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Development of riparian tree roots in compacted coarse gravel mixtures

Analysis of alternative measures to decrease asphalt damages caused by tree roots

MASTER THESIS

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Abstract

The development of riparian tree roots is the cause of the majority of asphalt damages of the Treppelwege along the Danube. Cracks and bumps in the asphalt occur when tree roots enter the interface between the top layer and the base course and lift the pavement through secondary growth. Condensation underneath the asphalt increases the moisture creating a favorable environment for roots. The international waterway operators 'viadonau' faces high maintenance work due to these damages and thus increasing costs to ensure the standards of these roads. To prevent root penetration and development in the road structure, different mitigation and prevention methods have been developed by experts.

A promising strategy seems to be the use of crushed coarse gravel mixtures as base course filling as it changes the drainage effects of the condensation water within the base course and reduces the prerequisites for root development. Furthermore, the coarse fragments of the material create gaps, which are ill-suited for root penetration and development.

This method is tested in a small-scale field experiment, where coarse gravel mixtures are examined according to penetration, establishment, and development of poplar and willow roots. The gravel mixtures have different average grain size distributions of 0/32, 04/32, 08/32, 16/32, 0/63 and 16/63 mm. Additionally, a hydraulically stabilized mixture is tested.

The results show that the smallest amount of root biomass was found in the hydraulically stabilized mixture compared to the other substrates. In the same substrate, the smallest biomass increase was observed from 2015 to 2016, whereas the root biomass in the 16/63 mixture increased drastically, followed by the 0/32 mixture. The horizontal root distribution displayed a root biomass increase with depth, with the extent of this rooting behavior depending on the gravel mixture. The highest root biomass in lower levels was found in the 16/63 gravel mixture. When comparing the relative root biomass close to the surface, the highest amount of root biomass was found in the gravel mixtures with large shares of fine fragments (0/32 and 0/63), whereas the 16/63 and hydraulically stabilized mixtures accommodated the smallest relative biomass. The highest weight share of roots was observed in the diameter class between 0 and 2 mm. The share of roots that underwent secondary thickening up to 10 mm was dependent on the gravel mixture. Thicker roots were not found in any mixtures.

After two vegetation periods, a trend is observed that the hydraulically stabilized mixture inhibits root development the most, followed by the 16/63 mixture, when considering the potential rooting zone close to the surface.

Zusammenfassung

Gewässernahe Gehölzwurzeln verursachen an den sogenannten Treppelwegen am Flussufer der Donau immer wieder erhebliche Fahrbahnschäden. Erhebungen und Risse im Asphalt entstehen wenn Baumwurzeln unter der Deckschicht einwurzeln, sich ausbreiten und durch Dickenwachstum Kräfte auf den Asphalt ausüben. Dabei begünstigt die Bildung von Kondenswasser an der Unterseite des Asphalts das Wurzelwachstum. Dies führt unweigerlich zu intensiven Reparaturarbeiten und hohen Instandhaltungskosten für die Österreichische Wasserstraßen-Gesellschaft ‚viadonau'.

Um solche Fahrbahnschäden vorzubeugen, wurde eine Vielzahl an Strategien entwickelt, deren Effizienz und Umsetzbarkeit jedoch von den jeweilig lokalen Gegebenheiten abhängig sind. Die Verwendung von groben Kantkorn als Unterbau wird als eine vielversprechende Maßnahme angesehen um Asphaltschäden durch Gehölzwurzeln vorzubeugen. Das grobkörnige Substrat ermöglicht veränderte Drainageeffekte und es entstehen zudem auch vergrößerte Zwischenräume, welche den Feinwurzeln weniger Halt bieten.

Im Zuge dieser Arbeit wurde daher besagte Methode in Form von Kleinfeldversuchen getestet und das Einwurzeln und Ausbreiten von Pappel- und Weidewurzeln in Grobkantkorn untersucht. Substratmischungen mit einer Korngrößenverteilung von 0/32, 04/32, 08/32, 16/32, 0/63 und 16/63, sowie einer hydraulisch stabilisierten Mischung wurden als potentielles Unterbaumaterial zur Testung herangezogen.

Die Analyseergebnisse zeigen, dass die geringste Wurzelmasse im hydraulisch stabilisierten Substrat gefunden wurde. Auch die Entwicklung der Wurzelmasse innerhalb einer Vegetationsperiode war in diesem Substrat am schwächsten. Der stärkste Zuwachs wurde in den Mischungen 16/63 und 0/32 vermerkt. Eine Analyse der horizontalen Verteilung ergab, dass die Wurzelmasse mit zunehmender Tiefe anstieg. Dieses Phänomen war besonders im 16/63 Substrat stark ausgeprägt. Ein Vergleich der relativen Wurzelmasse in Oberflächennähe zeigte, dass die Substrate mit hohem Feinmaterialanteil ein erhöhtes Wurzelaufkommen verzeichneten. Im Gegensatz dazu zeigten das 16/63 Substrat und die hydraulisch stabilisierte Mischung den geringsten Anteil an oberflächennaher Wurzelmasse auf. Der größte Gewichtsanteil wurde im Wurzelbereich der Durchmesserklasse 0 bis 2 mm erhoben. Der Anteil an Wurzeln, welche einen Durchmesser von 2 bis 10 mm aufweisen, war stark vom Substrat abhängig. Wurzeln mit einem Durchmesser von mehr als 10 mm wurden in keinem Substrat entdeckt.

Nach zwei Vegetationsperioden ist der Trend ersichtlich, dass das hydraulisch stabilisierte Substrat die Wurzelentwicklung am stärksten. Bei Betrachtung der oberflächennahen Durchwurzelung erzielte auch das 16/63 Substrat gute Ergebnisse.

Abbreviations

PS	Planting strip
RSB	Road structure box
SB	Substrate box
hs	hydraulically stabilized
M_{DLB}	Weight of dry leaf biomass
M_{DWB}	Weight of dry wood biomass
M_{PS}	Weight of dry root biomass extracted from the planting strips
M_{RSB}	Weight of dry root biomass extracted from the road structure boxes
M_{SB}	Weight of dry root biomass extracted from the substrate boxes

1 Introduction

The paths next to the Danube have a long history and have been used in various ways over the years. The necessity to transport goods upstream was one of the most influential requirements on these paths (Jungwirth et al., 2014). It was common to tie boats together to form a caravan, which was accompanied by several smaller boats. The larger caravans reached a length of 500 m and up to 60 horses towed such caravans upstream (Jungwirth et al., (2014). Such tasks required skilled men and trained horses, as well as accessibility to towpaths, also called Treppelwege. Therefore, the riparian vegetation was cleared (Donau Österreich, s.a.). Combined with the impact of the horses and the natural processes of the river, this lead to erosions along the stream, which made river bank stabilization a pressing matter (Jungwirth et al., 2014). Although the shipping industry changed profoundly, the need for towpaths remained (viadonau, 2016c). Nowadays, the Treppelwege serve non-public transport, with the exception of uses that do not impair its initial purposes, such as recreation and tourism. The towpaths are used by emergency vehicles and power plant operators, for towing activities and maintenance work. Furthermore, the 250 km of the Treppelwege are serve as paved cycle tracks and can be used by inline-skaters (on specifically marked sections) (RIS, 2017; viadonau, 2016b and 2016c). The proximity to the river increases the attractiveness for tourism and leisure, but causes the majority of damages on the towpaths (Weissteiner, 2015). The asphalt shows damages such as cracks and bumps, which occur when roots enter the road structure and lift the asphalt layer (Weissteiner, 2015; Kopinga, 1994). This impairs the security of pedestrians and cyclists. The company responsible for the maintenance of the Treppelwege, viadonau, is faced with high costs to maintain good quality standards of these utility roads. Since the exposure to heavy vehicles is limited, the roads are often constructed with a thin top layer and shallow base course (viadonau, 2016b). It is therefore relatively easy for riparian tree roots to penetrate the road structure and lift the asphalt, which subsequently creates cracks (Reichwein, 2002). These damages should not be underestimated since they pose a hazard to the users of the Treppelwege. To reduce the maintenance costs and increase the longevity of the road repairs, it is necessary to implement effective strategies. Therefore, viadonau addressed the University of Natural Resources and Life Sciences, Vienna to investigate different strategies to reduce asphalt damages by tree roots (Weissteiner, 2015). The project includes the examination of the causes and mechanisms of root penetration in road structures and the processes leading to damages of the top layer. Additionally, methods to reduce and mitigate potential damages of road structures, which are suitable for the riparian environment of the Treppelwege, are tested. Overall, a reduction of the maintenance costs through implementation of effective measures is aspired (Weissteiner, 2015).

Damages of road structures are not only an issue for paths close to rivers, but are also a major concern in urban areas (Kopinga, 1994; Reichwein, 2002). A variety of strategies have been developed to decrease the potential impairments. The environmental conditions need to be considered when choosing the right method (Reichwein, 2002). These measures can be categorized in mitigation and prevention methods, as well as tree-based strategies, infrastructure-based strategies and root zone-based strategies (Costello and Jones, 2003; Reichwein, 2002). Based on the effectiveness, the environmental conditions and the feasibility, some measures are more suitable than others. Kopinga (1994) researched the method of using rubble as base course material consisting of coarse brick debris. According to the author, the results showed a lack of root development underneath the pavement even after six years, when the experiment ended. Kopinga (1994) explains this outcome with the mechanical resistance of the debris and the structure of the road bed filling. The roots cannot bridge the gaps in the material, when finer material is missing (Kopinga, 1994).

This master thesis is part of a larger project of the Institute of Soil Bioengineering and Landscape Construction examining the method of using crushed coarse gravel as base course mixtures, similar to the measure Kopinga (1994) has been studying. In a small-scale field study, different sized coarse gravel mixtures are tested to observe the effects on root penetration, development and architecture over a period of time and to assess a suitable gravel mixture. The field experiment is set up in three stages to examine the root development after the first, second and fifth vegetation period (Weissteiner, 2015).
In the course of this master thesis, the subject areas focusing on the issue of root penetration in road structures are addressed, including an introduction into root growth and behavior and road construction. Furthermore, an overview of the interaction between plants and infrastructure is given. The common mitigation and prevention methods are listed and analyzed according to their effectiveness and feasibility. The aim of the thesis is the evaluation of the second stage of the experiment located in Groß Enzersdorf, examining the overall developments, as well as the changes from 2015 to 2016. The underground biomass evaluation will elucidate whether the root biomass can be redirected and/or reduced by the means of crushed coarse gravel. If such changes in rooting behavior are present, the success rate of the different substrates will be rated and the gained information will be used for the third stage evaluation of the experiment. However, the prediction of long-term effects of this method is rather challenging after the short time of only two vegetation periods. Therefore, an evaluation of rooting trends is a more feasible approach.
In the scope of this thesis, the following questions will be addressed:

- What level of impact can be observed regarding the grain size distribution of the gravel on the root development?

- How does the root biomass develop spatially?
- What differences can be observed comparing the root biomass collected in 2015 to the one collected in 2016?

2 Background

Since the vast majority of road damages of the Treppelwege are bumps and cracks created by riparian tree roots, it is indispensible to understand the processes and agents involved in the issue. In addition to the road structure itself, the penetration pattern of roots undermining the asphalt is of great importance. Environmental conditions can influence root development with regards to their architecture and the extent of their production. Once these conditions have been evaluated at a specific location, interference to decrease pavement damages through roots can commence, including various mitigation and prevention methods (Urban, 2008; Reichwein, 2002).

This chapter will provide information on root development and functions and their reaction to environmental influences. Subsequently, an overview of riparian vegetation will be provided, followed by an introduction into road engineering and road structure. Additional information on the Treppelwege and the local conditions will be given, together with a short summary of the umbrella project, which this research is a part of. Finally, commonly applied mitigation and prevention methods will be listed, following an illustration of the conflict between infrastructure and vegetation with a focus on root penetration and development underneath paved roads.

2.1 Tree roots

The roots of a tree usually stay within the first 2 m of the soil profile in order to fulfill their functions (Crow, 2005). The availability of oxygen and water are higher in the upper layers of the soil profile, where a transfer of oxygen and carbon dioxide between air and soil is possible. The local conditions such as soil type, compaction and drainage affect this interaction and therefore the extent of the rooting space, which makes any predictions about the rooting depth difficult (Urban, 2008). According to Crow (2005), about 80 to 90% of the roots are located within the first 60 cm. Randrup et al. (2001) state that approximately 60 to 90% can be found in the first 20 cm of mineral soil.

2.1.1 Root functions

Roots have the capacity to anchor a tree, absorb and transport water and dissolved nutrients and storage reserves of photosynthetic products (Beck, 2005; Urban, 2008, Owens and Lund, 2009). Furthermore, they provide the location of hormonal synthesis (Reichwein, 2002). According to the age, thickness and growing area, the functions are divided between the roots in a root system. The fine, young roots are able to absorb water and nutrients, which is possible because they are made up of non-corky, absorptive cells (Reichwein, 2002). The reserve substances are stored by medium roots, which include starch, lipids, mineral salts and water. The coarse, woody roots stabilize the tree and balance out any forces impacting the tree aboveground (Reichwein, 2002). Regardless of age and structure, all roots are able to transport water and nutrients from the ground to the stem, shoots and leaves aboveground. Woody roots resemble the structure of branches or the stem. They are differentiated into the inner xylem and the outer phloem. The xylem conducts water and minerals to the locations of photosynthesis, whereas the phloem transports assimilates produced in the leaves (Reichwein, 2002).

2.1.2 Root development and growth

Starting point of a root is a seed containing an embryo with a root meristem, from which the initial tap root is produced. It branches and grows to support the young plant by developing a root system (Pallardy, 2008). Similar to the aerial portion of the tree, the root growth occurs in the tip of the root, where rapid cell division takes place (Reichwein, 2002). Fig. 1 illustrates the root tip with the different zones.

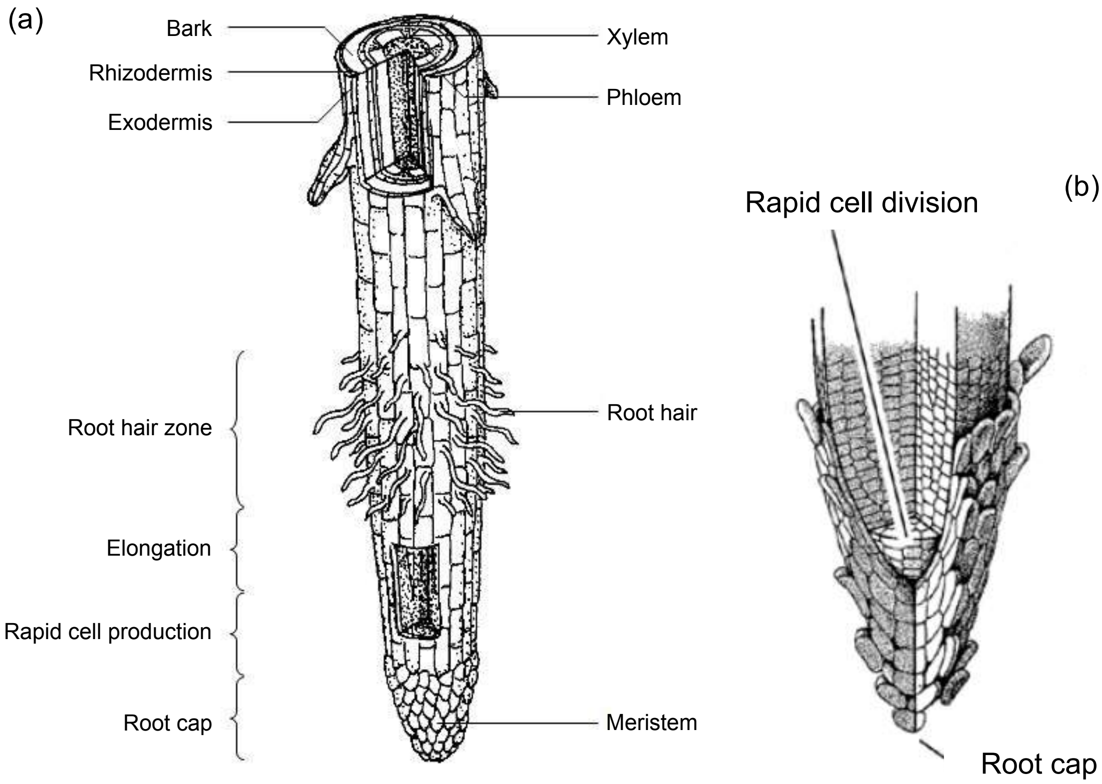

Figure 1 *Schematic overview of tip of root with different root zones (a) (Biostudies, 2009); schematic overview of root cap (b) (Streckenbach, 2012a, modified).*

The root tip is protected by a mass of living cells forming the root cap or calyptra (Pallardy, 2008; Reichwein, 2002). The meristem produces cells, which either supply the root cap or are expanded in the elongation zone located behind the root cap (Urban, 2008). A gelatinous sheath formed from dead cells, microorganisms, organic matter and minerals, covers the root tip (Owens and Lund, 2009). Functioning as contact area between root and soil (Pallardy, 2008), it facilitates the penetration of the surrounding space (Reichwein, 2002). The elongation zone following the root cap is only a couple of millimeters long and responsible for the longitudinal growth of a root. After the elongation, the cells are differentiated into xylem, cambium and phloem (Reichwein, 2002; Urban, 2008). The part of the root behind the elongation zone is able to produce root hairs and therefore called root hair zone. The root is capable of an increased water and nutrient uptake through the expanded surface area by the root hairs, which are very fine and usually don't exceed 10 mm in length (Reichwein, 2002) Although limited in length, the all of the fine roots make up approximately 90% of the length density and total root system length (Day et al., 2010). They only live up to a few hours, days or weeks, die off and are shed subsequently (Owens and Lund, 2009). The root hairs are replaced by a corky exodermis, which is, to a smaller extent, still capable of water and nutrient uptake (Reichwein, 2002). The branching of a root takes place after the root hair zone, where the cambium cells are able to differentiate further and thus enable the root to grow radial. The secondary thickening usually starts during the first or second year (Owens and Lund, 2009) (Fig. 2).

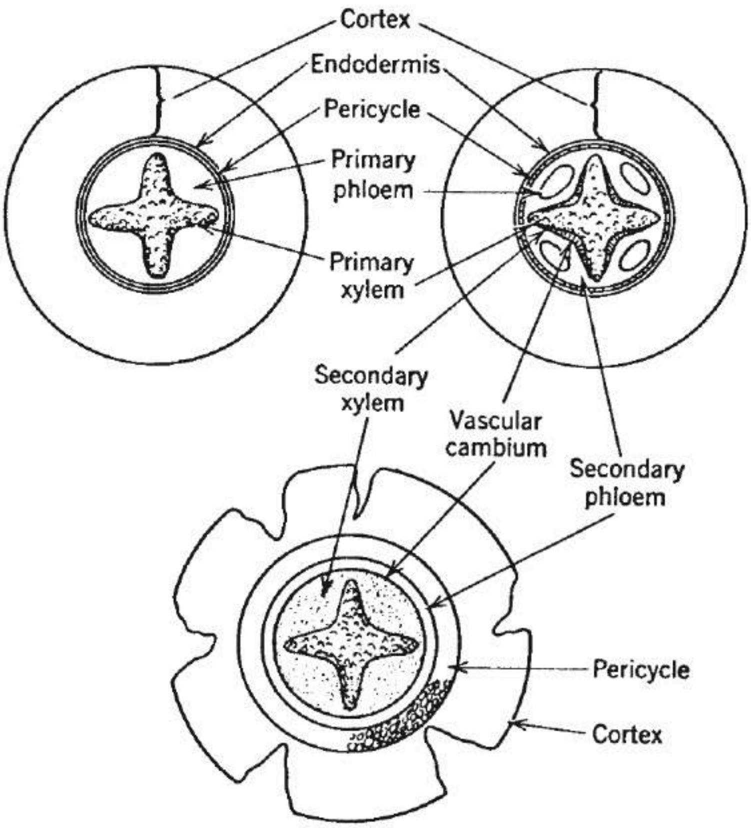

Figure 2 *Secondary thickening of tree root (Pallardy, 2008)*

It is commenced through the change of the star-shaped cambium, which grows into a ring shape, whilst producing xylem cells towards the inside of the root and phloem cells towards the outside (Reichwein, 2002). The outer tissue cannot withstand the pressure and tears. The corky periderm resembles the bark of the aerial share of the tree (Reichwein, 2002).

Once the roots become woody, their function changes from absorbing water and nutrients to stabilizing and anchoring the tree in the ground. After this process, the roots are called structural roots. They are considered a part of the root framework, which consists of five to 15 structural roots and form the frame of the tree root system (Crow, 2005; Day et al., 2010).

Within close proximity of the tree trunk, structural tree roots are represented in higher numbers compared to further from the stem, where less roots have undergone secondary growth. Typically, structural roots grow vertically in close proximity of the tree trunk, whereas with increasing distance, they level out and spread horizontally (Day et al., 2010; Crook et al., 1997).

To ensure stability as well as maintain a high level of available resources, the roots need to be able to react according to the local environmental conditions (Streckenbach, 2012b). The primary roots are typically characterized by vertical growth, which is triggered by geotropic stimuli and also called gravitropism. Lateral roots of the first order are plagiotropically influenced and grow slantingly downwards, whereas lateral root of high orders are dominated by other stimuli than gravity (Reichwein, 2002). Changes in the immediate environment of the root will effect the growth direction. These include variations in oxygen, water, and nutrient availability, as well as mechanical changes and the resulting penetrability of the ground. This ability to is called tropism (Streckenbach, 2012a). They differ from each other according to the present stimulus:

- Thigmotropism: the ability to react to touch. The gravitropic and thigmotropic reactions of a root correlate closely. They are essential for the root to prevent encountering impermeable obstacles (Kafkafi, 2008; Bengough et al., 2005)
- Oxytropism: to ensure sufficient oxygen levels, the root growth is positively steered towards areas with greater aeration. Therefore, it is able to avoid oxygen-deprived environments (Kafkafi, 2008)
- Hydrotropism: similar to the oxytropic response, the root tip grows in the direction of high moisture levels (Streckenbach, 2009; Kafkafi, 2008)
- Phototropism: the phototropism ensures that the plants react negatively when it develops towards light and changes direction (Sutton and Tinus, 1983)

Reichwein (2002) mentions that the concept of opportunistic root behavior is challenged by some scientists such as Perry. Perry is of the opinion that roots are able to grow in environments with enough resources, whereas locations with inadequate resources their growth is hampered (Reichwein, 2002). The tree roots elongate and thicken quicker in locations of resources surplus, which creates the illusion of an ability to detect and seek out these places (Crow, 2005; Urban, 2008).

Generally speaking, roots develop faster than branches and can reach up to 3 m per year (Urban, 2008). By developing roots accordingly to external forces such as wind, branch removal or change of sun exposure, the tree is able to equilibrate imbalances to avoid additional stress on the tree trunk. These forces can be especially harmful to the trunk flare, the location where the trunk meets the roots. To avoid damage, the tree grows reaction wood to thicken the trunk (Urban, 2008).

2.1.3 Root systems

When developing undisturbed, a tree creates a distinct root system that is genetically defined. Three different categories describe the general appearance, as shown in Fig. 3 (Crow, 2005; Streckenbach 2012a; Reichwein, 2002). These standard forms of root system are noticeable in the root system of young trees, when ideal environmental parameters prevail (Streckenbach and Stützel, 2010).

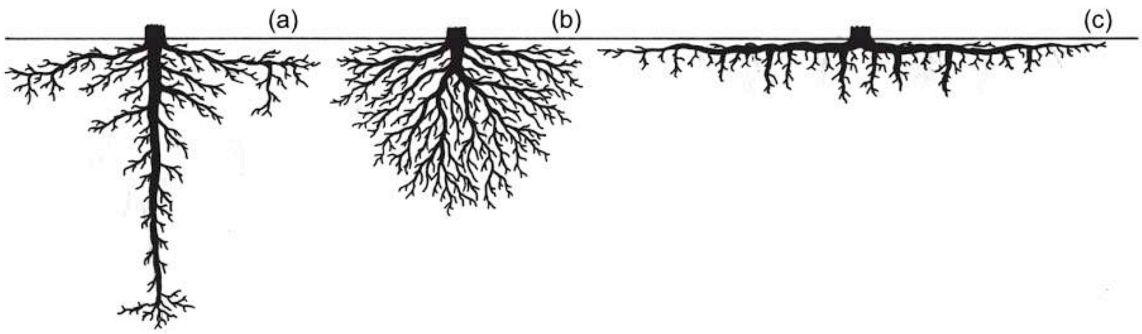

Figure 3 *Simplified taproot system (a), heart root system (b) and surface root system (c) (Roloff, 2016).*

- Taproot system: is defined by one large taproot that grows vertically from the tree collar. Trees at locations with loose and unconsolidated soil tend to form such roots. Examples are oak, pine and fir (Streckenbach and Stützel, 2010; Crow, 2005)
- Heart root system: is defined by an evenly distributed vertical and horizontal growth. The tree produces many vertical main roots, which form a heart shaped and compact root system, together with the lateral roots. These systems occur in deep, nutrient rich soils. Examples are birch, beech, larch and maple (Streckenbach and Stützel, 2010; Crow, 2005)
- Surface or plate root system: the roots grow close to the surface and within shallow depths, due to shallow soils. They lack in larger vertical roots and develop short roots, which then grow vertically. The main roots develop horizontally. Examples are ash, aspen, Norway spruce and white pine (Streckenbach and Stützel, 2010; Crow, 2005)

2.1.4 Environmental influences on root architecture

The environmental conditions influence the roots greatly (Urban, 2008). To establish its roots and develop further, the tree covers a large area to increase the chance of optimum conditions. Often, the highest nutrient concentrations, as well as the best aeration and microclimate can be found close to the surface (Urban, 2008). The soil conditions can influence the roots in their growth direction, speed, and form (Streckenbach, 2012b), as mentioned in the section ‘Root development and growth’. When reaching an obstacle, they divert and change the course of growth, until the obstacle is passed. Subsequently, they maintain the same direction away from the tree trunk (Crow, 2005). Such growth patterns are common for trees in urban areas or close to infrastructure, because the soil conditions change quickly on a small-scale (Streckenbach, 2012b).

Depending on the soil characteristics, available space, water availability, temperature and chemical features, the tree can prosper or be hampered in its development. Water shortage or abundance, as well as lack of nutrients are stressful conditions for plants and act as limiting factors (Bengough et al., 2005). This phenomenon makes it difficult to predict a tree's root development. Different tree species usually develop a more or less distinct root system, due to their genetics, as mentioned in the section 'root systems', but the local conditions are often the main force in determining the depth and range of the roots (Kafkafi, 2008; Day et al., 2010; Randrup et al., 2001). According to Crow (2005), these influences can be grouped into four categories: mechanical resistance, aeration, fertility and moisture. Other authors, such as Eavis (1972), list oxygen supply, water availability and mechanical resistance as limiting factors, but neglect the nutrient aspect of soils. The parameters are known interact and a shortage in either one can diminish the development of the tree, even if the other factors are ideal (Bengough et al., 2005).

In the following, some environmental influences are described further.

Mechanical resistance

The existence of coarse and medium pores facilitates the expansion of the root system due to small shearing forces. Under these conditions, fine roots are able to elongate, compared to soils with greater shares of fine pores, which leads to reduced elongation and linear growth. Compacted soils are more difficult to penetrate. The roots' physical appearance changes in such soils, undergoing some thickening and shortening of the root cap (Balder, 2000). Due to high bulk density of the soil, the roots are not able to grow as far as they would under more suitable conditions. Soil horizons that show great shares of bedrock, stony soils or fine sand, clayey soils or iron pans often hamper root development (Crow, 2005).

Aeration

The access to oxygen is essential for the survival of plants. Limiting the access or the total lack of soil oxygen leads to a stagnation in root growth. Through oxytropism, the roots can prevent penetrating areas that are oxygen-deprived (Kafkafi, 2008). The oxygen levels often correlate with the water balance in soils. Roots tend to avoid insufficiently aerated environments, which can result in upwards growth closer to the surface, where more oxygen is available. This can be observed in areas where compaction decreases the attractiveness of soils to plants and oxygen is less available (Balder, 2000; Crow, 2005).

Fertility

The dependence on the right nutrient levels greatly influences the plant development. Nitrogen plays an important role in root growth: rising levels lead to branching and an increase in root density, whereas once an optimum level is exceeded, the fine roots are hampered in longitudinal growth (Balder, 2000). Trees, which grow in infertile soils, have the tendency to develop long roots along the surface without many branches (Crow, 2005). Table 1 lists some of the most important nutrients for plant development, according to Balder (2000) and the effects of a lack thereof.

Table 1 *Essential nutrients and their effects on root development (Balder, 2000, modified).*

Nutrient	Effect on root	Deficiency symptoms
Nitrogen	Enhanced root sprouting	Elongated roots; few lateral roots
Phosphorus	Enhanced root biomass production	Elongated roots; few lateral roots; red-brown colored
Calcium	Regulation of swelling in cytoplasm	Short, bristly roots; dark colored; dying root tips
Sulfur		Enhanced lateral root production; white colored
Iron		Short roots; brown colored; enhanced lateral root production

Moisture

The right level of water availability is crucial for the tree development. Although it can tolerate unfavorable situations, its development is stalled in soils that are too dry or waterlogged. Both conditions can lead to shallow root systems to either avoid anaerobic soil horizons or to maximize the uptake of rainwater by extending the contact area (Crow, 2005).

In dry environments, such as the space underneath sealed surfaces, the occurrence of increased moisture promotes rapid root development. This behavior leads to increased growth underneath pavement, where condensation raises the moisture level (Balder, 2000). The ability to grow towards soils with higher moisture levels is called hydrotropism. Root elongation is often driven by the search of water (Kafkafi, 2008).

Balder (2000) also lists ground temperature as an important factor. Temperatures above 0°C are absolutely necessary for most plants to grow, which explains the dormancy during winter months. Some trees can develop best at approximately 20°C. Especially in urban areas, the local soil temperature is dependent on shading, soil moisture, surface sealing and air circulation and (Balder, 2000).

Usually, these changes in soil conditions affect the root growth vertically. The horizontal growth can be limited due to local competition of the plants in close proximity. Lateral roots usually cover a larger radius compared to the crown (Crow, 2005).

2.2 Pioneer vegetation

According to Weissteiner (2015), the existing woody vegetation along the Treppelwege includes natural floodplain vegetation, short rotation coppice and individual tree plantation, with a dominance of the tree species robinia, poplar, alder and willow at locations of damage. All species have characteristics of pioneer vegetation, such as rapid growth over a short timespan, especially at the juvenile stage (Weissteiner, 2015). Kopinga (1994) describes a correlation between poplar and willow species and pavement damage in the Netherlands, which was also observed along the Treppelwege, at locations with severe road damages. Furthermore, Weissteiner (2015) states that the typical floodplain species (poplar, willow and alder) were found at damage sites close to the Danube, whereas robinias were causing problems at drier locations. The increased occurrence of poplars at dry as well as wet sites can be attributed to the intensive use of hybrid poplars for short rotation coppice (Weissteiner, 2015). In the small-scale field experiment, which examines the penetration and development of roots in different sized crushed gravel mixtures, hybrid poplar and hybrid willow cuttings were planted. These species were chosen due to the their frequent occurrence along the Treppelwege, which correlates with the high risk of road damage that relates to their rooting behavior. Additionally, their rapid root growth and vegetative reproduction from parts of the shoots, are helpful features for the study.

2.2.1 Poplar

The poplar belongs to the *Salicaceae* family and has been valued for its fast growth, appearance, easy propagation, usefulness in rehabilitation of disturbed land and restoration of landscapes (Isebrands and Richardson, 2014). The genus *Populus* has characteristics, which are favorable for examining the root behavior: the possibility of vegetative propagation through cuttings, the ability to produce root suckers and fast initial development in the juvenile stages (Isebrands and Richardson, 2014). Its natural distribution covers the northern hemisphere, with little altitudinal preferences. Nowadays it can be found in the southern hemisphere as well, due to wide spread planting (Isebrands and Richardson, 2014). The use of cuttings, usually from one-year-old shoots, has had major influence on silviculture and horticulture. When planted in spring, the cuttings can quickly develop roots from existing primordial in the bark of the hardwood and grow shoots from lateral buds on the cutting. Depending on the climatic and soil conditions, the shoots can reach a length from 1 to 4 m within one vegetation period. Poplars, among other species, have the ability to sprout from latent buds at a later stage of their maternity. These sprouts are call suckers and form new branches or trees. Suckers develop from surface roots. The mechanism becomes active when the tree's canopy or an adjacent tree next to it is removed by decay, windfall or human activity and suddenly shaded areas get direct sunlight, well as mechanical damage to the root or when a still living root is separated completely (Urban, 2008; Kopinga, 1994).

The fast growth assures results within a short period of time, which is highly appreciated by farmers, crafts people and forest products industries (Isebrands and Richardson, 2014; Hofmann, 2005). Furthermore, they are amongst the first trees to grow at disturbed sites. Their typical habitat is at the border of alluvial, riparian and wetland habitats. They are known for their well adaption to seasonal flooding; for some riverine poplars it is vital that the locations are regularly flooded to ensure germination of seeds (Isebrands and Richardson, 2014).

2.2.2 Willow

The genus *Salix* is known for its widespread occurrence and high tolerance of climatic ranges. Similar to the poplars, it is most common in the northern hemisphere, with only a few native species in the southern hemisphere. Willows can occur in many different forms, such as trees, shrubs, prostrate plants or groundcovers. Furniture, arrows, fishing gear, fences and medicinal remedies are a few products that have been fashioned out of the different willow parts over the centuries (Isebrands and Richardson, 2014). Whilst clonal propagation is unusual for most species, some can develop colonies by layering or reproduce vegetative by broken branches. The ability to develop from cuttings has been used in horticulture and silviculture, as well as the resprouting from harvested trees. Willows can survive and grow again from stumps or stools (Isebrands and Richardson, 2014). The riparian and alluvial species require substrates, which are well aerated and in which changes moisture levels occur. A wet environment is favorable for germination for the colonists, such as willows. Through adventitious rooting of stems that have been buried underneath alluvial soil and flushing of dormant buds, the trees are able to endure flooding (Isebrands and Richardson, 2014).

2.3 Traffic areas

The requirements of roads usually determine the type of traffic area (Blumer, 1977). Such requirements include (Blumer, 1977):

- Function
- Type of traffic (urban, regional, overseas, tourism)
- Traffic volume
- Composition of traffic (share of heavy vehicle, cyclists, pedestrians)

The following paragraphs will provide an overview of the basic road structure and furthermore infrequently used roads.

2.3.1 Common road structure

The dimension of a road foundation depends on the expected use and vehicle load. The basic structure is usually the same, starting at the surface: a top layer, the base course, the subbase course and the underlying subgrade (Niggemann, 2012; U.S. Army. and Air Force, 1994). The layer closest to the surface is exposed to higher pressures and loads than in lower levels. Using different layers for the road construction creates a smooth surface, which is necessary to ensure safety, optimum conditions for vehicles and little abrasion of the material (Niggemann, 2012). Through compaction of each layer, the loose material becomes solid and stable (Niggemann, 2012). Materials used for base course construction are either natural, processed or others. Natural materials can include rock fragments (gravel), soils with gravel and/or sand, lime rock, shell, coral, and some caliches, if others aren't available. Occasionally, some modification of the material is necessary such as crushing or the extraction of oversized material. Conventional recommendations for road construction include that uncrushed, washed and clean gravel is inadequate as base course due to missing fines, which act as binding agent. Processed materials are modified gravel, rock or slag that has been crushed and screened (U.S. Army. and Air Force, 1994). Fig. 4 shows a schematic overview of typical sections of a basic road structure.

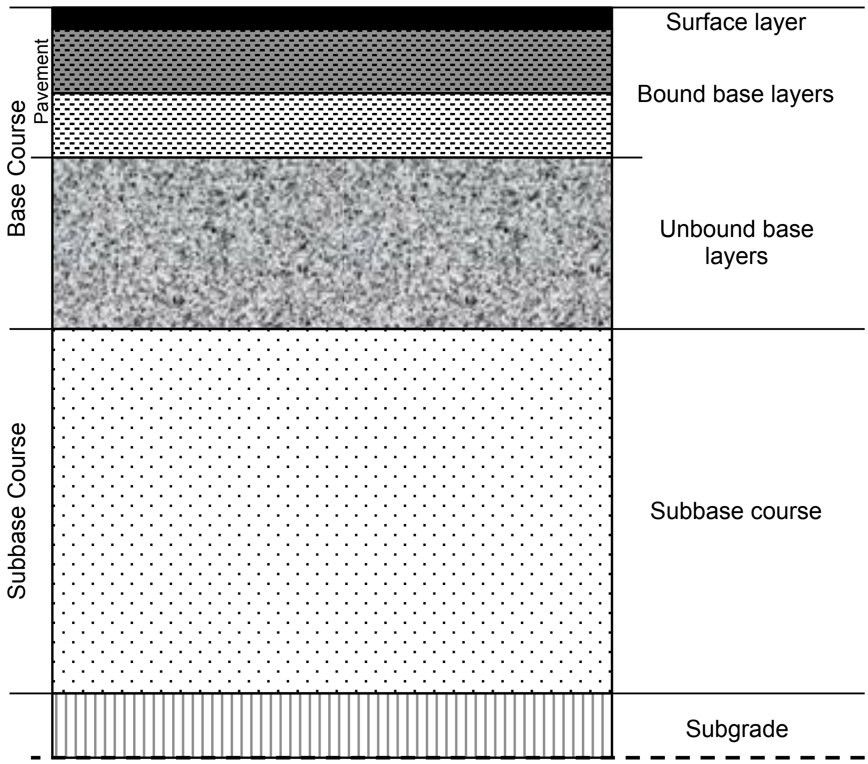

***Figure 4** Schematic cross section of common road structure (U.S. Army and Air Force, 1994; Niggemann, 2012; RSV, 2009; modified)*

Starting with the lowest layer, the **subgrade** is also called roadbed or natural ground. It is made up of the native material and can be modified to increase its stability and ensure enough supporting strength for the subbase and base courses (RSV, 2009; U.S. Army. and Air Force, 1994). On top of the subgrade, the **subbase course** is situated, separating the base layers from the subgrade. It is often made up of aggregated native material. For the construction of roads for light traffic, this layer is optional (U.S. Army. and Air Force, 1994). The **base course** consists of a variety of layers with different functions and its structure is designed to resist the potential traffic loads and transmit pressure and forces onto the lower levels (U.S. Army. and Air Force, 1994; Richter and Heindel, 2008). Commonly used for the construction are natural aggregates of crushed or round gravel or industrially produced recycled and recovered aggregates. The grain size distribution of the aggregates used for the base course depends on the type of base course and the maximum grain size defines the thickness of the layer (Reichwein, 2002). In Austria, the deformation modulus, compaction balance and degree of compaction are legally defined by the Federal Ministry for Transport, Innovation and Technology (RSV, 2009). The base layers can be categorized in unbound and bound base layers. Unbound layers are located above the subbase course and have different features depending if they function as upper or lower unbound base layers. The lower unbound base layers are also called frost protection layers. Their purpose is protecting the subbase course and subgrade from damages by frost and freeze-thaw actions (U.S. Army. and Air Force, 1994; Richter and Heindel, 2008). The second type of base layer is characterized by adding a binding agent. This process enhances the resistance and protection of the material against climatic and mechanical effects. Commonly used binders are bitumen, cement and lime. The bound material is able to resist freeze and thaw actions and its capillarity is decreased (Richter and Heindel, 2008): Homogeneity of the material and necessary thickness of the layer are important for the binding layer to function (RSV, 2009).

The **surface layer** is directly affected by the traffic and needs to be highly abrasion resisted. Furthermore, it seals off the base course and inhibits water from entering the structure. The top layer can be categorized according to its composition into: bituminous, concrete or paving stone surface layer (U.S. Army. and Air Force, 1994).

To withstand heavy loads, the base course needs to be thick enough, which means that the resistance of the base course need to be greater than the traffic loads. The load is dependent on the vehicles, the probability of occurrence, and the maximum axle load. The dimension of the road structure components, especially the base course, is undertaken with a dimensioning catalogue, in Austria according to the RSV 03.08.63. Ten load classes facilitate the allocation of traffic load and the necessary assessment and construction of the roads (Eberhardsteiner and Blab, 2016). Additionally, the correct dimension decreases the likelihood of frost and/or freeze-thaw damages. Frost-sensitivity classes assist with the selection of minimum thickness of the base course (Reichwein, 2002).

As shown in Fig. 5, a more complex base course provides better pressure distribution with much lower peak pressures than a thin structure.

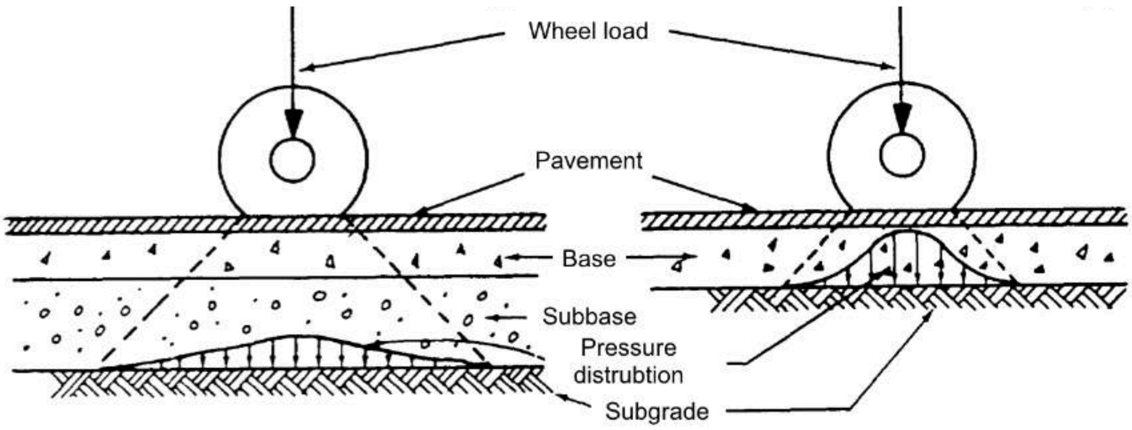

***Figure 5** Pressure distributions on different road structure designs (U.S. Army. and Air Force, 1994).*

In general, roads are designed to withstand the exposed loads and use. The layers have different service lives (Niggemann, 2012):

Base course: 60 years

Surface layer: 16 years

These estimations waver when the construction is flawed and damaging forces influence the road (Niggemann, 2012).

2.3.2 Treppelwege

The likelihood of infrequently used roads and cycling paths being damaged by tree roots is higher compared to roads with heavy traffic (Reichwein, 2002; Kopinga, 1994). Usually this type of road has shallower road structures due to the infrequency of traffic. Nevertheless, it is possible that they need to withstand greater loads due to delivery traffic, vehicle traffic on access roads and emergency vehicle traffic (Reichwein, 2002). For example, service roads are primarily used to access remote areas, which only few people use. Therefore, the frequency of traffic and traffic load are little, but often the vehicle axle load is considerably high. It is common that the layers of the road structure are reduced to decrease the costs (Niggemann, 2012). Some authors, such as Meschik (2008), recommend that even if the traffic load is limited, the dimensions of the base course and top layer are suitable for the maximum possible exposure to prevent future damages. At the same time, this measure can restrict possible adverse effects due to root penetration and growth to some extent (Meschik, 2008).

Having the characteristics of infrequently used roads, the Treppelwege are highly prone to asphalt damages, which is under the responsibility of the viadonau (viadonau, 2016b). The subsidiary of the Austrian Federal Ministry for Transport, Innovation and Technology, is furthermore responsible for flood protection along the Danube, the March and the Thaya and secure and efficient traffic management (viadonau, 2016a). Nowadays, the Treppelwege serve non-public transport, with the exception of uses that do not impair its initial purposes, such as recreation and tourism. Emergency vehicles and power plant operators are allowed to use the Treppelwege in case of emergencies, for towing activities and maintenance work (RIS, 2017; viadonau, 2016b and 2016c). A proper upkeep of the paths is indispensable for the accessibility of ambulance and fire brigade, administration and other officials. The safety of cyclists and pedestrian is another priority and constant maintenance is facilitated through the introduction of a maintenance management system (viadonau, 2016b). The viadonau are faced with high maintenance costs due to the damages of roads, which are caused by riparian tree roots. To reduce these costs, it is necessary to implement prevention methods to inhibit roots from entering the road structures.

Part of the ongoing project between viadonau and the University of Natural Resources and Life Sciences, Vienna, was an examination of the environmental conditions of the

Treppelwege and the damages (Weissteiner, 2015). 42 locations have been selected as representative samples for the course of the towpaths in Austria. The findings show that trees of the species robinia, poplar, alder and willow dominate the vegetation along the towpaths (Weissteiner, 2015). According to Weissteiner (2015), it was observed that in close proximity of the road sections with signs of damage, the majority of trees were poplars and robinias. The damages were mapped and categorized according to their intensity. A correlation of the vegetation and the damage intensity resulted in a high damage potential of poplar trees (Weissteiner, 2015). The dominant damage mechanism includes the root penetration of the interface between top layer and upper base course and the secondary growth of these roots, which lift the pavement and creates creeks and bumps (Weissteiner, 2015). The same mechanism has been addressed by Kopinga (1994) and Streckenbach et al. (2008). The materials used for the road construction of the towpaths are often inadequate, as they are made up of round gravel with fine and coarse sand (Weissteiner, 2015).

2.4 Interaction of plants and infrastructure

The majority of studies concerned with the interaction of vegetation and traffic areas examine urban settings. Although the Treppelwege do not meet the same prerequisites as streets in cities or heavily trafficked locations, the involved mechanisms and interaction processes are often similar.

It is inevitable that the presence of trees and other plants can cause problems in urban settings with high density of infrastructure (Urban, 2008).

Cities without vegetation could solve many problems with structural buildings and traffic network. Nevertheless, a holistic approach takes the benefits of trees such as improvement of microclimates, the psychological impact on citizens, positive effects on runoff and stabilization of soil into account (Heidger and Kurkowski, 2008; Costello and Jones, 2003). In order to minimize the conflict potential by implementing measures that allow plants to develop without impairments and ensure the durability of infrastructure, it is necessary to understand the interaction between vegetation and infrastructure.

2.4.1 Infrastructure affects vegetation

Traffic areas limit the available space for the tree roots and therefore, influences the growth path. The sealed surfaces interfere with the interaction of atmosphere and soil, which prevents natural processes in the pedoshpere. Processes such as introduction of organic material, water and air are limited or stopped all together. These aspects contribute to an ill suited environment for plant development (Streckenbach, 2009). According to Streckenbach (2012b) modified soils in urban areas are characterized by a high spatial variability in depth, the possibility of contamination, increased pH-values and the likelihood of sealed surfaces. Furthermore, limited aeration and drainage, intercepted nutrient cycle, a drop in plant activity, modified soil temperatures and higher possibility of soil compaction are typical for soils under or in close proximity of infrastructure (Streckenbach, 2012b). The soil body is impacted by traffic loads, compaction of modified subgrade and base course material increasing the load bearing capacity, as well as the effects of the vibrations caused by driving vehicles impact the soil body. This results in the rearrangement of soil particles and a reduction of the share of medium and coarse pores (Reichwein, 2002). Soil compaction can interact with other limiting location factors causing problems for the vegetation. Reichwein (2002) mentions several likely effects in urban areas:

- High penetration resistance for roots and limited access of the whole soil body
- Decreased levels of oxygen, increased carbon dioxide concentration
- Limited interaction of atmosphere and pedoshpere
- Limited infiltration due to sealed areas
- Increased surface runoff
- Possible reduction of water retention capacity
- Waterlogging
- Decrease in biological activity
- Reduced water and nutrient uptake

The microclimate in urban soils changes rapidly compared to undisturbed soils, which subsequently have direct and indirect effects on the root development. Well-drained, non-compacted and well-aerated soils are favorable for root growth and allow development in greater depth compared to ill-suited soils, which promote shallow root development (Costello and Jones, 2003).

Being able to react to environmental stimuli is essential for the survival of plants (Streckenbach, 2012b; Streckenbach, 2009). The roots choose the path of least resistance and subsequently resume their initial growth direction as soon as the obstacle is circumvented (Streckenbach, 2012a; Heidger, 2012). This behavior is severely restricted in urban soil, which can be considered heavily modified due to severe changes in soil characteristics such as available space, aeration, compaction and soil-water balance (Randrup et al., 2001). When diverting from their initial growth direction, the roots are like to branch. The branch, which reaches a more suitable environment, will take over and develop further. This can cause enhanced root development close to the surface, where compaction and the lack of oxygen and moisture are less dominant (Forest research, s.a.).

The modified temperature of the soil and the different water content might increase root growth and secondary thickening. The surface material can also enhance growth, e.g. concrete prohibits moisture to evaporate compared to other materials and favors root growth (Randrup et al., 2001). According to Kopinga (1994), the constant high moisture content underneath the top layer is one of the major driving forces leading to root development underneath the pavement. Whilst the degree of humidity fluctuates in the soil besides the road, gradually drying out between rainfalls, the moisture level stays the same underneath the pavement. This invites roots to penetrate the interface of top layer and base course (Kopinga, 1994).

The altered environmental conditions combined with restricted rooting space puts pressure on the plants and hampers their development. If the modifications are moderate, the plants are still able to penetrate their surroundings but the root growth is hampered and altered (Streckenbach, 2009). Deformations, instability and illness or pests are common effects of ill-managed vegetation in cities and rural areas with infrastructure (Streckenbach, 2009b).

2.4.2 Vegetation affects infrastructure

The impairment of infrastructure to some degree is almost unavoidable, since plants need their roots to explore the surrounding in order to optimize their resources such as water, oxygen and nutrients. Roots exploit the layer structure of roads by rooting into the material that provides pores large enough to penetrate or which hasn't been compacted enough (Reichwein, 2002). The interface between the layers serves as possible rooting space, especially directly underneath the top layer or along solid construction components. Any space created by frost and thaw actions or thermal expansion and contraction, as well as different sedimentation processes can be vital for roots (Reichwein, 2002). The verge of roads is often little compacted and serves as rooting niche (Reichwein, 2002).

Focusing on roads and paved paths, typical forms of damage are bump and crack formations in the pavement, which are transverse across the road or centrifugal from the tree (Kopinga, 1994). The secondary growth of roots creates pressure against constructed barriers resulting in deformation. Coarse roots with a diameter of 5 to 10 cm can already lift the top layer (Reichwein, 2002). Kopinga (1994) analyzed the mechanisms that lead to disturbance of cycle path through root growth, which can be related to the existing conditions at the Treppelwege. Cracks and bumps were frequently occurring damages created by roots growing underneath the pavement with diameters as little as at 2 cm (Kopinga, 1994). He observed that the roots' growth pattern changed once they entered the road structure. Underneath the asphalt, the roots were long with little lateral root formation, resuming their normal rooting behavior as soon as they exited the cycle paths. It is likely that the constant soil moisture underneath the top layer attracts roots that find little water in the verge, which is gradually drying out until the next rainfall (Kopinga, 1994). The roots absorb the moisture, which is at field capacity (Kopinga, 1994) causing soil shrinking and settling, which can damage the structure indirectly (Morgenroth, 2008). It also causes rapid apical root growth that lead to altered rooting pattern mentioned above (Kopinga, 1994). The degree of the road bed compaction is another of the reasons why roots penetrate the interface between top layer and base course. Limited in places to grow, the roots develop underneath the pavement, where the various expansion rates of top layer and base course material cause permanent or occasional space for root penetration (Kopinga, 1994). According to Robert Day, roots that travel underneath the pavement commence their usual growing activities once they reach undisturbed soil (Randrup et al., 2001). Damages can occur within the first years after construction of infrastructure (Kopinga, 1994), causing immense maintenance costs and illustrating the importance of planning and management before the construction of roads (Randrup et al., 2001; Reichwein, 2002).

2.5 Mitigation and prevention

A variety of mitigation and prevention methods has been developed over the years to minimize potential damage of tree root on infrastructure and vice versa. In the following paragraphs, an overview of common methods is given. Some of these measures focus on solutions in urban areas, which might be unfeasibly or inefficient in rural settings and on a larger scale.

From a purely engineering point of view, the easiest and most effective damage prevention method is avoiding an interaction of plant and infrastructure. This would lead to an avoidance of roads next to existing tree plantings and renounce of planting new trees next to infrastructure (Kopinga, 1994). Since this option is often not desirable, it is important to either mitigate the already occurred damages and/or prevent degradation of infrastructure. The probability of pavement damages is high if certain factors are present (Randrup et al., 2001):

- Fast growing tree species with large maturity stage, as well as trees, which are older than 15-20 years
- Planting trees in restricted space
- Modified soil properties such as a shallow top-soil layer and compacted soil
- Lack of foundation underneath the pavement
- Close proximity of trees and sensible construction (less than 2-3 m)
- Lack of planning beforehand, which allows the consideration of a interaction between plants and constructions

Methods for damage reduction can be tree-based, infrastructure-based and root zone-based (Costello and Jones, 2003):

- Tree-based strategies: species selection and root pruning (Costello and Jones, 2003)
- Infrastructure-based strategies: bigger planting space, curving sidewalks, tree islands, bridging, modified gravel layer, reinforced or thicker slab, expansion joints, compacted gravel, pavers (Costello and Jones, 2003)
- Root zone-based strategies: root barriers, continuous trenches, root paths, steel plates, structural soils or other modification of soil, water management (Costello and Jones, 2003)

Common remedial strategies are either the removal of the roots and/or the tree altogether, or the integration of tree roots by providing more space for growth (Reichwein, 2002). Such measures are often short-lived before structure failure commences again. Prevention promises greater success by inhibiting roots from entering the engineering structures. Typical measures are barriers that guide the roots away from sensitive objects or restrict the growth otherwise (Reichwein, 2002). Traps, deflectors and inhibitors are commonly used to protect roads from the influence of root development (Mullaney et al., 2015; Randrup et al., 2001). To some extend, a strategy has both remedial and preventive features (Costello and Jones, 2003). None of the commonly used methods can guarantee high effectiveness and the success rate of these countermeasures is highly dependent on their implementation, the local conditions and to some extent the tree species, age and size (Reichwein, 2002; Randrup et al., 2001; Costello and Jones, 2003). This dependence makes most prevention methods susceptible for malfunction and increases the necessity of alternative measures.

2.5.1 Mitigation methods

The right choice of mitigation method is always difficult depending on factors such as costs, effectiveness, durability and feasibility (Reichwein, 2002). From a structural point of view, it is often advisable to restore the original road, which requires the removal of tree roots. Keeping the demands of the vegetation in mind, the approach of widening the available area for root growth is optimal. This method preserves the tree's roots, which should not be harmed or removed and enables future development. These methods can be categorized in root preserving methods and methods with root removal (Reichwein, 2002). Some of them are described in the following paragraphs.

Root preserving methods

- Widening of the tree zone

Prerequisite for this method is the spatial possibility of widening the tree zone without affecting the traffic space negatively. Additionally, the roots need to be protected from traffic loads and cared for by experts. Additional rooting space is made available by removing the restricting barriers, the pavement, the base course and any material, which hampers root growth. The border to the structure of the road is reinstalled further away from the tree trunk and the new tree zone filled with plant substrate (Fig. 6). During the process, special attention is paid to the roots to avoid damaging them. The method works well on small tree zones and for trees with coarse roots close to the surface. A drawback is the high level of tree care and increased protection of the tree zone (Reichwein, 2002).

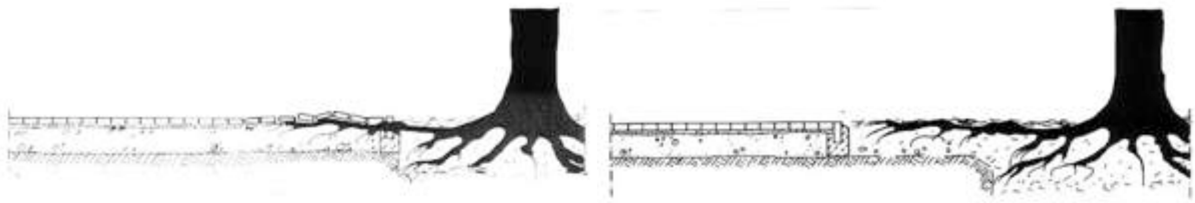

Figure 6 *Schematic cross section of tree zone before and after widening (Reichwein, 2002).*

- Root Bridge

The installation of root bridges, also called tree grates, prevents pressures and traffic loads compromising the development of tree roots (Fig. 7). At first, the tree zone is widened (see widening of tree zone). Self-supporting steel grids are placed on previously fixed foundations, leaving room for growth between the roots and the grid. It is necessary to ensure that the foundation elements do not impair the roots. Usually, the surface level is raised, which makes an adjustment of the surroundings inevitable. This is often financially challenging (Reichwein, 2002).

Figure 7 *Installed root bridge in Prague, Czech Republic (Prague, December, 17. 2016).*

- Replacement of top layer

The damaged top layer is replaced by flexible water-bound top layers, aggregate blends, or asphalt (Reichwein, 2002). This cost-efficient method allows some adjustment of the surface when the tree roots thicken. It decreases the effects of raised surface levels and avoids edges. A disadvantage is the pressure load and the fast erosion and abrasion. It is possible that increased secondary growth creates cracks even in the more flexible top layer, which needs to be repaired at a later stage. This can be avoided by adding bitumen to the material (Reichwein, 2002). The use of gravel paving or stone dust is known to be a relatively cheap option, where the material has little effect on the tree trunk and can be installed leaving little distance to the stem (Urban, 2008).

- Creating the same level of the surrounding structure

Occasionally, the modification of the surface without the removal of tree roots is only feasible be adding material and raising the surface level in close proximity of the tree. Adverse effects of root growth such as cracks are repaired and tripping hazards removed (Reichwein, 2002). The new material is applied directly on top of the degraded structure (Fig. 8a). Pavers and panels need to be removed first before the area can be leveled out with additional gravel or sand. Subsequently, the new layer is installed (Fig. 8b). The modification causes the pavement to curve, which needs to be considered especially for paving stone layers (Reichwein, 2002).

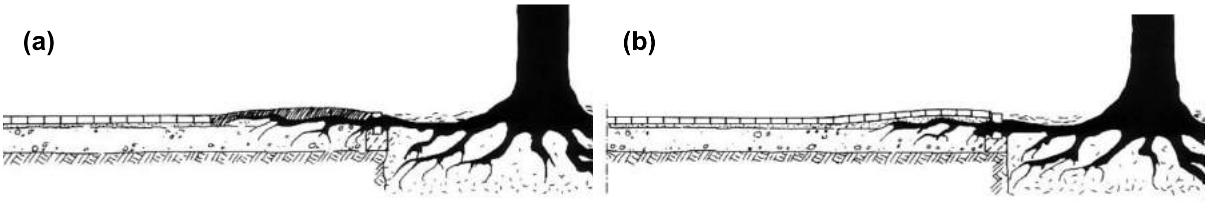

Figure 8 *Recovery of top layer with asphalt (a) and cobble stone (b) (Reichwein, 2002)*

Another method is the removal of some base course material to lower the level of the surface, which has been lifted by the roots (Fig. 9). The process is only feasibly if the roots grow in lower levels, otherwise some root damage cannot be prevented (Reichwein, 2002).

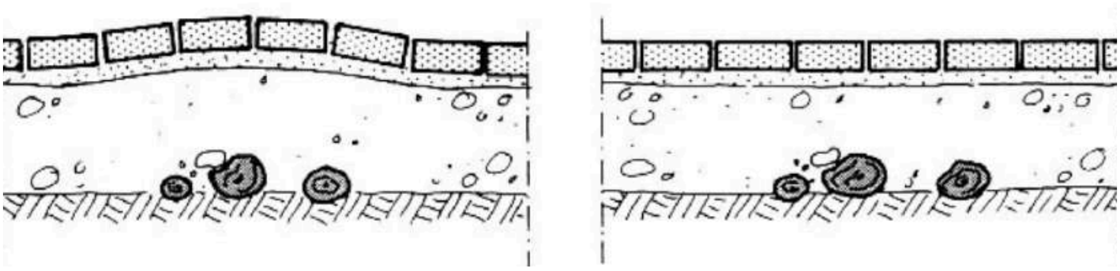

Figure 9 *Restoration of surface layer by removal of base course material (Reichwein, 2002)*

Methods including root removal

Root removal needs to be undertaken with special care and expertise, because it can damage the tree severely and lead to instability and further damages to the surrounding structures (Reichwein, 2002; Costello and Jones, 2003). Only roots with root diameter less than 3 cm should be extracted (Reichwein, 2002). Root size, share of roots removed compared to the whole tree, cutting proximity to the stem, root distribution and age of the tree influence the impact of root pruning. The risk of injuring the tree rises with the number of roots removed, the size of the individual roots, and the age of the tree (Costello and Jones, 2003). Root removal should not be the first choice of mitigation method, because of its adverse effects, and alternatives are highly recommended (Costello and Jones, 2003).

Occasionally, root pruning is undertaken at the same time as altering and remediating the road structure, depending on the amount of roots that impair the road. This can include replacing the top layer, the boarder of the tree zone (curving sidewalks) or the whole road structure, which is necessary when a tree needs to be removed completely (Costello and Jones, 2003; Reichwein, 2002). The effectiveness differs and depends on the extent of the method, the local conditions and the removal itself. Fine roots can cause similar problems after secondary growth, even if larger roots are removed (Reichwein, 2002).

2.5.2 Prevention methods

To avoid any harmful interaction between plants and infrastructure, planning and management are essential. Implementing structures that prevent road failure and tree damage can save maintenance costs (Costello and Jones, 2003). The selection of a tree is considered a preventive strategy, since the genetic setup influences the appearance of the aerial and underground portions of a tree. The development of buttress roots, and large trunk flares, as well as root systems close to the surface are to be avoided (Costello and Jones, 2003). The authors mention that the reaction of the trees to the local conditions can affect the rooting behavior. Hence, recommendations need to be treated with care and the reliability of this method is not ensured (Costello and Jones, 2003).

It is important to keep in mind that the local conditions can influence any method to some extent. The right implementation is crucial for the success. This includes allowing enough space for the roots to grow, adjusting the method according to the existing plants and the local conditions as well as considering the soil. (Crow, 2005; Costello and Jones, 2003).

Enlarging the rooting space

The implementation of root bridges can also be considered a preventive method by reserving enough space for the tree to grow, which subsequently leads to less interaction of tree and hardscapes at a later stage of maturity. The concept of maximizing the distance between roots and infrastructure is applied by most root space enlargements, since this reduces the potential for degradation (Costello and Jones, 2003). Using material that is penetrable by roots without damaging the structure is another option. By ensuring high levels of aeration and water availability in greater depths of the soil body, roots are given incentives to grow deeper (Reichwein, 2002). Reichwein (2002) mentions that none of the above mentioned methods can guarantee success and little research has been undertaken to prove their effectiveness.

Root barriers

The concept of this method is redirecting roots away from sensible infrastructure by the means of chemical or physical restrictions (Reichwein, 2002; Costello and Jones, 2003). The physical barriers prevent damages by redirecting the roots in an assigned space. This often results in deflecting them into deeper soil layers underneath the sensible construction (Costello et al., 1997). Chemical barriers inhibit the growth through the application of chemicals such as herbicides (Randrup et al., 2001). The effectiveness has yet to be proven in different soils and the environmental impact needs to be considered (Reichwein, 2002). Gilman (2006) examined the effects of the chemical barrier ‘Biobarrier’, ‘DeepRoot’, polyethylene and a gravel layer under sidewalk over a period of 8 years. The author states that the strategy using ‘Biobarrier’ was effective in deflecting the roots into deeper levels even in poorly drained soil (Gilman, 2006).

The barriers can also be classified according to their types, which are according to Randrup et al. (2001) deflectors, inhibitors and traps. Deflectors are panels, sheets rolls and planters, mostly made out of plastic, redirecting the roots by mechanical means. They are solid and change the growth path of the roots sideways and/or downwards. Some deflectors have additional vertical ribs attached to prevent circular growth (Randrup et al., 2001). Inhibitors are landscape fabrics or screens, which have been treated with chemicals to stop root development and growth once the root is within the area of the barrier’s activity. Some inhibitors are impregnated with herbicides, others are copper-infused or made out of cupper altogether (Randrup et al., 2001; Reichwein, 2002). The third category consists of traps, such as screens, welded-fiber sheets or fabrics. The applied principle is that the tips of the roots are able to grow through the barrier, but their radial growth is restricted by the size of the holes in the traps (Randrup et al., 2001).

The barriers can be implemented linear or circular, depending on the requirements. Linear elements are placed along the sensitive construction before the tree´s planting or installed in trenches afterwards. Circular barriers surround the roots constricting the vertical growth and guiding the development into deeper layers of the soil (Costello et al., 1997; Randrup et al., 2001). It is possible that the root development is limited to the extent of harming the tree’s stability, especially in soils with poor quality (Randrup et al., 2001).

The effectiveness of root barriers is yet to be proven. Morgenroth (2008) has compared different studies on the subject and came to the conclusion that the studies all result in a heavy dependence on local conditions such as soil type, environmental conditions and species selection (Morgenroth, 2008). The barriers perform best in well-aerated soil with little compaction (Gilman, 1996), which is the opposite of most sites where the measures are implemented. In favorable soil, the roots remain growing in deeper levels rather than turning upwards again (Costello et al., 1997). Morgenroth (2008) mentions that more research is necessary regarding the optimal depth for root barriers. Most studies examine the effects of barriers installed in 30 cm depth. Whilst roots change their growth downwards in close proximity to the barrier, they resume their initial growth direction or venture into shallower soil levels. Implementing the barriers deeper into the soil body could improve their impact (Morgenroth, 2008). Reichwein (2002) voices her doubts concluding that root barriers might delay the development of roots but do not achieved the desired results of limiting and redirecting roots permanently (Reichwein, 2002).

Adaption of base course material

A strategy that has been commented positively by many scientists (Reichwein, 2002; Gilman, 2006; Costello and Jones, 2003) is the use of coarse gravel as base course material. Some of the commonly used material for the base course can force roots to penetrate the interface between top layer and base course, as described in the section 'Vegetation affects infrastructure'. Kopinga (1994) recommends the use of rubble as road bed filling, which prevented root development even after several vegetation periods. The material consisted of ground to course fragments of debris of bricks. At locations where sand was present in the base course after being washed in by rain, roots were able to develop. This lead to the assumption that the high mechanical resistance of the course fragments combined with their irregular structure results in an undesirable rooting space, which cannot be bridged by roots (Kopinga, 1994).

Costello and Jones (2003) mention base course modification such as large-diameter gravel, thicker layers or layers with increased density. They describe that the effects of large grain sizes reduce the water retention and therefore create an environment ill suited for root development. It is important to use coarse gravel and prevent fine fragments from entering the base course to air-prune roots (Costello and Jones, 2003). This requirement can decrease the feasibility of the method, especially in areas, which are known for heavy rainfall or flooding. As mentioned before, Gilman (2006) studied the effects of the barriers 'Biobarrier', 'DeepRoot', polyethylene and a gravel layer under sidewalk over a period of 8 years. The use of a clean gravel layer under the sidewalk was clearly the most successful strategy in well-drained soils, which he explains with the air space created by the coarse fragments and their drying nature (Gilman, 2006). The effects were less present in poorly drained soil, but remained as successful as the other barriers (Gilman, 2006).

The use of crushed course gravel as a vertical barrier for tree roots is currently implemented as a remedial strategy along the Treppelwege (Weissteiner, 2015), after consultation with the University of Natural Resources and Life Sciences. The strategy of using crushed course gravel with different grain size distributions as base course material is examined separately as a small-scale field experiment in Groß Enzersdorf, which will be described in the chapter 'Material and method'.

3 Material and methods

The following chapter describes the setup of the field experiment in Groß Enzersdorf and the progress of gathering the necessary information to answer the research questions. The information about the initial setup, the structure and the building process is based on Michael Müllner's master thesis "Woody roots as cause of damages on paved paths. Penetration of riparian tree roots in matrix stone mixtures with different grain size distributions" (2016), in which he presents the results of the first stage of the field experiment.

3.1 Groß Enzersdorf

The small-scale field experiment is located in Groß Enzersdorf, a municipality in the district Gänserndorf in Lower Austria, east of Vienna. The experimental farm of the University of Natural Resources and Life Sciences BOKU is situated at the border of the town.
The area is characterized by Pannonian climate influences, such as high temperatures and low humidity during the summer months, as well as cold winters with little snowfall. The average annual temperature is 9,8°C, the average annual rainfall 545 mm, and the relative annual humidity 75%. The soil shows properties of a chernozem soil. It is profound, medium hard and has compounds of silty clay (DNW, 2017).

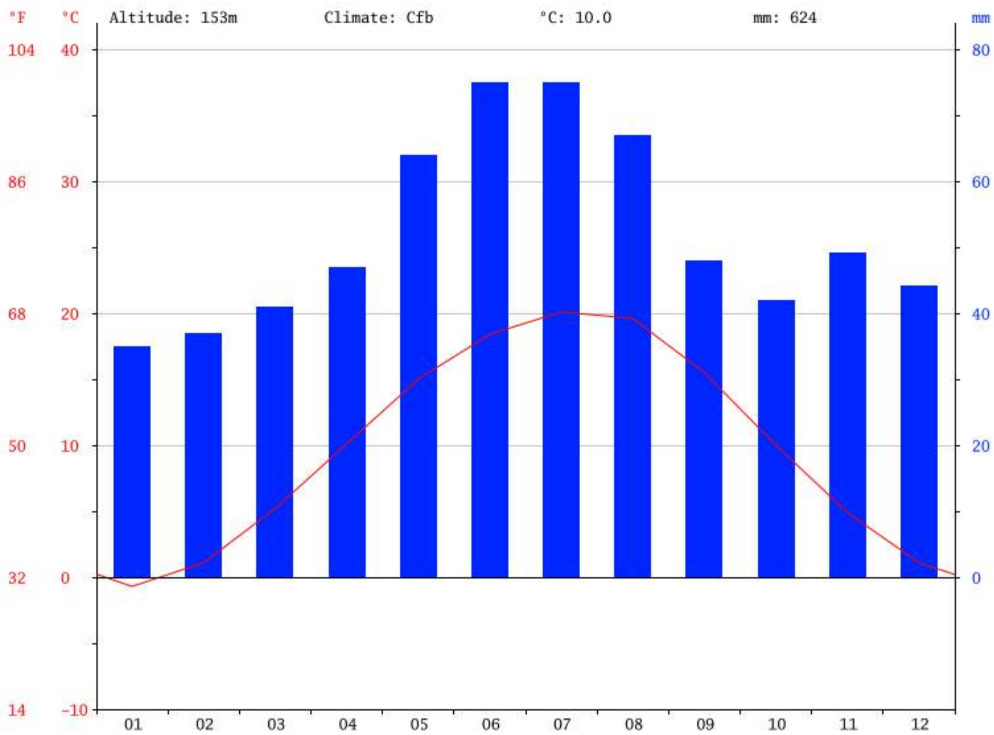

Figure 10 *Annual precipitation and temperature change in Groß Enzersdorf (Merkel, 2017).*

January receives the least amount of rainfall with 32 mm, whereas in June, the highest rainfall with 75 mm was recorded (Fig. 10). In average, the hottest month is July with 20,1°C.

The monthly average temperature of -0,7°C is documented for January, which makes it the coldest time of the year (Merkel, 2017).

3.2 Experimental setup

The field experiment was set up in 2015 and is documented by Müllner and Weissteiner (2016) and Müllner (2016). It is aimed at gaining short- and long-term information about penetration and development of roots in different sized coarse gravel mixtures. The repetitive setup of the experiment made it possible to divide the biomass extraction in three stages (Fig. 11):

- Stage 1: after one vegetation period (2015)
- Stage 2: after two vegetation periods (2016)
- Stage 3: after several vegetation periods (presumably 2019)

According to Müllner and Weissteiner (2016) each repetition was built the same way, guaranteeing the comparability of the different stages. The focus of the experiment lies on six different sized coarse gravel mixtures (0/32, 04/32, 08/32, 16/32, 0/63 and 16/63) and one hydraulically stabilized mixture (08/32 hs) (Müllner, 2016). The mixture with the finest fragments has an average grain size distribution between 0 – 32 mm, whereas the 16/63 mixture contains the coarsest gravel with an average grain size distribution between 16 – 63 mm. They are examined according to their suitability as base course for infrequently used roads. Factors such as grain size distribution, aeration of the soil, drainage effects and the resulting soil-water regime contribute to the outcome of the experiment and the performance of road bed fillings (Müllner, 2016).

Two box types were set up on a lower base course layer that consists of a 0/63 substrate for the whole area. According to Müllner and Weissteiner (2016) and Müllner (2016), the first type of box, called road structure boxes (RSB), facilitate an examination of the influence of the gravel mixtures, as well as the effect of the top layer on the soil water regime. This type of box resembles a road structure including a top layer, a base course divided in two separate layers (unbound with the exception of the hydraulically stabilized mixture) and a subgrade (Müllner, 2016). The upper layer of the base course is made up of the different sized gravel (0/32, 08/32, 16/32, 0/63, 16/63 and 08/32 hs) covered by a concrete top layer (Müllner, 2016). The second type of box, called substrate boxes (SB) are not covered with a top layer and are smaller then the road structure boxes. They are filled with 0/32, 04/32, 08/32, 16/32, 0/63 and 16/63 gravel mixtures. This box type ought to enable an analysation of the impact of the gravel mixtures on root biomass production without the potential condensation effects underneath the top layer (Müllner, 2016).

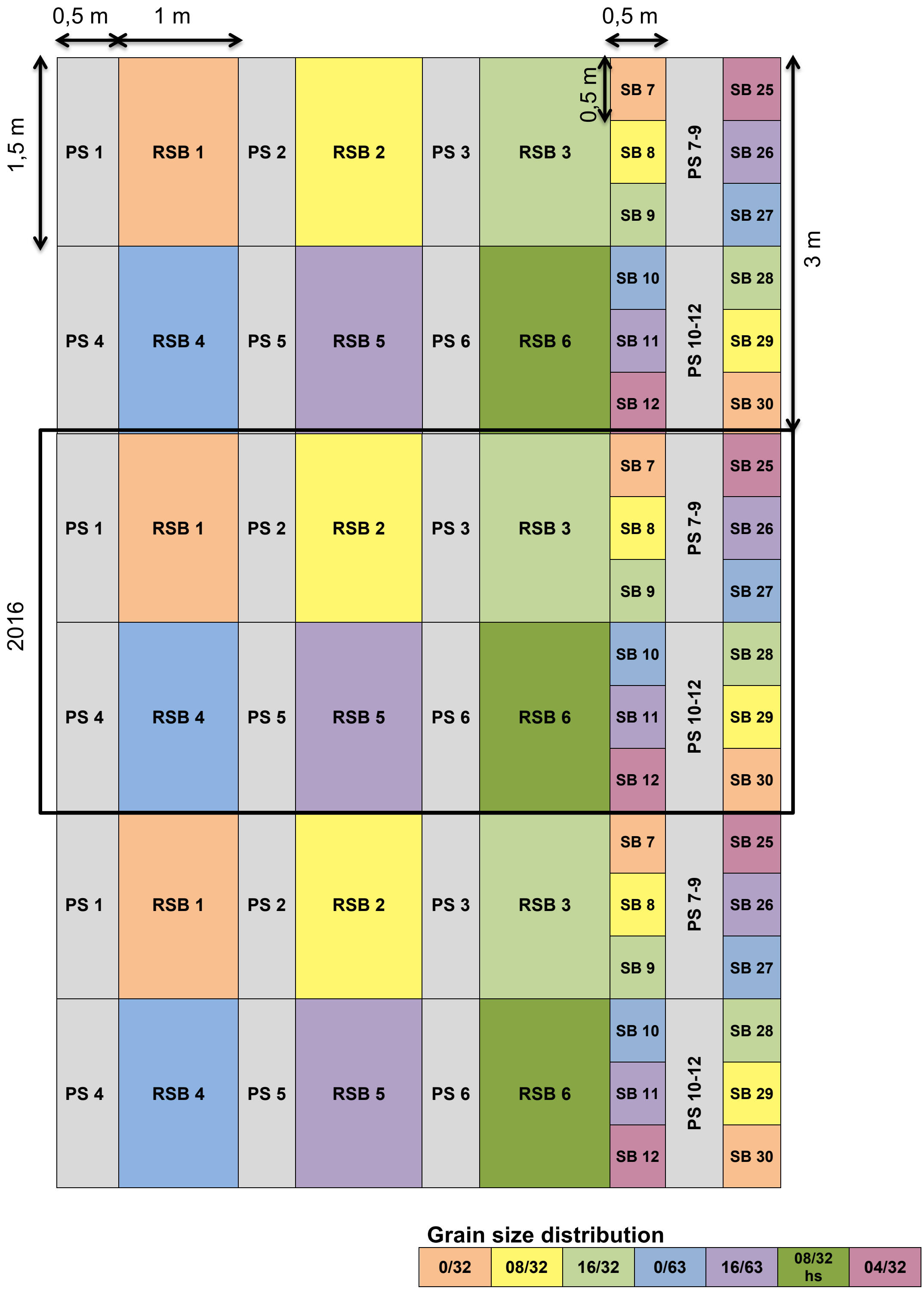

Figure 11 *Schematic set up of field experiment in Groß Enzersdorf (Müllner and Weissteiner, 2016; modified).*

An area of 54 m^2 was uncovered (6 x 9 m) and a hole of 0,8 m depth excavated. The first 25 cm were filled with crushed gravel of the grain size distribution 0/63. This was topped up with 0/32 crushed gravel of 5 cm depth to create a smooth surface. Subsequently, it was compacted with the aid of a vibrating plate. These two unbound mixtures are the lower layer of the base course, which should enhance the drainage and stability (Müllner, 2016; Müllner and Weissteiner, 2016). To separate the lower and the upper layer of the base course, a drain geomembrane (200 g/m^2) was installed. Afterwards, a system of different sized boxes was constructed to enable the two different testing methods (road structure box and substrate box). The road structure boxes have the measurements 1,5 x 1 x 0,5 m. Three walls of the box are constructed of wooden formwork elements. The fourth wall is facing the planting strip and a set of geotextile (coconut fiber), mesh wire (0,7 mm thickness and 13 x 13 mm mesh size) and reinforcement steel mesh (8 mm thickness and 10 x 10 cm mesh size) (Müllner, 2016; Müllner and Weissteiner, 2016). The geotextile functions as a border between soil and gravel to prevent soil material from entering the gravel mixture. The reinforcement mesh stabilizes the construction and the mesh wire reduces the mesh size. This structure allows roots to penetrate the gravel mixtures (Müllner, 2016; Müllner and Weissteiner, 2016). To prevent any deformation of the boxes during filling process, the reinforcement mesh is connected with the opposite wooden wall by two cross bracing steel of 6 mm thickness. A plan- and sectional view of the road structure box setup with its different elements is shown in Fig.12. This overview includes the humidity sensors that were placed in the six of the 18 road structure boxes. These boxes are part of the last stage of the field experiment and will therefore not be included in this thesis (Müllner and Weissteiner, 2016; Müllner, 2016).

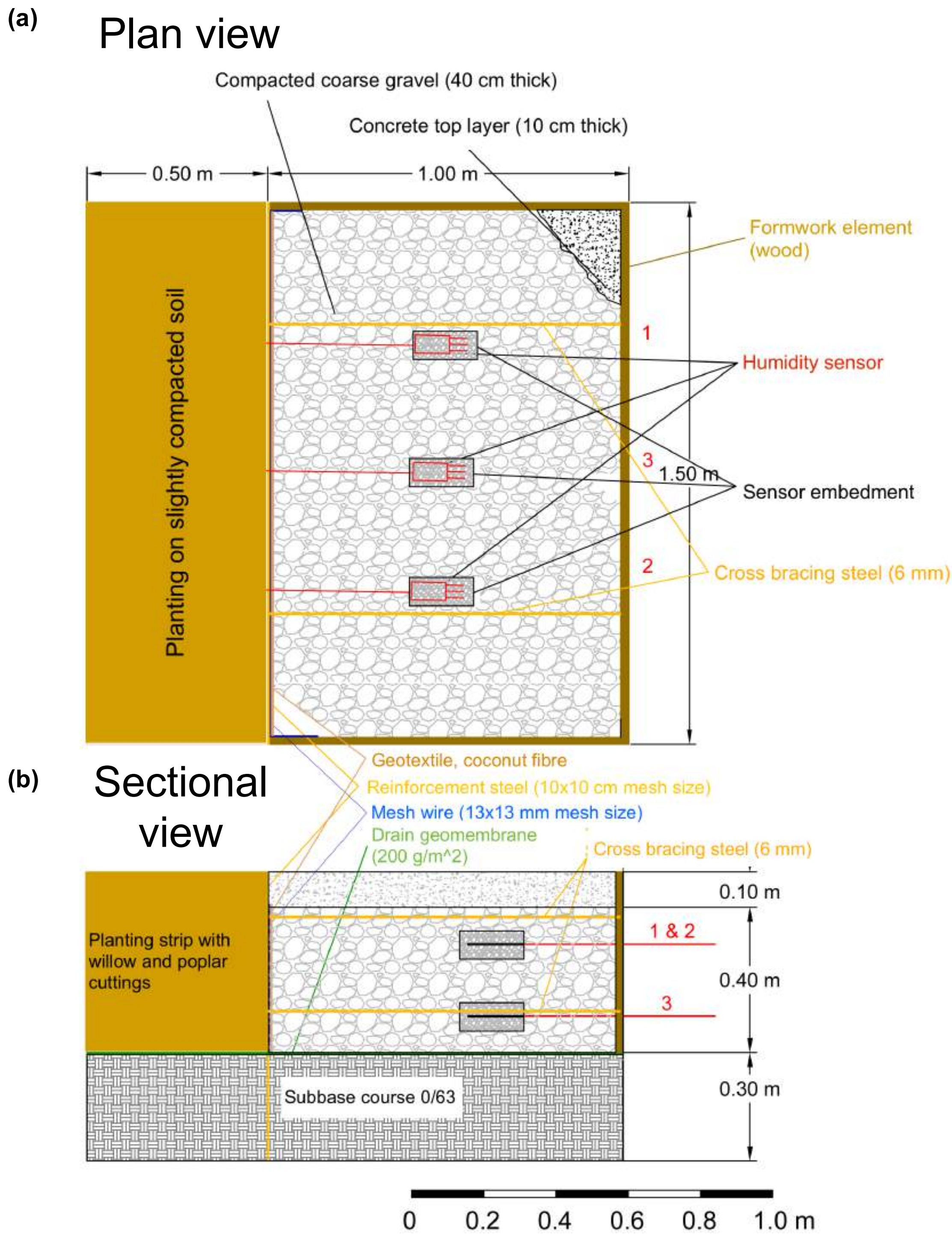

Figure 12 *Schematic plan view (a) of road structure box and sectional view of road structure box (b) (both: Müllner and Weissteiner, 2016; modified)*

Three rows of each six road structure boxes were placed in 0,5 m distance on top of the drain geomembrane, facing one way (Fig.13a). In three repetitions, the boxes were filled with the same sequence of different coarse gravel mixtures (Müllner, 2016; Müllner and Weissteiner, 2016). The schematic overview in Fig. 11 illustrates the gravel mixture series. By distributing the substrates in a set order, the repeatability of the extraction at different times is ensured (Müllner, 2016).

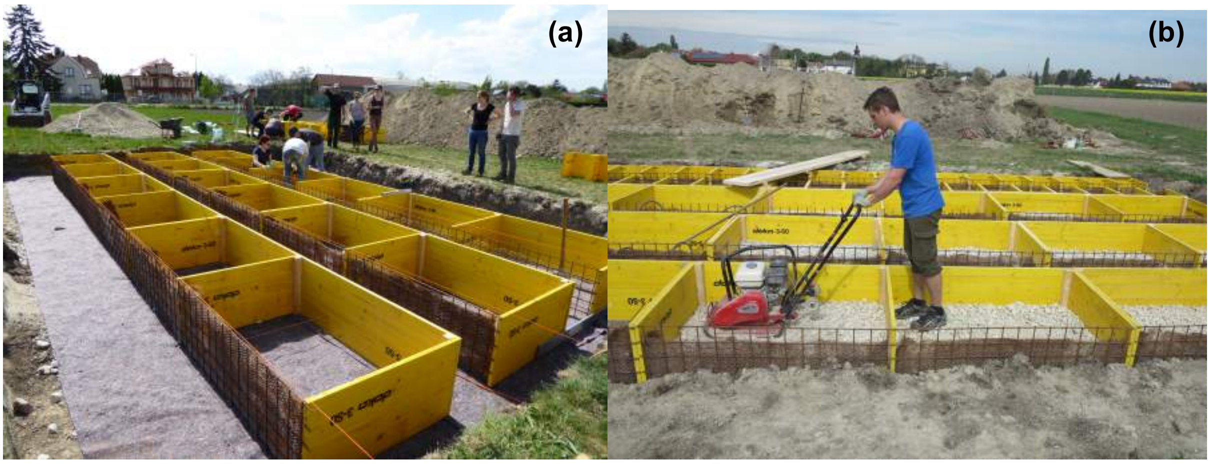

__Figure 13__ Construction of experiment: road structure boxes on drain geomembrane (a) and compaction of gravel mixture with a vibrating plate (b) (Müllner, 2016).

The filling process of the boxes was undertaken in two stages. First, a layer of the gravel mixtures with a depth of 20 cm was installed, which was compacted with a vibrating plate. Subsequently, it was topped up by another 20 cm layer of the same gravel mixture and compacted as well. Three of the 18 boxes were filled with substrate with the grain size distribution 08/32, which was stabilized with 3% cement. While the boxes were filled with gravel, the space between the boxes was filled with soil, where the poplar and willow cuttings were planted afterwards (Fig. 14b) (Müllner, 2016; Müllner and Weissteiner, 2016). To create a setting that resembles an urban area, the soil was slightly compacted. The concrete mixture C25/30 XC1 GK 16 F45 CEM II 42,5N was chosen as top layer material, because it is easily installed in small areas. The condensation effects are assumed to be very similar to asphalt, because the light coloring of the concrete counters the greater thermal conductivity compared to asphalt. The concrete mixture covers the road structure boxes with the thickness of 10 cm (Fig. 14a) (Müllner, 2016).

__Figure 14__ Construction of experiment: smoothing the concrete top layer (a) and planting of willow and poplar cuttings (b) (Müllner, 2016).

The substrate boxes have the measurements of 0,5 x 0,5 x 0,5 m, and are similarly constructed to the road structure boxes, as described by Müllner (2016) and (Müllner and Weissteiner (2016). Fig. 15 shows the plan view and sectional view of the substrate boxes.

Three walls are constructed of formwork elements; the fourth wall is made up of an arrangement of geotextile, mesh wire and reinforcement steel mesh (Müllner, 2016; Müllner and Weissteiner, 2016). In contrast to the road structure boxes, the substrate boxes were placed on the fleece facing each other. The permeable walls are 0,5m apart, as shown in Fig. 15. In three repetitions, the boxes were filled with six different substrates, whereby a 04/32 coarse gravel mixture replaces the 08/32 hs substrate. The use of the vibrating plate was not feasible due to the smaller sizes of the boxes. Therefore, the gravel mixtures were manually compacted. The planting strip between the two rows of substrate boxes was filled with soil at the same time as the gravel mixtures to decrease potential deformation and slightly compacted (Müllner and Weissteiner, 2016; Müllner, 2016).

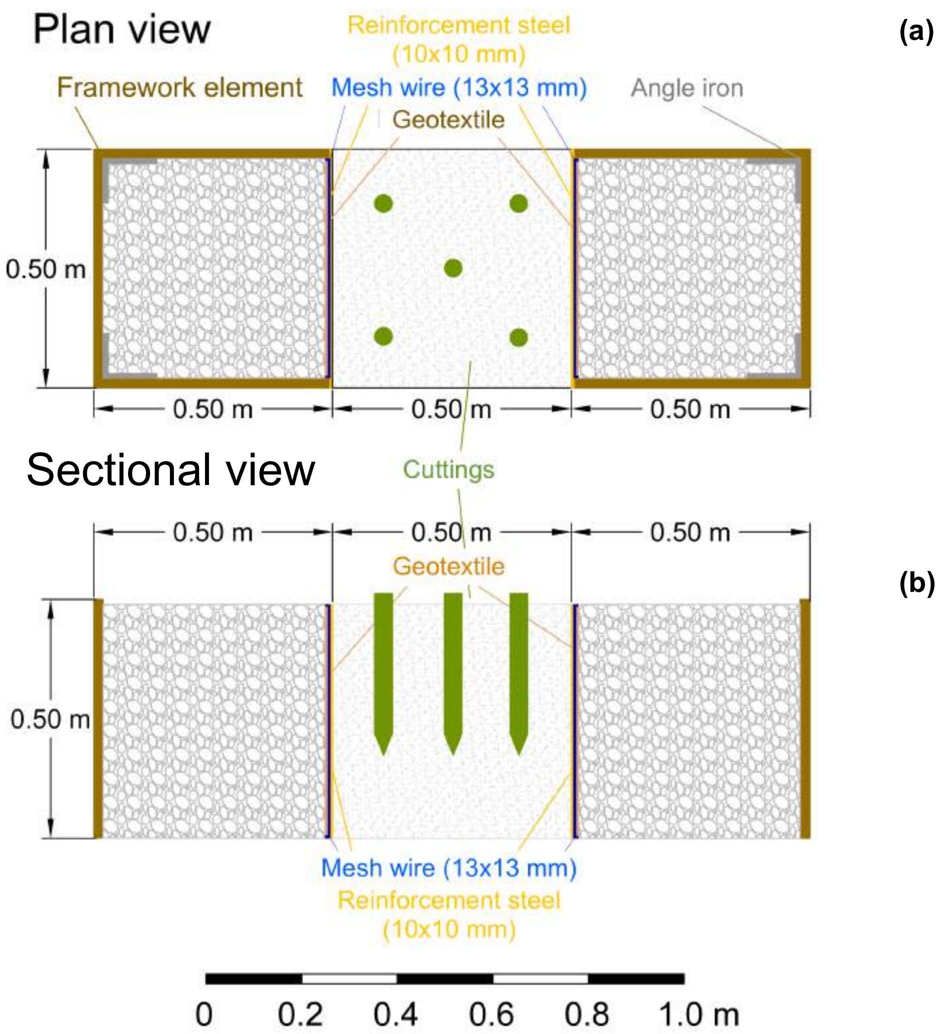

***Figure 15** Schematic plan view (a) and sectorial view (b) of substrate boxes (Müllner, 2016; modified).*

As mentioned before, the planting strips accommodate the plants and therefore the root source. Willow and poplar cuttings were planted evenly distributed (Fig. 14b). Approximately eight cuttings per linear meter were planted in the planting strip next to the road structure boxes, whereas up to 14 cuttings in the planting strip between the substrate boxes. The number of cuttings was increased because the planting strips connected to the substrate boxes function as root source for more boxes compared to the planting strips next to the road structure boxes. The cuttings have an average length of 40 cm and a diameter variety of 1,5 – 5 cm (Müllner and Weissteiner, 2016; Müllner, 2016).

The biomass data collection was undertaken in fall, once the plant growth stagnated. Each stage of the field experiment includes the harvest of six road structure boxes and their connecting planting strips, as well as twelve substrate boxes and the planting strip between them.

3.3 Biomass extraction

In the following paragraphs the planting strips are also referred to as PS, road structure boxes as RSB and substrate boxes as SB.

To collect the data, which was required to gather information about the development of the tree roots in the different coarse gravel mixtures in 2016, the extraction of the biomass was split into several stages:

1) Collection of aboveground biomass
2) Extraction of underground biomass

Removal of concrete top layer
Collection of planting strip roots
Collection of road structure box roots
Collection of substrate box roots

The biomass collection started with the harvest of the aboveground biomass of the first planting strip, followed by extraction of the roots of the same planting strip. One planting strip after the other was attended to in this fashion. Before the planting strips between the substrate boxes were harvested, the concrete top layers were removed. This was done with the use of a concrete cutter.The layers were cut longitudinally, and smashed into smaller pieces with a sledge and a chisel. The concrete pieces were removed, uncovering the coarse gravel mixtures underneath. This procedure is shown in Fig. 16.

***Figure 16** Removal of concrete top layer on road structure boxes (Groß Enzersdorf, September, 22.2016)*

Afterwards, the aboveground harvest of the remaining planting strips was undertaken. This order of excavation was chosen to minimize the effects of the removal of the aboveground biomass on the underground biomass. Subsequently, the roots in the road structure boxes were extracted, followed by the roots in the substrate boxes.
The detailed description of the procedure is structured according to aboveground biomass, underground biomass of the planting strips, the road structure boxes and the substrate boxes.

3.3.1 Aboveground biomass

As a first step, the planting strips PS1, PS2, PS3, PS4, PS5 and PS6 were divided into squares of equal size (16,6 x 16,6 cm) and a grid was sprayed onto the soil. This measure facilitated the allocation of the cuttings and their biomass data as well as the recording of the spatial distribution. Nine rows (subfields) and three columns were used to number the squares, additionally to the planting strip field number. Each square received an individual set of numbers according to the planting strip, row and column. The grid in planting strips between the substrate boxes differed in size. The squares were larger with the dimensions of 25 x 25 cm. This variation in sizes is due to the position and function of PS7-9 and PS10-12. They were located between the substrate boxes and their construction allowed root penetration of all substrate boxes. A deformation of the planting strips PS7-9 and PS10-12 was observed, which might have been occurred during the initial construction in 2015 or during the development of the plants over the past two years. Close to the border to the next set of boxes from stage three, the soil filled strip was only 30 cm wide. A schematic overview of the grid formation of the planting strips connected to the road structure boxes, as well as between the substrate boxes is illustrated in Fig. 17.

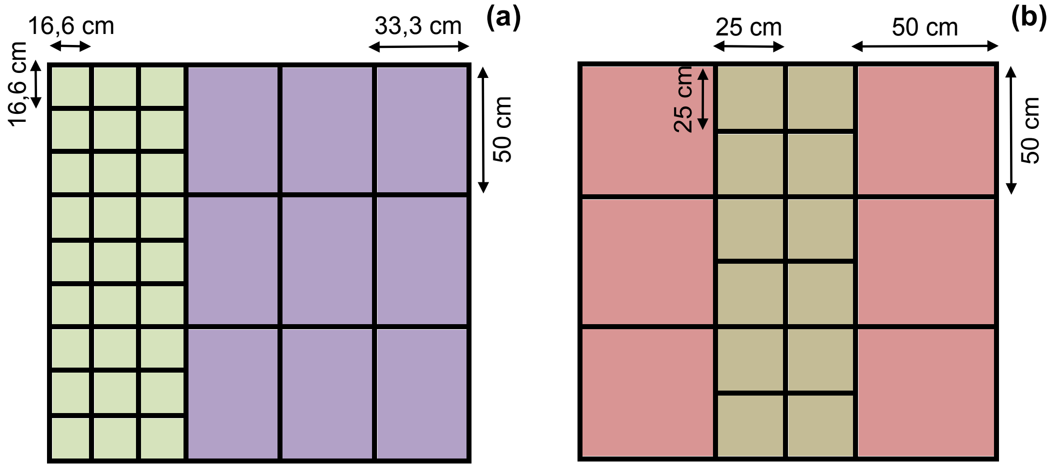

Figure 17 *Schematic layout of grid system on planting strip and connecting road structure box (a) and grid system on planting strip between substrate boxes (b)*

Following, the information was collected from each cutting (Fig. 18a, Fig. 18b):

- Vitality [dead or alive]
- Species [poplar or willow]
- Diameter of cutting [mm]

- Length of longest shoot [cm]
- Number of shoots [-]
- Depth of penetration (data collected during underground biomass extraction) [cm]

Subsequently, the aboveground harvest commenced. From each cutting, the leaf and wood biomass was collected and weighted to assess the wet biomass (Fig. 18c, Fig. 18d).

By drying the biomass at 80°C in a drying cabinet until constant weight, the dry biomass was retrieved.

Figure 18 *Diameter measuring of cutting (a), penetration depth measuring of cutting (b), weighing of wet leaf biomass (b), weighing of wet wood biomass (d) (Groß Enzersdorf, August, 25. – September, 27.2016).*

3.3.2 Underground biomass - planting strips

The grid, which was used for the aboveground biomass collection was kept intact and used for the underground biomass extraction as well. Additionally to the two dimensional grid, a third dimension was used to divide the soil into three levels of 16,6 cm depth (Fig. 19a). This resulted in a segmentation of the field into 81 soil cubes, which are referred to as plots. Each plot in PS 1-6 had the dimension 16,6 x 16,6 x 16,6 cm. The planting strips PS7-9 and PS10-12 were divided into two levels and each had 24 plots with 25 x 25 x 25 cm.

Figure 19 *Planting strip and road structure box with three dimension grid system (a) (Müllner, 2016) excavation of soil plots (b), cutting with roots (c), collected wet root biomass (d) (Groß Enzersdorf, September, 14. 2016).*

Each soil cube was extracted individual by using shovels or spades. During the extraction, special attention and care was paid to the roots within the soil, which were severed according to the borders of the plots (Fig. 19b). The roots, which grew directly from the cuttings, were separated as closely to the wood as possible (Fig. 19c). Occasionally, the soil was very moist, in which case the plots were spread out to dry. By sieving the soil, the root biomass was retrieved and stored according to the plot (Fig. 19d). Roots that grew into and underneath the drain geomembrane were collected separately.

The next step included drying the root biomass in a drying cabinet until it reached constant weight. Any residual soil was removed and subsequently, the roots were categorized according to their diameter:

- 0-2 mm: fine roots
- 2-10 mm: medium roots
- 10 mm: coarse roots

The roots, which grew close to the bottom (third level), were occasionally covered in mud, which made it necessary to clean them before the drying process. They were soaked in water and rinsed carefully, and subsequently dried again. Each category of roots was weighted individually for each plot (Fig. 20).

Figure 20 *Sieving and separating dry root biomass (a), weighing of fine dry roots (b) and weighing of medium dry roots (c) (BOKU Vienna, October, 6. 2016).*

The results of the sieving analysis can be found in the Appendix.

3.3.3 Underground biomass - road structure boxes

The collection of the biomass from the road structure boxes started after the planting strips were excavated. A grid system was applied to gather information about the spatial distribution. Similar to the planting strips, the boxes containing the gravel mixtures were divided into equally sized squares of 33,3 x 50 cm and into three levels of 13,3 cm depth. This resulted in 27 plots for each road structure box (Fig. 21).

Figure 21 *Road structure box with grid system (Groß Enzersdorf, September, 27. 2016),*

The root biomass was retrieved using two different techniques. The first one resembled the procedure used for the planting strips: the plot was excavated and sieved in a coarse sieve (Fig. 22a). If the substrate was moist, the plot was spread out on a tray to dry before it was sieved. Increased moisture levels were observed in lower levels close to the drain geomembrane (Fig. 24b).

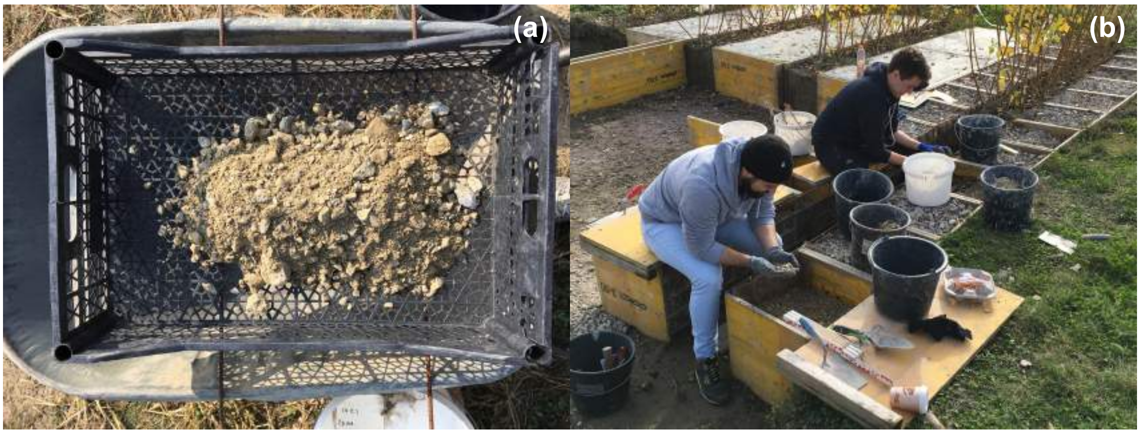

Figure 22 *Sieving process: extracted gravel plot in sieve (a), collecting roots from gravel mixture on site (b) (Groß Enzersdorf, October, 15. – October 28. 2016).*

The second technique was mostly applied for coarser gravel mixtures (16/63, 16/32 and 08/32 hs). The gravel was removed from the box and the roots retrieved by picking them out of the mixtures using garden claws and small shovels (Fig. 22 (b)). The root biomass was collected for each plot. Some examples of the exposed roots are shown in Fig. 23.

Figure 23 *Roots in coarse gravel mixtures (Groß Enzersdorf, October, 27. 2016).*

Some roots grew in and under the drain geomembrane (Fig. 24a) and were collected separately. The formwork elements of the boxes effected the root development, which was notable through an increased growth of fine roots along the framework elements. These roots were collected separately.

Figure 24 *Roots growing in the drain geomembrane (a), muddy drain geomembrane and medium root in substrate box (b) (Groß Enzersdorf, October 15. - 29. 2016).*

The 08/32 hs mixture had to be broken up and loosened before an extraction was possible by driving an iron bar into the solid mixture.

Once the roots were collected, the biomass was dried in the same fashion as the roots extracted from the planting strips. Occasionally the roots, which grew close to the bottom were covered in mud and needed to be soaked in water before they were dried at 80°C in the drying cabinet until constant weight. Afterwards, the roots were categorized according to the root diameter and weighted (fine, medium and coarse roots).

3.3.4 Underground biomass - substrate boxes

The substrate boxes were not covered by a top layer and were mostly extracted directly from the box. Due to the size of the fields (50 x 50 x 50 cm), a grid system was not required. Instead, the boxes were divided into three levels of 16,6 cm depth. This resulted in three plots per substrate box. The substrate and the roots were dug up using small shovels and garden claws (Fig. 22b). The extracted root biomass was collected, cleaned or occasionally washed out and subsequently dried at 80°C until constant weight. Any residual soil was removed before the roots were categorized and weighed according to their diameter.

3.4 Root scans

During the collection and analyses of the root biomass, the root architecture was examined by categorizing it in different root diameter categories. Further examination of the architecture was undertaken by scanning the roots. In the course of a bachelor thesis, Hellerschmid (2017) analyzed samples of the root biomass from each gravel mixtures by scanning the wet roots. The applied program was WinRHIZO, an image analysis system for washed roots and arabidopsis seedlings (Hellerschmid, 2017). The possible uses of the program are morphology, topology, architecture and color analyses of scanned roots (Regent Instruments Inc., 2016). For the purpose of this root scan, Hellerschmid (2017) examined the length and diameter of the sample roots. These parameters help to draw conclusions about the root growth and architecture in the different gravel mixtures. In combination with the measured root length conclusion can be drawn about the suitability of the gravel mixtures as desirable root environment. In each box, one pillar of plots (subfield 2, column 1) was used as a repetitive, representative sample (Fig. 25).

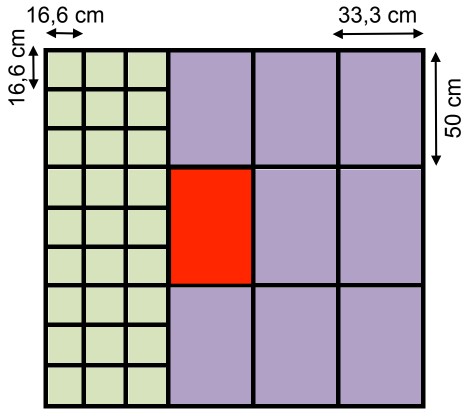

Figure 25: *Schematic plan view of planting strip (green) and road structure box (violet), including a highlighted plot from which the root scan samples were extracted.*

The extracted root biomass of the three levels was collected separately. According to Hellerschmid (2017), the biomass was carefully washed to remove any residual soil before the scan. Divided into smaller shares, the roots were placed in a Perspex tray filled with distilled water (Fig. 26a). Some of the fine root networks needed loosing to be scanned correctly (Hellerschmid, 2017).

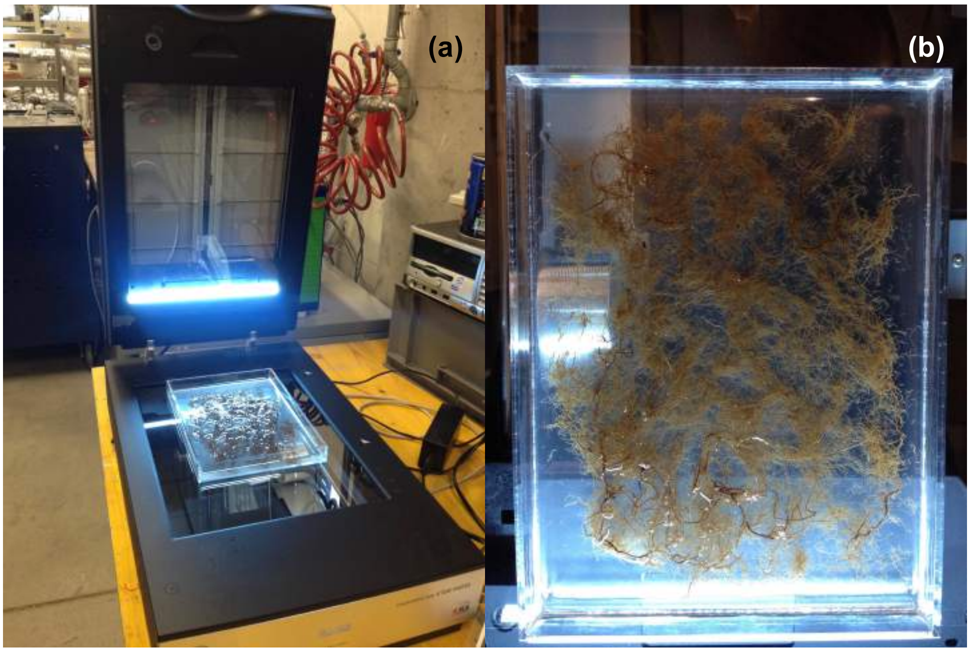

Figure 26 *Wet roots in Perspex tray (a), Epson scanner with Perspex tray, which contains the wet roots (b)(Hellerschmid, 2017).*

The trays were placed in the “Epson Perfection V700 Photo” scanner (Fig. 26b), which was connected to the WinRHIZO and enabled the necessary settings such as the scanning area and the resolution (Hellerschmid, 2017):

- Scanning area: 20 x 25 cm
- Resolution: 600 dpi (dots per inch)

- Diameter categories: at least 20 categories of 0,25 mm

. Depending on the diameter, the roots were categorized in four groups (Hellerschmid, 2017):

- Very fine roots (0-1 mm)
- Fine roots (1-2 mm)
- Medium roots (2-5 mm)
- Coarse roots (5-20 mm)

3.5 Sieving analysis

A sieving analysis was undertaken to examine possible sedimentation processes that could have occurred since the installation of the field study. Such processes could lead to an increase in fine particles in the lower levels of the gravel boxes and promote root growth closer to the bottom.

Two samples per road structure box were taken during the excavation: one from the first level and one from the third level. Additionally, one sample per level was extracted from planting strips PS2 and PS4, which should give insight in the composition of the soil and potential differences.

The samples were labeled and stored until the actual sieving analysis commenced in January 2017. The samples were dried in a drying cabinet at 105°C until they reached a constant. Each sample was placed in the sieve tower HAVER UWL 400 with twelve sieves (Fig. 27a).

Figure 27 *Sieve tower HAVER UWL 400: fully stacked with twelve sieves (a), Manual sieving of gravel mixture sample (b) (Groß Enzersdorf, January, 2. 2016).*

The mesh sizes were 63 mm, 45 mm, 31,5 mm, 16 mm, 8 mm, 4 mm, 2 mm, 1 mm, 0,5 mm, 0,25 mm, 0,125 mm and 0,063 mm. The soil and gravel samples were sieved for 20 minutes. Subsequently, each screen was sieved manually, as shown in Fig. 27b. The substrate in each sieve was carefully collected and weighed. The remaining particles in the collecting tray were weighted as well and documented as < 0,063 mm.

4 Results

In the following chapter the analyses of the collected biomass information is presented. The results are sorted according to aboveground biomass, planting strip roots, road structure box roots and substrate box roots. Furthermore, the outcome of the root scans and the sieving analyses are demonstrated. For the analysis of the temporal development of the field experiment, the collected data is compared to the results of the first stage of the field experiment in 2015.

4.1 Aboveground biomass

The biomass collected aboveground consists of leaf biomass and wood biomass, as well as the information about the planted cuttings. The results are listed according to the planting strip field number. The roots in the planting strips PS 1-6 were allowed to penetrate the road structure boxes, whereas the roots in the planting strips PS7-9 and PS10-12 entered the substrate boxes. Therefore, PS7-9 and PS10-12 are sometimes analyzed separately.

During the examination of the aboveground biomass, the species and survival rate was recorded. 32 of the 121 planted cuttings have died since the planting in 2014, which makes 26% of the cuttings. The surviving 90 cuttings were made up of 20 poplar cuttings (17%) and 70 willow cuttings (57%). The distribution according to the planting strip is illustrated in Fig. 28.

Figure 28 *Distribution of the cuttings in planting strips*

A higher number of cuttings was planted in PS7-9 and PS10-12, since the planting strips were connected to all substrate boxes and therefore served more substrates as root source. This might have resulted in a more competitive environment for the plants, which could explain the comparatively lower leaf biomass in PS7-9 and PS10-12, as shown in the following figures.

The findings of the dry aboveground biomass analysis show that the accumulated poplar leaf biomass exceeded the willow leaf biomass, with the exception of PS3, PS5 and PS10-12 (Fig. 29), although the species were outnumbered by willow cuttings. This is most likely attributable to the shape of the leaves. The dry wood biomass of the willow cuttings was usually higher than the poplar dry wood biomass, except for PS2 and PS4 (Fig. 30). This can be explained by the higher numbers of planted willows. One poplar cutting grew distinctively larger than the other cuttings with a dry wood biomass of 1100 g. This is noticeable in Fig. 29 and Fig. 30 in PS4.

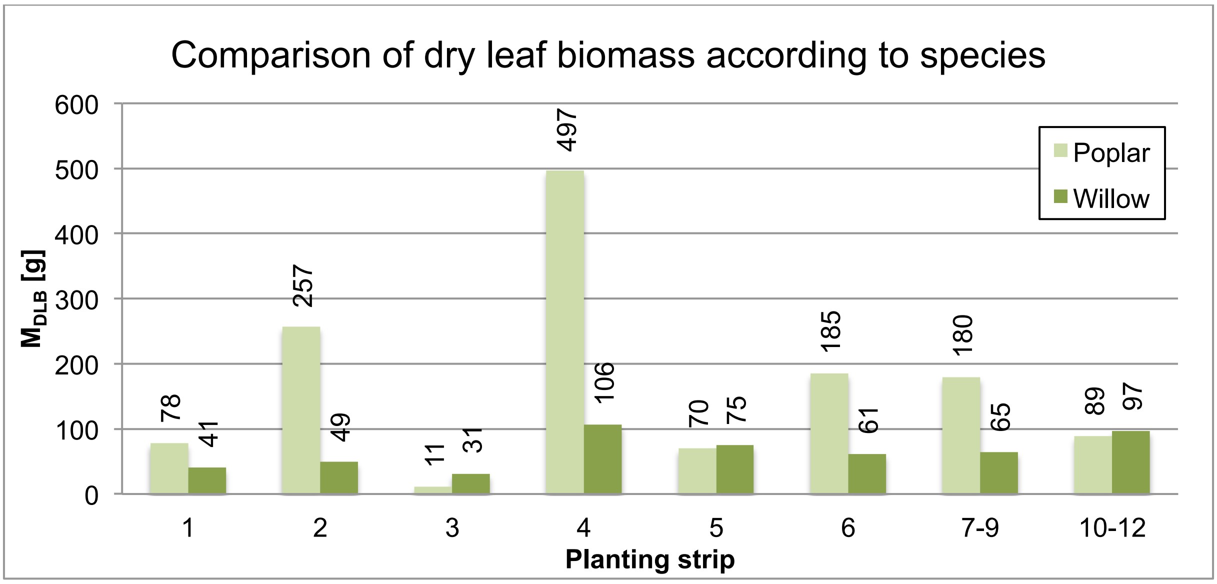

Figure 29 *Dry leaf biomass according to species and planting strip*

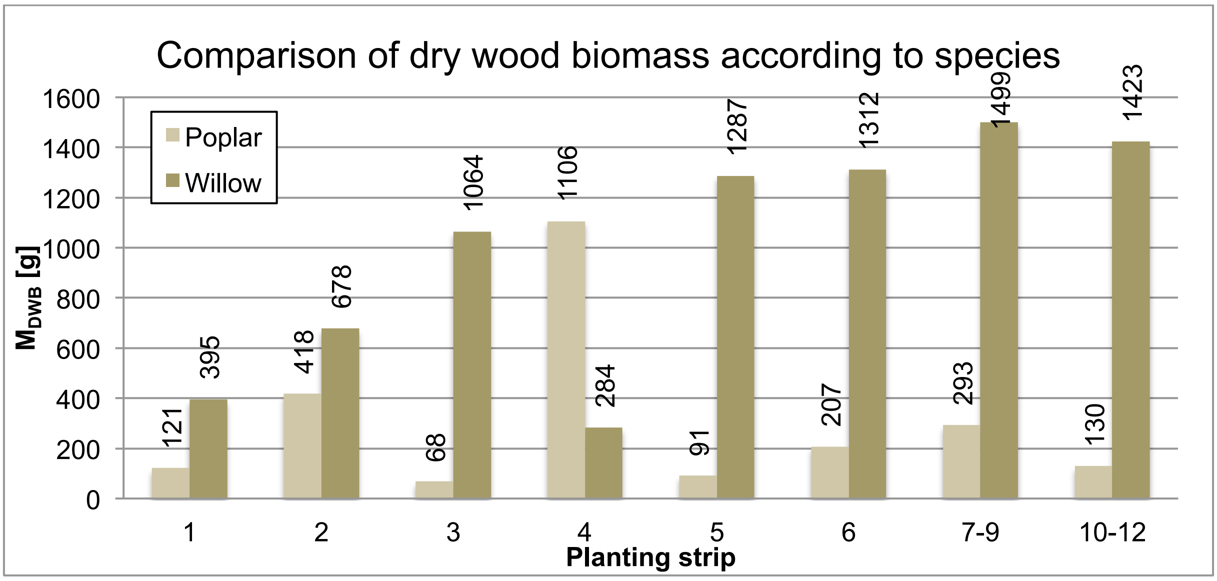

Figure 30 *Dry wood biomass according to species and planting strip*

When relating the dry leaf and wood biomass, a positive correlation between dry wood and leaf biomass is observed (Fig. 31). The poplar biomass increased more drastically than the willow biomass, due to the leaf anatomy. The large poplar in PS4 was not included in this diagram.

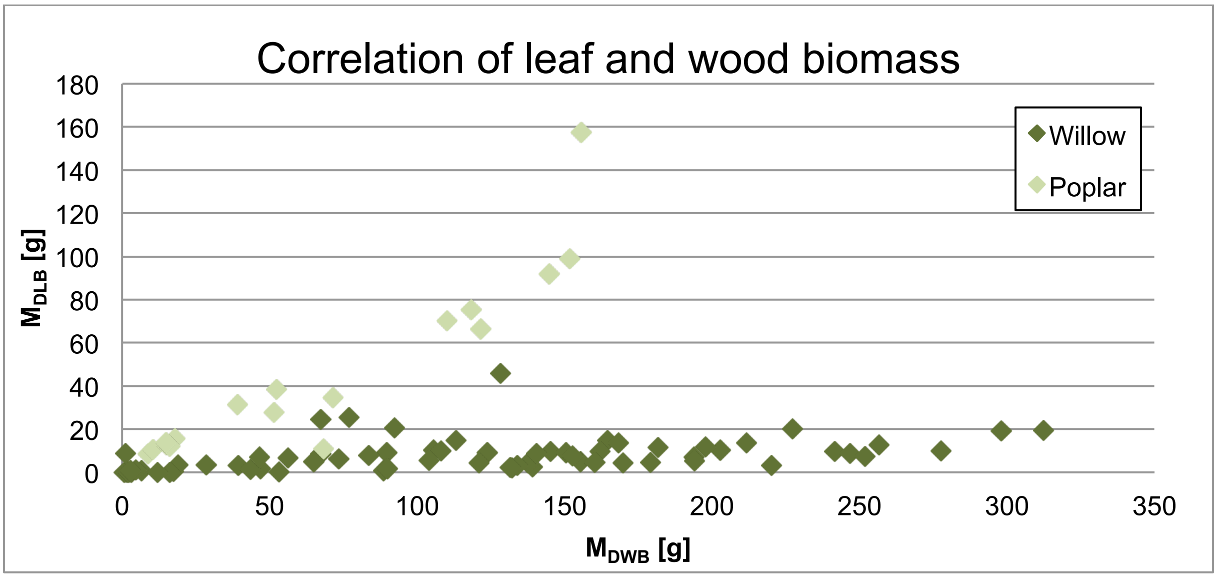

Figure 31 *Dry leaf and wood biomass of willow and poplar cuttings without poplar outliner*

Some plants showed signs of wilting, disease and/or pests, which could have influenced the leaf biomass to some extent. Nevertheless, the majority were healthy individuals with an average maximum shoot length of 140,39 cm (for poplar cuttings) and 184,55 cm (for willow cuttings). More detailed information about the development of the cuttings can be found in the appendix.

4.2 Root biomass

The extracted root biomass is categorized according to the set up of the field experiment in planting strips, road structure boxes and substrate boxes.

4.2.1 Planting strips

The total dry root biomass is demonstrated in Fig. 32. The highest amount was retrieved from PS6 with 692 g, followed by PS5 and PS2. PS7-9 and PS10-12 accommodated the smallest amount of dry root biomass with 414 g and 438 g, although the highest number of cuttings was planted in these planting strips. A possible explanation is the increased competition between the plants, which resulted in less root development.

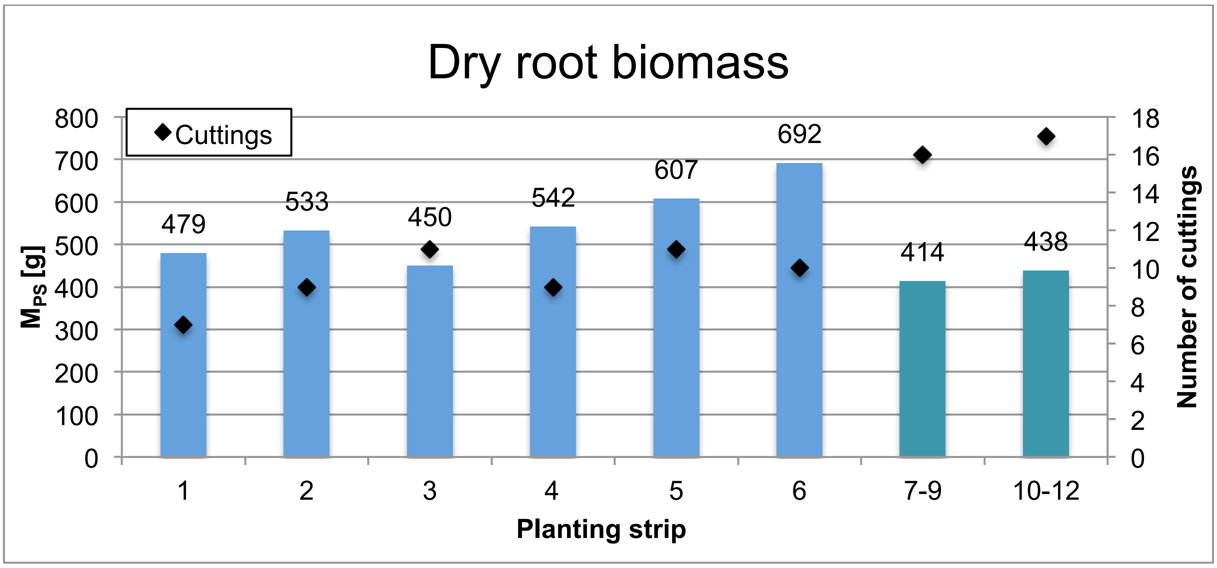

Figure 32 *Total dry root biomass extracted from the planting strips*

Since the spatial distribution is as relevant as the amount itself, the biomass was analyzed according to the levels in which it developed, as shown in Fig. 33. The majority of roots occurred in the third level, with the exception of PS2. In the first level, the smallest amount of biomass was found, except in PS8, which accommodated more roots in the second level. Overall, the biomass increased with the proximity to the bottom of the boxes. Reasons for this development might be higher moisture levels close to the drain geomembrane as well as the penetration depth of the cuttings at approximately 30 cm. Cuttings usually root at the lower end, which was located at the border between second and third level.

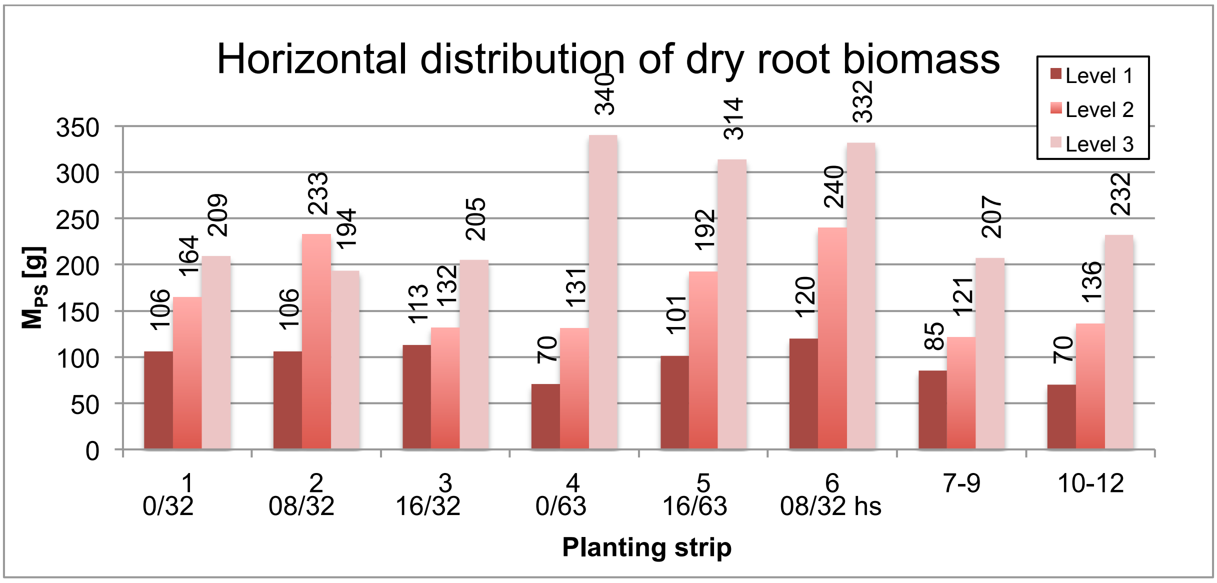

Figure 33 *Spatial distribution of dry root biomass in planting strips connected to road structure boxes*

The development of the biomass was also analyzed regarding the roots' thickness. The biomass was separated into three diameter categories of fine, medium and coarse roots.

Fine roots	0-2 mm
Medium roots	2-10 mm
Coarse roots	> 10 mm

Their occurrence is illustrated in Fig. 34. The 48% of roots were categorized as medium roots (1934 g), followed by the 47% of fine roots (1934 g) and only 5% (227 g) grew larger than 10 mm.

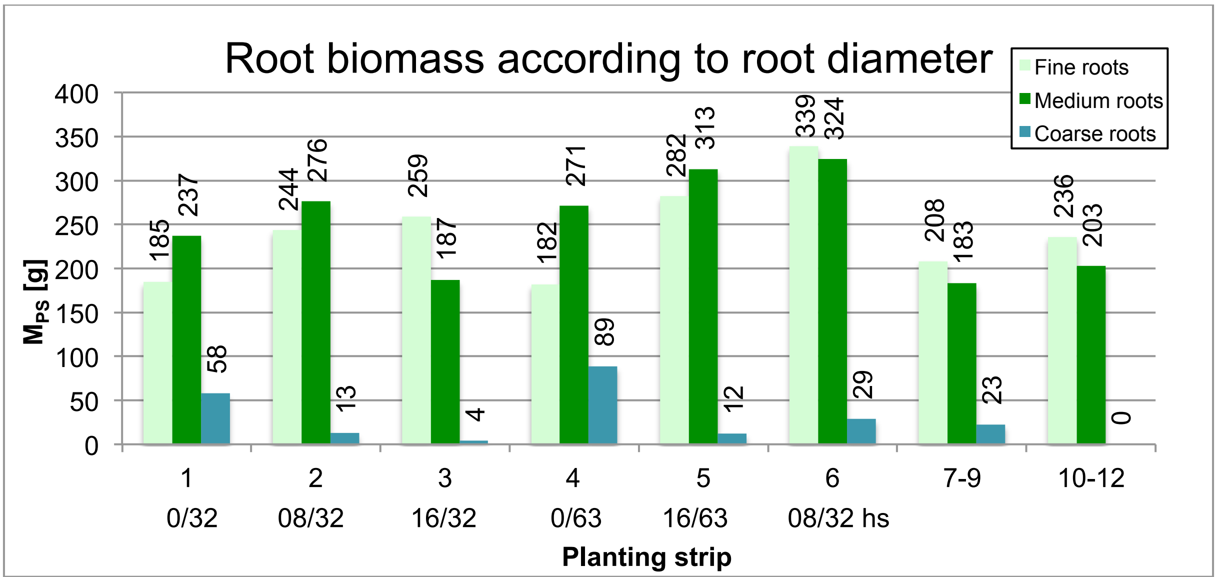

Figure 34 *Dry root biomass of planting strips according to the root diameter*

PS4 had the highest amount of coarse roots with almost 90g. It is possible that these roots belonged to the large poplar individual in PS4.

The results of the level analysis were paired with the ones from the diameter categories to gain insight in the distribution of the fine, medium and coarse roots within the levels (Fig. 35). The amount of dry roots smaller than 2 mm and between 2 and 10 mm was similar in each level. Solely in PS1 and PS3 coarse roots were retrieved in the first level. The third level accommodated the highest amount of fine and medium roots. Overall, an increase in root biomass per diameter category and level was observed.

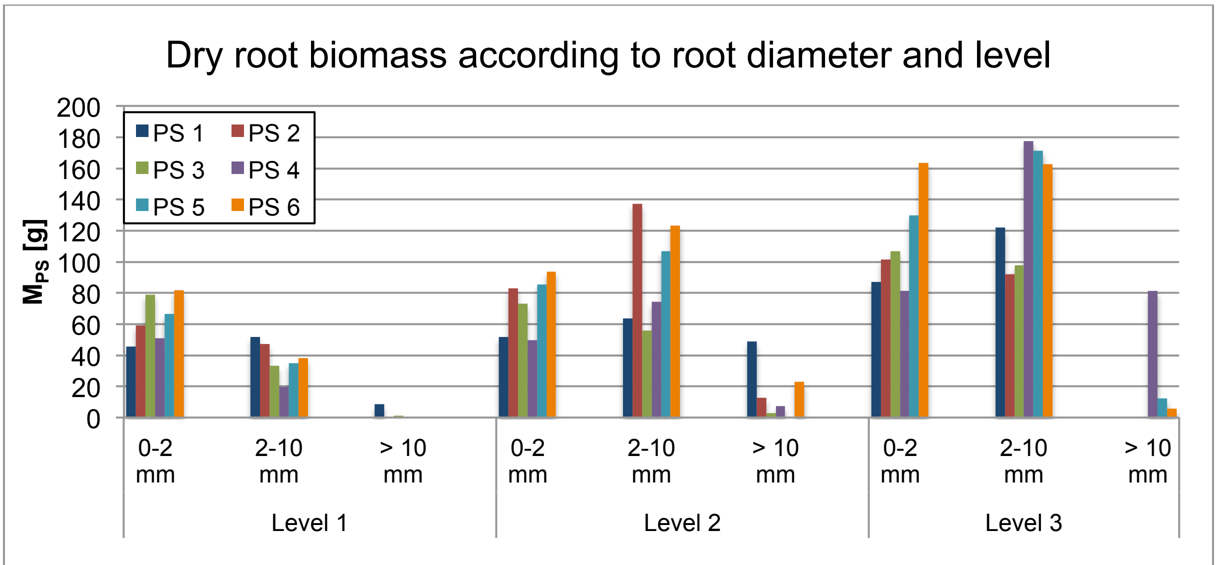

Figure 35 *Dry root biomass from planting strips according to the level and root diameter category*

When looking at the above- and underground biomass retrieved from the planting strips, the underground biomass made up about one quarter of the total biomass. This share of underground biomass correlates with the aerial-underground biomass ratio for temperate trees (Owens and Lund, 2009). Fig. 36 shows the distribution of root, wood and leaf biomass in absolute values. An exception to this was PS1, where the plants' underground biomass (479 g) was almost the same as their aboveground biomass (635 g).

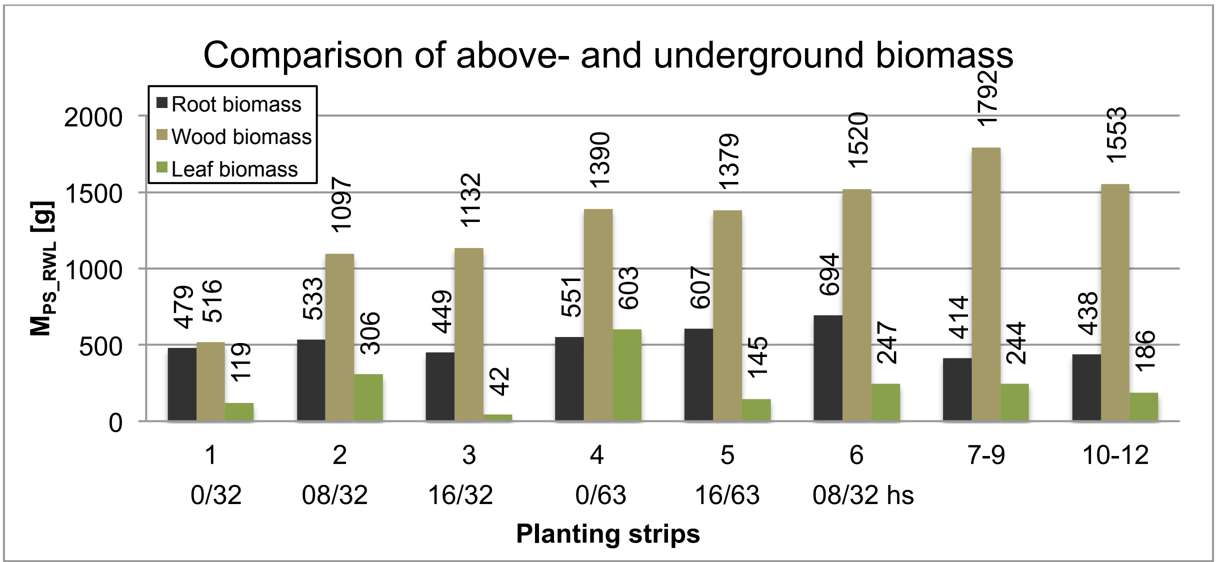

Figure 36 *Comparison of dry leaf biomass, dry wood biomass and dry root biomass collected from the planting strips*

4.2.2 Road structure boxes

The road structure boxes resembled a common road structure with top layer and base course. This way, the effects of condensation between the top layer and the base course could be examined indirectly. The base course fillings were five different sized gravel mixtures and one hydraulically stabilized mixture.

The highest amount of dry root biomass was found in the 16/63 substrate with 225 g, followed by the 0/32 mixture (160 g) and the 16/32 mixture (158 g). In the 08/32 hs mixture, the smallest amount of root biomass occurred (84 g). The cumulated dry root biomass of the road structure boxes is shown in Fig. 37.

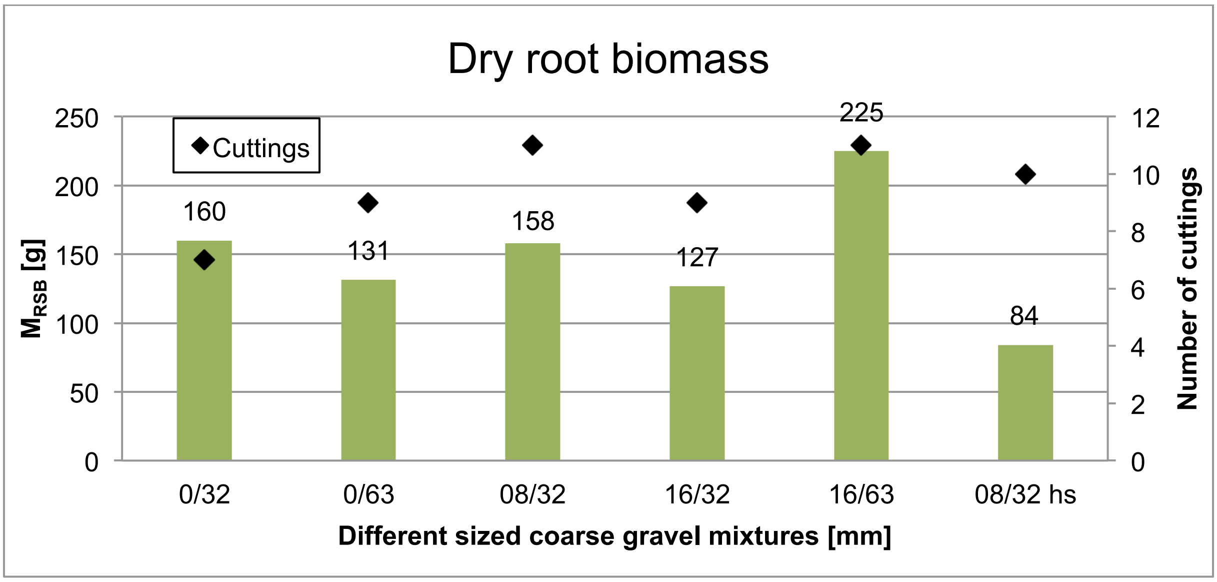

Figure 37 *Total dry root biomass found in different sized gravel mixtures*

These results differ when the biomass is related to the root biomass of the connected planting strips (Fig. 38). The substrates with the highest relative biomass were 16/63, 0/32 and 08/32 mixtures. The hydraulically stabilized mixture accommodated the smallest relative biomass with a ratio of 0,12.

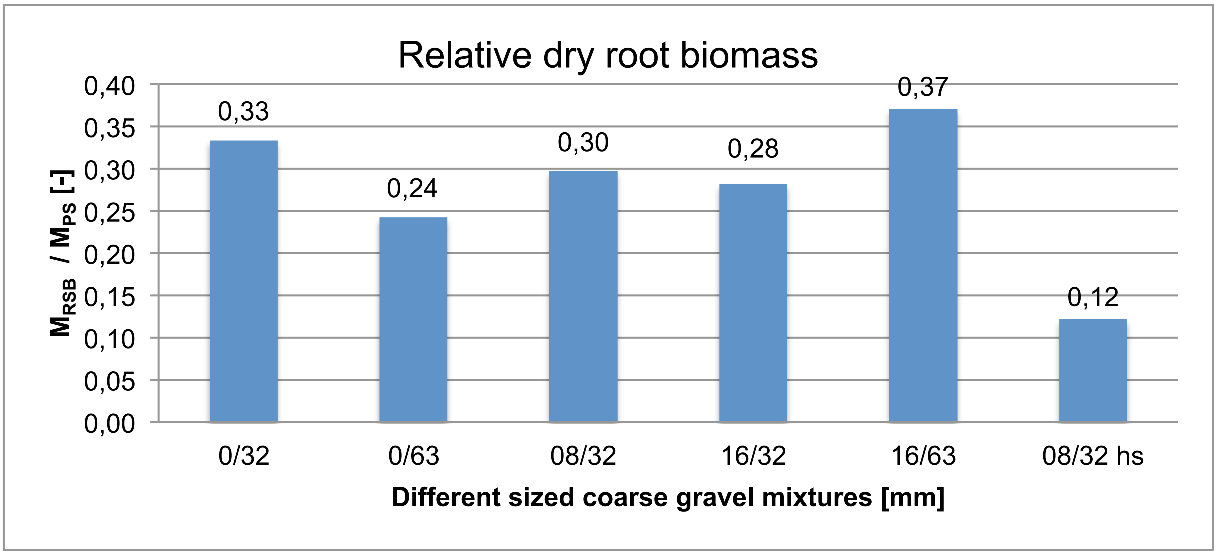

Figure 38 *Dry root biomass of road structure boxes in relation to dry root biomass of planting strips*

The spatial development of the relative root biomass is shown in Fig. 39. The roots were allocated according to the level, from which they were collected. With the exception of substrates 16/32, a steady rise in root biomass was detected with increasing depth. The 16/32 mixture had a larger root biomass share in the second level. The highest relative biomass was found in the third level of the 16/63 mixture, which accounts for the high biomass retrieved from this substrate.

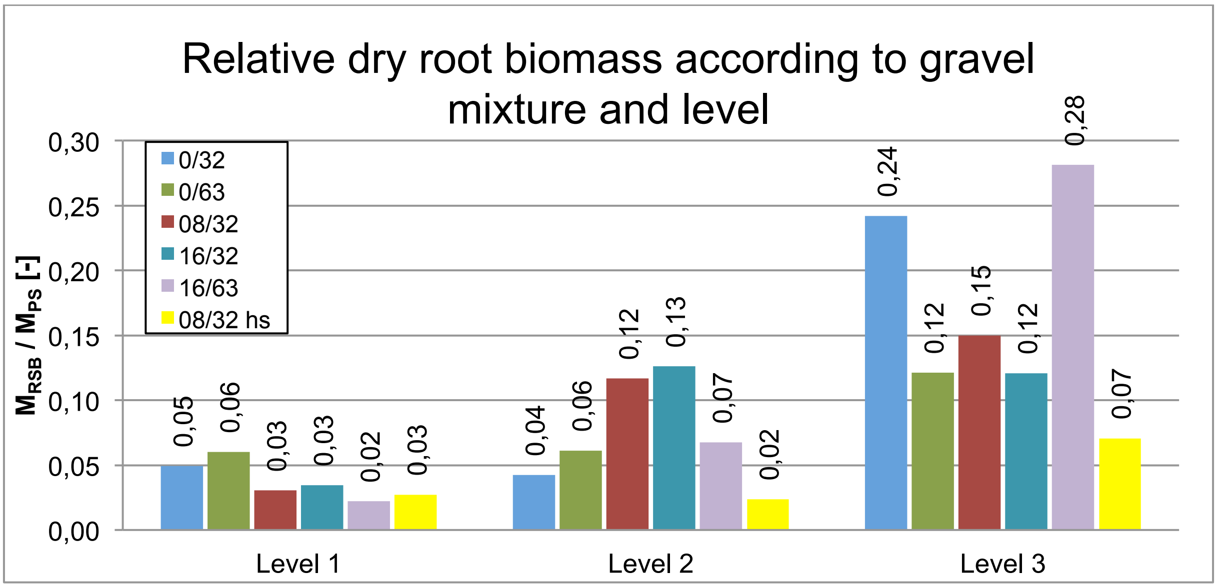

Figure 39 *Dry root biomass of road structure boxes in relation to dry root biomass of planting strips according to gravel mixture and level*

When examining the share of relative roots according to the column (Fig. 40), it became apparent that the proximity to the source of roots (the planting strips) influenced the root development.

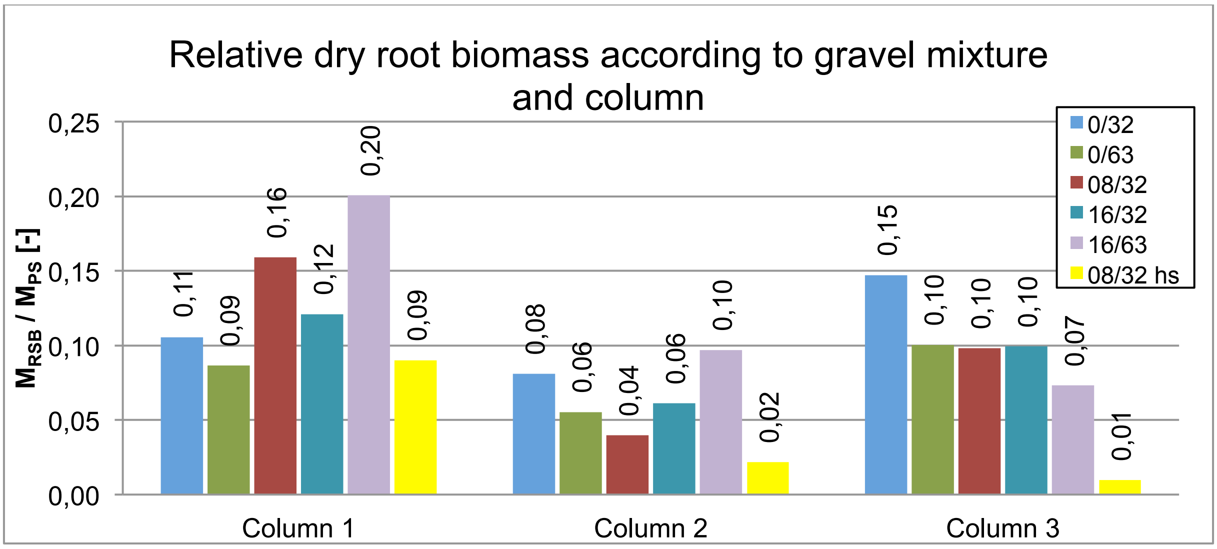

Figure 40 *Dry root biomass of road structure boxes in relation to dry root biomass of planting strips according to gravel mixture and column*

A continual decrease of root biomass was observed with increasing distance to the planting strip in the mixtures 16/63 and 08/32 hs. Substrates 0/32 had a high share of biomass in the third column. In substrates 9/63, 08/16 and 16/32, the highest share of root biomass was found in the second column. Further information on spatial distribution can be retrieved from the appendix.

When separating the roots into diameter categories, a lack of coarse roots was detected. None of the roots, which were extracted from the road structure boxes, were thicker than 10 mm. The majority of roots didn't grow thicker than 2 mm, as shown in Fig. 41. In the 16/63 mixture, the highest amount of medium roots occurred with 55 g. The 0/32 mixture had the least medium root development with 10 g.

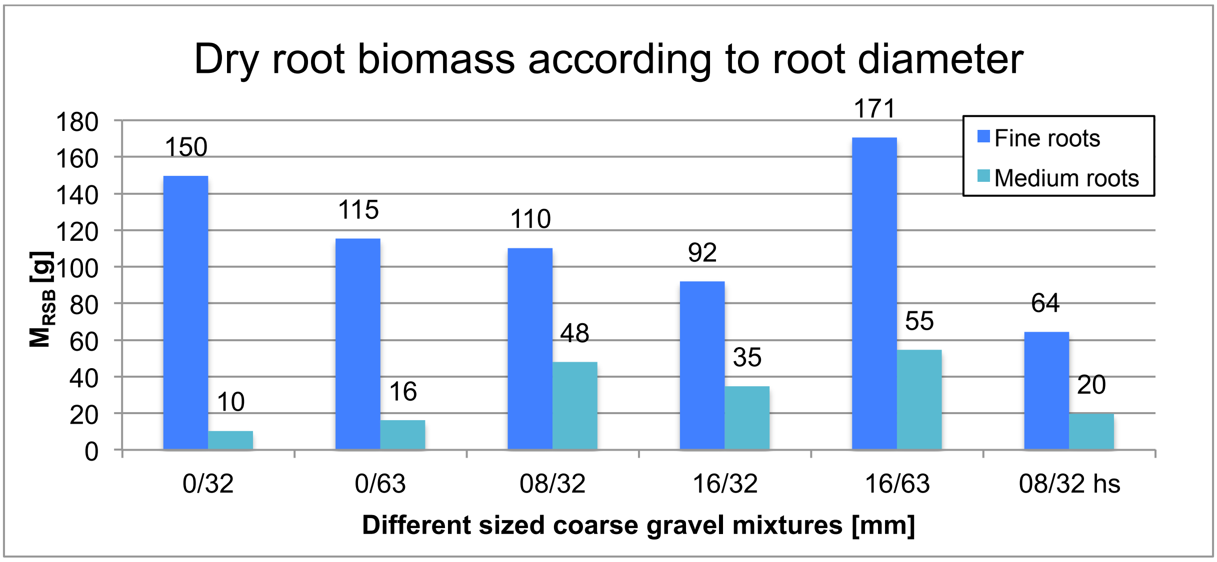

Figure 41 *Dry root biomass of road structure boxes according to the root diameter*

The root biomass was split up according to the level of occurrence and the root thickness, as shown in Fig. 42. For all substrates, the largest amount of roots was thinner than 2 mm and located in the third level. The 0/32 and 16/63 mixture had the highest numbers in this category with 106 g (0/32) and 129 g (16/63). Thicker roots were mostly retrieved from the second and third levels.

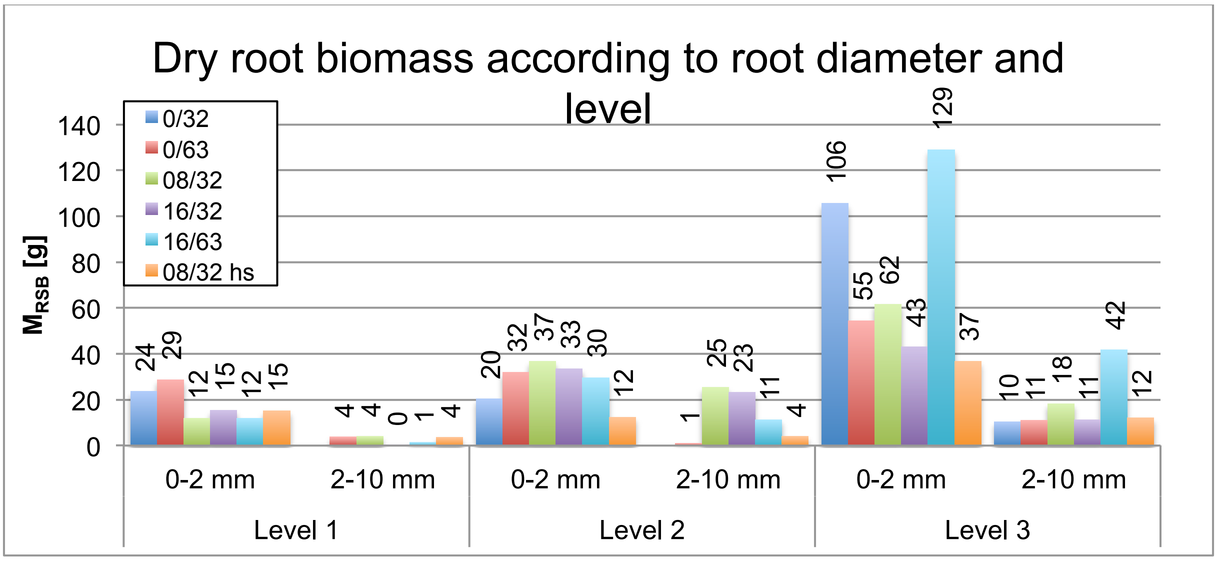

Figure 42 *Dry root biomass of road structure boxes according to level and diameter category*

The diameter category analysis according to columns showed that the roots thicker than 2 mm were located in the first column in every substrate, as shown in Fig. 43.

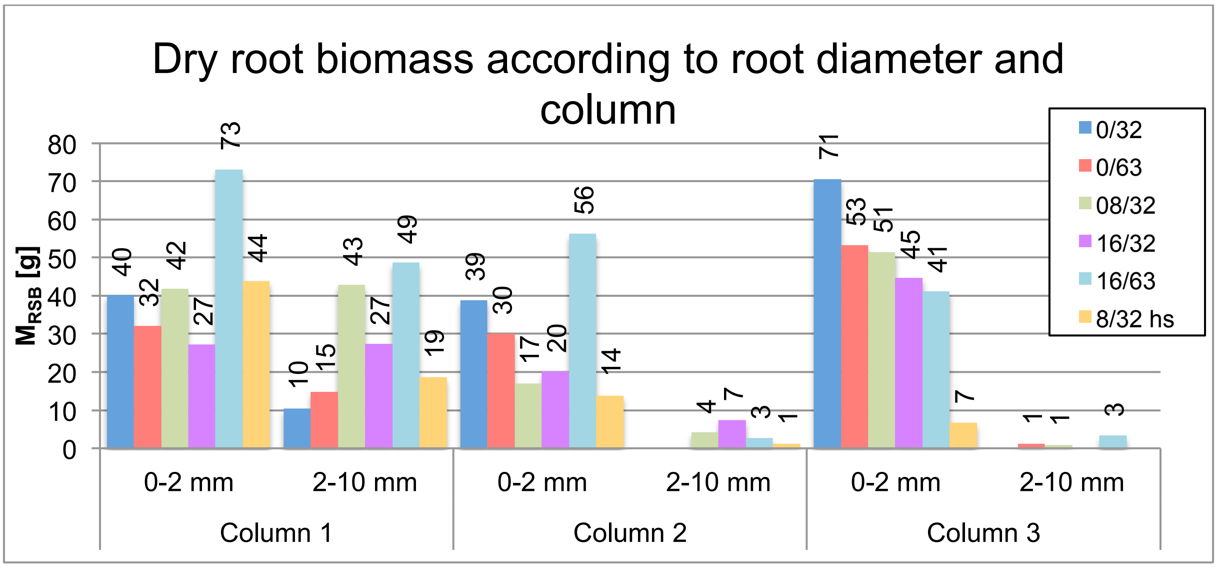

Figure 43 *Dry root biomass of road structure boxes according to column and diameter category*

The drain geomembrane had been placed between the base course layers to prevent the different sized gravel from mixing (Müllner and Weissteiner, 2016). Simultaneously, it influenced the drainage and retained more moisture. The increase in root biomass close to the bottom of the boxes, as well as the development of roots in and under the geomembrane might have resulted due to this setup. Additionally, the cuttings' penetration depth was 30 cm on average, which is approximately the same depth of the border between the second and the third level. Most cuttings developed the initial roots at the end of the cutting, which lead to higher root biomass in these levels. To retrieve information about the substrates without the possible influence of the geomembrane and the penetration depth of the cuttings, only the biomass collected from the first and second level were analyzed in Fig. 44. This evaluation puts the focus on the space close to the surface, where the root penetration and development effect the pavement the most, since the forces of root thickening damage the top layer (Müllner and Weissteiner, 2016).

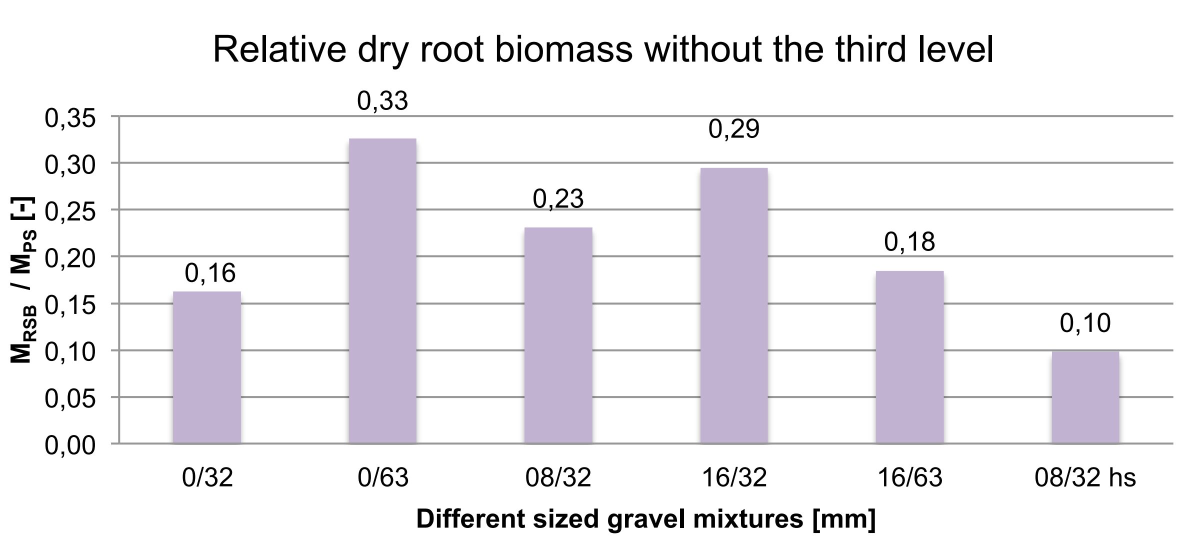

Figure 44 *Dry root biomass of road structure boxes in relation to dry root biomass of planting strips according to gravel mixtures, without the third level*

The neglect of the third level changed little in the outcome of the root biomass ratio of the 08/32 hs mixture, which remained the substrate with the smallest share of roots. A drastic change was observed in the relative biomass of the mixtures 0/32 and 16/63, which had large shares of third level roots. The 0/32 has the second smallest ratio of 0,16, followed by 0,18 in the 16/63 mixture. The 0/63 mixture has the highest relative biomass of 0,33, whereas little change was registered in the 16/32 substrate. An overview of the total and relative biomass comparison is displayed in the appendix.

4.2.3 Substrate boxes

The twelve substrate boxes were filled with six different gravel mixtures similar to the road structure boxes. The hydraulically stabilized mixture was replaced by a 04/32 substrate. Fig. 45 shows the biomass found in the substrate boxes. The 0/32 mixture in box 30 contained the smallest amount of biomass with only 14 g, whereas the highest biomass of 73 g was found in 08/32 (box 8) and 16/32 (box 9).

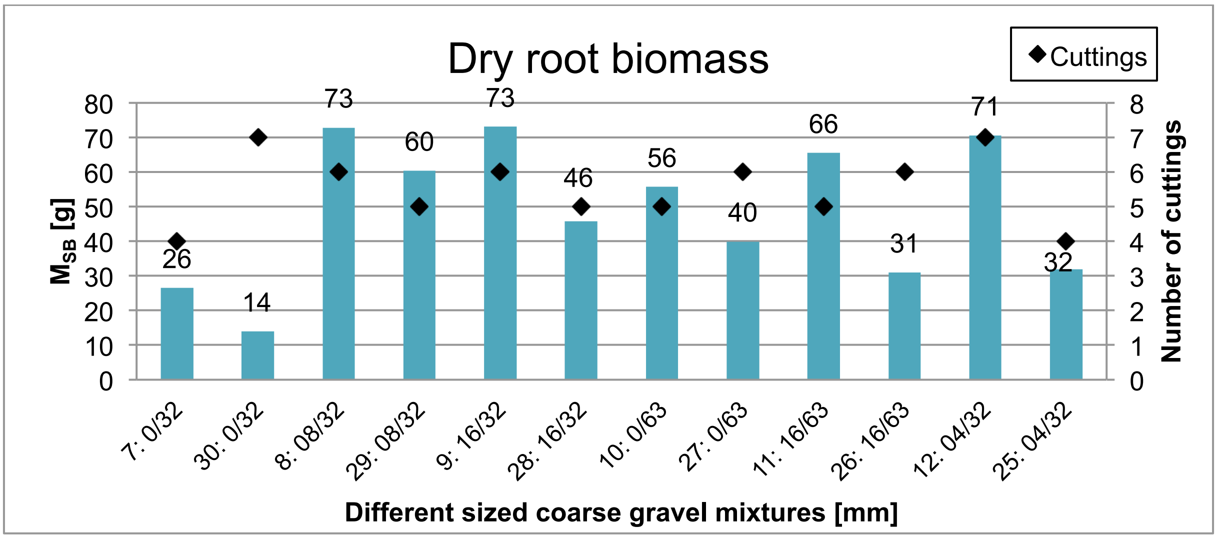

Figure 45 *Total dry root biomass extracted from substrate boxes, according to box number and gravel mixture*

Putting the data in relation to the planting strip biomass, the substrates with the smallest amount of biomass remained the same (box 30 with 0/32 substrate), whereas the highest relative biomass was found in 04/32 (box 12) (Fig. 46). It is noticeable that none of the boxes filled with the same substrate have the same relative root biomass. The highest difference is found in SB12 and SB 25 (04/32 substrate), which have a relative root biomass of 60% and 25%. This inconsistency might have resulted from differences in the manual compaction of the substrates or exposure to different influences such as wind and incidence of light as well as different competition between the plants.

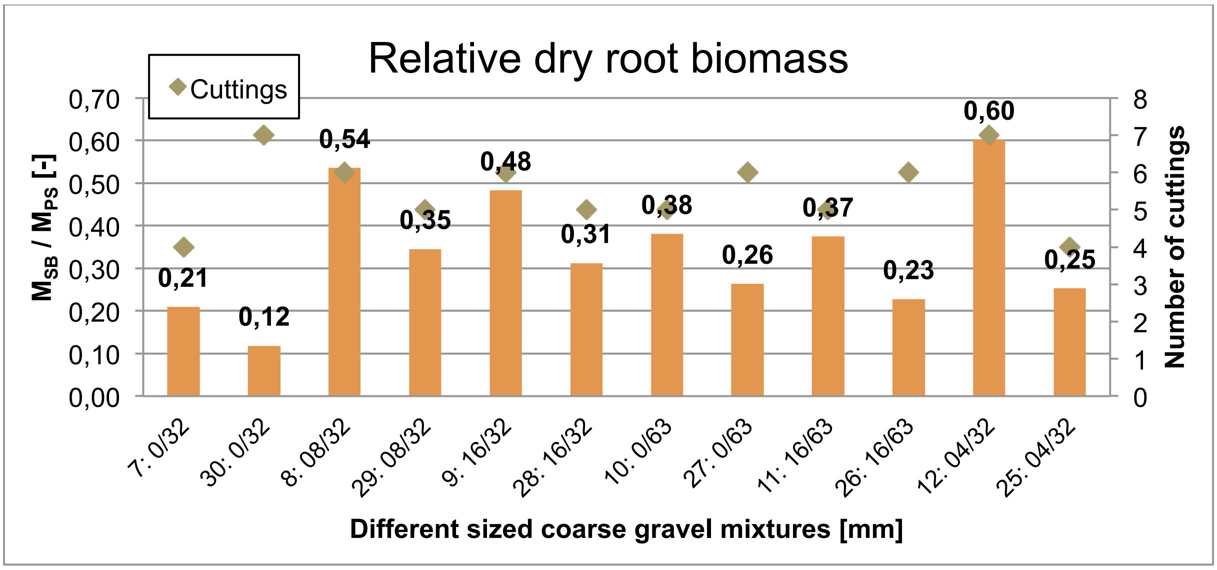

Figure 46 *Dry root biomass from substrate boxes in relation to dry root biomass from planting strips according to box number and gravel mixture*

The analysis of the diameter distribution of the roots revealed that the majority of roots were between 0 and 10 mm thick (Fig. 47). Roots thicker than 10 mm were only found in the 16/32 mixture. Although the substrate boxes held less root biomass compared to the road structure boxes, the amount of medium roots was noticeable higher in the substrate boxes. This could indicate that the environmental conditions in the substrate boxes were more favorable by the roots over those present in the road structure boxes. Possible explanations could be the lack of a top layer and the subsequent entry of nutrients, the higher number of cuttings planted or the exposure to rainfall.

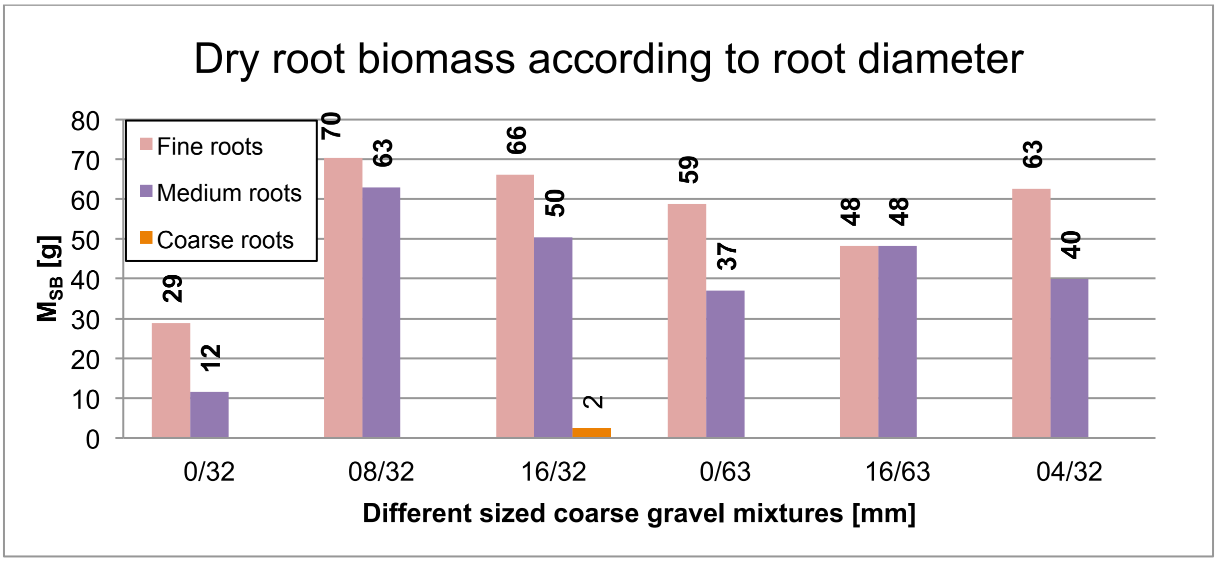

Figure 47 *Dry root biomass from substrate boxes according to root diameter*

The analysis of the horizontal root distribution showed that the development of the biomass in the substrate boxes was similar to the development in the road structure boxes (Fig. 48). The third level accommodated the highest relative root biomass, especially in the 08/32, 16/32, 16/63 and 04/32 mixtures, and a steady rise in root biomass was observed with increasing depth.

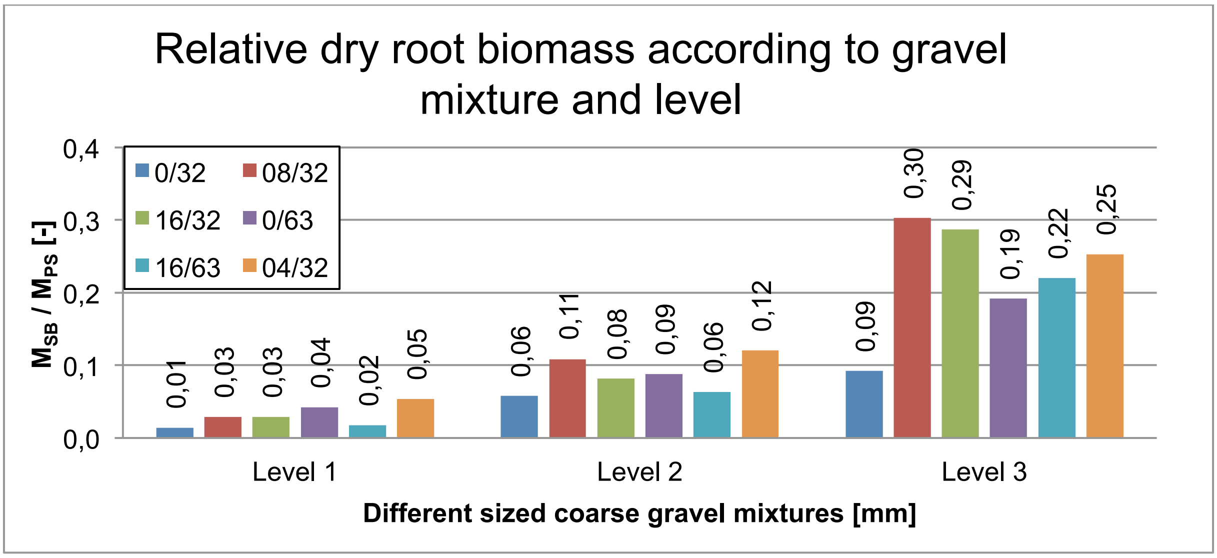

Figure 48 *Distribution of dry root biomass of substrate boxes according to levels*

Relating the results of the level analysis with the results of the diameter evaluation confirmed the assumption that the structure box roots grew similar to the road structure box roots (Fig. 49). All substrates had high biomass shares of roots between 0 and 10 mm in the third level.

The first level accommodated almost exclusively fine roots and the amount of medium roots was distinctively high in the third level.

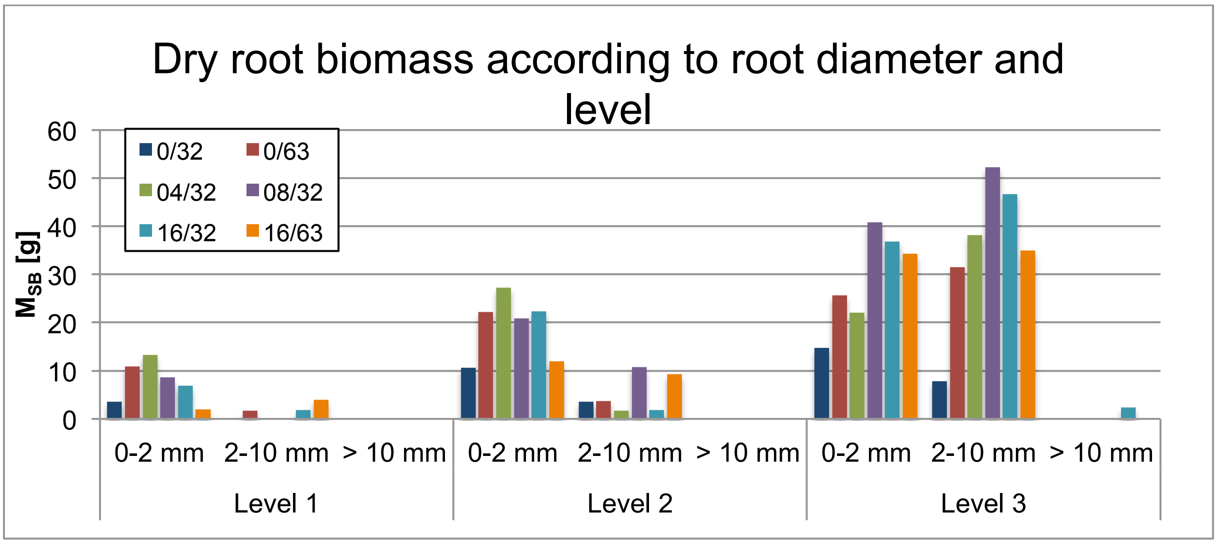

Figure 49 *Dry root biomass substrate boxes according to level and diameter category*

4.3 Root scans

As mentioned in the methodology section, the roots were categorized according to their thickness in very fine roots (0-1 mm), fine roots (1-2 mm), medium roots (2-5 mm) and coarse roots (5-20 mm).

According to Hellerschmid (2017), who evaluated the scans in the scope of a bachelor thesis, the highest share of roots was found in the very fine root category, as shown in Fig. 50. When comparing the different gravel mixtures, the highest share of roots was retrieved in the 16/63 mixture with a total length of 177.862 cm, of which 175.485 cm were less than 1 mm thick (Hellerschmid, 2017). The smallest share was found in the 0/63 mixture with 23.937 cm, of which 22.460 cm were very fine roots (Hellerschmid, 2017). The evaluation of the root length distribution correlates with Pallardy's statement (2008) that coarse roots might make up most of the roots biomass, but contribute little to the total length of the roots.

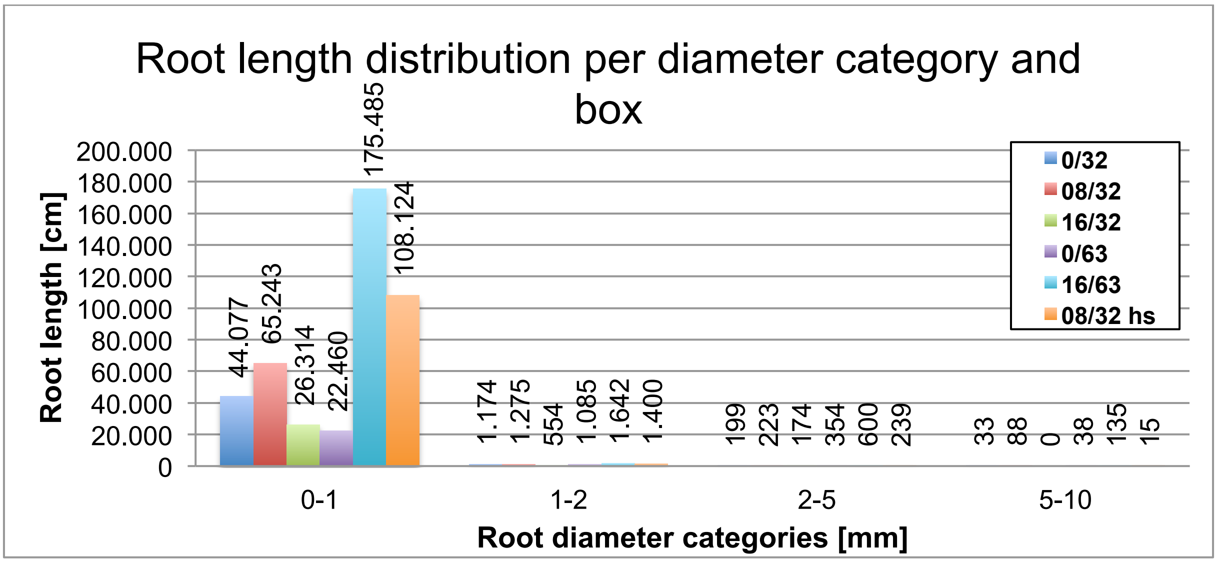

Figure 50 *Total root length of dry root biomass from road structure boxes according to root diameter*

The dominance of root biomass within the third level was observed in all gravel mixtures but 0/63. An overview of the accumulated root length in each level is shown in Fig. 51.

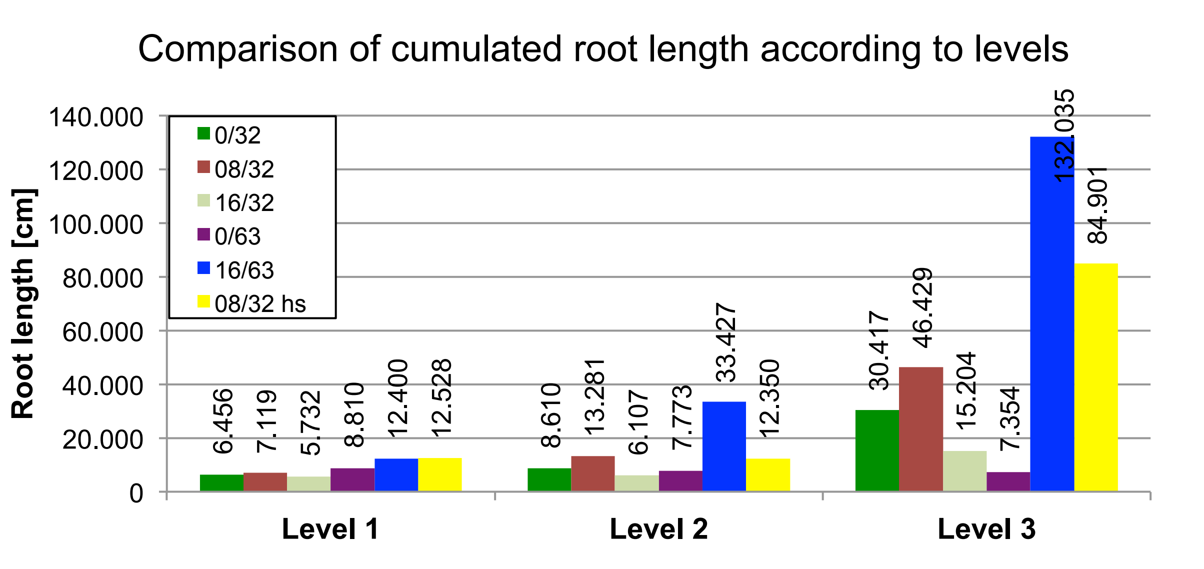

Figure 51 *Total root length of dry root biomass from road structure boxes according to levels*

The results of the root scans did not necessarily reflect the evaluation of the total root biomass. For example, the hydraulically stabilized mixture had the second highest share of root biomass of 109.779 cm, whereas in the analyses of the total biomass it had least amount of biomass. Possible explanations will be addressed in the chapter "discussion and outlook".

4.4 Temporal development of biomass

In the scope of a master thesis, Müllner (2016) collected the root biomass of the first stage of the field experiment. The roots were retrieved after the first vegetation period in fall of 2015. A comparison of the root biomass from 2015 and 2016 is shown in the following paragraphs. The extend of the biomass increase in the different seized gravel mixtures is another aspect that needs to be considered when choosing a substrate as bed road filling.

Road structure boxes

In Fig. 52, the relative root biomass of both years is displayed. In the hydraulically stabilized substrate the relative biomass increased the least, from 9 % to 12 %. The relative biomass of the 0/63, 08/32 and 16/32 mixtures changed approximately the same. The changes in the 0/32 and 16/63 substrates seem drastic in comparison. The highest difference was found in the 16/63 mixture of 29 %, followed by the 0/32 substrate of 26 %. These are the same substrates with significantly high shares of third level root biomass in 2016.

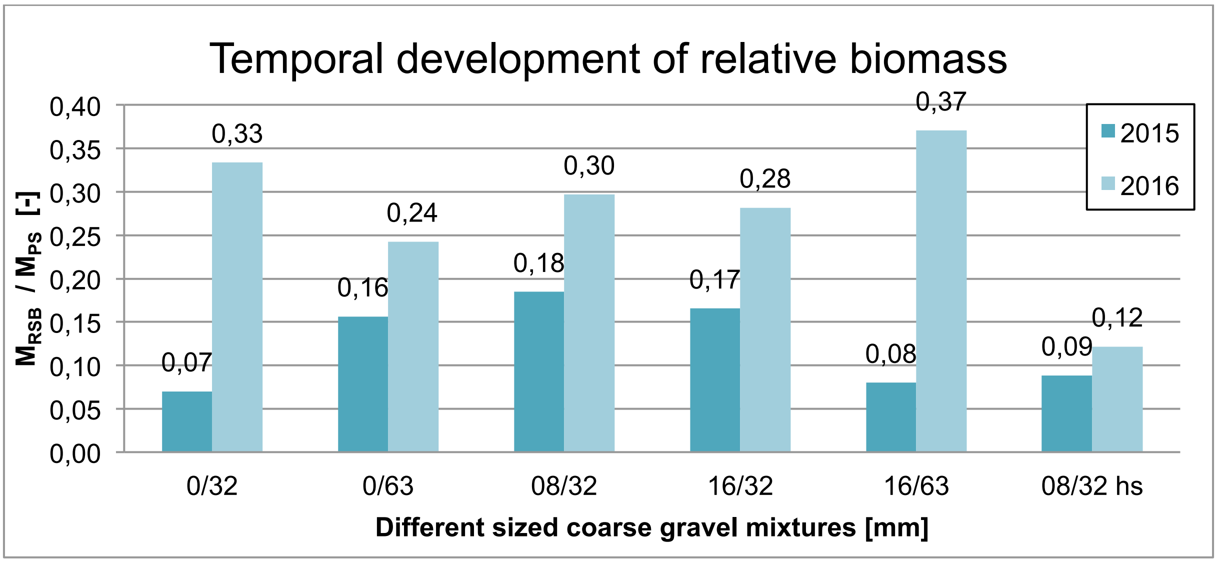

Figure 52 *Temporal development of relative dry root biomass from the road structure boxes*

The trend of a root biomass rise with increasing depth continued form 2015 to 2016, as shown in Fig. 53. The figure displays the significantly higher amount of roots in the lower levels of the 16/63 and 0/32 substrates.

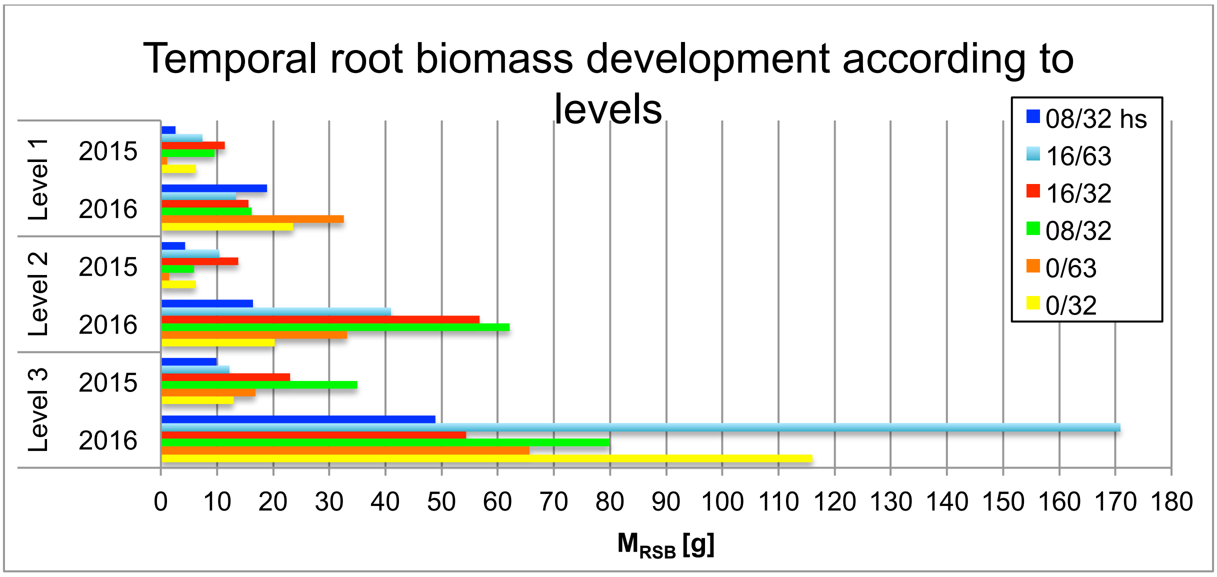

Figure 53 *Temporal development of dry root biomass of road structure boxes according to levels*

Since the space close to the surface is of high interest for the implementation of coarse gravel as road bed fillings, the changes in the different substrates were evaluated without the third level root biomass. As shown in Fig. 54, the least relative biomass was found in the 08/32 hs mixture, which changed little when neglecting the third level roots. In substrates 0/32 and 16/63, the difference between the 2015 and 2016 relative biomass was still high, nevertheless they accommodated the second and third least relative biomass. The highest relative biomass was found in the 0/63 mixture, followed by the 16/32 substrate.

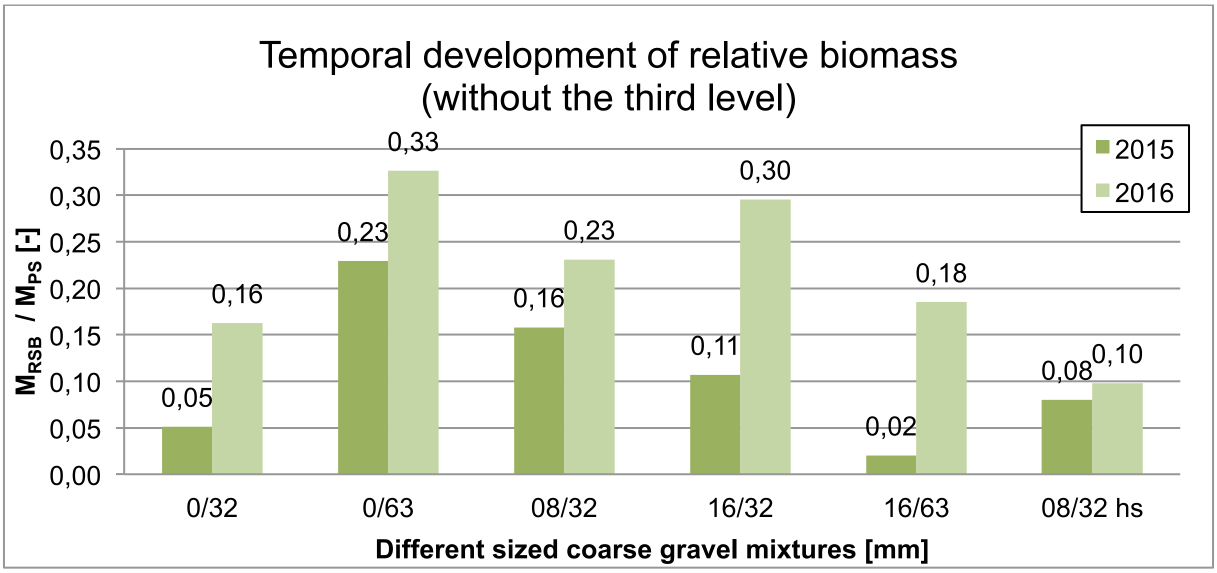

Figure 54 *Temporal development of relative dry root biomass from road structure boxes without the third level*

Substrate boxes

The temporal development of the relative root biomass was analyzed according to the different sized gravel mixtures, as shown in Fig. 55. The mean relative biomass of the substrate fields with the same gravel mixture was used. The highest difference was detected in the 04/32 substrate (27 %) and the 16/63 (20 %) substrate. The mixtures 08/32 changed insignificantly by 4 %. The relative biomass was higher in 2016 for every substrate except the 0/32 mixture, which decreased about 4 %.

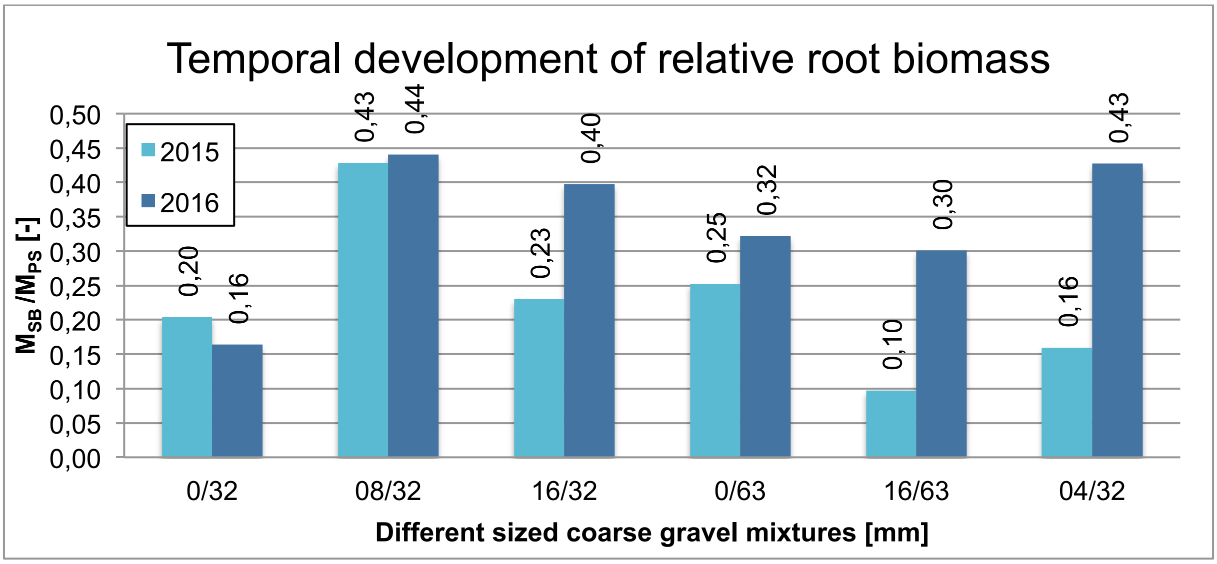

Figure 55 *Temporal development of relative dry root biomass from substrate boxes*

Looking at the relative biomass without the roots close to the bottom, it becomes apparent that relative biomass in the mixtures 0/32, 08/32 and 0/63 decreased, whereas an increase occurred in 16/32, 16/63 and 04/32, as illustrated in Fig. 56. The highest difference was observed in the 04/32 mixture of 29%.

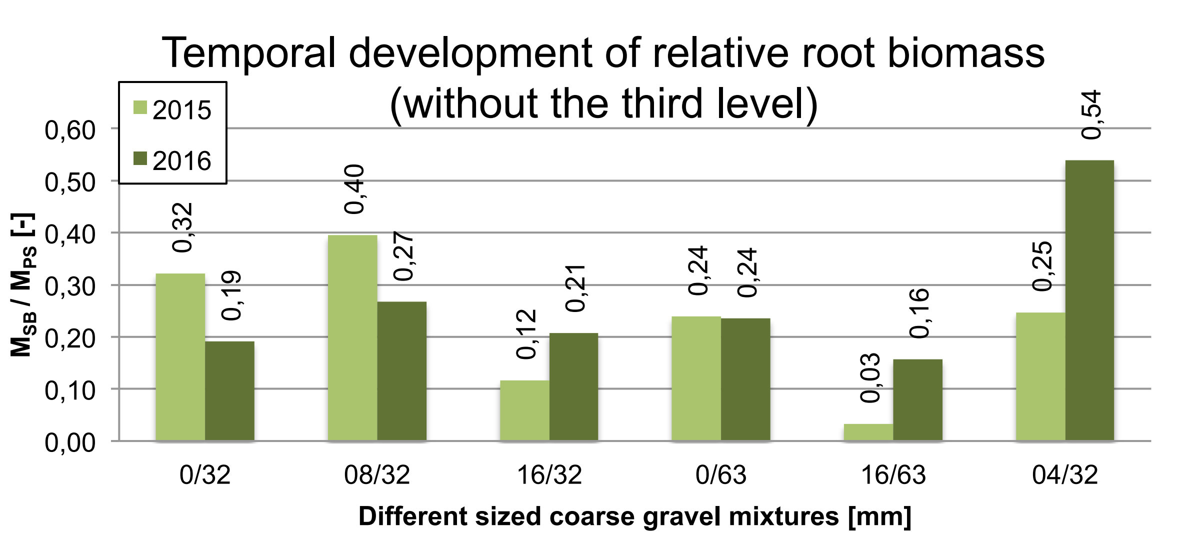

Figure 56 *Temporal development of dry root biomass from substrate boxes without third level*

Additionally, the vast majority of roots in 2015 was less than 2 mm thick, whereas in 2016, the share of fine roots was almost as high as the share of medium roots in the substrate boxes. The road structure boxes accommodated 80% fine roots and 20% medium roots.

5 Discussion and outlook

The field experiment in Groß Enzersdorf has been set up to examine the effects of crushed coarse gravel mixtures on root penetration. Incentive for the experiment was the road damages of the Treppelwege along the Danube. Coarse gravel is implemented on site as a vertical barrier to prevent roots from entering the road structure and forming cracks in the top layer. After comparing different strategies, Reichwein (2002) comes to the conclusion that as for now, no mitigation or prevention method achieves permanent damage prevention. Nevertheless, damage reduction is feasible in terms of reducing the frequency of occurrence and the magnitude of the damage. The author describes vertical structural separations between rooting space and sensitive infrastructure as a cost-effective and efficient method, emphasizing on the importance of adapting the strategy to local conditions (Reichwein, 2002).
To examine the strategy of adapted base course filling and the impact of crushed coarse gravel on root penetration and development, a small-scale field experiment was started in 2015 (Weissteiner, 2015).
The root biomass development, the spatial distribution of the roots and the temporal development were analyzed.

In the planting strips, the roots developed in every level, but the highest amount of biomass accumulated the second and third level. With increasing depth, the amount of medium and coarse roots rose, which can be related to the penetration depth of the cuttings. The lower end was planted in approximately 30 cm depth. Therefore, the initial roots developed between the second and the third level, leading to higher biomass occurrence. These roots often already underwent secondary growth compared to roots further from the cuttings that were too young at the time of the extraction to undergo such change. Another factor is the installation of the drain geomembrane, which was implemented to separate the upper and lower layers of the base course, but simultaneously acted as a drainage barrier. It prevented some of the condensation water from seeping away, possibly resulting in higher moisture content close to the bottom.

The **0/32** gravel mixture contained grains with an average size variation between 0 and 32 mm and thus had the largest share of fine fragments compared to the other tested gravel mixtures. 160 g root biomass was extracted from the substrate, which translated to a relative biomass of 33% once related to the roots from the connected planting strip. The substrate had the second most relative biomass compared to the different mixtures. The largest share of roots was found in the third level, leading to only 16% relative biomass when neglecting the third level roots. The relative biomass without the roots collected in the third level was calculated to draw the attention on the potential rooting space underneath the top layer and to decrease the influence of the experiment setup (drain geomembrane and penetration depth of cuttings). With only 16%, the substrate had the least relative biomass, after the hydraulically stabilized mixture. The distribution of the relative root biomass according to the columns was less pronounced. Interestingly, the 0/32 substrate roots made up the largest share of biomass (15%) of all substrates found in the third column. It is possible that moisture accumulated at the back wall and increased fine root development. With 71 g dry biomass, the substrate had the highest amount of fine roots in the third column and the second highest amount of fine roots in the third level (106g). Comparing the findings of 2015 and 2016, the total relative biomass increased by 26% and the relative biomass of levels 1 and 2 rose by 11%.

The share of fine fragments in the substrate could be a possible explanation for the comparatively high root biomass in the third level. Nevertheless, large shares of fine roots in the level closest to the bottom had been observed in the 16/63 substrate as well, with an average grain size distribution of 16 mm to 63 mm.

In the **0/63** gravel mixture the gravel sizes varied from 0 mm to a maximum of 63 mm. With 131 g total biomass and the resulting relative biomass of 24%, the substrate had the second least relative biomass compared to the other mixtures. The shares of root biomass were similar to those of substrates 08/32 and 16/32, having slightly more roots in the first level and slightly less in the second level in comparison. The same can be said about the distribution in the columns. Disregarding the third level roots, the relative biomass was at 33% and thus the highest root penetration percentage of all mixtures. A possible explanation for this result is that the coarse gravel provided a structure that prevented a compaction too high for roots to penetrate and thus the fine fragments filled the bigger spaces created by the coarse gravel to an extent that enabled roots to bridge the gap. Kopinga (1994) observed that the strategy of rubble as road bed filling achieved overall very good results; only when sand was washed in by rainfall, roots were able to develop within the road structure.

The root scan of the 0/63 sample resulted in the smallest share of biomass in the very fine root category with a total length of 22.460 cm. The biomass was evenly distributed over all three levels.

The **08/32** mixture had a average minimum grain size of 8 mm and a maximum grain size of 32 mm, excluding very fine gravel and coarse sand from the mixture, as well as gravel larger than 32 mm. With a relative biomass of 30% and 23% relative biomass without the third level roots, the substrate ended up in a middling position compared to the other mixtures. The highest root biomass was found in the third level and first column; a rather large share of the collected roots was between 2 and 10 mm thick (48 g of 158 g total biomass). Looking at the distribution of roots according to column and root diameter, the highest share of root biomass was found in the third column and consisted of fine roots, followed by the medium roots in the first column.

The biomass collected in the **16/32** mixture weighed 127 g with two-thirds of fine roots and one-third of the medium roots. The amount of biomass translated to 28% relative biomass in total and comparatively high 29% relative biomass without the third level roots. Similar to the 08/32 substrate, the highest amount of roots was found in the third column and fine root category.
Lösken, Heidger and Lieseck (2011) have used gravel mixtures to guide root growth underneath the road structure into deeper levels reducing the occurrence underneath the top layer (Reichwein, 2002). The study resulted in intensive rooting behavior in the 16/32 substrate (Reichwein, 2002), which correlates with the high relative biomass in levels 1 and 2.

The **16/63** mixture, which hasd the largest average minimum grain size of 16 mm compared to the other substrates, contained the highest root biomass of 225 g, resulting in a relative biomass of 37%. This result did not correlate with the evaluation of 2015: after only one vegetation period, the second least total relative biomass and the least relative biomass disregarding the third level roots were found in the 16/63 substrate. It is likely that the results of 2015 and 2016 differ from each other to this extent due to the increase in third level roots. The 16/63 substrate had the highest share of third level biomass and the lowest share of first level roots compared to the other substrates. The root share in the first column was significantly high.
The root scan revealed that the 16/63 substrate had the highest share of very fine roots (less than 1 mm thick) with 175.485 cm, which were located in the third level. The relative root biomass without the third level roots was only 18%, resulting in the third least relative biomass extracted from the substrates.
It is possible that the drainage effects were considerably high in the 16/63 mixture due to the lack of fine fragments, resulting in a higher impact of the drain geomembrane. Roots would have little incentive to grow underneath the top layer when the condensation water seeps away freely but accumulate in lower levels with increased moisture.

The **hydraulically stabilized 08/32** mixture contained the least biomass of only 84g, as well as the least relative biomass of 12% compared to the other substrates. It had the most

severe decrease in biomass from first to third level, resulting in solely 2% difference of relative biomass when neglecting the third level roots. Concerning the biomass distribution within the columns, its share of biomass in the third column was negligibly small. The medium roots made up one-third of the biomass, which was higher than in the 0/32 and 0/63 mixtures.
The root growth over the last vegetation period was stalled the most compared to the other mixtures, with only 3% difference in total relative biomass and 2% difference in relative biomass without the third level roots. The unique characteristic of this gravel mixture is the extra process step of stabilizing the loose gravel with cement. It became a solid, hardly penetrable mass, which created an ill-suited environment for root development. The survival rate of penetrating roots in such a bed road filling is potentially diminished.

The evaluation of the biomass, which developed in the **substrate boxes**, shows that the share of cumulated medium roots is much higher compared to the road structure boxes, even though the size of all substrate boxes is one-third of the size of all road structure boxes. It is possible that the manual compaction during the set up of the experiment was less effective compared to the compaction with the vibrating plate. Furthermore, without the concrete top layer, organic material was introduced in the gravel. This might have functioned as a nutrient resource for the plants and filled the gaps created by the coarse fragments, which could have enhanced root development. Another aspect is the number of cuttings in the planting strips between the substrate boxes, which was higher compared to the number of cuttings in the planting strips connected to the road structure boxes. Constructing the substrate boxes with the same measurements as the road structure boxes could have facilitated the comparability of the substrates with and without a top layer.

Overall, the spatial distribution of the roots in all coarse gravel mixtures displays the tendency of roots to develop close to the bottom of the boxes. One of the potential influences is the penetration depth of the cuttings is 29 cm in average for the poplar cuttings and 30 cm for the willow cuttings. The majority of roots growing from a cutting are located at the end of the cutting, which is the same depth as the border between the second and third level. The drain geomembrane might have impacted the moisture content, restraining the moisture from seeping into the ground.
When constructing the field experiment, the drain geomembrane was installed to separate the subbase and base course. The effects on moisture content were not intended. Nevertheless, the use of a geomembrane could function as a prevention strategy by redirecting roots into deeper levels and away from sensible road structure. Whilst the third

stage of the field experiment might provide further information on the subject, additional research is necessary.

According to Reichwein (2002), a strategy that prevents any root penetration of road structures has yet to be developed. Too many factors influence the success rate of the methods, such as tree species, age and distance to the sensible infrastructure, as well as local conditions and implementation of the method (Reichwein, 2002). A delay in root development is a more realistic approach, which has been observed when using porous base course material (Reichwein, 2002).
As for now, the hydraulically stabilized mixture has the highest potential to delay root development. The small difference in relative root biomass from 2015 and 2016 indicates such effects. Whilst this theory is based on the root development after only two vegetation periods, the third stage of the experiment will provide more information on the issue.

The success rate of the crushed coarse gravel installed as a vertical barrier along the Treppelwege will be evident in the years to come, when damages become visible or ideally remain absent. The same can be said about the long-term effects of the different gravel mixtures as base course filling. The development of the roots over the next few vegetation periods, will give an insight to the suitability of the different sized coarse gravel mixtures and their performance at preventing roots from entering the interface between top layer and base course.

The results shall be of use for the final extraction of root biomass in 2019 when determining the success rates of the different sized gravel mixtures. Regarding the next stage of the experiment, it might be advisable to reduce the parameters of the aboveground biomass, since they provide limited information for the root development. The sieving analysis had little impact on the findings and the results were to some extent inconclusive. The adjusted succession of aboveground harvest and underground excavation (addressing the road structure boxes and connecting planting strips first, and subsequently harvesting the substrate boxes and planting strips in-between second) might have decreased the effects that pruning has on root development, and should be continued.

This thesis thrives to give information about the progress of the root development in coarse gravel mixture after two vegetation periods and to compare the results with the findings after the first year. It shall be useful for further research to reduce root damages.

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7 List of figures and tables

8 Appendix

I. Aboveground biomass

Detailed information about the cuttings and the dry wood and leaf biomass in each planting strip arranged according to the tree species:

Table 2 *Aboveground biomass evaluation of planting strips*

Poplar		PS 1	PS 2	PS 3	PS 4	PS 5	PS 6	PS 7-9	PS 10-12
	Number of cuttings	1	3	1	2	2	2	5	3
	Leaf biomass [g]	78	257	11	497	70	185	180	89
	Wood biomass [g]	121	418	68	1106	91	207	293	130
Mean	**Number of shoots**	1	2	1	2	1	2	1	1
	Ø Cutting [mm]	31	32	25	36	29	24	32	28
	Depth [mm]	32	29	35	33	31	17	31	25
	Height [cm]	102	174	70	253	137	170	115	104
Minimum	**Number of shoots**	1	1	1	1	1	1	1	1
	Ø Cutting [mm]	31	30	25	16	14	20	23	12
	Depth [mm]	32	25	35	30	30	2	27	19
	Height [cm]	15	157	70	165	128	140	73	67
Maximum	**Number of shoots**	1	3	1	2	1	3	2	2
	Ø Cutting [mm]	31	35	25	56	43	28	46	44
	Depth [mm]	32	32	35	35	31	31	35	30
	Height [cm]	188	195	70	340	145	200	205	165

Willow		PS 1	PS 2	PS 3	PS 4	PS 5	PS 6	PS 7-9	PS 10-12
	Number of cuttings	5	6	10	7	9	8	11	14
	Leaf biomass [g]	41	49	31	106	75	61	65	97
	Wood biomass [g]	395	678	1064	284	1287	1312	1499	1367
Mean	**Number of shoots**	2	2	2	3	2	3	2	3
	Ø Cutting [mm]	22	23	22	18	21	22	25	26
	Depth [mm]	35	30	28	32	33	30	31	27
	Height [cm]	110	198	211	91	209	244	220	195
Minimum	**Number of shoots**	1	2	1	2	1	1	1	1
	Ø Cutting [mm]	12	17	15	11	2	17	20	20
	Depth [mm]	19	26	20	17	27	25	25	24
	Height [cm]	25	30	40	35	115	220	100	95
Maximum	**Number of shoots**	3	2	3	4	4	6	4	5
	Ø Cutting [mm]	33	34	29	25	29	31	32	36
	Depth [mm]	42	32	32	44	38	41	36	31
	Height [cm]	300	320	360	180	310	295	300	290

II. Spatial distribution of road structure boxes

The following figures give an overview of the root distribution within each level of the road structure boxes.

Field 1: 0/32

Level 1	Column 1	Column 2	Column 3
Subfield 1	7%	4%	34%
Subfield 2	4%	4%	12%
Subfield 3	8%	11%	16%

Level 2	Column 1	Column 2	Column 3
Subfield 1	8%	8%	20%
Subfield 2	11%	5%	12%
Subfield 3	20%	4%	14%

Level 3	Column 1	Column 2	Column 3
Subfield 1	16%	11%	15%
Subfield 2	10%	9%	14%
Subfield 3	7%	7%	12%

Field 2: 08/32

Level 1	Column 1	Column 2	Column 3
Subfield 1	11%	6%	12%
Subfield 2	9%	12%	3%
Subfield 3	33%	3%	11%

Level 2	Column 1	Column 2	Column 3
Subfield 1	44%	6%	12%
Subfield 2	4%	3%	5%
Subfield 3	14%	2%	9%

Level 3	Column 1	Column 2	Column 3
Subfield 1	12%	6%	18%
Subfield 2	22%	6%	7%
Subfield 3	11%	2%	14%

Field 3: 16/32

Level 1	Column 1	Column 2	Column 3
Subfield 1	12%	2%	29%
Subfield 2	7%	1%	8%
Subfield 3	20%	9%	12%

Level 2	Column 1	Column 2	Column 3
Subfield 1	18%	5%	13%
Subfield 2	4%	1%	6%
Subfield 3	24%	20%	9%

Level 3	Column 1	Column 2	Column 3
Subfield 1	20%	6%	10%
Subfield 2	7%	7%	14%
Subfield 3	14%	8%	14%

Field 4: 0/63

Level 1	Column 1	Column 2	Column 3
Subfield 1	1%	3%	3%
Subfield 2	13%	8%	13%
Subfield 3	18%	16%	25%

Level 2	Column 1	Column 2	Column 3
Subfield 1	3%	4%	12%
Subfield 2	12%	5%	9%
Subfield 3	17%	8%	29%

Level 3	Column 1	Column 2	Column 3
Subfield 1	10%	4%	10%
Subfield 2	19%	3%	11%
Subfield 3	10%	16%	17%

Field 5: 16/63

Level 1	Column 1	Column 2	Column 3
Subfield 1	30%	0%	3%
Subfield 2	13%	2%	5%
Subfield 3	36%	2%	7%

Level 2	Column 1	Column 2	Column 3
Subfield 1	20%	2%	13%
Subfield 2	31%	4%	8%
Subfield 3	9%	5%	7%

Level 3	Column 1	Column 2	Column 3
Subfield 1	11%	8%	8%
Subfield 2	17%	17%	5%
Subfield 3	23%	6%	5%

Field 6: 08/32 hs

Level 1	Column 1	Column 2	Column 3
Subfield 1	14%	1%	0%
Subfield 2	19%	2%	1%
Subfield 3	27%	36%	1%

Level 2	Column 1	Column 2	Column 3
Subfield 1	16%	9%	1%
Subfield 2	20%	4%	0%
Subfield 3	33%	13%	5%

Level 3	Column 1	Column 2	Column 3
Subfield 1	45%	5%	8%
Subfield 2	17%	0%	0%
Subfield 3	20%	2%	2%

0%	0-5%	5-10%	10-20%	20-30%	30-40%	>50%

Figure 57 *Root distribution in road structure boxes according to level and column*

III. Road structure box biomass comparison with and without third level

***Table 3** Overview of root biomass in road structure boxes*

Coarse Gravel Mixture	Total biomass	Total biomass - level 3	Difference of total biomass	Relative biomass	Relative biomass - level 3	Difference of total biomass
0/32	159,99	43,91	116,08	0,33	0,16	0,17
0/63	131,41	65,75	65,66	0,24	0,33	-0,09
08/32	158,19	78,29	79,9	0,30	0,23	0,07
16/32	126,67	72,27	54,4	0,28	0,29	-0,01
16/63	225,19	54,34	170,85	0,37	0,18	0,19
8/32 hs	84,18	35,26	48,92	0,12	0,10	0,02

IV. Sieving analyses

The analyses of the substrate and soil samples were plotted in sieving curves. Two samples per gravel mixture were examined, one taken from the first level and the other one extracted from the third level. The following figures show a visualized comparison of first and third level per substrate.

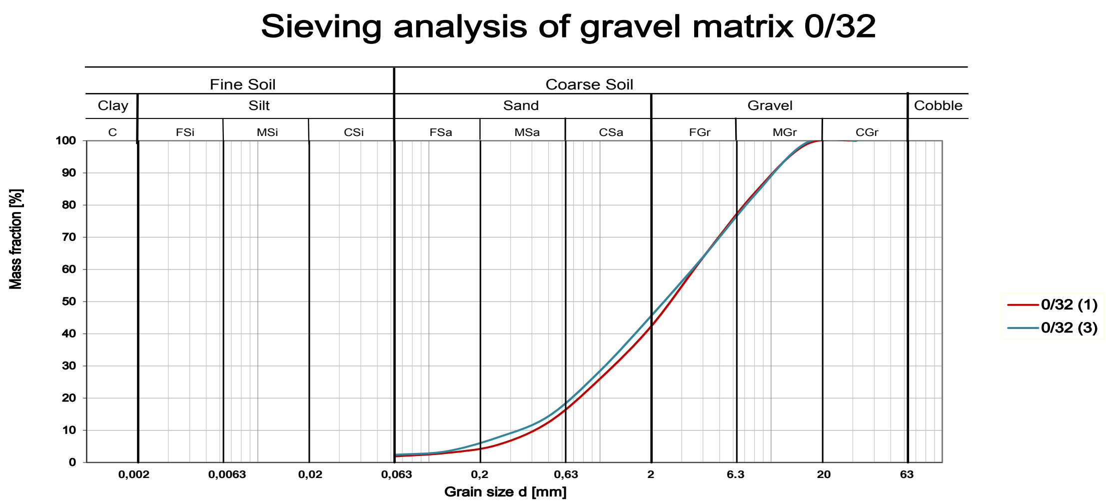

***Figure 58** Grading curve of 0/32 gravel mixture sample*

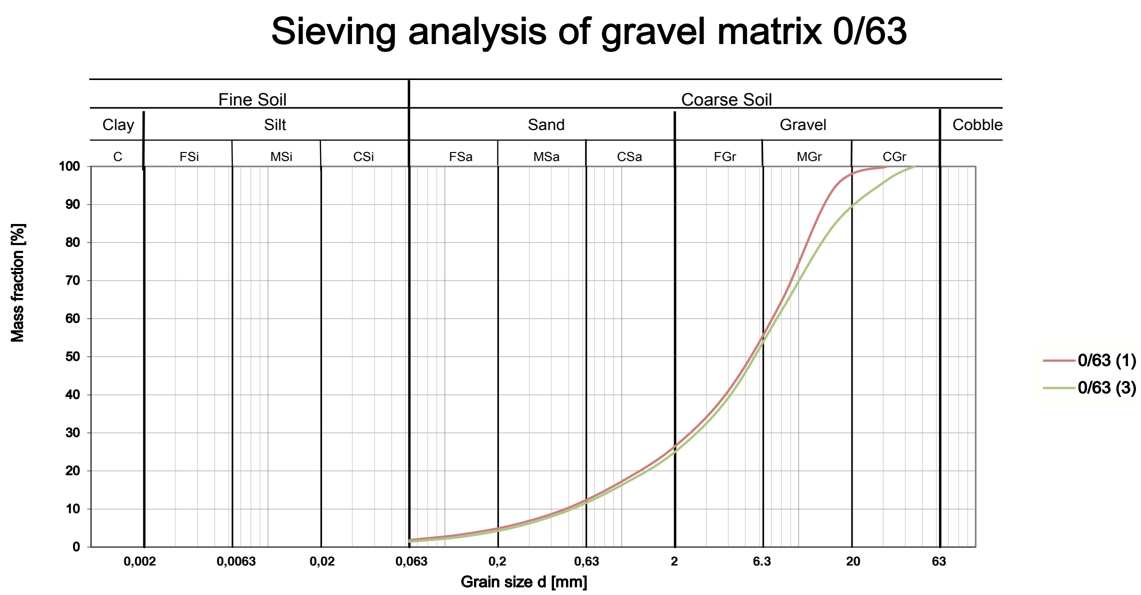

***Figure 59** Grading curve of 0/63 gravel mixture sample*

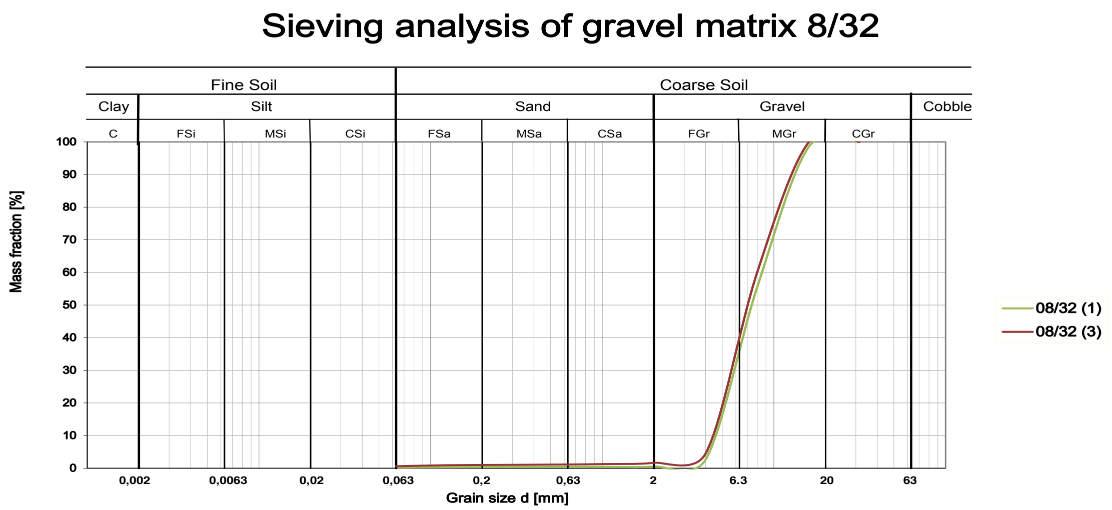

Figure 60 *Grading curve of 08/32 gravel mixture sample*

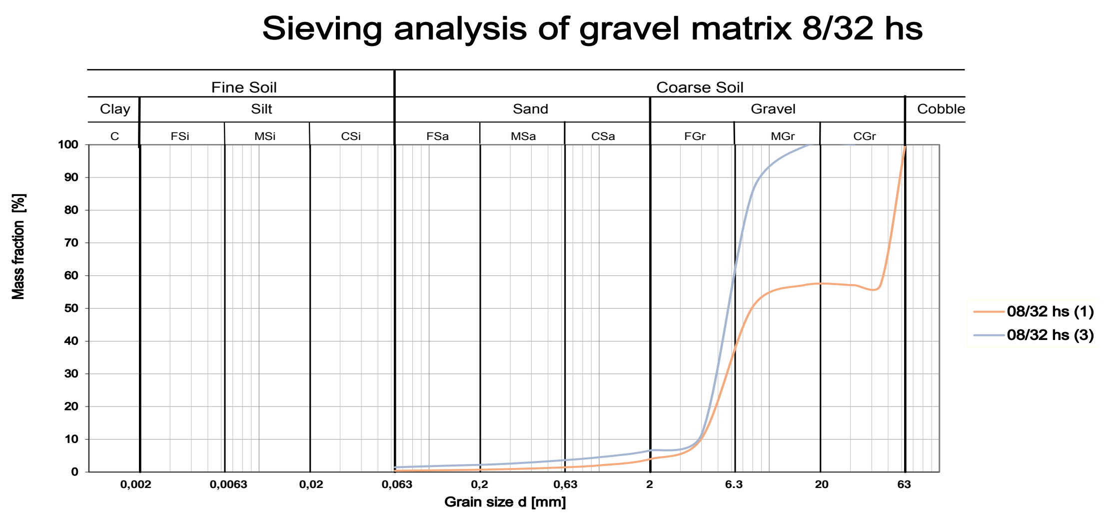

Figure 61 *Grading curve of 08/32 hs gravel mixture sample*

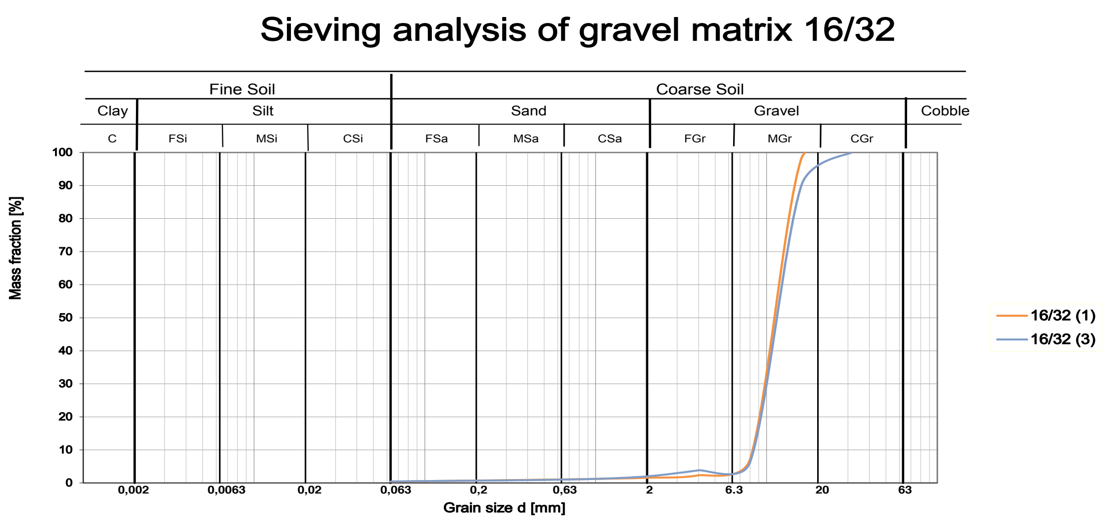

Figure 62 *Grading curve of 16/32 gravel mixture sample*

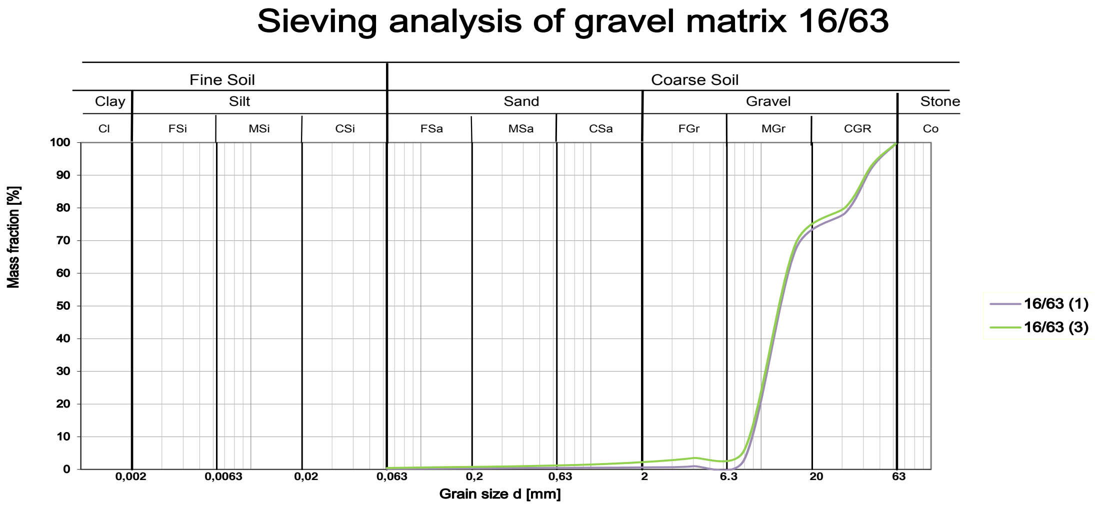

Figure 63 *Grading curve of 16/63 gravel mixture sample*

When comparing the grain size distributions of the first and third level of each sample, the share of sand is slightly higher in the lower level. This can be an indication that some sedimentation processes have occurred during or since the implementation of the field experiment. Nevertheless, these differences are too small to draw definite conclusions. With the exception of the 08/32 hs mixture, the gravel mixtures vary little between the upper layers and the lower layers in the boxes. The 08/32 hs mixture displays a larger portion of coarse gravel in the first level. Due to the stabilization with cement, the gravel mixture had to be broken up in smaller pieces with an iron bar. This was done manually and the focus was solely on collecting the roots. Therefore, it is possible that lumps of the cement-gravel-mixture remained solid and might change the outcome of the sieving analysis.