Estimating the mechanical contribution of willows and balsam poplar in soil bioengineering projects in Alberta

By

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Abstract

After the floods in 2013 in Alberta, the effort towards reducing the impact of conventional approaches on the environment and improving the desirable effects of vegetation protecting the water bodies has been an increasing trend in most cities. Soil bioengineering designs with fast-growing plants and natural or synthetic support materials for reinforcement and reducing soil erosion have been becoming common alternatives to conventional engineering to treat streambank failures, banks where pipelines cross water bodies and road rehabilitation among other applicatio. Moreover, recovery of riparian vegetation with these techniques has increased in the last decades in response to concerns over water quality, fisheries, wildlife, flooding damages and aesthetics. However, despite the policies promoting greener solutions, the lack of precise technical information about the effect of plant roots on soil strength and the associated uncertainties means engineers are resistant to recommend the use of soil bioengineering, and then maintain the preference for conventional approaches even where soil bioengineering is appropriate. Therefore, the move from the use of traditionally "hard" elements to "greener solutions" as a functional material in streambank soil stabilization has been challenging for decision makers.

The focus of this study was to quantify the strength provided by roots of species commonly used in soil bioengineering projects in Alberta, such as willows (*Salix spp*) and balsam poplar (*Populus balsamifera*).

We built a large-scale shear box to validate models calibrated with data from the mentioned species. We also assessed root architecture and strength variation, often called 'biological uncertainties' under engineering perspectives. The results indicated that the mechanical contribution to the soil stabilization of mature willows (*Salix spp*) and balsam poplars (*Populus balsamifera*) assessed increased the soil cohesion up to around 0.3 m deep, where we found the majority of roots. The large-scale direct shear tests suggested that Fiber Bundle Model (FBM) and Wu and Waldron Model (WWM) consistently underestimated the total force from the plant roots. Systems to calculate slope or streambank stability that includes models for plant root contribution should incorporate factors of strength variation so they can help us move beyond overly conservative factors of safety and provide engineers with the data required to make informed decisions about the strength of soil treated with soil bioengineering.

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Table of Contents

List of tables

Table of Figures

1 INTRODUCTION

Soil bioengineering is the use of plants as structural components to increase soil strength and decrease soil erosion. It is an integrated watershed-based technology that uses engineering practices with ecological principles to repair erosion damage and slope failures, or as a method to enhance already healthy, functioning riparian zones (Gray and Sotir, 1996; USDA/NRCS, 2007). There are three types of soil bioengineering projects when used for streambank or soil stabilization (USDA - FS, 2000; USDA/NRCS, 2007): The first type only uses plants with no significant support structures. The second uses plants that can grow from cuttings, which make temporary structures, such as wattle fences or lined poles, that help control the erosion while providing support to the plants until they establish. Finally, there are the projects designed to be hybrid systems where engineered structures (such as riprap or wooden crib walls) provide additional temporary or permanent support while the plants mature. Regardless of the type of project, one of the main objectives of soil bioengineering projects is to improve soil strength by increasing the soil cohesion with the roots from the vegetation. Rood et al. (2015) found that fast-growing woody riparian plants, such as the most often used poplars (*Populus* spp.) and willows (*Salix* spp.), are more effective than grasses at resisting bank and floodplain erosion from major river floods for mountain region river because of the more profound and woody roots. Especially in drier climates, such as Alberta, roots penetrate deeper in the soil seeking for the moisture from the water table instead of developing shallow roots to capture the water from precipitation (Rood et al., 2015). Consequently, the soil stability increases with the presence of larger diameter, length and rigidity of tree roots.

Over the past few decades, it has become apparent that hard engineering structures (riprap, concrete tiles or gabions) have challenges related to degradation of riparian ecosystems and reduced resiliency (USDA/NRCS, 2007). Soil bioengineering projects can provide resiliency and increase ecosystem health and often have lower costs of installation and maintenance. Despite these benefits and an increasing public desire for promoting greener solutions, there is a lack of technical information required for soil bioengineering project design (Coppin et al., 1990; Gray and Sotir, 1996; Indraratna et al., 2015). The City of Calgary identified that there was not enough guidance to civil and river engineers on appropriate locations for hard engineering rip-rap or soil bioengineering structures for streambank erosion control (The City of Calgary, 2017). Thus, a 'Riparian Decision Matrix' for river engineering projects was developed to help guide where soil bioengineering projects are appropriate and preferred mostly based on the landscape (The City of Calgary, 2017).

One of the significant limitations facing the implementation of soil bioengineering is the lack of a widely accepted method that can be used to determine the contribution of plant roots to soil strength. This challenge is most evident in larger projects where engineers are required to provide designs that are expected to protect infrastructure or buildings (Fatahi et al., 2015). In these projects, engineers avoid including plants as functional elements and rely on classic methods of streambank stability. The effect of roots in the soil has been described as similar to the concept of reinforced concrete, as roots have higher tensile strength and ductility, counteracting the low tensile strength and ductility of soil (Gray and Sotir, 1996; Macginley and Choo, 2001). In this way but of course with lower intensity than the concrete, the soil-root matrix can be continuously stressed (soil in compression, roots in tension) to improve the behaviour of the final structure under working loads. Although the processes have been well studied, the challenge is that plants and native soils are not engineered products, so the processes governing the soil mechanical reinforcement by roots is complicated and has a high amount of biological uncertainty.

The province, municipalities and private companies noticed this challenge when there was a dramatic increase in the desire to have the benefits of soil bioengineering solutions for streambank stabilization subsequently the 2013 flood in Alberta. In late June of 2013, heavy rainfall triggered catastrophic flooding, described by the provincial government as the worst in Alberta's history. It was the most massive flood since 1932 in the Calgary area where five lives were lost, and there were $6 billion in financial losses and property damage across southern Alberta (The City of Calgary, 2019). Since then, authorities have spent millions of dollars on streambank restoration and installation of engineered structures to protect riparian zones and infrastructure against future flood damages (Inkpen and Eyk, 2016; The Government of Alberta, 2014). As part of this recovery program, the Province of Alberta, the City of Calgary, and non-governmental organizations (NGOs), such as Cows and Fish and Trout Unlimited surveyed riparian areas to determine which areas to treat with soil bioengineering projects as a means to improve the flood resiliency. These sites included natural riparian areas impacted by the flood and other disturbances such as resource roads, off-highway vehicle (OHV) recreation use, cattle and engineered structures damaged during the flood. In the following years, many of these sites have been treated with soil bioengineering techniques that included native plants, such as willows (*Salix spp*.), poplars (*Populus spp.*), redosier dogwood (*Cornus stolonifera*), dwarf birch (*Betula pumila*) and saskatoon (*Amelanchier alnifolia*) (Cows and Fish, 2019; Fatahi et al., 2015; The Government of Alberta, 2014; USDA/NRCS, 2007; Wonneck et al., 2018).

None of the soil bioengineering projects in Alberta included calculations of the soil–root strength, so they were installed based on conservative designs, previous experience of professionals, or as test sites. There are models available that can estimate the soil mechanical contribution of roots (Table 1), but they were not used during the design of the projects. Two of these models are the Fiber-Bundle Model (FBM) (Pollen and Simon, 2005) and the Wu and Waldron Model (WWM) (Giadrossich et al., 2017; Waldron, 1977; Wu et al., 1976). Larger engineering systems that are available for use in slope stability projects have incorporated both of these models (Greenwood, 2006; USDA/ARS, 2018). To be used in Alberta, these models require input data on the strength of the roots of local plants and descriptions of the root morphology and root distributions.

The tensile root strength is the main input data required to use the FBM and WWM. There are several methods used to measure root strength; however, pullout tests are most commonly used to assess individual root tensile strength in the field (Giadrossich et al., 2017; Greenwood et al., 2003; Pollen and Simon, 2005; Schwarz et al., 2013; Wu et al., 1976). The pullout tests are used to build a relationship between the diameter of the roots and the breaking strength, or force required to pull the root from the soil for a plant species. The test consists of attaching a load cell to a root exposed at the face of a soil pit. Then, the load cell is pulled perpendicular to the soil pit with steadily increasing force until the root breaks or is pulled from the soil. The FBM and WWM models use the relationship between the root diameter and strength along with the root diameter distribution found in the soil to estimate the total root cohesion provided to soil (Giadrossich et al., 2017; Pollen and Simon, 2005; Schwarz et al., 2013; Waldron, 1977; Wu et al., 1976). In addition to determining the strength of roots, the pullout test method provides information on the natural variability of root strength and the soil-root cohesion (Loades, 2010; Schwarz et al., 2011).

Different species have distinct characteristics that respond to environmental conditions (Stokes et al., 2008). The amount of lignin and cellulose, components of vascular tissues in the root (woody material), are related to root strength (Genet et al., 2005; Hales et al., 2013; Hales and Miniat, 2017; Zhang et al., 2014). Air temperature, precipitation, and soil moisture content influence the quantity of vascular tissue of stem wood, supporting stronger and denser wood

(Zhang et al., 2014). Therefore, these factors might affect root strength because roots have a similar vascular structure to stem wood (Genet et al., 2005; Hacke et al., 2001; Hales et al., 2009). Hales et al. (2017) found that roots with a higher moisture content of tulip tree (*Liriodendron tulipifera)* and sweet birch (*Betula lenta)* were weaker than drier roots in the field and the laboratory. Moreover, the soil saturation also changes the cohesion between the soil and the root bark, leading to more pulled-out than broken roots in pullout tests (Duncan and Wright, 2005; Endo, 1980; Fatahi et al., 2015; Loades, 2010; Mitchell and Soga, 2005; Stokes et al., 2008). There are other sources of variability such as the root length because of the higher probability of having weak points due to the internal structure in longer roots (Danjon et al., 2007; Giadrossich et al., 2017; Loades, 2010; Schwarz et al., 2013). The total root strength may also change depending on the root architecture. The geometry of how roots are arranged in the soil may change the resistance to the shear force. Thus, individual roots may provide higher or lower total strength depending on the root architecture (Danjon et al., 2007; Ghestem et al., 2014; Nicoll et al., 2006).

In application, methods use the average root distribution and strength to calculate the average effective root cohesion and distribute it over the entire hillslope or streambank (Greenwood, 2006; USDA/ARS, 2018). Other methods have detailed surveys of root architecture (Danjon et al., 2007; Ghestem et al., 2014; Nicoll et al., 2006) to calculate spatial distribution of root mechanical reinforcement in grids (Danjon et al., 2007) or in finite element models of soil combined with root strength (Mickovski et al., 2011). These studies have shown how spatially diverse the effective root cohesion is within the streambank and how the distribution relates to the root architecture. Plants are living material, and root architecture develops in response to many variables, including the need to transfer the force of tree structure into the ground (Stokes et al., 2008). As a result, root systems provide stability to the plant as it responds to topography or mechanical stress (e.g. wind loading) resulting in asymmetric shapes (Nicoll et al., 2006; Stokes et al., 2008). There are no general rules that determine how roots grow on slopes (Danjon et al., 2007; Stokes et al., 2008); however, information on the shape and distribution of the roots for plants of common species can provide information on the potential spatial distribution of the mechanical reinforcement (Danjon et al., 2007; Ghestem et al., 2014; Nicoll et al., 2006). Besides, the depth distribution of the roots will affect how deep in the soil mechanical reinforcement can be expected in soil bioengineering projects.

Collectively, the variation in root strength and the spatial distribution of roots create biological uncertainty and is a challenge for application to engineering projects. A few publications have used a "factor of safety" to address this uncertainty. For Example, Greenwood (2006) suggested including a factor of safety of 8 in Slip4Ex system. To our knowledge, observed variation did not support these factors. Similar to methods for engineered products, they are rather chosen to be conservative and limit the possible complications of overestimating the contribution of root strength in slope stability projects (Greenwood et al., 2003; Greenwood et al., 2004; Pollen and Simon, 2005).

Even though there have been studies of the mechanical behaviour of plant roots, few studies have validated the model results with direct measurements of root-soil matrix strength, especially for mature woody plants used in soil bioengineering projects. One of the most common tests used to characterize the global behaviour of the root-soil matrix is the direct shear test (Das and Sivakugan, 2016; Giadrossich et al., 2017). Direct shear tests use a "shear box", which is metal box split horizontally into halves. A normal force is applied to the lid, and the shear force is then applied by moving one half of the box relative to the other to cause failure in the soil specimen (Endo, 1980; Giadrossich et al., 2017; Shibuya et al., 1997; Yildiz et al., 2018). The result is a direct measure of the force required to shear a specimen of soil. These tests are most commonly conducted in the lab for small soil specimens; however, a few studies have made use of custom-built shear boxes for application in the field (Mickovski et al., 2011; Pollen, 2007; Shibuya et al., 1997; Yildiz et al., 2018) or with larger soil sample and planted vegetation (Endo, 1980; Yildiz et al., 2018). These methods have reported the difference in strength between specimens of soil only and soil-root matrix (Endo, 1980; Ghestem et al., 2014; Mickovski et al., 2011; Pollen, 2007; Shibuya et al., 1997; Waldron, 1977; Yildiz et al., 2018). They also provide an opportunity to validate models by comparing modelled effective root strength results to direct institute measurements of the soil-root matrix surrounding mature or planted plants that used for soil bioengineering projects.

1.1 Objectives:

1. Collect data from root-pulling tests with native willows and balsam poplar to calibrate root-soil models;
2. Validate root-soil models with a large-scale direct shear test; and

3. Assess the root architecture of willows and balsam poplar, and root strength variation to help inform biological uncertainty.

2 METHODOLOGY

2.1 Study sites

We obtained data from two sites. The first site, Lost Knife Trail, was a site where volunteers planted willow cuttings to stop erosion and stabilize the streambank in 2014. It was public land at 51° 19' 09.3" -114° 57' 37.2" and approximately 100 km west from Calgary, AB. The volunteers planted an area of approximately 1000 m^2 with native willow cuttings. The cuttings were 1 m long, over 25 mm in diameter, planted 0.8 m deep and at a density of 2 plants/m^2, but there were only 0.5 plants/m^2 when we took the measurements. Most of the slope was 9º and pitched up to 21º at the top. Following the root pulling methods presented by Pollen and Simon (2005), we dug seven soil pits and measured the root strength of the planted willows.

The second site was historically a small tree nursery and is referred to as the "Tree Farm" herein. It was private land, approximately 50 km west of Edmonton (53° 36' 58.1" -114° 14' 44.8") with a small stand of naturally established willows, and balsam poplars ranging in age from 10 to 49 years, determined by counting the growth rings. At this site, we dug 33 soil pits and measured root strength of the mature plants also following the method by Pollen and Simon (2005). We also excavated 20 plants to describe the root morphology and used a 'Large-Scale Shear Box' to obtain shear strength data of 7 institute soil samples with varying amounts of roots.

2.2 Root architecture

We used a towable excavator and shovels to excavate 20 plants at the Tree Farm. For the willow roots, we measured the root diameters every 5 cm along each root to determine the root shape factor. Balsam poplar roots had crooked shapes that did not allow for accurate measurements of the shape factor. We photographed the excavated root balls on four sides, the top and the bottom to describe the root architecture. For roots above 10 mm in diameter, we measured the root diameters 10 cm away from the main stem and used filled-radar charts to describe the horizontal distribution of the large root system (Gilman et al., 1987; Sakals and Sidle, 2004).

2.3 Root strength

We used the pullout method presented by Pollen and Simon (2005) to measure root strength of 21 willows and 17 balsam poplar at the Tree Farm site and 7 willows at the Lost Knife Site. First, we used a towable excavator to excavate soil pits (approx. 0.4 m wide, 1 m deep and 2 m long) approximately 0.3 m beside plants (Giadrossich et al., 2017; Pollen and Simon, 2005). Once we had the roots exposed in the soil pits, we identified the species. Even though the soil pits were close to the target plant, some soil pits contained roots from many different plants. We were able to identify the willows because the roots had a distinctive red tone, and the balsam poplar roots had yellow/brown peeling bark. We then measured the root strength using the 'Pull-a-root' on loan from the United States Department of Agriculture USDA – Agricultural Research Service – National Sedimentation Laboratory (USDA/ARS, 2018). The 'Pull-a-root' was a metal frame and a manual winch attached to a load cell that connected to the root with a cable and U-bolt assembly. In our case, the U-bolt crushed the roots and caused them to break at the connection point. Giadrossich (2017) encountered the same problem and suggested an epoxy layer to protect the root at the contact with the cable to the load cell. In the end, we modified the connection point to include a 60.5 mm diameter piece of ABS pipe to work like a pulley. The device significantly reduced the number of roots broken at the connection point, although we needed at least 15 cm of the exposed root to attach to the device. The 'Pull-a-root' measured the peak load required to break or pull the root out of the soil. We measured the diameter of the roots outside the bark at the breaking point with a digital calliper (Mitsutoyo CD6GS). If the root pulled from the soil, rather than broke, we measured the root diameter at the connection point between the load cell and the root. For all roots, we measured the root depth to the nearest 1 cm, corresponding to the tench depth. Finally, we measured the root moisture content of a subset of the roots with a wood moisture meter (Agelec HM-520).

2.4 Large-Scale Direct Shear Test (LSDST)

We used a custom-built large-scale direct shear box with internal dimensions of 0.8 m x 0.8 m x 0.6 m and split horizontally at 0.3 m (Figure 1). The lower portion of the box was connected to a front-end loader of a small tractor (approx. 20 hp). The tractor hydraulic system drove two hydraulic cylinders that pushed the upper part of the box, producing a maximum shear force of 81.5 MPa across the shear plane. A pressure-compensated flow valve was used to slow the hydraulic flow rate so that the box moved at a rate of 0.06 m/min. A single hydraulic cylinder driven by an independent pump at constant 5.17 MPa produced a normal force, which was equivalent to 8.07 MPa pressure on the soil. Rails on the lid prevented its rotation (Shibuya et al., 1997; Yildiz et al., 2018). We used metallic 30 cm rulers to measure vertical and horizontal displacements and pressure gauges to measure the hydraulic forces in the hydraulic cylinders. Video cameras recorded the displacement and pressure, which were later used to produce force/displacement relationships for each test.

To use the shear box, we carefully excavated around a 0.8 m x 0.8 m x 0.6 m block of soil and roots, being sure not to disrupt the soil and root matrix. We then positioned the shear box and backfilled it with soil to level the surface, if needed. Backfilled soil was added in 0.2 m lifts and compacted with a 0.15 x 0.15 m, 4 kg rammer released from a height of 0.4 m, ten times. After each shear test, we carefully excavated to the shear plane and measured the diameters of roots outside the bark with a digital calliper (Mitsutoyo CD6GS) at the breaking point (Endo, 1980; Giadrossich et al., 2017; Mickovski et al., 2011; Shibuya et al., 1997). We used the shear box on 4 institute blocks of soil that contained plants: 1) a willow with 2 main trunks (diameters 45 mm and 32 mm), 2) a balsam poplar (diameter 101 mm), 3) a willow (42 mm) combined with a balsam poplar (38 mm), and 4) a balsam poplar (diameter 230 mm). We also tested two blocks of soil with roots but not the entire plant. We also used the shear box with backfilled soil to obtain a measurement of only the soil shear strength. For this run, we filled the box with only soil in 0.2 m lifts and used the rammer to compact each layer.

2.4.1 Models for total strength

We used the measurements of the root diameters from the Large-Scale Direct Shear Tests, and the force-diameter relationships from the pullout tests in the Fiber-Bundle Model (FBM) (Figure 2) (Pollen and Simon, 2005) and Wu & Waldron Model (WWM) (Giadrossich et al., 2017; Waldron, 1977; Wu et al., 1976) to calculate the total cohesion provided to soil by roots.

For Monte Carlo simulations, we converted the force-diameter relationship to natural logarithm scale to have a linear relationship so we could use the MS Excel NORM.INV tool. This function returned a force (kPa) within the prediction range (1) for each root diameter based on the random probability in normal distribution around the average force. Finally, we had a list with 1000 different total forces calculated through Fiber Bundle Model with all roots with random forces within the prediction range.

$$Deviation = t_\alpha * SE * \sqrt[2]{1 + \frac{1}{n} + \frac{(X - X_m)^2}{SS_{xx}}} \quad (1)$$

Where t_α is Student t at 95% of confidence; SE: Standard Error of residue; Xm: average of root load; SSxx: sum of squares of deviations of datapoints from the mean; n: total number of entries. All parameters were from the root-pulling dataset. X: diameter; Y: Load predicted by the force/diameter relationship.

3 RESULTS

3.1 Root architecture

The root architecture is important because the horizontal distribution and spatial coverage of the roots will determine the potential uniformity of the root strength contribution of each species used for soil bioengineering projects. Authors have presented a standard system with radar charts to describe the root system of trees to aid in the description of root architecture, spatial coverage and depth (Mekonnen et al., 1998; Sakals and Sidle, 2004). The results for our twelve balsam poplar (*Populus balsamifera*) and eight willows (*Salix* spp.) are in Figure 3 and Figure 4 showing that the architecture varied considerably. However, some similarities can be used to classify the root systems of the two species. The willows (Figure 4) had shallow horizontal root systems with few vertical roots. There were only a few (1 to 3) large roots in a vertical or oblique angle and likely for mechanical support. We classified as an intermediate between heart and tap root systems (Stokes et al., 2008). The balsam poplar (Figure 3) appeared to have different root architecture for smaller and larger trees. The smaller balsam poplars (trunk diameter (DBH) less than 60 mm) had large lateral roots and a few vertical roots, and we classified these as a plate root system (Stokes et al., 2008). The larger balsam poplars (diameter 60 mm and greater) had large lateral roots and main roots on the vertical plane, which we classified as a plate root system with tap root system characteristics (Dobson, 1995).

The shape of the individual roots was different for the two species; balsam poplar (*Populus balsamifera*) roots were brittle, fewer and dryer than the willow (*Salix* spp.) roots. The shape of the balsam poplar was crooked, shorter and thicker than the willows (Dobson, 1995). Many of the roots broke when we excavated the trees. We developed a length-diameter relationship from 28 willow intact roots to determine the possible distance that we could expect roots to contribute strength past the soil pits. We measured the diameter of these roots every 5 cm and had an equation, with r^2= 0.96, that could estimate the length of the willow roots based on a measured diameter (2):

$$Root\ Length\ (m) = 0.1403 * Root.Diameter^{0.7995} \qquad (2)$$

The balsam poplar roots were crooked so we could not develop a similar relationship. We estimated that most of the root length would be within 1 m of willow plants, by using root diameter distributions from the soil pits and excavated trees (Figure 5) and the equation (2). Thus, our results suggest that the mechanical effect of willows is asymmetrical for many trees and less than 1 m from the plant.

3.1.1.1 Depth distribution

The depth distribution will help determine how deep soil bioengineering projects will affect the soil strength. We observed most of the roots for both species were shallow and concentrated in the first 0.3 m of soil, with only a few roots at a depth of 0.5 m when we aggregated all the soil pit data, (Figure 6). Some larger mature balsam poplars (*Populus balsamifera*) did have a tap-root system with deeper roots, but these roots were close to the tree and not found in the soil pits. Also, we observed two-year-old willow (*Salix* spp.) cuttings regenerating with roots concentrated in the upper 0.3 m of the soil, even though the cutting was planted much deeper (photo in Figure 7, data not presented). Although not conclusive, this suggested that willows and balsam poplars are shallow rooted species and they provide the mechanical support to the upper 0.3 m of the soil.

3.2 Calibration - Root strength

Figure 8 and Figure 9 show the breaking load for the root diameters of willows (*Salix* spp.) and balsam poplars (*Populus balsamifera*), respectively. The results show similar force/diameter relationships to Pollen and Simon (2005) findings with similar species such as sandbar willow (*Salix exigua*) and cottonwood (*Populus fremontii*) (Figure 10). The curve for 153 balsam poplar roots (*Populus balsamifera*) calculated in this study was close to the Pollen and Simon (2005) findings of 90 cottonwood (*Populus fremontii)* roots. However, the willows (*Salix* spp.) in this study had a curve with higher forces than the one presented by Pollen and Simon (2005) for sandbar willow (*Salix exigua*). The tree-sized willows among the smaller plants may have affected the results because of the stronger roots if compared to shrubs of sandbar willows. Pollen and Simon (2005) measured 44 roots of sandbar willows (*Salix exigua*) in Kansas, USA to establish the force/diameter relationship. We measured 213 willow (*Salix* spp.) roots, however, without knowing the subspecies.

We only had 24 roots pulled from the soil, rather than break, which may be due to higher root-soil cohesion found at our sites. This is much less when compared to other publications. For example, Pollen and Simon (2005) observed that river birch (*Betula nigra*) roots below 3.5 mm were more likely to be pulled out because most of the roots below that size came out of the ground during the root-pulling test. The root-pulling data had a significant amount of variation ($r^2 = 0.77$ for balsam poplar and $r^2 = 0.80$ for willows, Figure 16). The variation is not unexpected in a natural material tested in the field and may be attributed to internal root structure differences, tortuosity, elasticity, and root moisture (Gray and Sotir, 1996; Nicoll et al., 2006; Rood et al., 2011). The roots were also pulled at the right angle to the soil pit face, which results in different angles of the pulling force relative to the face of the trench (Giadrossich et al., 2017; Pollen and Simon, 2005).

Hales et al. (2017) showed that the moisture content of roots could affect the strength. We measured the moisture content of a subset of the roots tested and compared the strength-diameter relationships of roots above and below 15 % moisture content for willows (Figure 11) and above and below 20 % for balsam poplar (Figure 12). The results showed the opposite behaviour between the two species. Smaller (< 8 mm) willow (*Salix* spp.) roots had more strength with higher moisture content, and the effect is less with increasing root diameter, and at 8 mm there is no apparent difference in strength. Balsam poplar roots appeared to have more strength with lower moisture content (below 20%) and an increasing trend with root diameter. The results for balsam poplars was contrary to publications which tested young roots in the laboratory where drier roots had higher strength (Giadrossich et al., 2013; Giadrossich et al., 2017; Hales and Miniat, 2017; Yildiz et al., 2018). Although not conclusive, the species had a different trend that could guide their use along a streambank. There are not many publications relating the moisture content of roots from mature plants right after excavation to make any comparison related to the soil stability.

3.3 Validation - Large-scale direct shear test

Published data on the soil shear strength can be variable, and the shear strength depends on the soil properties (angle of friction and the cohesion), the organic content, compaction, moisture content and other factors influencing soil strength. Although it is challenging to determine the potential shear strength from the soil classification, it provides support to determine if the results are within the expected range. We hand textured the soil at our site and classified the soil as a Silty Clay Loam with organic matter. Thus, the soil can be classified as a mix between organic and inorganic silts and clays, varying from CL/OL (inorganic clay with low plasticity/organic silts and clays with low plasticity) to CH/OL (inorganic clay with high plasticity/organic silts and clays with low plasticity) for estimating a range of expected strengths (Transportation, 2017). The organic part has insignificant cohesion, but the inorganic portion can range from 11.01 kPa as saturated to 102 kPa as compacted (Das and Sivakugan, 2016; Lindeburg, 2006). Our results (Figure 13) showed a progression of shear strength, starting at the low end of these published amounts at 11.3 kPa for the ‘Soil only’, which was the soil packed into the shear box. As expected, the two tests without a plant in the middle of the test, ‘Misc02’ and ‘Misc03’ were next at 24.11 kPa and 21.90 kPa. The ten roots in Misc 02 were calculated to only contribute with an effective root cohesion of 5.88 kPa (WWM) and, 3.35 to 6.03 kPa (95% C.I. of FBM Monte Carlo simulations (Figure 14)). Similarly, ‘Misc 03’ had six roots that were calculated to contribute with an effective root cohesion of 5.58 kPa (WWM) and 3.33 to 6.91 kPa (95% C.I. of FBM Monte Carlo simulations (Figure 14)). When we compare the blocks with roots to the soil only results (calculated root cohesion + 11.3 kPa to the ‘Soil only’: 11.3 kPa), it suggests that the model underestimates the effective cohesion of the roots. However, there could be other reasons for this difference in strength, such as the undisturbed soil was more compacted than the soil we compacted manually (‘Soil only’).

Figure 13 shows the results for all the tests, including the four with plants of increasing sizes. As expected, the shear strength increased with the size of the plant and the number of roots involved. The shear strength of the root-soil with the largest balsam poplar (‘balsam poplar big’) was greater than the force of the shear box, and it stopped after 5 cm displacement. Thus, we reported 81.52 kPa here, but the strength was above 81.52 kPa. The plant had 41 roots broken and one unbroken large tap root (66 mm diameter) at the shear plane. Similar to the ‘Misc02’ and ‘Misc03’ tests, the FBM and WWM estimated mechanical reinforcement from roots plus 11.34 kPa (‘Soil Only’ test), and they were consistently below the value measured by the shear box.

When adding the ‘Soil only’ result of 11.34 kPa, the Fiber Bundle Model (FBM) had the closest prediction ‘Misc 03’ with 31%. Wu and Waldron Model (WWM) with the same case underestimated the resistance to shear in 23% (Figure 15). ‘Willow’ run had the second furthest underestimation with 75% (FBM) and 64% (WWM). ‘Balsam poplar big’ run would have the furthest because the tap root resisted to the shear force and did not break. In this case, the models would estimate less than 25% of the strength presented in the shear test.

4 DISCUSSION

The effectiveness of the root cohesion added to the soil is not immediate after planting. The plants need to establish, develop the root system to increase the soil-root matrix properties, and this takes years. However, for example, willows planted at the Lost Knife site were four years old and already had a significant contribution to soil cohesion because willows (*Salix* spp.) is a fast-growing plant like balsam poplars (*Populus balsamifera*).

The contribution to soil strength also relates to where the roots are and the geometry of their arrangement. The spatial variation will result in root strength distributions that vary along a bioengineered streambank. Our results suggested that willow roots have short lengths (up to 1 m in length) in addition to the asymmetrical shape. Theoretically, plant communities would form root networks as they mature, and that make use of more underground space, providing more uniform strength to the entire area (Stokes et al., 2008). We observed this in the mature stand at the Tree Farm site, where roots formed a network that was difficult to dig through. We also found roots from many different plants in the soil pits close to the target plant, which was not the case at the four-year-old Lost Knife site.

Descriptive root architecture is useful in understanding how the soil-root mechanical properties are distributed around the plant, vertically and horizontally, and if there are voids without roots expected within a planted streambank (Dupuy et al., 2007; Nicoll et al., 2006; Rood et al., 2011; Stokes et al., 2008). Each plant we excavated presented a different spatial distribution of roots (Figure 3 and Figure 4), mostly with asymmetric distributions. Also, there were a few large roots positioned in only one or two directions. Others analyzed root architecture using excavation with pressurized air, 3D ultrasound projection, and other techniques and observed similar asymmetry and uneven distribution around the main stem (Danjon et al., 2007; Giadrossich et al., 2017; Loades, 2010; Nicoll et al., 2006; Stokes and Mattheck, 1996; Stokes et al., 2008). Danjon et al. (2008) used pressurized air to excavate two mature white oak (*Quercus alba*) roots on a slope and found that roots were thicker upslope than downslope. Almost 70% of the roots were shallow, up to 0.4 m below ground. Moreover, it is not possible to determine the exact position of the roots in the soil-root matrix (Danjon et al., 2007). Nicoll (2006) found that roots systems of Sitka spruce (*Picea sitchensis*) trees on horizontal terrain were not clustered to any direction. On the other hand, the root system was clustered across the slope in the windward position. Dupuy et al. (2007) chose poplars (*Populus* spp.) data to feed a 3D root and soil model in a finite element modelling software, and they found a massive central vertical root (taproot) up to 1 m deep with asymmetrical lateral roots with an average density of 24 lateral roots per meter.

The plants of both species surveyed had shallow root depths, concentrated in the upper 0.3 m of soil. Pollen and Simon (2005) also found roots of cottonwood (*Populus fremontii)* and sandbar willow (*Salix exigua*) only up to 0.5 m deep. This is not surprising because willows (*Salix* spp.) and poplars (*Populus* spp.) are shallow root species (Rood et al., 2011). The USDA (2019) and University of Alberta – Alberta Center of Reclamation and Restoration Ecology (2019) also classified willows (*Salix* spp.) and balsam poplars (*Populus balsamifera*) as species with shallow root systems (Alberta, 2019; NRCS, 2019).

The four-year-old Lost Knife site had willow cuttings planted as deep as 0.8 m, but the soil pit data showed most of the roots concentrated at 0.3 m (Figure 6). Planting a variety of riparian species may be an effective strategy that can help overcome the challenges of asymmetric root architecture and shallow root depths (Rood et al., 2015; Rood et al., 2011; Stokes et al., 2008). Rood et al. (2015) found that trees, such as cottonwoods (*Populus* spp.) and willows (*Salix* spp.), are more effective than grasses at resisting bank and floodplain erosion from major river floods for mountain region river because of the deeper and woody roots. However, some mat-forming grasses could also provide surficial erosion resistance as a revetment and trapping sediments (Rood et al., 2015; Rood et al., 2011). Different plant categories complement each other in soil protection, preventing surficial erosion. The different heights of plants can improve roughness, increasing the resistance to flow and reduce the local flow velocity, causing the stream to dissipate energy against the deforming plants, rather than the soil (Boudell et al., 2015; Hoag, 2007; USDA/NRCS, 2007). Diversity in the riparian ecosystem may have other benefits, including more resilience to droughts, insects, or other pathogens (USDA/NRCS, 2007).

Our shear box tests were limited, but they provided a possible method that can be used to validate a Slip4x modelling framework presented by Danjon et al. (2007). Danjon et al. (2007) used a low-frequency electromagnetic field sensing device to map detailed 3D measurements of roots from two white oak (*Quercus alba*) trees. They then made 3D virtual hillslopes with the roots from plants at different densities. Finally, they used the WWM and Slip4x to estimate the strength of the soil in grids of the hillslope and showed the spatial variability of strength. As expected, and supported by the modelling results in the virtual hillslope (Danjon et al., 2007), our shear box results show the highest shear strength around the plants and increasing strength with plant size.

The soil strength between the plants represented by the soil blocks with roots but without the plant inside ('Misc 02 and 03') was 2 to 4 times less than around the plants. However, the FBM and WWM modelled results consistently underestimating the measured shear strength of the root-soil matrix, which ranged from 29% to 75% depending on the method or test, including the variation in the root strength measurements using the Monte Carlo simulations. Our 'Soil only' run, which became the base soil strength likely had lower strength than the native soil because the soil block was dug to remove the roots and then compacted manually in the shear box. However, even if we consider the 'Misc 02 and 03' tests (with only few willow roots) to be the base soil strength (approx. 25 kPa instead of 11.34 kPa ('Soil only')) the modelled estimates of the root strength are still lower than the measurements.

This underestimation may also be related to our limited number of shear box tests or other factors; such as the direction that the root-puller device pulls the roots. Root strength test methods apply a longitudinal force to the root (Giadrossich et al., 2017; Pollen and Simon, 2005), which is different from the majority of the lateral forces observed in the shear box test. The roots have longitudinal fibres implying different resistance between lateral and longitudinal directions to break them (Dobson, 1995; Eab et al., 2015; Endo, 1980; Ghestem et al., 2014; Giadrossich et al., 2013; Loades, 2010; Mickovski et al., 2011; Stokes and Mattheck, 1996; Veylon et al., 2015). However, we suggest that the most likely source of the uncertainty is the large roots in the shear box tests that were outside the range of the root pull out measurements. These large roots could provide more strength to the soil matrix than expected or predicted by the data from the root puller. In our tests the large roots pulled along the shear plane instead of breaking, which is expected because the root-soil cohesion is thought to be lower than the root strength (Endo, 1980; Gray and Sotir, 1996; Stokes and Mattheck, 1996; Stokes et al., 2008; Zhang et al., 2014). Thus, these large roots provide less mechanical support than their breaking strength; however, we observed that these large roots were part of an interconnected network of roots that formed a dense close matrix. This root-soil matrix may provide more complex interactions between the soil and the roots. Thus, the soil (acting in compression) and the roots (acting in tension) may be more than the sum of the individual components along the shear plane, as they are treated in the models. Doing more tests with the shear box, studying the different directional strengths in the roots (Giadrossich et al., 2017; Pollen and Simon, 2005) may provide insights, or comparing shear box test results to more detailed finite element models (Dupuy et al., 2007; Mickovski et al., 2011) may help determine the cause of the model underestimation found here.

A factor of safety is often used to account for the uncertainty in the materials used in engineered projects. When safety or expensive infrastructure is at risk, it is often preferred to underestimate rather than overestimation the design (Pollen and Simon, 2005). Following this, Greenwood (2006) recommended dividing the root strength by 8 to compensate biological uncertainties as a factor of safety in Slip4Ex. However, excessive underestimation results in higher construction costs, and may also discourage the use of soil bioengineering at appropriate sites. The methods and results presented here attempted to build a framework that could account for the biological uncertainty into the design of soil bioengineering projects.

Systems designed to help project designers to account for the effect of plant roots in soil stability, such as Bank Stability and Toe Erosion Model (BSTEM) (USDA/ARS, 2018) and Slip4Ex (Greenwood, 2006) would improve the results if they incorporate the variation of root strength instead of account for only the average strength. An averaged number for the strength does not represent the biological reality. The strength would change from the bank top to the toe due to the soil moisture content. This moisture changes with the seasons and the designer should know the dynamics through time under the safety perspective. The root architecture would also change the total root strength depending on the geometry of root arrangement.

If hard engineering is not required, Slip4Ex has the possibility of input different root cohesions and architectures in the same bank, and then it could show the nuances of soil reinforcement along the treated bank during the diverse moisture contents along the year. In this case, it would be useful to see the weakest spots, which could be reinforced with bioengineering techniques or conventional engineering if required. Finally, it could calculate the factor of safety through time, which could be a range based on the variation of root strengths.

5 CONCLUSION

Soil bioengineering techniques can improve soil stability by increasing the cohesion of the root-soil matrix. However, it takes time for the roots to establish and mature, and then initial soil reinforcement is usually required. Most projects make use of fast-growing shrubs and trees to ensure roots establish quickly. However, we consistently found that the roots concentrated in the top 0.3 m of the soil at our study sites. This was the case for both mature, naturally established plants (except for a few deeper tap roots), and willow cuttings with planted deeper (up to 0.8 m) four years ago. The cause behind the shallow root system is not clear, but the results suggest that the mechanical root support of these species will be limited to the upper 0.3 m of the soil. We also found that the root architecture was asymmetrical with most willow roots predicted to be less than 1 m in length. Therefore, the mechanical root strength will vary across a hillslope. However, at the Tree Farm, in the older diverse stands, we observed a dense root network that made digging the soil pits and excavating the plants challenging. This observation is limited, but it does support the idea that a diverse set of shrubs and trees species that are well suited to the ecosite will provide more complete root network in the soil (Boudell et al., 2015; Cows and Fish, 2019; Hoag, 2007; USDA - FS, 2000; USDA/NRCS, 2007). This may result in a more continuous and interconnected root network and other benefits, such as overall ecosystem resiliency.

We used a large-scale shear box to test the outputs of root-soil strength models and found that the models consistently underpredicted the amount of strength in the soil. More work is needed to determine the factors contributing to the underestimation; however, we observed that the root-soil matrix interactions around the plants were more complex than the simple additional cohesion added within models. Future studies could use more detailed measurements (Dupuy et al., 2007; Kokutse et al., 2006; Tai et al., 2018) of the total root distribution and architecture, along with more complex models (e.g. Hydrologic Engineering Center's River Analysis System (HEC-RAS) which has incorporated Bank Stability and Toe Erosion Model (BSTEM) (USDA/ARS, 2018), or (Tai et al., 2018)) to determine if the soil-root matrix distributes forces more completely throughout the soil block.

The modelling framework presented by Danjon et al. (2007), using Slip4ex (Greenwood, 2006) along a slope, and validated here provides a method that could be used to determine factors required for designs of soil bioengineering projects. Monte Carlo simulations of virtual hillslopes and data from established plant root architecture would provide an expected range of the mechanical support the roots of plants would provide to a streambank. A more detailed dataset of roots from sites planted for soil bioengineering could also be obtained if less destructive methods of mapping root architecture were used (Danjon et al., 2007; Ghestem et al., 2014; Nicoll et al., 2006). This information will help us move beyond overly conservative factors of safety and provide engineers with the data required to make informed decisions about the strength of soil treated with bioengineering.

6 TABLES AND FIGURES

Table 1: History of models for root strength estimation (Giadrossich et al., 2017).

Model	Reference Author(s)	Relevant use (Year)	Assumptions
Wu and Waldron Model (WWM)	Wu; Gray and Lesser; Waldron etc.	1976	Perpendicular roots on a shear plane. Soil Shear strength = f(Total area of roots*Tensile strength of roots) All roots break at once
Energy Approach Model	Ekanayake; Phillips	1997	The energy exchanged during the direct shear test in situ relates directly to the area between the stress-displacement curve and the x-axis. The total energy capacity of the soil-root system is the area under the soil with roots, up to the shear displacement at peak shear stress
Finite Element Model (FEM)	Zienkiewicz and Taylor	1998	Spatial discretization of root-soil medium that aims at reducing the continuum field functions - force, displacement, stress or strain - to their values at particular points (nodes)
Finite Difference Model (FDM)	Frydman and Operstein	2001	Spatial discretization of root-soil medium that aims at reducing the continuum field functions - force, displacement, stress or strain - to their values at particular points (nodes)
Fiber Bundle Model (FBM)	Pollen and Simon; Hidalgo	2005	Fibre Bundle Model (FBM) Roots break progressively redistributing the load to the remaining ones which present different strengths according to their diameter; an initial shear force is applied to the bundle and assumes that each root in the bundle can resist an equal portion of the applied force.
Limit Equilibrium Method (LEM)	Greenwood	2006	The Factor of Safety is calculated as the ratio between the shear strength, provided by the Moh-Coulomb failure criterion, and the actual shear force that applies at the slip surface.
Root Bundle Model (RBM)	Schwarz	2010	Strain-step loading
Root Bundle Model Weibull (RBMw)	Schwarz	2013	Takes into account the variability of the force at breakage for a given root diameter class using Weibull survival function.

Figure 1: Large-scale shear box built for this study. 0.8 m x 0.8 m x 0.6 m (H) split in half height, the upper part of the box is pushed by two hydraulic cylinders to shear the soil block. There is a lid on the top for Normal force powered by a single hydraulic cylinder with an independent pump. On the right, cylinders fully extended to a displacement of 0.3 m.

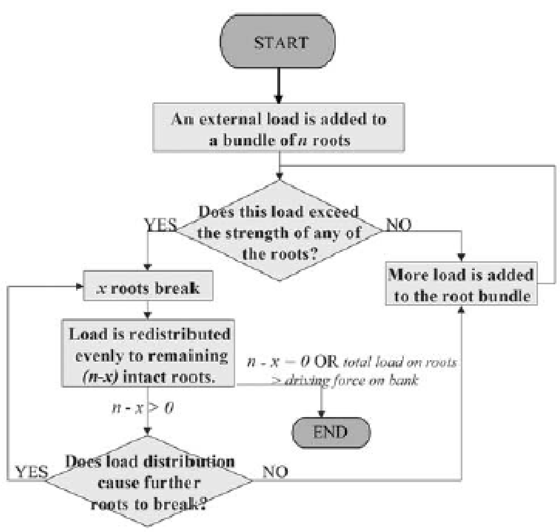

Figure 2: Flowchart for the Fiber-Bundle Model presented by Pollen and Simon (2005). The weakest root breaks, then the load is equally redistributed to the remaining roots, and the load is increased until the next weakest root break (Pollen and Simon, 2005).

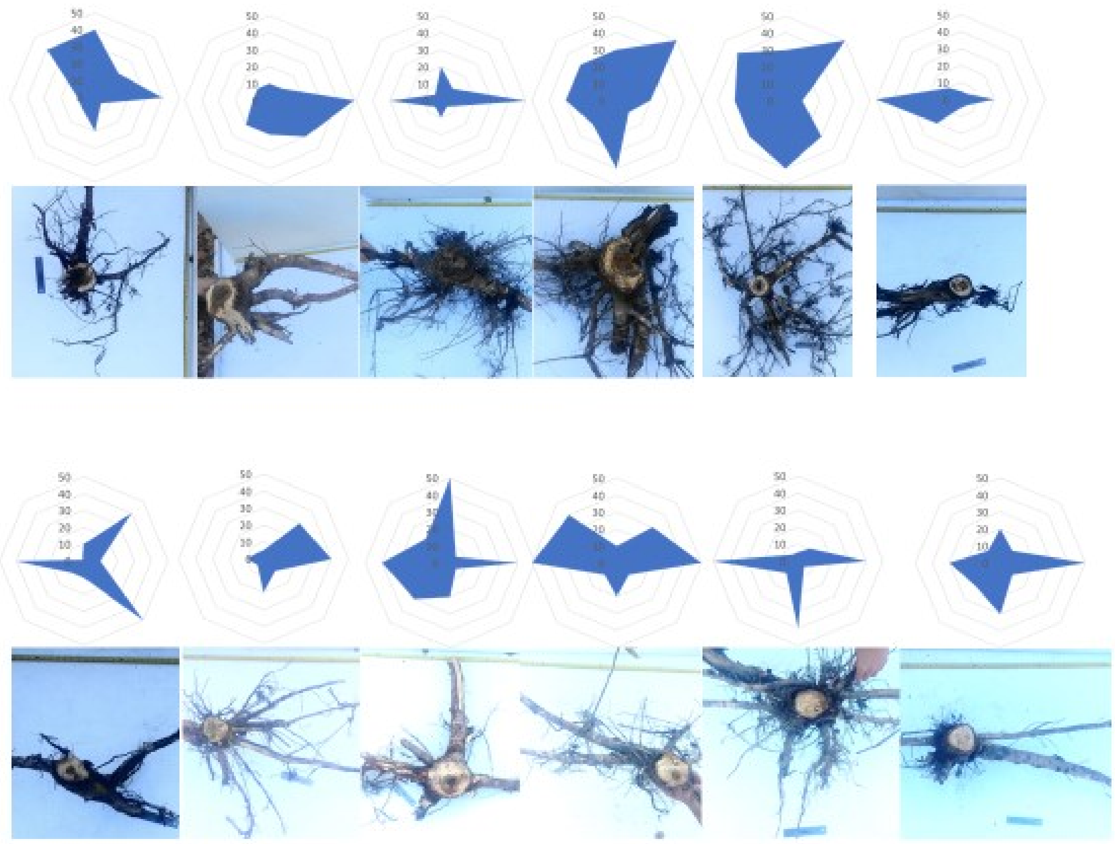

Figure 3: Pictures from the top of roots and diagrams for the horizontal distribution of 12 balsam poplars (*Populus balsamifera*) excavated on the Tree Farm. The blue area corresponds to the root coverage around the plant (10 mm diameter and greater). The white area corresponds to voids around the plant without roots.

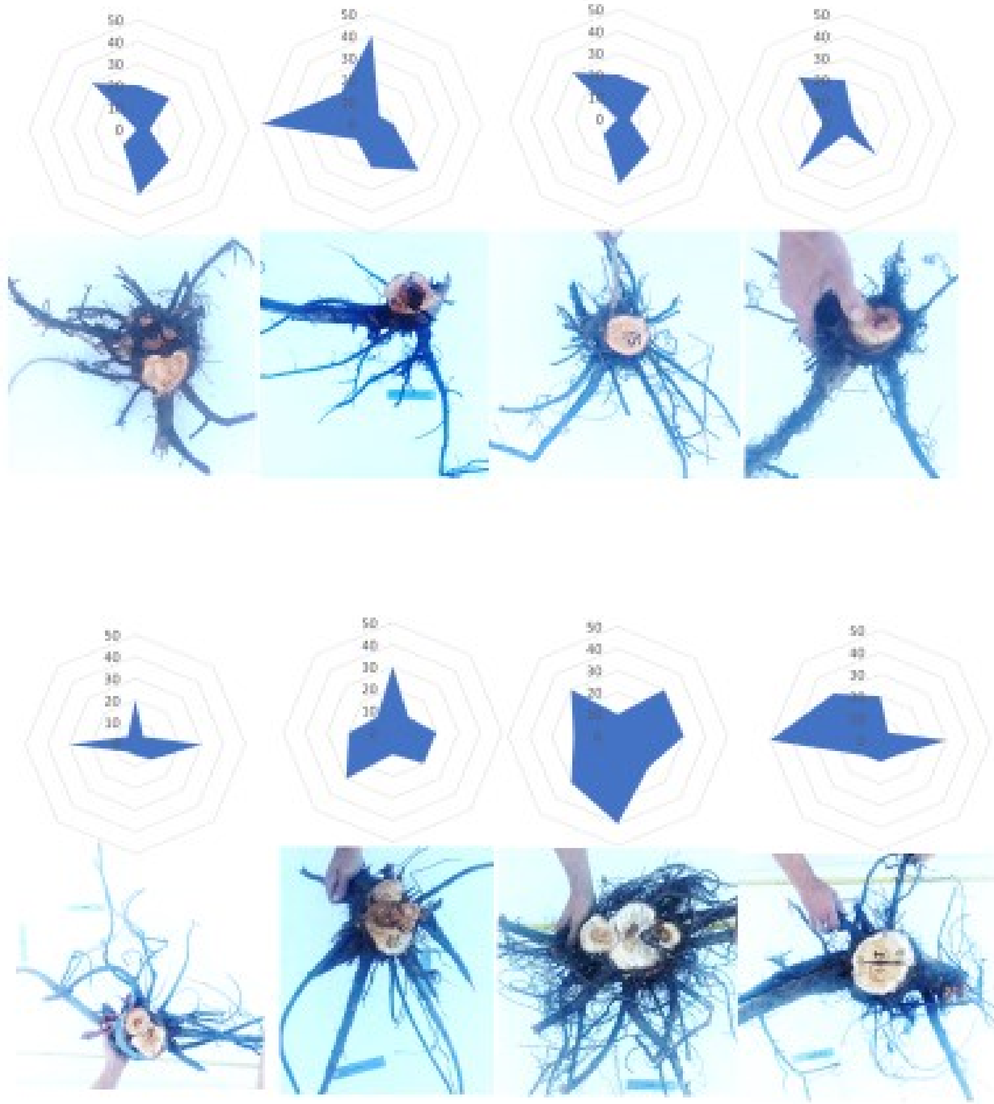

Figure 4: Pictures from the top of roots and diagrams for the horizontal distribution of 8 willows (*Salix spp*) excavated on the Tree Farm. The blue area corresponds to the roots coverage around the plant (10 mm diameter and greater). The white area corresponds to parts around the plant without any roots.

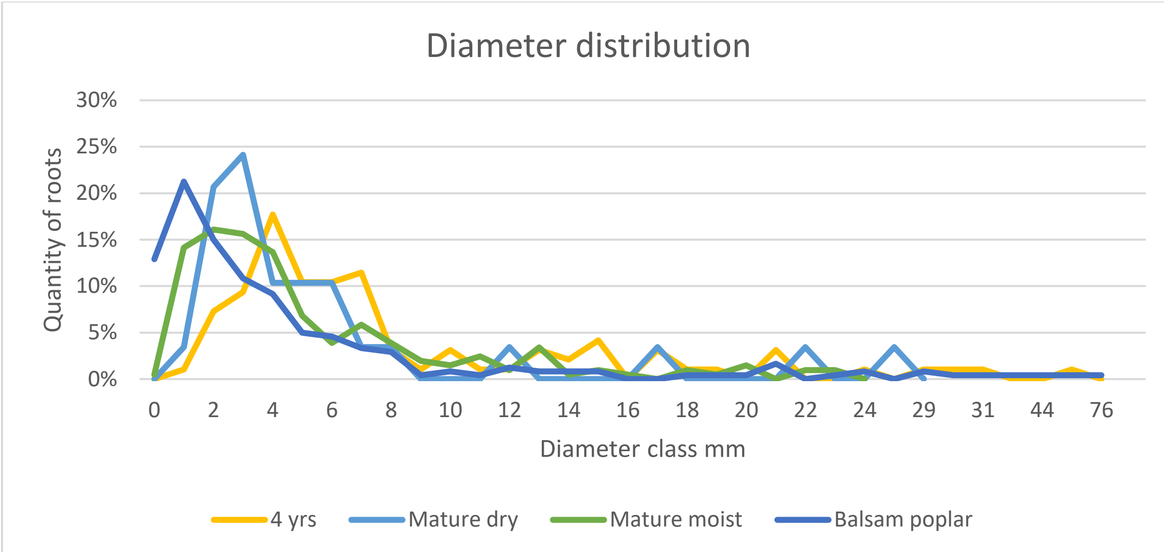

Figure 5: Root diameter distribution. Percentage of the number of root diameters for willows (*Salix spp*) after four years and at the mature stage (over 20 years-old measured through growing ring counting). For balsam poplars, the data is only for mature plants.

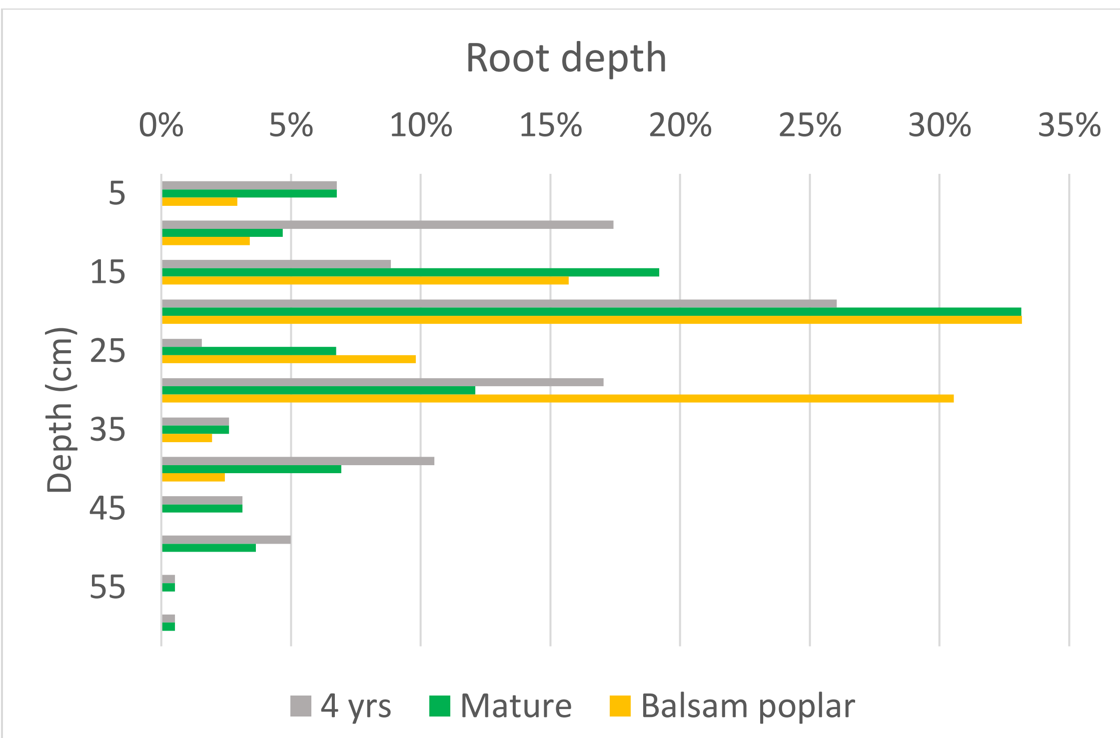

Figure 6: Percentage of the number of roots found in different depths for willows after 4years and at the mature stage (around 20 years-old measured through ring counting). For balsam poplars, the data is only for mature plants.

Figure 7: Two-year-old willow cutting with a root system in the upper portion of the soil, despite being planted deeper.

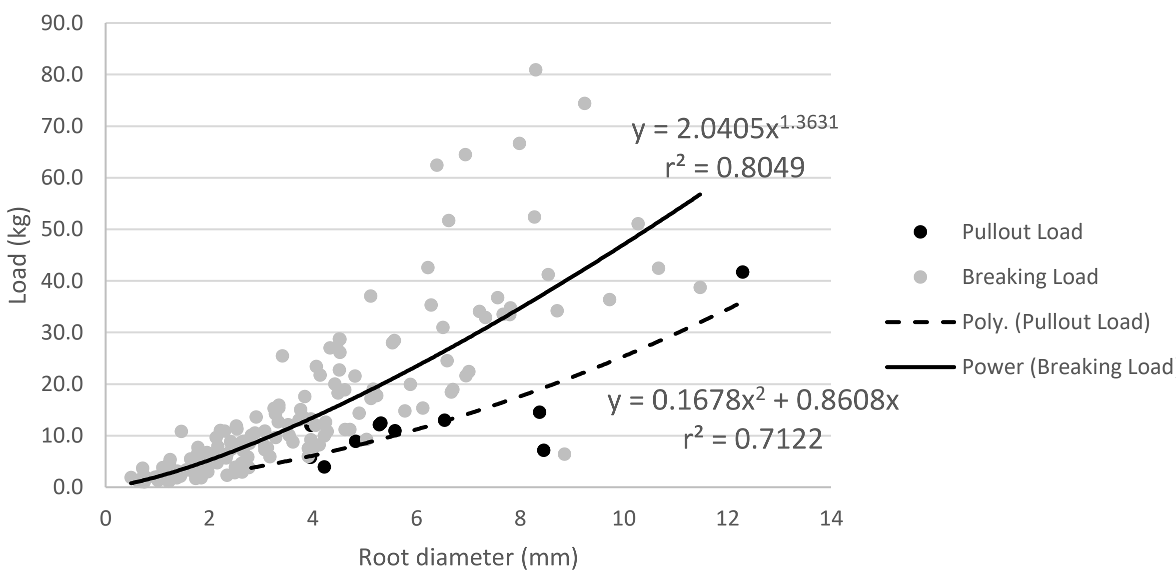

Figure 8: Force required to break and pull-out willow roots. Pull-out curve had fewer points than the broken roots. The load cell limited the load to 100 kg, most common in diameters above 10 mm.

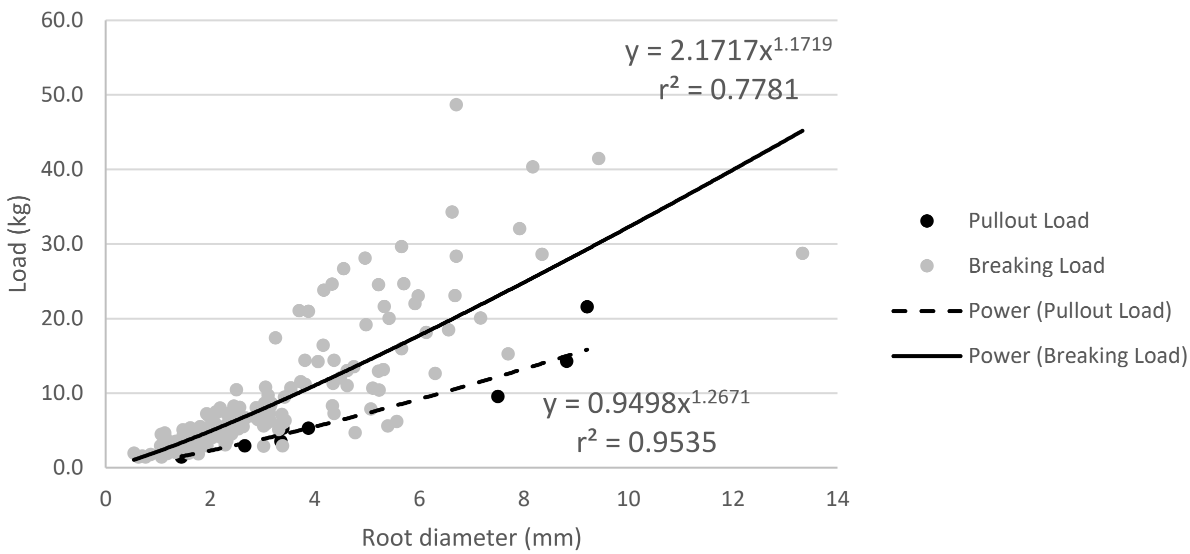

Figure 9: Force required to break and pull-out balsam poplars roots. Pull-out curve had fewer points than the broken roots. The load cell limited the load to 100 kg, most common in diameters above 10 mm.

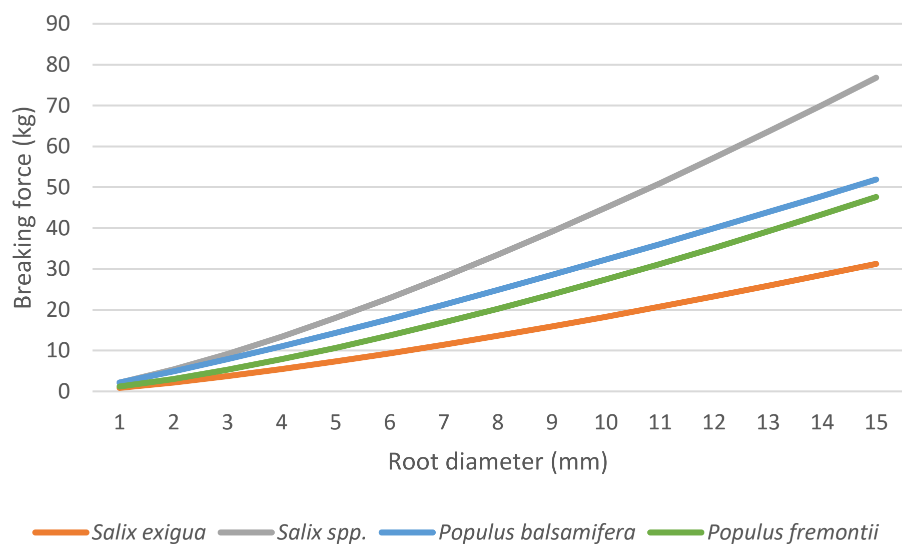

Figure 10: Relationship force/root diameter. Salix exigua and Populus fremontii from Pollen and Simon (2005*).* *Salix* spp. and *Populus balsamifera* from this study.

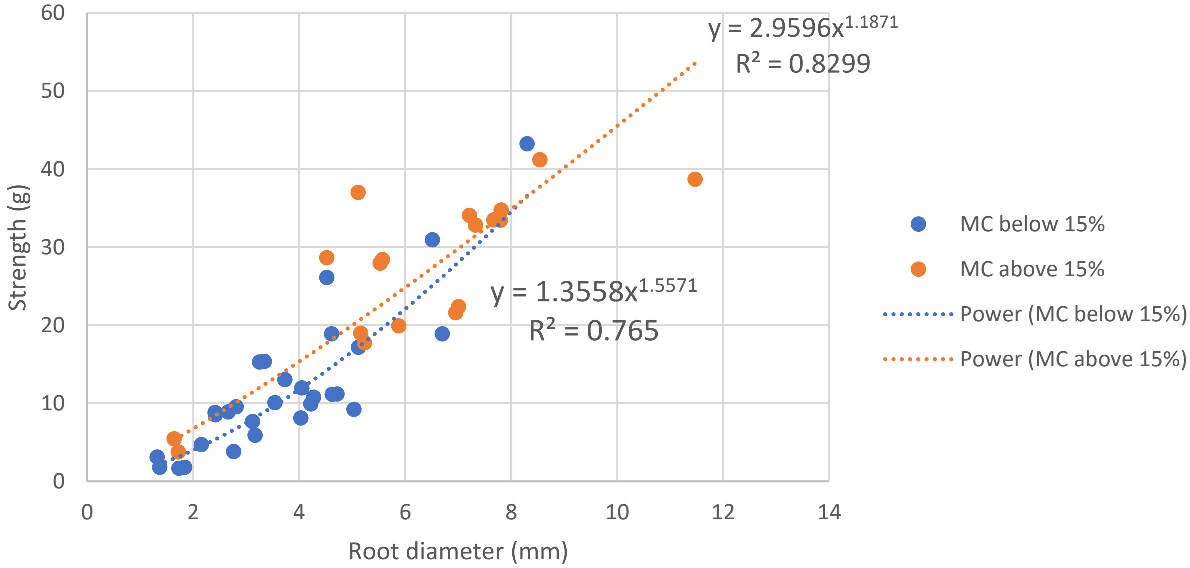

Figure 11: Variation of moisture content in willow (*Salix spp*) roots by diameter classes. Each class includes ± 0.5 mm.

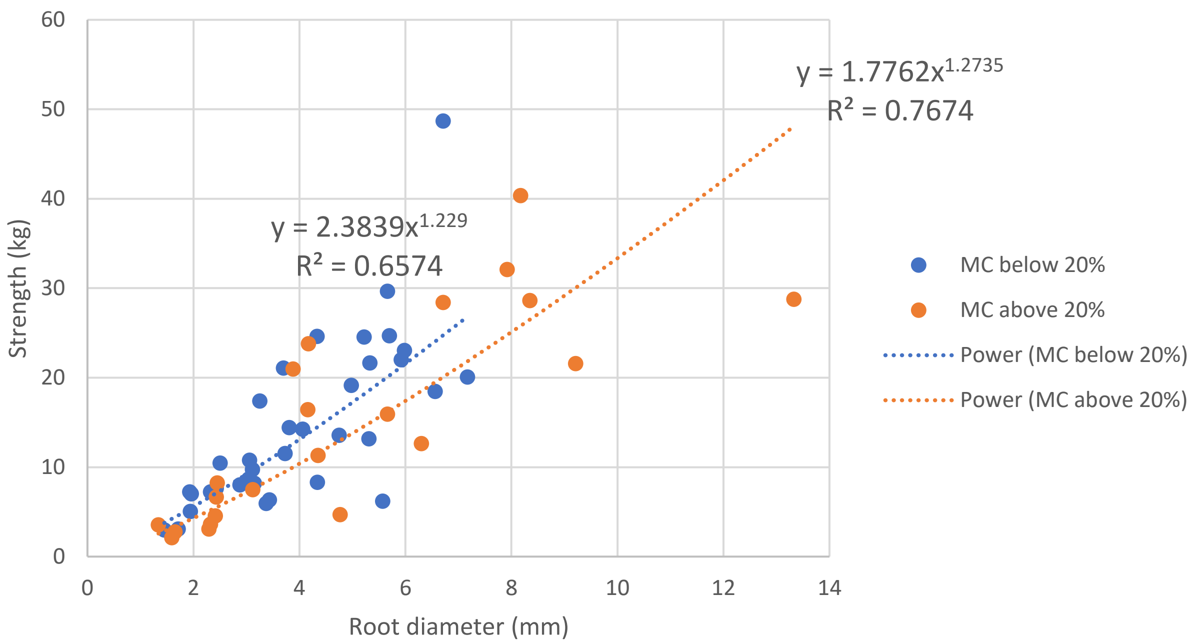

Figure 12: Variation of moisture content in balsam poplar (*Populus balsamifera*) roots class by diameter classes. Each class includes ± 0.5 mm.

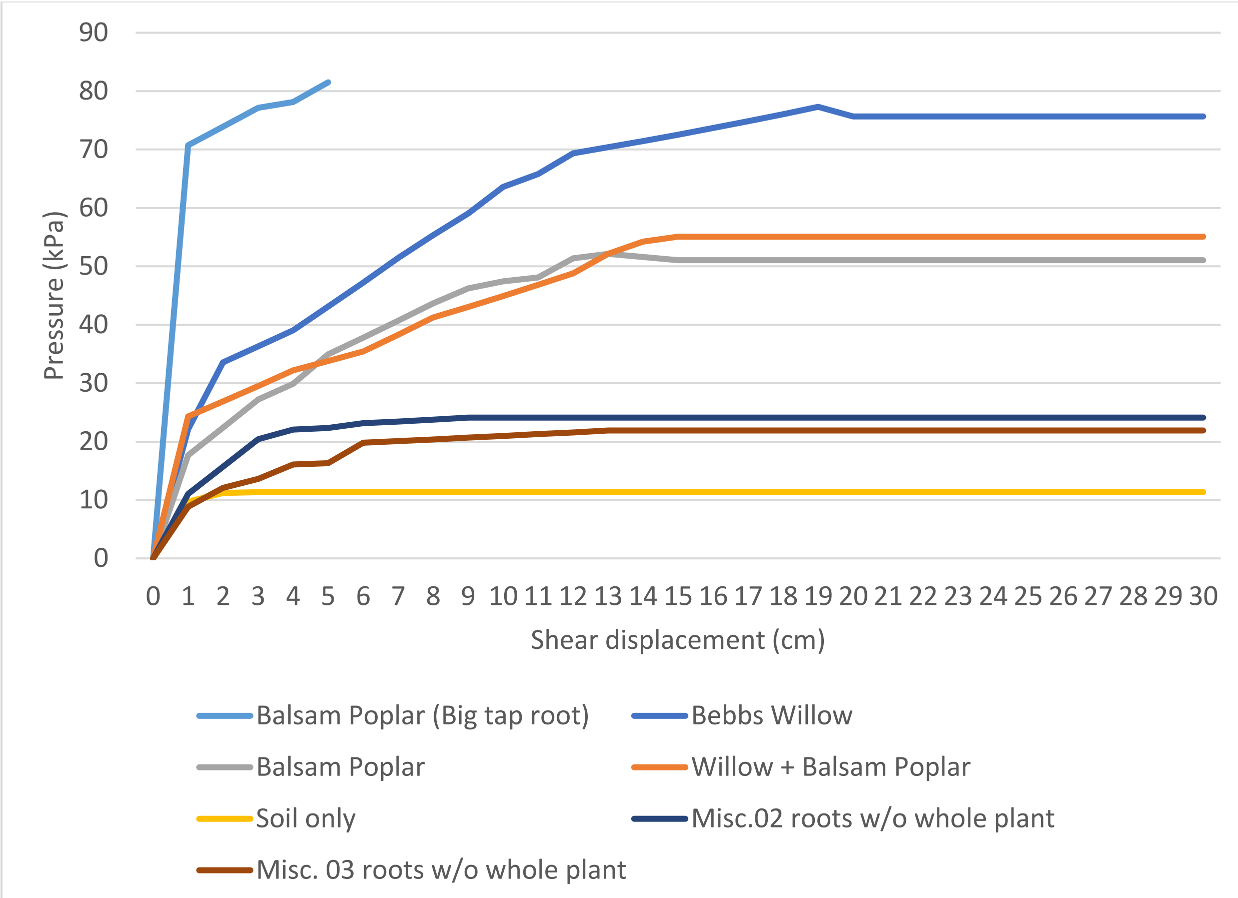

Figure 13: Results of Large-Scale Direct Shear Test. 'Balsam poplar (Big tap root)' was a mature balsam poplar with a tap root (66 mm diameter) that stopped the movement of the box after 5 cm. 'Bebbs Willow', 'Balsam Poplar' and 'Willow + Balsam Poplar' were mature plants in the middle of the shear box. 'Misc 02 w/o whole plant' and 'Misc 03 w/o whole plant' were soil blocks with roots of mature plants, without the plant inside the shear box.

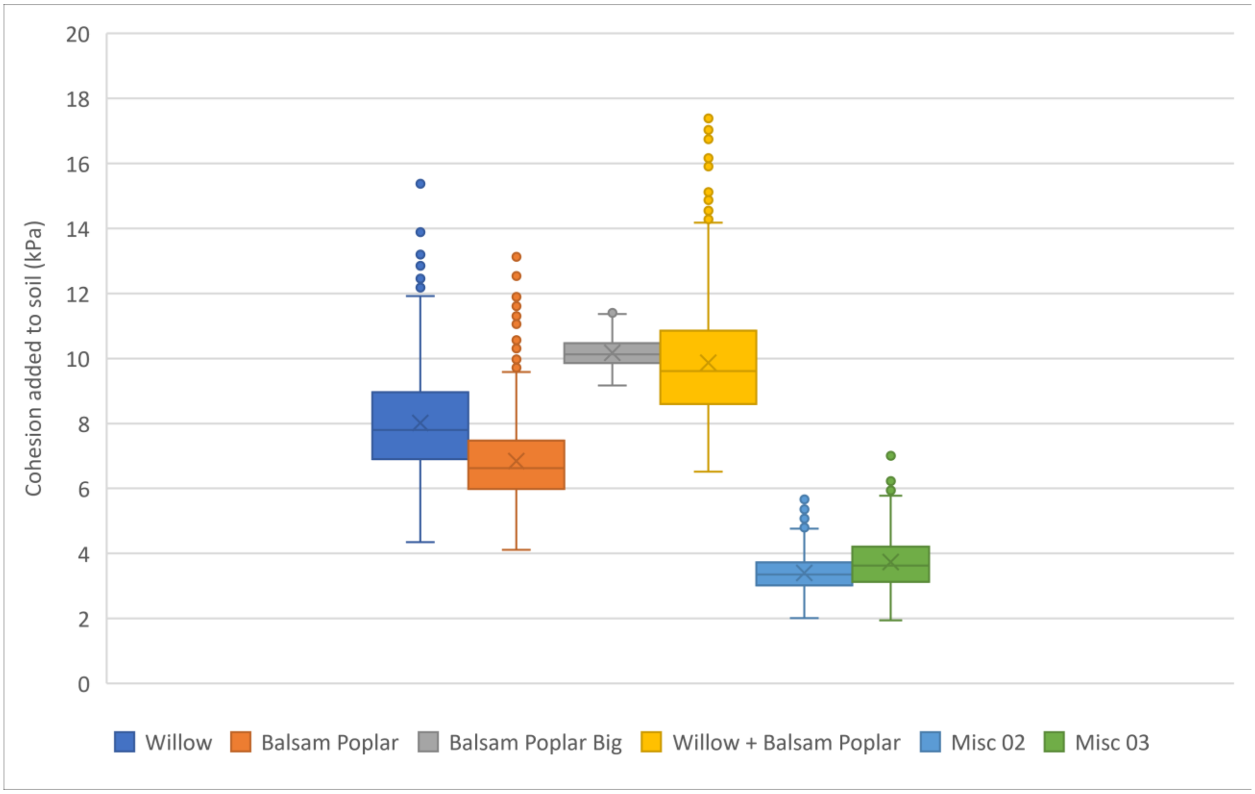

Figure 14: Results of variation of root strength from the Monte Carlo simulation of 1000 plants using FBM method. The confidence interval of root strength from calibration data provided the random strengths for the 1000 runs, from where we had a range of total cohesion added to the soil by each root set from the shear test runs. ** The values for roots over 10 mm diameter did not have calibration points, although estimated by the regression from calibration data.

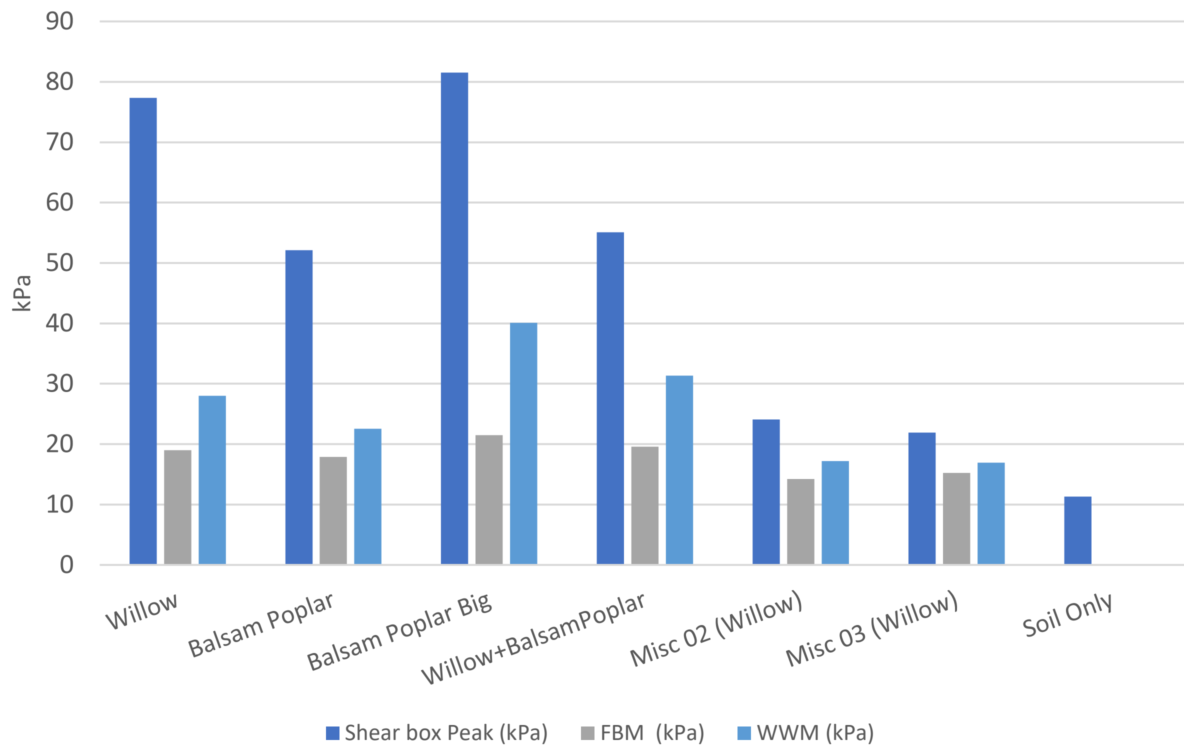

Figure 15: Validation: results from the shear test compared to the total strength estimations from the models FBM and WWM. ** The values for roots over 10 mm diameter did not have calibration points, although estimated by the regression from calibration data.

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8 APPENDIX

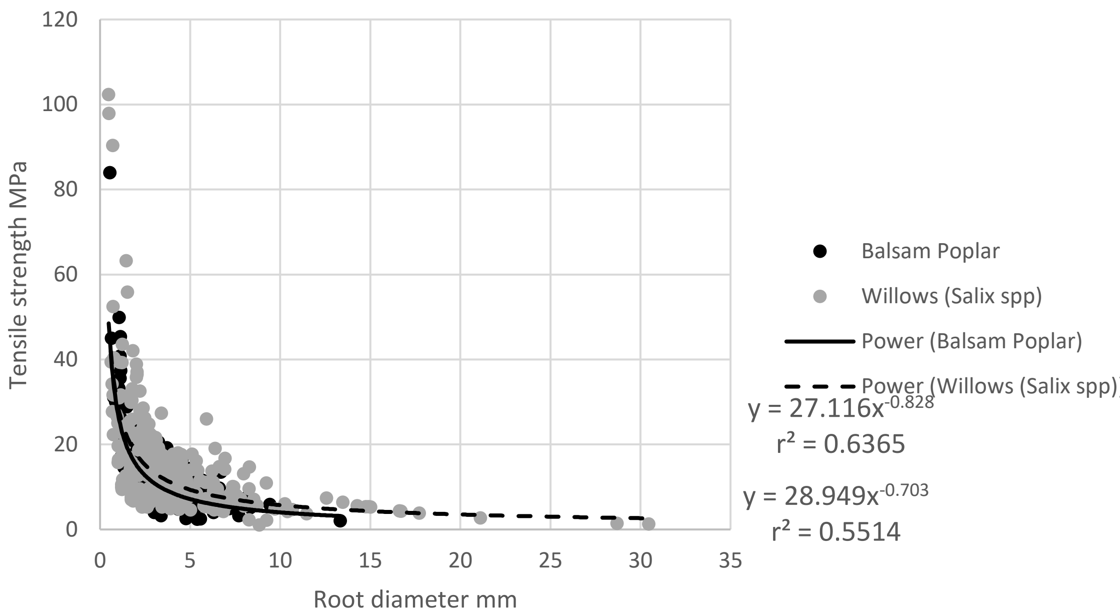

Figure 16: Tensile strength data for willow (*Salix* spp) and balsam poplar (*Populus balsamifera*). The force divided by the root area at the breaking point provided this distribution.

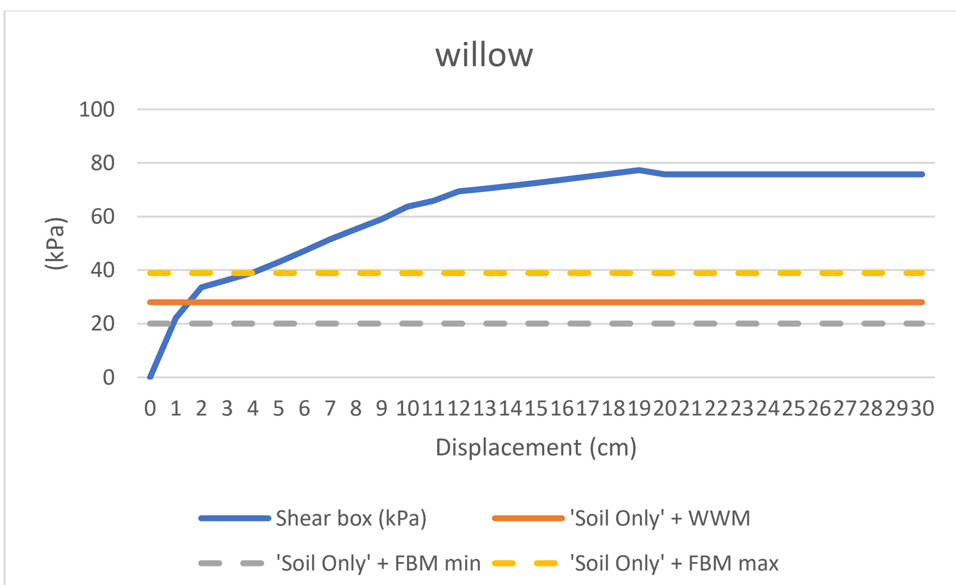

Figure 17: Shear box measurement compared to Wu and Waldron Model (WWM) and the range for Fiber Bundle Model (FBM) for 'willow'. The measurement of 'Soil only' was added to the models.

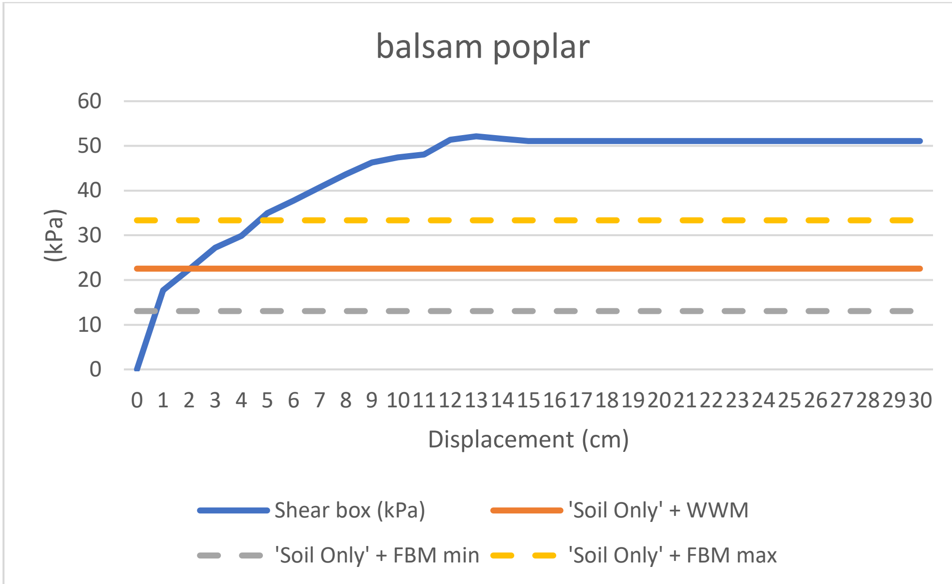

Figure 18: Shear box measurement compared to Wu and Waldron Model (WWM) and the range for Fiber Bundle Model (FBM) for 'balsam poplar'. The measurement of 'Soil only' was added to the models.

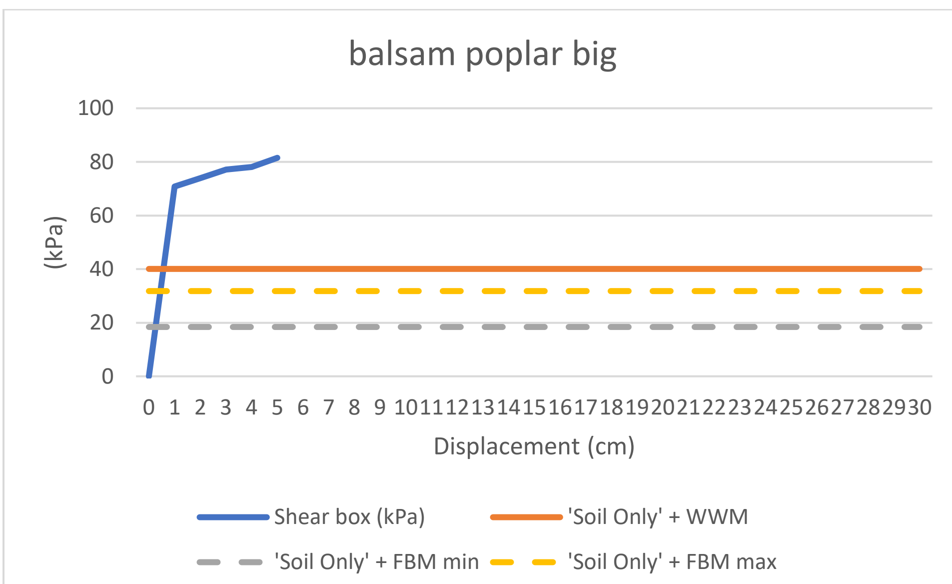

Figure 19: Shear box measurement compared to Wu and Waldron Model (WWM) and the range for Fiber Bundle Model (FBM) for 'balsam poplar big'. The measurement of 'Soil only' was added to the models.

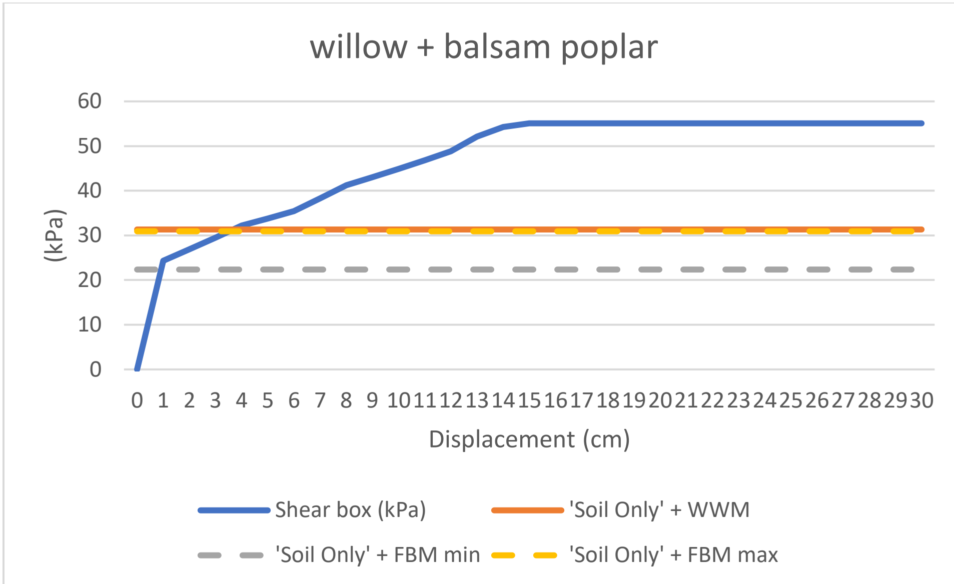

Figure 20: Shear box measurement compared to Wu and Waldron Model (WWM) and the range for Fiber Bundle Model (FBM) for 'willow + balsam poplar'. The measurement of 'Soil only' was added to the models

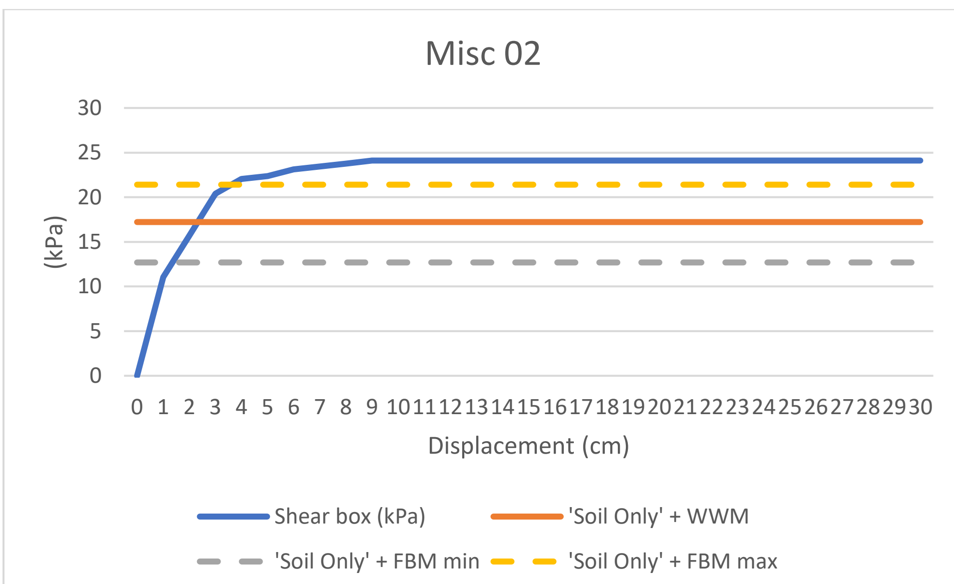

Figure 21: Shear box measurement compared to Wu and Waldron Model (WWM) and the range for Fiber Bundle Model (FBM) for 'misc 02'. The measurement of 'Soil only' was added to the models

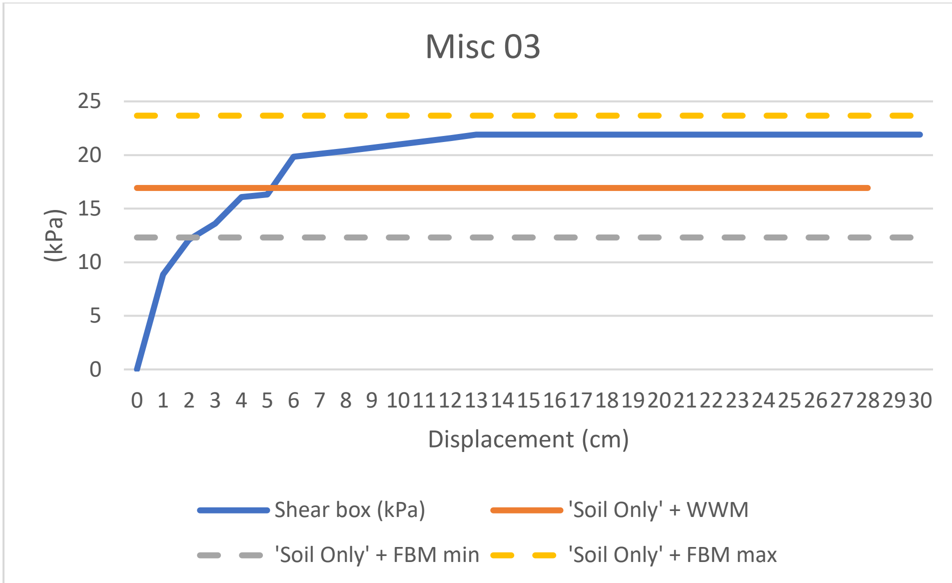

Figure 22: Shear box measurement compared to Wu and Waldron Model (WWM) and the range for Fiber Bundle Model (FBM) for 'misc 03'. The measurement of 'Soil only' was added to the models

Top	Bottom	Side 1	Side 2	Side 3	Side 4

Figure 23: Balsam Poplar (*Populus balsamifera*) root systems. Pictures were taken from the ‘Top’, ‘Bottom’ and four sides rotating 90° for each side.

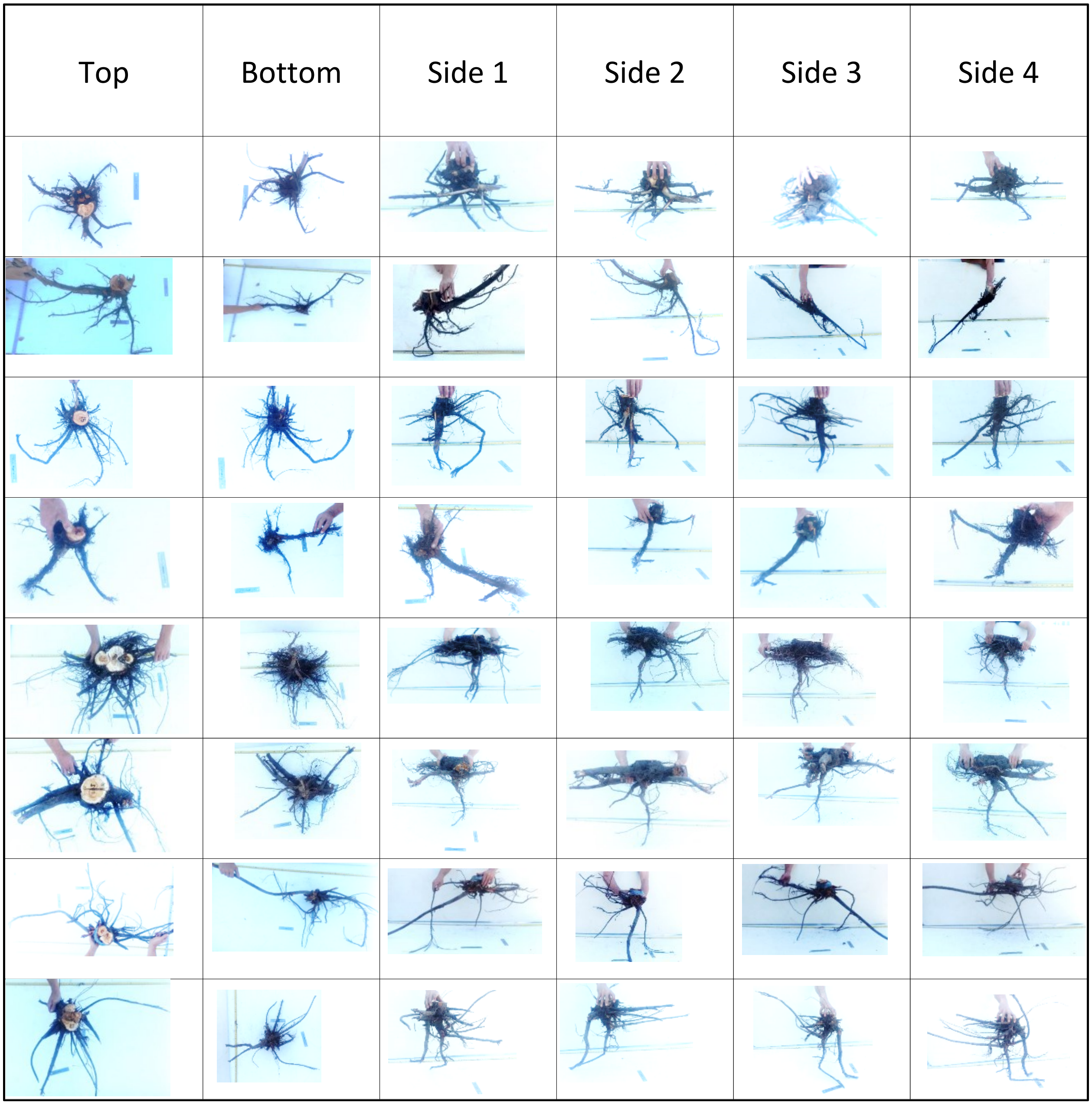

Figure 24: Willow (*Salix spp*.) root system. Pictures were taken from the 'Top', 'Bottom' and four sides rotating 90° for each side.