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Soil permeability, aggregate stability and root growth: a pot experiment from a soil bioengineering perspective

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ABSTRACT

Assessing the joint development of vegetation cover and soil properties is crucial to evaluate the efficiency of soil bioengineering techniques, especially during the most critical initial phase of vegetation colonization. We set up a laboratory experiment to quantify and disentangle the effect of *Alnus incana* roots on soil permeability and aggregate stability. Plants were grown in pots in a climate chamber for four different growing periods (1, 2, 4 and 8 months). Pots were filled with a soil coming from a moraine of a landslide area in Central Switzerland. After each growing period, surface permeability, soil volume permeability and soil aggregate stability were measured together with the development of the root systems. Our results show that alder roots significantly improve both surface and whole soil volume permeability already after 2 months of growth. Nevertheless, an increase in root length density does not necessarily correspond to an increase in permeability. We could set as a threshold a root length density of 0.1 cm/cm^3 until which an increase in root development corresponds to an increase in soil permeability, whereas after this threshold we observed a decrease in soil permeability. A significant increase in soil aggregate stability could be observed only with a root length density of 2 cm/cm^3. No obvious correlation between soil permeability and aggregate stability could be found. Future work should validate these laboratory results with field data.

KEY WORDS soil permeability; soil aggregate stability; root growth; soil bioengineering

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INTRODUCTION

Soil permeability and aggregate stability are critical factors when evaluating the efficacy of soil restoration methods, as in the case of soil bioengineering techniques.

Soil permeability (or surface and near surface saturated hydraulic conductivity, k_s) is a key hydrological property affecting different fields of interest: from agriculture to forestry to slope stability and flood protection (Collison *et al*., 1995; Bens *et al*., 2007; Gonzales-Sosa *et al*., 2010; Hencher, 2010; Pagenkemper *et al*., 2014; Rienzner and Gandolfi, 2014). It controls the partitioning of precipitation into vertical and lateral pathways, thus influencing the generation of runoff and subsurface pore water pressure (Archer *et al*., 2013; Greenwood and Buttle, 2014).

Soil aggregate stability expresses the ability of soil to retain its structure when exposed to different stresses; it is critical for plant growth and soil erosion and has been found to be directly related to the shear strength of soil (Frei *et al*., 2003).

These two soil properties are intimately correlated. Permeability is typically controlled by soil structure and aggregate stability (Boxell and Drohan, 2009): high aggregate stability enhances soil porosity and, therefore, soil permeability (Bronick and Lal, 2005). Degradation in the soil structure may result in a reduction of soil porosity and infiltration capacity, reducing the cohesion between soil particles and increasing the erosion rate by water (Andreu *et al*., 2001).

Several studies showed that the development of a vegetation cover has beneficial effects on the stability of soil aggregates (Burri *et al*., 2009). Plant roots enmesh soil particles and release exudates, resulting in physical, chemical and biological interactions influencing aggregation (Bronick and Lal, 2005). Soil aggregate stability increases with increasing root length density, microbial association diversity and percent cover (Rillig *et al*., 2002). Furthermore, the biochemical composition of plant residues in the soil also affects the stability of aggregation (Bronick and Lal, 2005).

The effects of plants on soil permeability are instead more controversial. As reviewed by Chandler and Chappell (2008) and recalled by Archer *et al*. (2013), it is commonly accepted that trees enhance soil permeability (Lorimer and Douglas, 1995; Greenwood and Buttle, 2014). However, the results of an increasing number of studies suggest that this is not universally true and depends on the soil type, the ‘disturbance history’ of the soil and the vegetation cover

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type (Gabr *et al*., 1995; Chappell and Franks, 1996; Bonell *et al*., 2010; Lichner *et al*., 2010; Ghimire *et al*., 2014).

Root growth is the driver of the main mechanism by which plants enhance soil permeability, namely the development of a macropore system, also called rhizopores (Ghestem *et al*., 2011). Water flows through two domains in soil: the soil matrix, consisting of both uniform saturated and unsaturated flow through fine pores, and preferential flow pathways, consisting of single or interconnecting macropores. Macropores may represent a small fraction of the total porosity; however they control the water flux close to saturation: even a low macroporosity can increase the flux density of saturated soil by more than one order of magnitude in soils of low to moderate matrix conductivity (Beven and Germann, 1982). Macropores may be associated with either live or decayed roots, which appear to be the most important agents for preferential flow paths, even if not all the roots are necessarily associated with them (Perillo *et al*., 1999). In his review on rhizosphere control on soil hydrologic properties, Bengough (2012) shows that saturated flow depends strongly on pore sizes corresponding to the dimensions of plant roots. Root channels can represent up to 70% (Noguchi *et al*., 1997) or even up to 100% (Newman *et al*., 2004) of the macropore population in the upper soil layers and up to 35% of the macropores of the total soil volume. Besides the amount and diameter of macropores, their length, connectivity, orientation and tortuosity are important factors which affect the water drainage in soil (Ghestem *et al*., 2011; Bengough, 2012).

The negative effects of vegetation on soil permeability are instead mainly because of the accumulation of potentially hydrophobic organic compounds produced by roots, such as sugars, amino acids and phospholipids (Bengough, 2012). Additionally, decomposing organic matter and soil microorganisms, particularly fungi, can lead to water repellency (Doerr *et al*., 2000; Lichner *et al*., 2007; Morales *et al*., 2010). Furthermore, the soil acidification because of the decomposition of the acidic litter, particularly in conifer plantations, can lead to a collapse of the soil aggregates and thus reduce macroporosity (Chappell and Franks, 1996).

In general, the scientific studies directly demonstrating the impact of vegetation and in particular of root development on infiltration and drainage in the soil are far less abundant than the suggestions based on practical experience (Germann *et al*., 2012). There is still little information about the quantitative impact of roots on hydropedology: plants with different root architectures generate distinct pore networks and have different effects on soil permeability (Archer *et al*., 2002; Ghestem *et al*., 2011) and to use plants as management utilities, one need to know how far specific species can influence water flow and soil structure. This is particularly important in the case of soil bioengineering measures. On soils affected by erosion and sliding processes, the pore structure is strongly destabilized because of the break-up of the aggregates (Graf and Frei, 2013). These conditions are extreme also for pioneer plant species, as water and nutrients are not retained by the soil and are immediately leached out. In particular some experiments showed that one of the main factors driving the possibility of plant colonization and succession (i.e. changes in community composition over time) in eroded areas is the very short retention time of available water in soil (Garcia Fayos *et al*., 2000). This is why the first phase of establishment of the biological measures is also the most critical for the long-term success of restoration techniques. It is therefore crucial to evaluate the joint development of the vegetation cover and soil properties, which reciprocally affect each other.

So far, most of the existing studies on hydrologic properties of soils related to vegetation focus on the effects of reforestation (Bonell *et al*., 2010; Greenwood and Buttle, 2014) and on the comparison between forest soils and degraded pasture or grasslands through paired catchment studies (Archer *et al*., 2013; Ghimire *et al*., 2014). To our knowledge there are no studies related to soil bioengineering methods. In this rising field, a major challenge is in particular to define the period required for the hydrological and soil structure recovery of bioengineered slopes, depending on the soil type, the kind of association aimed to and the correspondingly selected revegetation measures.

The objective of this study was to define the response of soil permeability from disturbed to restored conditions in the context of soil bioengineering measures and to link this property to the growth of plant root systems and the development of the soil structure.

Graf *et al*. (2014) proved that already relatively short time laboratory experiments can provide meaningful information at least for the first stage of colonization in soil bioengineering measures. Therefore, we set up a laboratory experiment to work under controlled conditions in order to disentangle the effects of root development keeping the other influencing factors constant. We used *Alnus incana* (white alder), a species widely adopted in restoration projects in the Alps and a soil coming from a landslide site in Central Switzerland.

This study aimed to answer the following research questions:

(i) Does the development of *A. incana* roots increase soil permeability?
(ii) Which degree of root development is needed to sensibly modify this property (i.e. how long does it take a macropore system to develop)?
(iii) Does root growth increase the stability of soil aggregates and has a certain threshold in root development to be exceeded to observe this increase?
(iv) Are soil aggregate stability and saturated hydraulic conductivity positively correlated?

MATERIALS AND METHODS

Experimental setup

Cylindrical pots with 34-cm diameter and 35-cm height were used in the experiment. The pots had at the bottom seven holes of 1-cm diameter to allow the drainage of the water.

The soil used for the experiment is a moraine of the subalpine landslide area 'Hexenrubi' in Dallenwil-Wirzweli, central Switzerland (Burri *et al.*, 2009). The grain size distribution including coarse fraction up to 63 mm was classified as clayey gravel with sand (GC-CL), while the fraction smaller than 10 mm was classified as poorly graded sand and silty sand (SP-SM) (Bader, 2014), based on the unified soil classification system (USCS).

The fraction smaller than 10 mm coming from the oven dried soil was wetted to reach a gravimetric water content of 6%.

Each pot was then filled with 3 cm of gravel (mean diameter 0.5 cm) at the bottom, to facilitate the drainage and to avoid the loss of soil material during the tests. Subsequently, the <10-mm fraction of soil was added, according to Graf *et al.* (2009), until reaching the targeted soil thickness of 20 cm and the unit dry weight of 16 kN/m^3.

A. incana (*L.*) *Moench* was selected as the study species as it is widely used in slope restoration projects in the Alps, not least due its capacity to fix nitrogen and its symbiosis with both ecto and arbuscular mycorrhizal fungi. After the first month of growth in small germination pots, we planted one specimen into each pot, and kept them in a climate chamber at a day time temperature of 25 °C and relative humidity of 75%, and at a night temperature of 17 °C and relative humidity of 55%, with 15 h of light per day with 80% light.

Four different growing periods were distinguished (1, 2, 4 and 8 months). For each growing period seven planted replicates were set up, as well as three control pots with only bare soil treated the same way as the planted pots (i.e. same amount of water and same fertilization), accounting to total 40 experimental pots. Pots were watered every day during the first month of growth, three times per week from the second to the 4th month, and twice a week the rest of the growing period. They were fertilized every two week with 1 l of a common NPK fertilizer (2 ml/l of water).

At the end of each growing period, before the saturation phase (see next section), the bulk density of the soil of each pot was determined by weighting the pot and measuring the effective height of the soil to calculate the volume. To obtain the effective weight of the soil, we subtracted from the total weight of the pot the weight of the empty pot and the gravel.

Hydraulic conductivity tests

Saturated hydraulic conductivity was measured both at the soil surface and considering the whole soil volume, applying in the first case a well-documented standard method and in the second case a modified method subsequently explained more in detail.

To measure surface permeability we used a Decagon minidisk infiltrometer (Boxell and Drohan, 2009; Lichner *et al.*, 2010; Ronayne *et al.*, 2012). The measurements were taken both on planted and control pots every month, excluding the first month of growing. The minidisk infiltrometer is a tension infiltrometer; therefore it measures the flow in the soil matrix only, excluding macropores with a given diameter depending on the tension applied (Watson and Luxmoore, 1986). To have a condition as closest as possible to the saturation, the measurements were performed with a tension of −0.5 cm. Given the capillarity equation:

$$r = -\frac{2\ \sigma cosa}{\rho gh} \cong -\frac{0.15}{h} \tag{1}$$

where σ is the surface tension of water, α is the contact angle between the water and the pore wall (commonly assumed 0°), ρ is the water density, g the acceleration because of gravity and h is the applied tension, pores with diameter bigger than 6 mm were excluded.

We performed three measurements per pot at a constant distance from the plant stem (5 cm). The conductivity was calculated from the data recorded in the transient period of the infiltration with the Zhang's method (Zhang, 1997), according to the mini Disk Infiltrometer user manual (Decagon, 2005). We adopted the van Genuchten moisture retention parameters $N = 2.28$ and $\alpha = 0.124$ (Carsel and Parrish, 1988) which are representative values for a loamy sand soil, based on the grain size distribution of the fraction of soil with diameter smaller than 10 mm. The average value of hydraulic conductivity obtained for each pot was then considered for the analysis.

To measure the saturated hydraulic conductivity of the whole soil volume we adapted the standard falling head procedure (Bagarello and Iovino, 2010) to the pot experiment. After each growing period, the plants were cut, and each pot was fully saturated from the bottom by placing it in a bigger pot and slowly filling it with water. The pots were saturated for 2 h, allowing the air to slowly escape without remaining in the soil; subsequently they were then removed, and the gravimetric water was allowed to drain. The slow saturation of the pots aimed to reduce as much as possible air entrapment in the soil, as this significantly reduces conductivity values up to 100 times with an increment of the 5% of the air in the soil (Koga, 1987).

After the drainage of the whole gravimetric water, a water head of 4 cm was established above the soil in the pot, using a diffusor to avoid disturbing the soil surface. The time needed to reach a level of 3 cm above the soil was then recorded with a stopwatch; the head of 4 cm was then re-established, and the measure was repeated. As the soil was already saturated, the steady state was normally reached immediately, and the average of three consecutive measurements was taken as the conductivity value. To consider the test valid the difference between the consecutive measurements should not be bigger than 3%. Saturated hydraulic conductivity k_s was calculated as (Bagarello and Iovino, 2010):

$$k_s = \frac{aL}{A(t_2 - t_1)} ln \frac{H_1}{H_2} \tag{2}$$

where L is the thickness of the soil, A is the section of the sample (i.e. the pot), H_2 is the water level at the time t_2 and H_1 is the water level at the time t_1. In our case a and A are the same (i.e. the section of the sample).

The temperature of the water used for the test was measured in both methods (mini disk and falling head) in order to take into account the change in water viscosity with temperature (Rienzner and Gandolfi, 2014). The values of k_s were corrected as follows obtaining the saturated conductivity at the reference temperature of 20 °C:

$$k_s = k_{s\ (T)} \frac{\mu_{(T)}}{\mu_{(20)}} \tag{3}$$

where μ_{20} is the water viscosity at 20 °C (0.001 Pa s^{-1}), $k_{s(T)}$ is the measured k_s, T (°C) is the temperature of the water and μ_T is the corresponding water viscosity (Likhachev, 2003):

$$\mu(T) = 0.000024152 \times 10^{(247.7/(T+273.15-139.86))}. \tag{4}$$

Soil aggregate stability measurements

The samples for the soil aggregate stability (*sas*) determination were taken with a specifically designed and produced cylindrical steel tool. A plastic tube and a plastic sheet were placed inside the tool to allow the removal of the soil sample without damaging it. The dimension of the soil core was 14-cm height and 7-cm diameter. A sample for each pot was taken, and the soil aggregate stability was determined in the laboratory with the wet sieving method described in Graf and Frei (2013). The roots were cleaned, spread out in a water-filled transparent plastic container and analysed with a flat-bed scanner. The total root length was determined using software WinRhizo ® (2004). The root length per sample volume (cm/cm^3) was used as an indicator for plant growth.

Plant parameters and root system measurements

After each growing period we measured the heights and diameters of the plants.

After the conductivity tests and the soil aggregate stability sampling, each root system was carefully excavated from the pots. Finally, the roots were analysed as described in the previous paragraph. Root length density was then calculated as the root length per soil volume in each pot. We analysed separately root length density of fine (<2 cm) and thick (≥2 cm) roots, on the basis of a widely accepted classification (Lange *et al*., 2009; Archer *et al*., 2013).

Statistical analysis

Differences between the treatments were detected applying the Mann Whitney test. The variables plant diameter and surface k_s were transformed using the Box and Cox's power transformation to meet the assumptions of normal distribution. We evaluated each regression model by applying residual analysis (QQ-plots, Tukey–Anscombe plot). All the analysis were performed using R, version 3.0.3 (R Development Core Team, 2011).

RESULTS

Surface permeability

Surface permeability values range between 6.69e − 06 and 3.23e − 05 m/s for the control pots, and between 1.33e − 05 and 4.95e − 05 m/s for planted pots.

The values obtained for planted pots were always higher than the ones of the corresponding controls (Table I and Figure 1). The difference is significant for the 3 months, 5 months and 8 months pots (p = 0.008, p = 0.03, p = 0.016) and close to significance for the 4 months and 7 months pots (p = 0.058 and p = 0.09). Surface permeability increases with the age of plants, while in the control pots the values tend to remain stable.

We calculated for each growth period the difference between the average value of conductivity of the planted pots and the average value of the control pots: the difference increases linearly with growth time (Figure 2), with $R^2 = 0.55$ (p-value = 0.08). A linear relationship can be also established between the log-transformed values of surface permeability and the log-transformed diameter of the plants (Figure 3), with $R^2 = 0.39$, (p-value = 8.36e − 08).

Soil volume permeability

After the saturation phase we had usually an immediate convergence to steady state, performing three consecutive measures with minimum differences between the obtained values of time. In case of a steady increase of time from one measurement to the next, we excluded the test because of the likely presence of air in the soil.

Hydraulic conductivity values of the whole soil volume range between 1.32e − 05 m/s and 6.69e − 04 m/s for the control pots, and between 1.89e − 05 m/s and 8.64e − 04 m/s for the planted pots. The values obtained for the planted pots fall in the range reported in literature (Standard 670010b, Association of Swiss Road and Traffic Engineers) for the same class of soil (Figure 4), with the exception of the values

Table I. Average values and standard deviations for each of the measured variables for the different treatments for each growing period; ks surf = surface k_s; ks volume = soil volume k_s; sas = soil aggregate stability; r_l_d = root length density.

Treat	Age (months)	Mean ks surf (m/s)	ks surf (st. dev.)	Mean ks volume (m/s)	ks volume (st. dev.)	ks volume – ks surf	Mean sas	sas (st. dev)	Mean r_l_d (cm/cm3)	r_l_d st. dev.
c	1	na	na	4.88E − 04	2.66E − 04	na	0.22	0.09	0	0
c	2	2.08318E − 05	1.10567E − 05	7.34E − 05	5.22E − 05	5.26E − 05	0.24	0.15	0	0
c	4	1.49765E − 05	4.71E − 06	3.07E − 05	3.01E − 05	1.57E − 05	0.33	0.09	0	0
c	8	1.39975E − 05	7.41362E − 06	6.12E − 05	6.06E − 05	4.72E − 05	0.18	0.00	0	0
p	1	na	na	6.60E − 04	1.21E − 04	na	0.28	0.13	0.023	0.011
p	2	2.7911E − 05	1.02982E − 05	3.74E − 04	1.39E − 04	3.46E − 04	0.26	0.14	0.050	0.034
p	4	1.49765E − 05	4.71E − 06	1.47E − 04	1.54E − 04	1.32E − 04	0.28	0.10	0.135	0.129
p	8	3.18513E − 05	9.01462E − 06	6.24E − 05	2.31E − 05	3.06E − 05	0.50	0.10	2.102	0.860

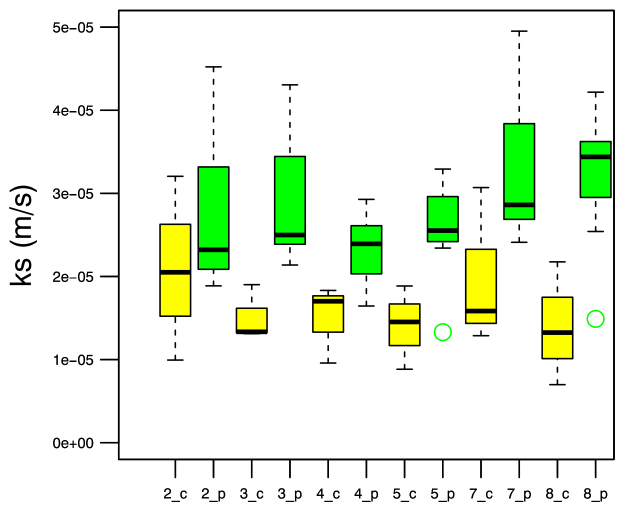

Figure 1. Surface k_s values for the different treatments: the numbers indicate the month of growth, p is planted pot and c is control pot. Boxplot referring to planted pots are green; the ones referred to control pots are yellow.

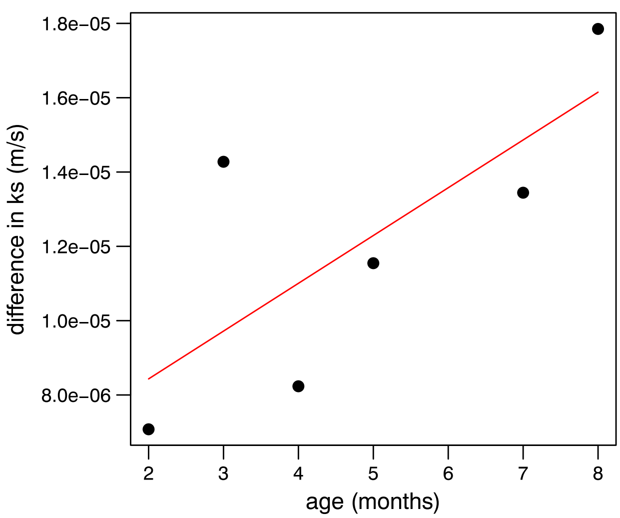

Figure 2. Differences between the mean values of surface k_s obtained in the planted pots and the ones obtained in the control pots, plotted as function of the age of growth.

obtained for the 1-month control pots. Planted pots have always higher values of conductivity than control pots; this is significant for the 2-month pots ($p = 0.008$) and close to significance for the 4-month pots ($p = 0.058$).

Considering only the planted pots it is apparent that the conductivity decreases with increasing plant age. Nevertheless a same pattern is observed also for the control pots: the older they are the lower is the conductivity. We therefore hypothesized a role of soil compaction responsible for this decreasing conductivity values, because of the effect of watering and gravity and the rearrangement of soil particles in the pots. In order to account for this issue we calculated a 'softness index' of the soil which is given by the difference between the soil height before and after

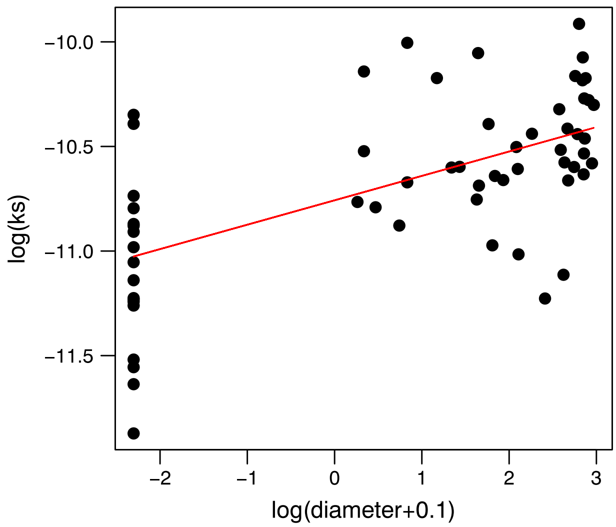

Figure 3. Log-transformed values of surface k_s plotted as function of log-transformed values of the plant diameter.

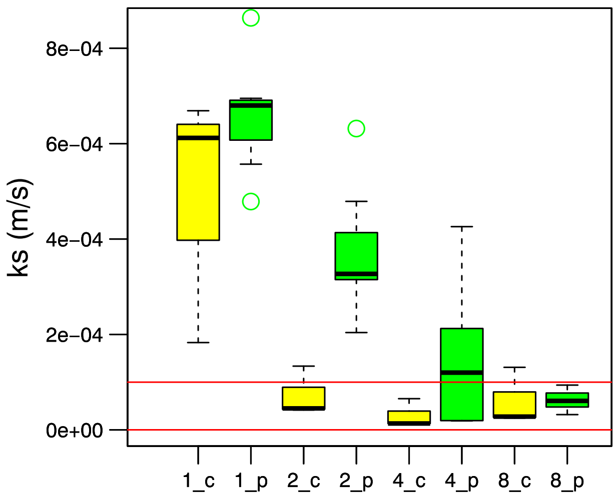

Figure 4. Whole soil volume k_s values obtained for the different treatments; the numbers indicate the month of growth, c is control pot and p is planted pot. Boxplot referring to planted pots are green; the ones referred to control pots are yellow. The red lines indicate the maximum and minimum values of k_s reported in literature for the same soil type.

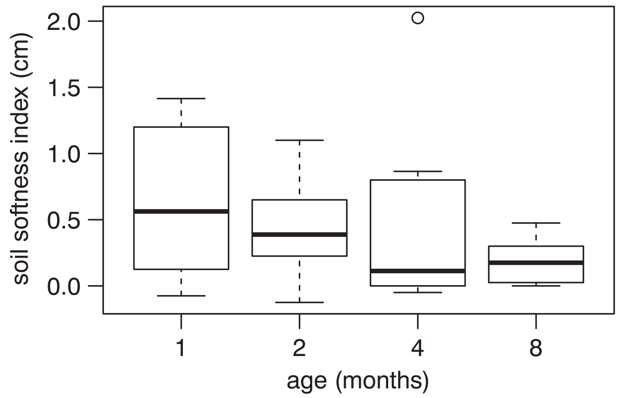

Figure 5. Soil softness index for the different 'soil age'. Both planted and control pots are considered.

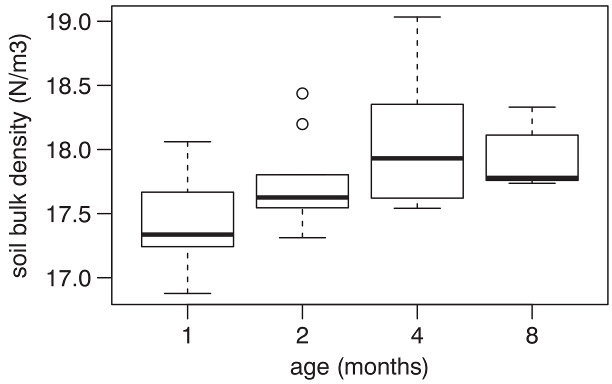

Figure 6. Soil bulk density for the different 'soil age'. Both planted and control pots are considered.

pot saturation. This softness index can be considered as a proxy for soil compaction: the bigger this difference, the less the soil is compacted. Soil softness decreases with age of the pots (Figure 5), meaning that there is an increase in the degree of compaction of the soil with time. The same process can be demonstrated by analysing the bulk density of the soil in the pots at the end of each growing period: soil bulk density increases with the age (Figure 6).

To compare the results of the different aged planted pots we therefore have to consider the 'age of the soil', which means a different degree of compaction. To take into account soil compaction we divided each conductivity value by the mean value of the corresponding control pots:

$$ks_{stand\,i} = \frac{ks_i}{\frac{1}{n}\sum_{c=1}^{n} ks_{ci}} \tag{5}$$

where ks_{stand} is the normalized value of saturated hydraulic conductivity of a pot of age i, ks_i is the measured value of saturated hydraulic conductivity of a pot of age i, ks_{ci} is the measured value of saturated hydraulic conductivity in control pots at that age and n is the number of control pots.

Looking at the normalized k_s values (Figure 7), still the planted pots have higher values than the control ones, but there is an increase in hydraulic conductivity until 2 months of growth, followed by stabilization at 4 months and a subsequent decrease.

Root development and correlation with soil permeability

Root length density values range between 0.007 cm/cm^3 and 3.2 cm/cm^3 (average values and standard deviations are reported in Table I), and most of it consist of fine roots (Figures 8 and 9). As expected there is an increase in root

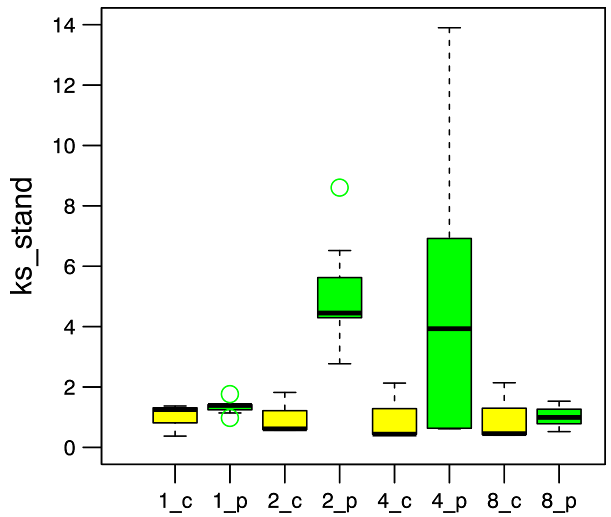

Figure 7. Normalized values for the whole sole layer k_s obtained for the different treatments; the numbers indicate the month of growth, c is control pot and p is planted pot. Boxplot referring to planted pots are green; the ones referred to control pots are yellow.

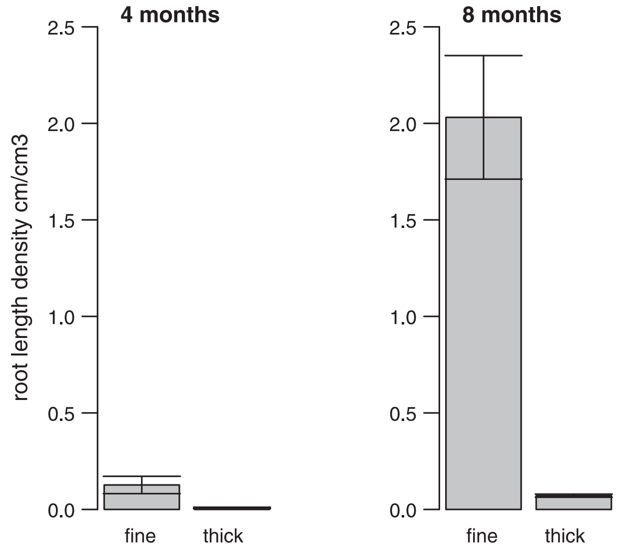

Figure 9. Average values of root length density for the fourth and eighth month of growth, divided in fine (≤2 mm) and thick (>2 mm) roots. Bars indicate the standard error. The scale is different than in Figure 8.

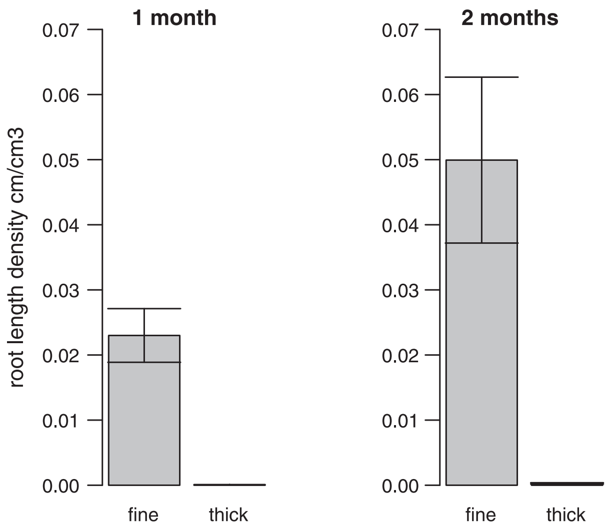

Figure 8. Average values of root length density for the first and second month of growth, divided in fine (≤2 mm) and thick (>2 mm) roots. Bars indicate the standard error.

length density with plant age, and this increase is huge in the 8-month-old alders. In this case we had an unexpected root development, which resulted in a constraining effect of the pot on the root system. The roots developed following the pot boundaries and enmeshed the bottom of the pots, resulting in a wrapping of the entire soil block.

We therefore excluded these treatments from the analysis, because of the fact that the roots were in this case a physical obstacle to the water flow due to the particular architecture they assumed because of the limitations exerted by the pot: hydraulic conductivity values were indeed extremely low for these treatments. Limiting the analysis to the other treatments where root systems were not constrained, we found an increase in permeability until a root length density of 0.1 cm/cm^3 and a decrease after this threshold (Figure 10). The increase in permeability with root length up to the threshold of 0.1 cm/cm^3 can be described by an exponential law (Figure 11), with $R^2 = 0.44$ (p-value = 0.0002).

Soil aggregate stability

The average values of soil aggregate stability range between 0.18 and 0.33 in control pots and between 0.26

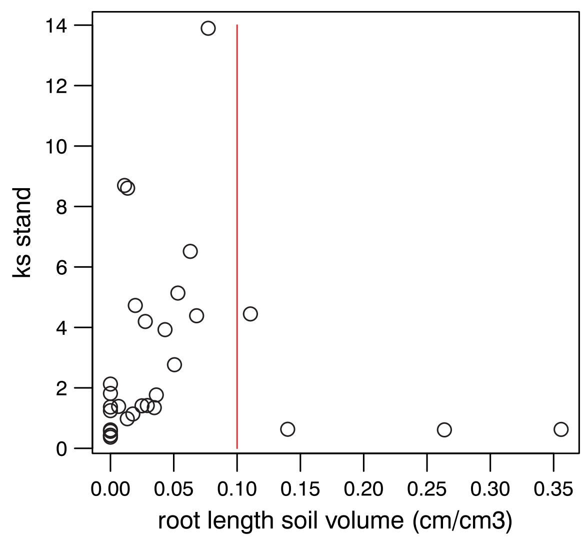

Figure 10. Normalized values of the whole soil layer k_s as function of root length density, excluding the 8-month-old planted pots. The red line indicates the root length density threshold.

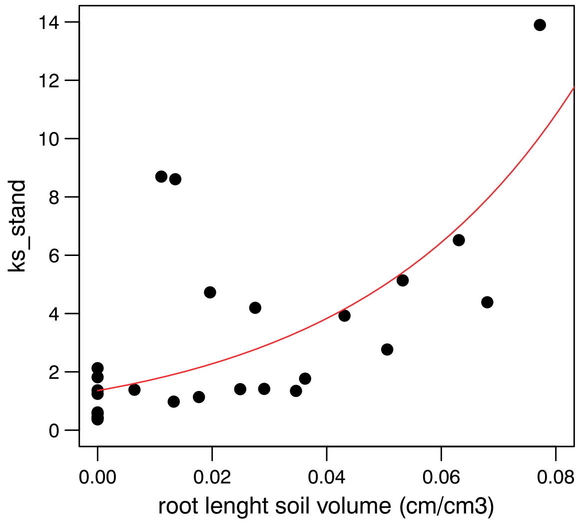

Figure 11. Normalized values of the whole soil layer k_s as function of root length density, up to the threshold of 0.1 cm/cm^3. Increase in normalized k_s as function of root length density can be described by an exponential law.

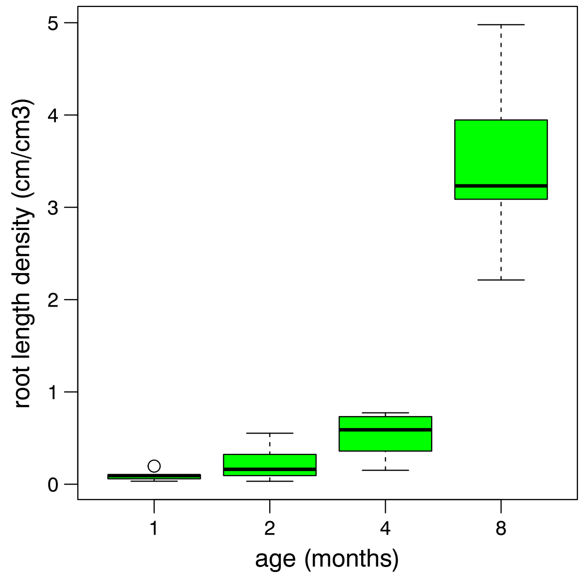

Figure 13. Root length density values found in the soil aggregate stability samples as function of the age of growth.

and 0.50 in planted pots (Table I). We obtained a quasi-constant value of stability of aggregates for the first 4 months of growth (Figure 12). We can observe a difference between planted and control pots only after 8 months of growth, and this difference is significant ($p = 0.002$). This corresponds also to a significant increase in the root length per soil volume in the soil aggregate stability samples (Figure 13). The root length per soil volume in the soil aggregate stability samples is positively correlated with soil aggregate stability, and we could establish a linear relationship between these two variables (Figure 14), with $R^2 = 0.38$ (p-value = 3.77e − 05).

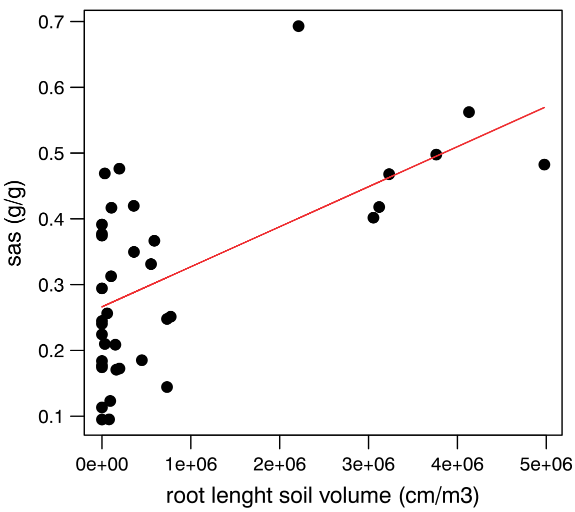

Figure 14. Linear relationship between the root length per soil volume in soil aggregate stability samples and soil aggregate stability.

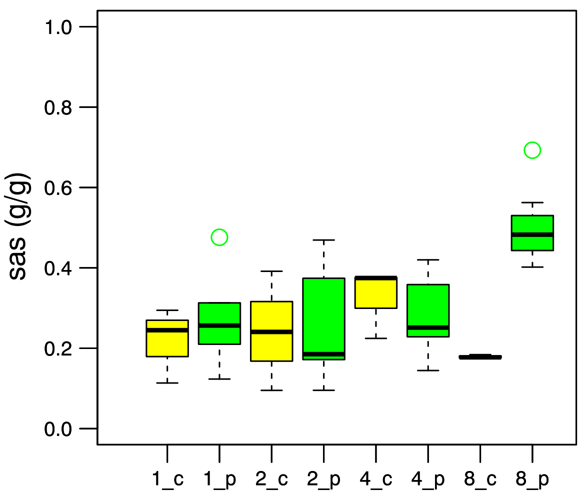

Figure 12. Soil aggregate stability values obtained for the different treatments; the numbers indicate the month of growth, c is control pot, and p is planted pot. Boxplot referring to planted pots are green; the ones referred to control pots are yellow.

Correlation between soil aggregate stability and permeability

We could not find a correlation between soil aggregate stability and saturated hydraulic conductivity values, even eliminating the data of the 8-month-old pots (Figure 15).

DISCUSSION

Uncertainty in saturated hydraulic conductivity determination

Saturated hydraulic conductivity is one of the most spatially variable soil characteristics (Fodor *et al.*, 2011). The measurement of k_s is difficult and always involves a high

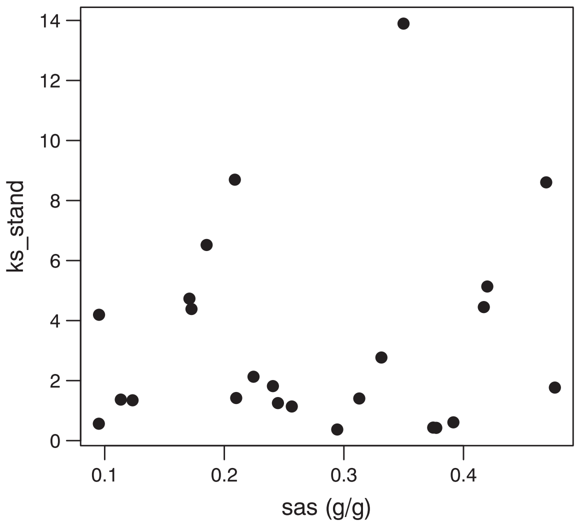

Figure 15. Normalized whole soil volume k_s values plotted as function of soil aggregate stability.

degree of uncertainty, depending on the scale (volume of the measured soil) and the technique used (Fodor *et al*., 2011; Ghimire *et al*., 2014).

In this work we adopted a 'pot scale' and correspondingly adapted to this scale the traditional falling head method usually applied to smaller laboratory samples (Bagarello and Iovino, 2010). This choice presents advantages as well as shortcomings that we want to discuss here. A laboratory experiment allows working under controlled conditions, limiting the variability which can be huge at the field scale. Our purpose was to apply exactly the same conditions to the bare and rooted soil in order to disentangle the effect of roots on the investigated soil properties. The 'pot scale' for the evaluation of the saturated hydraulic conductivity was chosen in order to apply the concept of Representative Elementary Volume (Bagarello and Iovino, 2010). The focus was the development of root systems, and the pot scale allows considering it as an entire system, overcoming problems traditionally related to laboratory measurements where small core samples are used and the root as well as the macropore network are 'cut' (Rienzner and Gandolfi, 2014). Several authors assessed that considering a bigger volume of soil results in more representative estimates of k_s values (Kumar *et al*., 2010; Fodor *et al*., 2011).

Li and Ghodrati (1994) used the same scale (column of soil) as in the present study in order to compare the preferential transport of nitrate with alfalfa and corn roots.

Nevertheless, this approach has some shortcomings, mainly because of the boundary conditions necessarily introduced with the use of pots, which can affect the flow of the water and also constrain the growth of the root systems (see next paragraph in the discussion). Concerning the first point, we could not establish the entity of the water flux along the boundaries of the pots, but as our main purpose was the comparison between the different treatments and the boundary conditions were the same in all the treatments, we think we can neglect this effect. Certainly, the data here presented have to be considered as laboratory data with certain boundary conditions that need to be verified in the field. Furthermore, it has to be underlined that only the soil fraction < 10 mm was used, and this of course affected the water flow in the soil. Nevertheless, the k_s values obtained for the control pots fall in the range reported in literature for the same soil type (Standard 670010b, Association of Swiss Road and Traffic Engineers), indicating that the results obtained can be considered reliable also from an absolute point of view. An exception is given by the first month control pots, where the obtained k_s values are higher. This can be ascribed to the fact that the pots were manually filled with soil and 1 month after the preparation the compaction process was still at a very early stage and the soil correspondingly loose.

When determining the surface k_s, a much smaller surface is explored with the mini disk infiltrometer and only a reduced portion of soil and root system are considered. We used values of the van Genuchten moisture retention parameters taken from literature, on the basis of the grain size distribution of our soil, and did not address the water retention curve of the soil. Clearly there is uncertainty in the values of these moisture retention parameters, and this can lead to further uncertainties in the determination of the k_s values, as Fodor *et al*. (2011) and Ronayne *et al*. (2012) demonstrated.

The values of surface k_s obtained with the minidisk infiltrometer are always smaller than the values of the whole soil volume k_s, and this difference increases (one order of magnitude) as the role of macropores created by roots becomes more important (Table I: 2-month planted pots and 4-month planted pots). This difference can be explained with the methodology adopted which excludes part of the macropores (tension infiltrometer) as well as with the different measurement scales (Ronayne *et al*., 2012).

Constraining effect of pots on root systems

Concerning the limitations of the plant growth because of the pot, the constraining effect on the root system became relevant only in the 8-month old plants. Under the light, temperature and fertilization conditions applied in the experiment, we had an average monthly growth of alder roots of 0.47 cm/cm^3 between the 4th and 8th month of growth. The use of bigger pots would have avoided the constraining effect on the roots system. Nevertheless, it has to be considered that the use of pots of bigger size would have made them almost impossible to handle because of the considerable weight, and would have required an excessive demand of infrastructure, e.g. a much larger climate chamber, a crane, etc. All these aspect must be taken into account when designing this type of experiment.

Effect of root development on hydraulic conductivity and aggregate stability

Our data show that surface k_s is improved by the development of a root system, already from the first stages of growth. This can be mainly ascribed to the increased roughness of soil surface because of the shallow root architecture of alder. It has to be underlined that Zhang's method used to evaluate k_s is particularly sensitive to the local heterogeneity of soil (Fodor *et al.*, 2011); therefore the increased soil roughness is likely to have a major role in explaining the obtained results.

The findings confirmed the importance of the establishment of a vegetation cover in respect of reducing run off and, therefore, soil erosion. From a soil bioengineering point of view it is important to underline that even in the first phase of colonization by vegetation the effect on surface water infiltration is important in comparison with bare soil.

Concerning the whole soil volume k_s, the normalized values are always higher in planted pots than in bare soil, demonstrating the positive effect of the root system development on soil permeability. Lange *et al.* (2009) found root length densities between 0.44 and 2.21 cm/cm^3 in the topsoil of a mixed Norway spruce-Silver fir forest stand, which corresponds to the values we obtained for the 4-month and 8-month old alders. In our study most of the alder roots were smaller than 2 mm in diameter, confirming the importance of the role of fine roots and mesopores (0.5–2 mm in diameter; Sidle *et al.*, 2001; Lange *et al.*, 2012) and even of root hairs (Bengough, 2012) in preferential flow paths and saturated flow.

In the case of the 8-month treatments the pots confined the roots, inducing an artificial root growth which heavily affected the saturated hydraulic conductivity results. In this case the geometry of roots acted as a physical limitation to the water flux.

Nevertheless, even excluding the 8-month grown alders, we have an increase in k_s with increasing root length density only until a certain threshold. Above a certain root length density the effect of roots resulted in a decrease of k_s, and this cannot be ascribed to the constraining mechanisms of the pots. From our data it is apparent that an increase in root length density does not necessarily correspond to an increase in soil permeability, which is in line with the results of Lange *et al.* (2009). Applying the rivulet approach, Lange *et al.* (2009) observed an increased thickness of the film of mobile water associated with lower root densities. They explained this phenomenon with the fact that lower root densities imply fewer pores. As a result, the potential contact area between mobile water and soil is reduced and the film thickness of mobile water increases, resulting in an acceleration of the water flux. Above a certain root density threshold the film became too thin, and the limit for the occurrence of preferential flow was reached.

Based on our results this root length density threshold value can be set at 0.1 cm/cm^3, which is an order of magnitude lower than the one reported by Lange *et al.* (2009) for forest soils. This divergence can be because of the different soil structures considered. A forest soil with a root length density of 1 cm/cm^3 has developed a more stable and complex soil structure than 4-month-old alders in pots. This is mainly because of the longer time period allowing the creation of different soil horizons, a considerable amount of organic matter incorporated in the soil and a high level of microbial activity. All this factors are reasonably expected to allow a better drainage even with higher root length densities. The value proposed in this work can be considered reliable for poor structured landslide soil which needs to be restored with vegetation.

On the other hand, we could appreciate an increase in soil aggregate stability only for root length densities higher than 2 cm/cm^3. It is important to stress that in this experiment no Mycorrhiza inoculum has been added to the roots, as this could significantly change the soil aggregate stability values, through better root growth as well as by the cementing effect of microbial polysaccharides (Graf and Frei, 2013).

The observed improvement in soil permeability can therefore be attributed exclusively to the formation of root channels, and not to an improvement in soil structure, which is apparent only at higher root densities. This highlights the capacity of the root system to improve soil drainage during a short period of time, even before contributing to improve the soil aggregate stability and therefore the structure of the soil. This is extremely important from a slope restoration point of view.

We obtained root length density values in the soil aggregate stability samples between 0.03 cm/cm^3 and 4.9 cm/cm^3: these values fall in the lower range reported by Bast *et al.* (2014), who found root length densities between 2.6 and 45.4 cm/cm^3 after the first vegetation period of an assortment of different species (alders, willows and shrub species) used to restore a slope. These values are, however, exceptionally high: in his review Bengough, 2012, reports values of root density up to 30 cm/cm^3. The values reported by Burri *et al.*, 2009, for a 25 years old revegetated site (stand dominated by *A. incana*) on the same moraine soil used in the present study are closer to the values we obtained in the pots, with an average root length density of $1.51 + -0.67$ cm/cm^3 for the upper ten centimetres of soil. Conclusively, alders grown under for one vegetation period under laboratory conditions can develop a comparable amount of roots as found for a naturally grown alder stand on a landslide slope, which proves the approach of combining laboratory experiments with field observation to be promising in this area of application (Graf *et al.*, 2014).

After 8 months of growth we obtained a mean soil aggregate stability value of 0.5, which is comparable to the one observed by Bast *et al.* (2014) after one vegetation period (respectively, 0.61 in non mycorrhized plots and 0.49 in mycorrhized plots). Concerning bare soil, we obtained mean values ranging between 0.18 and 0.33 depending on the 'age' of the soil, which is lower compared to 0.42 reported by Bast *et al.* (2014) and 0.38 reported by Burri *et al.* (2009) for control sites in the field. The explanation is based on different factors: in control sites in the field a small amount of roots and organic matter is always present, as well as soil biota (Graf *et al.*, 2014). Microorganisms and in particular fungi contribute to soil aggregation through chemical stabilization and the organic matter provides a cementing effect. All these processes did not take place in the laboratory samples, where the soil was oven dried and did not contain any organic matter or micro-organisms.

Correlation between soil aggregate stability and permeability

We were not able to find the expected correlation between soil aggregate stability and soil permeability. First and foremost this is probably because of a spatial scale issue: the two properties were measured on different sample sizes, and therefore are not directly comparable. Furthermore, there seems to be a temporal scale problem: the root length density required to improve the soil aggregate stability ($>2\,cm/cm^3$) is bigger than the threshold above which an increase in root development decreases soil permeability ($0.1\,cm/cm^3$). As already mentioned, it can be speculated that the short time duration of the experiment did not allow the creation of a well-developed and sufficiently stable soil structure. However, the macropore system developed by root growth seemed to be able to increase soil permeability during this short period where the soil structure was not modified enough to influence soil aggregate stability. An increase in soil aggregate stability could therefore be appreciated just as a consequence of a huge root development and of the activity of roots in enmeshing soil particles. If this process would have been accompanied by a development of soil structure, e.g. supported by micro-organisms, particularly mycorrhizal fungi, probably a minor root length density would have been required to improve the stability of soil aggregates. It has also to be considered that in this short time laboratory experiment the natural decomposition and incorporation of organic matter in the soil layer is virtually zero, so there is no organic carbon contribution to the soil structure. Rasse *et al.* (2000) found neither a correlation between soil aggregate stability and k_s, nor between soil aggregate stability and root number in their experiment with alfalfa roots. They suggest that aggregate stability is more affected by carbon source from root decomposition than by factors specific to root activities as the enmeshing of soil aggregates and enhanced wetting and drying cycles.

The results obtained in this work should be validated with observations coming from field bioengineering measures, where all the complex mechanisms of the soil biota can be taken into account; furthermore, the study can be extended to other plant species used in bioengineering measures, starting with laboratory experiments and then extending the research to the field scale.

CONCLUSIONS

The comparison of planted and bare soil of a pot experiment revealed that alder roots improve soil permeability.

Already after 2 months of growth under laboratory conditions we can appreciate a significant increase in soil permeability, both at the surface and at the soil volume level, because of an increased roughness of the soil and to a development of a macropore system, respectively.

Larger root densities do not necessarily correspond to higher permeability values. Based on our results, a threshold up to which root development improves soil permeability can be set at a root length density of $0.1\,cm/cm^3$. This value needs, however, to be verified in the field, where a more complex soil structure is expected. An increase in soil aggregate stability can be measured only after 8 months of growth, in correspondence of a significant increase in root length per soil volume ($>2\,cm/cm^3$). The lack of an obvious correlation between soil aggregate stability and soil permeability may partly be attributed to the experimental design and the associated scale issue. Further work is required to validate the obtained results with field data.

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