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The effect of root architecture on soil stability during a landslide simulation

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Abstract

Soil bioengineering is becoming an important method for slope stabilization. As it relies on the use of plants along with engineering practices, it is crucial to learn more on the effects of plant roots, especially their different architectures and the mix of these rooting systems, and how plant establishment plays a role in slope stabilization. As can be seen from the literature, mixing different root architecture would improve the soil stability. For this, ryegrass and red clover, two plants often used in pastures, were used to study how fine grass roots and clover tap roots affect the soil stability when they are grown over a 3-month period. The grass was grown alone and in mixture with clover to look at the effect of combining different rooting systems. After 3 months a slope failure was triggered, during which the movement and fail time were monitored, and some soil samples were taken from the failure area for further physical and chemical analysis in the lab. Rather unexpected, ryegrass alone did better than when mixed with red clover, and although the different physical and chemical soil properties did not significantly differ between treatments, the influence of water content on the failure rates can be observed in the different samples. We concluded that ryegrass has a more important role on slope stabilization compared to red clover particularly in the early stage of the development.

Kurzfassung

Die Bodenbiotechnologie entwickelt sich zu einer wichtigen Methode zur Hangstabilisierung. Da es sich um die Verwendung von Pflanzen und um technische Verfahren handelt, ist es wichtig, mehr über die Auswirkungen von Pflanzenwurzeln zu erfahren, insbesondere ihre unterschiedlichen Architekturen und die Mischung dieser Wurzelsysteme. Und inwieweit die Pflanzenansiedlung bei der Hangstabilisierung eine Rolle spielt. Wie aus der Literatur hervorgeht, würde eine Mischung unterschiedlicher Wurzelarchitekturen die Bodenstabilität verbessern. Dabei wurde an Weidelgras und Rotklee, zwei häufig auf Weiden eingesetzten Pflanzen, untersucht, wie sich Feingraswurzeln und Kleepfahlwurzeln bei einer 3-monatigen Anzucht auf die Bodenstabilität auswirken. Das Gras wurde allein und in Mischung mit Klee angebaut, um die Wirkung der Kombination verschiedener Wurzelsysteme zu untersuchen. Nach 3 Monaten wurde ein Hangbruch ausgelöst, bei dem die Bewegung und die Ausfallzeit überwacht wurden und einige Bodenproben aus dem Bruchbereich zur weiteren physikalischen und chemischen Analyse im Labor entnommen wurden. Eher unerwartet schnitt Weidelgras allein besser ab als mit Rotklee gemischt. Obwohl sich die unterschiedlichen physikalischen und chemischen Bodeneigenschaften zwischen den Behandlungen nicht signifikant unterschieden konnte ein Einfluss des Wassergehalts auf die Ausfallraten in den verschiedenen Proben beobachtet werden. Wir kamen zu dem Schluss, dass Weidelgras insbesondere in der frühen Entwicklungsphase eine wichtigere Rolle bei der Hangstabilisierung spielt als Rotklee.

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1. Introduction

Soil stability is an important factor when it comes to landslides, as a loss of stability leads to a slope failure and thus a landslide. The risks associated to such slope failures are costly, monetary but also in terms of infrastructures and casualties (Stokes *et al.*, 2014). Thus, we can wonder if there are any suitable techniques to prevent or mitigate such events. Indeed, different methods exist for slope stabilization and to prevent such disasters. However, they are often targeting small scale interventions as they are quite site-specific since they depend on the vegetation, environment and variability, thus more research to generalize the methods are needed (Bischetti *et al.*, 2007). Such methods include the use of plants to reinforce soils. This is referred to as ecological engineering and is based on designing sustainable ecosystems which integrate humans within the natural environment, and it should benefit both humans and nature (Stokes *et al.*, 2014; Mitsch and Jørgensen, 2004). Two different techniques are often used for this purpose, soil bioengineering which uses engineering practices along with ecological principles as means to assess, design, construct and maintain the vegetation and to repair damages linked to erosion or failures. The other technique is eco-engineering which is a long-term, ecological, and economical strategy to manage sites affected by natural or man-made hazards (Stokes *et al.*, 2010). However, although this method has been used in many areas in Europe, America and Southeast Asia and their studies report their success, more knowledge is needed to improve their performance in mitigating failures or erosion and lower the costs. And they are worth researching, although classical civil engineering methods are more developed, the use of ecological engineering methods would be more enduring especially if long-term socioeconomic considerations are made as well (Stokes *et al.*, 2014). However, even with the current literature proving that plant roots play an important role in supporting soils, we can wonder if the use of a mix of different plant rooting structures could help in stabilizing slopes.

In the literature, ecological engineering often relies on the use of trees or other woody species in general, however, grasses and other plants can be used as well. The root architectures of different plant species and their specific effects on soil stability are still subjected to research. The fact that roots are hidden in the underground and thus are hard to access poses some difficulties in research (Reubens *et al.*, 2007). However, when it comes to root architectures and their effects on soil stability, it was presented in a review by Stokes *et al.* (2009) that the tap root systems and especially thick roots allow for a deep anchorage, like nails holding the soil. On the other hand, fibrous thin roots allow to provide tension and support the soil with their tensile strength. Moreover, Reubens *et al.* (2007) discussed that growing mixed species would lower erosion and that having a mix of deep growing roots and finer shallow roots allow to hold the soil together. As we can see different root structures have different benefits to improve soil stability and combining these root architectures by growing two different plant types would have a better stabilization effect compared to growing only one plant species. Thus, we can hypothesize that the combination of different root systems would improve further the slope stability and thus the shear strength of the soil during a landslide.

For this, the rooting structures that will be assessed are tap roots from a red clover and a fibrous root system with ryegrass. And we will see if as the literature showed, the ryegrass mixed with red clover leads to better slope stability compared to when grown alone, even when they are still poorly established, after only 3 months of growth.

2. Literature Overview

1.1 Soil/slope stability overview

1.1.1 Slope stability definition, characteristics and what affects it

Slope stability can be defined as the capacity of a soil mass to withstand its gravitational forces, additional loads and potential dynamic loads like earthquakes. When these forces exceed the soils' shear strength, the soil fails or moves which is also referred to as landslide. These can negatively affect infrastructures as well as lead to casualties (Geoengineer, 2021). These landslides can be of different levels of intensities depending on the trigger of the slope failure, such as earthquake, heavy rainfall, or poor mechanical soil property, and they also can occur fast or steadily. Several types of landslides exist and were classified by Varnes (1978), these depend on the type of material (rocks, soil, earth, mud, and debris) and landslide movement (fall, topple, slide, lateral spreads, flows and complex landslides). In this paper, we will focus more on slides and more specifically on translational slides. These occur on pre-defined planar surfaces with little to no rotation on the ground. These slides are mostly determined by weak surfaces or by contact with materials of different shear strengths. In theory, such translational slide could continue until the rupture surface inclination changes and/or the shear strength resistance becomes higher than the driving force (Geoengineer, 2020).

The issue regarding soil stability failures and thus landslides is that they are one of the main soil threats defined by the Joint Research Center from the European Commission in a report from the RECARE project (Preventing and Remediating Degradation of Soils in Europe through Land Care) (Szolgay *et al.*, 2015). Indeed, they lead to the loss of soil functions (Huber *et al.*, 2008), these include principally the structure functions of soils, and can even destroy them completely during intense landslides. Moreover, the fact that different factors affect landslide events make their prevention and mitigation difficult. This problem is emphasized by climate change and the variations in precipitation (Lehtonen *et al.*, 2014). Another point is that landslides affect other soil threats such as soil salinization and contamination and they are clearly linked to soil erosion due to water as they are one of the main sources of such occasional intense erosion leading to more losses of sediments (Borrelli *et al.*, 2014).

However, while the soil movement due to landslide could negatively affect food production and other environmental functions in the case that agricultural fields and natural areas are targeted, landslides can also lead to improvement or development of new biological and ecological systems due to a certain rejuvenation of soils. Plus, the soil functions can be restored after only a couple of years, less than 5 years (Restrepo *et al.*, 2009). There are different types of movements which include fall, topple, slide, lateral spread, and flow.

1.1.2 Factors affecting soil stability

The different processes affecting soil stability include hydrological processes. Indeed, soil moisture has an important effect on slope stability as it decreases soil shear strength when the moisture content increases (Zhu and Xiao, 2020). Moreover, as mentioned in the landslide overview, rainfalls are one of the main factors triggering a landslide. Thus, looking at the soil hydrology in regard to soil shear strength and stability of a slope is important (Zhu and Qi, 2017).

Water can have some physical effects on soils, as it increases the bulk density and can lead to sliding of slopes. It also indirectly decreases the soil's shear strength through the water flow which softens the soil (Zhu and Xiao, 2020). This shear strength is decreased through decrease in soil cohesion or through the creation or extension of cracks which can lead to slip surfaces (Djukem *et al.*, 2020). Indeed, water in the pores can exert pressure on the surrounding soil. At rest or when the water is saturated, the pressure is equal in all directions thus there is no shear stress, however, if water is drained or absorbed by plants, this movement of water changes the pressure applied on soil particles. In the case that these pores are continuous, hydrostatic principles are fulfilled, however this is rarely the case in soils (Verruijt, 2006). However, the water content in pores have generally low effects on shear stress transmission. It can only lead to viscous shear stress, which does not amount to much.

Soil stability is also affected by several mechanical processes, such as, effective stress. This stress is described by the concentration of forces acting on the contact points of a granular material. These forces cause rolling and sliding in contact points and thus overall lead to deformation of the granular material. This occurs only under normal stresses such isotropic stresses which is due to forces between particles and by some water pressure. These normal stresses lead to a compaction of the soil. While shear stresses which can only be transmitted by grain skeleton, lead to a distortion of the soil as grains slide on each other (Verruijt, 2006).

Since shear strength is related to the shear and normal forces, the ratio of these forces can be calculated and compared to the friction coefficient. This allows to estimate if the soil remains in equilibrium or not and until which point it can remain in equilibrium. Which lead to the critical shear stress equation:

$$\boldsymbol{\tau_f = c' + \sigma' tan\phi'} \tag{1}$$

with $\boldsymbol{c'}$ the effective cohesion, $\boldsymbol{\phi'}$ the effective angle of internal friction and $\boldsymbol{\sigma'}$ the normal or effective stress. Soil slope failure is thus determined by this critical stress equation, as long as the shear stress measured is lower than this critical value, the slope will not fail, if any shear stress equals the critical value the slope will face shear deformation and fail (Verruijt, 2006).

Shear strength can also be used to express the soil stability. As it represents the ability of the soil to hold together until it breaks apart due to too much pressure. Indeed, a greater shear strength means a greater soil stability (Earle, 2019). This soil strength is important during events such as landslides as it can affect how fast two soil parts will break apart.

1.2 Soil and plant characteristics affecting soil stability

1.2.1 Soil characteristics: especially mineralogy

Certain soil physical properties affect the soil stability, these include bulk density, cohesion, and shear strength (Bidyashwari *et al.*, 2017). Soil particles can have different strength which in turn affects the shear strength and slope stability. Indeed, the weakest are sand and silt particles, while clays are overall a little stronger, and when clays are mixed with sand, they make the soil even stronger (Earle, 2019). However, although in general, the finer deposits are stronger and can even stabilize a steep slope, landslide occurrences were attributed to the abundance of clays in soils collected from landslide sites (Soto *et al.*, 2017; Schäbitz *et al.*, 2018). Moreover, the variations in the inner composition and structure of rocks can have a great effect on their strength. For example, an element like schist can have rich layers in sheet silicates (such as mica or chlorite) but they will tend to be weaker than other layers (Earle, 2019).

Finally, some minerals are more susceptible to weathering than others, however, the product of such weathering leads to weaker material, such as the clays formed from feldspar (Earle, 2019). Indeed, one of the factors contributing to the changes in shear strength parameters is weathering (Komadja *et al.*, 2020). These alterations are due to the formation of fine-grained clays, which tend to increase in the soil as the weathering increases (Che *et al.*, 2013; Summa *et al.*, 2018). It was also demonstrated through the characterization of mineralogical and geotechnical of debris, that these fine particles reduce the engineering geotechnical slope parameters and thus weaken slope stability (Komadia *et al*., 2021). Moreover, the particle size as well as the pore distribution in the soil matrix influences the mechanical behavior of soils and have an influence on soil stability (Bidyaschwari *et al.*, 2017). Indeed, Li *et al.* (2021) observed that soils that are well-graded have greater shear strength compared to poor-graded soils which have a high clay content. Indeed, all clay minerals are affected by water as they will absorb some which will reduce their strength. This issue is especially true for expanding clays minerals with swelling and shrinking characteristics based on soil moisture levels, as this characteristic can also induce slope failures (Bidyaschwari *et al.*, 2017). Indeed, the water absorption varies between clay types, and for clays like smectite which can absorb a lot of water, it can lead to the expansion of the mineral as the water pushes the layers of the clay apart. The swelling of such clay lead to a high loss of strength and makes the soil very slippery, lowering the slope stability (Earle, 2019). It was shown that phyllosilicates like smectites lead to more frictional sliding of slopes, even if the amount of these silicates is small (10-30%) (Collettini et al, 2009). In the same way, illite clays also increases risks of landslides as they have a lower shear strength as well as a quite high swelling-shrinking behavior (Neupane and Adhikari, 2011). And in general, the abundance of hydrophilic minerals which include kaolinite, illite and other mixed-layered clays is linked to landslides occurrence, as these clays have a plate morphology they can move with less friction or more smoothly and thus are a higher risk for slope stability (Summa *et al*., 2018; Anis *et al*., 2019).

Other than creating finer-grained particles, weathering can also reduce the water infiltration in the soil which can affect the soil stability, especially since it can also retain the water, which increases the shear stress through the increase in the pore-water pressure and consequently leads to reduction in effective stresses, which may result in slope instability (Komadja *et al.*,2020). As mentioned, water plays a role in soil stability and affects the strength of certain soil minerals especially depending on the amount of water present in that material. This is especially true for unconsolidated materials. These sediments tend to be stronger when moist as it creates a surface tension holding the grains together. On the other hand, when they are dry these sediments are held together thanks to the friction between the grains and depending on the organization of grains (well sorted or not) or the shape (well rounded…), or both, the cohesion between the grains can be weak. Finally, when the sediments are saturated, they are usually at their weakest as the large amount of water pushes the grains apart, which reduces the friction between the grains, especially if the water is under pressure (Earle, 2019). Finally, overall, the presence of water will increase the mass of the soil on a slope, and thus increase the gravitational pull on the soil. As an example, a saturated soil with 25% porosity weighs around 13% more than when completely dry, so the gravitational shear force would also be about 13% higher, in some cases this increase in weight is enough to create a slope failure. Moreover, the water pressure in the soil can gradually build up within the slope and weaken the rock or soil mass until the shear strength becomes lower than the shear force which would also lead to a slope failure (Earle, 2019). For clarification, the shear force, which is related to slope angle, does not change fast. However, the shear strength can change faster for different reasons, and a trigger for slope failure is when the shear strength lowers rapidly and becomes lower than the shear force. An increase in water content is the most common mass-wasting trigger, this can happen after rapid snow-melting or heavy rainfalls. However, it can also happen that a *decrease* in water content leads to failure. This happens mostly with clean sand deposits; these tend to lose their strength as the water around the grains becomes scarce (Earle, 2019).

1.2.2 Plant roots effect on the factors affecting soil stability

There are two major factors when it comes to slope stability reinforcement from vegetation, which are mechanical root reinforcement and evapotranspiration (Świtała and Wu, 2018).

Indeed, as roots uptake water, they reduce the weight of water in soil pores reducing the shear force on the soil (Capilleri *et al.,* 2016). As the water goes through evapotranspiration, it leads to more suction in soils which also affects the soil shear strength over time and thus the slopes' stability (Springman *et al.*, 2003; Yildiz *et al.*, 2018).

Another effect of roots is that they can alter the soil water retention curve as well as the hydraulic conductivity function (Scanlan and Hinz, 2010; Leung *et al.*, 2019). Indeed, roots can create macropores increasing the water infiltration rates, although this could potentially lead to higher risks of landslides as it may increase the water table and seepage pressures (Reubens *et al.,* 2007). To look at the effect of roots on water retention Leung *et al.* (2019) made an experiment through hydration of the roots and suction of the water from the roots over time. Through this, they found that plant roots can hold greater amounts of water compared to soils and have a higher retention of water, more suction is needed for the roots to dehydrate. Even at 7-8MPa of root suction the roots held 20% of the water present after root hydration.

Since water plays a role when it comes to slope failure, especially when a soil is at or close to saturation, the effects of roots on soil water could prove beneficial. As water uptake and evapotranspiration by plants could slow the soil's saturation under heavy rainfalls for example. Moreover, as mentioned, roots can provide mechanical reinforcement of the soil.

Indeed, plant roots tend to reinforce soils as they can connect the upper soil layers with the deeper layers when their roots grow perpendicular to the soil surface (Capilleri *et al.*, 2016; Reubens *et al.,* 2007). Roots can also cross potential failure surfaces or shear plans, when they grow parallel to the soil surface, and thus prevent or slow down a landslide (Waldron and Dakessian, 1982; Yildiz *et al.*, 2018). In terms of stabilization or soil mechanical reinforcement, roots play an important role with their tensile strength. This is mostly influenced by the root diameter, the moisture and location where the plants are growing among other parameters (Capilleri *et al.*, 2016). This strength is based on the tension from the soil which can be transferred to the roots. For this, the shear stress from the soil goes through the roots and due to the friction on root surfaces the soil shear stresses are transformed into tensile resistance (Gray and Barker, 2004).

Different methods have been used thus far for measuring the effect of roots on soil shear strength. These methods are direct shear tests, tests on roots for the tensile strength, tests on blade penetration using penetrometers and centrifuge tests (Yildiz *et al.*, 2018). Direct shear tests results can allow to quantify the shear strengths of soils containing roots. These quantifications can be made using Mohr circles representing the effective normal stress with internal friction or without frictions. The “root cohesion” value is then determined from the interception on the shear stress axis of the Mohr circle diagram (Yildiz *et al.*, 2018). The root effect on soil shear strength can also be determined by looking at the difference between the peak shear stress of a bare soil and plant-soil system. The results from these differences can be then used to compare the root cohesion values or can be used in slope stability calculation or even correlated to different root traits (Mickovski and van Beek, 2009; Ghestem *et al*., 2014).

1.3 Root architectures and their effects on soil stability

1.3.1 The different possible root architectures and how they can support soil

Root architecture can be defined as the spatial configuration of root systems in soils (Gregory, 2006). This structure varies per plant species but also depending on the environment. The topology and geometry are the determining factors of the root architecture. The topology specifies the branching pattern or the connection between plant components and the geometry is the shape, size, orientation, and spatial location of the root components (Gregory, 2006). These properties allow to characterize a rooting system based on the size of the roots, the branching properties, and the number of roots per soil area or volume of soil. This classification of rooting system describes 5 different structures, namely H-, R-, VH-, V- and M-types (Yen, 1987). Where H-type has roots extending mostly horizontally and widely, R-type grow their roots obliquely, some lateral roots, VH-type have a strong tap root and lateral roots which extend widely and in a low orientation compared to the horizon, V-type have well-grown almost vertical roots, few narrow lateral roots, and M-type have a lot of branching in various directions. The types which have the most stabilizing effect are the R-type followed by the VH- and H-types.

When it comes to stabilizing slopes with roots, the number, size, tensile strength and bending stiffness of roots crossing the slip surface of soils are the most important factors (Reubens *et al.*, 2007; Wu, 1995). This would point to a better stabilization of soils with more fine compared to less coarse roots. Indeed, fine roots have been positively corelated to soil reinforcement as they can act as tensile elements in soil matrix. As thin and fine roots are able to act in tension during a slope failure, and if the slip surface is crossed by these roots it allows to reinforce the soil through the addition of cohesion (Stokes *et al.*, 2009). Moreover, these finer roots also tend to stay in their position even if they break, and thus continue to support the soil, while coarser roots would slip out of the soil (Ennos, 1990).

On the other hand, coarse roots are thought to play a lesser role compared to finer roots in terms of soil fixation, however, the role of coarse roots should not be underestimated. Indeed, coarse roots like tap roots can penetrate deeply and anchor in soils allowing to fix shallow soil layers. These thick roots tend to act like nails in the soil of slopes, they are thus reinforcing the soil like concrete being reinforced by steel rods (Stokes *et al.*, 2009). Coarse roots are also able to withstand both tension and bending while fine roots have a low bending stiffness (Bischetti *et al.,* 2005). However, it should still be noted that the anchorage effect coarse roots have strongly depends on the density of such roots in terms of depth and space (Reubens *et al.,* 2007). In many cases the depth of the roots cannot prevent mass wasting/landslide processes, although this depends on the depth of the slip surfaces themselves, as well as the type of fail and the slope steepness. And in terms of spatial density, if the rooting system is not dense enough, the soil will not be held in place and move around the roots.

Thus, a combination of both dense fine roots in the upper soil layers and coarse deep penetrating roots would be the most beneficial for soil stability (Reubens *et al.,* 2007).

1.3.2 Growing mixed vs sole grass/clover and how it affects slope stability

As mentioned, plant roots have various advantages when it comes to their effect on soil stability. And to further improve these effects on slope stability, a method would be to mix the different rooting systems. Indeed, growing a mix of species would lead to a variety of different root architectures which perform different functions. It would also appear that when growing mixed species, the rooting system is denser and deeper compared to grown separately which would be due to the competition leading to more investment in root growth for survival (Reubens *et al.*, 2007). This is the case for natural grasslands and managed pastures, which are usually composed of different plant species which have different rooting systems. These grasslands are often composed of perennial ryegrass (*Lolium perenne* L.) mixed with legumes like clovers (red or white – *Trifolium*), the use of such mixtures is especially quite widespread in the UK (Marshall *et al.*, 2016). These ecosystems have shown to have an important ecological role and provide several services which include prevention of soil erosion and improvement of soil structure (Marshall *el al.*, 2016).

When looking at the two plant species, it was demonstrated that ryegrass produces a very large below-ground biomass especially in the upper soil layers. Indeed, in a survey done by Dickinson and Polwart (1982) on an old grassland in the UK they recorded that in the top 15cm of soil there was about 5t/ha of root biomass. However, as mentioned the roots of ryegrass do not grow very deep, and most of the plant breeding focused on the above-ground biomass and was not looking at the root traits. If more research was made on these, the ecosystem services provided by this grass could be further improved as well as the persistency and yields overtime (Humphreys *et al.*, 2014; Marshall *et al.*, 2016). Moreover, ryegrass roots also showed to reduce soil detachment during a rainfall simulation of 27 weeks by 90% (Zhou and Shangguan, 2007; Ola *et al.*, 2015)

On the other hand, it was shown that clovers produce deep penetrating roots and a high-density root mat which thus increases the soil porosity, especially the macroporosity (Papadopoulos *et al.*, 2006; Holtham *et al.*, 2007; Marshall *et al.*, 2016). Clovers having a different rooting system compared to ryegrass leads to a different soil structure around the roots and improves the porous system and thus water drainage. Red clovers also lead to better particle aggregation compared to ryegrass, growing them together would overall improve a ryegrass field (Mytton *et al.*, 1993; Holtham *et al.*, 2007).

Finally, when mixing the different rooting systems of these two plant genera (*Lolium* and *Trifolium*), it can lead to improving the soil structure through better aggregation properties of the roots and stabilization of the soil whose effect vary between plant species and even between varieties of one species (Marshall *et al.*, 2016). However, these improvements on soil aggregates, structure and porosity revert rapidly once a different crop is grown but this effect may persist in long term grasslands (Papadopoulos *et al.*,2006; Marshall *et al.*, 2016). Moreover, certain plant species can interact better with microorganisms such as mycorrhiza. These interactions can improve the plants growth but also have a positive effect on soil structure such as aggregation. Perennial ryegrasses have low or even no interactions with such organisms while legumes, such as clovers, associate more with mycorrhiza (Hall *et al.*, 1984; Marshall *et al.*, 2016). These associations also lead to higher biological or microbial activity which enhance biodiversity, improving the ecosystem overall. Thus, combining different plant species not only improves the soil structure and its stability but also improves the soil biodiversity which is important for different soil functions.

3. Materials and Methods

3.1 Simulation experiment:

The tests were carried out in Harland, Sankt Pölten, during the period of April to July 2021. For these tests, wooden boxes of 150 cm in lenght, 50 cm width and 25 cm height were built. The boxes were cut in the middle and assembled for the growing season; the cut part would be the failure area when the landslide occurs.

Figure 1. Half boxes ready to be combined

Figure 2. Combined boxes

At the bottom of the boxes pieces of wood and screws were fixed to allow for some soil anchoring. A mix of soil and stones were placed at the bottom (on top of the pieces of wood), and a soil which was sieved at 10mm was added on top. The seed bed was prepared by adding a layer of 5mm sieved soil and the ryegrass and mixed ryegrass/red clover were sown at a rate of $20g/m^2$. 3 replicates for each treatment (sole ryegrass and ryegrass-clover mix) were used and one box was left with only soil making a total of 7 boxes.

Figure 3. Boxes ready with the screws and wood

Figure 4. Soil added to the boxes

The seeding was done on the 1st of April 2021. The boxes were kept at an 8 degree angle for the plant roots to grow in a vertical orientation. After 1 week the red clover started to germinate, while it took over 2 weeks for the ryegrass to emerge.

On the 1st and 2nd of July 2021, after 13 weeks, the landslide experiment was done. For this the boxes were moved onto a trailer which was elevated as to allow for the trailer to be placed at different angles. Wheels and rolling mechanisms were placed on the sides and the bottom of the lower box, respectively, to get the lowest friction during the slide of the lower box, while the upper part was fixed to the trailer.

Figure 5. Box on the trailer ready for simulation

Figure 6. Trailer elevated to allow for tilting

First, the piece of wood holding the box together was removed to allow for the movement of the lower box to occur. Then the trailer was tilted at a 5-degree angle for 5 minutes. After the 5 minutes the angle was increased to 10 degrees for another 10 minutes. The angle was further increased to 12.5 degrees for 30 minutes, then 15 degrees for another 30 minutes. And if the soil did not fail before then, the angle was increased to 17.5 degrees for another 30 minutes and then 20 degrees for another 30 minutes.

Figure 7. Instrument for measuring pressure

Figure 8. Soil sampling for lab analysis

During the experiment, the movement over time between the two parts of the box was measured, at the end of the landslide, the weight of the failed part was taken. Thanks to these, the weight and traction force were calculated for each sample, with the following formulae:

$$\textbf{Weight force = mass of failed box * G} \tag{2}$$

$$\textbf{Traction force = mass of failed box * G * sin}(\boldsymbol{\alpha}) \tag{3}$$

where **G** is the gravity of 9.81 m/s^2, and **sin(α)**=sin of the angle of inclination * π/180 to convert the degree angles.

This information is compared between treatment as well as with a similar experiment made over 3 growing seasons, between April 2018 and October 2020, in order to evaluate the effect of the plant establishment.

Finally, some soil core samples of the break area were taken for lab analysis.

3.2 Lab experiments:

Some of the soil used for the landslide experiment was kept for some physical and chemical analyses. These analyses include grain size and clay mineral and particle density, pH, total organic carbon (TOC).

1. Particle size distribution: Wet sieving and sedimentation analysis (ÖNORM EN 933-1, 2012)

Two methods were used to analyze the grain size, first the wet sieving was done. For this the 50 g of soil sample was placed in a beaker. Then the organic matter was oxidized using 10% of H_2O_2, the latter was added until no more foam was formed, which means that there was no more organic matter to be degraded. The H_2O_2 was then removed in water bath at 95 °C, considering that the sample should not dry out as it could irreversibly modify the clay minerals. Then to break the aggregates the beaker was placed in a sonic bath for 10min. The suspended soil sample was then sieved through 630, 200, 63 and 20µm using a vibrating sieve. The particles from each fraction were then collected and placed in cups which were then put in the oven to dry the particles overnight.

To determine the finer portions of the soil sample, the sediments smaller than 20µm, a micromeritics SediGraph III Particle Sizen Analyzer was used. The remains from the sieving which had been collected in a beaker were thickened, for this the beaker was placed in a hot water bath for the water to evaporate overnight. It was then left for a few days for sedimentation of the clays before pumping out the remaining water. The thickened sample is then mixed using a magnetic stirrer. Then 50mL of the mixed solution is pipetted out and 5mL of 0.05% Na-polyphosphate is added to prevent coagulation of the sample. The sample goes through the ultrasonic bath to break the aggregates or prevent aggregation and finally the sample goes through the Sedigraph for measurement. The sedimentation mechanism is based on Stokes law and the setting of the particle, and its velocity depends on the particle density and size, the viscosity of the liquid as well as the temperature. In order to measure this sedimentation, the sedigraph uses X-rays to determine the amount of particles of a defined size in suspension.

From these results we get the masses of the grains from sieving, which we convert to a percentage, and a percent mass from the sedigraph. These are then used to calculate the percentage of grain size and to make a cumulative sum curve.

2. Mineral analysis

To find out more on the minerals present in the soil sample, an X-ray analysis was performed. For this a dried soil sample was ground into a fine powder using a milling machine. A part of this powdered soil was then placed on a 27mm diameter disk for x-ray analysis. The analysis was performed using PANanalytical X'Pert PRO X-ray diffractometer. The samples were measured from 2-70° 2θ, with 0,017° step size, measurement time 25 s/step with 45kV and 40 mA. X-rays are emitted at different angles over time and are diffracted by atoms in the crystal of different minerals. This allows to identify the mineral phases thanks to the resulting characteristic peaks in the diffractograms. These peaks can then be compared to the database of minerals to find out which minerals are present in the soil sample.

3. Clay mineral analysis:

To further analyze the mineralogy of the soil sample, the clay fraction of <2µm were separated from the sieved samples of <20µm by centrifugation to be analyzed in the PANanalytical X'Pert PRO X-ray diffractometer. For this, the remains of the sieving, the particles smaller than 20µm and the deionized water which were recuperated in a beaker, were used. This beaker was placed on a stirrer for about 15 min to prevent the heavier particles from setting. In the meantime, 5mL of an anticoagulant (Calgon 2.5%) was added to a centrifuge bottle. Then, while still being stirred, the clays in suspension were pipetted out into a centrifuge bottle. To maintain the balance in the centrifuge, the bottle and its cap, and the suspension was weighed to about 300g. The bottles were then closed properly and shaken by hand before being placed in the centrifuge, which was then set to run at 1000rpm for 5 min. These velocity and time were set based on previous findings which pointed to the sedimentation of the particles greater than 2µm. The upper part was then removed and kept in a breaker. Deionized water was then added to the bottles, to reach the 300g, and the samples were centrifuged again for 5min, at the same velocity. And the upper suspension was again placed in the beaker. This step was repeated another time. From the beaker 50mL were pipetted into a cup which was then put in the oven for drying to measure the weight of the clay. Then in 2 tubes, 10ml of 4M KCl were put in one and 4M $MgCl_2$ in the other and the clay suspension was then added to fill up the 50ml tubes. These tubes were then placed on the shaker overnight. The next day, the tubes were centrifuged at 3500rpm for 35min for the clays to settle at the bottom. The upper solution was then discarded, and deionized water was added. The mixture was sonicated to break the clay aggregates and bring the clays back into suspension. With the weight of the clay, a simple calculation was made to figure out the appropriate amount, 20mg per disc, of clay suspension to apply to the disks.

The discs were then placed in the X'ray diffractometer and measured from 2-40° 2θ, with 0,017° step size, measurement time 25 s/step with 45kV and 40 mA. In a similar way to the bulk mineral analysis the clay minerals can be identified based on the diffracted X-rays and the peaks resulting from this.

Further steps were taken to differentiate between the different clay minerals such as chlorite, smectite and vermiculite for which the reflection peaks appear at the same angles (6degree = 14Å). After the first x-ray analysis, the 2 disks were placed in ethylene glycol which affects the expansion of the clay minerals and thus affects their angle of diffraction and allows to identify smectite and vermiculites. The discs were then measured again in the x-ray diffractometer from 2-32˚ 2θ. Finally, the disk with K was placed in dimethylsulfoxide and in the oven at 65degree to distinguish between poorly and well-ordered kaolinite and the disk with Mg was placed in the oven at 550˚C for 2 hours to verify the presence or absence of chlorite. And the discs were again placed in the x-ray diffractometer and measured from 2-26˚ 2θ

4. Soil density

The soil bulk density ($\boldsymbol{\rho_b}$) was determined by first saturating the soil with water and drying them in the oven at 105.5˚C. Before putting the saturated samples in the oven, the weight was recorded, and the weight after drying was recorded. The weight before saturating the soil was also recorded to obtain the water content. To make sure that the sample was fully dry, the weight was taken after two days and again after another day to see if the weight was constant. Then the density was calculated using the following formula:

$$\boldsymbol{\rho_b = \text{mass of dry soil / volume of core}} \quad (4)$$

The water content (**w**) was also determined using the following formula:

$$\mathbf{w = (\text{mass wet soil - mass dry soil}) / (\text{mass dry soil - mass empty cup})} \quad (5)$$

5. Particle density

The density of the soil was also determined using a gas pycnometer (Micromeritics AccuPyc II 1340). This device is based on the input of helium in a cup containing the sample, the amount of helium added equals the amount of air that was present in the sample thus allows the software to compute the density of the sample as the weight of the later was entered in the software.

From the particle ($\boldsymbol{\rho_s}$) and bulk ($\boldsymbol{\rho_b}$) densities, the porosity ($\boldsymbol{\phi}$) was calculated using the formula:

$$\boldsymbol{\phi = 1 – \rho_b / \rho_s} \quad (6)$$

6. Soil plasticity – Atterberg (ÖNORM EN ISO 17892-12, 2020)

The soil plasticity was determined using the Atterberg method, and liquid and plasticity limits were measured. The soil liquid and plasticity limits were determined using 3 soil different replicates for better statistical results. For this, the soil samples were sieved to 400μm and mixed with water and homogenized. Then, first the liquid limit (W_L) was determined using the Casagrande method. About 2/3 of a Casagrande cup was filled with the moist soil. A 2mm groove was created in the middle using a standardized tool. And the cup was dropped several times, until the groove closed over about 1cm. The number of falls was recorded, and a sample was taken from the part where the two sides of the soil touch for the water content. Thus, the wet weight was recorded before the samples were placed in the oven at 105.5˚C. This was repeated 5 times at different water contents/different number of falls before touching.

After the liquid limit test, the roll test was performed to estimate the plastic limit (W_p) of the soil, for this a piece of the homogenized soil was taken and rolled on a newspaper until it reached about 3mm diameter or until it broke apart. If it didn't break even when smaller than 3mm, the rolled soil was balled up again and the process of rolling was restarted. As the water content dropped due to evaporation the soil would break at the 3mm. These broken roll pieces were collected and placed in a ceramic cup for oven dry at 105.5˚C, the wet weight was also recorded to later determine the water content.

Thanks to the liquid limit ($\mathbf{W_L}$) and plastic limit ($\mathbf{W_p}$), the plasticity index ($\mathbf{I_p}$) is determined by:

$$\mathbf{I_p = W_L - W_p} \tag{7}$$

7. pH: (ÖNORM L 1083, 2006)

The H_2O and 0.01M $CaCl_2$-solution pH of the soil samples were taken. These measurements were made, according to the Austrian standard: 1 part soil and 2.5 parts water or $CaCl_2$.

8. Total Carbon: (ÖNORM L 1080, 2013)

To measure the total carbon, 200mg of soil were weight and placed in tin foil balls. These were then placed in the C-N-S analyzer LECO Tru-Spec, which determined the total C and N present in the samples through combustion with oxygen at 950˚C, the standards were placed first, 150mg and 300mg of the reference C were used for the calibration. This standard contains 2.42±0.05 C and 0.2±0.07 N.

9. Carbonate content (ÖNORM L 1084, 2016)

Using the Scheibler method, the carbonate content of the soil samples was determined. For this about 800 mg of soil was placed in reaction cup, and 5mL of 15% HCl was added in the middle part. The amount of carbonate was determined by volumetry thanks to a gas burette. The amounts of CO_2 released from the reaction of the soil with HCl relates to the carbonate content (calcium carbonate and dolomite present in the soil) and can be determined by the volume of 1M KCl-solution displaced in the burette. A correction factor for the pressure and temperature is needed in our case the air temperature was of 28˚C and the air pressure was of 741 mmHg.

Thanks to the total Carbon (**T_{tot}**) and the carbonate content (**C_{inorg}**), the organic carbon (**C_{org}**) and organic matter (**OM**) content could be calculated as well as the C/N ratio.

$$\mathbf{C_{org} = C_{tot} - C_{inorg}} \tag{8}$$

$$\mathbf{OM = C_{org} * 1.724} \text{ (correction factor for OM)} \tag{9}$$

$$\mathbf{C/N\ ratio = \%C_{org} / \%total\ nitrogen} \tag{10}$$

10. Above and below ground biomass

The dry matter above-ground biomass was measured from the cut grass and mixed cropping collected before the landslide experiment was made.

The dry matter below-ground biomass was also weighed after the roots were separated from the soil and cleaned. The cleaning of the root was made in beakers with water, and they were placed in the sonic bath for about 10min before rinsing the roots again, this step was repeated until the water around the roots was clear. The cleaned roots were then oven dried at 105˚C for at least 12hours. And their mass was recorded.

Before being placed in the oven, about 10 roots of each species were taken for scanning in order to look at the root architecture, as well as the area and volume of the different roots.

3.3 Statistics

To see if the different treatments had significant differences statistical tests were made using R. T-tests with unequal variances were done, as the variance between mixed and sole samples were not equal.

4. Results and discussion

In this section, the results will be presented and discussed. Firstly, the overall simulation experiment will be analyzed before looking in more details into which factors had effects on the different treatments (ryegrass, ryegrass-clover mix and bare soil). The factors that were considered include the soil mineralogy along with other physical properties (bulk and particle density, porosity, water content and soil plasticity) and the chemical properties of the soil (pH, C and N contents).

4.1 Simulation results

In order to estimate the effect of plant roots on soil stability, a bare soil box slope failure was done and compared to the planted boxes. As the soil is not reinforced by roots the only factors influencing its failure are the soil type as well as the water content. As shown in the literature, plants are more and more used for soil reinforcement in bioengineering methods, and we had hypothesized that, in our experiment, the results of the bare soil would fail before the planted boxes. Moreover, in order to look at the different rooting system effects on soil stability, ryegrass and a mix of ryegrass-red clover were evaluated. The literature had pointed towards a benefit of mixing different rooting systems and thus we had hypothesized that the mixture of ryegrass and red clover would fail later that the ryegrass alone. However, as we can see in the test results shown below, although the first hypothesis is correct as the bare soil failed earlier, the second hypothesis cannot be accepted as the ryegrass alone took a longer time before failure. These will be further discussed after a presentation of the results.

Reference results

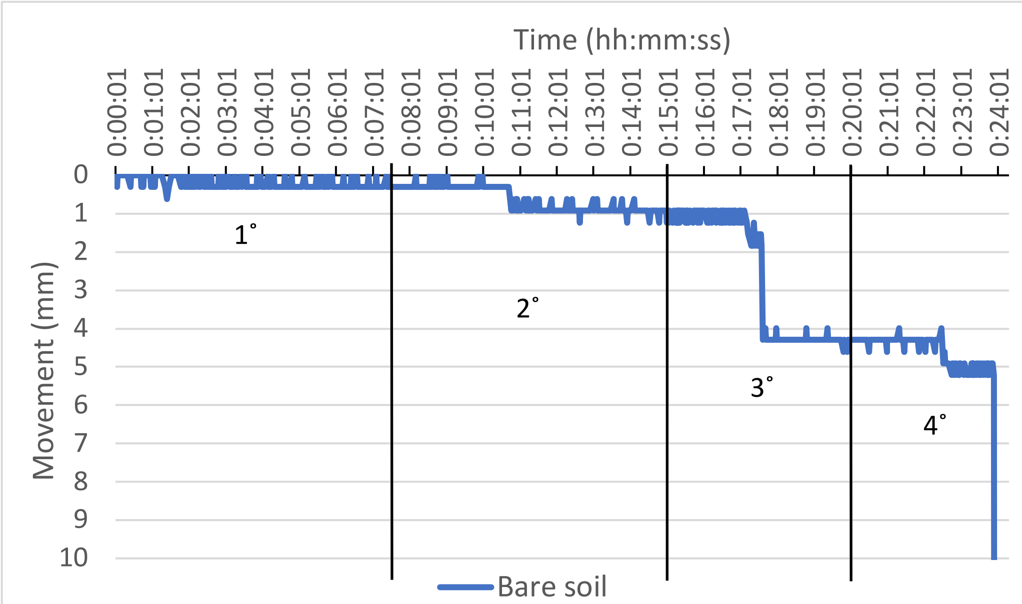

Figure 9. Graph representing the slope failures of the reference treatment over time. (bars show the increase in inclination at specific time: 7.5min: 1˚, 17.5min: 2˚, 5min: 3˚).

Treatment results

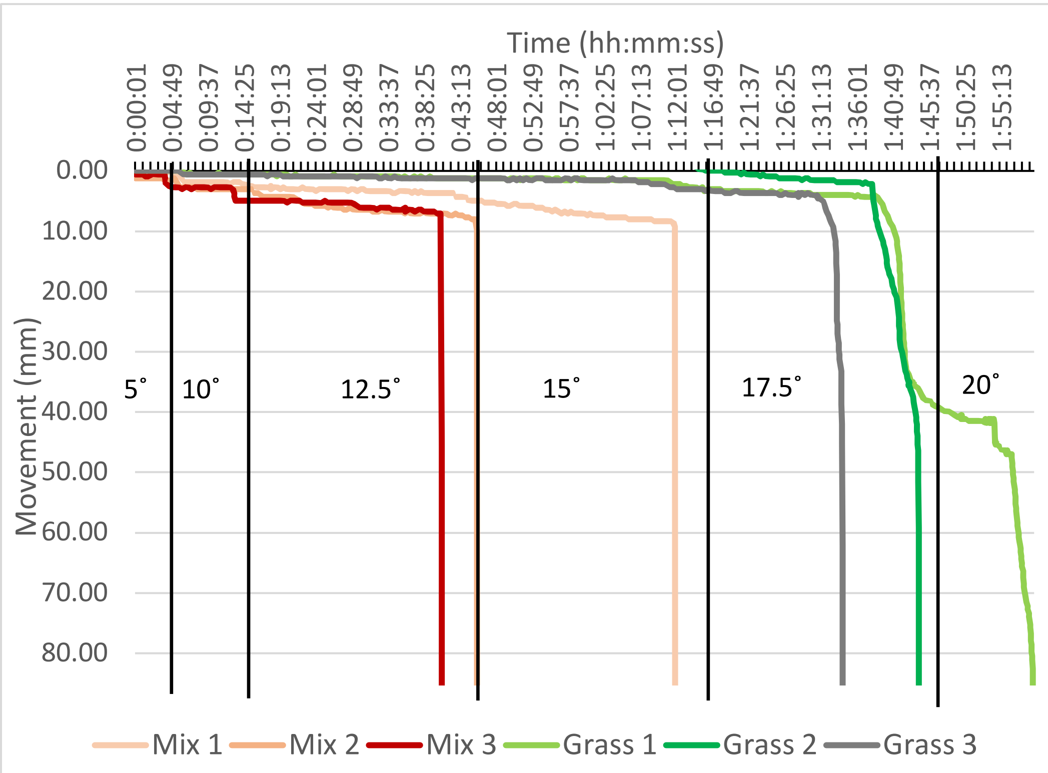

Figure 10. Graph representing the slope failures of the different treatments over time. (Mix n: treatment with mix of red clover and ryegrass, Grass n: treatment with only

ryegrass, bars show the increase in inclination at specific time: 5min: 5˚, 10min: 10˚, 40min: 12.5˚, 1h10min: 15˚, 1h40min: 17.5˚).

As we can see from these graphs, the bare soil sample failed at the low inclination (4˚) and after only about 24 minutes. This is before both the sole grass and the mixed samples, i.e. some 15 minutes before the first mixed replicate failed and 1 hour and 10 minutes before the first grass replicate failed. When it comes to the samples with mixtures of ryegrass and red clover, although we can see some variation in time of failure between replicates, they all failed before the samples with only ryegrass, between 20min to 1h20min before the fastest ryegrass fails. Moreover, the mixed samples had an abrupt failure as shown in the graph by the straight line at the time of failure. On the other hand, the grass samples seemed to retain the soil for some time before the failure occurred. This is especially seen in the first sample of grass which held on for almost another 30 minutes between the first cracking of the soil till the final failure.

These observations point towards the benefits of using plants to stabilize soils. However, in our experiment, only one replicate was used for bare soil, which could make it difficult to conclude simply from these results that the vegetation improved the soil stability, since soils are known to be quite heterogenous. Indeed, another bare soil replicate could have had different results, such as lasting longer or failing even earlier than the present one. However, since in our case the same soil was used for all samples, the mineralogy, and other chemical properties (pH, C and N…) would not have changed, only the soil water content would vary and perhaps the bulk density and porosity, as the soil was added manually affecting the compaction in the boxes. Indeed, a higher bulk density would lead to a higher stress in the slope stress with larger shear strain and soil displacement (Nie *et al.*, 2018). Moreover, as mentioned in the literature, a higher water content would decrease the slope stability as it increases the weight on the slope but also decreases several mechanical processes including cohesion and internal friction angle (Gusman *et al.*, 2018). An increase in water content also increases the plasticity limit of the soil making it slide more easily as the resisting forces on the slope decrease (Wahyuzi *et al.*, 2018). Thus, looking at the results for these factors will allow for better understanding on the triggers of the slope failures in our experiment.

Moreover, in contrary to our hypothesis, the grasses growing on their own were able to support the soil better than when combined with clovers. This could be explained by a potential lower root biomass in the mixed samples due to lower clover root biomass or due to competition which will be determined later when looking at the dry matter of roots. Indeed, in an experiment done by Robinson and Jacques (1958), they showed that after 4 months of growth, the root biomass of red clover was lower than perennial ryegrass, with about 1936kg/ha for ryegrass and 1415 kg/ha in red clover, in the first 10cm of soil. Moreover, it could also simply be due to the tensile strength provided by ryegrass which is more effective at this early stage compared to the taproots of red clovers. Indeed, as mentioned in the literature, fine roots which provide more tensile strength tend to have a more important role in stabilizing soils, and as the plants are still in their early stages of growth the effect of the taproots could be lower than anticipated (Stokes *et al.*, 2009). It could also be that the higher density of ryegrass in sole planting compared to mixed cropping led to better soil stability, this would lead to a need for further research in terms of planting density effects on slope stability. Moreover, the seeding was done by hand which may have affected the overall distribution of the seeds, there could have been higher density of ryegrass along the failure area in the sole planting compared to the mixed samples which would have allowed for the improved stability.

Moreover, there are some variations between the different replicates of one treatment. This could be due to different moisture contents as the simulation experiments were done over 2 days. Mix 1 and 2 and Grass 1 were done on the 1st of July and Grass 2 and 3 and Mix 3 and the bare soil were done the following day, however some rain occurred on this day which could have affected the amount of time before failure. Indeed, as mentioned, the water content in the soil and between the soil particles affects the soil stability, too much or too little water can lead to a faster slope failure (Earle, 2019). And as mentioned above, the manual seeding could have affected the distribution between treatments but also within treatments and thus led to variations between the different replicates.

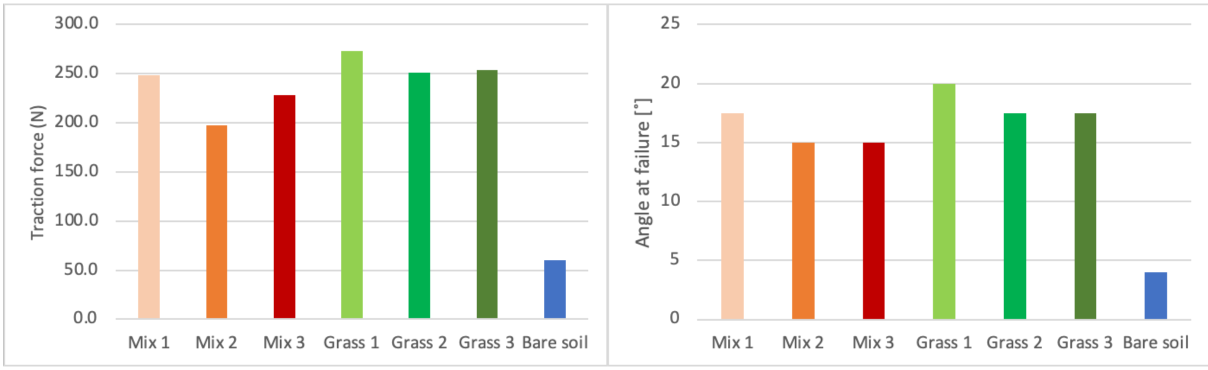

Figure 11. Graphs representing the traction force (left) and angle at failure (right) for the different treatments.

As we can see from these graphs, the traction force is higher in the planted boxes compared to the bare soil. Moreover, there is a slightly higher traction in the grass samples compared to mixed ones which is related to the higher angle at failure for the samples with grass only.

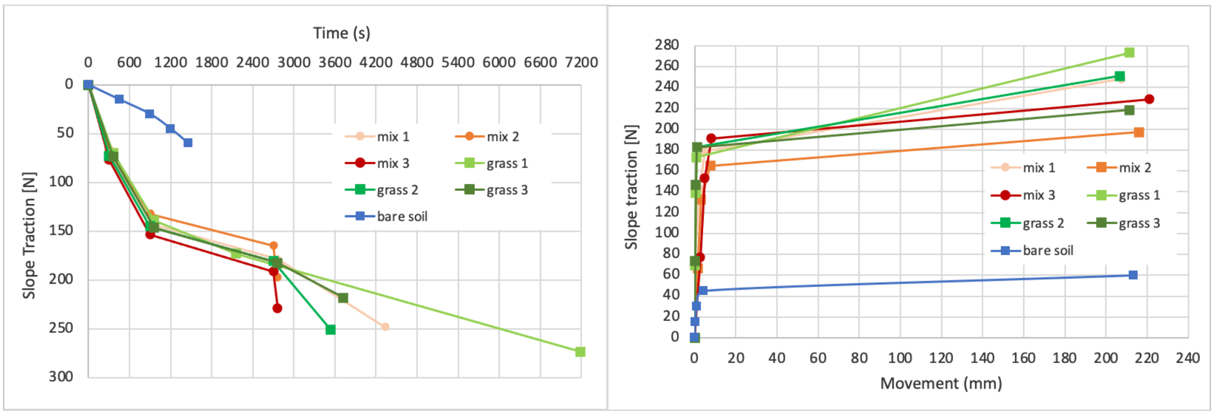

Figure 12. Graph representing the traction force overtime (left) and the traction force per soil movement (right) for the different treatments.

In these graphs, we can see how the traction force changes over time as the inclination of the slope is increasing. We can also see the traction force in terms of soil movement. As we saw in figure 3., the traction force is much lower for the bare soil, however when looking at the planted samples there is not much difference.

Although we do not see much difference between our two treatments, there is definitely a benefit of using grass only or a mix of grass and clover for improving the soil traction. This traction effect reinforces the soil thanks to a higher tensile strength in the root zone (Bibalani *et al.*, 2006). This is mainly due to lateral roots which grow more horizontally and are thus able to transfer stresses and reinforce the soil by holding it together, thanks to their tensile resistance and root-soil bond. This thus prevents the soil around the roots to move (Bibalani *et al.*, 2006; Zhang *et al.*, 2011).

To evaluate the effect of the length of the growing season, the results were compared to an experiment made with different grasses grown over 3 growing periods and completed in 2020.

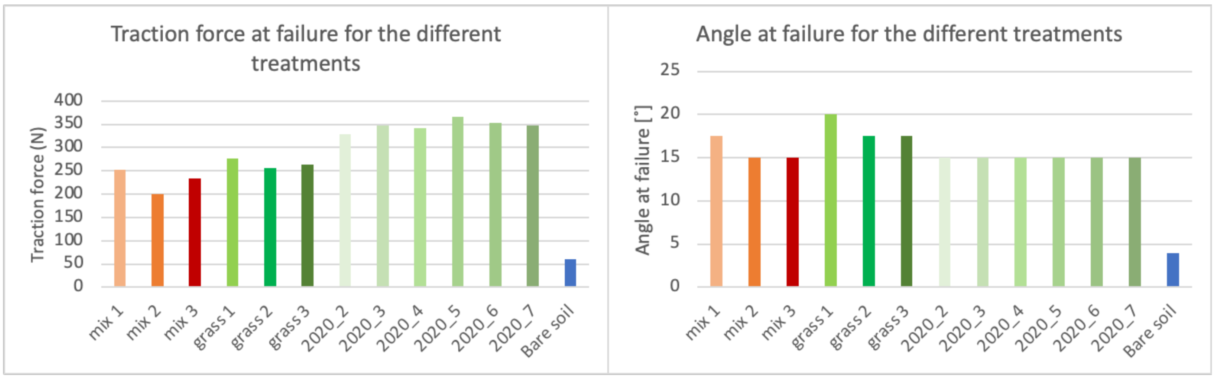

Figure 13. Graphs representing the traction force (left) and angle at failure (right) for the different treatments of the 2 experiments (2020_n: experiment completed last year).

As we can see from figure 5, the traction force is higher when the plants had a longer establishment time. Indeed, the t-test also showed a significant difference when comparing the long-term experiment (2020 samples) to the short-term experiment (mix and grass samples), with a p-value of $4.129 * 10^{-05}$. And this higher traction was achieved although the angles at failure were lower or equal to the ones this year.

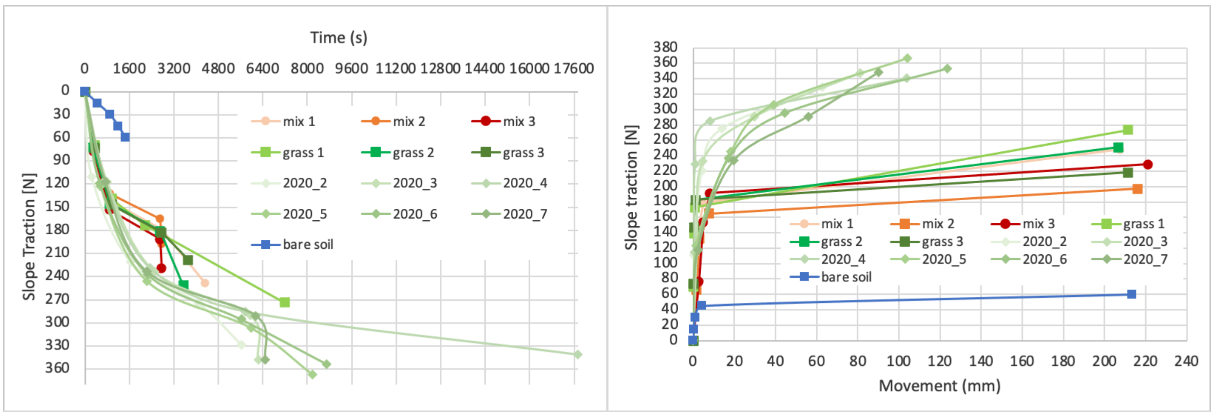

Figure 14. Graph representing the traction force overtime (left) and the traction force per soil movement (right) for the different treatments of the 2 experiments.

From this graph, we can again see that the traction over time as well as per movement is higher when the plants have a better establishment. This greater traction force could be due to a better rooting system with denser, longer and thicker roots. Indeed, the diameter of roots is also an important factor in root tensile strength and root effect on traction force. Rauchecker *et al.* (2019) showed that as the diameter of the roots increase, the traction force increases as well. Thus, as the grasses had a longer growing period, the roots may have been thicker and longer compared to our short-term experiment which thus led to a higher traction force.

4.2 Soil physical properties

4.2.1 Grain size analysis

From the wet sieving and sedigraph analyses made, we were able to identify the grain size of our soil sample and to create the following graph.

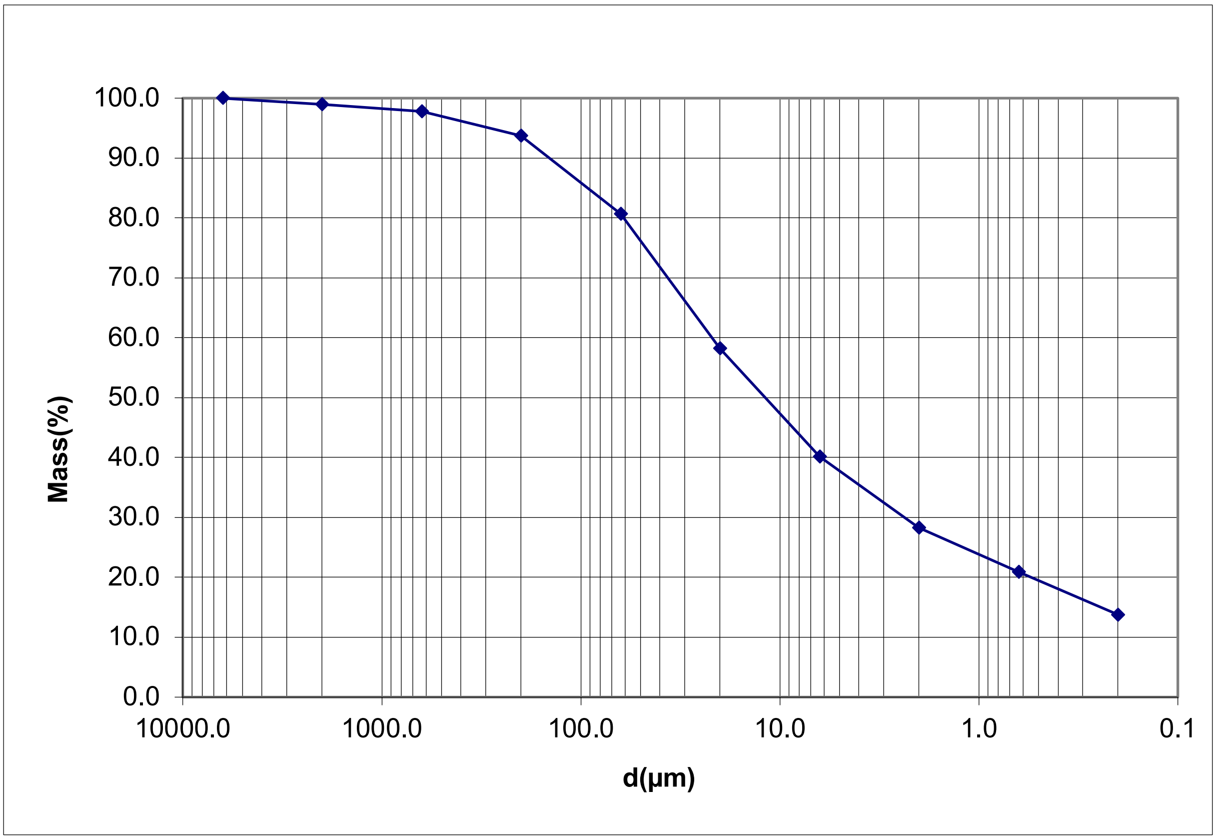

Figure 15. Graph representing the cumulative grain size

As we can see from the graph, the soil contains a wide range of particle size, from 0.2µm to 2mm. Which would point to a fine grained well graded soil. But a large part of the grains in our sample, 65.4%, had a size between 2 and 200µm.

As the grain size in the soil can affect the porosity, and how water is held within the soil, these results are of importance. Moreover, the shear resistance is also affected by grain size distribution as well as the shape and density of the particles, and by other soil properties (Getahun *et al.*, 2019).

Moreover, thanks to the grain size analysis the grain size class was determined, which can be found in the graph below.

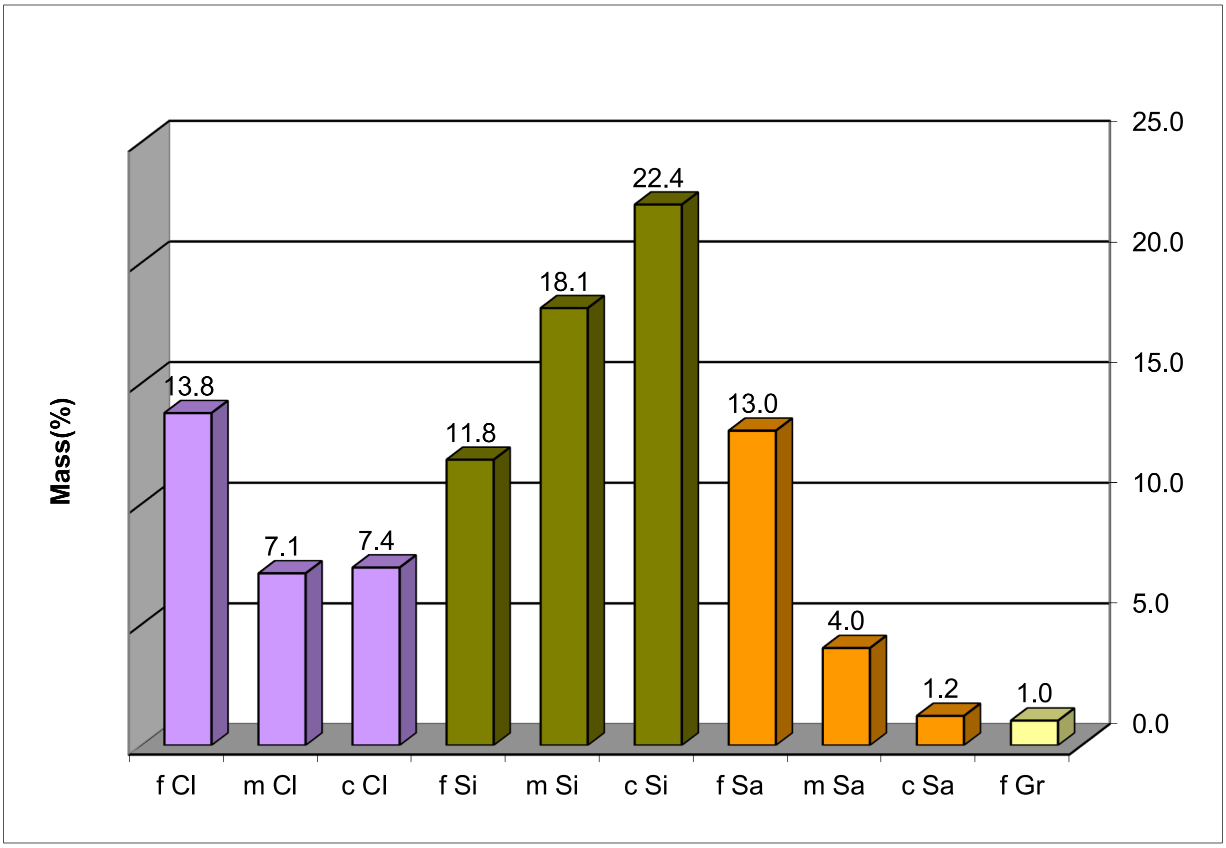

Figure 16. Graph representing the different classes and the corresponding amounts in each class (f=fine, m=medium, c=coarse, Cl=clay, Si=Silt, Sa=Sand, and Gr=Gravel).

We can see in this graph that the main element in our sample is silt with 52.4%. This is followed by clay with 28.3% and finally sand grains with 18.3%. With these percentages and thanks to the USDA soil texture triangle, the soil was to be of a silty clay loam texture.

As Sorensen (2005) presented in a science fair, the different soil types (clay, silt, loam, sand, and gravel) lead to different slope stabilities. Indeed, the project results show that the sand and gravel are the least stable when dry while clays are least stable when moist, as the moisture content reaches 30% degree of saturation clayey soils become unstable. On the other hand, silt soils and sands increase in strength and stability as water content increase, though as for clays too much water would also lead to slope failure. This again points towards the importance of water content when it comes to slope stability. In our case, a silty clay loam could tolerate more moisture than a pure clay soil.

Indeed, the weakest are sand and silt particles, while clays are overall a little stronger, and when clays are mixed with sand, they make the soil even stronger (Earle, 2019). However, although in general, the finer deposits are stronger and can even stabilize a steep slope, landslide occurrences were attributed to the abundance of clays in soils collected from landslide sites (Soto *et al.*, 2017; Schäbitz *et al.*, 2018). The silty clay loam soil we have could thus be quite strong though this also depends on the mineral composition of the particles. Indeed, the variations in the inner composition and structure of rocks can have a great effect on their strength.

4.2.2 Mineral analysis

As stated, the mineral composition of particles plays an important role in the overall particle strength. Thus, the bulk mineral and the clay mineral of our soil presented below will be discussed.

Bulk mineral analysis

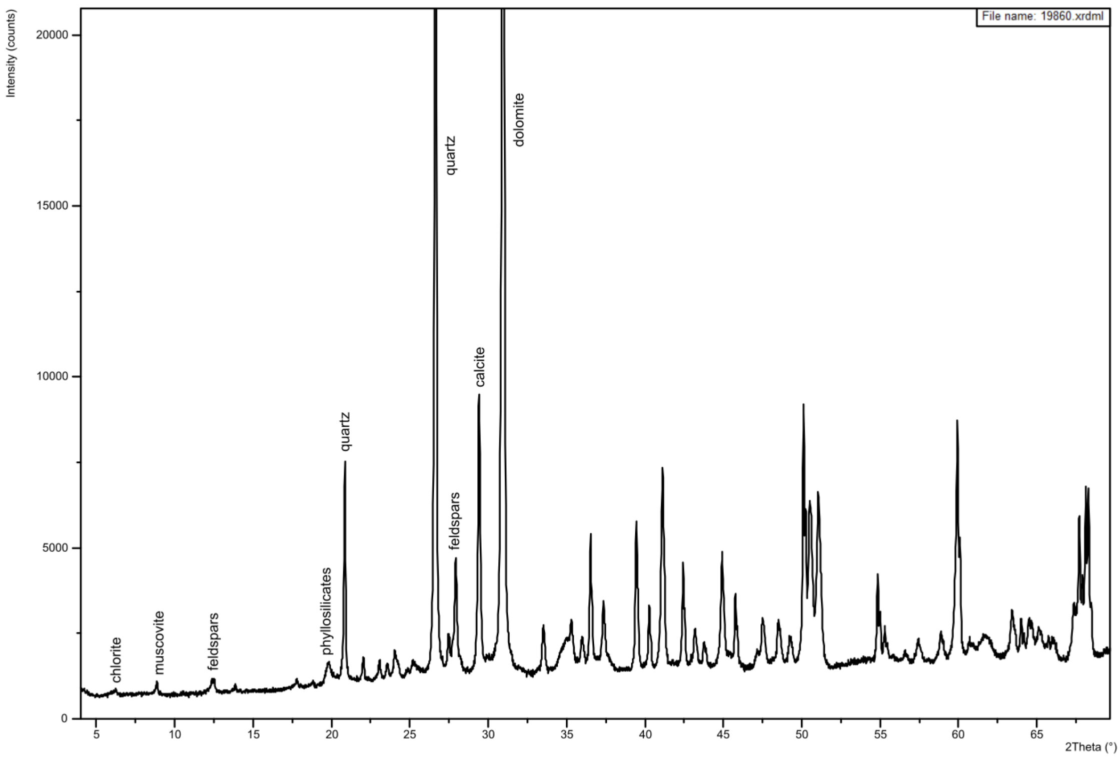

Figure 17. Graph representing the mineral composition of the bulk soil.

From this graph we can see that the main minerals present in our soil are quartz, dolomite, calcite, feldspar and some chlorite and muscovite. Indeed, based on these peaks, and more specifically the area of the peaks, we can determine to mass of the minerals. Which, as can be seen in the table 1, showed that dolomite was the most prominent mineral with 58% of the total mass of soil, followed by quartz with 21%.

Table 1. table representing the different bulk minerals and their mass content in our soil

mineral class	**minerals**	**mass %**
carbonates:	dolomite	58
	calcite	6
tectosilicates:	quartz	21
	plagioclase	5
	potassium feldspar	2
phyllosilicates:	chlorite	4
	muscovite	4
inosilicates:	amphibole	< 0,5/traces

The soil mineralogy can have an effect on soil stability. Indeed, as minerals have different shapes, they exert different frictions on each other.

Clay mineral analysis

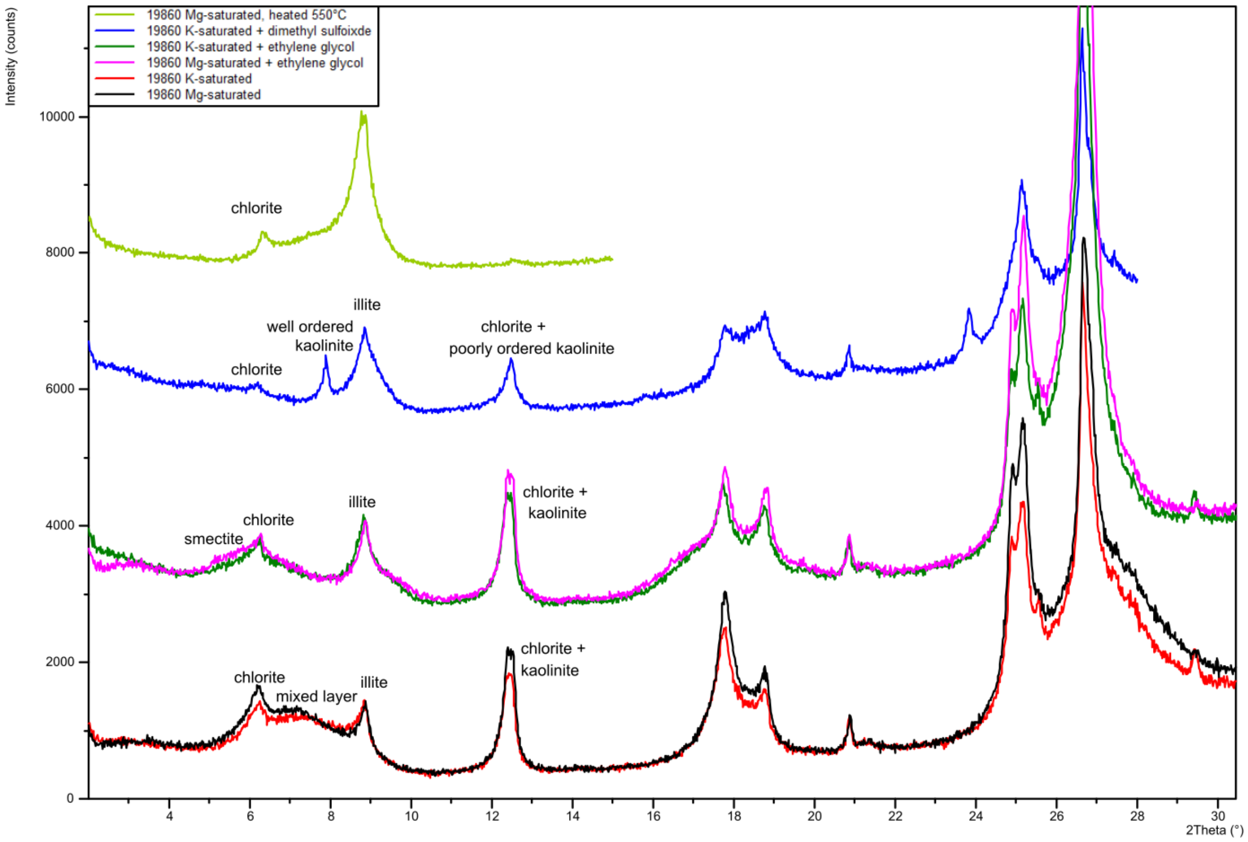

Figure 18. Graph representing the clay mineral composition of the fraction <2µm.

From this graph we can see that the main minerals present in the clays are chlorite, illite, kaolinite and some smectite. Indeed, based on these peaks, and more specifically the area of the peaks, we can determine to mass of the minerals. Which, as can be seen in the table below, showed that illite was the most prominent mineral with 63% of the total mass of soil, followed by chlorite with 24%.

Table 2. Table representing the different clay minerals and their mass content in our soil

clay mineral	mass %
chlorite	24
illite	63
smectite (only in mixed layer)	2
well-ordered kaolinite	6
poorly ordered kaolinite	5

The clay mineralogy can also affect the soil stability. That is especially when they come in contact with water and that affects even more clays which are expansible, this is the case for smectite in our soil. Indeed, the soil shear strength decreases as the water content increases, this is due to an increase in the space between the layers of expandable clays such as smectites and vermiculites as they fill with water (Bidyaschwari *et al.*, 2017; Neupane and Adhikari, 2011). Moreover, the frictional sliding effects of certain phyllosilicates like smectites increase slope instabilities (Collettini et al, 2009). Finally, clays with a plate morphology like kaolinite, illite and other mixed-layered clays move more smoothly leading to more landslide occurrences or higher slope instability risks (Summa *et al.*, 2018; Anis *et al.*, 2019).

4.2.3 Soil bulk density

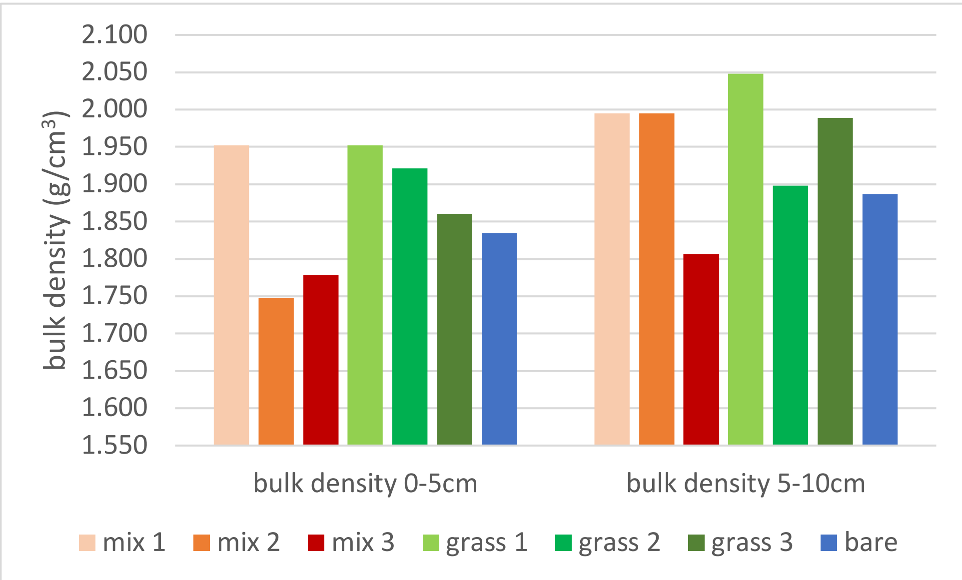

Figure 19. Graph representing the bulk density of the different treatments in different soil layers (0-5cm and 5-10cm).

As we can see from the graph, although the t-tests showed no significant difference between the treatments, the bulk density tends to be slightly lower in the mixed treatments although the variability within treatments is high. Also, although the differences in bulk density between the different layers are not significant, it seems the bulk density in the upper layer (0-5cm) is slightly lower compared to the lower layer (5-10cm). Indeed, in average the mixed samples had 1.83g/cm^3 in the upper layer against

1.93g/cm^3 in the lower layer and for the grass sample, the averages were 1.91g/cm^3 in the 0-5cm layer and 1.98g/cm^3 in the 5-10cm layer.

As previously mentioned, soil bulk density can affect the slope stability as a higher density would decrease the slope stability (Nie *et al.*, 2018). However, in our experiment the bulk density did not show any statistical differences according to the t-tests. Moreover, in contrary to the previous statement, when the bulk density was higher in mix 1 and grass 1, the soil failed later compared to the mix 2 and grass 3 which had the lowest bulk densities in each treatment. Thus, we can say that in our experiment, the bulk density was not the key player for slope stability.

Moreover, thanks to the pycnometer, the particle density was determined to be 2.617g/cm^3. This value is in the typical range for mineral particles, 2.4-2.9g/cm^3 (Ruehlmann and Körschens, 2020). Soil particle density varies between different soils as it is affected by the mineralogy of the soil, which refers to the mineral fractions (silt, clay, sand) and their chemical composition, and is also affected by the organic matter content of the soil which tends to reduce the overall particle density of soils (Ruehlmann and Körschens, 2020).

Thanks to the particle and bulk density, the porosity was calculated and can be found in the following graph:

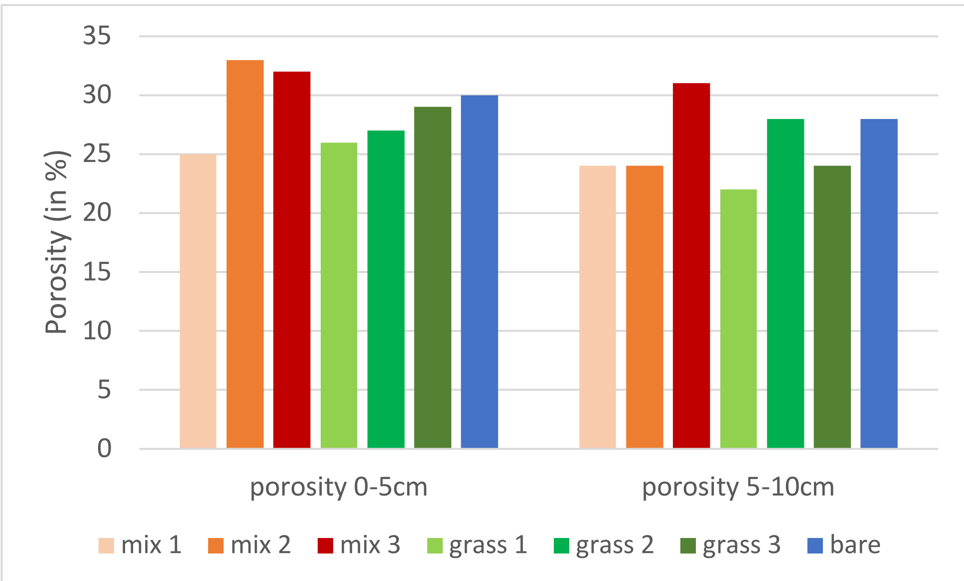

Figure 20. Graph representing the porosity of the different treatments in different soil layers (0-5cm and 5-10cm)

From this graph we can see that the porosity between treatments is very similar though slightly higher in the mixed samples with averages of 30% and 26.3% in the two layers, 0-5cm and 5-10cm respectively, compared to 27.3% and 24.6% in the grass layers. Moreover, between the layers there is also a slightly higher porosity in the upper layer compared to the lower layer though as for the difference between treatments these differences are not statistically significant.

It was shown in a paper by Mukhlisin *et al.* (2006) that a higher soil porosity would increase the time before a slope failure as it allows for more water holding capacity which delays the infiltration of water in the subsurface and thus the pore water pressure. Although this higher water content in the soil can also have a negative effect as the higher moisture leads to longer distance travelled by the soil and debris during a landslide. From our experiment, the porosity was not very high overall. There was a slightly higher porosity in the upper layers which could be due to the presence of roots. Indeed, Vogelmann *et al.* (2012) showed the same results, with higher overall porosity and microporosity in the top 0-5cm, which they associated to higher organic matter content as well as larger amounts of roots. Similarly, the slightly higher porosity in the mixed samples could be due to the tap roots from the red clover which are thicker than the ryegrass roots and thus can create macropores. Indeed, the different rooting structures and the plant species affect the soil structure differently. Clovers tend to improve soil aggregation better than ryegrass which thus leads to better soil structure. Also, red clover leads to higher formation of macropores thanks to its taproots and dense root mat (Marshall *et al.*, 2016).

4.2.4 Soil water content

As previously mentioned, soil water content plays an important role in soil and slope stability.

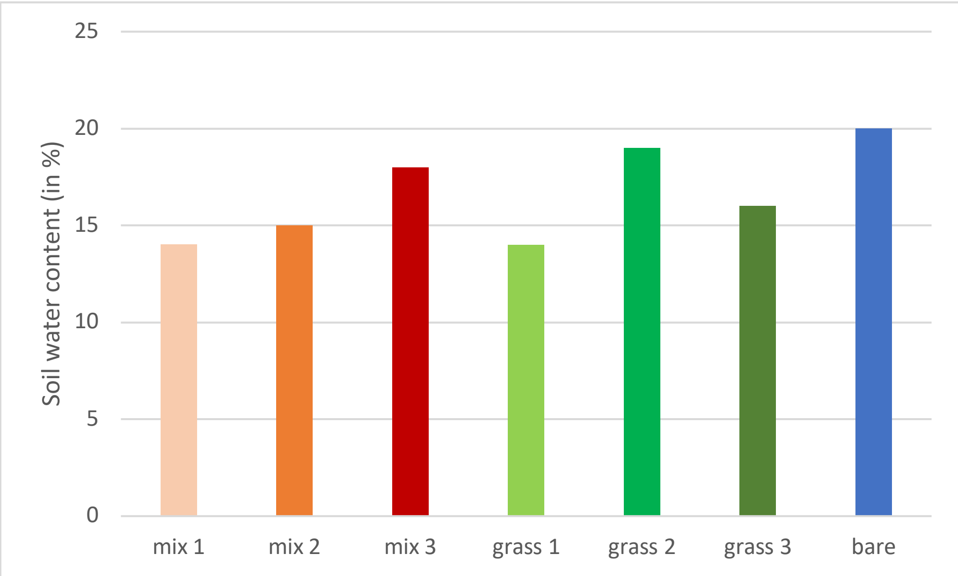

Figure 21. Graph representing the soil water content in the different treatments and their replicates.

From this graph and the t-test made, it was found that the water content did not differ significantly between treatments. The highest soil water content was recorded in the control (bare soil). However, when we compare the moisture content with the failure times, we can see a trend for the drier samples to have more stability as the failure occurred later, while the moister samples failed earlier. This is seen in the mix 1 and grass 1 which are drier (less than 15% water content) and failed later compared to the other samples containing more than 15% water. Thus, we could say that to some extent the water content may have played a role in the slope stability, as was stated by Komadja *et al.* (2020) and Earle (2019). Moreover, the presence of plants may explain the lower water content in the planted boxes compared to the bare soil, as they increase the evapotranspiration due to water uptake which in turn improves the soil stability as it decreases the water weight and pressure in soil pores (Świtała and Wu, 2018; Yildiz *et al.*, 2018).

4.2.5 Soil plasticity

The different plasticity and liquid limit tests result in the following graphs.

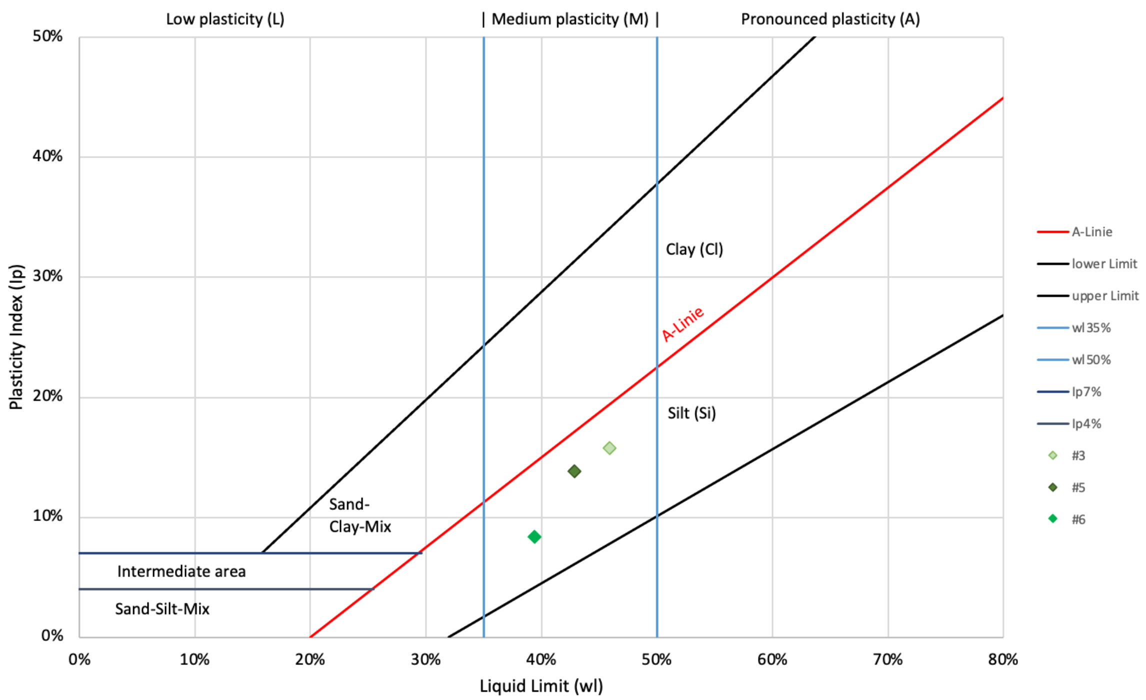

Figure 22. Graph representing the diagram of plasticity according to Casagrande of 3 of the 7 samples.

As we can see from the above graph, the soil from our experiment is moderately plastic and has a silty texture, as the soil has a liquid limit (wL) between 39 and 46% and plasticity index (Ip) between 8 and 16%. As the same soil was placed in the different boxes, it makes sense that the plasticity index and liquid limit are in similar ranges for the different samples used.

The plasticity index is often related to expansion as well as the residual angle of internal friction. Moreover, it was shown that as the plasticity index increases the soil becomes more unstable and plastic (Bidyashwari *et al.*, 2017). In our case, the plasticity indices are in the medium range meaning that the soil can have a moderate expansion and that it has a moderately stable property.

4.3 Soil chemical properties

4.3.1 Soil pH

All the treatments and their replicates had the same H_2O- and $CaCl_2$-pH values, 7.7 and 7.2 respectively. Thus, in our experiment, pH did not influence plant growth and thus the slope failures were also not affected.

4.3.2 C and N contents

The C and N contents of a soil can affect the plant growth due to the availability of nutrients in the soil. Thus, looking at the total C and N as well as the inorganic and organic C can give an idea on the soil quality and fertility. These results are further discussed below.

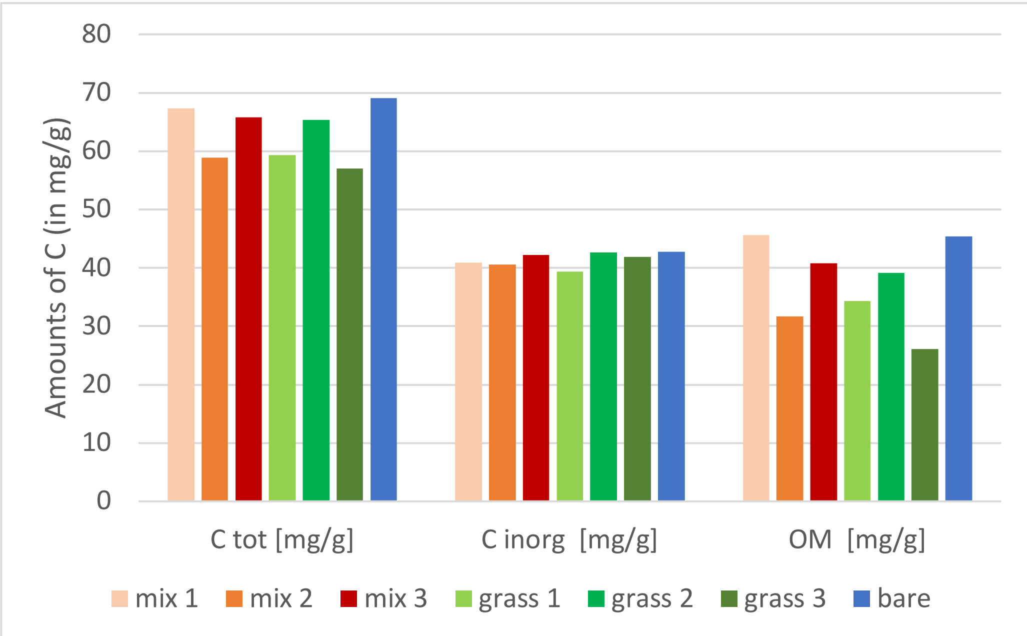

Figure 23. Graph representing the total, inorganic carbon, and organic matter present in the soils with different treatments.

According to the t-tests, there are no significant differences in the different C content of the different treatments and the variability between replicates is quite high. However, when looking at this graph, we can see a trend for a higher total carbon in the mixed samples compared to the sole grass samples, 64.0mg/g versus 60.5mg/g total carbon, in average for the mixed and sole grass respectively. And this is mostly explained by a slightly higher organic matter content in the mixed treatments, 39.4mg/g and 33.2mg/g OM in average for the mixed and sole grass treatments, as the inorganic carbon contents do not seem to differ much, 41.2mg/g and 41.3mg/g of inorganic carbon in average for the mixed and sole treatments. However, since the growing season was only for 3 months and it is widely known that soils have a high heterogeneity, it is difficult to say if these trends are due to the ryegrass-clover mixture or simply because of the OM in the soil put in these boxes was originally higher. Especially since the bare soil had the highest OM content compared to the other two treatments, 45.4mg/g of OM. Also, the samples taken from the boxes and the 200mg sample placed in the CN analyser may not be fully representative of the approximately 0.1125m^3 soil volume contained in the boxes. Thus, we can say that as the differences are not statistically different and the variability is high, the effects of carbon content in the soil had little effect on plant growth and thus on the soil stability.

In terms of N content, there was also no significant difference, though as can be seen in the following graph, the N content in the bare soil is higher, suggesting the use of N from the plants for growth. Moreover, the N content in the mixed cropping is slightly higher which could be due to the lower N uptake by clovers or the input of N thanks to rhizobia interaction allowing for N fixation in clover roots. However, since the establishment had only been for 3 months, the presence of nodules will have to be checked when looking at the root biomass and architecture.

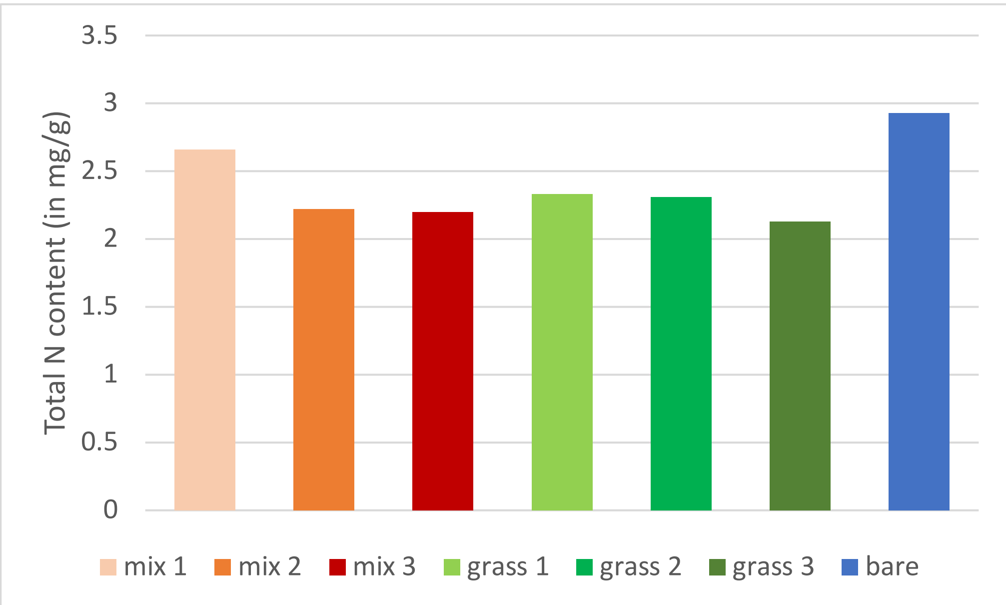

Figure 24. Graph representing the total soil N content in the different treatments and their replicates

4.4 Above- and below-ground biomass:

The dry matter of the above-ground biomass showed significant difference between mixed and grass (p-value=0.0047), more above-ground biomass was produced in the mixed system compared to when grass was growing alone. This could be because clover germinated faster than ryegrass allowing for more biomass production overall, but also because of simply more biomass production in clovers compared to ryegrass, especially in the early stages of establishments (after 3 months).

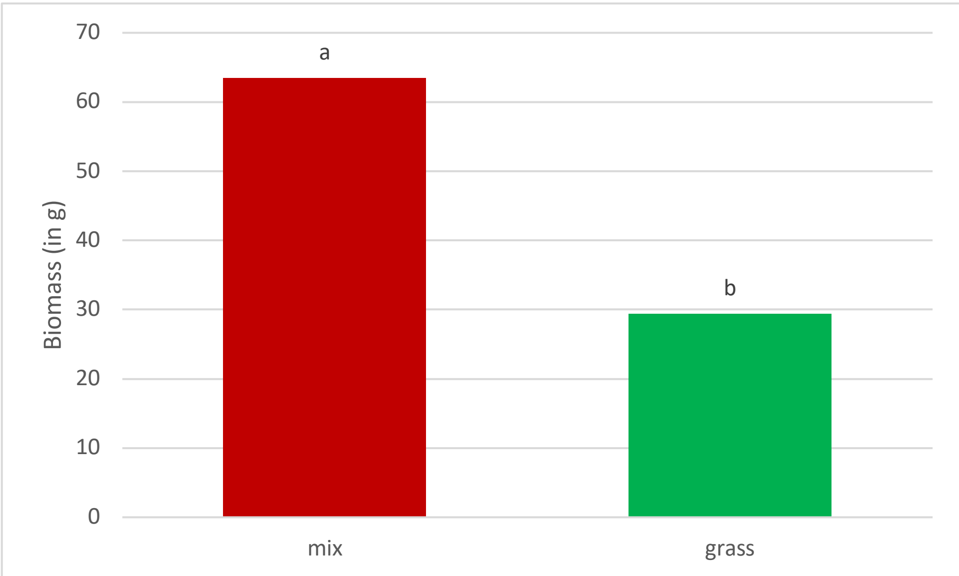

Figure 25. Graph representing the dry matter of the above-ground biomass in the ryegrass treatment compared to ryegrass-clover treatment (a: significant difference between treatments with $\alpha = 0.05$).

From this graph we can see that as the t-test showed, there is a significant difference in biomass between the sole ryegrass and the red clover-ryegrass mix. With the mixed sample having a greater above-ground biomass compared to the sole grass. This can be simply explained by an overall greater biomass production in red clover compared to ryegrass.

Moreover, the root biomass was also analyzed in order to see how the plants grew underground.

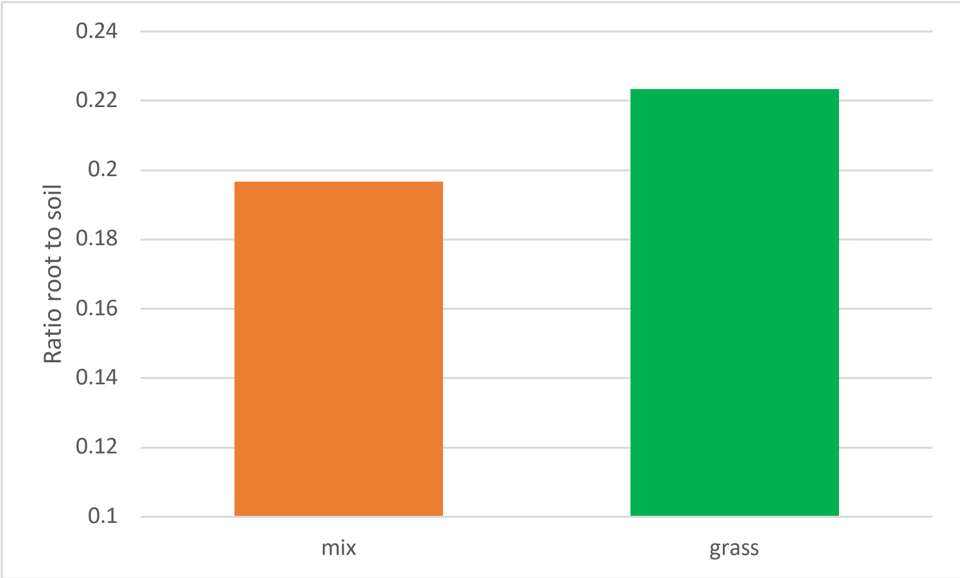

Figure 26. Graph representing the average ratio of the mass of roots present in a mass of soil in the different treatments (red clover-ryegrass and sole ryegrass).

Although the t-test showed no significant difference, we can see from this graph that the grass root biomass per soil mass was greater than the clover-ryegrass root biomass. When comparing figure 25. and 26 we can see that the different cropping system show differences in their growing characteristics. While the ryegrass has a greater root mass, the clover has a higher shoot mass. Indeed, the experiment of Robinson and Jacques (1958) showed that after 4 months of growth, the root biomass of red clover was lower than perennial ryegrass, with about 1936kg/ha for ryegrass and 1415 kg/ha in red clover, in the first 10cm of soil. This was observed for this short growth period however, when looking at 12 and 20 months after sowing, the red clover showed higher root biomass compared to perennial ryegrass. However, these were observed when the 2 plants were grown separately thus, we can expect some competition for growth when they are mixed together.

4.5 Root architecture

Plant roots have different architectures depending on the species and these thus have a different effect on soil reinforcement. The different architectures of ryegrass and red clover will be discussed below.

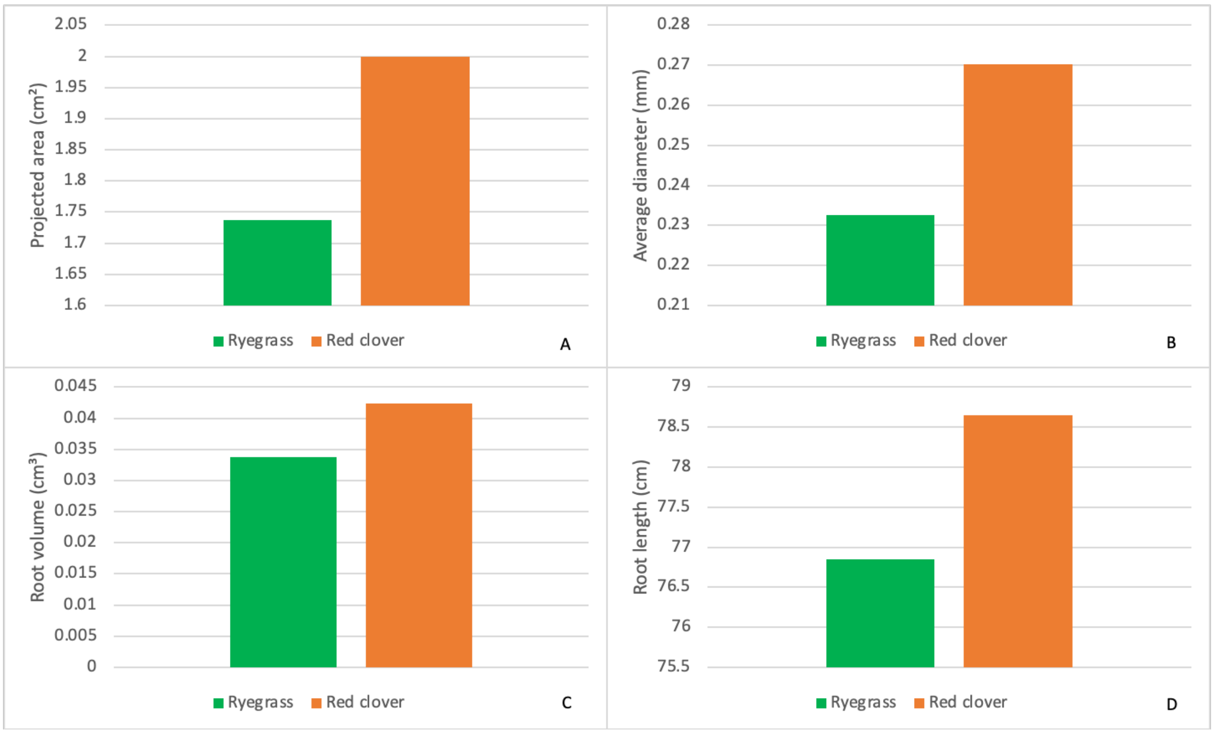

Figure 27. Graph representing different parameters of clover and ryegrass roots, average projected area (A), average root diameter (B), average root volume (C) and average root length (D).

From this graph, we can see that the red clover had an overall larger rooting system. Indeed, the root length and root diameter are in average larger in red clover compared to ryegrass. However, the t-test showed no significant difference between the two rooting systems.

Thanks to the scans below, we can get an idea of the root architectures of the different plants involved in the experiment, ryegrass and red clover.

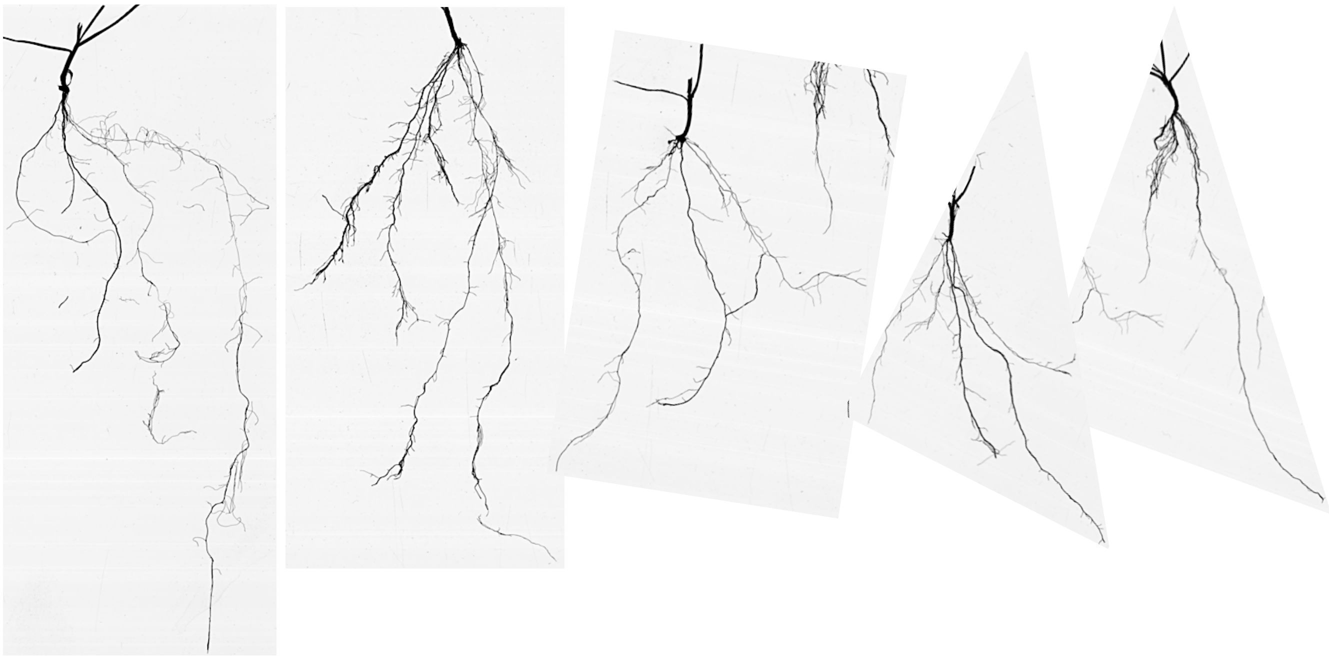

Figure 28. Scans of ryegrass roots

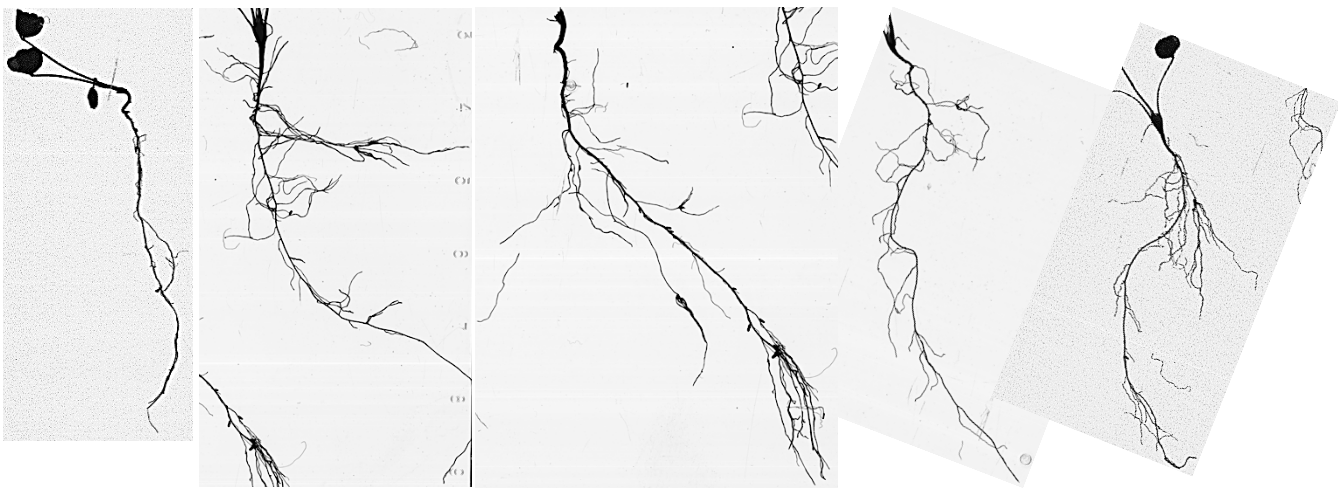

Figure 29. Scans of red clover roots

As we can see from these scans, the ryegrass roots have more branching and fine roots compared to the red clover which have longer and thicker roots, as it was also shown in the graphs above.

As the plants were still quite young, only 3 months old, the taproots of red clovers were not as long as they could have been after a longer growing season. This fact could explain the lower effect of red clover in supporting slopes, unlike what we had expected.

Grass roots can provide reinforcement in the shallow soil layers where their fine roots are concentrated (Masi *et al.*, 2021). Moreover, as we can see from the scans, ryegrass have more lateral roots which have an important role in terms of traction force. As previously mentioned, lateral roots increase this traction force through tensile strength and root-soil bond and thus allow to maintain the soil in place until the traction resistance of the roots becomes lower than the load on the roots. When this happens, the traction of the root fails, either the lateral root is pulled out as the root-soil bond breaks or the root breaks due to a lack of tensile strength. The latter is most prominent as the several branching on lateral roots would prevent pulling it out (Zhang *et al.*, 2011). Moreover, the diameter of the roots also plays a role in the traction force roots have. Indeed, Rauchecker *et al.* (2019) did an experiment on Timothy grass (*Phleum pratense* L.) roots looking at the traction force exerted by roots of different diameter, and determined that as the root diameter increases, the traction force from the root increases. In our experiment, the roots were in average of 0.23 and 0.27mm for the grass and clover respectively, which would point towards a slightly higher traction force exerted by clover compared to ryegrass. However, as previously pointed out, the ryegrass had more roots per plant and these lateral roots were also longer thus affecting also the traction force the roots have. Thus, we can say that although the ryegrass roots are slightly thinner (non-significant) compared to the red clover, they are still able to exert a higher traction force thanks to their more numerous and longer lateral roots.

5. Conclusion

From this experiment we can say that in the early development of such perennial plants, growing ryegrass alone has a better effect in slope stabilization compared to mixing with red clover. In terms of physical and chemical properties, the water content, as well as the bulk density and porosity may have had an influence on the failure rates. However, since the differences between treatments were not significant, no clear conclusion can be made. When compared to the bare soil, the presence of plants significantly improves the duration before failure thanks to a greater traction force exerted by the roots. As this traction is especially demonstrated by lateral roots which appear to be numerous and longer in ryegrass. This fact could explain the better performance in the sole ryegrass than the mixed cropping in our experiment. However, when looking at the longer-term behavior, the literature seems to suggest the use of diverse rooting systems as their combination allow for further improvement in slope stabilization. Moreover, as the higher ryegrass density present in the sole cropping may have had a beneficial effect on stabilizing the slopes, compared to the mixed cropping which had half the density of ryegrass and the other red clover, it may be interesting to study the planting density in a future study. Indeed, root reinforcement is known to depend on the root density in soils (Masi *et al.*, 2021). More research would be needed to determine how these densities actually affect the stability.

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