Technical University Munich
Faculty of Civil, Geo and Environmental Engineering
Chair of Landslide Research

MASTER THESIS:

Monitoring slope stabilization with willow (*Salix* spec.) and mycorrhiza in the Hexenrübi catchment (Switzerland)

April 13th, 2015

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Declaration of Independence

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München, den 13. April, 2015

Acknowledgement

First of all, I would like to thank the head of different institutions Professor Michael Krautblatter, Dr. Manfred Stähli, and Dr. Peter Bebi for enabling me to do this master's thesis at the Chair of Landslide Research (TU Munich), WSL (Eidg. Forschungsanstalt für Wald, Schnee und Landschaft, Birmensdorf) and SLF (WSL-Institute für Schnee- und Lawinenforschung SLF, Davos).

Special thanks to Michael Krautblatter for being supervisor at the TU Munich and Frank Graf and Chiara Vergani for being supervisors at the SLF.

Special thanks to Chiara Vergani, Frank Graf, Regula Christon, Adrien Gaudard and Ueli Schmid for helping me with the fieldwork. Without them the time-consuming and hard work in the field would have not been manageable.

I would like to thank Regula Christon and Samuel Stolz for their introduction and help with the wet-sieving analysis. Many thanks as well to Dr. Martina Peter and Barbara Meier for showing me how to perform the clearing and staining of the *Salix* roots and highly supporting me with the estimation of the different kind of mycorrhizal fungi.

Special thanks to Chiara Vergani and Frank Graf for their tremendous effort and impeccable support during the elaboration of the thesis. Moreover, they patiently introduced and explained me statistical principles.

Abstract

In recent years, biological measures for slope stabilization have been gaining a new importance due to their environmental and economic sustainability. However, differently from technical measures, where guidelines and standards exist, for biological measures only methodical manuals without the basis for assessment and quantification of the stabilization effect and duration are available. Therefore, it is of high interest to get more knowledge on the quantitative impact of plants on the stability of slopes.

This Master's Thesis is embedded in the research project REVENUES (Reinforced Vegetation Numerical Evaluation of Slopes) and aims to answer the question how different willow species (*Salix* spp.) can be best employed to stabilize slopes. Therefore, a field-study was implemented in Hexenrübi, a bare gully located in the catchment area of the Flüeligraben in Central Switzerland. In this area, in addition to technical measures, different *Salix* species have been planted in the years 2009 and 2011 and are arranged in 15 plots along the slope. In order to be able to see the effect of different species, planting strategies and artificial inoculum on the stabilization effect provided by the *Salix* plants, 10 out of the 15 plots were chosen. The plants were either 3 or 5 years old and belonged to two different willow species (*Salix daphnoides* Vill., *S. purpurea* L.), and were either planted as rooted saplings or pushed in as cuttings and either inoculated with a commercial inoculum ("Forst", INOQ GmbH) or not.

As part of the investigation, trenches between selected *Salix* plants were excavated and the above- and below-ground biomass was measured. Besides, the soil aggregate stability and the field-saturated hydraulic conductivity have been determined in order to evaluate the effect of the applied biological measures on slope stability. The soil core samples for the soil aggregate stability tests were taken as close as possible to a *Salix* plant and later on analyzed by using a wet-sieving analysis in the lab. For the determination of the field-saturated soil hydraulic conductivity the ponded infiltration method from a single ring after Reynolds and Elrick (1990) was used. Moreover, *Salix* roots were excavated, and cleared and stained in the lab in order to determine the degree of mycorrhization by AMF (arbuscular-mycorrhizal fungi) and EMF (ectomycorrhizal fungi). Statistical analyses were performed using a test called Wilcoxon rank sum test and linear regression models.

The results indicated that the artificial inoculum did not significantly affect the performance of the above- and below-ground biomass, as well as there was no difference in the performance of the planting strategies between the species. However, the performance of inoculated cuttings of *S. purpurea* was significantly better compared to rooted samples of the same species regarding the above-ground biomass and number of roots. Additionally, it was found that the performance of the below-ground biomass (number of roots) could be predicted by the above-ground biomass in the case of cuttings. Considering the soil aggregate stability no significant increase between the 3- and 5-year-old plants was revealed. However, the increase between the year 2006, when only bare soil was present until the year 2014, when the applied biological measures were 3 and 5 years old was significant. A high coefficient of variability both between and inside the plots was found in case of the field-saturated soil hydraulic conductivity, which was furthermore not affected by the different species, plantings strategies and kind of inoculation. Regarding the degree of mycorrhization on *Salix* roots, EMF significantly increased between the 3- and 5-year-old plants in case of *Cenococcum geophilum* L. However, this was not found for the degree of AMF, which was moreover much lower compared to the degree of EMF.

The result of this study provides a benchmark for the slope stabilization by *S. purpurea* and *S. daphnoides*, on which further studies can be based on. It is recommended to use cuttings due to the better performance of the above- and below-ground biomass and due to the possibility to make predictions for the number of roots by the performance of the above-ground biomass. Moreover, it was revealed that artificial inoculum did not affect the performance of the plants. The presence of *Cenococcum geophilum* L. might be a hint that natural inoculation took place. Therefore, it is recommended to question the application of artificial inoculum or to specify it for *Salix* plants by adding *Cenococcum geophilum* L.. The increase in soil aggregate stability could be correlated with the development of the vegetation, which supports the application of vegetation in order to increase the stability of slope. Nevertheless, further research is needed to confirm the findings of the present thesis due to the fact that the findings only refer to *S. daphnoides* and *S. purpurea* as well as to the specific soil and environmental conditions in Hexenrübi.

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1. Introduction

Vegetation has the power to naturally reinforce slopes, mainly by penetrating the soil with roots. Due to this fact, the use of plants in respect of stabilizing slopes and protecting against erosion has been used since early history (Goulas and Graf 2003). Unfortunately, with the development of technical stabilization measures the role of vegetation seemed to fell for a period into oblivion. In recent years, however, environmental and economic sustainability had become more and more important, so former biological measures have been revalued and improved, and new technologies have been developed. The use of a combination of both technical and biological measures is known as eco- or soil bioengineering. For the implementation of the technical part guidelines and standards exist. However, for the biological part only methodical manuals without the basis for assessment and quantitative data regarding the stabilization effect and duration of the biological measures are available. This leads to the necessity to gain more knowledge about the potential of vegetation in order to reinforce slopes. Among other criteria, two soil properties are supposed providing the potential to be used as indicators for the quantification of the mechanical and hydrological effects of vegetation on soil stability: soil aggregate stability and hydraulic conductivity. The first one has been proven to be an indicator of the ecosystem status (Angers and Caron 1998). Furthermore, correlations were found between this parameter and important soil mechanical properties such as dry volume weight and shear strength (Frei, et al. 2003). The second one, hydraulic conductivity, determines the steady state infiltration capacity of the soil, activating run off and subsurface flow paths, with important effects on slope stability (Ilstedt, et al. 2007; Nimmo, et al. 2009).

This Master's thesis is embedded in the research project REVENUES (Reinforced Vegetation Numerical Evaluation of Slopes), consisting of four project partners, two research institutes BOKU (Vienna, Austria) and SLF/WSL (Davos/Birmensdorf, Switzerland) as well as a software and consulting company (ITASCA) and an engineering enterprise (KRISMER). REVENUES focuses on the advanced development and implementation of a comprehensive numerical tool to evaluate and calculate the qualitative and quantitative impact of plants on the stability of slopes. It is based on a combined approach aimed at quantifying and experimentally verifying the influences of root reinforcement related to hydraulic conductivity under consideration of the interaction with precipitation

As part of REVENUES, the present thesis aims at answering how different willow species (*Salix* spp.) can be best employed to stabilize slopes. The analysis was performed in the Hexenrübi area in Central Switzerland, where additionally to technical measures different *Salix* species have been planted to stabilize the slope of a gully between the gabion walls. In order to be able to determine the performance of the vegetation, the shoot height and shoot diameter of the *Salix* plants, as part of the above-ground biomass, were measured. The below-ground biomass includes the diameter and number of roots of the *Salix* plants. The aim of the present thesis is to find out whether the performance of *Salix daphnoides* and *Salix purpurea* is affected by a combination of planting strategies (cuttings and rooted samples) and artificial mycorrhizal inoculation. Furthermore, it was tested if the performance of the above-ground biomass affects the below-ground biomass making it possible to draw conclusions from shoots to roots. This would make the evaluation of the stabilizing effect of vegetation much easier.

The effect of the biological part on two important parameters affecting the stability of slope has been determined: soil aggregate stability and the field-saturated hydraulic conductivity. More in detail, the objective of the present thesis is either to confirm or reject the following hypothesizes.

1. The stabilization effect of vegetation and mycorrhizae on slopes strongly develops over time.
2. Above- (shrub height and shrub diameter) and below-ground (roots) biomass is positively correlated.
3. The performance of the plants differs according to the different planting strategies (cuttings and rooted plants).
4. The artificial inoculum has a beneficial effect on the development of plants
5. Mycorrhization degree is developing over time.
6. Soil aggregate stability increase over time.
7. The soil hydraulic conductivity is affected by different boundary conditions like different species, planting strategies and inoculation.

2. State of the Art

2.1 General Aspects of Slope Stabilization

In recent years, intense settlement activity, tourism facilities and transport infrastructure were extended even in endangered areas. In the year 1959 the foundation for the first alpine highway, the Brenner highway, were laid. Growing tourist sites need more space for parking, ski lifts and hotels leading to increasing surface sealing. Large urban centers in the Alps like Grenoble, Innsbruck and Bozen have a population number of 750.000, 250.00 and 150.00, respectively, and are still increasing (Kaufmann 2012). Resulting consequences like forest decline, sealed surfaces, road construction and construction of ski slopes increase the surface runoff and thereby can trigger floods, erosion, landslides and avalanches (Schneider 1988). These alpine hazards mean a risk for man, nature and infrastructure and endanger the livelihood of the population. With growing demand to prosperity and quality of life also the need of security and protection among the population increases (Forsttechnischer Dienst für Wildbach- and Lawinenverbauung Vorarlberg 2011). Slope stabilization measures contribute to the protection by increasing the stability just after slope failure occurred or even before the slope gets destabilized.

Slope failure is triggered by an increase in shear stress and/or a decrease in shear resistance. The shear stress increases by loading or unloading of weight on the slope. This is achieved either by putting more weight on top of the slope or taking away some weight on the foot, thereby creating an imbalance. Increasing the pore water pressure causes a decrease in the shear resistance (Ortigao and Sayao 2004). Hence, precipitation, which increases the pore-water pressure, is one of the most common triggering factors (Gärtner 2007, Crozier 2010, Huggel et al. 2012) and its frequency and intensity is supposed to increase with the global warming. Stabilizing measures are commonly put in place, firstly by draining the area and then either by reducing the driving forces or increasing the resistance forces. A reduction is achieved by excavating material of unstable ground areas and by draining water, which reduce the hydrostatic pressure. The resistance force is increased by drainage, elimination of potential failure zones, building retaining structures and chemical treatment to increase the shear strength of the ground (Abramson 2001).

In the past, people used on-site material to implement these measures. Check dams made of wood and/or stones were constructed in order to stabilize the base of hillsides and vegetation was used to drain and stabilize the corresponding slopes. Such a combination of technical and biological measures is today called eco-engineering and has a long tradition. However, with the introduction of construction machines and concrete, the traditional stabilization measures got more technical and massive. Further, the implementation was made possible in areas where it was technically not feasible in the past. The current stabilizing measures are re-sloping, drainage, surface protection, retaining walls or soil nailing. Retaining walls can be either gravity walls made with stones, gabions or soil-cement bags or reinforcing concrete walls (Ortigao and Sayao 2004). Key criteria in choosing the method are steepness, accessibility, expenditure and hazard potential. Among the most used plants in eco-engineering are species from the genera *Salix*. They have been proving successful in practice due to slugfest roots, a high root to shoot ratio and high resistance against extraction. Further, *Salix* can develop long roots growing in low depths with a wide rooting net. All these are important requirements for proper stabilization (Schiechtl 1992, Florineth 2004).

At the moment sustainability becomes an increasingly important issue and the awareness is sharpened for environmentally compatible solutions (Fowler and Hennessy 1995, Frei et al. 2006 and

Mitsch 2012). Thus, the eco engineering approach represents an important opportunity in the mitigation strategy of natural hazards, because it ensures a significant reduction in the costs and a lower environmental impact. A more detailed description of the slope stabilization using trees and shrubs is given in chapter 2.2.1.

2.2 The biological component in slope stabilization

2.2.1 Slope stabilization using trees and shrubs

The application of trees and shrubs to stabilize slopes and embankments has a long tradition (Goulas and Graf 2003). These techniques are called either bio- or eco-engineering and are partly provided by the “Waldgesetz, Artikel 19” in Switzerland since the year 1991. Today modified old as well as new techniques are applied combining technical and biological measures in manifold ways (Florineth and Gerstgraser 1996). Slope geometry and hydrology as well as the shearing resistance of the soil are crucial for the technical constructions (Böll 1997). From a biological perspective it is important to know the biotechnical properties and abilities of the plants, chosen for the measure (Schiechtl 1973). The planted vegetation is particularly used to stabilize the soil between technical measures where their support is low or missing (Figure 1). Vegetation has the aim to generate a sufficient protective cover as well as to accelerate the development of humous soil (Luzian 2002). Dependent on species and geotechnical conditions, it stabilizes the soil down to a depth of 0.5 to 2 meters (Florineth 2004).

Figure 1: Biological measures (*Salix* plants) between technical measures (gabion walls) in the lower part of Hexenrübi (Gerber et al. 2009).

Using cuttings or rooted plants, mainly willow, is one of the most common and promising option for stabilizing a slope. There are three different methods depending on the kind of samples (rooted or cutting samples) used. If rooted plants are employed it is called a hedge layer, whereas brush layer are implemented with un-rooted samples. The combination of both is called hedge brush layer (Florineth and Gerstgraser 1996) (Figure 2). A stable vegetation cover with a large number of species, reducing erosion and susceptibility to shallow landslides, is the aim of these measures. Thus, undisturbed soil formation is possible, leading to better soil conditions and higher soil aggregate stability. The more dense, deep, and layered the root system, the higher is the stabilizing effect of the plants (Schiechtl 1973). However, in case the application of only vegetation is not sufficient a combination of living and dead material is used. Measures like planted pole walls, live slope grids, live wooden crib walls, vegetated stonewall, and vegetated gabions combine living material with wood, stones and wire (Florineth and Gerstgraser 1996) are applied.

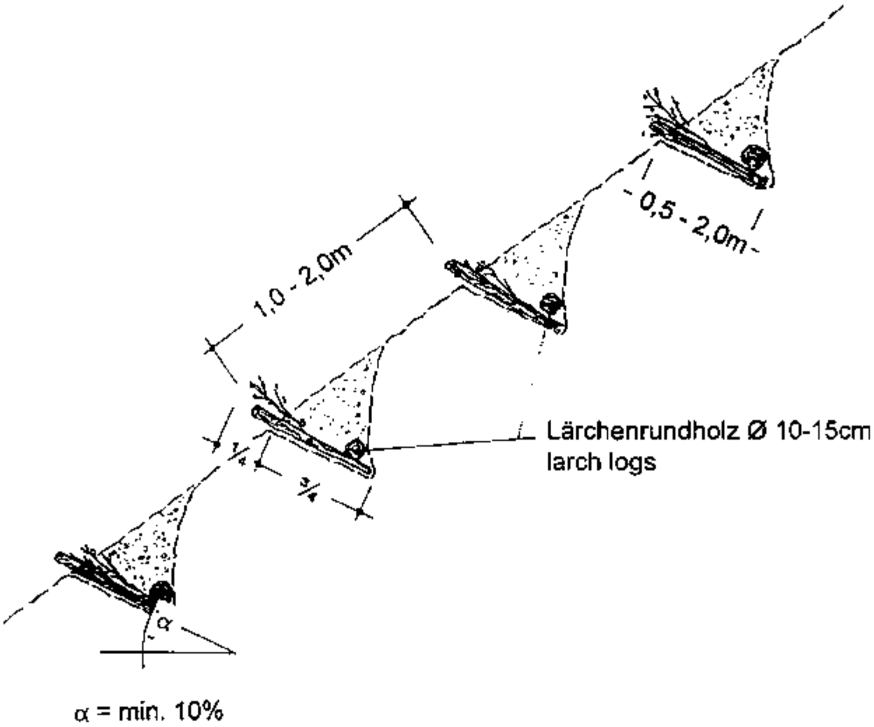


Figure 2: Application of a hedge brush layer on slope with length and angle specification (Florineth and Gerstgraser 1996).

The application of vegetation can have beneficial as well as adverse effects on slope stability. It increases both the interception and evapotranspiration and thereby reduces the pore-water pressure. Additionally, the soil is reinforced by roots, which, in turn, increases the strength (Greenway 1987, Morgan and Rickson 1995). Apart from that, root systems can reduce the existing subsurface pore-water pressure by draining it. They promote drainage by acting as a preferential flow path and, as a result, the subsurface water is lead away from unstable sites through long and wide root channels. However, critical zones can evolve when the local pressure increases through dead-end-paths and collapsed channels. Critical zones can cause a decrease in slope stability, and can trigger shallow landslides during heavy rainfall events (Sidle et al. 2001, Ghestem et al. 2011). At the same time vegetation can also increase the weight, surcharge and wind resistance and consequently the load on the slope (Morgan and Rickson 1995). Effects of the root system itself are the increase of permeability and infiltration and thus the increase of pressure (Ghestem et al. 2011). Other functions of the root system are the absorption and storage of water and nutrients, anchorage and physical support, mycorrhizal formation (Esau 1965, Russell 1977) as well as the support of the soil microbial abundance and its diversity (Stokes at al. 2009). Depending on the root size, the effects on slope stability differ. Roots thicker than 10 mm serve as anchor (Tisdal and Oades 1982, Graf and Gerber 1997) and provide a structural skeleton supporting the fine roots. Conversely, medium to fine roots (<10mm) absorb water and nutrients (Zobel 2005, Stokes at al. 2009) and influences the soil aggregate stability by growing in the pores between soil aggregates and thereby stabilizing them (Lang et al. 2010). The stabilizing effect is often quantified in combination with root growth and development and depends on the growth form and root morphology (Miller and Jastrow 1990, Miller and Jastrow 2000). Furthermore, roots are able to influence soil structure due to root penetration, change in soil water regime, root exudation, dead root decomposition and root entanglement (Degens 1997). Root penetration decreases the formation of stable macro-aggregates during the growth period, since they break up macro-aggregates (Nimmo 2004). Roots are also able to change the soil water regime by up-taking water and thereby drying the soil (Reid and Goss 1982). Moreover, root exudation reduces the wetting rate thus reduces the slacking of aggregates (Caron and Espinolda 1996). The soil structure is further affected by the release of organic material like mucilages, produced by roots, which sticks soil particles together (Six et al. 2004). Root decomposition promotes the soil structure through the delivery of organic material (Rillig and Mummey 2006). The development of soil structure due to root entanglement is highlighted by many studies (Tisdal and Oades 1982; Miller and Jastrow 1990). However, it is not easy to attribute these effects just to roots, since in most cases also mycorrhizae, in particular arbuscular (AMF) and ectomycorrhizal fungi, are present. In order to distinguish between the effect of roots and hyphae on soil structure Thomas et al. (1993) used a screen only permeable for hyphae. Their results show that both roots and AMF are able to stabilize soil (Thomas et al. 1993). Yet, it needs to be taken into account, that roots are not permanent organs, thus not permanent binding agents.

Compared to technical applications, eco-engineering measures generate less construction, maintenance and repairing costs (Smoltczyk 1987). Nevertheless, the use of eco-engineering measures is not universally acknowledged. The main problem is the lack of principles to quantify the effect of biological measures (Böll and Graf 2001). This is attributable to the fact that the system plant-soil is a dynamic system. Therefore, using plants that are adjusted to the site of revegetation is a crucial factor. Furthermore, it is important to make use of a diversity of species in order to promote natural succession (Graf 2009) and it has to be kept in mind that the stabilizing effects of vegetation develop over time (Graf et al. 2015).

2.2.2 Slope Stabilization using the effects of mycorrhizal fungi

In addition to roots, there are even smaller units that have an effect on soil structure and stability. Mycorrhizal and saprobic fungi are the most important soil microorganisms contributing to the formation and stabilization of aggregates (Six et al. 2004). Thereby they affect the stability on different levels, for example on the levels of plant community, roots and fungal mycelium (Rillig and Mummey 2006). General aspects of mycorrhizal fungi and their effect on slope stability are described in this chapter.

Most plants and nearly all species used for eco-engineering measures live in a symbiotic relationship with mycorrhizal fungi. Mycorrhizae are highly evolved, mutualistic associations between soil fungi and plant roots (Harley and Smith 1983). Beneficial associations between roots and fungi are usually called symbiosis and represent the relationship between a host plant and fungus (Harley 1989). The autotroph host plant produces carbon during photosynthesis and receives mineral nutrients from the fungus. In contrast, the fungus is heterotroph and, therefore not able to produce carbon itself. Conclusively, the fungus needs the plant as an external organic carbon source. In turn, it supplies the host plant with water and essential minerals. The nutrient and organic carbon exchange is either intracellular, via arbuscules and vesicles structures of arbuscular mycorrhiza, or intercellular, via fungal mycelium (Hartig net) of ectomycorrhizal fungi growing between the plant root cells (Harley and Smith 1983, Smith and Read 2008).

Numerous benefits result from the symbiosis between fungus and host-plant. When fungi colonize roots the root-hair-formation is suppressed and instead a fungal mycelium develops. It expands into the surrounding soil and creates a much higher absorption surface. Thus, the mobilization and absorption of water and nutrients is more effective when mycorrhizal fungi are present. Besides, the fungus protects the host plant against soil borne pathogens and toxic elements (Brunner 2001). Mycorrhizal fungi, moreover, influence plant diversity, ecosystem productivity and regulate and accelerate succession processes (Van der Heijden et al. 1998).

Spores can be propagated by water, erosion and human activities or by being suspended in moving air currents. Likewise, animals for example mammals, grasshoppers, worms, ants or birds can propagate the spores, since they remain viable even after being digested (Trappe and Maser 1976). Intense fire and exposure of subsurface soil can negatively affect the propagation of mycorrhizal fungi. Other processes interfering with the propagation are human interventions like topsoil disturbance and agricultural practices, for example tillage, long fallow periods, soil compaction and stock piling (Brundrett and Kendrick 1990). Small-scale disruptions like frost action, shrinkage of drying soil, compaction and activities of soil animals can have a detrimental effect on hyphae in soil (Read and Birch 1988).

Currently, seven types of Mycorrhiza association are distinguished: arbuscular, ecto, ectendo, arbutoid, monotropoid, ericoid and orchid (Harley and Smith 1983). Common for all of these types are their not permanent organs and the fact that they pass different phases: the initial, the mature and the senescent phase (Harley and Harley 1987).

2.2.2.1 Vesicular-arbuscular mycorrhizal (VAM) fungi and ectomycorrhizal fungi (EMF)

The present thesis focuses on the degree of endomycorrhizal and ectomycorrhizal fungi on *S. daphnoides* and *S. purpurea* roots. Hence these two kinds are subsequently explained in more detail in this segment.

The mycorrhiza formed by arbuscular mycorrhizal fungi, also called vesicular-arbuscular mycorrhiza (VAM) is the most common and widespread type (Harley and Harley 1987). Nearly all fungal species of this symbiosis belong to the Glomeromycota and are associated with Bryophyta, Pteridophyta, Gymnospermae and Angiospermae (Morton and Benny 1990). They are abundant in the soils of most ecosystems and form mutualistic symbiotic associations with the roots of about 80 % of all terrestrial plant species (Van der Heijden et al. 1998). There are approximately 150 VAM forming fungal species known today and about 300.000 VAM forming plant species. This low fungus to host ratio shows that the fungi are not host-specific and have a high functional redundancy among fungal species (Klironomos 2000).

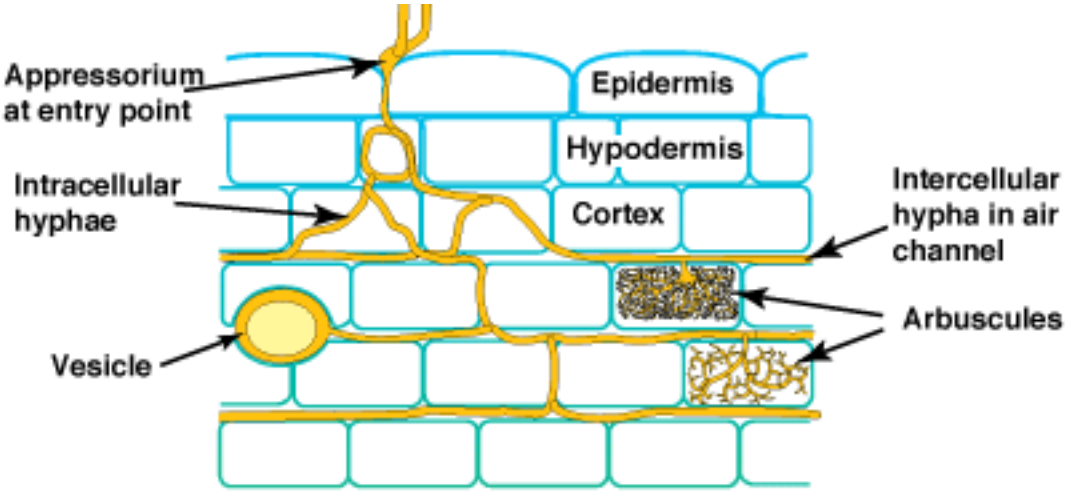


Figure 3: Transverse section (upper part) of a root showing the intraradical structures of AMF (Brundrett 2008)

Intraradical structures like hyphae, arbuscules and vesicles (Figure 3) are characteristic for arbuscular mycorrhiza as well as the absence of an external sheath or mantle. The hyphae penetrate between and into the living cells of the cortex and the epidermis (Harley and Harley 1987, Brundrett and Kendrick 1990). The penetration is either performed directly or rarely via root hairs. Hyphae within the cells form vesicles or arbuscules (Harley and Harley 1987). The latter are the primary site of nutrient and carbon exchange between the symbiosis partners (Smith and Read 1997). The vesicles are also described as hyphal swelling, containing cytoplasm and lipids and are furthermore considered to function as storage organs (Biermann and Lindermann 1983, Harley and Harley 1987). All these intraradical structures are connected to an extraradical mycelium (ERM). It is able to link individual plants of the same species (Hirrel and Gerdemann 1979, Whittingham and Read 1982) as well as of different species. The ERM makes sharing nutrients possible (Grime et al. 1987, Hart and Klimonos 2002) and is thereby able to regulate the plant species coexistence (Van der Heijden et al. 2003). Even connections with non-host plants are possible. However, just vesicles and no arbuscules develop in the non-host plant (Ocampo et al. 1980). Other functions of the mycelium are the formation of spores and runner hyphae (Smith and Read 1997) and furthermore, the improvement of the soil structure through the formation of water stable soil aggregates. Hence the resistance to erosion increases (Miller and Jastrow 1992). The arbuscular mycorrhizal fungi are reproducing by heavy asexual clamydospores and hyphal fragments, which can be transported by animals and soil (Allen 1991).

For the identification of AMF mainly the arbuscules instead of the vesicles or hyphae are used (Brundrett and Kendrick 1990). Vesicles and hyphae are unreliable indicators, which is constituted by the fact that they can also occur in non-host species. Arbuscules are often overlooked or missed due to their particularly evanescence structure and the fact that they persist in active form only for 1-15 days (Harley and Harley 1987). Nevertheless, in young or growing roots, where AMF is present, arbuscules are more likely to be observed (Brundrett and Kendrick 1990).

Ectomycorrhizae (ECM) is the other type focused on in this thesis. Most fungi forming ectomycorrhiza are septated and belong to Basidiomycota, Ascomycota and a few non-septated representatives to the Glomeromycota. There are thousands of ectomycorrhiza forming fungal species belonging to 25 families of Basidiomycetes, seven families of Ascomycetes and one Zygomycete family (Miller 1982). In contrast to AMF, EMF is low in plant species diversity, but high in fungal species richness with more than 5400 species (Allen et al. 1995). They mainly colonize woody plants and only occasionally, on herbaceous and graminaceous plants (Harley and Harley 1987, Trappe 1987).

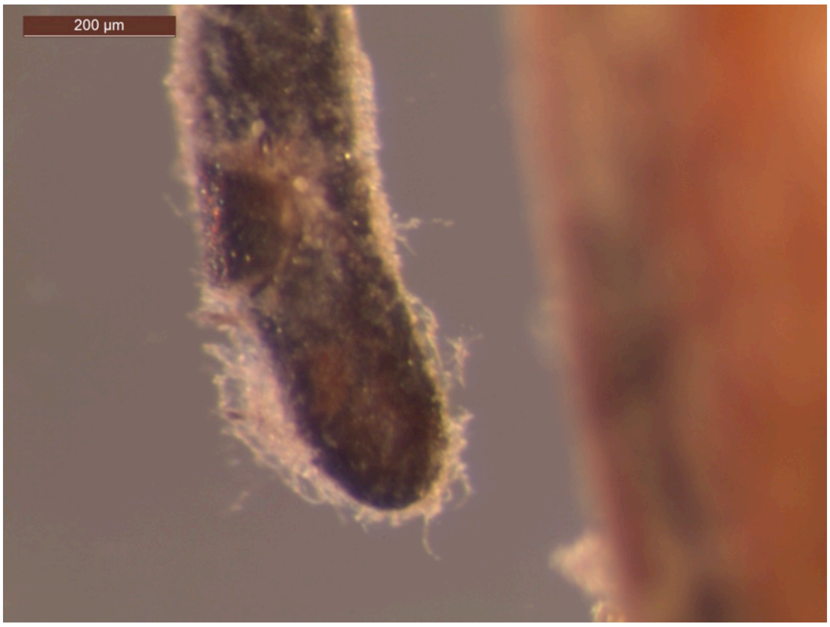


Figure 4: Root-tip with ectomycorrhizal fungi, building an external fungal sheath.

Characteristic for EMF is the formation of an external fungal sheath or mantle (Figure 4) that can be 20 to 100 µm thick and may be differentiated into layers. Hyphae penetrate between the epidermal and cortical cells. The thereby emerging network is called Hartig net and is responsible for the transfer of organic carbon and nutrients between the fungi and the host plant (Harley and Harley 1987, Smith and Read 2008). Compared to the AMF mycelium, the EMF one is much vaster (3-600 m per gram of soil) (Leake, et al. 2004) and the diameters are bigger (so called rhizomorphes up to 100 µm). Hence, the nutrients can be transported over a longer distance (Marschner 1995). In comparison to AMF, EMF can produce more hyphae, concentrate more hyphae near the growing roots, have more hyphae on the surface of roots, responds more rapidly to root initiation and redistribute resources to sites of root growth more efficiently (Chen et al. 2000). In addition, EMF obtain more energy from the host plant and, therefore, more hyphal activity is possible (Smith and Read 1997). Roots containing EMF associations persist normally for one or more years, protected by mantle hyphae (Harley and Smith 1983). Ectomycorrhizal fungi are reproducing by the formation of sexual spores in epi- or hypogeous fruit bodies, which can be transported over long distances by wind (Allen 1991). The success of EMF propagation is dependent on the ability to spread through the soil to new roots as well as on the outcome of competition with indigenous fungi (McAfee and Fortin 1986).

Previous research projects reveal that several mycorrhizal fungi can colonize on one plant root system (Burri 2006, Beglinger 2011) and plant species that can host both AMF and EMF are found for example in the genera *Populus*, *Salix* and *Alnus* (Lodge 1989). Beglinger (2011) observed that the colonization by EMF had some adverse effects on the colonization by AMF. Her findings are supported also by other studies and can be explained by different factors. Arbuscular mycorrhizal fungi seem to be more important in the juvenile phase of plants and roots and are faster in initially colonizing roots. Opposed to this, EMF colonize on maturing plants and roots and overgrow AMF in the end (Last et al. 1983, Chilvers et al. 1987). Additionally to the fact that the composition is an effect of time, it also depends on the seasonal availability of nutrient and stress factors, including water scarcity or density increase (Van der Heijden and Vosatka 1999, Baum et al. 2002, Van der Heijden et al. 2003, Smith et al. 2010). Van der Heijden (2001) found that the plant varies the composition of AMF and EMF depending on the demand of phosphorus and nitrogen. Lodge (1989) demonstrated that AMF respond positively to stressful conditions, while EMF are negatively affected by stress. Likewise, it is demonstrated that soil moisture can influence the composition in a way that under very moist conditions AMF decline whereas EMF increase (Gehring et al. 2006).

2.2.2.2 Soil aggregation and soil aggregate stability through mycorrhizal fungi

The previous described mycorrhizae have the property to contribute to soil structure and thereby soil aggregate stability on different levels (Figure 5) like the plant community, the individual root and the soil mycelium in general (Rillig and Mummey 2006). Mycorrhizal fungi can affect the stability either directly via the hyphae or indirectly by affecting the growth of above- and below- ground biomass.

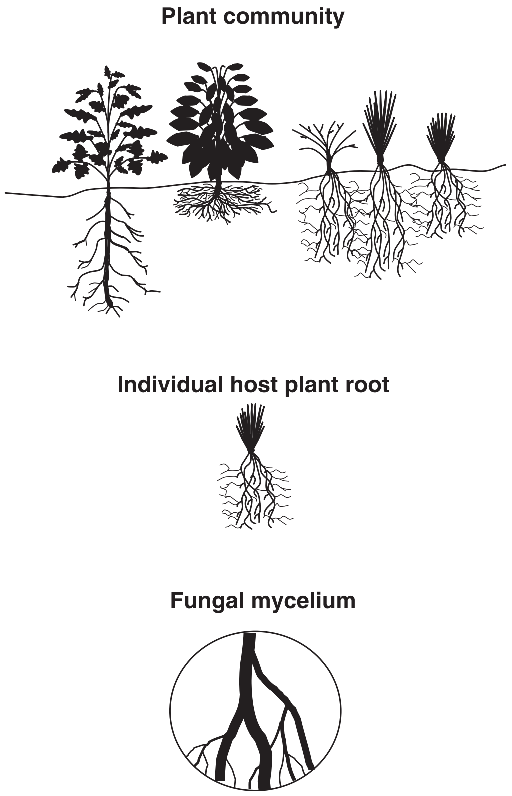


Figure 5: The three different levels on which mycorrhizal fungi can contribute to soil structure and thus stability (Rillig and Mummey 2006).

First of all, mycorrhizal fungi can influence the composition of plant communities by controlling the share of nutrients and thereby giving different benefits to the members of the symbiosis (Van der Heijden et al. 2003). Further, AMF have the ability to affect the productivity of the plant and thereby control the root growth, which is essential for the soil aggregation process. (Van der Heijden et al. 1998) More detailed information on soil aggregate stability affected by roots is given in chapter 2.2.1.

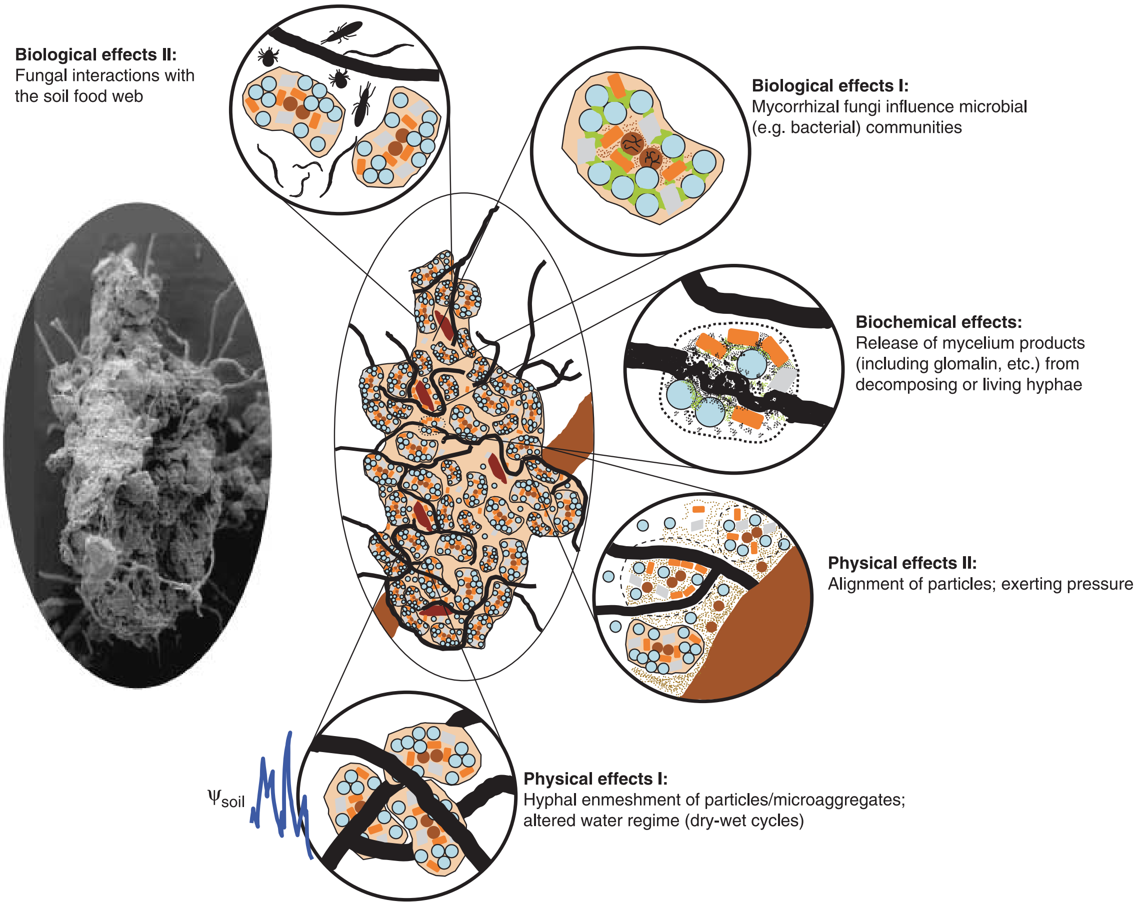


Figure 6: Overview of various mechanisms (including hypothesized processes) that are hyphal mediated and influence the formation or stabilization of soil at macroaggregate and microaggregate scales. Mechanisms are divided into physical, biochemical and biological processes; these are discussed separately in the text, and their interactions are highlighted. (Rillig and Mummey 2006)

Finally, mycorrhizal fungi are able to contribute to stability on the fungal mycelium level. Rillig and Mummy (2006) categorize the effects of fungal mycelium on aggregation and stability into biological, biochemical and physical mechanisms (Figure 6). Biological mechanisms involve the fungal interaction, the controlling of the productivity of plant communities and the fact that hyphae have the ability to affect the composition of plant communities and by this providing benefit to their members (Van der Heijden et al. 1998). The release of fungal mycelium products, like Glomalin, a glycoprotein from AMF, and glomalin-related soil protein, polysaccharides and hydropholins is summarized as biochemical effect (Tisdal and Oades 1982, Miller and Jastrow 2000, Rillig and Mummey 2006). It was found by Tisdall (1991) that soil aggregates stabilized by extracellular polysaccharides persisted for longer, if polyvalent cations were present. Polyvalent cations form bridges between fungal hyphae and particles of clay. Besides, Wright and Upadhyaya (1998) found a correlation between the amount of Glomalin in soil aggregates and their stability. Alignment of particles, hyphal enmeshment of small inorganic and organic soil particles and small aggregates contribute to stability via biophysical mechanisms (Tisdal and Oades 1982, Miller and Jastrow 2000, Rillig and Mummey 2006). All these processes are leading to a higher soil aggregate stability and are closely interlinked (Rillig and Mummey 2006).

As outlined above, mycorrhizal fungi affect the aggregate stability directly and indirectly, dependent on the kind of mycorrhizal fungi. The direct effect of AMF on soil stability, soil aggregate structure and pore space via the extraradical hyphae is highlighted in recent literature (Tisdall 1994, Miller and Jastrow 2000, Smith and Read 2008, Smith et al. 2010). Roots and AMF hyphae generate a network covered with extracellular polysaccharides to which micro-aggregates are bonded (Tisdall 1994). Rillig and Mummey (2006) assume that mycorrhizal fungal mycelium products contribute to aggregation at the micro-aggregate level. The effectiveness of the hyphal network, stabilizing macro-aggregates, depends on the length of the AMF hyphae (Tisdal and Oades 1979, Tisdal and Oades 1980, Miller and Jastrow 1990). This implies that the length of the hyphae is more essential to stability than the degree of mycorrhization (Smith and Read 2008). Besides AMF, EMF also seems to contribute to soil aggregate stability. Emerson et al. (1986) found that EMF are able to stabilize macro-aggregates in forest soil and further helps to explain the more stable aggregates when both AMF and EMF are present. Research of Emerson et al. (1986) revealed highest stability for AMF alone, followed by the combination of AMF and EMF. Also Graf and Gerber (1997), Cosentino (2006) and Graf et al. (2006) and showed that samples inoculated with EMF have a significantly higher soil aggregate stability compared to non-inoculated samples. In contrast to the findings of Emerson et al. (1986), the results of Beglinger (2011) revealed a higher stability for EMF than AMF and values in between for the combination of EMF and AMF.

In addition to the direct stabilizing effect of mycorrhizal fungi via hyphae, they can also influence the stability indirectly by affecting the development of biomass. Beglinger (2011) found that the root biomass increased with the application of AMF compared to non-mycorrhized samples and the study of Graf and Frei (2013), a lab experiment with *Alnus incana*, revealed higher root length per soil volume for mycorrhized samples with EMF. Exactly the opposite was revealed by the investigation of Bader (2014), where the root length per soil volume was lower in case of mycorrhized samples with a combination of EMF and AMF. Further, the root weight did not differ concerning mycorrhizal treatment in case of the investigation of Bader. However, the above-ground biomass in her Master thesis was affected beneficially by mycorrhization, which is supported by the findings of Kipfer et al. (2012) who found higher above-ground biomass when EMF were applied. The results of the studies, mentioned above, show that mycorrhization with EMF revealed a higher soil aggregate stability, whereas it did not increase the root growth as much as the mycorrhization with AMF did. That implies that EMF affect the stability more in a direct way than indirectly. Differently, AMF did not affect the stability but increased the root growth, thus the effect on the stability was indirect (Beglinger 2011).

Anja Bader (2014) investigated the soil aggregate stability in soil samples planted with *Alnus incana* and / or *Poa pratensis* either inoculated with mycorrhizal fungi or not. The results showed the highest value in soil aggregate stability for the non-mycorrhized samples. Graf and Frei (2013), also investigating *Alnus incana* showed that the plants produced more than twice the root length density within 20 weeks if inoculum was applied. The study of Bast et al. (2014), an investigation on hedge layers, could not confirm the significant findings of the lab tests implemented by Graf and Frei (2013) after the first vegetation period. However, this changed after the third vegetation period when the results of Bast et al. (2014) agreed with the findings of Graf and Frei (2013).

2.3 Quantifying the effect of the biological part in slope stabilization

2.3.1 Soil aggregate stability

Stable soil aggregates are an essential requirement for successful and sustainable re-colonization of slopes affected by shallow landslides with a protective vegetation cover and, therefore, important for the long-term slope stabilization (Graf et al. 2015). Aggregates are a group of particles, including clay, silt sand and organic fragments (Tisdall 1994), which stick together stronger than connecting to the surrounding particles (Nimmo 2004). All these particles are charged, with clay having the highest charge (Tisdall 1994). This results in higher soil aggregation rates in soils with high clay content (Nimmo 2004). Clay in general is negatively charged, which attracts positively charged particles like Ca and Mg, but the total charge depends on the type of clay (Tisdall 1994). A prerequisite for the formation of micro- and macro-aggregates is the formation of packets, smaller than 20 µm (Oades and Waters 1991). They consist of organic material, including polysaccharides, hyphal fragments and bacterial cells and colonies, which are encrusted with particles of clay (Tisdall 1994). Clay packets form the basis for micro-aggregates (20-250 µm), which are formed by organic binding agents. The closer the particles, the more opportunities for hydrogen bonding between oxygen and hydroxyl groups and for other intermolecular bonds to develop (Kemper and Rosenau 1986). Macro-aggregates are generated due to physical entanglement of micro-aggregates by roots and hyphae of fungi, particularly, mycorrhizal species (Tisdal and Oades 1982). Elliott and Colemann (1988) suppose that in the initial phase of soil aggregation the mechanical effects of roots and fungal hyphae are crucial. Later, organic binding agents merge the soil particles chemically and the stability increases until equilibrium between establishing and degrading processes is reached (Elliott and Colemann 1988). The stability and the size of the aggregates directly relate to cohesive forces between the particles (Kemper and Rosenau 1986). Interparticle cohesion is affected by different physical, chemical and biological influences, including air-water surface tension, intermolecular attractive forces between water and solids, cementation by precipitated solutes, entanglement by roots and fungal hyphae and different chemical processes. Hence, they are important to understand soil erosion and surface sealing (Nimmo 2004). Aggregation of stable soil aggregates is a key process that affects infiltration, drainage (Tisdall 1994), soil structural stability, water and nutrient supply (Graf 1997, Graf and Frei 2013) as well as growth of roots (Nimmo 2004). Stable aggregates are able to resist to a certain extent to disruptive forces like tillage and water and wind erosion (Gromke and Burri 2011). However, increasing size of aggregates decreases the stability. This is because in bigger aggregates, the occurrence of zones with bindings of lower strength is more likely. Roots penetrating into the aggregates can also cause a break-up. Additional disruptive forces include impact of raindrops, pore water pressure, freezing and thawing cycles (Nimmo 2004). It is important to know the soil aggregate stability as a basis to estimate the ability of soil to maintain good water infiltration rates and adequate aeration for plant growth (Emerson et al. 1986, Kemper and Rosenau 1986, Böll and Graf 2001). Beyond, a correlation between the soil aggregate stability and the shear strength of the soil has been found. Therefore, the soil aggregate stability can be considered as an indicator of slope stability (Frei et al. 2003).

In order to determine the soil aggregate stability several methods are provided, for example wet- and dry-sieving methods, ultrasonic dispersion (Diaz-Zorite et al. 2002) and sprinkling tests (Gollany et al. 1991). Key criteria in choosing the method are the needs of application, where erosion applications relate to stability and hydraulic and gas transport properties relate to the size distribution. Further, the prevailing field conditions decide whether wet or dry aggregates are used.

Using wet aggregates allows the prediction of erosion due to rainfall and runoff. Additionally, it gives an idea of the soil water behavior, for example its infiltration and redistribution as well as the soil aeration (Nimmo 2004). Bast et al. (2015) developed a method for coarse-grained soils that is described in chapter 4.3.2. It is simple, cheap and timesaving compared to other methods and the computed Aggregate Stability Coefficient (ASC) is an appropriate measure to determine the soil aggregate stability in steep and mountainous regions (Bast et al. 2014). The soil aggregate stability is affected by the size of the soil aggregates, the sieve and sample size, the method of sample wetting, the water temperature and the duration of the wet-sieving procedure (Kemper 1966). Besides, tests of Kemper (1966) resulted in decreasing stability with increasing rate of wetting.

Schwarz (2006) investigated soil aggregate stability in eco-engineering areas of different ages. The results revealed that stability increased with the development of vegetation. Degens et al. (1994) and Idowu (2003) investigated aggregate stability of agricultural soil in dependency of vegetation parameters. Their results support the findings of Schwarz (2006). However, it is important to take into account that they applied different methods to different kind of soils. Therefore, the comparison of their results with soil exposed to erosion and slides needs careful interpretation.

More detailed information on soil aggregate stability affected by roots and mycorrhizal fungi is given in chapter 2.2.1 and 2.2.2.

2.3.2 Soil Hydraulic conductivity

Hydraulic conductivity (K, m/s) is a key hydrologic parameter that represents the aptitude of the porous medium (the soil) to transmit the water. It controls the partitioning of net precipitation into vertical (infiltration) and lateral (overland flow and trough flow) pathways (Ilstedt et al. 2007, Zimmermann et al. 2009): the nature and variability of this partitioning affects slope stability and soil erosion and is therefore an important aspect to consider when evaluating bioengineering measures (Nimmo et al. 2009). Furthermore, it constitutes the basis for the derivation of other parameters, for example sorptivity, macroscopic capillary length, mean pore radius and the wetting-front potential (Reynolds and Elrick 1990).

Hydraulic conductivity depends on pores geometry and on the soil water content (Reynolds 1993). Under saturated conditions, all the pores in the soil are full of water and the conductivity reaches its maximum value, which is usually denoted as K_{sat} and is assumed to be constant for a given space and time within a certain soil (Amoozegar and Wilson 1999).

The saturated hydraulic conductivity determines the steady state infiltration capacity of soil: an higher K_{sat} can have a positive effect because it reduces the run off and the surface erosion, which is a main issue in slopes to be restored, but also detrimental effects leading to higher infiltration rates and to the development of transitory, infiltration-induced, perched water tables (Collison et al. 1995).

The estimation of the saturated hydraulic conductivity in the field can not be performed under completely saturated conditions due to the entrapment of air in the porous medium: we therefore speak of field-saturated hydraulic conductivity, denoted as K_{fs}.

The measurement of K_{fs} in the field can be performed by different methods, like the constant head single- or double ring infiltrometer, the pressure infiltrometer, the borehole constant head infiltrometer (Dane and Topp 2002) and the tension infiltrometer (Reynolds 2008). When using the single- or double-ring infiltrometer the water is applied directly on the soil surface with a known positive pressure (Youngs 1987, Reynolds and Elrick 1990). In contrast, when using a tension infiltrometer a membrane lies on top of the soil and the water is applied with negative pressure (Ankeny et al. 1988). Attributes like time, effort, the specialized equipment required, volume explored and the degree of wetting of the soil differ depending on the particular method (Nimmo et al. 2009). Studies carried out by Gupta et al. (1993), Kanwar et al. (1989), Lee et al. (1985) and Paige and Hillel (1993) determined the reliability and usefulness of these measures and their performance under different field conditions. The results revealed different trends among various soil types and field conditions for each method. Different methods of measurements lead often to different results (Bagarello and Iovino 2010): further research is needed concerning the measurement of this variable in field conditions.

Interactions between the soil biota, the vegetation and the porous medium affect the soil hydraulic conductivity (Fodor et al. 2011). Processes like shrinking and expanding of the roots, dead root decomposition and earthworm burrows create macropores that are large continuous openings building an interconnected macropore network (Chan 2001, Wuest 2001). This network makes it possible for water to flow preferentially (Perillo et al. 1999), meaning that it flows in a non-homogenous way through the soil (Gish et al. 1998). The pathways also make it possible for water to move to deeper soil layers. Thus, the hydraulic conductivity increases and inaccuracies in predictions of water and solute transport can occur (Ritsema and Dekker 2000). In soil with a high amount of macropores it can be expected that the infiltration rates and the preferential flow increase (Beven and Germann 1982) hence the overall soil hydraulic conductivity is underestimated (Fodor et al. 2011, Rienzner and Gandolfi 2014). Besides macropores, proceedings like air entrapment, soil layering, surface desaturation and soil water repellency can increase the preferential flow (Bauters et al. 1998, Wang et al. 2000, Or et al. 2007).

The results of Pommier (1996) show that K_{fs} initially decreases with the establishment of roots, since the roots fill the macropores. However, when roots decay macropores are created and K_{fs} increases. Equilibrium is reached when roots fill old channels and new channels are formed by the decay of roots (Pommier 1996). Morgan et al. (1995) found that the presence of grass roots decreases K_{sat}, especially when they form a thick layer. The results of Archer et al. (2002) support the findings of Morgan, since they showed that fine roots, for example grass roots, do not necessarily increase K_{sat} whereas the presence of roots bigger than 2 mm in diameter increases the value. Rillig (2005) and Hallett (2007) investigated the different effects of fine and coarse roots on soil properties. The findings show that fine roots have a rapid turnover and form large amounts of fine organic material, which facilitates soil aggregation over time and thereby increase the water storage capacity. Conversely, coarse roots have a slower turnover rate and grow deep making it possible for water to percolate to lower soil depths. Lee and Foster (1991), Prince et al. (2010) and Yimer et al. (2008) showed that K_{fs} is higher under the vegetation cover. This can be explained by the greater organic matter content, lower bulk density and higher macroporosity due to macro faunal activity and the development of root networks (Lee and Foster 1991). High values of K_{fs} can be related to low silt contents as they depend on the size of the pores (Hillel 1971). This is obvious where high silt content increases bulk density, which then decreases the value of K_{sat}.

Shouse (1998), Basile et al. (2003), Buczko et al. (2006) and Kumar et al. (2010) showed that field measurements could produce more representative estimates of K_{fs} compared to laboratory measurements. This might be due to greater volumes of soil used in the field tests compared to the small soil cores used in the lab. Additionally, the soil conditions in the lab are modified by the preparation and implementation where cuttings through the macropore network might occur (Rienzner and Gandolfi 2014). Likewise, Scott (1998) found that the field measurements are more reliable due to closer approximation to natural conditions. However, the field estimated values of K_{fs} are only representative for the location and time they were measured: K_s shows a great spatial and temporal variability also on small surfaces and this makes it hard to upscale this value to a study area (Bagarello and Iovino 2010).

Until now the variability of the saturated soil hydraulic conductivity at the field scale is still not understood (Rienzner and Gandolfi 2014). Strudley et al. (2008) reviewed a large number of studies considering the factors that affect the soil hydraulic properties in the field: they found that the results were often contradictory and therefore no general rule could be made.

3. Study Site

The study site “Hexenrübi” is located in the catchment area of the “Flüeligraben”, which is part of the Community Dallenwil in the Canton Nidwalden in Central Switzerland (Figure 7). It is a bare gully of about 3 ha covering an altitude range of 200 m from 1120 to 1260 meter above sea level (Böll and Graf 2001, Burri et al. 2009).

Figure 7: Switzerland with the area of Dallenwil (Schweizerische Eidgenossenschaft 2014).

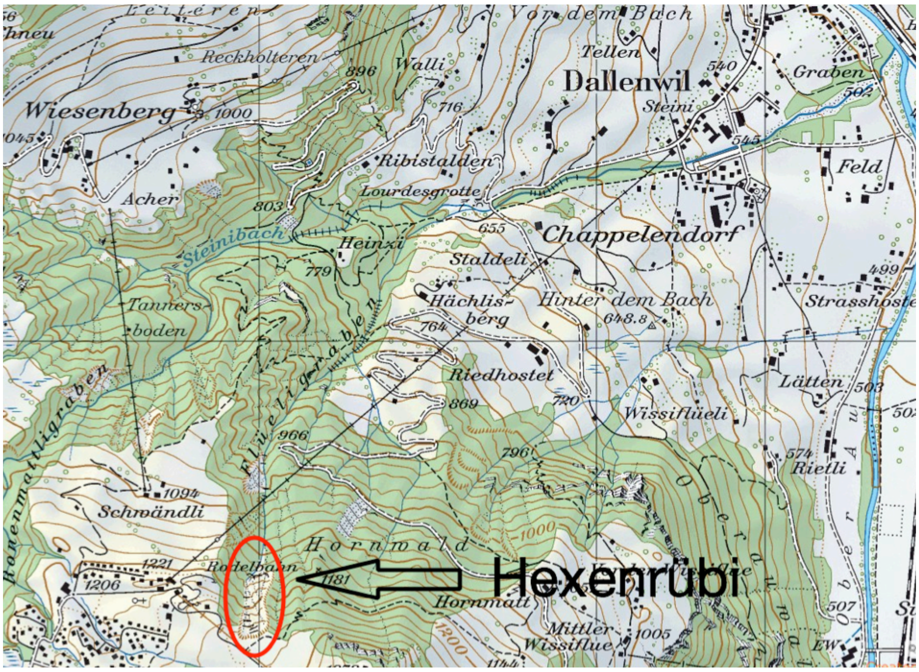


Figure 8: Map of the region Dallenwil-Wirzweli with the investigation area “Hexenrübi” (Schweizerische Eidgenossenschaft 2014).

The Flüeligraben consists of sediments of the Mezozoikum, Tertiary and Perm (Hsü and Briegel 1991). The penninic calcareous formation is lying over a layer of ultrahelvetic Flysch (Figure 9). The layer of unconsolidated rock originates from the deposition of dense moraine material of the Engelberg glacier. This layer leads to problems in the area of Hexenrübi. In this area the normally loose ground moraine material has a very high strength and compactness due to over-consolidation by glaciation resulting in steep and stable slopes. Continuous weathering has been resulted in surface erosion with subsequent increase of susceptibility to shallow landslides (Böll 1995, Gerber et al. 2009), and, therefore, preventing the establishment of a protecting vegetation cover.

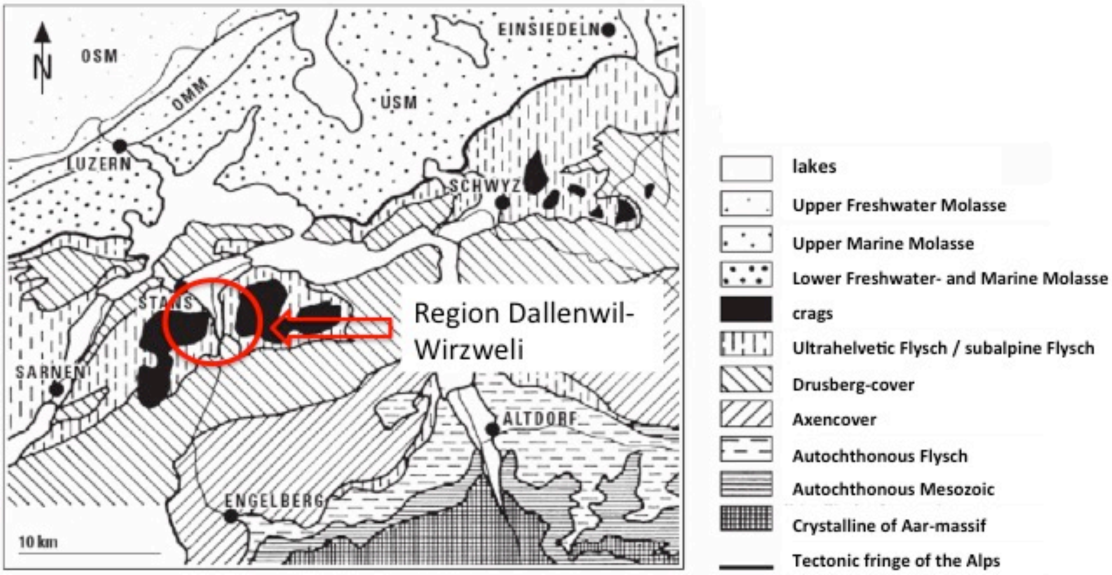


Figure 9: Overview of the geological units in the region around the Vierwaldstättersee (Heierli 1982).

In the past the village Dallenwil was partly destroyed several times by the uncontrolled Steinibach. The debris material transported by this torrent originated from the Flüeligraben and was responsible for its high damage potential (Gerber et al. 2009). As a result it has been decided to control the Steinibach at the end of the 1970s. Besides a conventional torrent control approach, the steep slopes were stabilized with technical and biological measures in order to prevent landslides and surface erosion. The aim of these measurements was the stabilization of the slope in order to reduce the bed-load discharge into the Flüeligraben as well as the protection of the pole of the cable car Dallenwil-Wirzweli (Böll et al. 2008). In the years 1987 and 1988 gully check dams were built and additional bed fixation was implemented. Until the year 2008 several gabion walls (Figure 10) were constructed to reduce, if possible, the slope angle from partly more than 45° to about 33° which corresponds to the angle of internal friction Φ’ of the soil material.

Figure 10: Gabion walls in the upper part of Hexenrübi in the year 2011 (Graf et al. 2014).

In the Hexenrübi the application of soil bioengineering measures started in 2008 right after finishing the last technical constructions/gabion wall. In a first step hydro-seeding was performed with the seeding-mixture "Sachseln". Subsequently, alder saplings (*Alnus incana* (L.) Moench) were planted more or less homogeneously over the whole area except for 15 plots of about 6 x 6 m^2 each. In these well-defined investigation plots different willow species (*Salix daphnoides* Vill., *S. purpurea* L.) were either planted as rooted saplings or pushed in as cuttings and either inoculated with a commercial inoculum ("Forst", INOQ GmbH) or not according to the scheme in Figure 12 and Table 1.

The main construction work was conducted by the “Amt für Wald und Energie des Kantons Nidwalden”, the WSL and the “Uertekorporation Dallenwil” (Gerber et al. 2009, Melk von Flüe 2010).

Figure 11: left side: Hexenrübi after the planting of biological stabilization measures in the year 2009. Right side: Same place in the year 2014 (Gerber et al. 2009).

Figure 12: Investigation plots 1-15 at Hexenrübi with years of planting. The 10 red-bordered plots were selected for the present study (WSL 2014).

For the present thesis 10 out of the 15 plots have been chosen, were *S. daphnoides* and *S. purpurea* were planted, as it was not possible to investigate all the plots. On the basis of these plots the effect of planting strategies and inoculation on the performance of the *Salix* plants was tested and the development over time was observed. Furthermore, the soil aggregate stability, the degree of mycorrhizal fungi on *Salix* roots and the field-saturated hydraulic conductivity were determined within each plot. More information on the applied tests is given in chapter 4.

Table 1: Investigation corresponding willow species, planting strategy, application of artificial inoculum, and the year of planting (WSL 2014).

Plot	**Species**	**Planting strategy**	**Inoculation**	**Year of planting**
1	*S. daphnoides*	Cuttings	control	2009
2	*S. Purpurea*	Cuttings	control	2009
3	*S. Purpurea*	Rooted samples	inoculated (INOQ Forst)	2009
4	*S. daphnoides*	Rooted samples	inoculated (INOQ Forst)	2009
5	*S. Purpurea*	Cuttings	inoculated (INOQ Forst)	2009
6	*S. Purpurea*	Cuttings	inoculated (INOQ Forst)	2009
7	*S. Purpurea*	Rooted samples	control	2009
8	*S. daphnoides*	Rooted samples	control	2009
14	*S. daphnoides*	Cuttings	inoculated (INOQ Forst)	2011
15	*S. daphnoides*	Cuttings	control	2011

4. Methods

4.1 Experimental design

In each of the 10 selected plots three trenches were excavated for the root analyses, three soil core samples were taken for soil aggregate stability tests, and three locations chosen for permeability tests (Figure 13). The exact location of the trenches, the soil core sampling points, and the permeability spots of all plots are documented in Appendix 6. First of all, every plot was marked with barrier tape. Then three rectangles, one plant in each edge, were selected for the trench-wall location. The plants were selected in respect of representing the general status of the whole plot as close to reality as possible. Care was taken to perform the sampling of the soil cores and the permeability tests in closest vicinity to a *Salix* plant. The different test procedures are explained in detail in the following chapters.

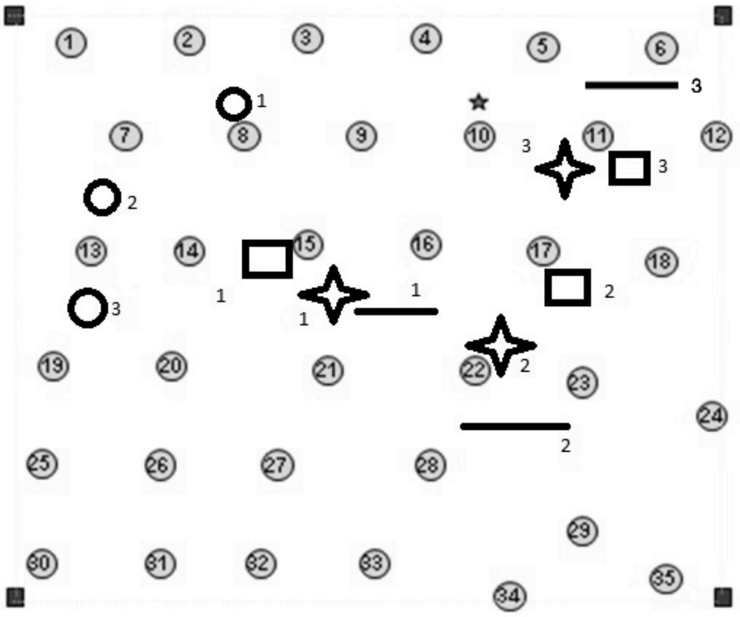


Figure 13: Plot 2 with the locations of the trenches, the location where the soil core samples were taken for soil aggregate stability tests, the location where *Salix* roots were extracted and the locations chosen for the permeability tests.

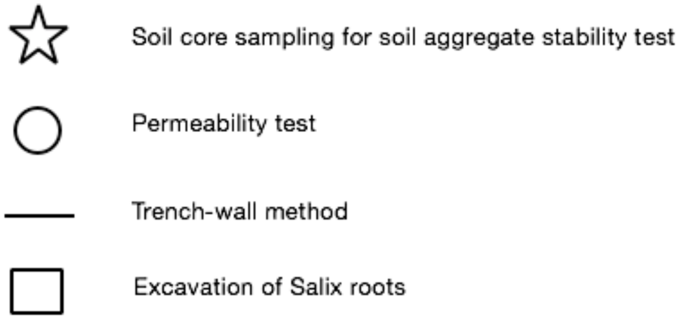


Figure 14: Legend explaining the symbols of the different tests performed in each plot.

4.2 Investigation on the above- and below-ground biomass

In each plot three trenches of 30 cm depth and 50 cm wide were excavated in the middle of four neighboring willows (at a distance of about 50 cm from each plant) in order to determine the below ground biomass of *S. daphnoides* and *S. purpurea*. The number of roots crossing the trench wall was counted, their diameter measure with a digital caliper, and the corresponding distribution recorded at five centimeters depth steps. (Figure 15) A mean root diameter for each trench was calculated out of all the diameters measured for each trench. The exact distance of the trench to each of the four *Salix* plants and their vitality were recorded. In addition, the study of the above-ground biomass included the status of each "trench-plant", the measurement of the stem diameter, and the height of the biggest shoot of each *Salix* plants. In order to evaluate the performance of the above-ground biomass corresponding to each trench a mean shoot height and a mean shoot diameter was calculated out of the four plants belonging to each trench.

Figure 15: Excavated trench wall in front of a *Salix* plant.

4.3 Soil Aggregate Stability Analysis

4.3.1 Soil core sample taking

The soil cores for the determination of soil aggregate stability were taken at three places per plot each close to a *Salix* plant and possibly free of coarse-grained material. The latter criterion was not easy to accomplish. Hence, taking the samples was quite time consuming and three times a new Humax core was needed.

The Humax, with a length of 250 mm and a diameter of 50 mm, was driven into the soil by a sledgehammer (5kg) (Figure 16). Compared to other methods, the Humax makes it possible to take soil samples with minimum disturbance and compression (Bast et al. 2015). The direction of the Humax was vertical to the slope angle (Figure 17). In case of big stones interfering the sampling, the procedure was stopped and continued at a new place. A new location was chosen also when the soil sample was not at least 10 cm long. The samples were stored vertical, with the opening at the bottom, in the fridge at 4°C.

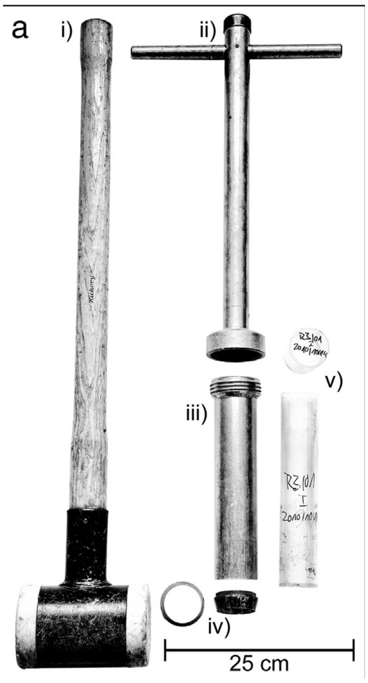


Figure 16: Sledge hammer (i), Humax with cross handle (ii), cartridge tube (iii) and core bit (iv). For the extracted soil core sample a plastic core (v) is inserted into the cartridge tube (Bast et al. 2015).

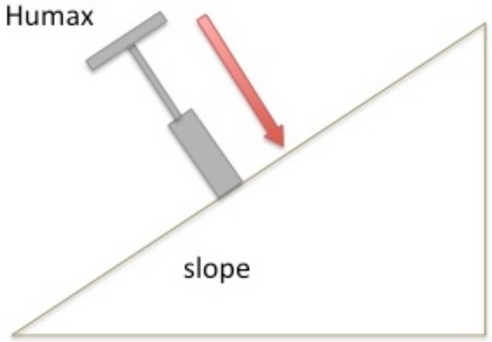


Figure 17: The Humax was driven into the ground vertical to the slope angle.

4.3.2 Wet-sieving analysis

To determine the stability of the soil aggregates a modified wet-sieving method was used. The set-up was based on Frei (2009) and Beglinger (2011). The soil aggregate stability test was performed with the soil core samples taken with the Humax, previously undergoing a preparation phase. Therefore, they were taken out of the plastic tube and a piece of 10 cm, measured from the top of the soil core, was cut from the entire sample (Figure 18). If a big stone was positioned at the 10 cm mark the sample was cut shorter or longer than 10 cm and the deviation was noticed. In case of a dense vegetation cover the upper 1-2 cm of the sample were cut before taking the length of 10 cm.

Figure 18: Soil core sample of plot 1 with vegetation cover (upper layer pointing to the right) and plastic core.

Likewise prepared sample was then put into a cylinder made of steel mesh (Figure 19, right side) and together placed onto a sieve-tower. Both the cylinder and the top-sieve (Prüfsieb; W20; Norm: DIN4188, Rohrer-Technik CH-8706 Feldmeile) had openings of 20 mm. The sieve below had openings of 10 mm (Prüfsieb; W10; Norm: DIN4188, Rohrer-Technik CH-8706 Feldmeilen) and the one at the bottom of 0.5 mm (Prüfsieb; W0.5; Norm: DIN4188, Rohrer-Technik CH-8706 Feldmeilen).

Figure 19: Wet-sieving analysis tools (left side: sieve tower in pot, right side: sieve tower with steel mesh cylinder).

This set-up was placed in a big Plexiglas pot (diameter: 300 mm, height: 300mm), which then was filled with water up to the bottom of the top sieve (Figure 19, left side). Afterwards the jar was filled up until the top level of the soil core was reached. The water stayed at this level for five minutes until it was released with a valve at the bottom of the jar. The mesh cylinder and the top sieve as well as the two sieves below were removed from the jar. The soil portion remaining on the top sieve (components > 20 mm) was examined for single stones > 20 mm and roots by carefully chopping the soil material with a fork (Figure 20). Roots as well as the big stones were weighted on a Mettler PM34 balance (Figure 21). The roots were preserved in 15% Ethanol in plastic bags and stored at 4°C for further analysis. The rest of the portion > 20 mm as well as the one ≤ 20 mm were separately oven dried for 48 h at 80-85 °C.

Figure 20: Remaining soil core material chopped with a fork and rinsed with water.

Figure 21: Mettler PM34 balance with a root sample stored in a plastic bag.

4.3.3 Calculation of the soil aggregate stability

The stability of the soil aggregates is calculated with the following formula, also used by Bader (2014) and Beglinger (2011).

$$stab\ [0,1] = \frac{m_{20}}{m_{total}}$$

Formula 1: Soil Aggregate Stability

stab= soil aggregate stability [g/g]

m_{20}= weight of the dried soil that was on the 20mm sieve after the wetting [g]

m_{tot}= weight of the dried fractions bigger and smaller 20 mm [g]

The values range from 0, reflecting complete dispersion during the test to 1, indicating a totally stable sample.

4.4 Mycorrhizal fungi

4.4.1 Collection of the root samples

In order to determine the mycorrhization degree of *S. daphnoides* and *S. purpurea* by arbuscular mycorrhizal fungi (AMF) and ectomycorrhizal fungi (EMF) roots of the two willow species were collected. For that purpose only roots were taken into account that could be traced back to the trunk of a willow. Due to the fact that generally only few roots per willow were reliably traceable they were not distinguished according to the different depth layers. The roots of each willow were separately packed in plastic bags and transported to the laboratory where they were stored at 4°C until further processing.

4.4.2 Clearing and staining of roots

In the laboratory the 30 root samples were carefully cleaned from soil and debris and rinsed with water. Half of the root material was then stored in the fridge in 15 % Ethanol at 4°C for the purpose of quantifying the ectomycorrhizal colonization. The other half of the roots was further processed for analyzing the mycorrhization degree of AMF.

Natural pigments and contents of the plant cells, making a direct observation difficult or even impossible, usually hide structures produced by glomeromycotan fungi. Hence chemical agents for clearing are used to remove cell contents and cell wall pigments and thereby make it possible to see internal features in plant tissue (Gardner 1975). A non-vital staining technique was applied following the recommendations of Vierheilig et al. (2005).

The roots of *S. daphnoides* and *S. purpurea* were put in 15 ml plastic tubes (Figure 22) and covered with 2.5% KOH (potassium hydroxide). To ensure that the KOH is in contact with every part of the roots the tube had to be shaken with a Vortex. Afterwards the tubes were placed in a 90°C hot water bath (Figure 23) for two hours. The time in the water bath depends on the thickness of the roots and the type of the plant.

Figure 22: Root sample stored in 15% Ethanol in a 15ml plastic tube.

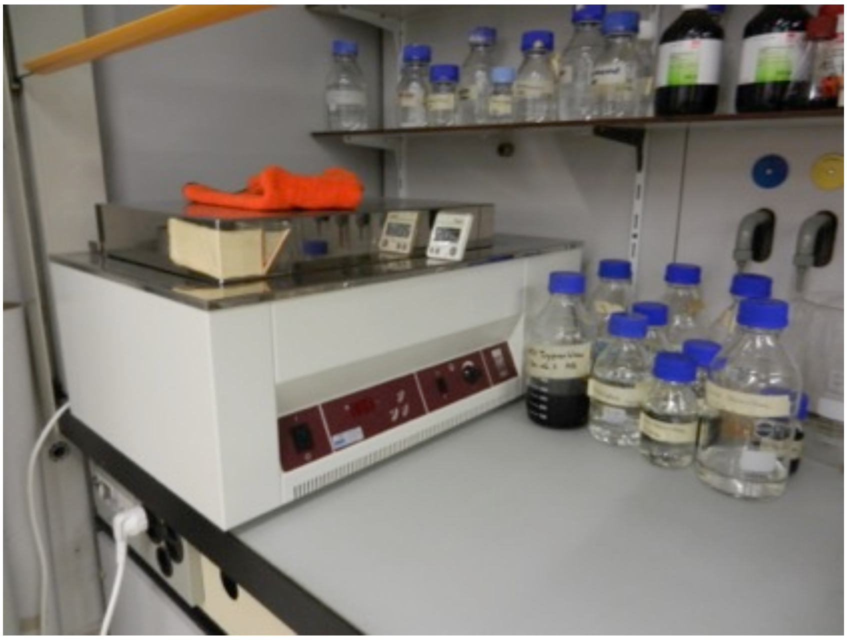


Figure 23: Water bath for the clearing and staining procedure of the roots.

In the beginning a heating time of 60 minutes was chosen. This duration of treatment was not sufficient and the roots were not cleared in a way that arbuscular mycorrhizal structures were visible under the microscope. Hence a heating time of 150 minutes was chosen, which provided good results.

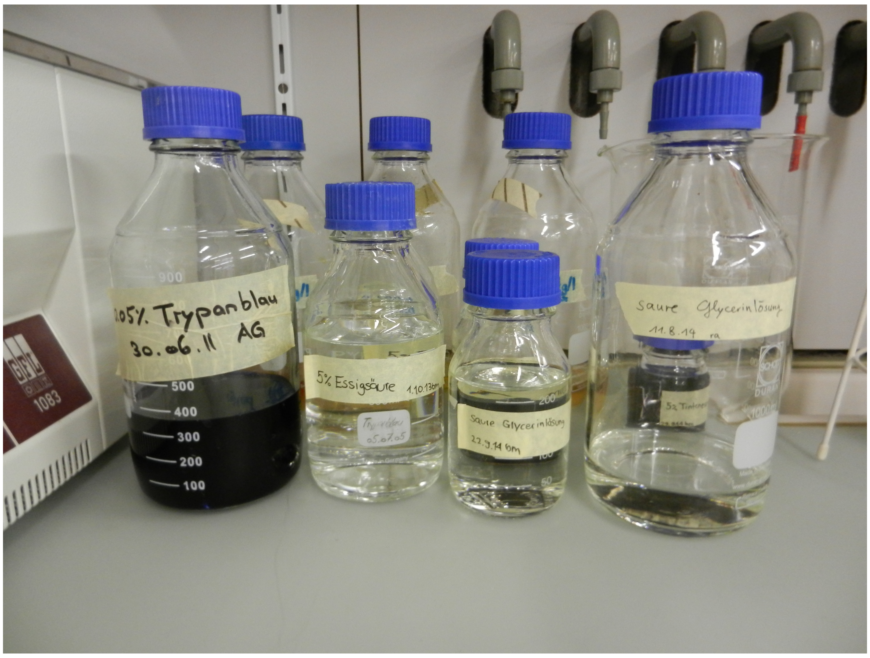


Figure 24: Clearing and staining chemicals (Trypan blue, acetic acid and acidic glycerol).

Subsequently, the roots were captured on a fine sieve and rinsed with water four times. After cleaning, the roots were put in the tube again and covered with HCl (Hydrochloric acid) to prepare them for the staining. The staining makes it easier to determine the mycorrhizal structures. The staining chemicals bind to fungal hyphae but do not excessively stain the background of the plant material (Vierheilig et al. 2005). Therefore, the cleared and acidified roots were put into new plastic tubes and Trypan blue (0.05%) (Figure 24, on the left) was added. Trypan blue is believed to bind most strongly to phenolic-like materials in hyphal walls but it also stains plant cell walls with encrusted phenolics and any residual cell contents (Brundrett et al. 1984). The tubes were stored in the water bath at 90°C for 20 minutes. The staining time depends on the specie, the root size and the age and can therefore range from minutes to hours (Vierheilig et al. 2005). After this proceeding the roots were again captured on a fine sieve and the Trypan blue was collected for disposal, as it is not allowed to be flushed. The roots were then stored in glass tubes filled with acidic glycerol (Figure 25). This chemical preserves the samples for several years.

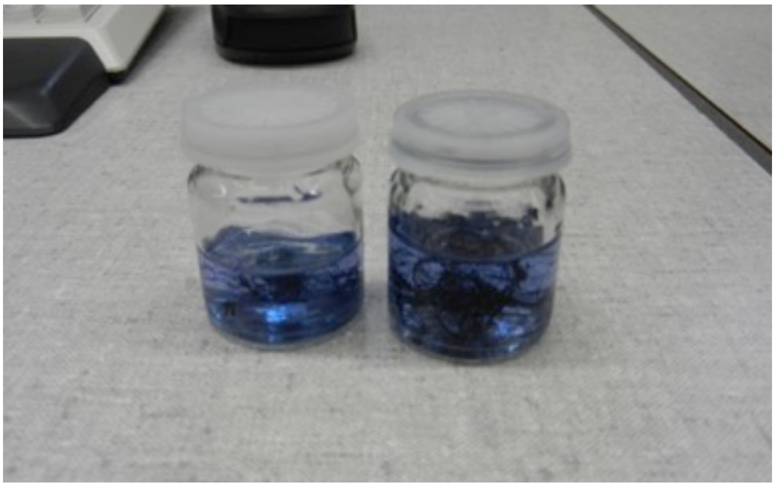


Figure 25: Cleared and stained *Salix* root samples stored in acidic glycerol.

4.4.3 Mycorrhization degree

4.4.3.1 Quantification of mycorrhization degree of AMF on Salix roots

Arbuscules are the morphological criteria that define AM associations (Brundrett 2004). In order to address the mycorrhization degree, the stained roots were further processed following the protocol of Beglinger (2011). There the quantification was conducted in a way that 10 equal pieces of the roots were cut apart from the bigger root parts with a scalpel and put vertically on the microscope slide. The parts were covered by a cover slide and the subsequent analysis was performed with a Leitz Laborlux S microscope (Figure 26). For the present study, the analysis was slightly modified as less than 10 pieces per plant were available due to the very small number and short length of roots. For a representative overview and comparable results 13 observation spots on the root pieces were randomly chosen and the number of arbuscules, vesicles and hyphae were documented. In case of presence of either arbuscules, vesicles (Figure 27) or hyphae a “1” was noted and in case of non-presence a “0” was documented. In the literature the arbuscules are mentioned to be the structures that are used to identify AMF (Harley and Smith 1983). Consequently, the degree was calculated just by the appearance of this intraradical structure Formula 2).

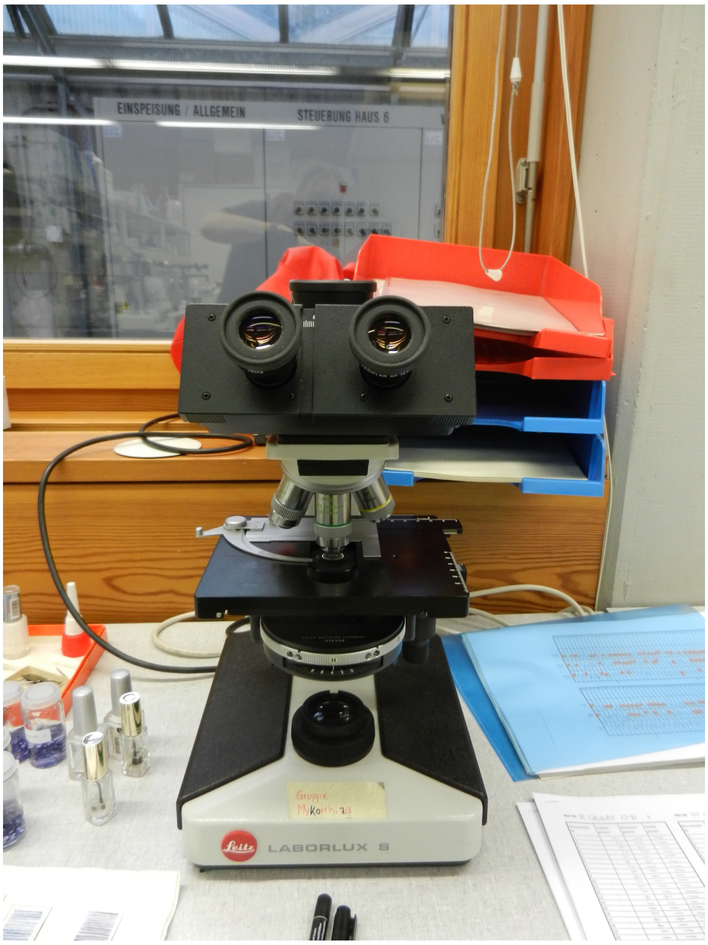


Figure 26: Microscope (Leitz Laborlux S) for identification of AMF.

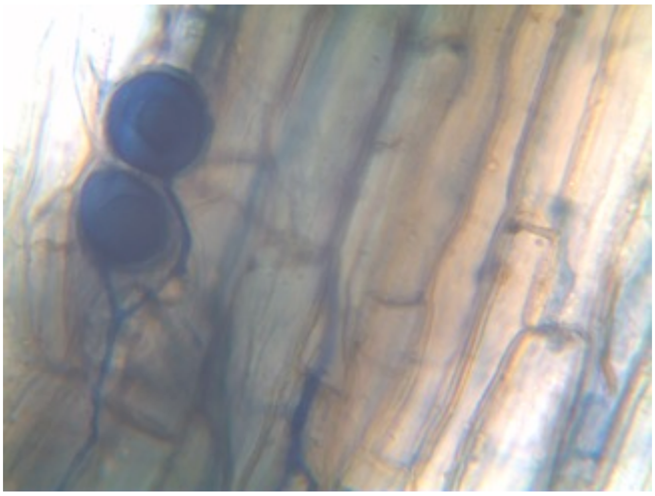


Figure 27: Endomycorrhizal fungi structures (blue stained vesicles) in one of the root samples.

The degree of mycorrhization by arbuscular-mycorrhizal fungi was calculated with the following formula:

$$\boldsymbol{degree\ of\ mycorrhization\ by\ AMF}\ [\mathbf{0},\mathbf{1}] = \frac{\boldsymbol{n_a}}{\boldsymbol{n_o}}$$

Formula 2: Degree of AMF colonization

n_a= number of arbuscules
n_0= number of observed spots on the roots

The values range from 0, reflecting that no arbuscules were present in the root to 1, indicating a totally mycorrhized (with AMF) root sample.

4.4.3.2 Quantification of mycorrhization degree of EMF on *Salix* roots

For the quantification of the mycorrhization degree of ectomycorrhizal fungi the not-cleared parts of the 30 root samples were used. The root parts were placed in a culture dish with tap water stored for a few days to avoid air bubbles. Then the root tips were analyzed with a stereo magnifier (Leica M7 95) (Figure 28) and pictures were made with the Leica DFC 290 camera. In total 30 tips per root sample were analyzed for the presence of ectomycorrhiza. Furthermore, black mycorrhized tips representing *Cenococcum geophilum* L. were distinguished from the rest of mycorrhized tips (Figure 29).

Figure 28: Stereo magnifier (Leitz Laborlux S) with Leica DFC 290 camera used to detect EMF.

Figure 29: Ectomycorrhized root tip (*Cenococcum geophilum* L.).

The degree of mycorrhization by ectomycorrhizal fungi was calculated with the following formula:

$$degree\ of\ mycorrhization\ with\ EMF\ [0,1] = \frac{t_m}{t_{total}}$$

Formula 3: Degree of EMF colonization

t_m= tips that are mycorrhized
t_{total}= total number of analyzed tips

The values range from 0, reflecting that no arbuscules were present in the root to 1, indicating a totally mycorrhized (with EMF) root sample.

4.5 Root Scanning (WinRHIZO)

To get the root length in the soil core samples the cleaned roots were analyzed with a flatbed scanner (EPSON Perfection V700 PHOTO) (Figure 30) and their length and volume were determined with the software WinRHIZO.

Figure 30: EPSON Perfection V700 PHOTO flatbed scanner.

The roots were taken out of the Ethanol solution and placed in a culture dish with tab water stored for a few days to avoid air bubbles. Then they were arranged the way that as less as possible parts were lying onto each other. Otherwise the scanner is not able to capture every single part of the roots and therefore the results will not represent the actual distribution. The software WinRHIZO then calculated the root length per soil volume, the total length, the diameter of the roots and the distribution for the different root classes.

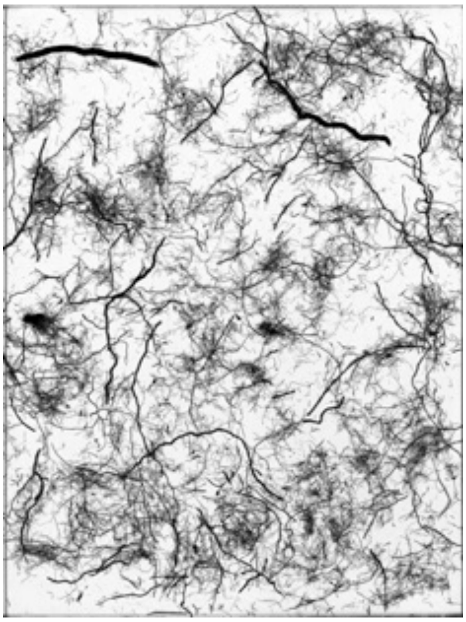


Figure 31: Root scan of plant 1 in plot 7.

4.6 Hydraulic conductivity

For the determination of the field-saturated hydraulic conductivity the ponded infiltration method from a single ring following Reynolds and Elrick (1990) was used. It takes into account soil capillarity, depth of ponding, ring radius and depth of insertion of the ring. The one-ponding depth approach was chosen because it has the advantage of speed and simplicity over the other procedures like two or multiple ponding depths. The hydraulic conductivity was calculated with the one-H-level calculation (Formula 4). The soil parameter α is estimated to be 12 m^{-1} (loam soil) by Reynolds and Elrick (1990). For the determination of the shape factor G_e Formula 5 is used. The effective shape factor G_e can be applied if the ponding depth is between 0.05 and 0.25 cm. The formula provides flexibility concerning the chosen depth of ring insertion and radius. This simplification can be used because the shape factor is nearly independent of soil hydraulic properties and the G_e values apply with reasonable accuracy over a wide range of soil types and ponding depth levels (Reynolds and Elrick 1990).

As single ring infiltrometer a cylinder with a radius of 5 cm was taken, placed on a flat surface and hammered 3 cm deep into the soil. To avoid water running out, the cylinder was surrounded by plastic modeling mass (Figure 32). Then the cylinder was filled with water up to the 8 cm level and the time was stopped until the water head reached the 7 cm level, later the Δt was calculated. The water was refilled until the time stayed constant three times in a row, which means that the steady state is reached.

Figure 32: Experimental set-up for the permeability test (cylinder core sealed with plastic modeling mass).

$$K_S = \frac{\alpha * G_E * Q_S}{(r * (\alpha * h_{mean} + 1) + (G_E * \alpha * A))}$$

Formula 4: Field saturated hydraulic conductivity (Reynolds and Elrick 1990)

$$G_e = 0.316 * \left(\frac{d}{a}\right) + 0.184$$

Formula 5: Effective shape factor (Reynolds and Elrick 1990)

Parameter information:

d = depth of ring insertion

a = r = radius of the cylinder

α = soil parameter

Q_S [cm^3/s]= $\frac{V}{mean\ t_S}$

$V = \pi * r^2 * (h_1 - h_2)$

mean t_s = mean of the three measured times

$A = \pi * r^2$

h_{mean} = $\frac{h_1+h_2}{2}$

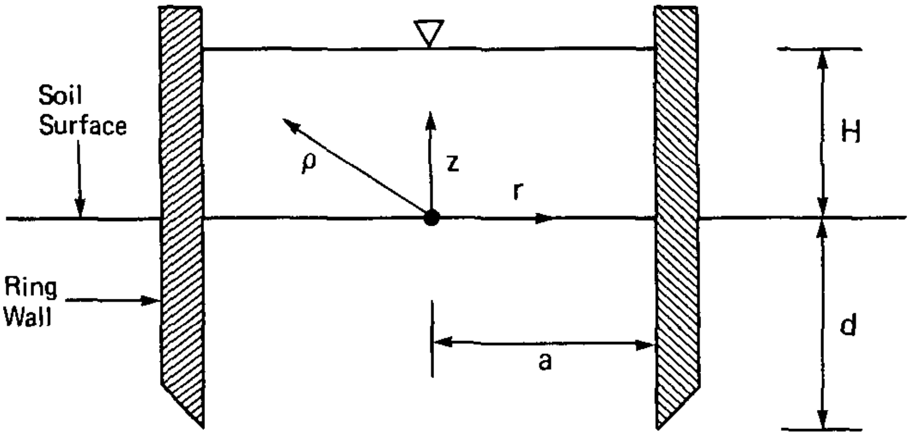


Figure 33: Schematic of ponded flow from within a ring (Reynolds and Elrick 1990).

4.7 Statistical Analysis

All the statistical analyses were performed with the software MATLAB R2014b. For the illustration of the data boxplots, bar plots, scatterplots histograms were used. In all tests the significance level of 0.05 was applied.

In order to determine the dependency and relationship between two parameters, above- and below-ground biomass, linear regression models were made. For every model the standard distribution of the data as well as the distribution of the residuals were verified. The latter was illustrated and investigated by means of QQ-plot, Tukey-Anscombe-plot, histogram of residuals and Cook's distance.

For the determination of differences between two data vectors the two-sided Wilcoxon rank sum test was applied.

5. Results

5.1 Above- and below-ground biomass

In order to evaluate the development of the above- and below-ground biomass, the variables mean height of the shoots, mean diameter of the shoots, mean diameter of the roots and number of roots were considered for each trench. The mean shoot height and the mean shoot diameter was calculated as the average value of the four plants surrounding the trenches. Through the evaluation of these variables we want to test if the above- and below-ground biomass are affected beneficial or adversely by the different factors, including species, planting strategy and kind of inoculation. Moreover, the variables can be used to see how the above- and below-ground biomass develops over time.

5.1.1 General Observation

Differences in the performance of the species

Considering the performance of the two species *S. daphnoides* and *S. purpurea* concerning the above- and below-ground biomass, only the generation of the year 2009 can be compared, since in the year 2011 only *S. daphnoides* was planted.

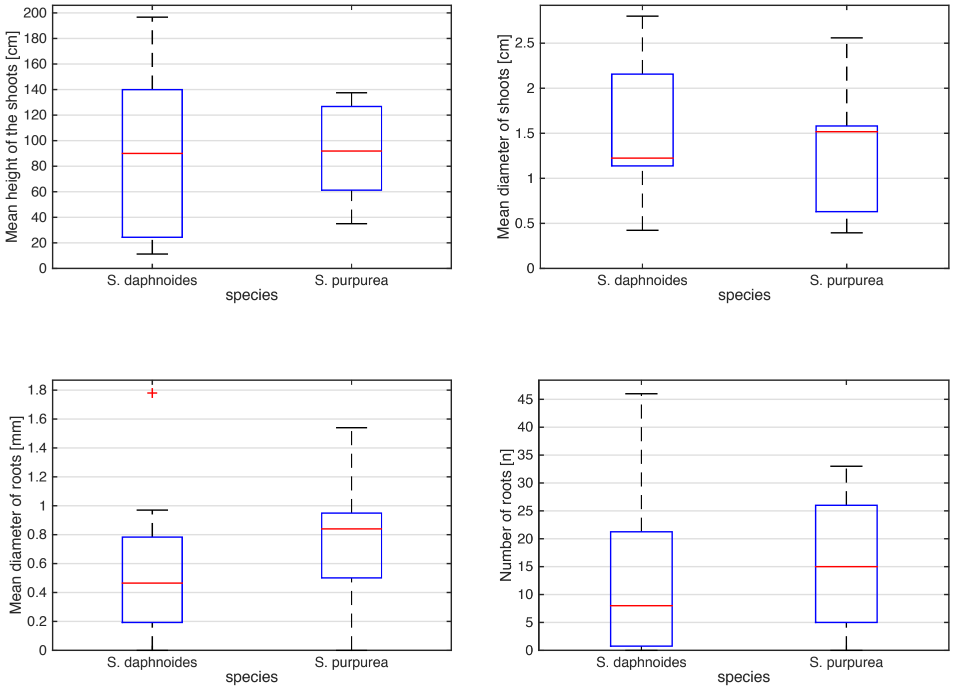
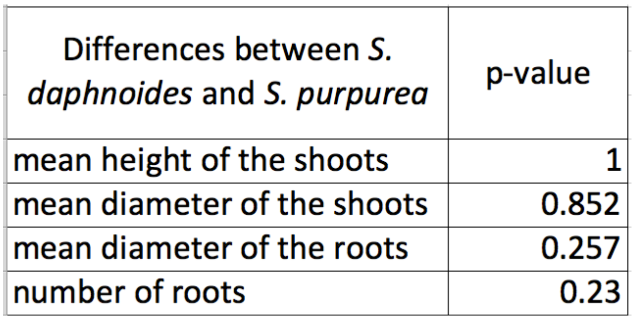


Figure 34: Boxplots illustrating the above- and below-ground biomass of *S. daphnoides* and *S. purpurea* (planted in the year 2009). The bottom and top edges of the boxes indicate the sample 25th and 75th percentiles. The whiskers represent minimum and maximum.

Figure 34 illustrates that *S. purpurea* performed slightly better in all four categories of the above-and below-ground biomass, but the Wilcoxon rank sum test revealed no significant differences between the two species (Table 2). *Salix purpurea* outcompeted the *S. daphnoides* barely with a median value of 91.88 cm compared to a median value of 90.0 cm for the mean height. Whereas for the mean diameter of shoots *S. daphnoides* exhibited a median value of 1.52 cm compared to 1.22 cm for the *S. purpurea*. The number of roots revealed a median value of 16 for *S. purpurea* compared to 8 for *S. daphnoides* and the median values of the mean diameter of the roots were 0.84 mm for the *S. daphnoides* and 0.47 mm for the *S. purpurea*.

Table 2: P-values of the Wilcoxon rank sum test for the evaluation of the differences between the species.



Differences between *S. daphnoides* and *S. purpurea*	p-value
mean height of the shoots	1
mean diameter of the shoots	0.852
mean diameter of the roots	0.257
number of roots	0.23

Effect of the artificial inoculum

In order to test the effect of the artificial inoculum on the biomass development, we consider separately the two generations of plants, planted in in the year 2009 and 2011. In this way it is possible to see if the effect of inoculation on the performance of the plants changes over time.

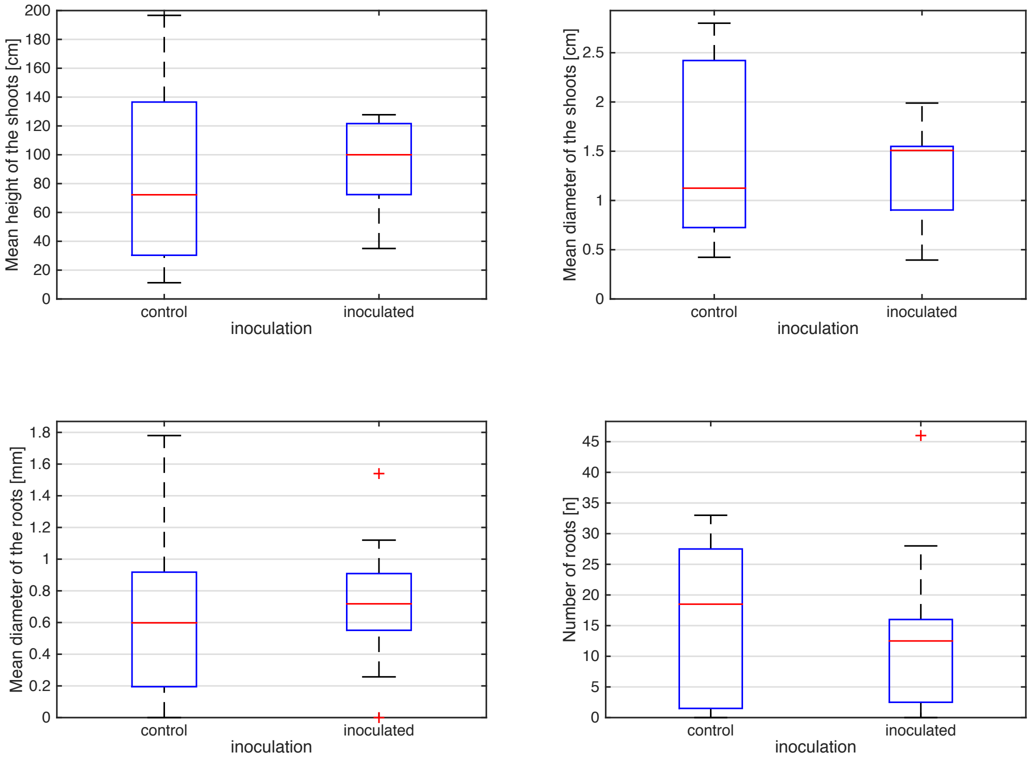


Figure 35: Boxplots showing the effect of inoculation on the 5-year-old generation concerning the above- and below-ground biomass (Expl. Figure 34).

Considering the 5-year-old generation, the above-ground biomass as well as the mean root diameter were slightly affected beneficially by the application of inoculum. However, the Wilcoxon rank sum test revealed no significant differences between inoculated and control samples (Table 3). The median values were 100 cm for the height and 1.51 cm for the shoot diameter compared to 72.25 cm for the height and 1.13 cm for the diameter of the shoots without inoculation. The root diameter with inoculation reached median values of 0.72 mm compared to a diameter of 0.6 mm for the samples without inoculation. Just the number of roots was affected adversely by inoculation with a number of roots of 13 compared to 18 for the control samples, but the difference was not significant (Table 3). It is interesting to notice that for every considered variable, the control samples showed a much higher variability than the inoculated samples (Figure 35).

Table 3: P-values of the Wilcoxon rank sum test for the differences between inoculated samples and control samples of the 5-year-old generation.

Differences between inoculated samples and control samples	p-value
mean height of the shoots	0.67
mean diameter of the shoots	0.75
mean diameter of the roots	0.71
number of roots	0.35

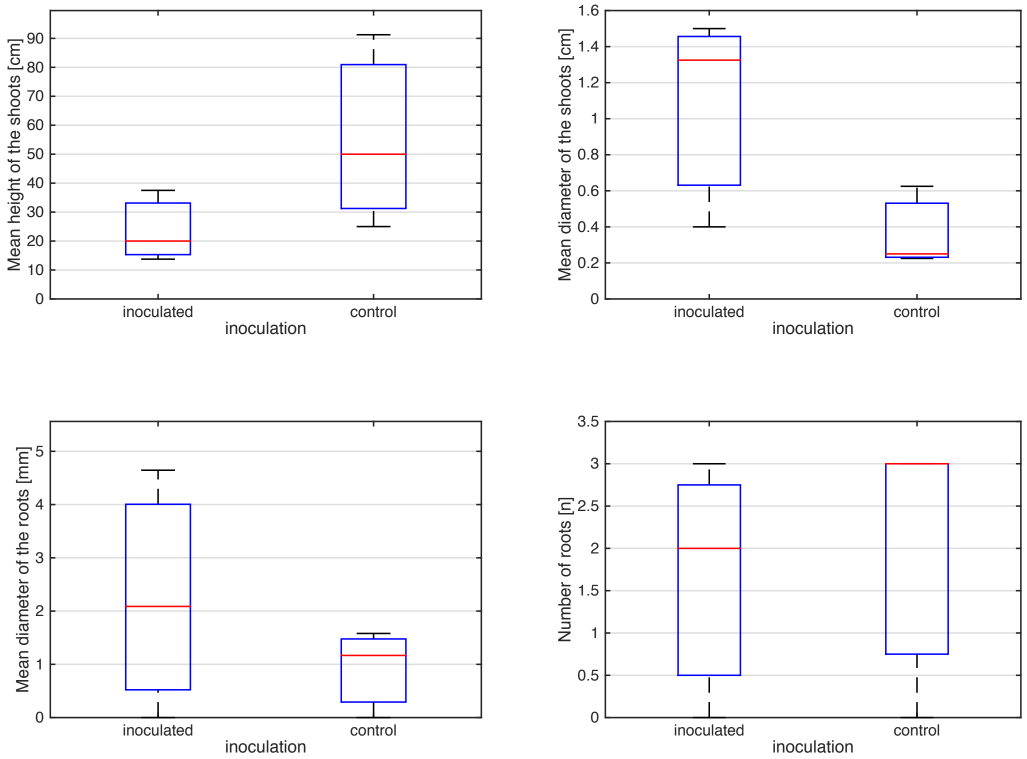


Figure 36: Boxplots showing the effect of inoculation on the generation of the year 2011 concerning the above- and below-ground biomass (Expl. Figure 34).

Figure 36 illustrates that the above- and below-ground biomass of the 3-year-old generation performed different compared to the 5-year-old generation. However, differences between control and inoculated samples are not significant in the case of the diameter of shoots and roots and the number of roots (Table 4). Just in case of the mean height of the shoots the samples without inoculum performed significantly better (Table 4).

Table 4: P-values of the Wilcoxon rank sum test for the differences between inoculated samples and control samples of the 3-year-old generation.

Differences between inoculated samples and control samples	p-value
mean height of the shoots	0.016
mean diameter of the shoots	0.2
mean diameter of the roots	1
number of roots	0.5

Effect of the planting strategy

When testing the effect of the planting strategies, only the generation of the year 2009 can be taken into account, since in the year 2011 only cuttings of *S. daphnoides* were planted.

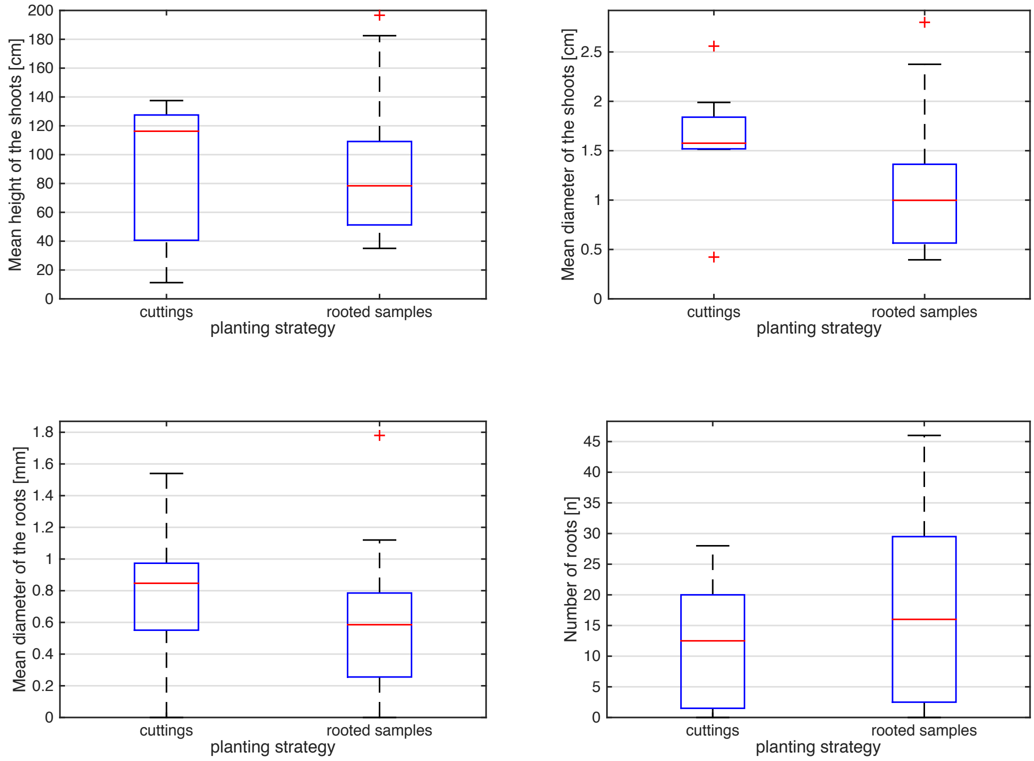


Figure 37: Boxplots of above- and below-ground biomass affected by the planting strategies: cuttings and rooted samples (Expl. Figure 34).

According to the Wilcoxon rank sum test no significant differences both in above- and below-ground biomass between cuttings and rooted samples were found (Table 5). Figure 37 illustrates that cuttings performed better than rooted samples for the above-ground biomass and the diameter of roots, but the differences were negligible.

Table 5: P-values of the Wilcoxon rank sum test for the differences in the above- and below-ground biomass of the 5-year-old generation between cuttings and rooted samples.

Differences between cuttings and rooted samples	p-value
mean height of the shoots	0.977
mean diameter of the shoots	0.051
mean diameter of the roots	0.285
number of roots	0.506

5.1.2 Combined effect of species, planting strategies and kind of inoculation

In order to see the combined effect of planting strategy and inoculation on the above- and below-ground biomass of *S. daphnoides* and *S. purpurea* a more detailed analysis was done. With respect to the lack of rooted samples in the generation of the year 2011, just the 5-year-old plots were taken into account. Three main observations were tested. First, if the inoculation has some effect on the above- and below-ground biomass considering the different species and the different planting strategies. Afterwards, the effect of the different species on the biomass development was tested, considering separately rooted samples and cutting. Finally, the performance of the two species was observed separately to see the effect of planting strategy in combination with the inoculum.

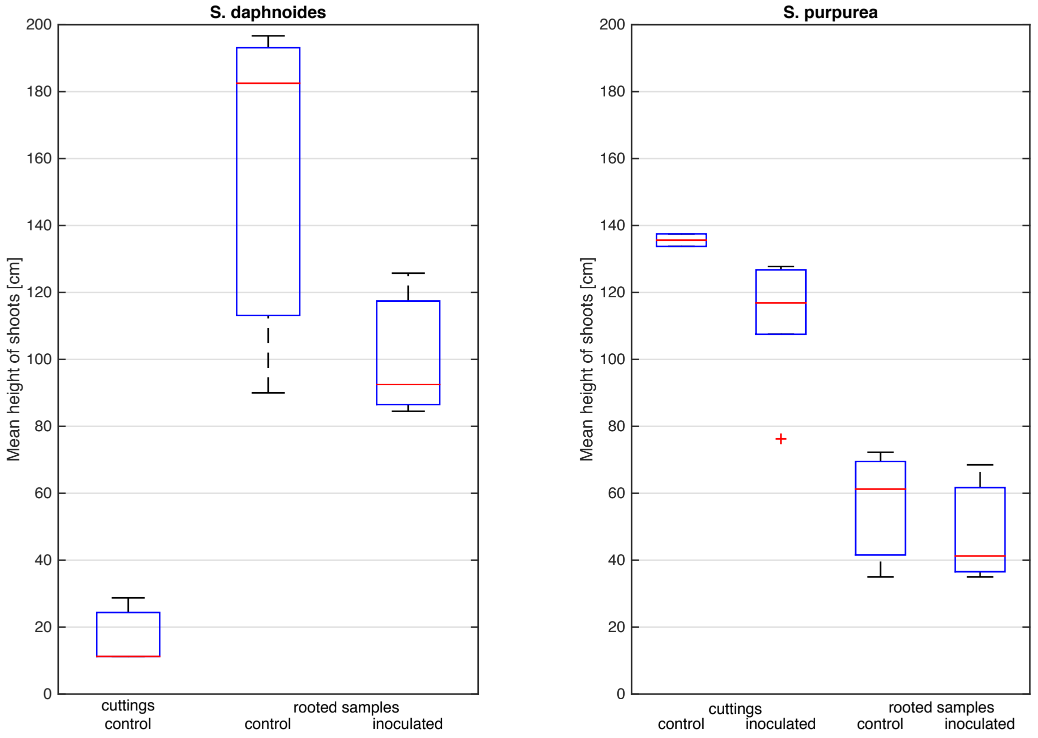


Figure 38: Mean height of shoots; differences between *S. daphnoides* and *S. purpurea* considering planting strategy and inoculation (Expl. Figure 34).

Considering the effect of inoculum on the height of the shoots, the rooted samples of *S. daphnoides* and *S. purpurea* performed slightly better without inoculum (Figure 38), but these differences between the inoculated and control samples were not significant (respectively p-value = 0.4 and 0.8); this was also the case for cuttings of *S. purpurea* (p-value = 0.07). Considering the effect of species on the performance of the planting strategies, the rooted samples of *S. daphnoides* both control and inoculated performed better, but without significance (p-value = 0.1 and 0.1), compared to the rooted samples of *S. purpurea*. Comparing the cuttings of both species was only possible for the control samples without inoculum. *Salix purpurea* had higher median values, but according to the Wilcoxon rank sum test no significant differences between the two species in the performance of both cuttings were found (p-value = 0.2).

Considering the effect of planting strategies inside the species, *S. daphnoides* performed better as rooted plant than as cutting, but the differences were not significant (p-value = 0.076). Opposed to this, cuttings of *S. purpurea* were generally better than the rooted samples of the same specie. However, there was a significant difference (p-value = 0.024) only between the inoculated cuttings and the inoculated rooted samples.

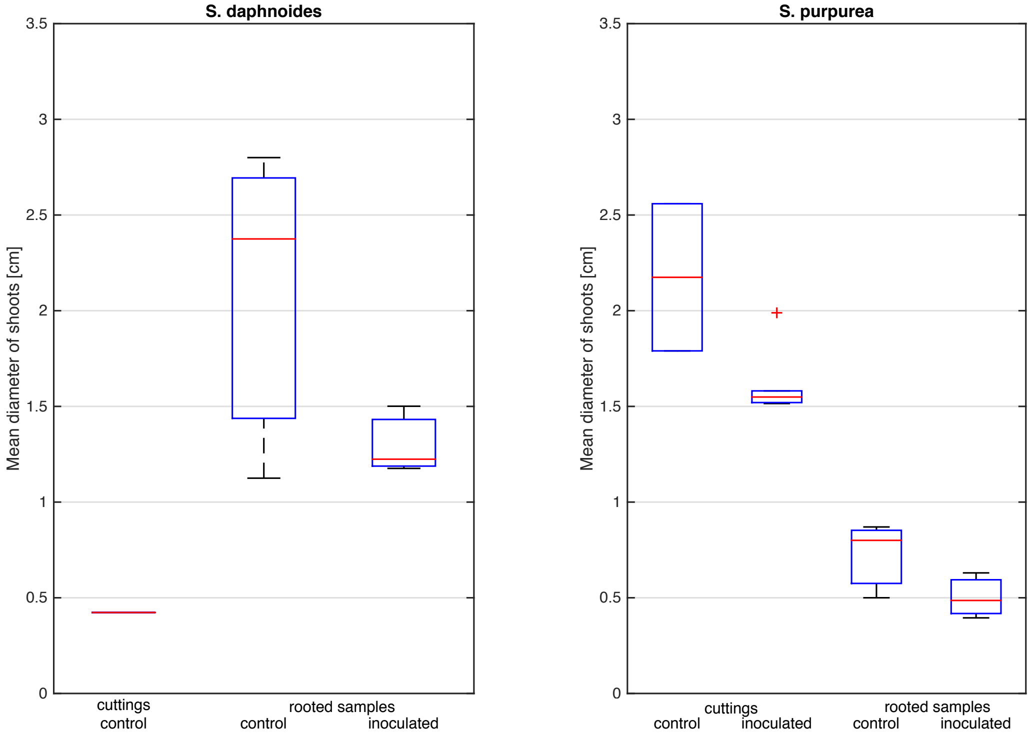


Figure 39: Mean diameter of shoots; differences between *S. daphnoides* and *S. purpurea* considering planting strategy and inoculation (just 5-year-old plots are considered) (Expl. Figure 34).

Concerning the mean diameter of the shoots, the rooted samples of *S. daphnoides* and *S. purpurea* performed slightly better without inoculum (Figure 39), but these differences between the inoculated and control samples were not significant (p-value = 0.7 and 0.2); this was also the case for cuttings of *S. purpurea* (p-value = 0.143). Comparing the performance of the species depending on the planting strategy revealed that rooted samples of *S. daphnoides* both inoculated and control performed better, but without significance (p-value = 0.1 and 0.1), than rooted samples of *S. purpurea*. Considering the two species separately, *S. daphnoides* performs better as rooted sample, whereas for *S. purpurea* cuttings performed better than rooted samples. However, just in case of the inoculated samples the panting strategy significantly affected the diameter of the shoots. The inoculated cutting samples were significantly bigger than the inoculated rooted samples (p-value = 0.024).

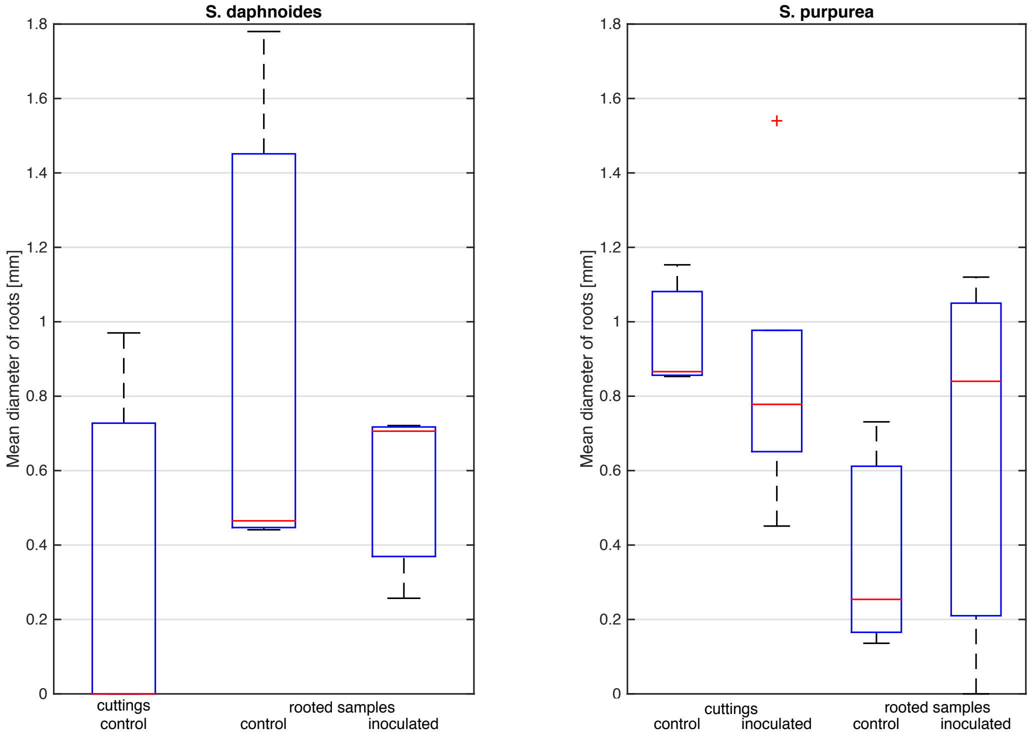


Figure 40: Mean diameter of roots; differences between *S. daphnoides* and *S. purpurea* considering planting strategy and inoculation (Expl. Figure 34).

Rooted samples of both *S. purpurea* and *S. daphnoides* were beneficially, but not significantly affected by inoculation (respectively p-value = 1 and 0.167), whereas cuttings of *S. purpurea* were adversely, but also not significantly affected by inoculum (p-value = 0.381). Cuttings samples (control) of *S. purpurea* performed better than the *S. daphnoides* ones, but the beneficial effect was not significant (p-value = 0.3). Regarding the rooted samples *S. daphnoides* control samples perform better than *S. purpurea* control samples, whereas for the inoculated samples the opposite is the case with better values for the *S. purpurea*. However, the differences were not significant (respectively p-value = 0.4 and 0.7). Looking at the performance of the species separately, the rooted samples of *S. daphnoides* had higher, but not significant different (p-value = 0.3) values than the cuttings. Contrary, *S. purpurea* cuttings without inoculum performed better than rooted samples without inoculum, but no significant difference was revealed (p-value = 0.1). In case of the inoculated samples of *S. purpurea* the rooted samples performed slightly better. However, the Wilcoxon rank sum test revealed no significance for the effect of planting strategy on the species (p-value = 0.9).

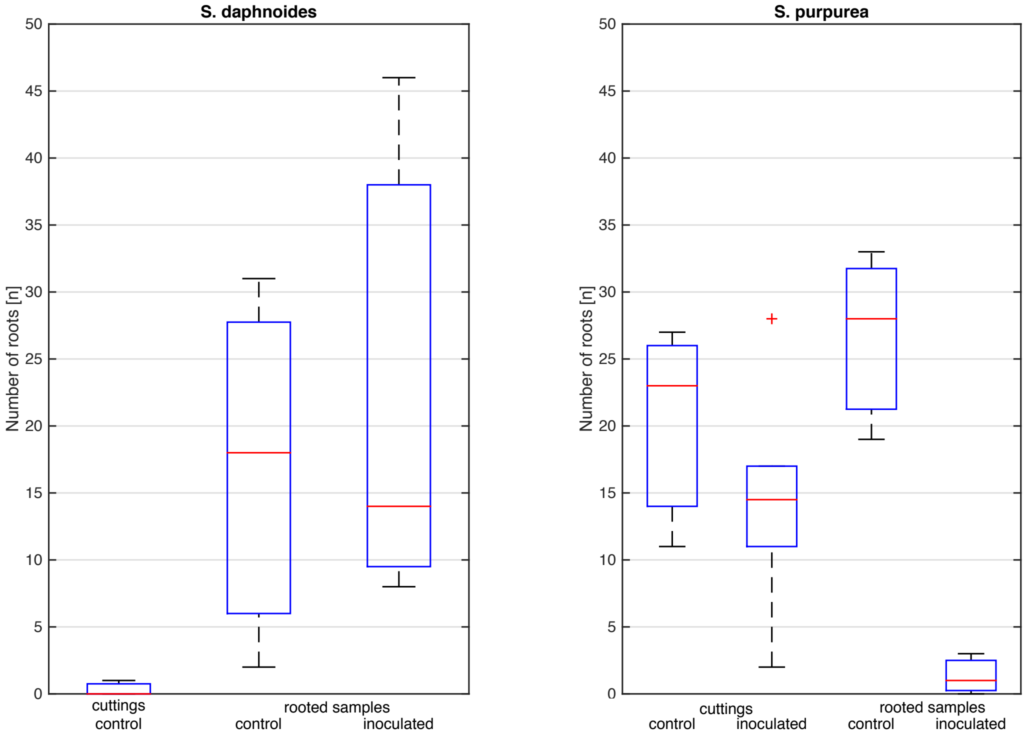


Figure 41: Number of roots; differences between *S. daphnoides* and *S. purpurea* considering planting strategy and inoculation (Expl. Figure 34).

Concerning the number of roots, rooted samples of *S. daphnoides* and *S. purpurea* were not significantly affected (respectively p-value = 0.1 and 0.071) by the application of inoculum; the same was found for cuttings of *S. purpurea* (p-value = 0.1). Considering the effect of species in planting strategies, cuttings, without inoculum, of *S. purpurea* performed better, but without significance (p-value = 0.1) compared to *S. daphnoides*. This was also the case for rooted samples without inoculum, whereas in case of inoculated rooted samples *S. daphnoides* performed better. However, for rooted samples both inoculated and control no significant difference between the species was found (respectively p-value = 0.1 and 0.4). Considering *S. daphnoides* separately, rooted samples without inoculum performed slightly, but not significantly (p-value = 0.3) better than the cuttings without inoculum. The same is true for the control samples of *S. purpurea* (p-value = 0.4). However, in case of the inoculated samples of *S. purpurea* the cuttings performed significantly better for the diameter of the shoots (p-value = 0.048).

5.1.3 Root distribution at different depths

Besides the number and diameter of roots, also the root distribution is important for the reinforcement of the soil. Thus it was analyzed how the number and diameter of roots were distributed along the soil profile in the trenches. For each plot an average number of roots per depth and diameter class was calculated. In order to see how the combination of planting strategy and inoculation affects the root distribution a more detailed analysis considering the species separately was done.

As for the other observations just the plants of the year 2009 were considered. On the basis of this analysis it can be said in which layers what number of fine, medium and coarse roots grows. In case of S. daphnoides only the rooted samples were taken into account because only a few cuttings in plot 1 were vital at the time of the investigation. It is important to keep in mind that the distribution was determined just for the first 30 cm of depth due to the practical problems in excavating the soil.

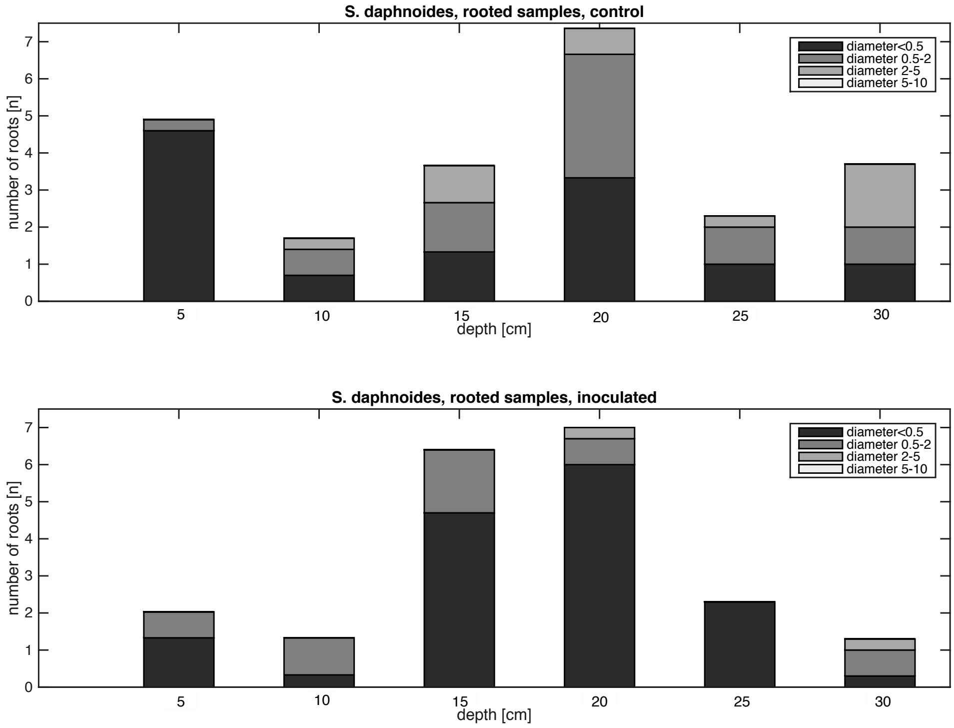


Figure 42: Average number of roots per depth and diameter class for *S. daphnoides* rooted samples, inoculated and control.

Rooted samples, both inoculated and control showed the highest number of roots at 20 cm of depth, and the lowest number in the second layer (10 cm of depth). The most roots with a diameter < 0.5 mm were found in the layer of 5 cm depth for the control sample and in the depth layer of 20 cm for the inoculated samples. Surprisingly, the inoculated samples had a much lower number of roots in the first layer (5 cm of depth), compared to the control sample. Thicker roots with a diameter of 2-5 mm were found in all layers apart of the first one for the rooted samples without inoculum. Compared to this, for the samples without artificial inoculum roots with this diameters were found only at 20 and 30 cm of depth.

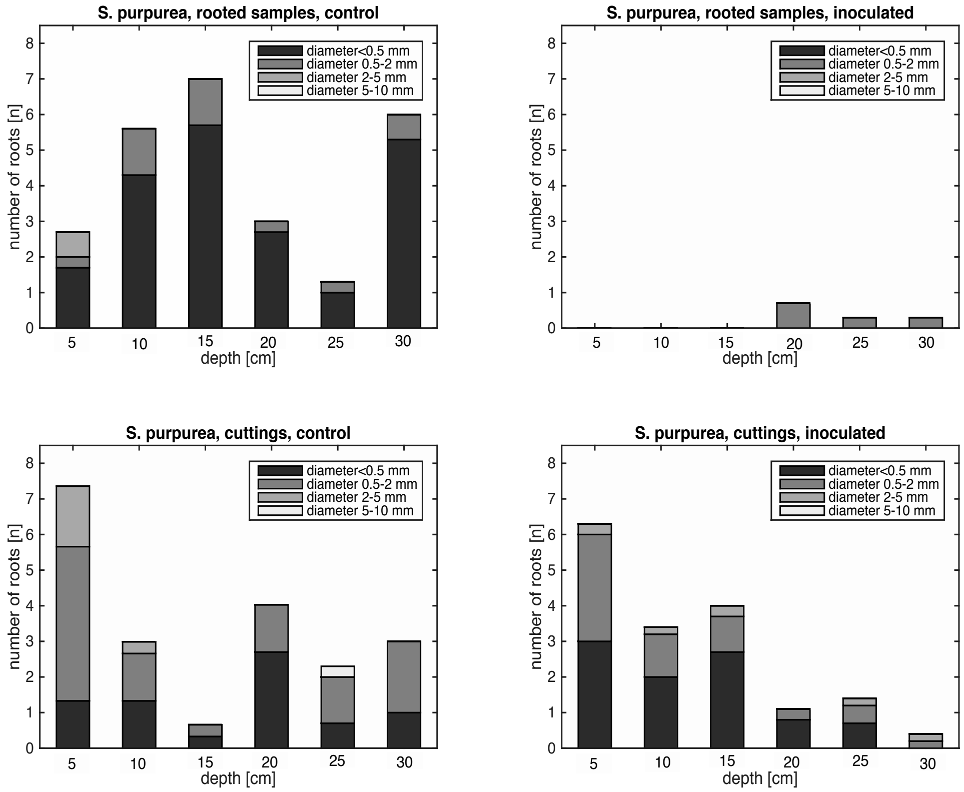


Figure 43: Average number of roots per depth and diameter class for *S. purpurea* rooted samples and cuttings, inoculated and control.

Looking at the cuttings of *S. purpurea*, control and inoculated samples, the overall number of roots generally decreased with increasing depth. For the rooted samples without inoculum the highest number was found in the depth layers 15 cm. However, no clear increase or decrease from the upper to the lowest depth layer was exhibited. In case of the rooted samples with inoculum no roots were present in the layers between 5 and 15 cm of depth and in the layers of 20 to 30 cm just a few roots were found. For the control samples of both planting strategies the most roots with a diameter between 2 and 5 mm were found in the first layer. In case of inoculated cuttings the distribution of diameter classes per depth were rather homogenous.

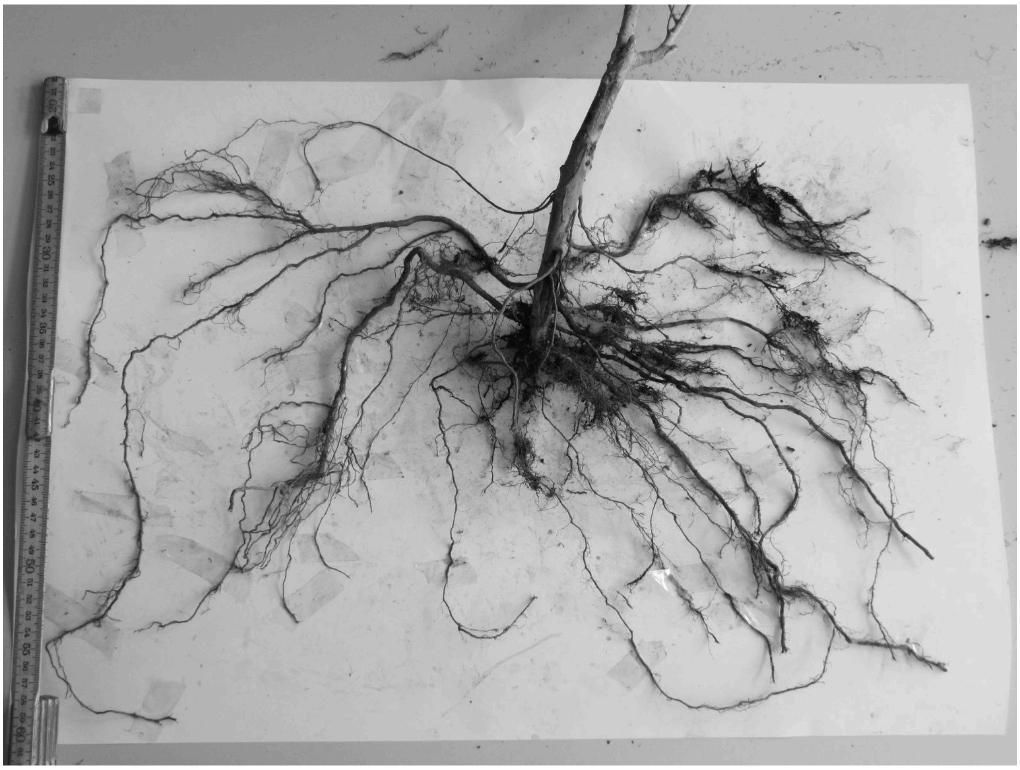


Figure 44: ***Salix purpurea*****, rooted sample excavated in plot 3.**

In order to get an idea on the root system architecture, one *Salix purpurea* plant was uprooted (Figure 44). It is visible that the *S. purpurea* showed an even distributed root system with the longest and thickest roots growing in horizontal direction.

5.1.4 Correlation between above- and below-ground biomass

In order to see if there is a correlation between above- and below-ground biomass a Spearman correlation test was applied. The general analysis was done for the biomass of all plots and afterwards a more detailed one was done considering rooted samples and cuttings separately.

It was found that a significant correlation exists between the number of roots and the diameter of shoots, the number of roots and the diameter of roots and the height and the diameter of shoots. According to these results, plants with a big shoot diameter were also higher as well as bigger and higher plants also had more roots compared to lower and smaller plants. The correlation between the height of the shoots and the number of roots was even more significant (Spearman value = 0.60, p-value = 6.14e-04) than the correlation between the diameter of shoot and the number of roots (Spearman value = 0.52, p-value = 5.71e-03). For the correlation between the height and the diameter of the shoots the highest Spearman-value of 0.78 (p-value = 1.53e-06) was found. No correlation was found between the other biomass parameters.

Linear regression: all plants (log(height of shoots)_log(number of roots+0.1))

```
Estimated Coefficients:

              Estimate     SE       tStat      pValue

              ________   ________   ______   __________

(Intercept)    1.6187    0.059105   27.387   3.1032e-21

x1            0.28368    0.056601    5.012   2.9492e-05


Number of observations: 29, Error degrees of freedom: 27

Root Mean Squared Error: 0.261

R-squared: 0.482, Adjusted R-Squared 0.463

F-statistic vs. constant model: 25.1, p-value = 2.95e-05
```

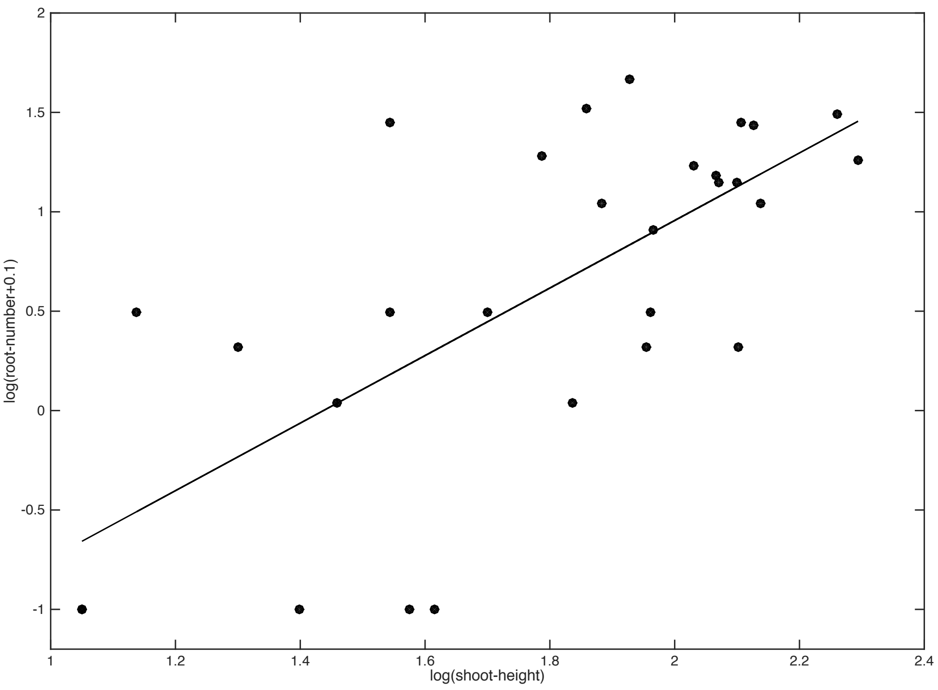


Figure 45: Linear regression model (shoot height and number of roots of all investigated *Salix* plants)

Linear regression: all plants (log(diameter shoot)_log(number roots+0.1))

```
Estimated Coefficients:

                Estimate      SE       tStat      pValue

                _________   _________   ________   ___________

(Intercept)    -0.18505    0.063758    -2.9024     0.0076233

x1             0.24923     0.06087     4.0945     0.00038854


Number of observations: 27, Error degrees of freedom: 25

Root Mean Squared Error: 0.242

R-squared: 0.401, Adjusted R-Squared 0.377

F-statistic vs. constant model: 16.8, p-value = 0.000389
```

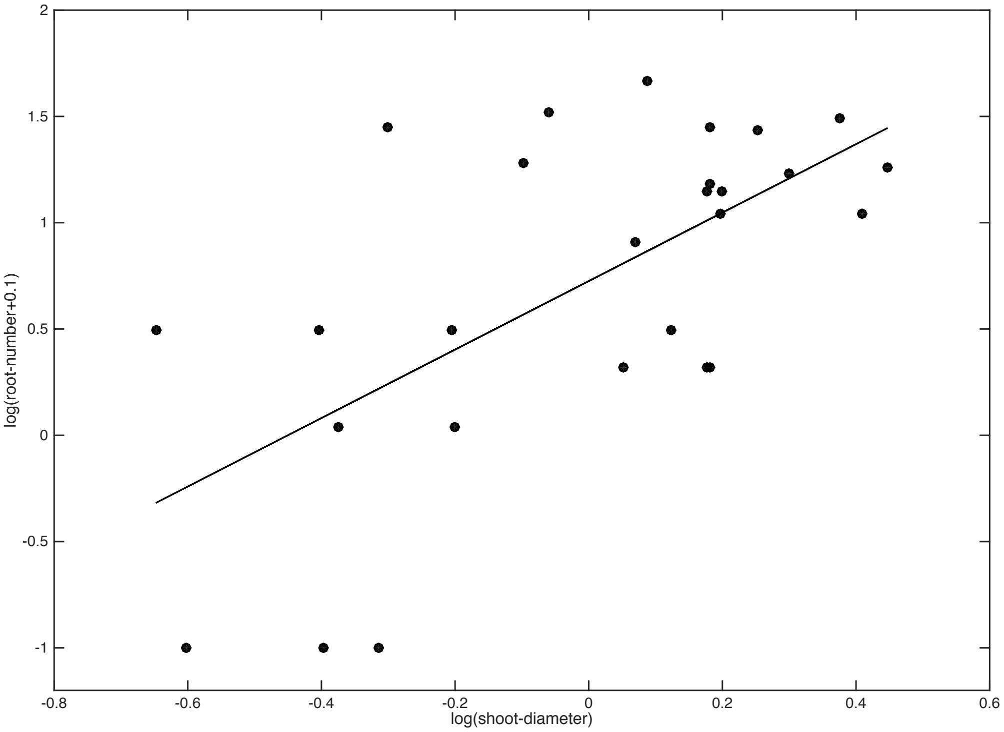


Figure 46: Linear regression model (shoot diameter and number of roots of all investigated *Salix* plants)

Considering the planting strategies (cuttings and rooted samples) separately revealed similar results to the general investigation presented before. The analysis revealed that cuttings, 3 and 5 years old, had more roots if they were taller as well as if they had a bigger diameter. The correlation between the height of the shoots and the number of roots (Spearman-rho-value = 0.76, p-value = 4e-04) were even more significant than the correlation between the diameter of shoots and the number of roots (Spearman-rho-value = 0.70, p-value = 3.9e-03). Similar to the previous analysis also in this case a correlation between the height and the diameter of shoot was present (Spearman-rho-value = 0.72, p-value = 3.3e-03).

Linear regression: Cuttings (log(height of shoots)_log(number of roots+0.1))

```
Estimated Coefficients:

                Estimate      SE        tStat       pValue

                ________    ________    ______    __________

(Intercept)     1.5748     0.069751    22.577    5.4123e-13

x1             0.35604     0.073043    4.8744     0.0002022


Number of observations: 17, Error degrees of freedom: 15

Root Mean Squared Error: 0.262

R-squared: 0.613, Adjusted R-Squared 0.587

F-statistic vs. constant model: 23.8, p-value = 0.000202
```

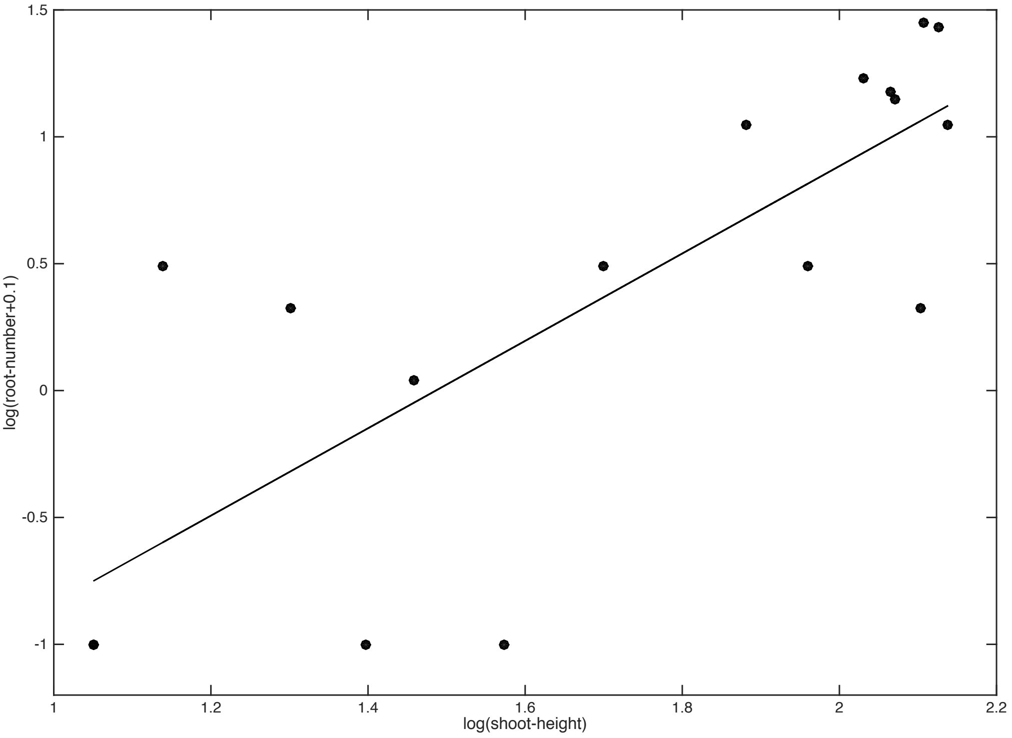


Figure 47: Linear regression model (shoot height and number of roots for cuttings)

Linear regression: Cuttings (log(diameter shoot)_log(number roots+0.1))

```
Estimated Coefficients:

                 Estimate     SE       tStat      pValue

                 ________   _______   _______   __________

(Intercept)    -0.19523    0.07684    -2.5408     0.024619

x1             0.33381    0.08099     4.1216    0.0012035


Number of observations: 15, Error degrees of freedom: 13

Root Mean Squared Error: 0.236

R-squared: 0.566, Adjusted R-Squared 0.533

F-statistic vs. constant model: 17, p-value = 0.0012
```

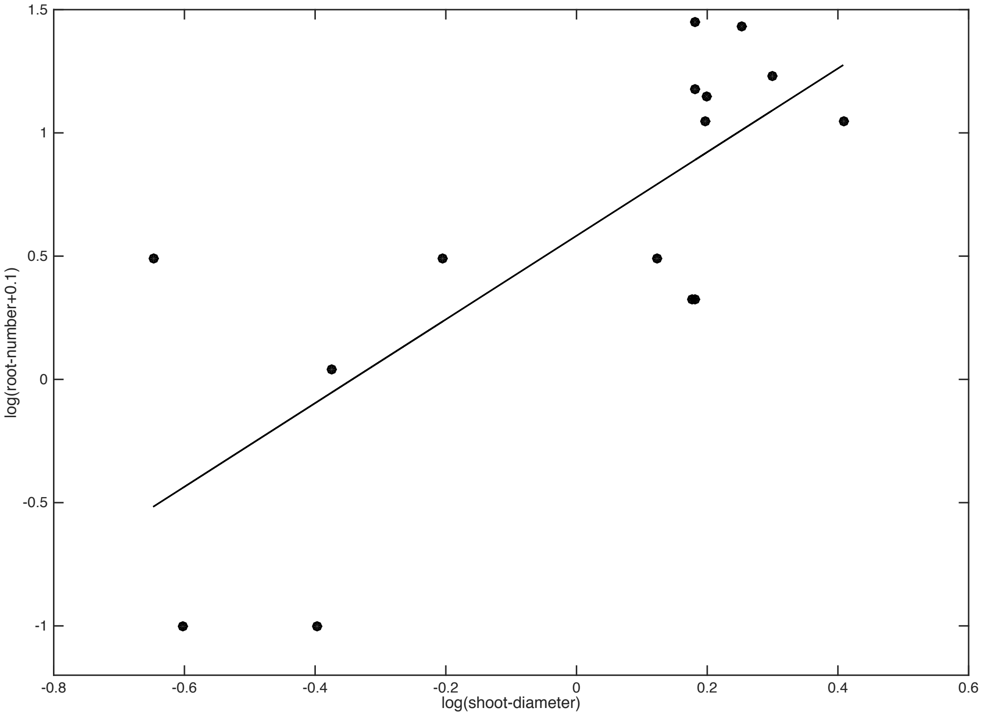


Figure 48: Linear regression model (shoot diameter and number of roots for cuttings)

Compared to the cuttings, for the rooted samples the Spearman values revealed generally a lower correlation between the above- and below-ground biomass. However, a very significant correlation (Spearman-rho-value = 0.96, p-value = 2.15e-08) was found for the parameters of the above-ground biomass, thus plants with a bigger shoot diameter were also taller.

A linear regression model was applied to see if it is possible to predict the below-ground biomass from the above-ground biomass. In order to meet the assumptions of a linear model (see the analysis of residual in Appendix 3), the values of the number of roots were transformed with log10 (number of roots + 0.1) and the height and diameter of shoot with log10 (diameter of shoot, height of shoot). With the transformed values a linear regression was implemented. The distribution of the residuals was verified by using the Tukey-Anscombe plot, the normal QQ-plot and the leverage histogram.

The results showed that there is a quit strong correlation between the above- and below-ground biomass in case when cuttings are considered (see chapter 0 and 0). This is not the case for the rooted samples (number of roots_shoot height: p-value= 0.19, R^2 = 0.16, number of roots_shoot diameter: p-value= 0.1, R^2 = 0.25). However, both planting strategies show a significant correlation between the mean height of the shoots and the diameter of the shoots.

5.2 Soil aggregate stability

In order to get representative results, the soil core samples that were longer or shorter than 10 cm or very loose before performing the test, were not included in the evaluation. Further, the samples of plot 1 were not taken into account, since most plants in this plot were not vital at the time the tests were performed and just a few *Salix* roots were found.

5.2.1 Development of the stability over time

In order to see whether the stability increased over time the values of the test were separated for the 3- and 5-year-old generation.

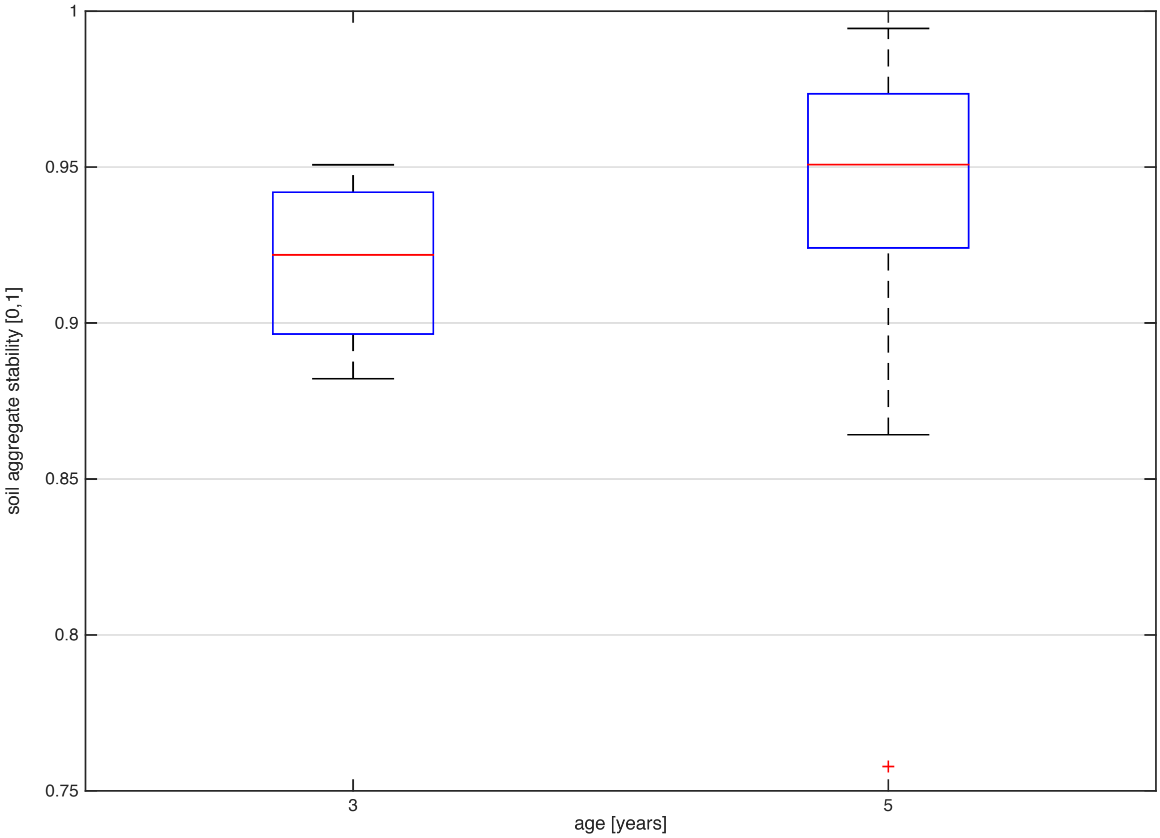


Figure 49: Boxplots showing the stability depending on plant age without plot 1, loose and shorter or longer than 10 cm samples (Expl. Figure 34).

Figure 49 shows that the soil aggregate stability increased just slightly (3 %) from a median value of 0.92 for the 3-year-old generation to a median value of 0.95 for the 5-year-old generation. According to the Wilcoxon rank sum test no significant difference (p-value = 0.19) for the two generations was revealed.

5.2.2 Stability in the plots

Roots and stones affect the soil aggregate stability. In order to see the effect of the vegetation cover, the soil aggregate stability of the plots was related to the vegetation cover of the plots. Further, the correlation between the roots and stones in the soil core samples and the soil aggregate stability was determined.

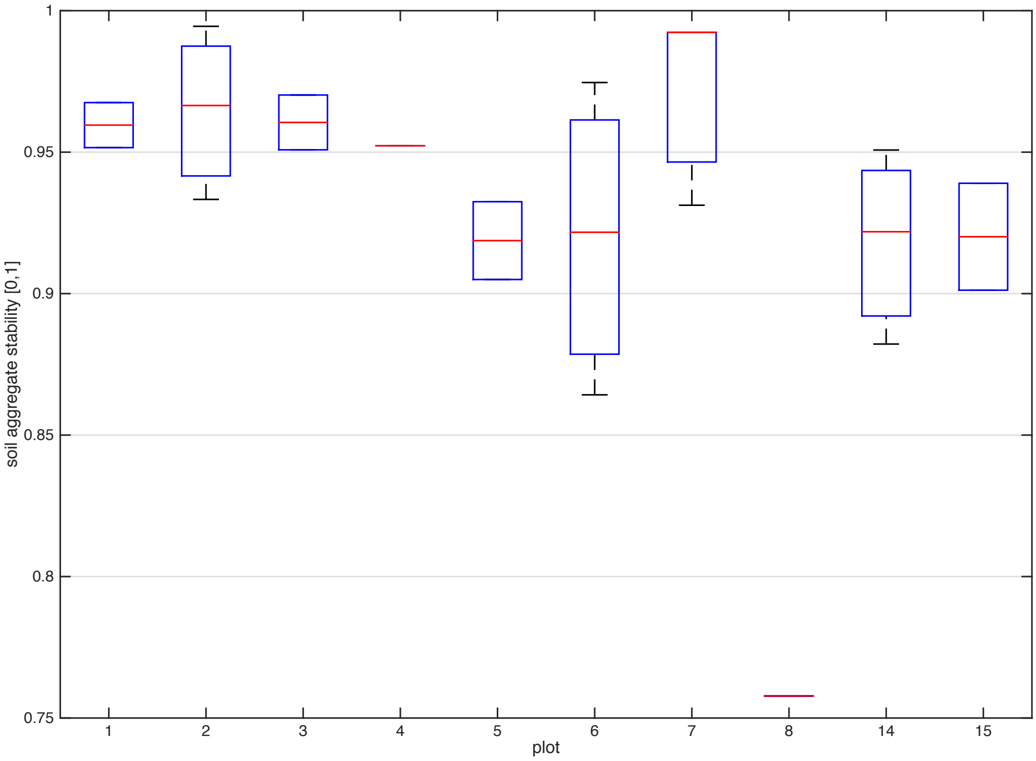


Figure 50: Boxplots showing the soil aggregate stability in the different plots without the values of the broken or totally loose samples (Expl. Figure 34).

Figure 50 illustrates, that the highest soil aggregate stability was found for plot 7 with a median value of 0.97, whereas the lowest value was given for plot 8 with a median value of 0.76.

Plot 5 and 6 have exactly the same parameters (age, specie, planting strategy and inoculation) but the values for the aggregate stability differ. The median values looked quite similar but for plot 6 the variety was the biggest of all plots and plot 5 showed one of the smallest range of values.

The most dense vegetation cover was found in plot 2, 5 and 6 and the lowest vegetation cover with a lot of stones was found in plot 1, 8, 14 and 15. In case of plot 8 this supports the low values of soil aggregate stability and within plot 14 the stability was also among the lowest. The very dense vegetation cover in plot 2 could be related to high stability values but for plot 5 and 6, which also had dense vegetation cover this was not the case.

5.2.3 Correlation between the stability and the weight of stones > 20mm, the weight of the roots and the length of the roots per soil volume of the soil core samples

The values of the Spearman correlation revealed that the correlation was rather low between the stability and the weight of the stones > 20mm (Spearman-rho-value = -0.37, p-value = 0.2), the weight of the roots (Spearman-rho-value = 0.29, p-value = 0.2) and the length of the roots per soil volume of the soil core samples for the aggregate stability test (Spearman-rho-value = -0.014, p-value = 0.957). Only between the parameters weight of the roots and length of the roots a significant correlation was revealed (Spearman-rho-value = 0.92, p-value < 0.001).

5.3 Mycorrhizal fungi (AMF and EMF)

5.3.1 Mycorrhization (AMF and EMF) development over time

Besides other factors, it is mentioned in literature that the composition of mycorrhizal fungi on roots depends also on the age of the roots (Chilvers, et al. 1987; Last et al. 1983). Therefore, the mycorrhizal degree of AMF and EMF on roots was determined for the roots of the 3- and 5-year-old *Salix* plants. In case of EMF it was possible to distinguish between *Cenococcum geophilum* L. and other kind of mycorrhizal fungi (species unknown).

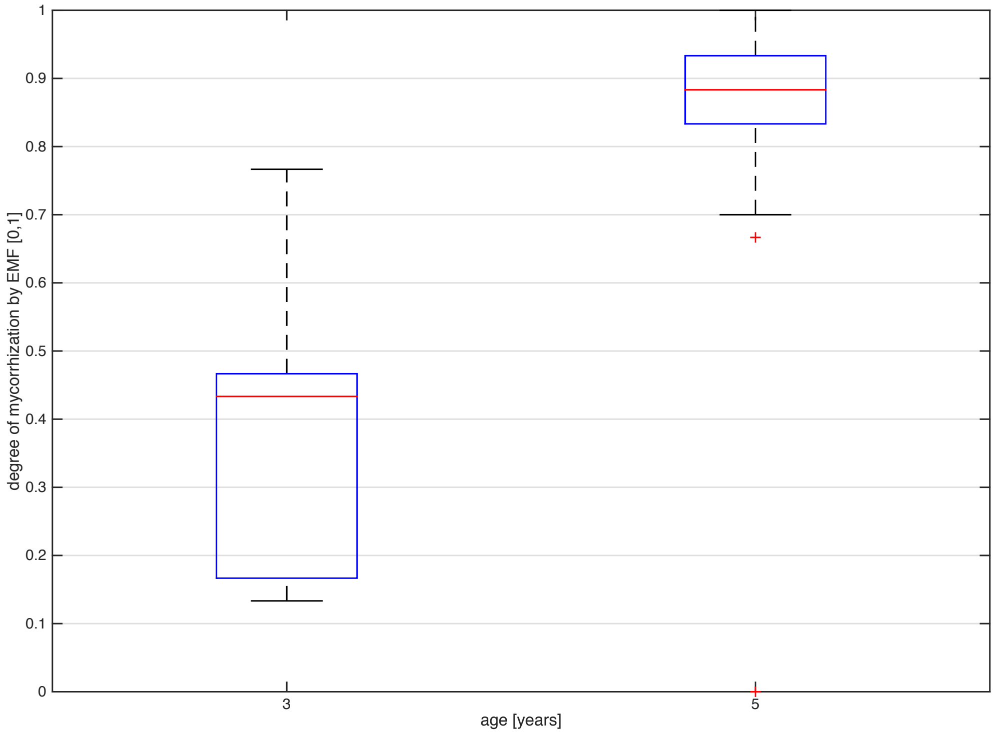


Figure 51: Boxplots showing the degree of mycorrhization by EMF (*Cenococcum geophilum* L. and other kind of EMF), differences between the generation of the year 2009 and the year 2011 (Expl. Figure 34).

Considering the age of the plants separately revealed a significant increase of the degree of mycorrhization (*Cenococcum geophilum* L. and other species of EMF) over time (p-value = 0.0011). For the 5-year-old generation a median value of 88 % was present and for the 3-year-old generation a median value of 43 %, visible in Figure 51.

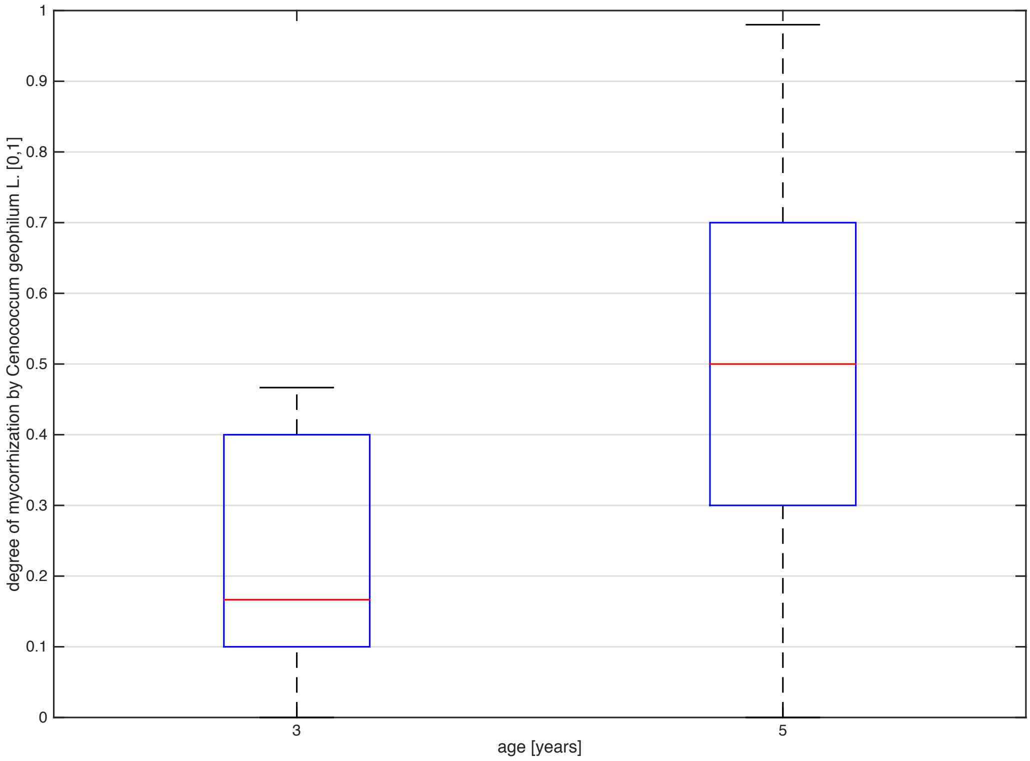


Figure 52: Boxplots showing the degree of mycorrhization by EMF (*Cenococcum geophilum* L.), differences between the generation of the year 2009 and the year 2011 (Expl. Figure 34).

As well as the total degree of EMF, the degree of *Cenococcum geophilum* L. significantly increased between the 3- and 5-year-old plants (p-value = 0.042). It is notable that compared to the total EMF the values for the 5-year-old plants varied over a wide range, from 0 to almost 1 (Figure 52).

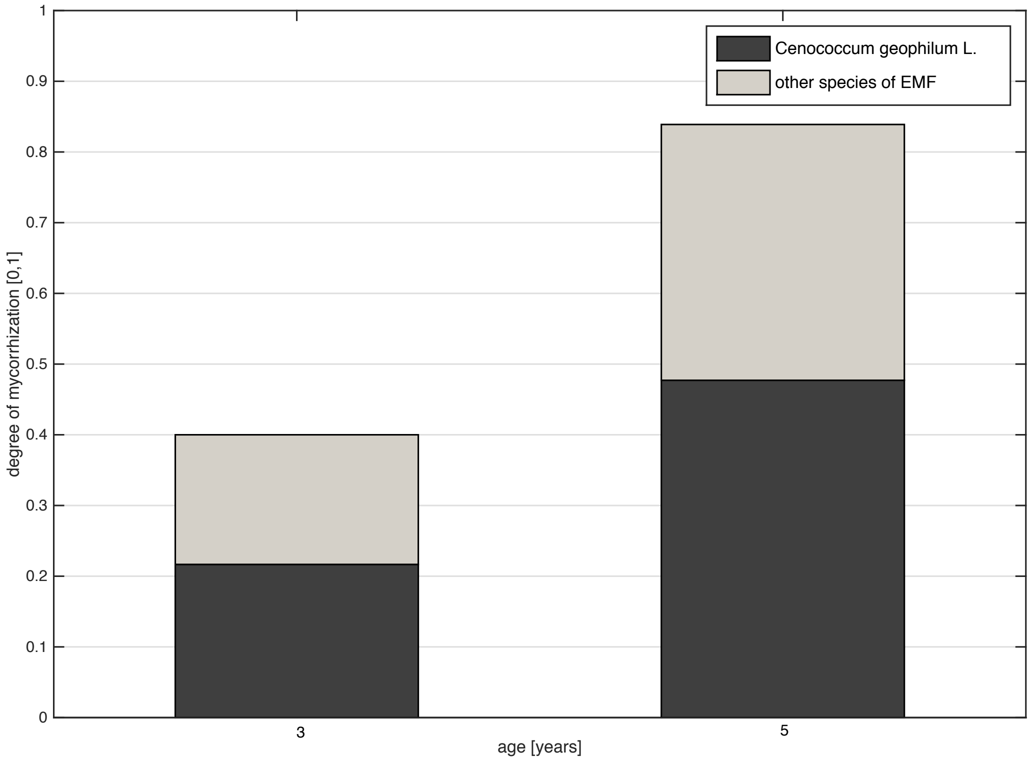


Figure 53: Average degree of mycorrhization by *Cenococcum geophilum* L. and other species of EMF for the 3- and the 5-year-old generation.

Besides the degree of *Cenococcum geophilum* L., also the degree of mycorrhization by other species of EMF increased over time. However, according to the Wilcoxon rank sum test no significant increase in case of other species of EMF was revealed (p-value = 0.11).

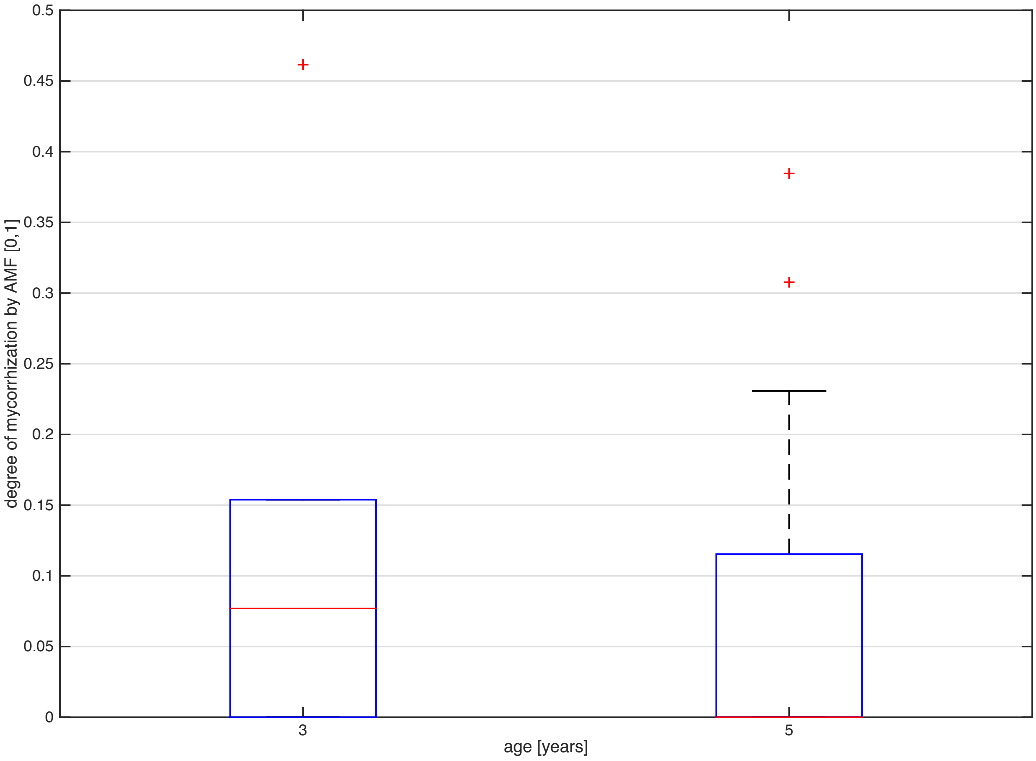


Figure 54: Boxplots showing the degree of mycorrhization by AMF, differences between the generation of the year 2009 and 2011 (Expl. Figure 34).

Contrary to the results of the analysis of the degree of EMF on roots, the mycorrhizal degree of AMF on roots was lower for the 5-year-old generation compared to the 3-year-old generation. However, the Wilcoxon rank sum test revealed no significant difference (p-value = 0.59). The variability within the values of the 5-year-old generation is however much higher than for the 3-year-old generation. The yielded median values were 0.08 for the 3-year-old generation compared to a median value of 0 for the 5-year-old generation (Figure 54).

5.3.2 Combined effect of planting strategy and inoculum on mycorrhization degree of AMF and EMF on *Salix* roots

Previously the effect of time on the composition of mycorrhizal fungi was tests. Besides the time, other factors can have an effect on the degree of mycorrhizal fungi. Therefore the combined effect of planting strategy and inoculation on the degree of mycorrhization of AMF and EMF on roots of *S. daphnoides* and *S. purpurea* was tested. In this case just the generation of the year 2009 was considered.

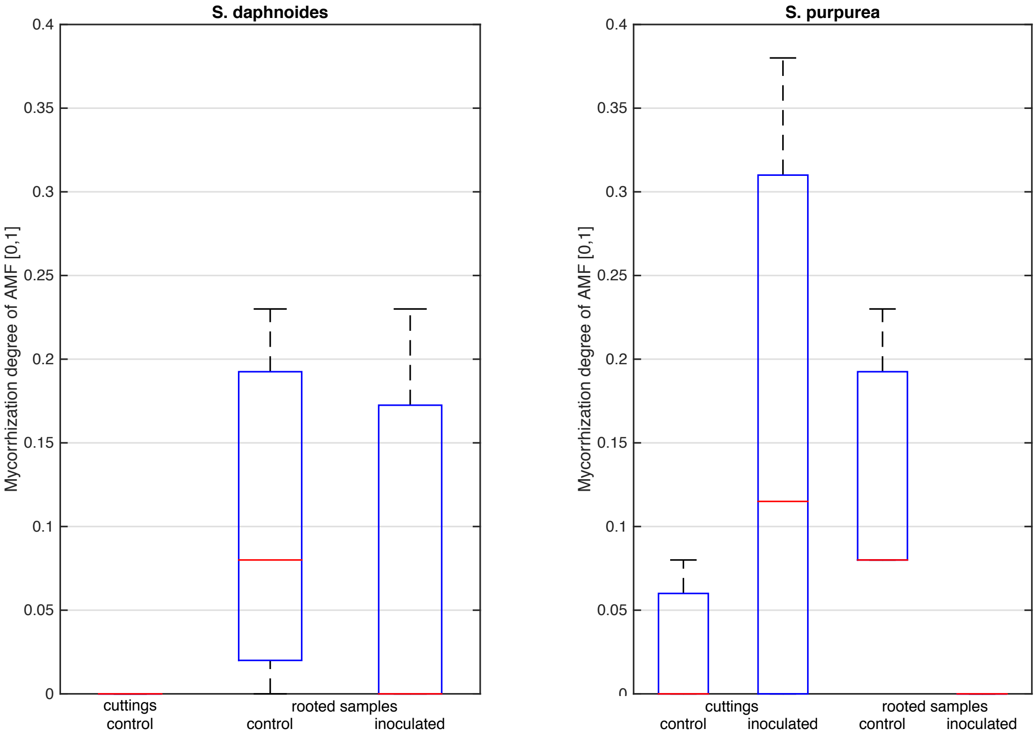


Figure 55: Boxplots showing the mycorrhization degree of AMF; Differences between *S. daphnoides* and *S. purpurea* considering planting strategy and inoculation. (Just the 5-year-old generation is considered, since in the year 2011 only *S. daphnoides* have been planted.) (Expl. Figure 34)

Figure 55 illustrates, the mycorrhization degree of AMF on rooted samples of both species was higher, but without significance (p-value = 1 and 0.1) when no inoculum was applied. The cutting samples of *S. purpurea* were beneficially affected by inoculum, but also in this case the effect was not significant (p-value = 0.38). Comparing the effect of species on the planting strategy showed that the median values of the rooted samples were exactly the same, independent of the specie. This was also the case for the cuttings without inoculation. In this case it should to be noted that the values of the cuttings (control) of *S. daphnoides* and the rooted samples (inoculated) of *S. purpurea* were three times zero. Considering the effect of the plantings strategies in the species, it was revealed that for *S. daphnoides*, rooted samples without inoculum reached a higher, but not significant different degree compared to the cuttings without inoculum (p-value = 0.4). *Salix purpurea* performed best as inoculated cuttings. However, also in this case the differences were not significant (p-value = 0.38).

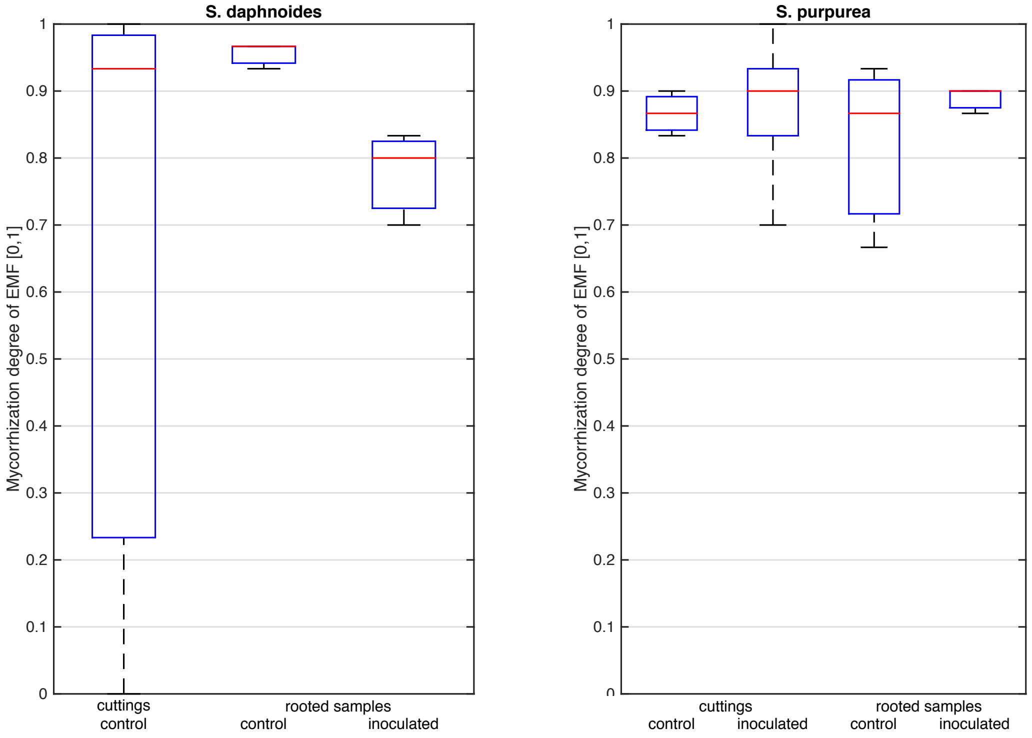


Figure 56: Boxplots showing the mycorrhization degree of EMF; Differences between *S. daphnoides* and *S. purpurea* considering planting strategy and inoculation. (Just the 5-year-old generation is considered, since in the year 2011 only *S. daphnoides* have been planted.) (Expl. Figure 34)

As it is visible in figure 56, the mycorrhizal degree on rooted samples of *S. daphnoides* was beneficially but not significantly affected if no inoculum was initially applied (p-value = 0.1). Contrary, cuttings and rooted samples of *S. purpurea* got slightly but not significantly higher median values when inoculum was applied (p-value = 0.74 and 0.9). The analysis of the effect of species on the planting strategy revealed that rooted samples (control) of *S. daphnoides* performed better compared to *S. purpurea*. The opposite is the case for rooted samples, which are inoculated. However, for both cases no significant differences were revealed (p-value = 0.2 and 0.1). The cuttings (control) of *S. daphnoides* performed slightly but not significantly better compared to *S. purpurea* (p-value = 0.7). It is notable, that the values of cuttings (control) of *S. daphnoides* varied over the range from 0 to 1. Opposed to that, the other boxplots showed a much lower variability.

5.4 Field saturated soil hydraulic conductivity

In order to get an overview of the variety of the values measured at Hexenrübi, they are graphically represented for each plot (Figure 57).

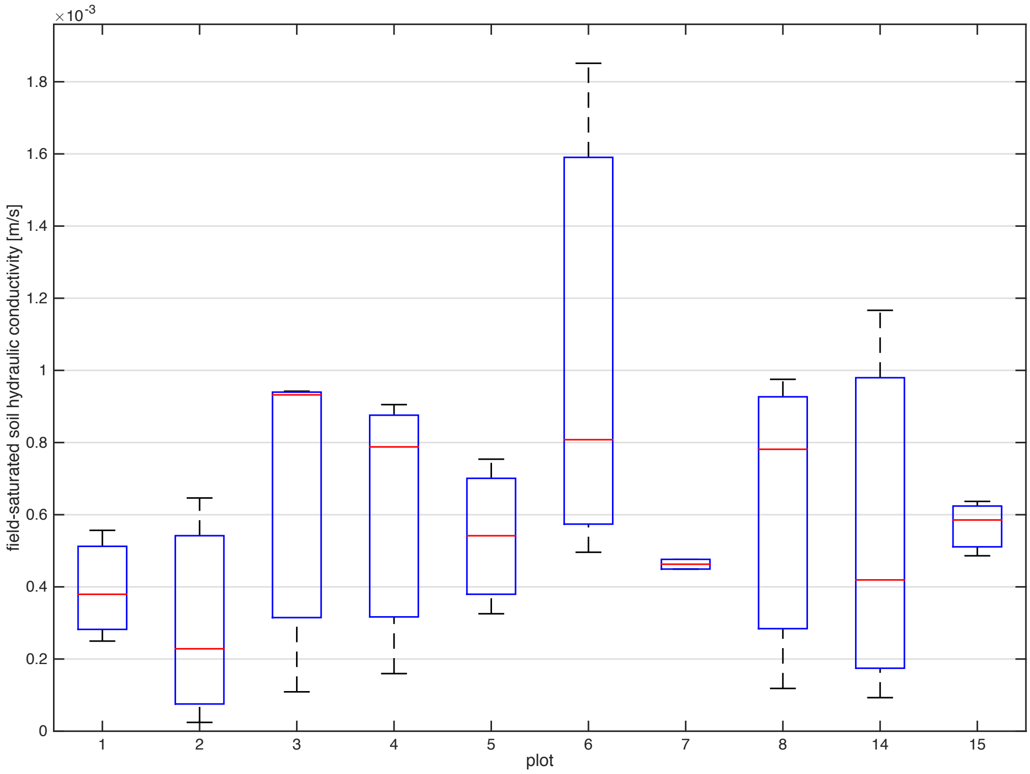


Figure 57: Field-saturated soil hydraulic conductivity in the different plots (Expl. Figure 34).

As it is visible in figure 57, the values of the hydraulic conductivity varied considerably among the different plots and varied even more within the individual plots. The lowest value (2.4e-05 m/s) was measured in plot 2 and the highest value (1.9e-03 m/s) in plot 6. This means a coefficient of variability of 60 %. The highest median value was yielded in plot 3 with 9.0e-04 m/s and the lowest value was found for plot 2 with a median of 2.3e-04 m/s. The raw values of soil hydraulic conductivity for each plot and test are listed in Appendix 7.

The most dense vegetation cover was found in plot 2, 5 and 6 and the lowest vegetation cover with a lot of stones was found in plot 1, 8, 14 and 15. However, this pattern was not reflected for the values of field saturated hydraulic conductivity. It is rather interesting that the lowest values are found in plot 2, which is one of the densest vegetated plots.

In the scope of the present thesis it was tested if the soil hydraulic conductivity was affected by species, planting strategies and kind of inoculation. However, according to the Wilcoxon rank sum test no significant differences were revealed (Appendix 2). Moreover, the boxplots exhibited that a few outliers exist in every graph (Appendix 2).

6. Discussion

6.1 Error control

In this paragraph the measurement errors are described and some propositions to improve further research are made.

6.1.1 Above- and below-ground biomass

It was surprising that the number of *Salix* roots was quit low in some of the excavated trenches. In plot 1 and 3, both located on the left side of the investigation area, and in 14 and 15, from the year 2011, the number of *Salix* roots varied between 0 and 3. This is attributable to the fact that in plot 1 almost no *Salix* plant was vital and in plot 3 the plants were very small and the soil was very coarse-grained. The latter was true also for plots 14 and 15 and in 2 cases big stones were in front of the *Salix* plant. It may be possible that, therefore, the roots of the plants grew particularly upwards and not in the direction of the trench. Furthermore, the *Salix* plants in plot 14 were not vital or very small.

Additionally, also some of the other plots showed a low number of roots. Possible explanations for this are:

1. The location of the trenches: They were located in the middle of four *Salix* plants to guarantee that upward as well as downward growing roots are considered. Due to the fact that some plants are rather small the distance between trenches and individual willow plants might have been too large.
2. The vitality of the “trench-plants”. Some of the plants building the square of the trench have been dead. In some plots it was not possible to find four vital plants building a square, therefore this compromise had to be made.
3. Cuttings had fewer roots than rooted samples. Trenches, excavated in plots with cuttings or plants of the year 2011, revealed a lower number of roots. Uprooting of some plants showed that particularly the cuttings had just one or two bigger roots.

All these are explanations why in the trenches no roots or just a small number of roots with small diameter have been found.

A possible solution to this problem is given in chapter 6.7.

However, from the soil reinforcement point of view the trench location was the best option. In this case it is better to have an idea of how the roots perform at the edge of root expansion. Like this it is possible to make assumptions about the stabilizing effect of roots at “weak “ points (between the rows of plants) on the slope.

When evaluating the performance of the biomass some of the statistical analysis could have been distorted. This was on the one side due to the low number of observations, especially in plot 1. On the other side just two plots were of the year 2011 and for inoculated cuttings of *S. daphnoides* no plots from the year 2009 were available.

6.1.2 Soil aggregate stability

Soil cores for the soil aggregate stability tests were taken with the Humax. However, the very stony soil was a big challenge. Several attempts were needed to get the 30 soil core samples, since the test had to be redone frequently when the sample length was less than 10 cm or the Humax was blocked. By reason of the high amount of big stones it might be possible that some soil samples got compacted and changed their natural stage modifying the soil aggregate stability and resulting in non-representative values.

Root analysis of the soil cores yielded over 98 % roots not originated from willows. Therefore, no sound correlation between the soil aggregate stability and the roots of *Salix* plants was possible. The soil core samples were taken as close as possible to *Salix* plants, but this was apparently not enough to ensure the presence of *Salix* roots in the sample. A possible solution to this problem is given in chapter 6.7

6.1.3 Mycorrhizal fungi

Based on the absence of *Salix* roots in the soil core samples the roots for the determination of the degree of mycorrhization were excavated in an additional step. Thus, no correlation between the soil aggregate stability and the degree of mycorrhization of *Salix* roots could be made. In order to guarantee that just *Salix* roots were observed, only roots that could be traced back to the trunk were collected. A particular disadvantage of this method was that by excavating the roots some tips were lost by breaking and a considerable number (up to 90%) were damaged by squeezing making the analysis of EMF degree very difficult and, to a certain extent, not fully comparable. A further problem was the very low number of collected roots in some cases only one root fragment was available. This was especially the case for cuttings and plants of the year 2011. Therefore, particularly with regard to the quantification of the endomycorrhizal fungi only small quantities of material were available. Additionally, some roots were too thick, and the chosen clearing time too short. Thus, it was difficult or even impossible to see the AMF structures in these roots. In case of thinner roots the clearing time was sufficient but it was still difficult to find arbuscules, the indicators for AMF. The presence of arbuscules probably would have been higher, if more young roots were taken into consideration or the sampling was done during the active phase of root-growth (spring/summer). The absence of arbuscules was explicable with the fact that arbuscules are mainly present in the juvenile phase of the roots (Last et al. 1983). Further, they are ephemeral structures and thereby only present for up to a few weeks (Brundrett and Kendrick 1990).

6.1.4 Field-saturated soil hydraulic conductivity

Determining the field saturated soil hydraulic conductivity was the most difficult part. It was very difficult to find places where the test could be implemented basically due to surface irregularities, very stony surface and dense vegetation cover. Hammering the cylinder into the soil occasionally created holes, since big stones in the subsurface were pushed downwards and thereby changed the structure of the soil matrix. Another place for the test was chosen, when the water ran off too fast because of big holes.

It might be possible that the activities of the fieldwork modified the soil conditions and thereby the values of the soil hydraulic conductivity. These activities include on the one side walking all over the place in order to find spots for the location of the trenches and the performance of the tests and on the other side preparing the soil surface for the soil hydraulic conductivity test with a shovel.

6.1.5 Further noise factors

Apart of the difficulties performing the tests, there were other factors affecting the results of the investigation.

As there is other vegetation than willows in Hexenrübi, it is difficult to attribute the determined values just to the *Salix* plants. This is particularly the case for results of the soil aggregate stability test and the permeability test, which could not be directly correlated with *Salix* roots. However, when performing field tests the presence of other vegetation is unavoidable and needs to be taken into account.

As for a lot of other research projects the “space-for-time” substitution was chosen due to the fact that the initial conditions in Hexenrübi are homogenous to a certain extent. This technique assumes that spatial and temporal variations are equivalent (Pickett 1989) and it implies that within an investigation area series of different-aged samples are present. Hence, long-term investigation can be omitted and the effect of time can be investigated at the same time.

Finally, some aspects like the exposition and the surrounding environment of the plots differ to some extent, even if they are in the same slope. Thus the external influences, as for example insolation, differ among the plots. Furthermore, the run-off among the plots differs due to the fact that above the upper plots on the right side rather dense vegetation is growing. It is noticeable that the plots located on the left side of the investigation area have smaller *Salix* plants, less grass, and more gravel. One assumption is that the exposition and thereby insolation plays an important role as well as the fact that they are stronger climatically affected than the plots on the right side. In comparing the results of the plots, all this differences and variations have to be taken into consideration.

6.2 Above- and below-ground biomass

The analysis of the performance of the above- and below-ground biomass dependent on species, planting strategy and artificial inoculation has been done in order to evaluate which species, in combination with which planting strategy and eventually artificial inoculation is the most efficient for slope stabilization. The results revealed that the artificial inoculum had no effect on the performance of both the above- and below-ground biomass. Furthermore, no significant effect of the species on the different planting strategies was found. However, the performance of *S. purpurea* was significantly affected by the choice of the planting strategy in one case: inoculated cuttings performed significantly better for the above-ground biomass and the diameter of roots than the inoculated rooted samples.

It is important to mention that, with respect to the effect of mycorrhizal fungi, it was just possible to distinguish between initially inoculated samples (INOQ Forst) and control samples. It was found that all the roots were mycorrhized by AMF and EMF, but it was not possible to make a statement whether the samples were inoculated by artificial or natural inoculum.

It can only be assumed why artificial inoculum did not beneficially affect the performance of the biomass in our study case. A possible explanation might be that the inoculation by the artificial one never took place and instead natural inoculum occurred. Another possible explanation is that the natural inoculum replaced the artificial one after a few weeks or months, due to the fact that the artificial one was not as sufficient as the natural one for the *Salix* plants. The precise listing of all the species of mycorrhizal fungi can be found at Appendix 5. Surprisingly, all the roots were mycorrhized with *Cenococcum geophilum* L., which was not applied with the artificial inoculum. Thus, the presence of *Cenococcum geophilum* L. might be an indicator that natural inoculation has taken place. Therefore, based on our results, it would be advisable to add *Cenococcum geophilum* L. to artificial inoculum used for *Salix* plants.

The results of the present thesis, considering the effect of the artificial inoculum, were rather contradictory to the findings of other research projects. The study of Beglinger (2011) revealed that the root system performed better when the roots were inoculated with AMF compared to non-mycorrhized samples. Moreover, in the study of Bader (2014) the above-ground biomass was affected beneficially by mycorrhization, which supported the findings of Kipfer et al (2012), who found higher above-ground biomass when EMF was applied.

Considering the planting strategies, inoculated cuttings of *S. purpurea* performed significantly better than the inoculated rooted samples regarding the above-ground biomass. According to the fact that this is just the case for inoculated *S. purpurea* the results need to be confirmed by other studies. Yet, these findings are contradictory to some other studies. Alam et al. (2014) showed that the performance of cuttings of purslane (*Portulaca oleracea* L.) was significantly lower compared to rooted samples for the above-ground biomass of the plants. Further, Ky-Dembele et al. (2010) found bigger shoot diameter for seedlings compared to cuttings. A possible explanation for these results is that cuttings perform worse due to the procedure of cutting of the plant and the transportation shock (Kathiravan, et al. 2009). The analysis of the root development in this study revealed that cuttings (inoculated) of *S. purpurea* have more roots in the deeper layers (15-30 cm) than rooted samples (inoculated). Conversely, Sasse and Sands (1997) found that cuttings of eucalyptus produce fewer primary roots, often without tap roots and a shallower root system.

The difference in the performance of rooted samples and cutting can often be explained by the fact, that the planting strategies in most cases have a different genetic background. This is confirmed by the study of Gaspar et al. (2005), who found no difference between rooted and cutting samples for eucalyptus plants of the same genetic background. Additionally, it was reported that growth in cuttings of radiate pine was similar to that of seedlings when cuttings were taken from juvenile trees, which were less than 10 years old (Talbert et al. 1993). Another explanation for the differences between the planting strategies, especially in the beginning of the growth, is the poor plant quality of the cuttings. The quality is a critical factor, at least in the initial stage of the development of the plants. (Gaspar et al. 2005) Moreover, the performance of cuttings after planting is influenced by the maturity of the donor plant, the morphology of the regenerated root system, the vigor of the propagules and the elapsed time (Ky-Dembele et al. 2010).

A possible explanation for the better performance of cuttings concerning above-ground biomass in the present thesis is that they might had a better quality compared to the rooted samples and probably generated energy for the growth of the above-ground biomass out of the trunk during the first years. Furthermore, the nutrient uptake from the trunk and via the mycorrhizal fungi might have been sufficient enough. Orfanoudakis et al. (2010) found that plants put more energy in the growth of the above-ground biomass when the nutrient uptake by mycorrhizal fungi was satisfactory. Hence, the plant neglected the growth of roots and when the energy of the trunk was consumed they stopped the growth of above-ground biomass and started to put energy in root growth. In case the soil was too dense or otherwise not suitable and beneficial for root growth the cuttings died after they used the energy, available in the trunk, for the growth of the above-ground biomass (Böll and Gerber 1986). Using this information the bad performance of the cuttings in plot 1 can be explained. It was visible that they developed sprouts out of the cuttings, but at the time of the observation most of the plants were dead. This needs to be kept in mind when the performance of *S. daphnoides* cuttings is analyzed. Opposed to cuttings, rooted samples initially need some time to adapt to the soil conditions before they can put energy in the growth of the above-ground biomass (Sage 1999). This might be a reason why the rooted samples lag behind the cuttings regarding the performance of above- and below-ground biomass. However, they might overgrow the cuttings in the next years, since the cuttings have to invest energy in root growth after the energy of the trunk is consumed. Finally, it needs to be kept in mind that the morphological variation in plants is very normal and depends on the variety, soil and environment (Alam et al. 2014).

In this context, it is important to mention that the analysis of the combined effect of planting strategies and inoculation was heavily affected by the dimension of the considered samples (number of data). The graphic analysis of the boxplots revealed in some cases differences that were not confirmed by the Wilcoxon rank sum tests. This deviation might be explained by the fact that the number of data available in some cases was really low Hence, it can be assumed that in some cases no significance was found due to the small amount of data, and further investigations are needed to confirm these results.

No significant evaluation of the above- and below-ground biomass development over time was possible. That was due to the fact that no rooted samples of *S. daphnoides* were planted in the year 2011. Further, no cuttings of *S. daphnoides* with inoculum were planted in the year 2009. Strictly speaking, just a comparison between cuttings of *S. daphnoides* without inoculum of the year 2009 and 2011 could be made. Based on this, no relevant claim was possible.

Additionally to the evaluation of the above- and below-ground biomass, it is very important to consider how the number and diameter of roots were distributed per depth, since this is also crucial for the stabilization of slope. However, it is important to consider that the root distribution was determined only for the first 30 cm of depth. Therefore, no assumptions on the deep-ranging part of the root system can be made.

Salix belongs to the plants with extensive root growth, expressed in wide- and deep-ranging root systems. In case they grow on slope the roots fulfill two different functions; one part stabilizes the plant the other part supports the plant with nutrients (Schiechtl 1973). Analyzing the number and diameter of roots exhibited that just for cuttings of *S. purpurea*, both inoculated and control, a decrease of root number with increasing depth was present within the first 30 cm of depth. Such a smooth decrease is found in most environments (Kummerow 1981) and according to Fitter (1991) it depends on the availability of resources, which is higher in the upper layers of the soil. Compared to other rooted samples, the rooted samples of *S. purpurea* without inoculum had no roots in the depth of 0 to 15 cm. This is really surprising, since all the other rooted samples showed quit a high number in the first 15 cm of depth. According to Schiechtl (1973) the more dense, deep and homogenous the root system the higher the stabilizing effect on the soil. The results of the present thesis exhibited a quit homogenous root distribution in the first 30 cm of depth.

Summing up it can be said that the root distribution is often affected by soil conditions, including dense layers, big stones and high amount of macropores (Nagarajah 1987). Unfortunately, in the scope of the present thesis no information regarding the soil condition were available and thus no general statement for the root distribution can be made.

Another aim of this study was to see whether the performance of the below-ground biomass could be predicted by the performance of the above-ground biomass. Therefore, the correlation was examined. It was revealed that the diameter of the shoot as well as the height of the shoot positively correlated with the number of roots. Further, the diameter and the height of the shoot showed a positive correlation. A more detailed analysis, separately for cuttings and rooted samples, revealed the same pattern for cuttings as for both cuttings and rooted together. However, the rooted samples exhibited just a high correlation between the diameter of the shoot and the height of the shoot. It is important to emphasize that the correlation between the height of the shoots and the number of roots was in all cases more significant than the correlation between the diameter of the shoot and the number of roots. Generally, the diameter of the stem at breast height (dbh) (Le Goff and Ottorini 2001) (Curt and Prévosto 2003) (Andersson, et al. 1998), the crown volume (Wynn 2004) or the sapwood area (Valentine und Mäkelä 2012) are associated with the number of fine roots, because the vertical development of the plant can be strongly influenced by external factors as light availability and weather conditions. In our case apart from the diameter of the shoot also the height of the shoots can be used to predict the number of roots. The correlation for both, diameter of the shoots and height of the shoots with the number of roots was also found by Curt and Prévosto (2003), who investigated the correlation between above- and below-ground biomass for beech plants. According to our results the performance of the above-ground biomass of cuttings can be used to make predictions on the below-ground biomass (number of roots). Surprisingly, this is not the case for rooted samples, where there was just a weak positive correlation between the diameter of shoots and the number of roots. However, a high correlation was found between the height of shoots and the diameter of shoots.

6.3 Soil aggregate stability

The stability did not significantly differ between the plots of the year 2009 and the year 2011. However, the mean values itself (92 % for the 3-year-old plots and 95 % for the 5-year-old plots) were quit high compared to the results of Burri (2006), who found a value of 38 % for the Hexenrübi area in the year 2006 on the bare slope. The strong increase in the stability can be attributed to the application of the biological measures since the values were rather low in the year 2006 and are 2.5 times higher 5 years after the biological measures have been implemented.

A lot of research considering the effect of the performance of vegetation on soil aggregate stability has been done. Burri (2006) investigated the development of stability over time on three different sites: Hexenrübi, where only technical measures were implemented, Schwandrübi, a re-vegetated site planted with *Alnus incana* and *Salix appendiculata* 25 years ago and Hornwald, a 150-year-old forest. The results show an increase in stability with increase in age of the biological measures. In the year 2006 the soil aggregate stability in Hexenrübi was 38% and the vegetation had a coverage degree of only 3%. The results of the present thesis reveal a mean stability value of 93 %, a higher vegetation cover and AMF as well as EMF, present on almost all *Salix* roots. In the year 2006 no biological measures have been implemented yet. Nevertheless, it is important to notice that within 8 years the stability increased from 38 % to 95 %. Schwarz (2006) got median soil aggregate stability values of 23 % for bare soil, 35 % for vegetated soil on 1- to 2-year-old eco-engineering sites and 52 % on 8-year-old eco-engineering sites. The results revealed a high dependency of the soil aggregate stability on the development phase of the vegetation, though the increase within the first two years was rather small. These results support the findings of the present thesis, where no significant difference between the 3-year and 5-year-old plots was found. Beglinger (2011), using the soil from Hexenrübi for pot experiments inoculated with mycorrhizal fungi, also got soil aggregate stability values of 93 %. Contrary to the present research, *S. appendiculata* was used and the plants were grown in the lab over a period of only 3 ½ months.

An explanation for the 2.5 times higher stability values found just after 5 years from revegetation measures, compared to 2.3 times higher values found 8 years (Schwarz 2006) after the biological measures have been implemented are the different soil and vegetation conditions. It might be that in case of Hexenrübi the soil conditions were more beneficial for plant growth and thus the vegetation cover developed faster than on the eco-engineering sites of Schwarz. Furthermore, it is possible that in case of the present thesis the underwood vegetation cover played an important role in the development of the soil aggregate stability. The analysis of the roots with the root scanner revealed that a lot of fine roots (no *Salix* roots) were present in the soil core samples of the soil aggregate stability test. This might be a possible explanation for the higher soil aggregate stability compared to Schwarz (2006). However, no information regarding the underwood vegetation in the study of Schwarz (2006) was given.

Although the effect of *Salix* roots and mycorrhizal fungi on soil aggregate stability could not be disentangled, results of other studies are presented. Research of the last years revealed incompatible results. Bader (2014) and Bast et al. (2014) found higher soil aggregate stability in samples without mycorrhization compared to mycorrhized samples after one vegetation period. Opposed to this, Beglinger (2011) as well as Graf and Frei (2013) found higher soil aggregate stability in samples of *S. appendiculata,* respectively *Alnus incana* mycorrhized with EMF compared to non-mycorrhized samples. However, the study of Frei (2009) on *Alnus incana* revealed no difference in soil aggregate stability between planted samples with and without inoculation.

Besides roots, the presence of micro-and macropores and stones in the soil can affect the soil aggregate stability. In order to see the effect of stones (>20 mm) and roots on the soil aggregate stability they were weighted and additionally the length of the roots per volume was determined. However, just very low correlation between the weight of the stones and the soil aggregate stability and the weight and length per soil volume of the roots and the soil aggregate stability was found. Contradictory to the findings of the present thesis, many studies show correlation between roots and stability. Burri et al. (2009) found higher stability on a re-vegetated site compared to a control site without vegetation. Further, the study of Bader (2014) as well as of Graf and Frei (2013) revealed a significant effect of the root length per soil volume on soil aggregate stability.

Unfortunately the length of the roots per soil volume and the weight of the roots in the soil core sample could not be correlated to the degree of mycorrhization. This is due to the fact that in the soil core samples no *Salix* roots were present and the degree of mycorrhization was determined on additionally excavated *Salix* roots. The study of Graf and Frei (2013) revealed higher root length per soil volume for mycorrhized samples with EMF. Conversely, Bader (2014) found lower root length per soil volume in case of mycorrhized samples containing a combination of EMF and AMF. Further, the weight of the roots did not differ concerning mycorrhizal treatment in case of her investigation.

6.4 Mycorrhizal fungi

Presence of mycorrhizal associations has a positive effect on plant stress tolerance and resource uptake (Smith and Read 1997) and is therefore very important for the re-establishment of vegetation cover in order to stabilize slope. This is especially the case in alpine ecosystems where soil and environmental conditions are rather harsh. Thus, it was the aim of the present thesis to see if the degree of both, AMF and EMF, increased over time.

The mean degree of EMF on *Salix* roots was 75 % for all the plants, which is comparable to the degree of 70-75 % reached after 3 months of growing time in the study of Van der Heijden (2001), investigating on *S. repens.* Almost as high, 64 %, was the degree of natural inoculation for the study area Schwandrübi, determined by the study of Burri et al. (2009). Opposed to this, Beglinger (2011) found a degree of EMF of only 31 % for *S. appendiculata*, grown in the lab. An explanation for the low colonization degree found by Beglinger can be due to the short incubation time, which was only 13-14 weeks.

Plant species that are able to live in symbiosis with both AMF and EMF are among others *Salix* plants, precisely *Salix purpurea* L., *Salix repens* L., *Salix viminalis* L. and *Salix caprea* L. (Harley and Harley 1987). According to the literature *Salix daphnoides* Vill. is not able to be host for AMF (Harley and Harley 1987), but surprisingly in the present thesis also AMF was found. Moreover, the degree of mycorrhization by AMF was almost the same for both species (p-value = 0.78). However, due to the fact that the findings of the present thesis were surprisingly and contradictory to literature (Harley and Harley 1987) further research is needed to confirm the results.

The results of the analysis over time showed no significant change in the degree of AMF over time, whereas the degree of EMF significantly increased. In determining the degree of EMF, it was possible to distinguish between the mycorrhization by *Cenococcum geophilum* L. and other species of EMF. However, in the scope of the present thesis the other species of EMF could not be investigated. It was found that the degree of mycorrhization by *Cenococcum geophilum* L. significantly increased over time, but the other species of EMF present on the roots showed no significant increase. Moreover, the degree of mycorrhization by EMF (both *Cenococcum geophilum* L. and other species of EMF) was much higher on the examined roots compared to the degree of AMF.

Field observation by Lodge (1989) revealed that on *Salix* and *Populus* species a dominance of one or the other mycorrhizal fungi (EMF and AMF) can occur. Similar to the present study, Van der Heijden et al. (1999) found a slight degree of AMF and a high degree of EMF on *Salix* roots. However, in case of Van der Heijden et al. (1999) the analyzed specie was *S. repens*. Chen et al. (2000) found that EMF replaced AMF on eucalyptus plants after several months of growth. One explanation is that the decrease in AMF resulted from the preferential occupation of new roots by EMF after several months due to the fact that the EMF becomes more aggressive in colonizing roots compared to AMF (Chen et al. 2000). Another possible explanation for the increase in EMF over time is that EMF maintain a higher inoculum potential and obtain more energy from the host plant than AMF (Smith and Read 1997). Van der Heijden and Vosatka (1999) found that host plants with potential for dual mycorrhizal colonization prefer EMF, which on the one side need more carbon from the host plant but on the other side are more efficient at nutrient uptake compared to AMF. Based on this, it might be that the older generation of the willow plants was able to provide more carbon compared to the 3-year-old plants and, therefore, was more colonized by EMF. Moreover, it was found that the presence of one fungus can inhibit mycorrhizal formation by another fungus, even if they occur on separate parts of the root system (Pearson et al. 1993). This inhibition by EMF can be the reason why the mycorrhization by AMF in the present thesis did not increase over time. Moreover, the formation of a sheath by EMF might act as a barrier for other mycorrhizal fungi to colonize the roots (Chilvers et al. 1987). The lower degree of EMF on the 3-year-old plants might additionally be explained by the fact that EMF can require several months to become established from spores or that the spore germination was delayed (Chen et al. 2000). However, this explanation does not apply to *Cenococcum geophilum* L., present on all investigated roots. The reason is that it forms no sexual or asexual spores, thus propagation takes place via animals transporting the fungus or by wind and erosion. Chilvers and Gust (1982) found that a strong increase after a slow start could be explained due to secondary infection from existing mycorrhizal roots. Further explanations for the low degree of AMF in our case are that by extracting the roots a lot of fine and young roots were pulled off. Compared to EMF, AMF is faster in initially colonizing roots and is therefore more present on young roots (Chilvers et al. 1987; Last et al. 1983). Thus, the root parts on which AMF mainly colonizes were reduced in number. Moreover, arbuscules, the organs used to determine the degree of AMF, are not permanent. Harley and Harley (1987) mention that arbuscules are active just for 1-15 days. Finally, the composition of mycorrhizal fungi is affected by the nutrient demand of the host plants (Van der Heijden 2001), the seasonal availability of nutrients and stress factors like water scarcity or increasing density (Van der Heijden and Vosatka 1999, Baum et al. 2002, Van der Heijden et al. 2003, Smith et al. 2010). In case of high water availability the AMF declines, whereas the EMF increases (Gehring et al. 2006). Unfortunately, in this thesis no statement about the nutrient content and the water availability can be made.

After giving all these possible explanations, it is important to mention that no information are available if the competition is mediated via plants (through root C supply or other means), by habitat-space limitations within roots or by interactions between hyphae in the soils.

It is further very important to mention that *Cenococcum geophilum* L. was present on all investigated roots, although it was not applied with the artificial inoculum. Thus, it can therefore be an indicator for natural inoculation.

Finally, it needs to be mentioned that the degree of mycorrhization by AMF and EMF was not significantly affected by applications like planting strategy, species and artificial inoculation. This is very important since based on this we know that even without artificial inoculation a sufficient mycorrhizal fungi system was able to develop on the roots of *Salix*.

6.5 Field saturated hydraulic conductivity

The variability of the soil hydraulic conductivity within the plots was very high with a coefficient of variations of 60 %. The occurrence of such high variations was supported by the findings of Johnston et al. (2009), who reported of coefficient of variations of 100 to 400 % for natural and artificial soil. Also in literature the extreme spatial variation of K_{fs} is mentioned and seems to be typical for natural and modified landscapes (Nielsen et al. 1973). Interactions between soil, biota and vegetation influence the development and modification of macropores by which the high variability in soil hydraulic properties, especially soil hydraulic conductivity can be explained (Rienzner and Gandolfi 2014). Interconnected macropores are created by root development, dead roots decomposition and earthworm burrows, and can enhance the soil hydraulic conductivity to a high extent (Chan 2001, Wuest 2001). Aubertin (1971) and Buttle and House (1997) showed that flow through macropores could be up to several hundred times faster than through soil matrix. Archer (2013) found that roots with a diameter > 2 mm increased soil hydraulic conductivity by creating channels for the water to flow preferentially. The results of Archer support the findings of Li and Ghodrati (1994), showing that the soil hydraulic conductivity was six times higher when root channels were present. Moreover, the soil hydraulic conductivity is highly influenced by bio-chemical actions generated by bacteria and fungi (Rillig 2005, Hallett 2007).

The analysis focusing on the effect of the application of different species, planting strategies and inoculation revealed that the field saturated hydraulic conductivity was not significantly affected by the different applications in the plots. The values varied highly even within the plots and no pattern was exhibited. Unfortunately, the hydraulic conductivity could not be linked to the results of the other observations, since it is probable that it is more affected by soil conditions like appearance of micro- and macropores, stoniness and the presence of roots. However, no statements regarding these parameters can me made, since they were not determined. Hence, knowing more about the modification and development of the macropores is essential to explain the high variability in soil hydraulic properties like the soil hydraulic conductivity (Rienzner and Gandolfi 2014) As opposed to the approach of the present thesis, Nimmo et al. (2009) excavated the spot of the sampling after performing the test to see the below surface structure, present macropores and the expansion of the water.

6.6 Synoptic discussion

In the following part the hypotheses are discussed in a general context. A more detailed discussion for each part of the investigation is given in chapter 6.2 to 6.5.

1. *The stabilization effect of vegetation and mycorrhizae on slopes strongly develops over time.*

The analysis of the soil aggregate stability revealed that the stability increased from 38 % for bare soil to 95 %, 5 years after biological measures have been implemented. The increasing stability can therefore be correlated to the development of vegetation. Regarding the development of the stabilization effect of mycorrhizal fungi over time no statement can be made in scope of the present thesis. Studies revealed contradictory results, with increasing soil aggregate stability when mycorrhizal fungi were applied (Beglinger 2011, Graf and Frei 2013) as well as decreasing aggregate stability (Bader 2014). Whereas the former authors used specific fungi cultivated from naturally growing host plants, the latter used the same unspecific commercial inoculum as was used in the Hexenrübi.

2. Abov*e- (shrub height and shrub diameter) and below-ground (roots) biomass is positively correlated.*

Concerning the second hypothesis, the above-ground biomass of *S. daphnoides* and *S. purpurea* cuttings is positively correlated with the number of roots. The correlation between the height of the shoots and the number of roots is even more significant than between the diameter of the shoots and the number of roots. Hence, the performance of the below-ground biomass (number of roots) can be estimated by the performance of the above-ground biomass. However, this is not the case for rooted samples, where a high correlation was only found between the height and the diameter of shoots.

3. *The performance of the plants differs according to the different planting strategies (cuttings and rooted plants).*

Salix purpurea (inoculated) performed significantly better for the above-ground biomass and the diameter of roots in case of cuttings compared to rooted samples. However, no such effect was found for *S. daphnoides*. Due to the fact that cuttings are the best option for *S. purpurea* and no difference was found for *S. daphnoides* it is recommended to use cuttings for the stabilization of slope. Moreover, based on the observations in our study the use of cuttings may be advantageous in so far as that the performance of the below-ground biomass (number of roots) can be estimated by the performance of the above-ground biomass. Thereby, it would be possible to save costs and make predictions regarding the effectiveness of the applied biological measures. However, it is important to keep in mind that this was found just for the inoculated samples of *S. purpurea* and needs to be confirmed by further studies.

4. *The artificial inoculum has a beneficial effect on the development of plants.*

The fourth hypothesis cannot be supported, since no significant effect of artificial inoculum on the performance of the above- and below-ground biomass was found. This is of great importance because based on this the application of unspecific inoculum can be dispensed and costs can be saved. However, the application of specific inoculum including e.g. *Cenococcum geophilum* L. might be beneficial related to the use of *Salix* plants. This recommendation arises from the fact that all the observed plants were naturally mycorrhized by this kind of EMF and the colonization degree even increased over time.

5. *Mycorrhization degree is developing over time*

Regarding the degree of EMF on roots a significant increase for *Cenococcum geophilum* L. was found. However, the degree of EMF (other species than *Cenococcum geophilum* L.) and AMF did not develop over time. Moreover, the degree of AMF was much lower than the degree of EMF (*Cenococcum geophilum* L. and other species of EMF together). This is consistent with the results of other studies where EMF of plants with dual mycorrhizal colonization is more present on roots after several months (Van der Heijden and Vosatka 1999, Chen et al. 2000).

6. *Soil aggregate stability increase over time.*

This hypothesis can only partly be supported. Soil aggregate stability did not significantly increase between the plots with 3- and 5-year-old *Salix* plants. However, a significant increase from 38 % to 95 % was found between the year 2006, when Burri (2006) measured at the time, when no biological measures were present and the year 2014, 5 years after biological measures have been implemented. The increase was 250 % from bare soil to re-vegetated soil, and can be associated with the development of the applied vegetation.

7. *The soil hydraulic conductivity is affected by different boundary conditions like different species, planting strategies and inoculation.*

The soil hydraulic conductivity did not vary significantly dependent on species, planting strategies and kind of inoculation. It seems likely that it is more affected by other conditions, including appearance of micro- and macropores due to interactions between soil, biota and vegetation and the density of the soil (Rienzner and Gandolfi 2014). Unfortunately, in this thesis no investigations regarding these parameters have been made.

6.7 Outlook perspectives

In the scope of the present thesis some difficulties have been identified regarding the test performance and the comparability of data. Hence, some recommendations are given in this chapter.

Considering the test performance, it would be beneficial to change the order to guarantee that the results are based on natural conditions. It is therefore recommended, that tests like the soil aggregate stability test and the soil hydraulic conductivity test, based on soil structure, are performed at first. Further, the experimental set-up in the plot should be from bottom to top in order to avoid compressing the soil by walking all over. The trenches, which are not dependent on undisturbed soil conditions, will be excavated afterwards.

Moreover, in case of the soil aggregate stability it is recommended to take the soil core samples at three points around each single *Salix* plant, even if this would require a huge effort in term of time spent for the field activity. Hence, the amount of *Salix* roots in the soil samples would probably have been higher and no additional *Salix* root excavation would have been needed. Besides, with presence of *Salix* roots in the soil core samples the correlation between the degree of mycorrhization and soil aggregate stability could have been determined.

Regarding the trench excavation, basis for the observation of the above- and below-ground biomass, a smaller distance between the trenches and the plants might be beneficial. Therefore, the excavation of two trenches per plot, where the first trench is excavated directly below the row of plants and the second one directly above the row (Figure 58) is recommended. This allows determining, whether more roots grow in upward or downward direction to the plants.

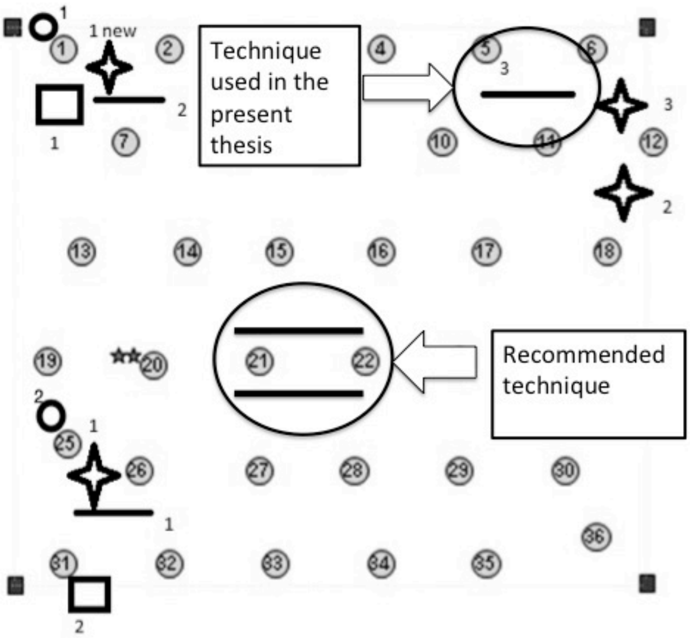


Figure 58: Suggestion for improvement of the trench excavation. The lower circle shows the used technique and the upper one the improvement to be closer to the *Salix* and see the difference between the root development above and below the plant.

Likewise, it would be advisable to have information of the first 3 years concerning the above- and below-ground biomass as well as some results of soil aggregate stability and permeability tests. Thus, a better comparison and more precise development study would have been possible. Additionally, the absence of rooted samples of *S. daphnoides* of the year 2011 has adverse effects on the evaluation of the results over time. Differences between the species and the planting strategies can just be determined within the generation planted in the year 2009.

An unambiguous assignment of the mycorrhizal fungi to the originally applied artificial inoculum or to natural inoculation or both is not possible as far as the artificially inoculated willows are concerned. To do so, root investigations, including molecular analysis of the fungal material of these plants would have been necessary within the first vegetation period. Only under these requirements positive evidence of an effect of the commercial inoculum can be achieved.

In order to get a better overview over the variability of field-saturated hydraulic conductivity values it is recommended to perform much more test in each plot. This was not feasible in the present study, due to the occurring difficulties and the limiting time available. Also in literature the extreme spatial variation of K_{fs} is mentioned and seems to be typical for natural and modified landscapes (Nielsen et al. 1973). In addition, the fact that each measurement represents just a small area makes it difficult to give a good K_{fs} characterization (Nimmo et al. 2009) and to upscale this values to a bigger area (e.g. at the slope scale). However, it is important to mention that taking more samples would have been very time consuming and the carrying of huge amounts of water along the steep slope was a big challenge.

Finally, it is important to mention that field test reveal results closer to the natural state compared to tests performed in the lab. However, the transferability and general applicability in this case is not fulfilled, since the tests were performed on a specific site.

7. Conclusion

This Master's thesis investigated the performance of the above- and below-ground biomass of *S. daphnoides* and *S. purpurea* dependent on a combination of planting strategies and kind of inoculation, in the context of bioengineering measures. Furthermore, the soil aggregate stability and the field-saturated hydraulic conductivity in the plots were measured in order to get an idea how these parameters are affected by the biological measures.

It was found that the application of unspecific artificial inoculum had no beneficial effect on the performance of the above- and below-ground biomass of *S. daphnoides* and *S. purpurea*. Moreover, there were no significant differences in the performances between the different species. However, *S. purpurea* performed significantly better for cuttings compared to rooted samples regarding the above-ground biomass and the number of roots. Surprisingly, this was found just for inoculated samples but may be explained by the low number of observations. In case of *S. daphnoides* no differences between the application of cuttings and rooted samples were found. In view of time and cost saving aspects, on the basis of the obtained results it is recommended to use cuttings instead of rooted samples of both species for slope stabilization at this altitude. The cuttings however should be of high quality and properly managed and set up. Based on the observations in our study, a further advantage of the use of cuttings is that the performance of the above-ground biomass can be used to establish a statement on the number of roots, which is an important aspect for slope stabilization. This would enable to evaluate the performance of the applied biological measures only by determining the above-ground biomass without excavating trenches. Hence, time and cost could be saved.

Apart of the recommendation to use cuttings for the two species, it is important to keep in mind that a variety of plant species has a much higher efficiency in slope stabilization than a monoculture. This is due to the diversity of root morphology and a higher resistance against diseases. Moreover, to ensure a sufficient vegetation development it is recommended to imply periodic inspection and selective pruning (Schiechtl 1973).

Investigations on the degree of mycorrhization revealed that the degree of EMF on *Salix* roots was significantly higher than AMF and additionally the degree of mycorrhization by *Cenococcum geophilum* L. (EMF specie) significantly increased over time. Unfortunately, the degree of mycorrhizal fungi (AMF and EMF) could not be related to the soil aggregate stability. Surprisingly, it was found that *S. daphnoides* was colonized by both EMF and AMF, although in literature it is written that it is host only for EMF. Further, all the plants were inoculated by *Cenococcum geophilum* L. Therefore, and due to the fact that the artificial inoculum did not affect the performance of the above- and belowground biomass, reflections are recommended on whether the application of artificial inoculum is worth it and further, if it might be an option to add *Cenococcum geophilum* L. to artificial inoculum for an optimal adjustment when applied to *Salix* plants.

In order to quantify the effect of the biological part in slope stabilization the soil aggregate stability and soil hydraulic conductivity were measured. The soil aggregate stability significantly increased from the year 2006, when only bare soil was present until the year 2014, when the applied biological measures were 3 and 5 years old. Therefore, the increase in stability can be attributed to the development of vegetation. These findings can be confirmed by other studies (Burri 2006, Schwarz 2006). Considering the field-saturated soil hydraulic conductivity, a high coefficient of variability for the values was found, which is in accordance to other studies (Johnston, et al. 2009), performed in the field. Unfortunately, in this case no statement regarding the effect of biological measures on the field-saturated hydraulic conductivity can be made, since no values were available of the time before the biological measures have been implemented.

The results provide a benchmark for slope stabilization by *S. purpurea* and *S. daphnoides*, on which further studies can be based on. However, it is important to keep in mind that the results of the present thesis are limited to the conditions present in Hexenrübi and need to be confirmed by other studies. Nevertheless, it would be interesting to see if these findings are also applicable to other species of *Salix* and to other slope as well as soil conditions.

8. References

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9. Appendices

Appendix 1

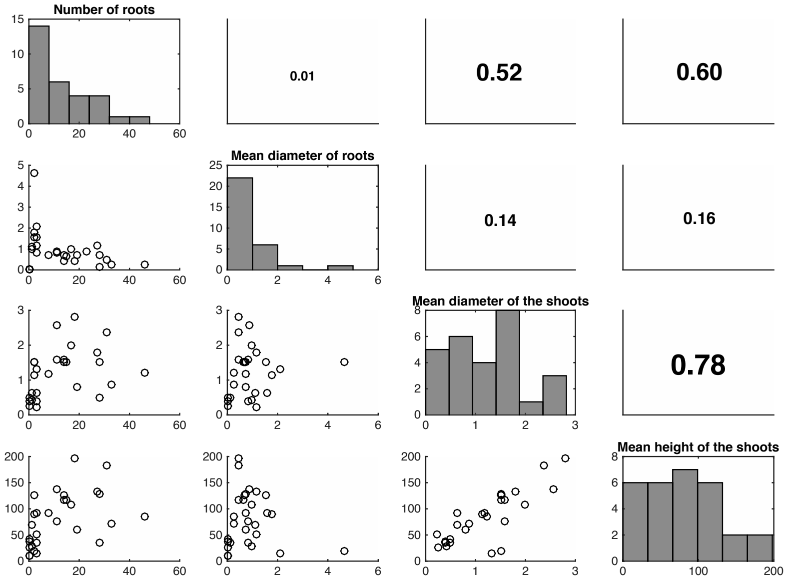

Figure 59: Correlation (Spearman) between above- and below- ground biomass (Spearman rho rank coefficient values).

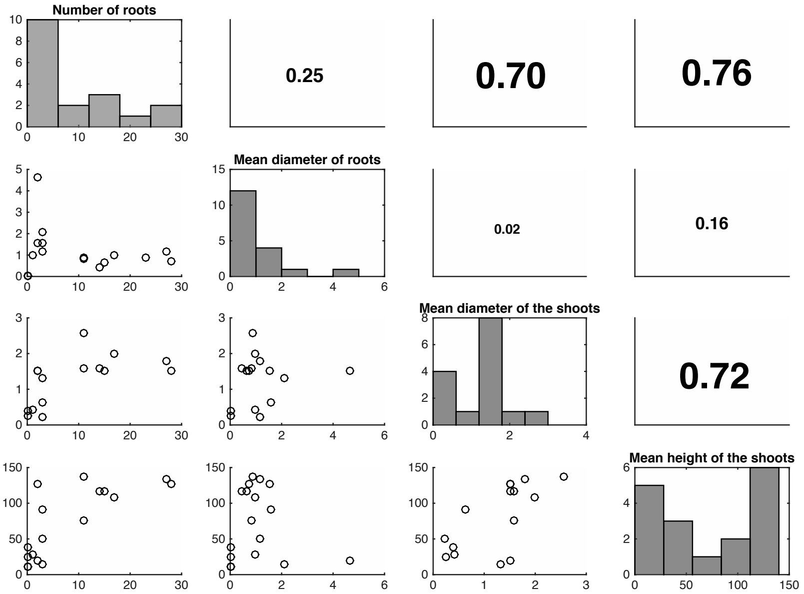

Figure 60: Correlation (Spearman) of the above- and below-ground biomass of the cuttings of the 5- and 3-year-old generation (Spearman rho rank coefficient values).

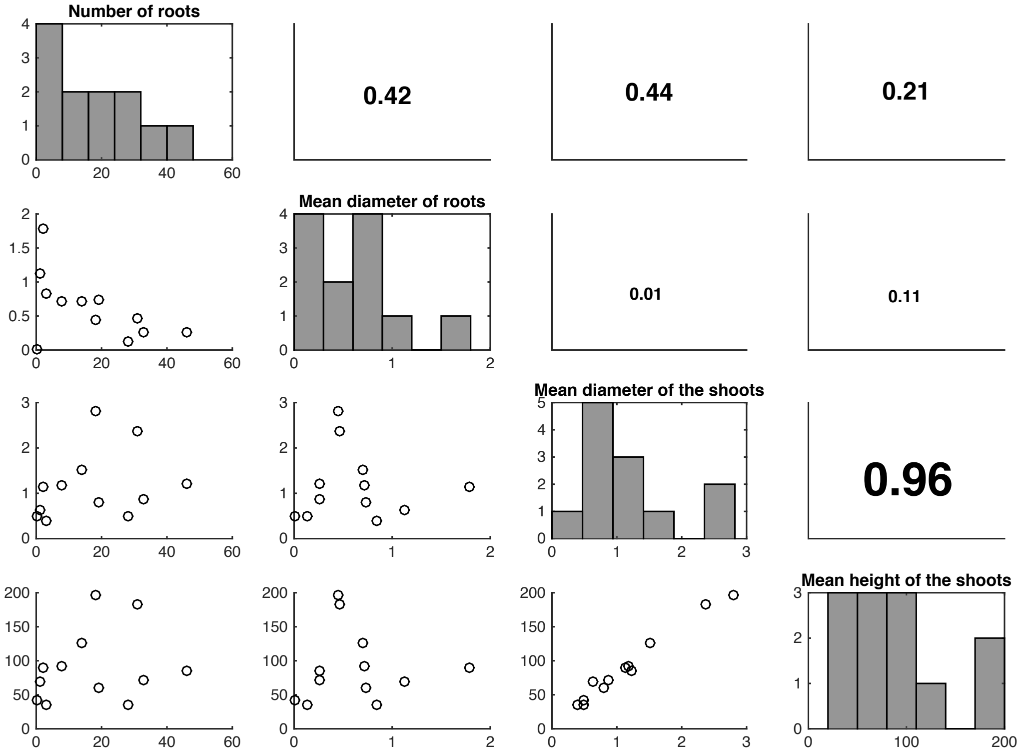

Figure 61 Correlation of the above- and below-ground biomass of the rooted samples of the 5-year-old generation (Spearman rho rank coefficient values).

Appendix 2

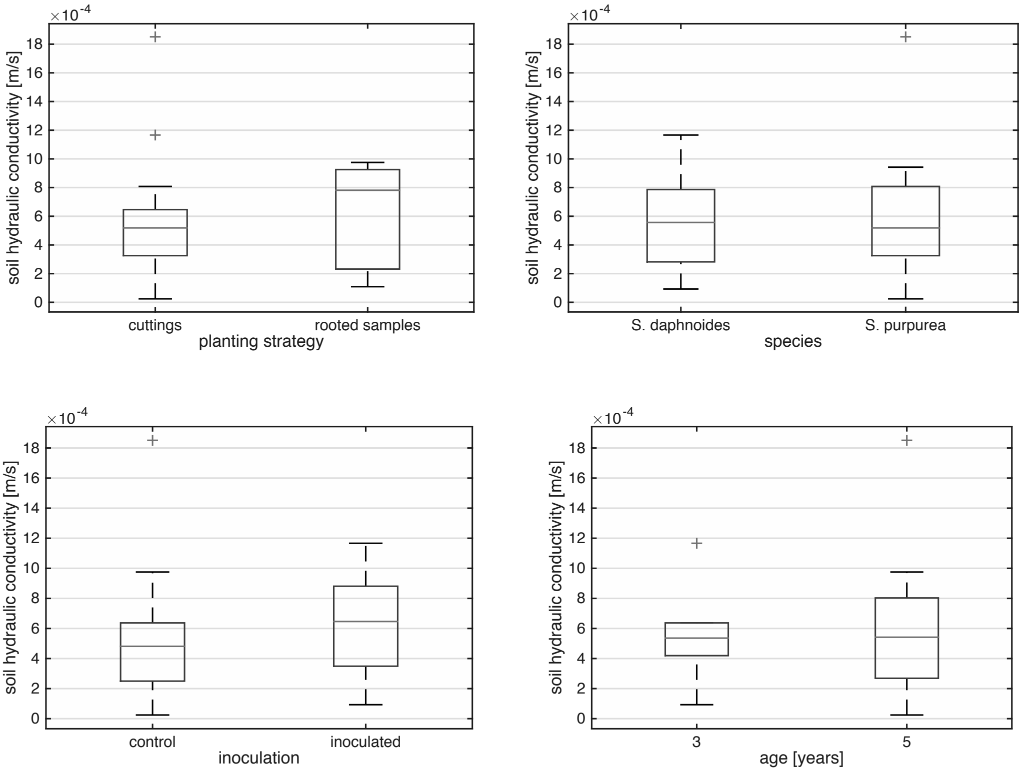

Figure 62: Soil hydraulic conductivity in dependency of planting strategy, species, inoculation and age.

Table 6: P-values of the Wilcoxon rank some test for the hydraulic conductivity regarding the different applications.

Soil hydraulic conductivity	p-value
3years-5years	1
inoculated-control	0.2136
cuttings-rooted samples	0.5146
S. purpurea-S. daphnoides	0.9478

Appendix 3

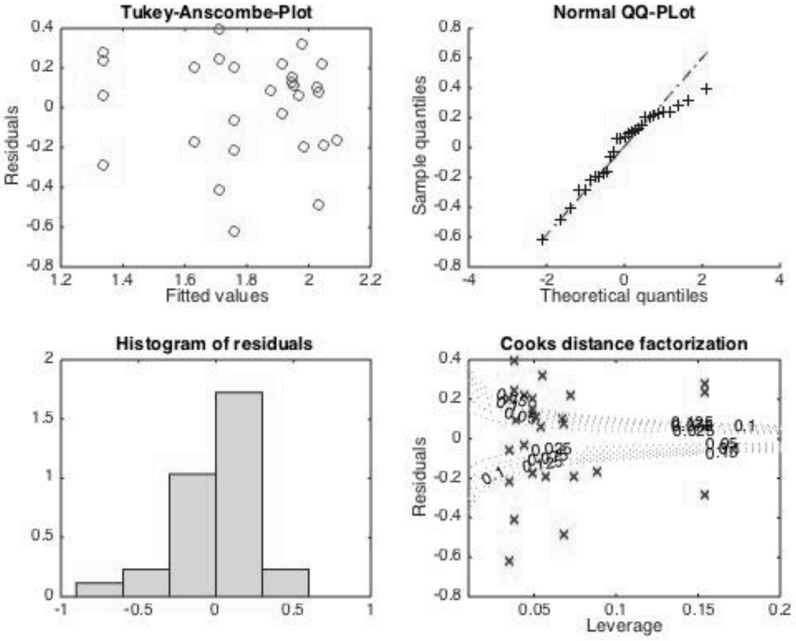

Figure 63: Residual analysis for all the plants (number of roots and height of the shoot).

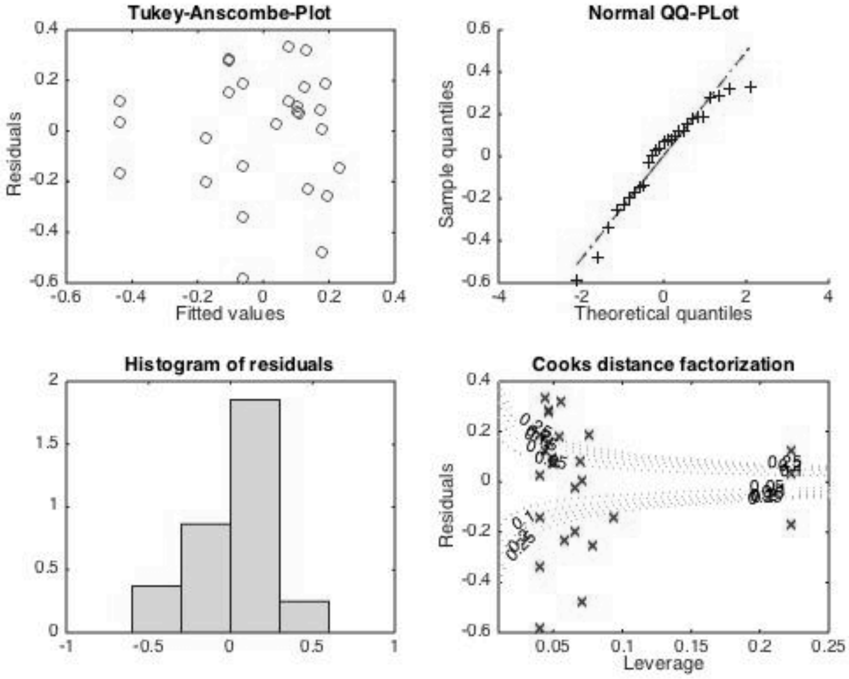

Figure 64: Residual analysis for all plants (number of roots and diameter of shoot).

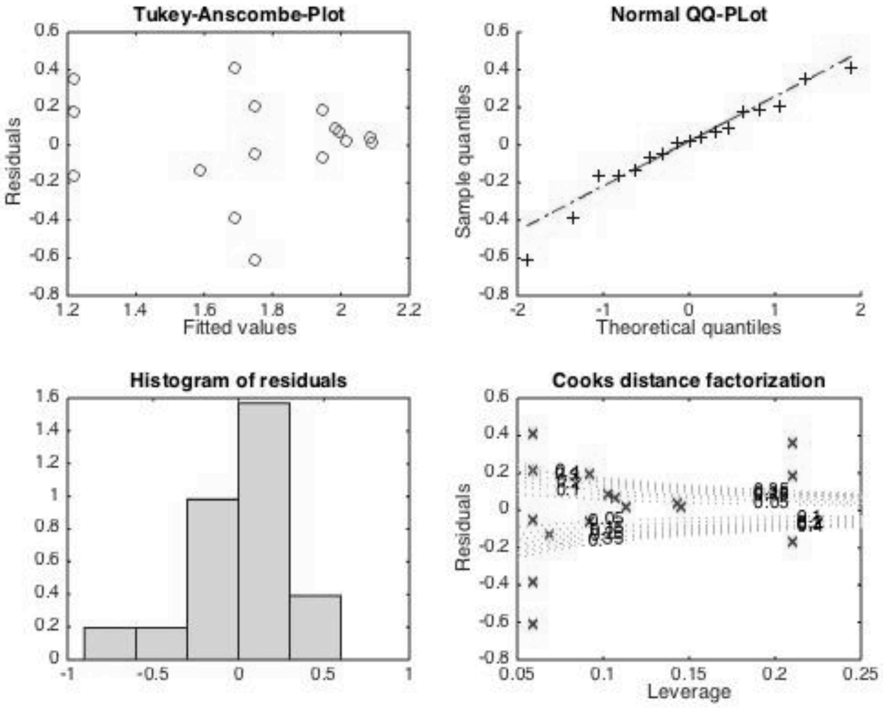

Figure 65: Residual analysis for cuttings (number of roots and height of shoot).

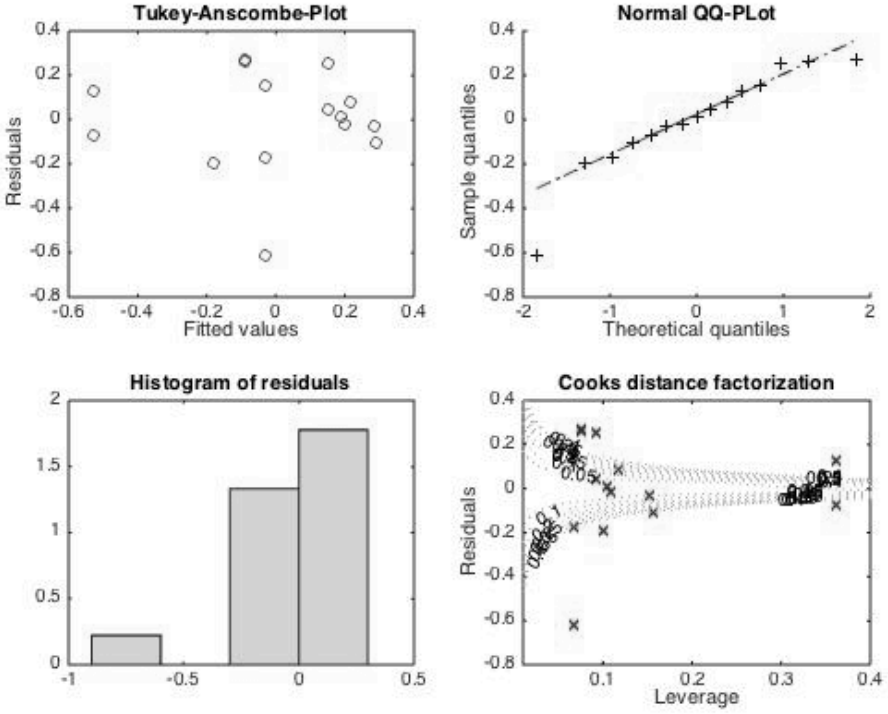

Figure 66: Residual analysis for cuttings (number of roots and diameter of shoot).

Appendix 4

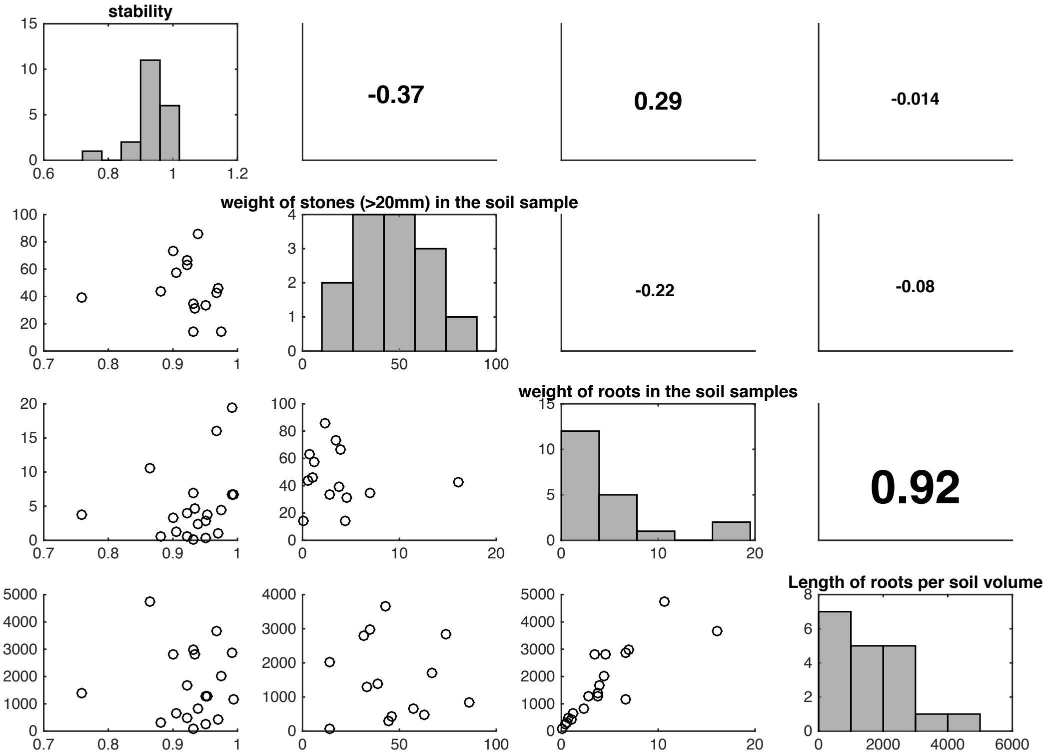

Figure 67: Spearman correlation between soil aggregate stability, the weight of the stones (>20 mm), and the weight and length of roots in the soil core samples (Spearman rho rank coefficient values).

Appendix 5

INOQ Forst

Garten- und Landschaftsbau, Rekultivierung, Dachbegrünung

Verbesserung der Bodenstruktur durch verschiedene Symbiosebildner
Erhöhung des Humusgehaltes
Erfüllt die FLL-Richtlinien
Gemäß EG-Öko-Durchführungs-VO 889/2008 Art. 3 (4) im Ökolandbau zugelassen

Bodenhilfsstoff

unter Verwendung von Hochmoortorf und lebenden Mikroorganismen

Gesamtphosphat (P_2O_5) 0,31 %, Gesamtkaliumoxid (K_2O) 0,18 %, Organische Substanz 32,6 %

Zur flächigen Bodenverbesserung und Erhöhung der biologischen Aktivität

Nettovolumen 10 l

Inverkehrbringer
INOQ GmbH, Geschäftsführung: Dr. Carolin Schneider, Solkau 2, 29465 Schnega
Tel. 0 58 42/98 16 72, Fax. 0 58 42/4 93, info@inoq.de, www.inoq.de

Ausgangsstoffe		
Trägermaterial		Torfsubstrat (H3-H6)
Lebende Mikroorganismen		Ektomykorrhizapilze Arbuskuläre Mykorrhizapilze *Rhizophagus irregularis*
Lagerung		2 Jahre, kühl und trocken
Anwendung	**Mischen mit Substrat**	5 bis 10 % (Empfehlung)
	Einbringen in Pflanzloch	20 ml / Pflanze (bis 15 cm ∅ Wurzelballen) bis 100 ml / Pflanze (bis 40 cm ∅ Wurzelballen)
	Bestehende Pflanzungen	Je nach Größe bis zu 100 ml / Pflanze in Bohrlöcher einbringen
	Flächenanwendung	bis 100 ml / m²

Weitere Hinweise

Ektomykorrhizapilze (heimische Stämme, enthält keine Gentechnisch Veränderten Organismen (GVO))	*Amanita muscaria, Boletus edulis* *Hebeloma crustuliniforme, Laccaria laccata* *Paxillus involutus, Pisolithus tinctorius* *Thelephora terrestris, Xerocomus badius.*
Endomykorrhizapilze (heimische Stämme, enthält keine Gentechnisch Veränderten Organismen (GVO))	*Rhizophagus irregularis* *(Błaszk., Wubet, Renker & Buscot)* *C. Walker & A. Schüßler comb. nov.*
Ektomykorrhiza-Besiedelungsindex	80 %
Endomykorrhiza Einheiten (pro cm³ Substrat)	180
Mykorrhizawirkung (Wuchsförderung [%] im Standardtest)	
Ektomykorrhiza	24 ± 5
Endomykorrhiza	32 ± 8
Schüttgewicht [g/l]	250-400
Verträglichkeit mit Fungiziden	Wurde geprüft
Sicherheitshinweise	Keine besonderen Vorkehrungen nötig Verschlucken und Inhalieren vermeiden, Freiheit von Phytopathogenen durch DNA multiscan® nachgewiesen Material Safety Data Sheet kann angefordert werden
Packungsgrößen	1 l Eimer 5 l Eimer 10 l Eimer 25 l Sack 1000 l BigBag

Figure 68: Product specification of the artificial inoculum INOQ Forst by INOQ GmbH.

Appendix 6

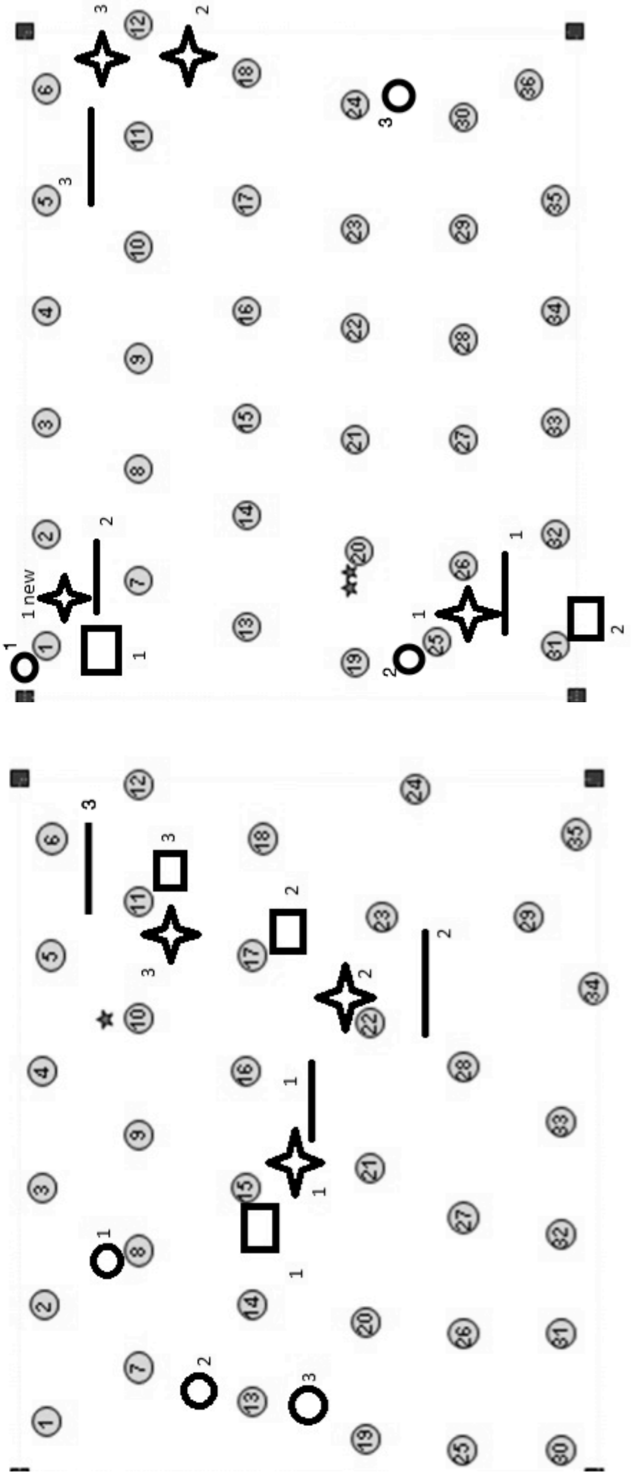

Figure 69: Location of the applied tests in plot 1 (left side) and plot 2 (right side). Legend with the explanation of the symbols is given in Figure 74.

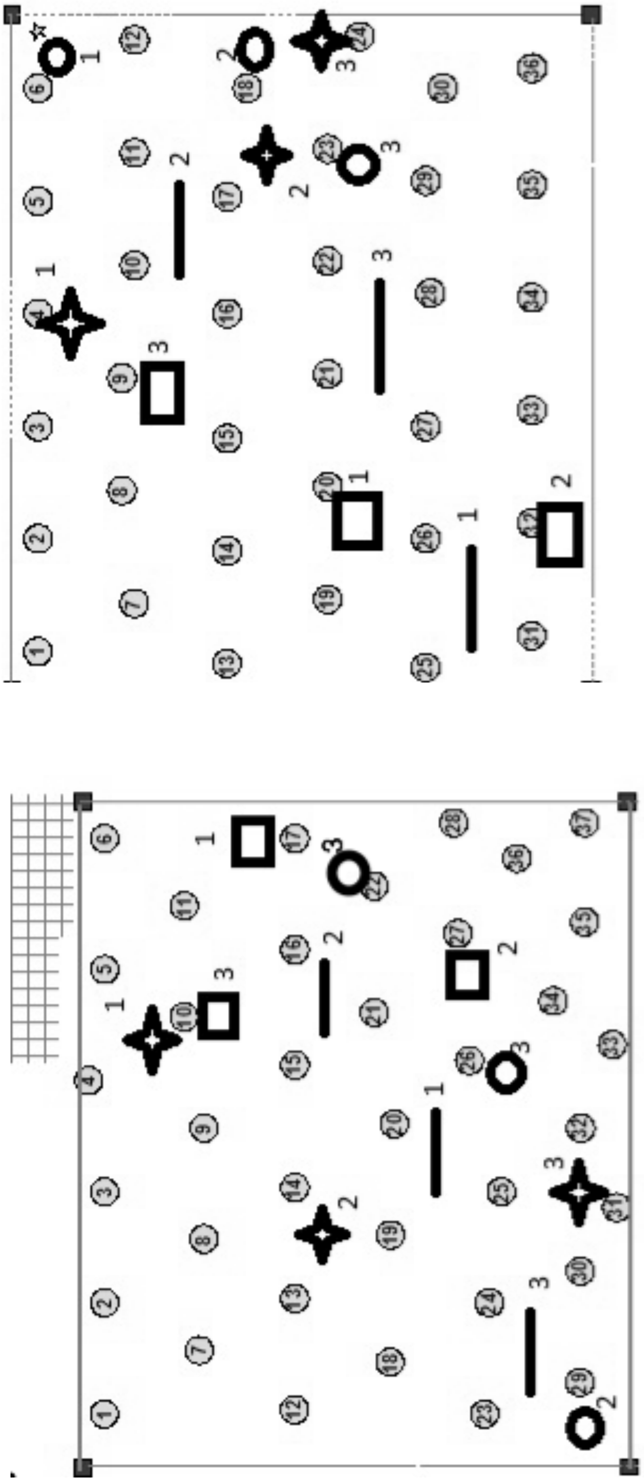

Figure 70: Location of the applied tests in plot 3 (left side) and plot 4 (right side). Legend with the explanation of the symbols is given in Figure 74.

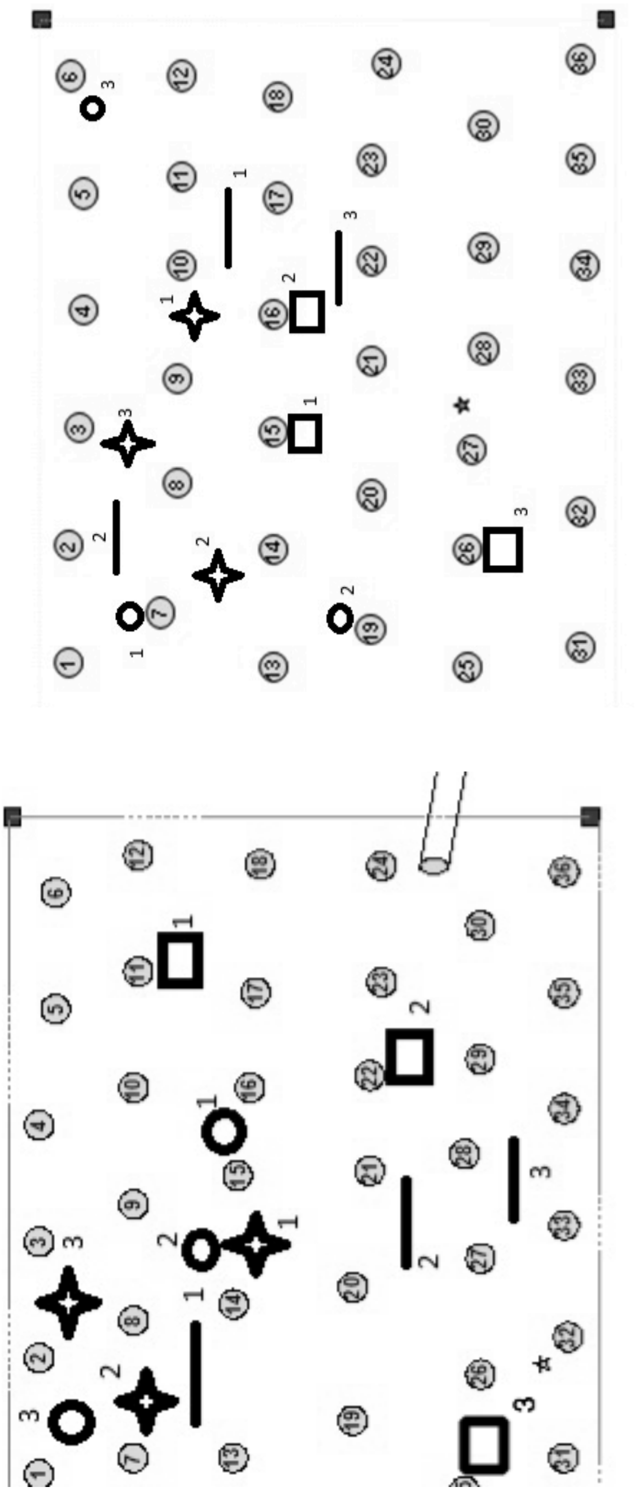

Figure 71: Location of the applied tests in plot 5 (left side) and plot 6 (right side). Legend with the explanation of the symbols is given in Figure 74.

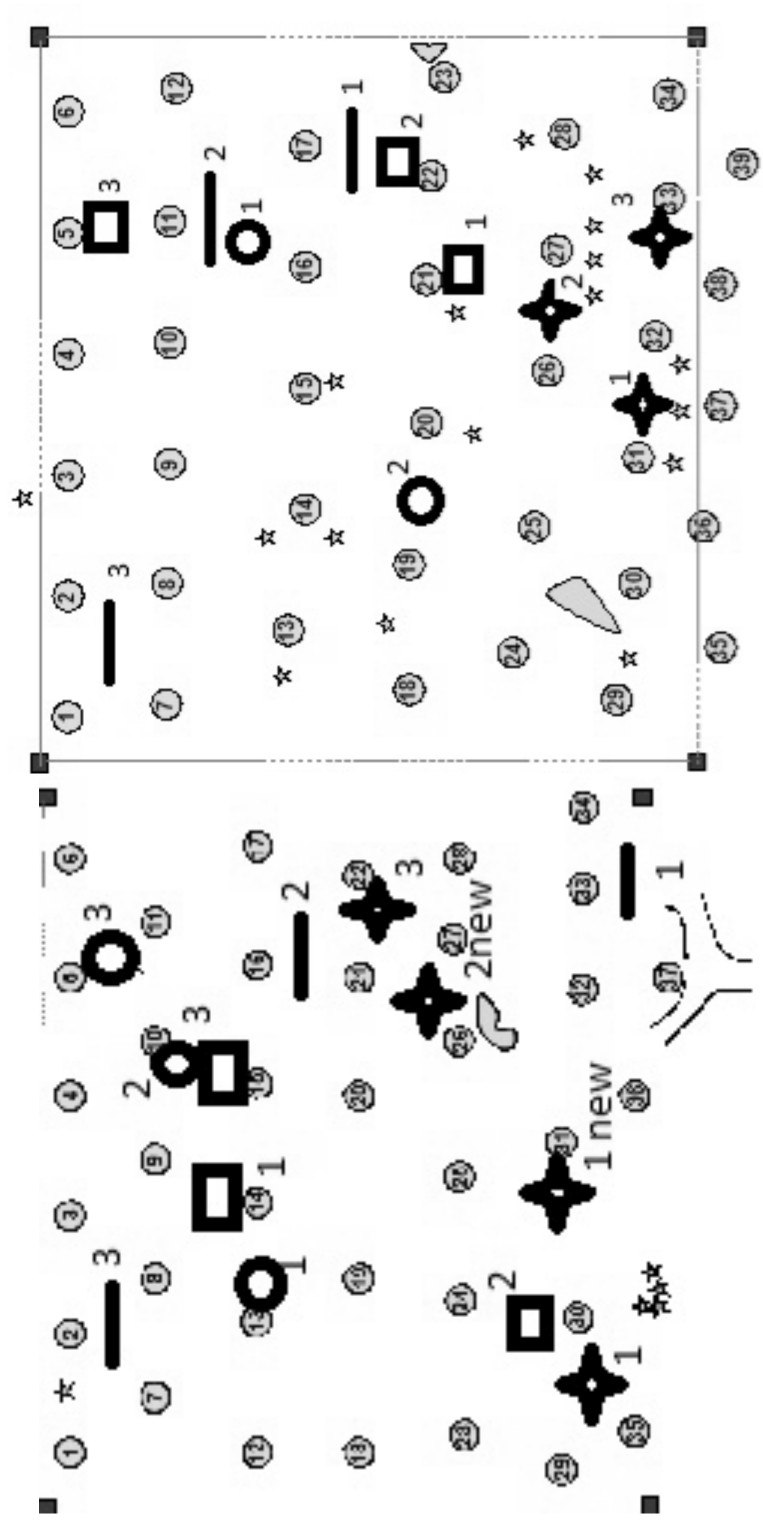

Figure 72: Location of the applied tests in plot 7 (left side) and plot 8 (right side). Legend with the explanation of the symbols is given in Figure 74.

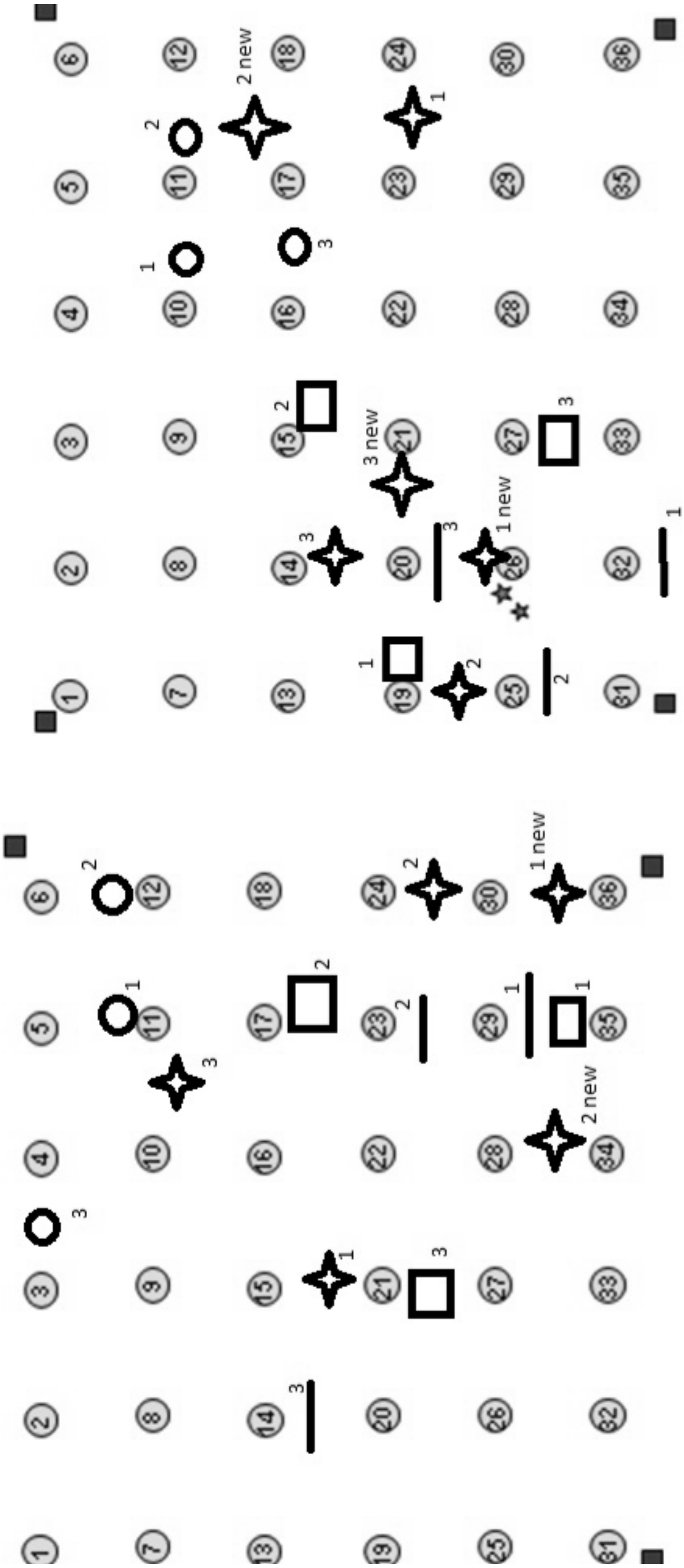

Figure 73: Location of the applied tests in plot 14 (left side) and plot 15 (right side). Legend with the explanation of the symbols is given in Figure 74.

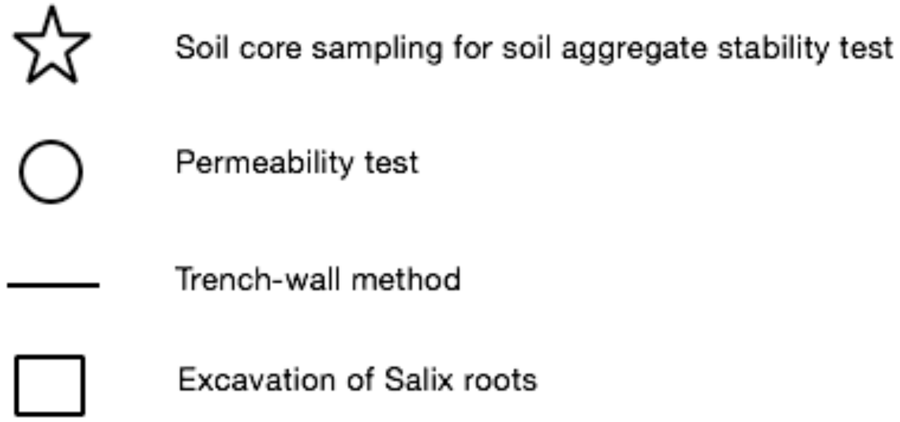

Figure 74: Legend explaining the four symbols for the tests, methods and root excavation.

Appendix 7

Table 7: Raw values of the field-saturated soil hydraulic conductivity test for each plot and test number

▨ steady state

plot	test number	depth (cm)	radius (cm)	h1 (cm)	h2 (cm)	t-1 (s)	t-2 (s)	t-3 (s)	t-4 (s)	t-5 (s)	t-6 (s)	t-7 (s)	t-8 (s)	t-9 (s)	t-10 (s)	t-11 (s)	t-12 (s)	t-13 (s)	t-14(s)	t-15(s)	t-16(s)	t-17(s)	t-18(s)	t-19(s)
1	1	3	5	8	7	10,37	9,16	11,68	10,54	11,75	10,6	11,54	11,35	11,6										
1	2	3	5	8	7	9,49	12	12	10	10,4	9,61	9,02	7,75	7,98	7,78									
1	3	3	5	8	7	12,25	12,1	9,96	11,08	12,36	14,11	14,47	14	13,76	16,49	16,35	18,22	17,44	19,37	17,84	19,87	17,36	17,46	17,59
2	1	3	5	8	7	80,23	171,46	185,38	177,4	179,49	180,39													
2	2	3	5	8	7	12,26	16,41	21,85	18,58	22,09	23,81	23,71	21,87	18,17	19,1	19,02	19,19							
2	3	3	5	8	7	7,33	7,59	7,65	7,97	7,36	6,78	6,7	6,77											
3	1	3	5	8	7	4,75	4,76	4,65	4,24	4,45	4,59	4,7	4,75											
3	2	3	5	8	7	3,75	3,55	4,31	4,97	3,81	3,55	4,11	3,53	5,36	6,24	5,3	4,49	4,75	4,47	4,67				
3	3	3	5	8	7	31,75	34,46	37,31	37,27	41,08	39,74	40,33	39,96											
4	1	3	5	8	7	35,98	37,4	43,97	41,55	41,72	46,05	53	46	24,27	27	28	27							
4	2	3	5	8	7	3,66	4,17	4,38	4,71	4,83	4,92													
4	3	3	5	8	7	3,02	2,69	3,08	5,08	5,04	8,02	6,01	5,02	5,7	4,7	5,41	5,92	5,69	5,43	5,49				
5	1	3	5	8	7	6,52	10	8,91	9,26	8,46	9,03	7,91	8,02	8,23										
5	2	3	5	8	7	11,65	12,7	10,91	14,49	13,07	14,58	13,92	13,94	10,86	12,26	11,07	12,71	13,46	13,24	13,51				
5	3	3	5	8	7	6,25	5,56	5,59	5,52															
6	1	3	5	8	7	5,15	5,31	5,46	5,32	5,42														
6	2	3	5	8	7	7,08	6,66	6,11	6,21	6,24	7,36	9,39	8,46	8,36	8,8	8,64	8,95							
6	3	3	5	8	7	1,52	1,47	1,53	1,8	1,71	1,88	1,82	1,5	2,36	1,75	1,58	1,75	2,04	2,28	1,97	2,36	2,31	2,4	
7	1	3	5	8	7	6,79	6,12	6,11	6,79	9,76	9,95	9,42												
7	2	3	5	8	7	8,77	9,22	8,82	9,32	8,91	9,25													
8	1	3	5	8	7	4,73	3,68	4,04	3,86	4,54	3,62	4,52	4,16	5,56	5,55	5,64								
8	2	3	5	8	7	5,53	4,43	4,51	4,1	4,26	4,81	5,97	4,98	4,78	5,16	5,12	4,53	4,42	4,47					
8	3	3	5	8	7	38,52	32,84	35,85	42,7	33,87	38,66	41	37,03	36,89	36,55									
14	1	3	5	8	7	2,77	3,7	2,77	2,55	3,08	3,2	2,99	4,13	4,18	3,85	3,48	3,42	3,7	3,76	3,76				
14	2	3	5	8	7	49,8	45,23	44,98	42,61	40,06	47,21	47,25	46,33											
14	3	3	5	8	7	8,36	9,19	8,81	9,7	11,3	10,09	10,61	10,52											
15	1	3	5	8	7	7,08	6,64	6,8	6,48	6,93	6,97	6,65												
15	2	3	5	8	7	8,03	8,04	7,43	6,97	7,72	8,19	7,29	8,14	9,74	7,52	7,37	7,47							
15	3	3	5	8	7	16,7	10,75	12,41	9,98	10,34	9,02	9,07	8,83											