3 and 11 years old, it can be said that the tensile strength of both tree groups was decreasing with increasing diameter until it reached a certain age (7 in the case of the three Acers and 4 in the case of Alnus trees 01 – 03). From this age on the trend stagnated. This is also true for ages > 11 years where the number of samples was too low (< 5) to be taken into consideration.

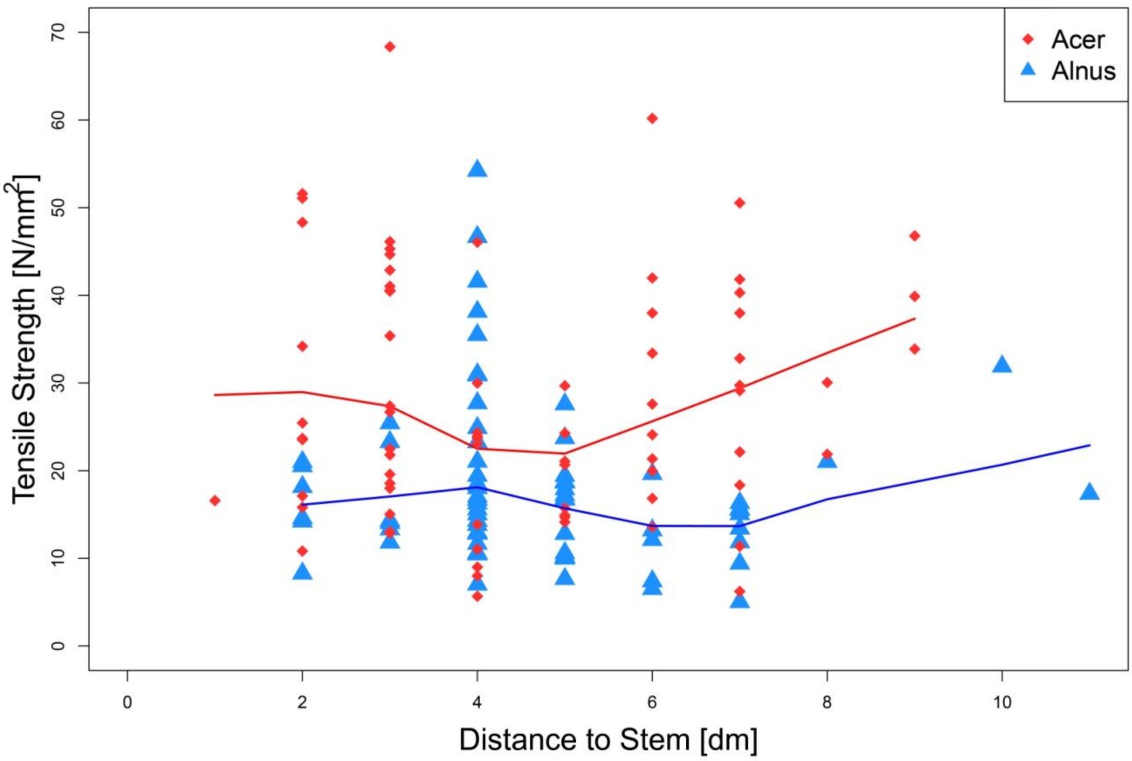

Fig. 4.4: Root tensile strength in relation to the distance of a root to the stem. The lines represent LOWESS smoothers; red: Acer 01 – 03 (n = 76); blue: Alnus 01 – 03 (n = 71).

The data presented in Figure 4.4 illustrates that the vast majority of the samples of both tree groups (65.8% for Acer trees 01 – 03, 77.5 % for Alnus trees 01 – 03) were located within a 50 cm radius of the stem. The highest number of samples (20) of Acer trees 01 – 03 was found in distance class 3 (20 cm - < 30 cm). Most samples (28) of one class of the three Alnus trees were found in class 4 (30 cm - < 40 cm). The exact number of samples of the distance classes of Acer trees 01 – 03 were as follows (distance [dm]: number of samples); 1: 1, 2: 10, 3: 20, 4: 11, 5: 8, 6: 10, 7: 11, 8: 2, 9: 3. No successful samples of the three Acer trees were found further away from the stem than 90 cm. The exact number of samples in each distance class of the three Alnus trees was (distance [dm]: number of samples); 1: 0, 2: 6, 3: 6, 4: 28, 5: 15, 6: 5, 7: 8, 8: 1, 9: 0, 10: 1, 11: 1.

Corresponding to Figures 4.2 and 4.3, the LOWESS smoothers of Figure 4.4 indicated the three Acer trees to have had a higher tensile strength than Alnus trees 01 – 03. Acer trees 01 – 03 showed a negative trend in tensile strength between distance classes 1 and 5. This trend became positive for classes > 5. The trend line indicated a strong trend in classes > 5. Since there were 10 samples in class 6 and 11 samples in class 7, this trend appears to be plausible, at least for these two classes. It is likely that more data in classes 8 (2 samples) and 9 (3 samples) would affect this trend. Therefore, it cannot be confidently said that the tensile strength of Acer trees 01 – 03 strongly increased in distance classes 8 and 9. It seems that the tensile strength of roots of the three Acer trees decreased with increasing distance to the stem for samples which lie within a radius of 50 cm. Samples which were located further away from the stem showed increasing tensile strength. Nevertheless, it has to be noted that the number of samples in classes > 5 was relatively low compared to classes < 5.

The trend of Alnus trees 01 – 03 was similar to the one of the three Acer trees, but not as distinct. It started out slightly positive between distance classes 2 and 4, but then became negative between classes 4 and 7. From classes 7 to 11 the trend again changed to positive. Since there were only 3 samples in the four classes > 7, this trend has to be considered with reservation. Due to this low number of samples it is possible that only a few more data points in classes > 7 would significantly change this trend. Therefore it cannot be said with certainty that the tensile strength of the three Alnus trees increased with increasing distance to the stem. If distance classes > 7 were to be ignored, one would have to say that even though the tensile strength of Alnus trees 01 – 03 increased between classes 2 and 4, the overall trend was at least constant, if not even negative.

4.2 Wood Anatomy

4.2.1 Selected Wood Anatomical Parameters

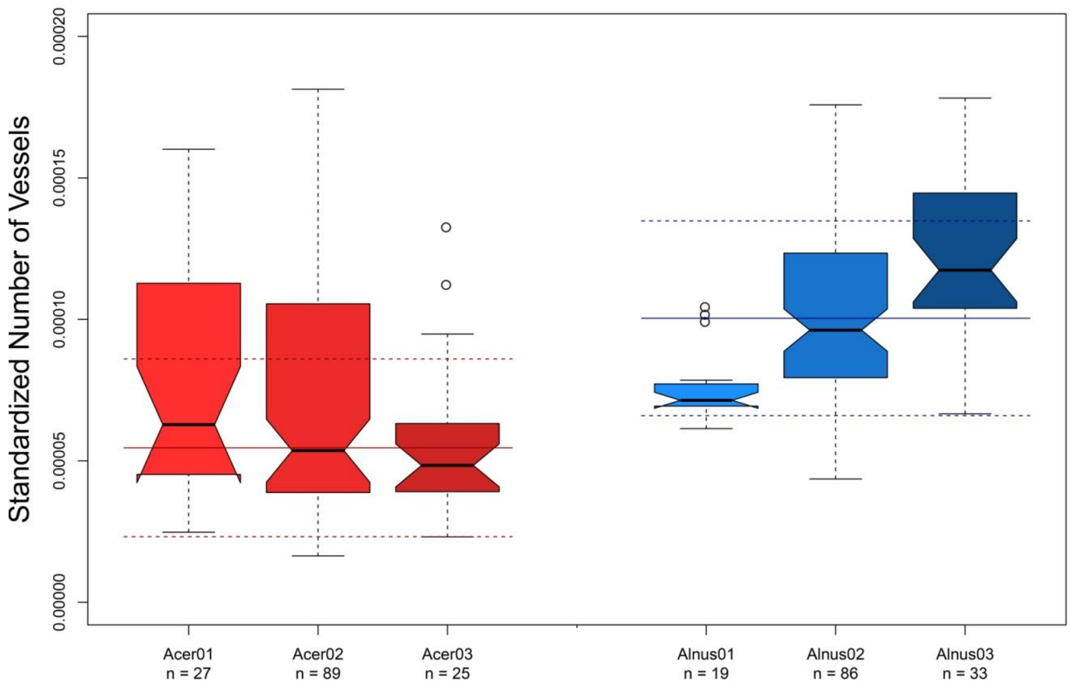

Fig. 4.5: Standardized number of vessels of Acer 01 – 03 and Alnus 01 – 03. The solid lines represent the overall median values within the respective group of trees. The dashed lines indicate the median absolute deviation.

In order to be able to achieve a reasonable size of the boxplots depicted in Figure 4.5, some outliers of the different trees had to be cut off. Of the three Acer trees there are two outliers missing in this figure, both were measured from Acer 02 (0.00031 and 0.00046). There is one outlier missing of Alnus 01 (0.00022), and three of each Alnus 02 (0.00023, 0.00035, 0.001) and Alnus 03 (0.00021, 0.00023, 0.00026).

The overall median of the three Acer trees (0.000056 ± 0.000031) was smaller than the overall median of Alnus trees 01 – 03 (0.0001 ± 0.000034) by a factor if 1.8. This means that Alnus trees 01 – 03 showed 1.8 times more vessels per unit of area (e. g., per 1 μm^2) than the three Acer trees. Despite of the similar MAD values of the two tree groups, the variation of the trees within their groups was not comparable to each other.

More than half of the samples (89) of Acer trees 01 – 03 came from Acer 02. Acer 01 had 27 samples, and Acer 02 reached 25 samples. Nevertheless, the notches of all three Acer trees suggested that their medians (Acer 01: 0.000062, Acer 02: 0.000054, Acer 03: 0.000048) did not differ significantly from each other. In addition to that it can be seen that there was not much deviation of the medians of the three Acer trees from the overall median. This implied that the number of vessels per unit of area (VPUA) did not vary greatly between the three Acer trees. If the outliers were not taken into account, it can be said that the range of the VPUA of Acer 01 and Acer 03 were similar. Acer 03 showed a lower range than the other two individuals. However, the range of Acer 03 did not lie outside the range of Acer 01 and 02.

There was more variation in the three Alnus trees than in Acer trees 01 – 03. The individual with the lowest median (0.000071) and number of samples (19) of this tree group was Alnus 01. The median of Alnus 01 was close to the lower MAD distance, but still lay within this border. Alnus 02 was not only the individual with the highest number of samples (86), but also the one with its median (0.000096) closest to the overall value. With a number of samples of 33, Alnus 03 showed the highest median (0.00012) of these three trees. The notches indicated that the median values of Alnus trees 01 – 03 were likely to be significantly different from each other. Alnus 01 showed by far the lowest range of values of the three Alnus trees. The ranges of Alnus 02 and 03 were comparable to each other, assuming the outliers were to be ignored. However, Alnus 03 showed a lower minimum value than Alnus 02. Compared to Acer trees 01 – 03, the three Alnus trees showed more variation within their group.

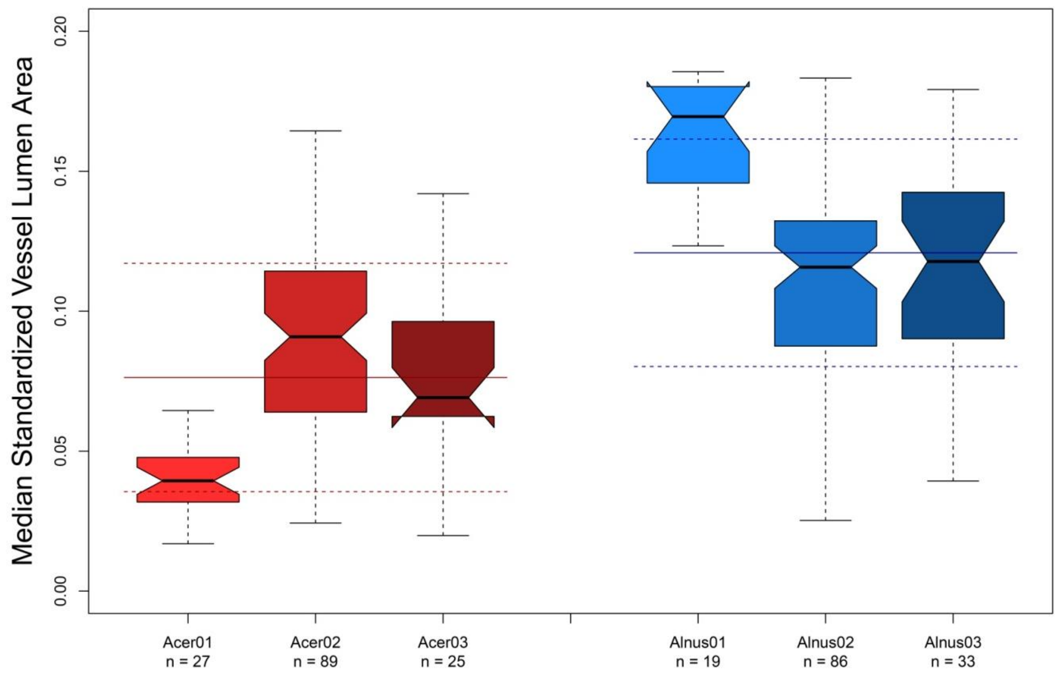

Fig. 4.6: Standardized vessel lumen area of Acer 01 – 03 and Alnus 01 – 03. The continuous lines represent the overall median values within the respective group of trees. The solid lines indicate the median absolute deviation.

In order to facilitate the interpretation of Figure 4.6, the outliers of the standardized vessel lumen area were excluded from the display. There were no outliers of Acer 01. From Acer 02 three data points were removed (0.22, 0.64, and 0.86). Acer 03 had one outlier (0.22) which is not depicted in Figure 4.6. Alnus 01 and 02 both had two outliers (Alnus 01: 0.24, and 0.8, Alnus 02: 0.22, and 0.45). No outliers were found for Alnus 03. Therefore all data of this individual is presented in Figure 4.6.

Since Figures 4.6 and 4.5 were generated using the same dataset, the number of samples of the six individual trees did not change. The overall median of the standardized vessel lumen area of Acer trees 01 – 03 was 0.076 (± 0.04). The corresponding value of the three Alnus trees was 1.6 times higher; 0.12 (± 0.04). For both groups of trees it appeared as if the first individual (Acer 01/Alnus 01) showed the worst fit within the respective group.

Acer 01 showed the lowest median (0.039) of the three Acer trees, which still lay within the MAD distance of the overall median. The notches of this individual also clearly suggested the median to differ from the other two values. The medians of Acer 02 (0.091) and 03 (0.069) were closer to the overall value. The notches of Acer 02 and 03 did not overlap, which means that the medians of these two trees probably were significantly different from each other. Compared to the overall value, Acer 01 showed a much smaller standardized vessel lumen area than the other two trees of the same group. The standardized vessel sizes of the other two trees were likely to vary from each other. Nevertheless these two values were closer to the overall median than the median of Acer 01.

The median of the standardized vessel lumen area of Alnus 01 (0.17) was much larger compared to Alnus 02 (0.116) and 03 (0.118). The notches also indicated Alnus 01 to most likely have had significantly larger vessels than Alnus 02 and 03. The median of Alnus 01 lay outside the upper MAD distance of the overall value. The notches of Alnus 02 and 03 implied that the median values, which when rounded, did not differ significantly.

Summarizing Figures 4.5 and 4.6 it does not only appear as if Alnus trees 01 – 03 had more vessels per unit of area, but also larger ones. Furthermore it is evident that Alnus 01 had a lower number of vessels compared to the other trees of the same group. However, the vessels Alnus 01 had were much larger than the ones of the other two individuals. Acer 01 showed a similar number of vessels in relation to Acer 02 and 03, but the standardized lumen area of Acer 01 was smaller in contrast to Acer trees 02 and 03.

4.2.2 Relation to Diameter

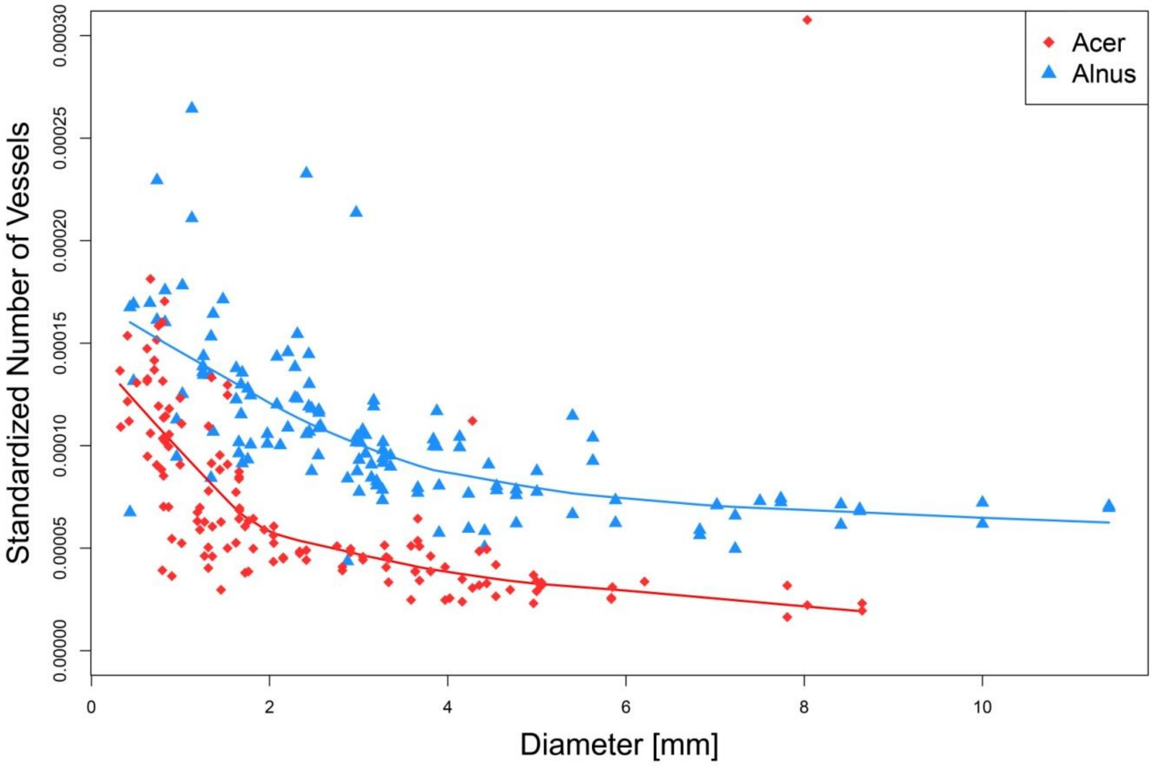

Fig. 4.7: Standardized number of vessels in relation to the root diameter. The lines represent LOWESS smoothers; red: Acer 01 – 03 (n = 141); blue: Alnus 01 – 03 (n = 138).

The general conclusion of Figure 4.5, that Alnus trees 01 – 03 showed more vessels per unit of area is also reflected in Figure 4.7. The diameter ranges have not changed for the two tree groups; Acer trees 01 – 03 showed diameters from 0.3 mm to 8.7mm, the diameters of Alnus trees 01 – 03 were distributed between 0.4 mm and 11.4 mm. The numbers of samples of the two tree groups were comparable to each other (141 samples of Acer trees 01 – 03, 138 samples of the three Alnus trees). The distribution of the samples was similar to the one described above (Fig. 4.2); small diameters were stronger represented than larger ones. This was especially the case for Acer trees 01 – 03, where 78 sample lay between 0 mm and 2 mm (39 of which between 0 mm and 1 mm). Alnus trees 01 – 03 had 42 samples between 0 mm and 2 mm (12 samples between 0 mm and 1 mm). The majority of the samples of the three Alnus trees lay between 2 mm and 4 mm (57 samples, 28 thereof lay between 3 mm and 4 mm). The rest of the samples lay between the following diameter ranges (range: number of samples); Acer trees 01 – 03: 4 mm - < 5 mm: 16, 5mm - < 6 mm: 6, 6 mm - < 7 mm: 1,. 7 mm - < 8 mm: 2, 8 mm - < 9 mm: 4; Alnus trees 01 – 03: 4 mm - < 5 mm: 13, 5mm - < 6 mm: 8, 6 mm - < 7 mm: 3, 7 mm - < 8 mm: 7, 8 mm - < 9 mm: 4, 9 mm - < 10 mm: 0, 10 mm - < 11 mm: 2, 11 mm - < 12 mm: 2.

The smoother of Acer trees 01 – 03 generally showed a negative trend. This trend was strongest between diameters from 0 mm to 2 mm. After 2 mm this trend became weaker, but it still was slightly negative. Except for one large outlier at 8 mm, the data of Acer trees 01 – 03 appeared to fit the trend line quite well, although the number of samples in diameters between 5 mm and 8 mm was much lower than in smaller diameters.

The three evaluated Alnus trees showed a similar trend. However, it was not as distinct as the one of Acer trees 01 – 03 and also showed a slight offset. Overall this trend line can also be described as negative, especially between diameters of 0 mm to 4 mm. At 4 mm the trend weakened and almost stagnateed. There were no major outliers in larger diameters. Hence, the LOWESS line appeared to fit the data well.

Especially for the three Acer trees, the relation between diameter and the standardized number of vessels appeared to be similar to the one between diameter and tensile strength (Fig. 4.2). With increasing diameter the tensile strength and the standardized number of vessels of Acer trees 01 – 03 decreased. For both parameters there was a change in the trend at a diameter of 2 mm.

Comparing the trends of the relation between tensile strength and diameter with the one of the standardized number of vessels and diameter of the three Alnus trees, it can be said that they were similar. However, they did not fit as well as the two described trends of Acer trees 01 – 03. The trend in tensile strength (Fig. 4.2) changed at diameters of 3 mm and 4 mm, whereas the trend between the diameter and the standardized number of vessels only changed at 4 mm. Nevertheless, the overall conclusion that both tensile strength and the standardized number of vessels of the three Alnus trees decreased with increasing diameter is still true.

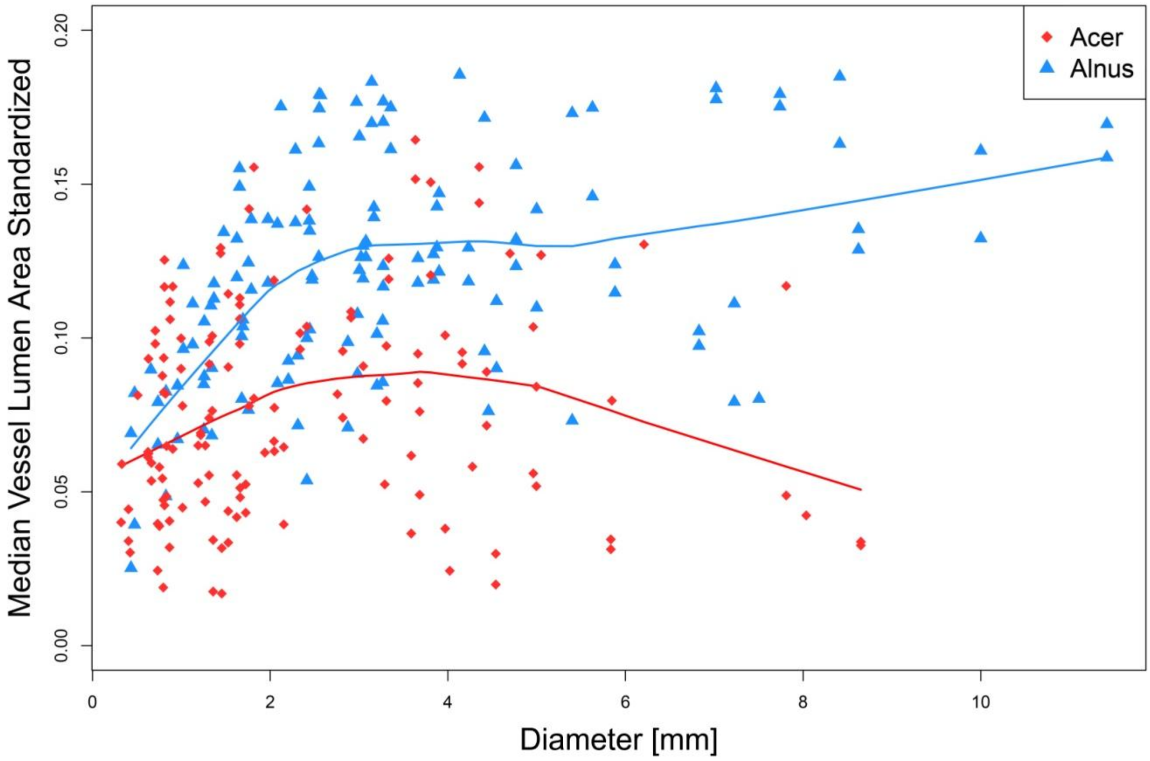

Fig. 4.8: Medians of the standardized vessel lumen area in relation to the root diameter. The lines represent LOWESS smoothers; red: Acer 01 – 03 (n = 141); blue: Alnus 01 – 03 (n = 138).

The diameter distribution of Figure 4.8 was the same as for Figure 4.7; small diameters were stronger represented than larger ones. Corresponding to Figure 4.6, the standardized vessel lumen area of Alnus trees 01 – 03 was generally higher than the same parameter of the three Acer trees (Fig. 4.8).

The trend line of Acer trees 01 – 03 indicated a positive trend in standardized vessel lumen area between diameters of 0 mm to 2 mm. Between 2 mm and 5 mm this trend stagnated, and then became negative in diameters > 5 mm. It has to be noted that the number of samples of Acer trees 01 – 03 in diameters > 5 mm was relatively low (12 samples between 5 mm and 9 mm). If more data was added it is likely that this trend would be less negative or even stagnate. If only the diameter range between 0 mm and 5 mm was considered, the data depicted in Figure 4.8 matches the trend seen in Figure 4.2 well. The tensile strength decreased with increasing diameter, whilst the standardized vessel lumen area increased. This changed at a diameter of 2 mm, where the standardized vessel lumen area stagnated (Fig. 4.8) and the decreasing trend in tensile strength weakened (Fig. 4.2).

The positive relation between standardized vessel lumen area and diameter was even more distinct for Alnus trees 01 – 03. There was a strong increase in vessel lumen area within a diameter range from 0 mm to 3 mm. After stagnating between 3 mm and 5.5 mm, another slight increase of the trend can be seen. This matches the trend described in Figure 4.2.

4.3 Root Tensile Strength in Relation to Wood Anatomy

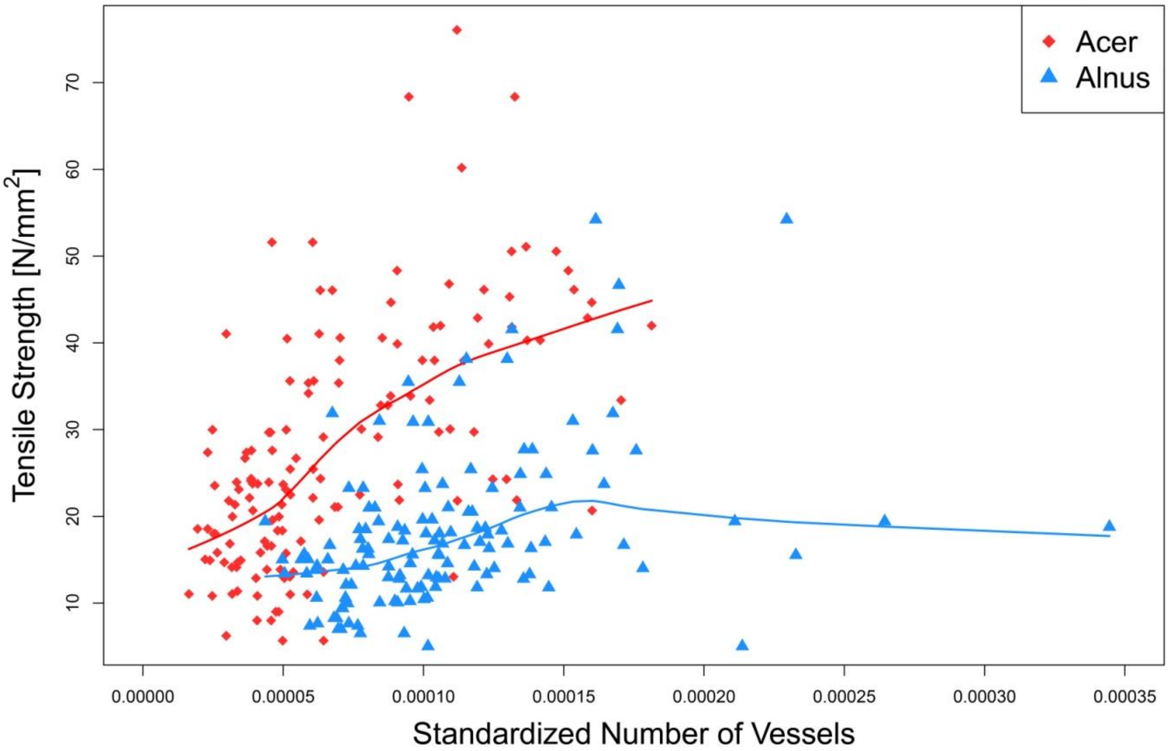

Fig. 4.9: Relation between root tensile strength and the standardized number of vessels. The lines represent LOWESS smoothers; red: Acer 01 – 03 (n = 141); blue: Alnus 01 – 03 (n = 131).

For Acer trees 01 – 03 there appeared to be a strong positive relation between the standardized number of vessels and tensile strength (Fig. 4.9). Most of the samples (74.5%) of the three Acer trees lay between 0 and 0.0001 vessels per unit of area (VPUA) (60 samples lay between 0 and 0.00005, 45 samples between 0.00005 and 0.0001). This was also where the smoother indicated the strongest trend. There was a positive relation between tensile strength and the standardized number of vessels between 0 and 0.00005 VPUA. Between 0.00005 VPUA and 0.000075 VPUA this trend became even stronger. At 0.000075 VPUA it weakened, but was still clearly positive. This means that the higher the standardized number of vessels of a sample of Acer trees 01 – 03, the higher tensile strength can be expected of the respective sample. This matches the observation of Figures 4.2 and 4.7 well; tensile strength increased with increasing diameter, as did the standardized number of vessels. Therefore the standardized number of vessels increased with increasing tensile strength.

A similar trend can be observed for the three Alnus trees. There were 2 samples between 0 and 0.00005 VPUA. 67 samples were found between 0.00005 VPUA and 0.0001 VPUA. With 52 samples between 0.0001 VPUA and 0.00015 VPUA, it can be said that 90.8% of the samples of the three Alnus trees lay between 0.00005 VPUA and 0.00015 VPUA. This was also the range where a positive relation between VPUA and tensile strength can be observed. However, this trend was not as distinct as the one seen for Acer trees 01 – 03. After 0.00015 VPUA this trend changed to being slightly negative. There were 18 samples between 0.00015 VPUA and 0.00035 VPUA, which compared to the range between 0.0001 VPUA and 0.00015 VPUA was low. Additional data between 0.00015 VPUA and 0.00035 VPUA could change this trend. Although the trend of the three Acer trees was stronger than the one of Alnus trees 01 – 03 it can be said for both tree groups that the tensile strength increased with an increasing number of vessels.

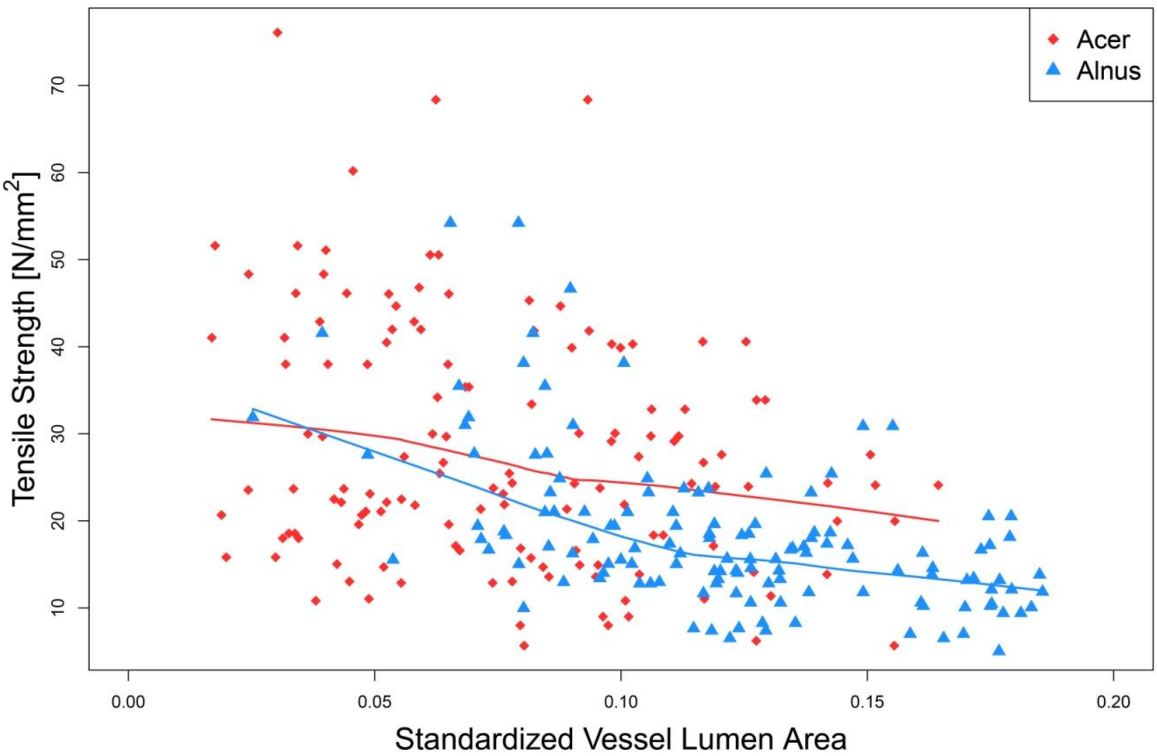

Fig. 4.10: Relation between root tensile strength and the medians of the standardized vessel lumen area. The lines represent LOWESS smoothers; red: Acer 01 – 03 (n = 137); blue: Alnus 01 – 03 (n = 134).

The observation that Acer trees 01 – 03 by trend showed lower values for the standardized vessel lumen area (Fig. 4.6) can also be made on the data distribution seen in Figure 4.10. The majority of the data (73.7%) of Acer trees 01 – 03 lay between standardized vessel lumen area (SVLA) values of 0 and 0.01. The exact numbers of sample of Acer trees 01 – 03 were (range of SVLA: number of samples): 0 - < 0.05: 37, 0.05 - < 0.1: 64, 0.1 - < 0.15: 31, 0.15 - < 0.2: 5. Meanwhile most data points (74.6%) of the three Alnus trees lay between SVLA values of 0.05 and 0.15. Alnus trees 01 – 03 showed the following numbers of samples in the different SVLA ranges were (range of SVLA: number of samples): 0 - < 0.05: 5, 0.05 - < 0.1: 36, 0.1 - < 0.15: 64, 0.15 - < 0.2: 29. Generally it can be said that the density of data points of Acer trees 01 – 03 was lower for higher SVLA values than for lower ones. The opposite was the case for Alnus trees 01 – 03, where there was a relatively small number of samples in small SVLA values compared to larger ones.

Due to the higher number of samples, the reliability of the trend line of Acer trees 01 – 03 is likely to be higher in smaller SVLA values than for larger ones. For Alnus trees 01 – 03 the reliability of the LOWESS smoother can be considered more reliable in higher SVLA values than for smaller ones. Both groups of trees showed a trend of decreasing tensile strength with increasing SVLA. This suggested that larger vessel size had a negative effect on tensile strength. Between SVLA of 0 and 0.05 the smoother of Acer trees 01 – 03 showed a slightly negative trend. Between 0.06 and 0.09 this trend intensifies. However, after 0.09 it weakened again and stayed constant. Since the sample count was relatively low in higher SVLA values, it is likely that a higher number of samples would influence this trend.

The smoother of Alnus trees 01 – 03 showed a similar trend as the one of the three Acer trees. Especially between SVLA values of 0 and 0.12, this trend was the more distinct one. After 0.12 it weakened. Even though both groups of trees showed decreasing tensile strength with increasing SVLA, the tensile strength of the three Alnus trees appeared to react more sensitively to a change in SVLA.

Overall the findings of Figure 4.10 met the previously presented results. Tensile strength increased with decreasing diameter. The SVLA showed a positive relation with diameter and therefore tensile strength decreased with increasing SVLA. There were differences in trend strength within the different tree groups, SVLA, diameter and tensile strength ranges.

5. Discussion

5.1 Root Tensile Strength

5.1.1 Distribution of the Data

In regard to the distribution of the root tensile strength values, the data showed a high variability within the two groups of trees. When comparing overall values of the two tree groups it has to be kept in mind that the variation within these groups was high, depending on the property which was displayed. This does not only apply to the Figure 4.1, but to all presented diagrams.

The coarse grained substrate the trees grew on was of high heterogeneity (Weisser, 2013), which could be held responsible for this variation, which is considered to exceed natural discrepancies in root growth. Even though the six evaluated trees were in close vicinity to each other, it cannot be assured that they experienced the same soil properties. Acer 02 and Alnus 02 were taken from the upper log cribwall, where larger rocks, compared to the locations of the other four trees, were found. According to Bischetti et al. (2007) site characteristics, like temperature, precipitation, or soil texture and structure, have a major influence on root development. Therefore the heterogeneous soil as well as differences in the availability of water (see below, Section 5.2.1) are likely to have contributed to the variation within the two tree groups.

Another factor is the different number of samples. Acer 02 and Alnus 02 had more successfully tested samples than the other two trees of the respective group combined. Since the ages of the trees were similar (Tab. 3.1), it can be imagined that the soil properties had an influence on the extent on the roots systems. This could have led to smaller root systems in some trees and therefore a smaller number of samples.

It was attempted to uncover as many roots as possible. Nevertheless it is probable that a larger part of the actual root system of Acer 02 and Alnus 02 as of the other four trees was retrieved from the field. This would have led to more samples of Acer 02 and Alnus 02 which ultimately could have caused the variation in the numbers of samples. This assumption cannot be judged, because the original extents of the untouched root systems were not determined.

In order to compare the trees with each other, it would have been preferable to have similar numbers of samples of the different trees. A higher number of samples would as well have been beneficial. Another method to apply the samples to the testing machine might have improved the number of successful tests. However, no better technique was found in the course of this work.

5.1.2 Relation to Diameter

For both tree groups it was found that the root tensile strength increased with decreasing diameter. This trend was stronger for Acer trees 01 – 03 than for the three Alnus trees.

There is no consensus whether or not the moisture of roots has an influence on their tensile strength. There are studies which did not find a relation between root tensile strength and root moisture (e. g., Tosi 2007). Others found strong indication that root moisture is one of the dominant influences on tensile strength (e. g., Hales et al. 2013). The figure in Appendix D shows that in diameters < 5 mm the trend line of the moisture data was little under 20%, which is close to the fiber saturation point of 25 – 30% (Hathaway and Penny, 1975). However, there was a large variation in the data, especially in small diameters (< 2 mm). Two major reasons could be responsible for this variation; (1) the use of two different scales to assess root moisture content and (2) the high sensitivity of small samples.

The moisture content was assessed using two different scales. The one at the ETH had an accuracy of 1 mg, the one at the WSL of 0.01 mg. This difference in accuracy led to a potential source of error.

The large variation in small samples is not surprising. The lightest sample weighed 2.1 mg. Such small samples were highly sensitive to weighing errors, especially when the scale had an accuracy of 1 mg, which was almost 50% of the weight of the samples itself. Unfortunately there was no scale with a higher accuracy available.

Under these circumstances it was not possible to rule out a moisture bias completely. For diameters > 2 mm it appeared as if the moisture content was stable. Due to the variation in diameters < 2 mm this cannot be said for these samples. However, it was attempted to perform all tensile tests in the exact same way. It is possible that there was a bias due to the moisture content. But it is assumed that such a bias would be equal for all samples, which makes the tensile test comparable with each other.

Both LOWESS lines of Figure 4.2 are well comparable with previous work concerning root tensile strength of trees (e. g., Genet et al. 2005; Nilaweera & Nutalaya 1999; Operstein & Frydman 2000), where the smallest roots showed the highest tensile strength. Overall it can be said that the conclusion of Figure 4.2 (tensile strength decreased with increasing diameter) fits well to previous findings. Hamza et al. (2007) stated that the mechanical behavior of roots is controlled by the plant's genotype. Therefore it is possible that the higher values in tensile strength of Acer trees 01 – 03 compared to the three Alnus trees was in some degree due to species specific differences.

Genet et al. (2005) did not find a significant difference in tensile strength between species in roots < 0.9 mm. This was explained with the low number of samples available. Even though no statistical testing was performed on this data so far, it appeared as if there was a difference in tensile strength in diameters < 0.9 mm between the two groups of trees evaluated in this work. The number of samples of Acer trees 01 – 03 in very small diameters (0.3 mm < 0.9 mm) was relatively high. The smoother indicated a strong positive trend in this diameter range.

The trend in diameters < 0.9 mm of Alnus trees 01 - 03 was much weaker than the corresponding trend of the three Acer trees. It has to be considered that the number of samples of Alnus 01 – 03 between 0.4 mm and 0.9 mm was relatively low. Additional samples of other Alnus trees in this diameter range could change the trend and possibly intensify it. On the basis of the data collected in the course of this work, it appeard as if there was a difference in tensile strength between species in diameters < 0.9 mm. However this is just an assumption, which has to be statistically confirmed. If proven correct, it would contradict the findings of Genet et al. (2005).

5.1.3 Relation to Age & Distance to Stem

Figure 4.2 revealed that the successfully tested samples of the three Acer trees had a larger range of diameters than the ones of the three Alnus trees. In addition to that Acer trees 01 – 03 showed the older samples than the Alnus tree group. Even though the relation between age and diameter was not evaluated, this suggests that the roots of the three Acer trees had a lower growth rate than the roots of the three Alnus trees.

In 2005, Genet et al. stated that the age of roots could have an influence on tensile strength. Figure 4.3 supports this assumption; younger roots of Acer trees 01 – 03 and Alnus trees 01 – 03 had a higher tensile strength than older ones.

Berrocal et al. (2004) found that the chemical composition of wood is affected by tree age. In the study of Berrocal et al. (2004) no roots were taken into consideration. Even though Zhang et al. (2014) argue that the wood evaluated by Berrocal et al. (2004) (*Pinus radiata* D. Don) is similar and therefore comparable to roots, the different findings contradict one another.

Berrocal et al. (2004) reported that the percentage of cellulose increased with increasing age. Genet et al. (2005) found that the cellulose content increased with decreasing root diameter. In the course of this work it was found that there was a positive relation between root age and root diameter in both tree groups (Appendix E). After Berrocal et al. (2004) older roots, which by trend showed larger diameters than younger ones, are supposed to show a higher cellulose content as younger roots. According to Genet et al. (2005) the opposite was the case: smaller, and by trend younger roots, showed higher cellulose contents than larger ones.

Genet et al. (2005) and Zhang et al. (2014) both found that the chemical composition (e. g., cellulose and lignin content) affects the root tensile strength of different species. Therefore it is not likely that the age related change in the chemical composition, as observed by Berrocal et al. (2004), would not affect the tensile strength. However, Berrocal et al. (2004) did not consider roots, but stem wood. It is probable that there is a difference between the wood examined by Berrocal et al. (2004), the roots considered by Genet et al. (2005), Zhang et al. (2014), and this work. In regard of the relation of the age of roots and their tensile strength, the findings of this thesis agree with the results of Genet et al. (2005), and therefore put the ones of Berrocal et al. (2004) into perspective.

In order to come closer to a concluding answer to this problem, it would be helpful to analyze the chemical composition of the root samples used in this work. This would be possible since these samples are currently stored at 4 °C in a cooling chamber at the WSL. For both tree groups it would be interesting to increase the number of samples and assess more roots which are older than 11 years, in order to find out if this trend remains constant or whether it increases again, or maybe decreases further.

The measurement of the distance of a sample to the tree stem was not trivial. After the images were rectified using ArcGIS (ESRI Inc, Redlands, CA, USA), the root systems were projected onto the grid it was placed on to take the picture. Radii were drawn around the stem with a spacing of scaled 10 cm. Then it was determined in which radius a root section was located and thus the distance to the stem was defined. The problem was the root's irregular way of growing. Therefore it occurred that a root sample which was e. g. 40 cm away from the stem would have been much further away if the root was laid out in a straight line (Fig. 3.2). Thus the distances to the stem which were used in Figure 4.4 have to be treated with caution.

The distance of a root to the stem is not necessarily equal to its length. Due to the uneven nature of their growth, their position in regards to the stem is misleading. A root that is seen further away from the stem than its neighboring root may as well be shorter than the other when both are straightened out. This leads to distortion in the measurement of the distance of roots to the stem, because the actual length of a root was not considered.

In order to estimate the real distance a sample would have to the stem, the entire root system would not only have to be rectified but every single root would have had to be digitalized. Since it was impossible to recreate the exact point of failure of a root, it happened that a sample was allocated to two radii. If this was the case the radius which contained the majority of the sample was chosen as the distance of the respective sample to the stem. It was considered to be sufficient to determine the distance of a sample to the stem using the described approximated method and thus abstain from the much more tedious and time consuming digitalization of the entire root systems.

It was assumed that the tree roots served different purposes (i.e., absorption and transportation of nutrients and water, or stabilization of the tree) depending on their distance to the stem. Figure 4.4 does not confirm this assumption fully, but indicates that, at least for the three Acer trees, it could possibly be true. Although the trend decreased between 0 cm and 40 cm, there was a strong positive trend in distance classes < 50 cm. This leads to the assumption that the primary purpose of roots further away from the stem was to stabilize the tree and withstand a greater amount of tension than roots closer to the stem. For Alnus trees 01 – 03 the trend line indicated a similar correlation between distance to the stem and tensile strength, but the number of samples was too low in order to allow a clear statement. Especially for the tree group Alnus, more samples are needed.

The statement which was made for Acer trees 01 - 03 corresponds to the findings of Stokes & Mattheck (1996), who also found that the tensile strength increases with increasing distance to the stem. With the current amount of data it is not possible to make a similar statement for Alnus trees 01 – 03.

The first research question was answered by the presentation and discussion of the increase of root tensile strength with decreasing root diameter. The differences between the two groups of trees, where Acer 01 – 03 showed higher values in tensile strength and a more distinct trend as the three Alnus trees, were covered as well.

The influence of the age and the distance to the stem was visualized and explained. This answers two thirds of the research question c); age appeared to have a negative effect on the tensile strength of both tree groups, whereas no clear statement could be made for the distance to the stem. The differences of the wood anatomical structure as well as their influence on root tensile strength will be discussed below.

5.2 Wood Anatomy

5.2.1 Selected Wood Anatomical Parameters

The overall median of the standardized number of vessel was higher for Alnus trees 01 – 03 than for Acer trees 01 – 03 (Fig. 4.5). The variation of the individual trees within their tree group was greater for the three Alnus trees than for the three Acer trees. Alnus 01 did not appear to fit well with the other two individuals of this group. This might be due to the locations of the trees. Alnus 01 was located at the edge of a plot which was afforestated in 1997 (Fig. 3.1). Right next to this plot was a zone with little to no vegetation, where the soil moisture appeared to be much higher than within the plot itself. No soil moisture measurements were conducted, therefore no quantitative information regarding soil moisture can be given. However, near surface runoff was clearly visible in the sparsely vegetated area and in near proximity to Alnus 01. At the locations of the other trees it was noticed that the soil was moist. However, no near surface runoff was seen at the time of excavation. Therefore it is assumed that Acer 01 and Alnus 01 had a higher availability of water than the other four evaluated trees. Except for the soil moisture, the environmental conditions of the sampled trees were considered to be equal. It appeared as if the high availability of water led to a lower number of vessels in Alnus 01. Acer 01 was located very closely to Alnus 01. Interestingly, the standardized number of vessels of this individual did not differ greatly from the other two trees of this group. The difference in soil moisture does not seem to affect the number of vessels of Acer 01.

In Figure 4.6, where the standardized vessel lumen area is displayed, the different soil moisture conditions appear to have had an influence on Acer 01. It showed much lower vessel lumen areas than the other two trees of this group. Even though the medians of the Acer 02 and 03 were likely to be significantly different from each other, Acer 01 appeared to be an outlier compared to Acer 02 and 03. Alnus 01 showed much higher standardized vessel sizes than Alnus 02 and 03. This is also assumed to be due to the location of the trees.

Since Acer 01 was right next to Alnus 01, it is possible that two trees were competing for water resources. Christensen-Dalsgaard et al. (2007) found that stress can lead to changes and adaptation of the vascular anatomy in tree roots. This corresponds with the finding of smaller vessels in a tree which was likely to suffer from drought stress.

It can be assumed that the differences in water availability led to the described variation within the two tree groups. Alnus 01 was believed to have had access to plenty of water, whereas Acer 01 is likely to have been suffering from drought stress due to the competition of Alnus 01. This leads to the conclusion that a surplus of water led to fewer but much larger vessels in Alnus 01. Acer 01 seemed not the change the number of vessels due to lack of water, but smaller vessels were developed compared to the other two trees.

The data presented indicated that the wood anatomical structure was influenced by differing environmental conditions (i. e. water availability and competition). It can be well imagined that not only the availability of water influenced the wood anatomical structure of roots. Other factors, such as accessibility of nutrients, symbiosis (e.g., mycorrhiza) or competition with other organisms, and the management of the plants, can be imagined to also have had an effect on the wood anatomy and therefore on the tensile strength.

This conclusion can only be applied to the data presented in this work. Since the number of sampled trees was relatively low and the environmental conditions the trees experienced were extreme, especially in regard to the slope and grain size distribution, no general conclusion for the species *Acer pseudoplatanus* L. and *Alnus incana* (L.) MOENCH can be drawn on the basis of this data. However, the results presented here, indicate that the wood anatomy of the two examined species reacts differently to altering environmental conditions. In order to confirm this assumption for the two species further research is necessary.

One may argue that Acer 01 and Alnus 01 distorted the results of Figures 4.5 and 4.6, because they were not comparable to the other two trees of their groups and therefore influenced the overall medians negatively. The number samples of Acer 01 made up 19 % of all the samples of this group of trees. 15.8 % of the total number of samples of the Alnus group came from Alnus 01. These two trees certainly influenced the overall median of their group. Since Acer 01 and Alnus 01 made up less than a fifth of the overall samples of their groups, the effect they had on the overall medians was considered to be tolerable. Appendix F shows that if Acer 01 and Alnus 01 were not taken into consideration, the overall medians (of Acer 02 & 03 and Alnus 02 & 03) of the two presented wood anatomical parameters would still be likely to differ significantly. Therefore the second research question can also be answered positively; there is a difference in the structure of the wood anatomy between the two evaluated tree groups.

5.2.2 Relation to Diameter and Tensile Strength

The diameter distributions of Figures 4.7 and 4.8 were similar but not identical to the one seen in Figure 4.2. For most but not all samples which were visualized in Figures 4.7 and 4.8 two values regarding the wood anatomical parameters were determined, since it was attempted to prepare two micro-sections for every successfully tested sample. There were two reasons why there were not always two values determined from each sample. Firstly, the quality of some of the micro-sections was not always high enough for a measurement with WinCELL. And secondly, some samples were destroyed during the preparation process.

It is noticeable that both tree groups showed similar trends in the examined parameters. However, Acer trees 01 – 03 showed more distinct trends than the three Alnus trees most of the time. Since prior to the excavation the trees with the same numbers (e.g., Acer 01 and Alnus 01) were located in such ultimate vicinity to each other that in two cases their roots would be grown together, it can be said that the trees were experiencing similar conditions. Therefore the fact that the three Acers showrf more distinct trends in the presented figures, leads to the assumption that the three Acers had a higher adaptability to their environment than the three Alnus trees.

For both tree groups Figure 4.7 suggested the number of vessels per unit of area to decline with increasing diameter. Acer trees 01 – 03 did not only show lower values for VPUA but also a more distinct trend than the three Alnus trees. This decline in VPUA came along with an increase in vessel size (Fig. 4.8). This would make sense, because the lower number of vessels had to be compensated with a larger lumen area in order to have at least a constant conductivity. By trend the root diameters increased as a tree gets older (Appendix E). As a tree grows older more aboveground biomass is produced, which requires more water and nutrients. Therefore a decrease in conductivity would be counterproductive and illogical.

This is the reason why the LOWESS line of Acer trees 01 – 03 in Figure 4.8 cannot be trusted for diameters > 4 mm. Not only was the number of samples in diameters > 4 mm relatively small, but the trend suggested a strong decrease in vessel lumen area, whilst the number of vessels per unit area also decreaseed slightly. This would lead to a decrease in conductivity when the trees grow older which could be fatal. Except for this part of the smoother of the three Acer trees, Figures 4.7 and 4.8 matched well; a decrease in VPUA was accompanied with an increase in vessel size, which at least ensured a constant or led to an even higher conductivity, depending on the increase rate of the vessel lumen.

The trends seen in Figures 4.7 – 4.10 were similar for both groups of trees. Although their distinction varied between tree groups and figures, they suggested that the number of vessels per unit of area decreased with increasing diameter, whilst the vessel lumen area increased. The number of vessels was positively correlated to the tensile strength. This would mean that a decreasing number of VPUA led to a decreasing tensile strength. This was confirmed when Figures 4.2, 4.7 and 4.9 were considered together; tensile strength decreased with increasing diameter, as did the standardized number of vessels, therefore the positive correlation of tensile strength and number of vessels (Fig. 4.9). This was also the case for the vessel lumen area, which increased with increasing diameter (Fig. 4.8: smoother of Acer trees 01 – 03 with diameter > 4 mm is not considered), and hereby showed a negative relation to the tensile strength as seen in Figure 4.10.

The data of Alnus 01 gave a good example for the described relationships. The standardized vessel lumen area of Alnus 01 was, compared to the other two Alnus trees, high (Fig. 4.6). The number of vessels on the other hand was lower (Fig. 4.5). The fact that the lowest values of tensile strength of the Alnus tree group were found for Alnus 01 (Fig. 4.1) confirmed that the wood anatomical structure was likely to have had an influence on the root tensile strength. Therefore the remaining third of research question c), that the wood anatomical structure has an influence on root tensile strength, can also be answered positively. This finalizes the reflection of all three research questions.

This study only indicated to what extent the different wood anatomical parameters influence the root tensile strength. The exact influence of a wood anatomical parameter on the tensile strength cannot be quantified. Mixed effects models as described by Zuur et al. (2009) are an interesting approach to gain knowledge of the relation of the different wood anatomical parameters and the resistance of roots to tension. It would be important to know which parameter influences the tensile strength in what way and also how the different parameters react to altering environmental conditions.

In the case of Acer 01 and Alnus 01 the presented data suggested that the water availability influenceed the number of vessels as well as their size. This in combination with the finding that the wood anatomical structure of roots affected their tensile strength is an interesting result in regard to ecological engineering.

6. Conclusion

Since this was the first study of its kind, the aim was not to quantify the exact effects of the different wood anatomical parameters on root tensile strength. The intention was to assess whether or not there is an influence of the anatomical structure of roots on their tensile strength and to point at a new approach of how to strengthen and deepen the understanding of the complexity of soil root interactions. The excavation and analysis of a total of seven trees (4 *Acer pseudoplatanus* L. and 3 *Alnus incana* (L.) MOENCH), growing on a steep coarse grained erosion prone slope, was the basis of the dataset presented. Several different parameters of the collected roots were determined, including tensile strength, moisture, diameter, and several wood anatomical parameters.

Except for one reservation, regarding the relation of the distance of a root to the stem and the tensile strength of the three Alnus trees, all proposed hypotheses were accepted.

The results showed for both tree groups that the tensile strength increases with decreasing diameter. The two groups of trees showed differences in tensile strength. The three evaluated Acer trees showed higher values and a stronger increase in tensile strength in small diameters than the three examined Alnus trees. This confirms the first hypothesis.

On the basis of the data presented, the second hypothesis can also be accepted. For both tree groups it was found that the standardized number of vessels correlates positively with the root tensile strength. The three Acer trees showed a stronger relationship regarding this parameter. Alnus trees 01 – 03 showed a similar trend. A negative correlation between tensile strength and the standardized vessel lumen area was detected for both tree groups. The group of Alnus trees showed a more distinct trend as the three Acer trees.

Age was recognized to affect root tensile strength of both tree groups negatively. The correlation of age and root tensile strength was negative until a certain age was reached (7 years in case of the three Acer trees, 4 years in the case of Alnus trees 01 – 03). Then the trend stagnated.

The trend lines describing the relation between the distance of a root to the stem and the tensile strength of the two groups of trees were not as clear. There seemed to be a correlation for the three Acer trees, where tensile strength tended to increase with increasing distance of a root to the stem. Due to the relatively low number of samples this cannot be said for the three Alnus trees. Therefore it is not possible to fully accept the third hypothesis.

This thesis can be seen as a first step in attempting to understand the relations between the wood anatomical structure of roots and their tensile strength. Statistical modeling of the data used is likely to deepen the understanding of the presented results. The dataset which originated from this thesis could be used for other studies e.g. as input data for the modeling of root failure (e.g,. FBMs or other models).

Knowledge and implementation of these relationships would lead to the possibility to enhance the tensile strength of roots and thus improve slope stabilization techniques. If it can be determined in what way the different wood anatomical parameters react to changing environmental conditions and what effects such changes of certain wood anatomical parameter have on the tensile strength, it would become possible to actively influence the tensile strength of roots.

When choosing a species to stabilize a certain slope, the root tensile strength is one of many factors to be considered. There are other potentially important ecological aspects that need to be taken into account. As well a species might not be best suited in regard of root tensile strength, but may enhance other important ecological aspects, such as complexity or connectivity of an ecosystem. When all important factors and their relations between each other are not only identified but were also understood, it would become possible to optimize the benefits of ecological engineering measures and not only reduce slope failure induced damage but also augment the values of ecosystems.

7. Outlook

The success rate of the tensile tests performed in the course of this work was satisfying. Only 33% of the tensile test performed by Genet et al. (2005) were successful. The overall success rate of this work lies at 41%. Nevertheless, there is still room for improvements in various aspects.

Although the success rate of the tensile tests was higher than the one of Genet et al.(2005), it can be imagined that it could be improved even more. There might be a better way to apply the root samples to the claws of the testing machine. The process of attaching the oak cuboids to the roots may also be accelerated in order to process a larger number of samples simultaneously. In order to find such possibilities for improvement and develop this method further, research and different experiments are necessary. Hathaway & Penny (1975) soaked their samples in water for an hour prior to testing the tensile strength. The moisture content reached 60 – 70% and was above the fiber saturation point of 25 – 30%. Even though some samples failed, almost all of them broke near the center of the root (Hathaway and Penny, 1975). This might be a possible way to increase the success rate of tensile tests. However, it would have to be considered to what extent this experiment set up is still comparable to field conditions.

It would have been preferable to have a larger number of samples, especially considering the distance to stem classes of Alnus trees 01 – 03. This distance to stem evaluation was performed by projecting the root system onto a plain and measuring the shortest distance from the stem to a root sample. This method assumes an ideal root system, where the roots grow away from the stem in a straight line. Due to the bent nature of the roots, this measurement can only be considered an approximation. If the twisted nature of the roots were eliminated and they were laid out in a straight line, the distance to the stem would increase. Measuring this real distance of a sample to the stem would require digitalizing the entire root systems using GIS. This could be done, however it would be time consuming.

Since it is possible that the moisture content of the root samples has an influence on their tensile strength, there would be an advantage in having a better estimation of the actual moisture content of the samples during the time of testing. The best solution would be to use the exact same scale for the measurement of the fresh and the dry weight, which are the basis for the calculation of the moisture.

It would also be interesting to evaluate the actual root moisture in the field. In order to do so, fresh root samples would have to be taken and their moisture would have to be estimated in the field. This way it would be possible to evaluate if the moisture conditions of the root samples at the time of testing were comparable to the actual conditions in the field and therefore are realistic.

It is possible that different soil moisture conditions have an influence on the wood anatomical structure of the samples. The measurement of the soil moisture would be helpful in order to assure that the chosen trees were exposed to the same environmental conditions. This would make the comparison of the data more powerful.

In a next step it would make sense to apply a mixed effects model to the data presented in this thesis. Unlike the descriptive approach used here, this would not only give indications of relations, but deliver statistical evidence for the influence of wood anatomy on tensile strength. Quantification of the influence of certain wood anatomical parameters on root tensile strength would be possible.

The dataset created in the course of this work is extensive. Only a part of it was exploited for this thesis. Only the successful 41% of the samples which were tested for tensile strength were evaluated so far. The other 59% of the tested samples, which failed the tensile tests, can still be assessed. Even though these data do not show a maximum tensile strength, a minimum value for the resistance to tension can be given for the samples. This can be valuable information, for example for the evaluation of models as mentioned in Section 1.4.1. A wood anatomical evaluation of these samples is still possible, as the pieces which were cut off the samples prior to the tensile tests are still in storage.

In the course of this work, no chemical analysis was performed. The determination of the cellulose and/or the lignin content of the successfully tested samples would be possible. The material which was left after the preparation of the micro-sections was put aside along with the material used for the determination of the moisture content. In most cases, there should be enough material of the individual root samples to perform such analysis.

The micro-sections were taken from both ends of a root sample. The part of a sample which was visible during a test was used for the assessment of the moisture content. Therefore it was not possible to determine the wood anatomical structure of the roots close to the point of failure. In some cases the point where the micro-sections were taken was up to 15 cm away from the point of failure. It would have been preferable to analyze the wood anatomy and the age of the roots closer to the actual point of failure. If a similar study was to be performed in the future, it could be considered to take the micro-sections much closer to the point of failure. This would possbily yield a more detailed and reliable insight of the relation between root anatomy and tensile strength

This study was conducted on an area with a very coarse grained substrate. The question arose what the wood anatomy and tensile strength of comparable trees would turn out to be like on a finer grained substrate. There is another area of interest in the Arieschbachtobel, which is further up the ravine than the here examined Patjänja 97 area. It would be interesting to conduct similar experiments there. Thus it would become possible to judge the influence of the grain size of the soil on the wood anatomy and the tensile strength of roots.

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Last but not least I am grateful to my family who are always there for me. You were the ones who made this possible.

Thank you.

10. Personal Declaration

I hereby declare that the thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the thesis.

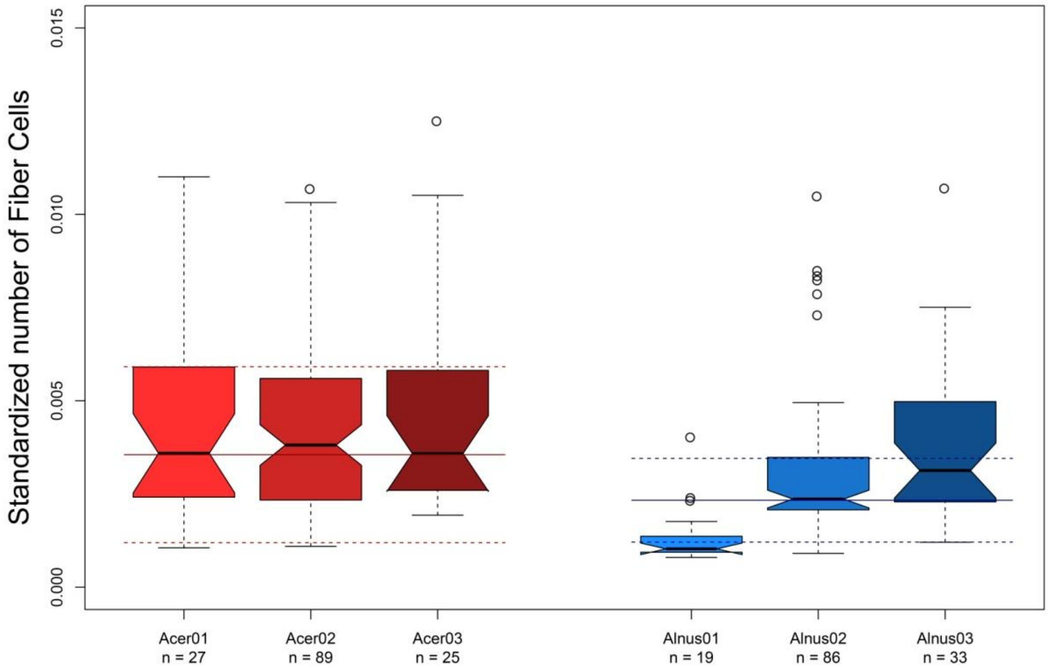
Zürich, 04.09.2014

Dimitri Kink

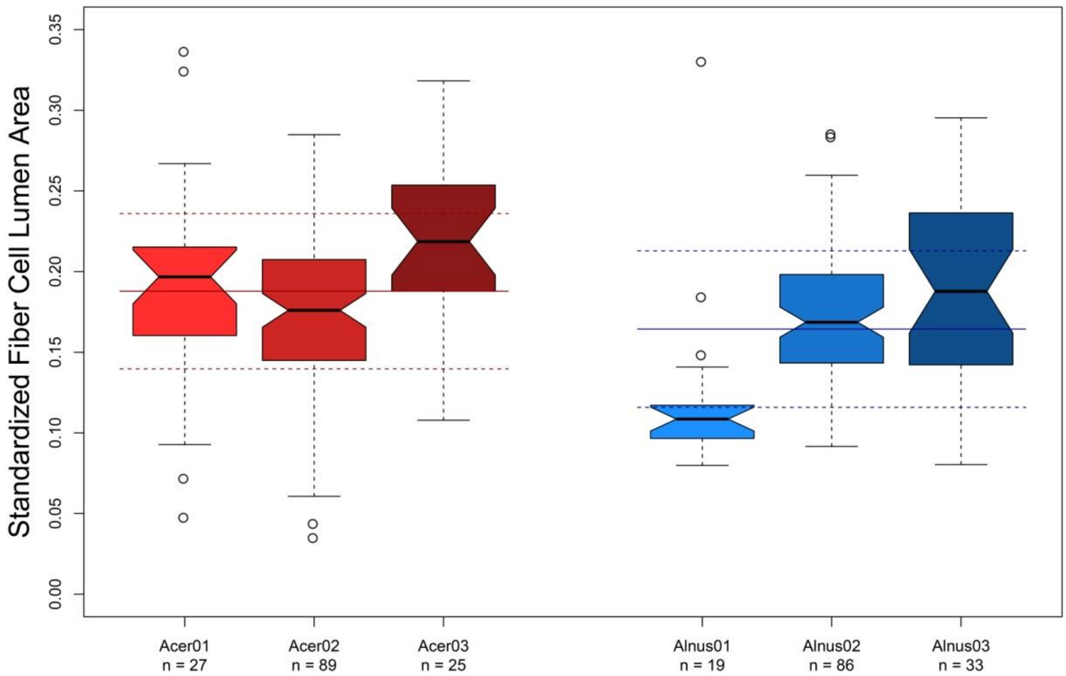
11. Appendix

Appendix Contents

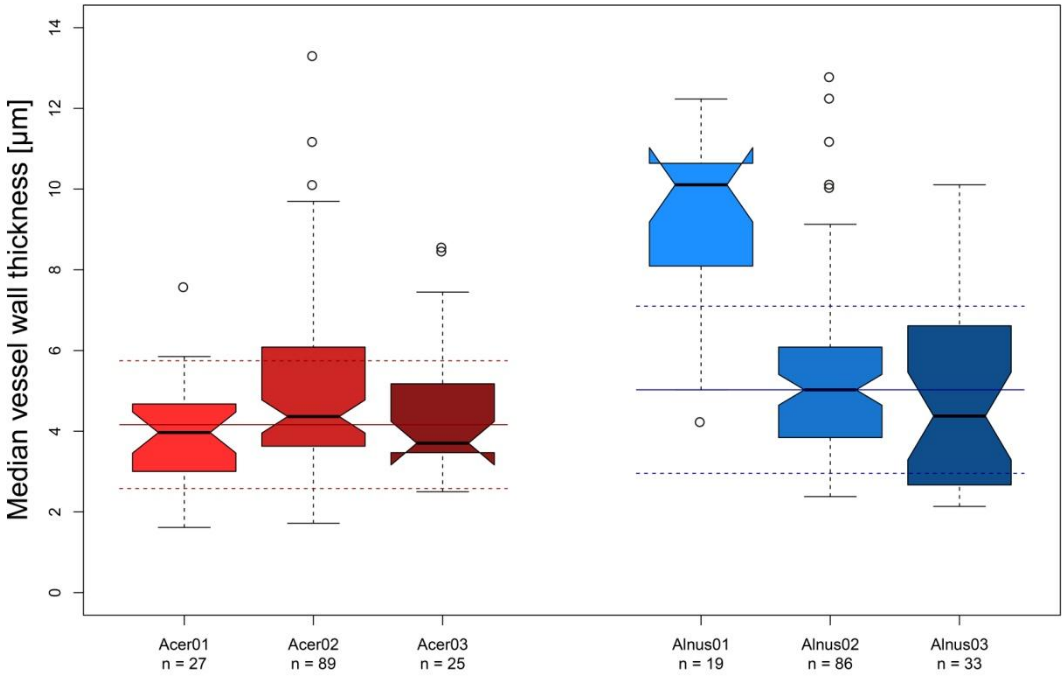
Appendix A – Wood Anatomical Parameters



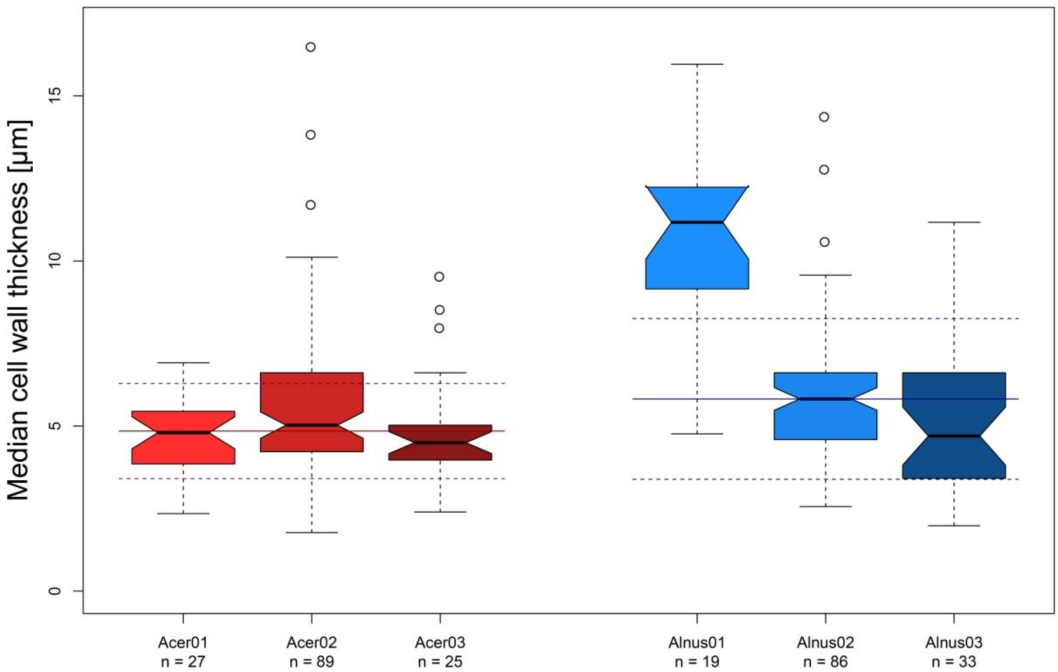
Appendix A.1: Standardized number of fiber cells of Acer 01 – 03 and Alnus 01 – 03. The solid lines represent the overall median values within the respective group of trees. The dashed lines indicate the median absolute deviation.



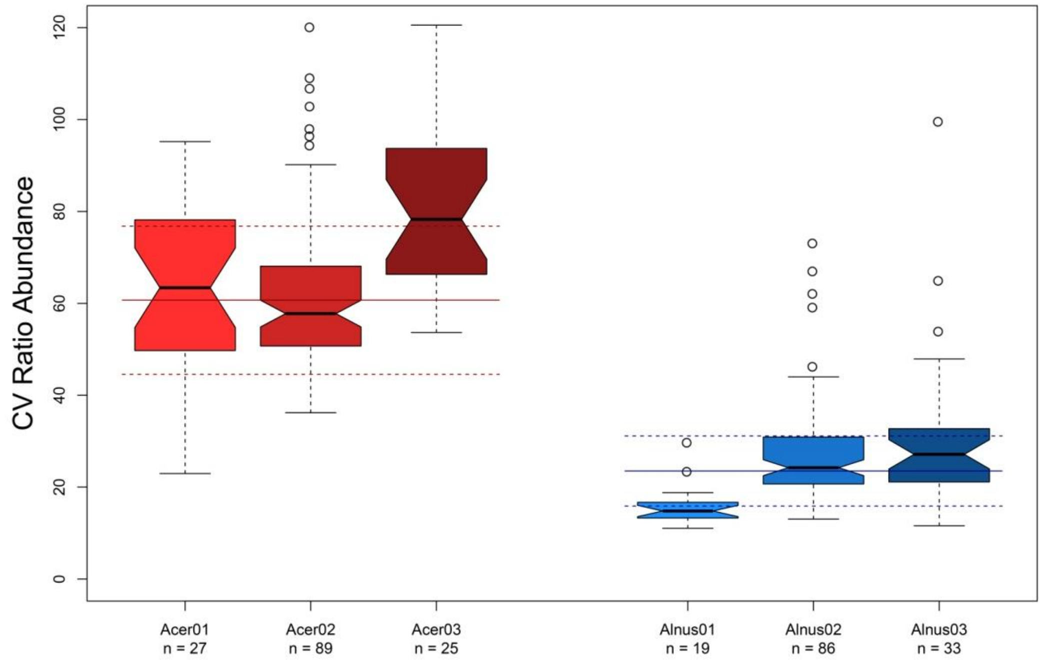
Appendix A.2: Standardized fiber cell lumen area of Acer 01 – 03 and Alnus 01 – 03. The continuous lines represent the overall median values within the respective group of trees. The solid lines indicate the median absolute deviation.



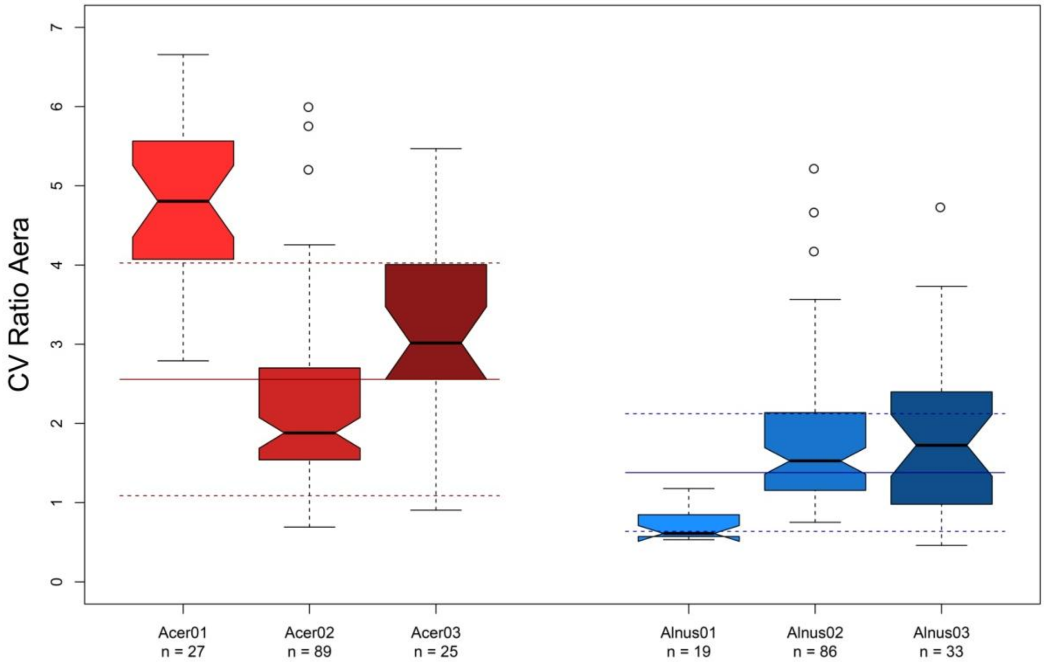
Appendix A.3: Standardized vessel wall thickness of Acer 01 – 03 and Alnus 01 – 03. The continuous lines represent the overall median values within the respective group of trees. The solid lines indicate the median absolute deviation.



Appendix A.4: Standardized fiber cell wall thickness of Acer 01 – 03 and Alnus 01 – 03. The continuous lines represent the overall median values within the respective group of trees. The solid lines indicate the median absolute deviation.

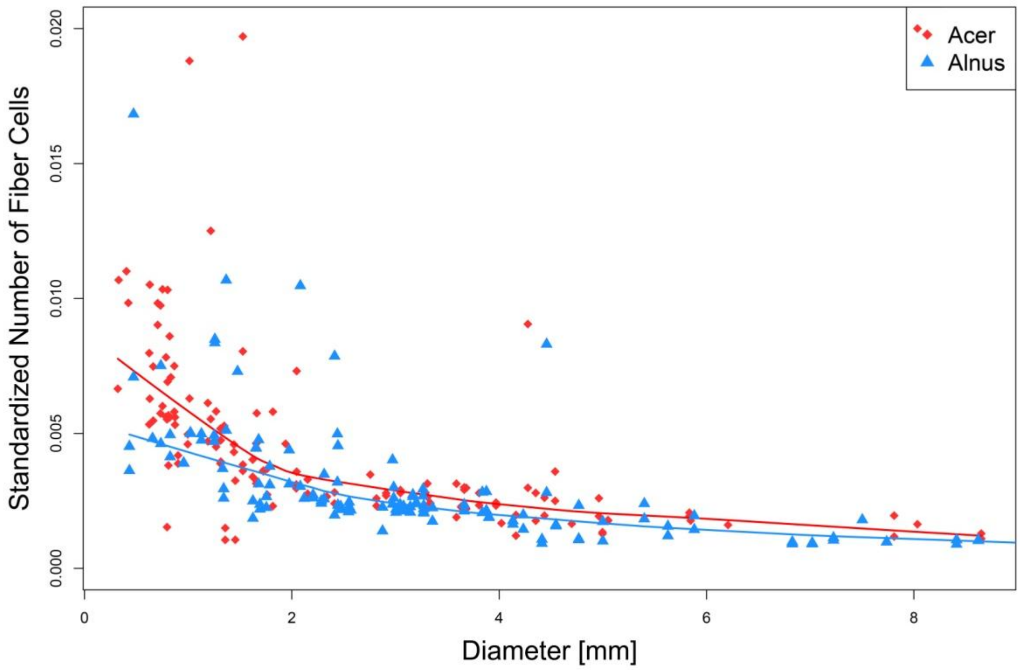


Appendix A.5: CV ratio abundance (number of fiber cells/number of vessels) of Acer 01 – 03 and Alnus 01 – 03. The continuous lines represent the overall median values within the respective group of trees. The solid lines indicate the median absolute deviation.

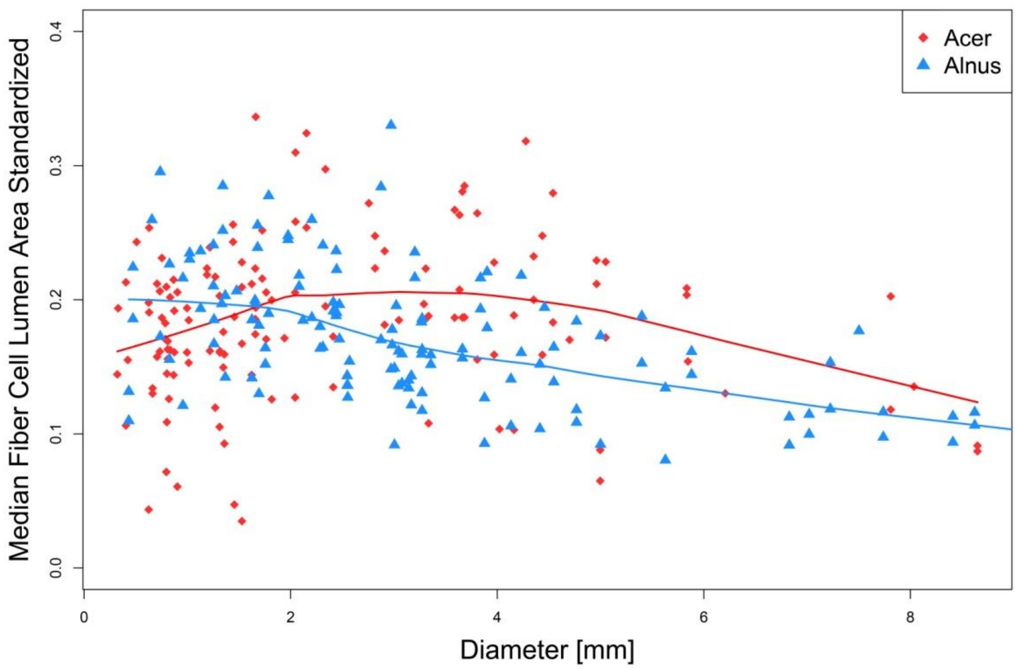


Appendix A.6: CV ratio aera (total fiber cell lumen arae/total vessel lumen area) of Acer 01 – 03 and Alnus 01 – 03. The continuous lines represent the overall median values within the respective group of trees. The solid lines indicate the median absolute deviation.

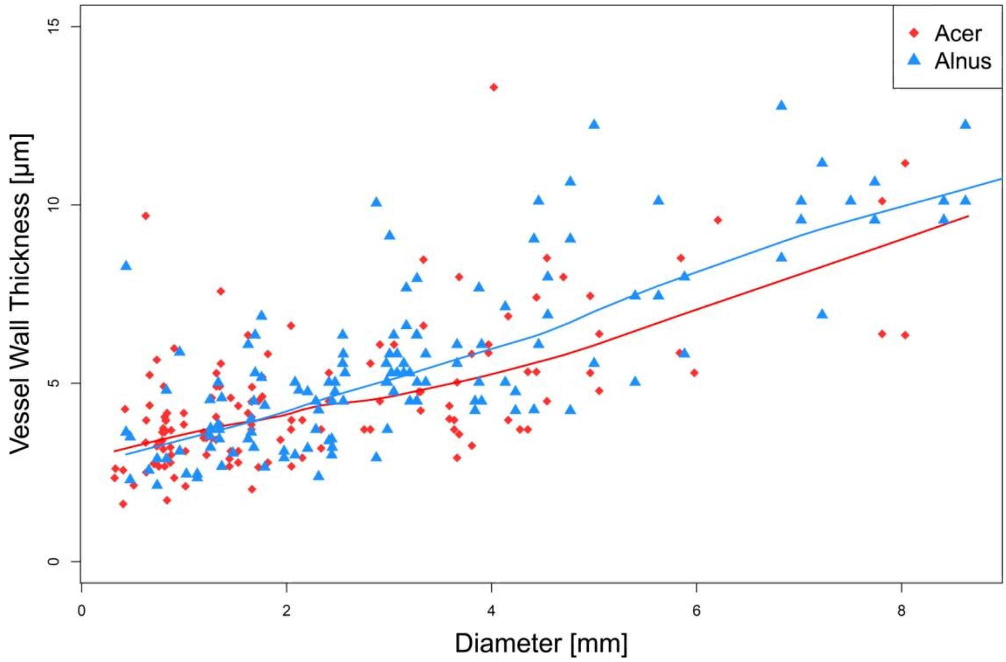
Appendix B – Relation of Wood Anatomy and Diameter



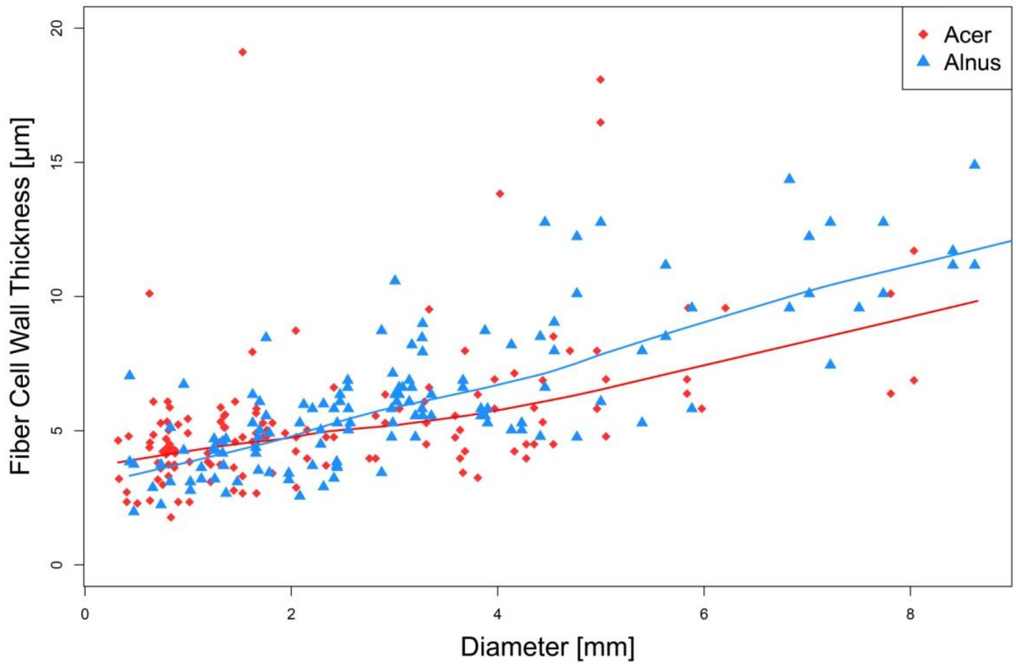
Appendix B.1: The standardized number of fiber cells in relation to the root diameter. The lines represent LOWESS smoothers; red: Acer 01 – 03 (n = 141); blue: Alnus 01 – 03 (n = 138).



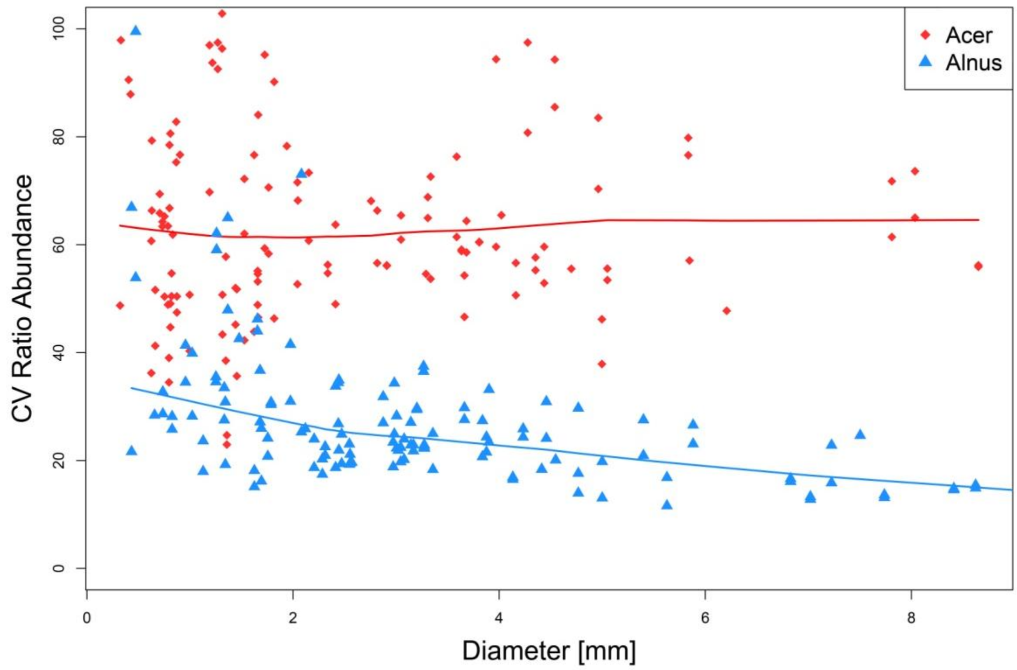
Appendix B.2: The standardized fiber cell lumen area in relation to the root diameter. The lines represent LOWESS smoothers; red: Acer 01 – 03 (n = 141); blue: Alnus 01 – 03 (n = 138).



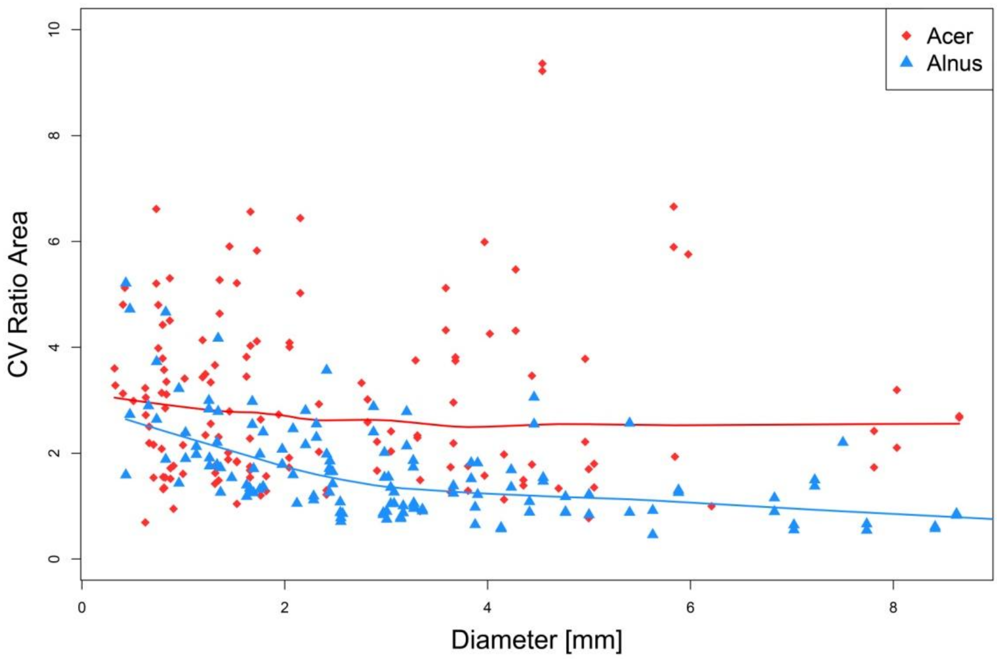
Appendix B.3: The vessel wall thickness in relation to the root diameter. The lines represent LOWESS smoothers; red: Acer 01 – 03 (n = 141); blue: Alnus 01 – 03 (n = 138).



Appendix B.4: The fiber cell wall thickness in relation to the root diameter. The lines represent LOWESS smoothers; red: Acer 01 – 03 (n = 141); blue: Alnus 01 – 03 (n = 138).

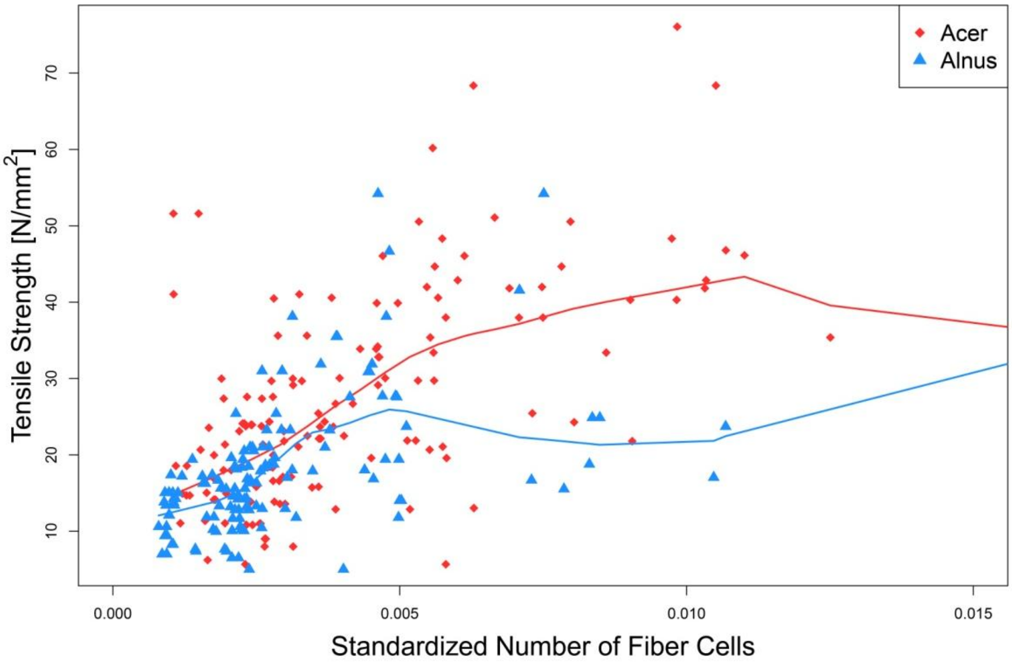


Appendix B.5: CV ratio abundance (number of fiber cells/number of vessels) relation to the root diameter. The lines represent LOWESS smoothers; red: Acer 01 – 03 (n = 141); blue: Alnus 01 – 03 (n = 138).

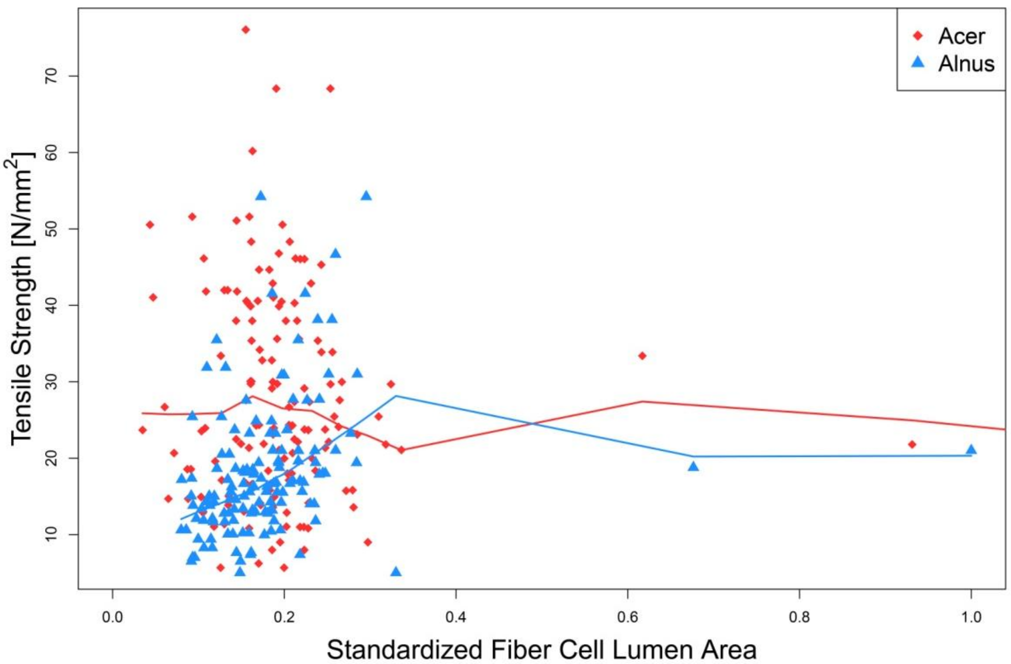


Appendix B.6: CV ratio aera (total fiber cell lumen arae/total vessel lumen area) relation to the root diameter. The lines represent LOWESS smoothers; red: Acer 01 – 03 (n = 141); blue: Alnus 01 – 03 (n = 138).

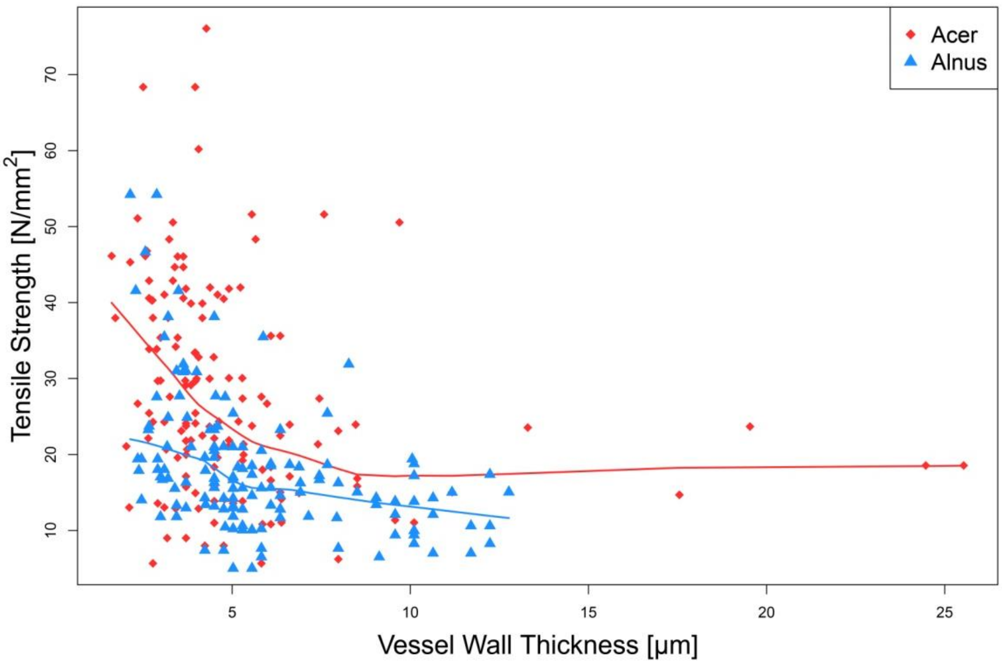
Appendix C – Relation of Wood Anatomy and Tensile Strength



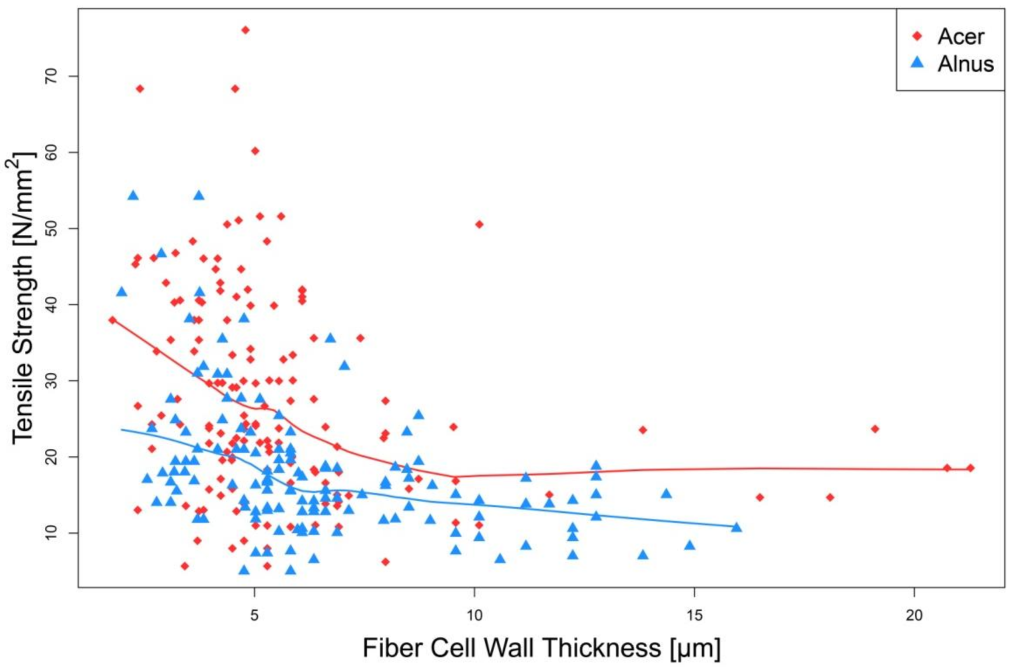
Appendix C. 1 The relation between root tensile strength and the standardized number of fiber cells. The lines represent LOWESS smoothers; red: Acer 01 – 03 (n = 141); blue: Alnus 01 – 03 (n = 131).



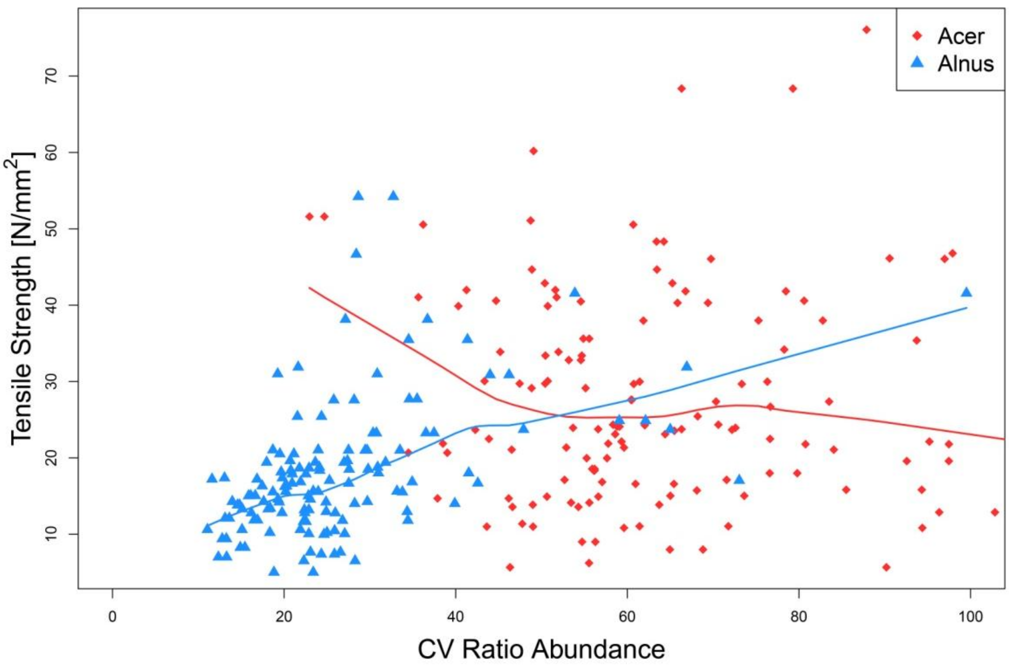
Appendix C.2: The relation between root tensile strength and the standardized fiber cell lumen area. The lines represent LOWESS smoothers; red: Acer 01 – 03 (n = 141); blue: Alnus 01 – 03 (n = 131).



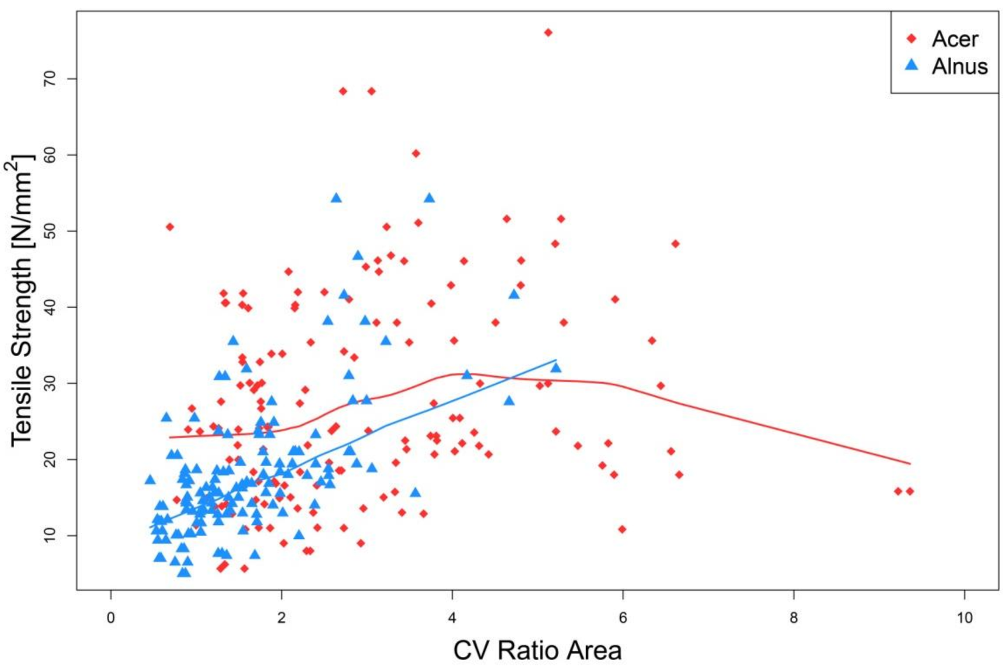
Appendix C. 3: The relation between root tensile strength and the vessel wall thickness. The lines represent LOWESS smoothers; red: Acer 01 – 03 (n = 141); blue: Alnus 01 – 03 (n = 131).



Appendix C.4: The relation between root tensile strength and the fiber cell wall thickness. The lines represent LOWESS smoothers; red: Acer 01 – 03 (n = 141); blue: Alnus 01 – 03 (n = 131).

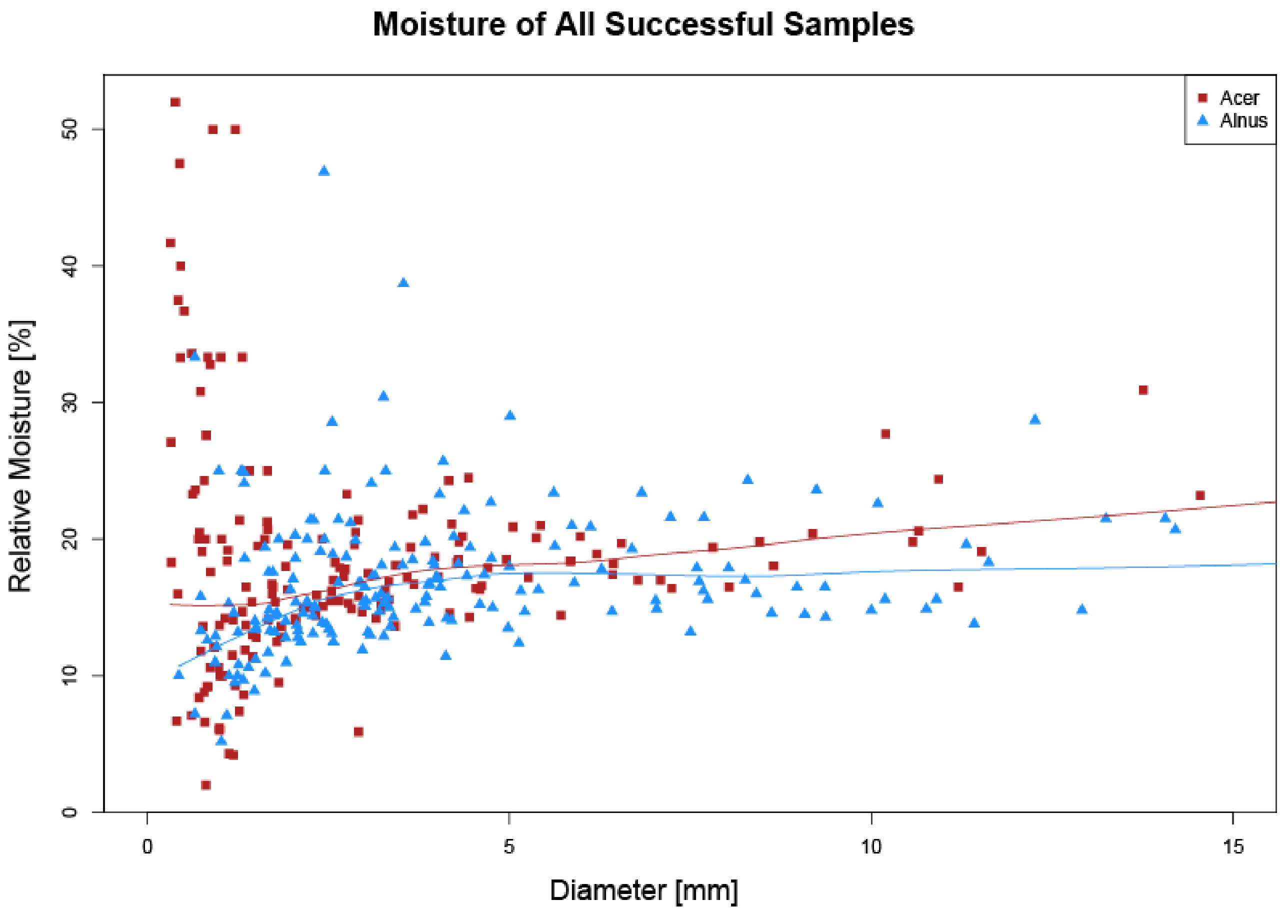


Appendix C.5: The relation between root tensile strength and the CV ratio abundance (number of fiber cells/number of vessels). The lines represent LOWESS smoothers; red: Acer 01 – 03 (n = 141); blue: Alnus 01 – 03 (n = 131).



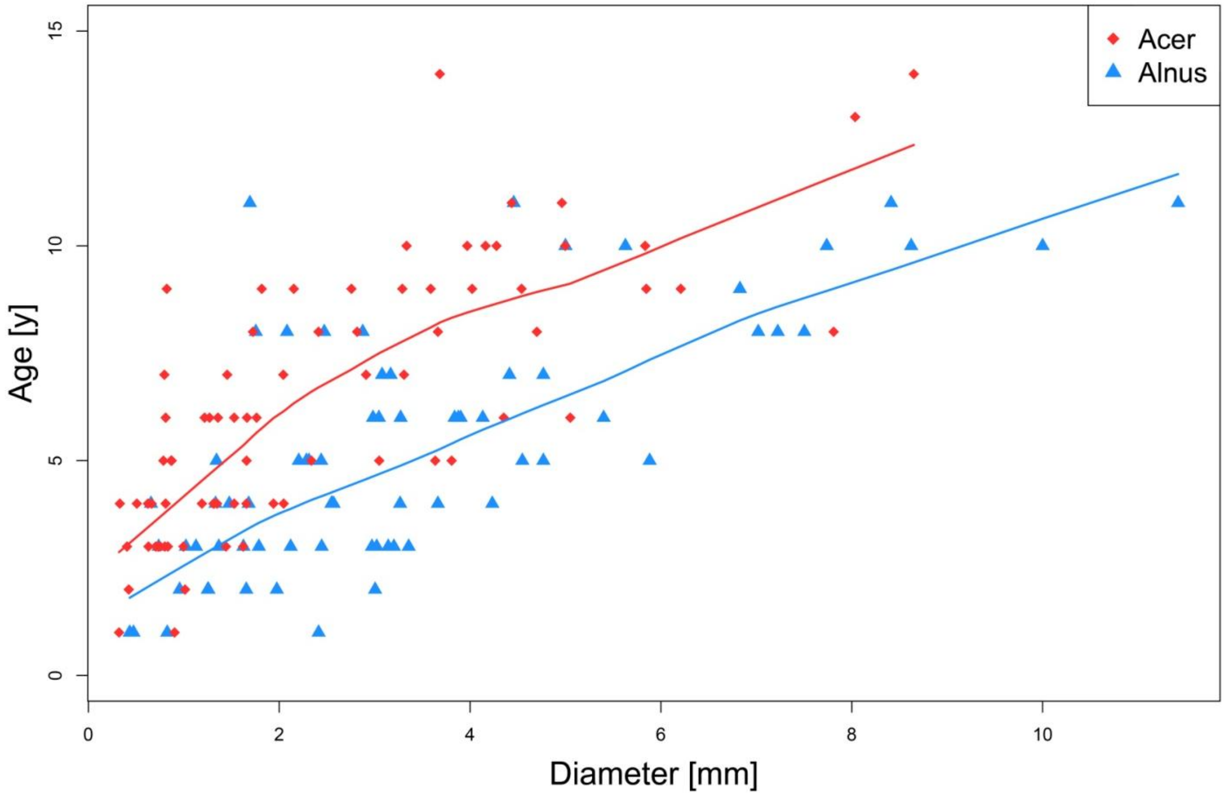
Appendix C.6: The relation between root tensile strength and CV ratio aera (total fiber cell lumen arae/total vessel lumen area). The lines represent LOWESS smoothers; red: Acer 01 – 03 (n = 141); blue: Alnus 01 – 03 (n = 131).

Appendix D – Root Moisture Content



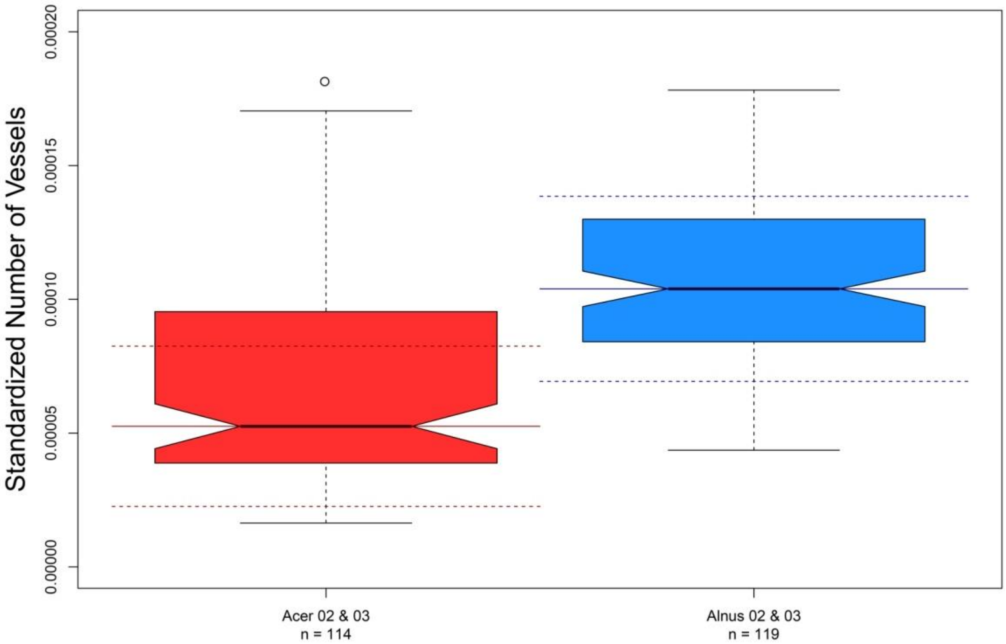
Appendix D.1: Relative moisture content of all successfully tested samples of Acer 01 – 03 (red, n = 171) and Alnus 01 – 03 (blue, n = 186). The lines represent LOWESS smoothers.

Appendix E – Relation of Root Age and Diameter

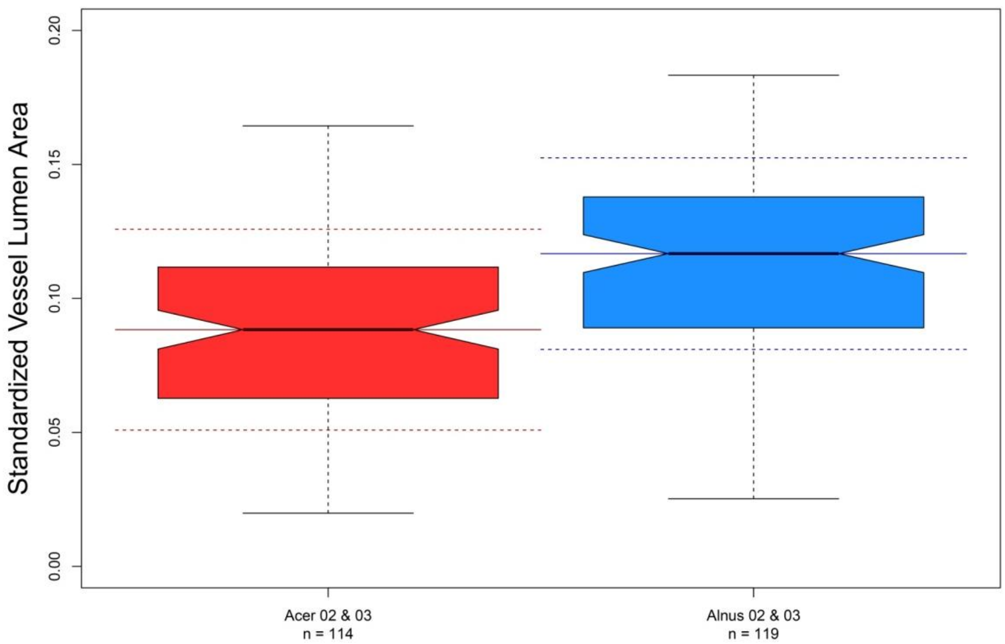


Appendix E.1: Root age versus root diameter of Acer 01 – 03 (red, n = 76) and Alnus 01 – 03 (blue, n = 71). The lines represent LOWESS smoothers.

Appendix F – Wood Anatomy of Acer 02 & 03/Alnus 02 & 03



Appendix F.1: Standardized number of vessels of Acer 02 & 03 and Alnus 02 & 03. The solid lines represent the overall median values within the respective group of trees. The dashed lines indicate the median absolute deviation. The notches do not overlap, which suggests the medians to be significantly different from each other. Some outliers are not depicted. These are for Acer 02 & 03: 0.00031, 0.00046, for Alnus 02 & 03: 0.00021, 0.000229, 0.000233, 0.00026, 0.00034, 0.001.



Appendix F.2: Standardized vessel lumen aera of Acer 02 & 03 and Alnus 02 & 03. The solid lines represent the overall median values within the respective group of trees. The dashed lines indicate the median absolute deviation. The notches do not overlap, which suggests the medians to be significantly different from each other. Some outliers are not depicted. These are for Acer 02 & 03: 0.216, 0.217, 0.64, 0.87, for Alnus 02 & 03: 0.22, 0.45.