HOSTED BY

ELSEVIER

Original Research Article

Quantifying the contribution of the root system of alpine vegetation in the soil aggregate stability of moraine☆

CrossMark

Csilla Hudek[a,b,*], Silvia Stanchi[a], Michele D'Amico[a], Michele Freppaz[a]

[a] University of Torino, DISAFA (Department of Agricultural, Forest and Food Sciences), Largo Paolo Braccini, 2, Grugliasco 10095, TO, Italy
[b] Train2Move Fellowship, University of Torino, DISAFA (Department of Agricultural, Forest and Food Sciences), Largo Paolo Braccini, 2, Grugliasco 10095, TO, Italy

ARTICLE INFO

ABSTRACT

One fifth of the world's population is living in mountains or in their surrounding areas. This anthropogenic pressure continues to grow with the increasing number of settlements, especially in areas connected to touristic activities, such as the Italian Alps. The process of soil formation on high mountains is particularly slow and these soils are particularly vulnerable to soil degradation. In alpine regions, extreme meteorological events are increasingly frequent due to climate change, speeding up the process of soil degradation and increasing the number of severe erosion processes, shallow landslides and debris flows. Vegetation cover plays a crucial role in the stabilization of mountain soils thereby reducing the risk of natural hazards effecting downslope areas. Soil aggregate stability is one of the main soil properties that can be linked to soil loss processes. Soils developed on moraines in recently deglaciated areas typically have low levels of soil aggregation, and a limited or discontinuous vegetation cover making them more susceptible to degradation. However, soil structure can be influenced by the root system of the vegetation. Roots are actively involved in the formation of water-stable soil aggregation, increasing the stability of the soil and its nutrient content. In the present study, we aim to quantify the effect of the root system of alpine vegetation on the soil aggregate stability of the forefield of the Lys glacier, in the Aosta Valley (NW-Italy). This proglacial area provides the opportunity to study how the root system of ten pioneer alpine species from different successional stages can contribute to soil development and soil stabilization. To quantify the aggregate stability of root permeated soils, a modified wet sieving method was employed. The root length per soil volume of the different species was also determined and later correlated with the aggregate stability results. The results showed that soil aggregate stability was significantly increased by the presence of roots. The lowest soil aggregate stability was found with *Epilobium fleischeri* followed by *Minuartia recurva* and *Leucanthemopsis alpina*. The highest aggregate stability was found with the graminoid species. These results show a close relationship between the development of root systems of the studied species and soil aggregate stability, a factor which can be taken into consideration in order to improve the accuracy of existing susceptibility mapping for early warning and civilian protection.

1. Introduction

Soils provide a wide range of ecosystem services that we are highly dependent on i.e. life supporting, regulating, provisioning and cultural (Brevik et al., 2015; Keesstra et al., 2016; Vargas, Castro, & Ziadat, 2015). Soils developed on mountains are generally shallow, poorly developed and highly diversified (Food and Agriculture Organization of the United Nations [FAO], 2015a). Furthermore, soils above the tree line are repeatedly disturbed by freezing, mass wasting and erosion processes. In mountain regions such as the Italian Alps, the effect of climate change, that modifies the hydrological cycle of the mountain ecosystem (e.g. due to the increased frequency and intensity of rainfall patterns) along with increasing pressure from human activities, increases the frequency and intensity of natural hazards such as severe erosion processes, landslides and debris flows (Gobiet et al., 2014). One of the key priorities for authorities is human safety under threat from natural hazards that affect the population of the entire region.

Vegetation cover plays a crucial role in the stabilization of mountain soils through influencing both biotic and abiotic processes, thereby reducing the risk of natural hazards affecting downslope areas. Both the above- and belowground section of plants play a significant role in erosion control and slope stability (Cerdà, 1999; Chiaradia, Vergani, &

Bischetti, 2016; van Hall, Cammeraat, Keesstra, & Zorn, 2017; Zhao, Gao, Huang, Wang, Xu, 2016a). The aboveground section such as stems and leaves reduces the energy of raindrops and runoff, increases surface roughness and traps sediment as well as reducing the water content of the soil via transpiration (Cerdà, 1998b; Keesstra, 2007; Keesstra, Kondrlova, Czajka, & Seeger, 2012; Zhao, Gao, Huang, Wang, & Zhang, 2016b). The root system of the plant improves soil structure, increases the soil organic matter content, lowers pore water pressure and increases soil shear strength (Liu, Wang, Cai, Li, & Cheng, 2014).

Soil aggregate stability is an important soil quality indicator of soil resistance to breaking up. It influences water, gas and nutrient movements in the soil and gives indications regarding the organic matter content and biological activities within the soil (Amezketa, 1999; Cerdà, 2000; Gelaw, Singh, & Lal, 2015; Mamedov, Huang, Aliev, & Levy, 2016). Aggregate stability can also be used as an indicator of soil erodibility as well as soil crusting and is often used in erosion and slope stability studies (Bast, Wilcke, Graf, Lüscher, & Gärtner, 2014; Burri, Graf, & Boll, 2009; Cerdà, 1996; Graf & Frei, 2013; Pohl, Graf, Buttler, & Rixen, 2012; Pulido Moncada, Gabriels, Cornelis, & Lobo, 2015; Stanchi, Falsone, & Bonifacio, 2015; Stanchi, Freppaz, Godone, & Zanini, 2013). The contribution of the root system and its mycorrhiza symbiosis to stabilization of soil aggregates has been defined previously (e.g., Amezketa, 1999; Cerdà, 1998a; Graf & Frei, 2013; Rillig et al., 2015). Yet studies on glacier forefields or pioneer alpine species are rare (e.g. Nagelmuller et al., 2016; Pohl, Stroude, Buttler, & Rixen, 2011). As stabilizing agent, root-derived organic matter is present in all stages (transient, temporary and persistent) of aggregation depending on its organic degradation stage (Amezketa, 1999). As a transient binding agent (i.e. microbial and plant derived polysaccharides) roots byproducts can be easily and quickly attacked by microorganisms. As a temporary agent, the decomposition by microorganisms is more difficult, root-derived organic matter can bind soil particles and stabilize micro-aggregates. As a persistent agent (i.e. humified materials), root-derived organic matter can be protected in the long term from decomposition by establishing joints with the soil mineral phase. (Amezketa, 1999; Kögel-Knabner & Amelung, 2014). Improving and sustaining soil aggregate stability in the long term would be desirable in mountainous areas to improve soil quality and minimize land degradation.

In freshly exposed moraine, soils typically have low levels of soil aggregation and vegetation cover as the soil conditions provide an unfavourable environment for plants to survive and thrive, thereby making the soil more susceptible to degradation (D'Amico, Freppaz, Filippa, & Zanini, 2014). Such harsh environments present a constant challenge for vegetation. Still, there are a number of plant species that are able to survive and adapt to these conditions and bring greater stability to their environment. An increased soil stability in high elevation mountain sites can secure the safety of its catchment areas. Since roots are actively involved in the formation of water-stable soil aggregation and increase the stability of the soil and its nutrient content, we were interested in quantifying the degree to which pioneer species from a freshly exposed moraine can contribute to soil aggregation through their root system. We were also interested in identifying root traits of the studied species that could be responsible for the increase in soil aggregation as studies on the root system of pioneer alpine vegetation is rare.

The overall aim of the present study was therefore to quantify and compare the contribution of the root systems of a variety of pioneer alpine species to the soil aggregate stability of a young moraine.

2. Materials and methods

2.1. Study area

The study area was located in the Lys Glacier forefield, in the Aosta Valley region, North West Italy (Fig. 1). The entire proglacial area lies between 1990 m and 2480 m a.s.l. The glacial till was deposited on a bedrock of granitic gneiss and paragneiss belonging to the Monte Rosa nappe (D'Amico et al., 2014) and composed of the same rock types, with small amounts of mafic rocks.

The selected moraine sector for the study site (25×25 m) lies above the present-day treeline, at 2350 m a.s.l. (D'Amico et al., 2014) with a south facing aspect (45°53′06″N; 7°48′58″E). The till deposited between 1950 and 2004 was selected for root system sampling. The soil is classified as Skeletic Eutric Regosol (FAO, 2015b) with a loamy sand texture and a high level of stoniness (Table 1) (D'Amico et al., 2014). The soil moisture regime is udic (Soil Survey Staff, 2010) with a mean annual rainfall of 1200 mm without any dry season (alpine subatlantic climate). The mean annual air temperature is −1 °C at 2400 m a.s.l., while the average winter temperature is below −4 °C (Mercalli, 2003). Vegetation cover is patchy, consisting of early, mid, late successional and ubiquitous alpine pioneer species. A detailed vegetation survey of the moraine can be found in D'Amico et al. (2014).

2.2. Soil and plant sampling and analysis

The 10 most dominant species of the forefield were selected (Table 2): three early successional (*Epilobium fleischeri* Hochst., *Trisetum distichophyllum* (Vill.) P.Beauve., *Trifolium pallescens* Schreb.), two mid successional, (*Luzula spicata* (L.) DC.,*Silene exscap* All.), two late successional (*Minuartia recurva* (All.) Schinz and Thell., *Festuca halleri* All.) and three ubiquitous species (*Poa laxa* Haenke, *Salix helvetica* Vill., *Leucanthemopsis alpina* (L.) Heyw). Sample collection was carried out between July and August 2015 by excavating 60 soil columns, containing an individual from the 10 studied species, with 6 replications for each species. Small individuals with no apparent neighbouring plants were excavated using a trowel. Due to the extensive stoniness of the till, direct coring was not possible. Intact soil columns (volume 350–450 cm^3) containing the root system of the individual plants were removed from the till and placed in plastic containers, securing the stability of the block and preserving the water content of the soil during transport. In the laboratory, all samples were stored in their individual containers at 3.5 C° until measurements began (Bast, Wilcke, Graf, Lüscher, & Gärtner, 2015).

The length and the weight of all soil columns were measured before the soil aggregate stability test was performed. To quantify the aggregate stability of the soil permeated by roots, a modified wet sieving method was employed (Burri et al., 2009; Frei, 2009) (Fig. 2). This method was specifically designed to test the effectiveness of the vegetation on soil aggregate stability of coarse-grained and skeleton-rich soils where the rock fragments of the soil is > 50% (Bast et al., 2015; Burri et al., 2009;). This is an easier and quicker method to apply compared to traditional techniques and has already been effectively used in a number of studies in the Swiss Alps (Bast et al., 2015; Burri et al., 2009; Frei, 2009; Graf et al., 2015).

Each column was placed on a 20 mm mesh sieve in a transparent container. The container was steadily filled with water over 45 s, covering the entire soil column which remained underwater for a further 5 min. The water level was then steadily reduced over 45 s. The soil and the root system remaining on the 20 mm sieve was placed into a container containing the stones larger than 20 mm, and the soil, which passed through the sieve, was placed in a separate container. The root systems of the plants were carefully cleaned of the remaining soil, placed into a 15% ethanol solution, and stored at 3.5 C° until further testing. The separated soil material was allowed to settle before being collected and dried at 105 C° for 24 h. Stones larger than 20 mm were separated from the soil.

To calculate the soil aggregate stability permeated by roots Eq. (1) was used:

$$\text{agg} = (m_{20} - m_{stone})/(m_{total} - m_{stone}) \quad [\text{g g}^{-1}] \tag{1}$$
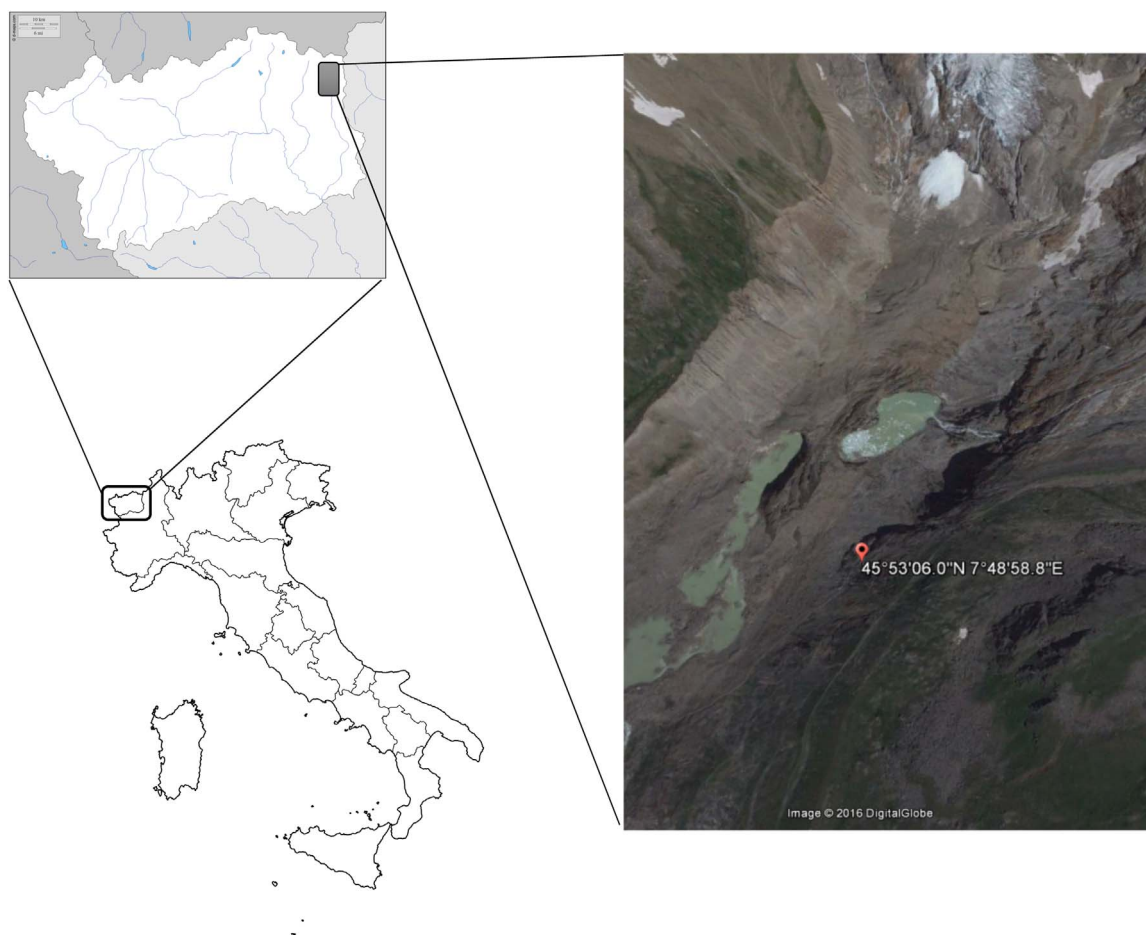
Fig. 1. Map of the study site placed in the forefield of the Lys Glacier in Valle d'Aosta in the NW of Italian Alps.

Table 1
Morphological and chemical properties of soil at the study site (data taken from D'Amico et al., 2014).

DepositionYear	Horizon	Depth(cm)	Munsell color (moist)	Sand(%)	Clay(%)	Structure (cementation)	Consistence (moist)	Rock fragments (volume, %)	pH	C(%)	Feo(g/kg)	Alo(g/kg)
2004	C1	0–8	5Y5.5/3	69.1	2.1	PL3/AB	loose	60%	6.6	0.04	0.87	0.21
	C2	8–47	5Y6/1	80.3	0.8	PL3/AB	loose	60%	6.8	0.00	0.80	0.18

PL=platy; AB=absent; 3=medium size class of the soil structure

Table 2
The selected pioneer plant species of the forefield of Lys Glacier according to their lifeforms, succession and family.

Species	Life form	Succession	Family
Epilobium fleischeri Hochst.	Forb	Early	Omagraceae
Trisetum distichophyllum (Vill.) P.Beauve.	Graminoid	Early	Poaceae
Trifolium pallescens Schreb.	Forb	Early	Fabaceae
Luzula spicata (L.) DC.	Graminoid	Mid	Juncaceae
Silene exscapa All.	Forb	Mid	Caryophyllaceae
Minuartia recurva (All.) Schinz and Thell.	Forb	Late	Caryophyllaceae
Festuca halleri All.	Graminoid	Late	Poaceae
Poa laxa Haenke	Graminoid	Ubiquitous	Poaceae
Salix helvetica Vill.	Dwarf shrub	Ubiquitous	Salicaceae
Leucanthemopsis alpine (L.) Heyw.	Forb	Ubiquitous	Asteraceae

agg=soil aggregate stability $[g\ g^{-1}]$
m_{20}=dry weight of the soil material remaining on the sieve [g]
m_{stone}=dry weight of stones with a diameter greater than 20 mm [g]
m_{total}=dry weight of the entire soil sample [g]

All soil samples were then sieved (2 and 0.5 mm mesh) and analyzed in the laboratory to determine soil pH using a 1:2.5 soil:water suspension, total organic carbon (TOC) and total nitrogen (TN) by dry combustion with an elemental analyzer (CE Instruments NA2100, Rodano, Italy) and available phosphorus (P) by using the Olsen extraction method, extracted with NaHCO₃. The soil water content of the samples was determined gravimetrically.

Root traits such as root diameter and total root length were determined by scanning the root samples with a flatbed scanner and analyzing the images with the WinRHIZO image analysis program (WinRHIZO™ 2013e). Root length density (RLD) was calculated by dividing the mean root length by the volume of the soil column.
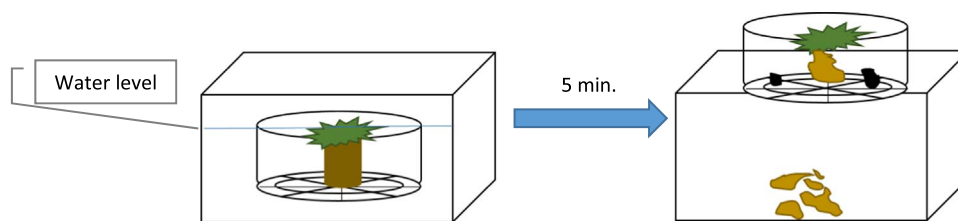
Fig. 2. Sketch of the soil aggregate stability test performed with the modified wet sieving method.

2.3. Statistical analysis

The differences in the measured soil (soil aggregate stability, pH, TOC, TN and available P) and root properties (RLD, mean root diameter) among the studied plant species were calculated with one-way ANOVA. Due to small group sizes, the Welch test was run in case the homogeneity of variances was violated. In cases when significant differences were found between the groups, the Tukey post hoc test was run to detect where the differences occurred between the groups.

To understand the relationship between the aggregate stability and root length density of the species the measured soil and root data were plotted and a robust simple linear regression model was fitted. Log transformation (log_{10}) on the RLD data and square root (sqrt(y)) transformation on the soil aggregate stability data was carried out to help better examine the distribution.

All statistical analysis was carried out with the statistical software SPSS Statistics 22.

3. Results

3.1. Soil analysis

A total of 47 suitable, undamaged samples were assessed and compared for soil and root properties. The measured soil and root properties from the top 10 cm of the soil layer are presented in Table 3. The soil at the study site had a sand content of 82.3% and a clay content of 1.1%, with a rock fragment content of 60%.

The chemical analysis of the samples revealed a slightly acidic soil (5.8–6.7 pH) with the amount of TN and TOC ranging from 0.002 to 0.017 g kg^{-1} and from 0.018 to 0.217 g kg^{-1} respectively. The available phosphorus was between 1.3 and 4.7 mg g^{-1}.

No significant difference was found in the soil chemical properties between the studied samples (TN, F (9, 50) =1.098, p=0.381; TOC, F(9, 50)=0.963, p=0.481; P, F (9, 50)=0.984, p=0.482).

Results showed that the root systems of all studied plant species significantly increased the aggregate stability of the soil compared to the soil without roots which showed an almost total lack of aggregate stability. However, there was a great variability among the studied species (40 g g^{-1}– 93 g g^{-1}) (Fig. 3). The lowest soil aggregate stability was found with *E. fleischeri*, *L. alpine* and *M. recurva* (40 g g^{-1},
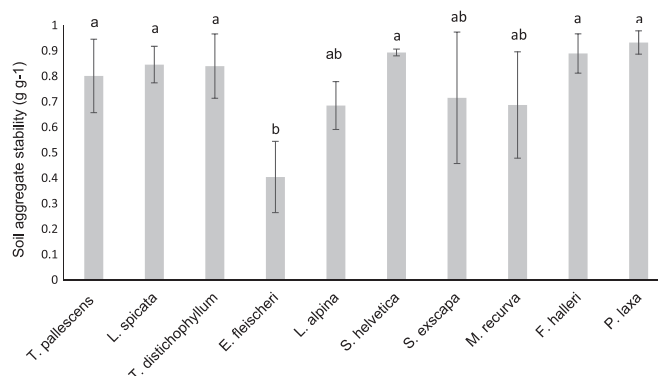

Fig. 3. Mean aggregate stability of the soil surrounding the root system of the ten pioneer alpine species considered in this study. Error bars indicate the standard errors of the mean.

68 g g^{-1} and 68 g g^{-1} respectively). The highest soil aggregate stability was recorded among the graminoid and shrub species *P. laxa*, *S. helvetica*, *F. halleri*, *L. spicata* and *T. distichophyllum* (93 g g^{-1}, 89 g g^{-1}, 88 g g^{-1}, 84 g g^{-1} and 83 g g^{-1} respectively).

A one-way ANOVA was conducted to compare the effect of the different plant species on soil aggregate stability. The results showed significant differences at the p < 0.05 level in aggregate stability among the 10 studied species F (9, 37) =4.002, p < 0.001. The actual difference in mean scores between the groups was large. The effect size, calculated using eta squared, was 0.49. Post-hoc comparisons using the Tukey HSD test indicated that aggregate stability differed significantly among *E. fleischeri* and six other species: *T. pallescens, L. spicata, T. distichophyllum, S. helvetica, F. halleri* and *P. laxa* (Table 4) (p < 0.05). There was no statistically significant difference in soil aggregate stability between the other species. Specifically, our results suggest that among the ten studied species, only *E. fleischeri's* root system provides a significantly lower level of soil aggregation when compared to the majority of the studied species (graminoid or shrub species). However, in the case of other forbs such as *S. exscapa, M. recurva* and *L. alpina, E. fleischeri* did not appear to show a significantly lower level of soil aggregate stability.

Table 3
Measured mean (± sd) soil and root properties of the ten studies species from the moraine of the Lys Glacier.

Species	n	Soil water content (%)	pH	P (mg g^{-1})	N (g kg^{-1})	C (g kg^{-1})	Average root diameter (mm)	Mean soil aggregate stability (g g^{-1})	Mean root length density (cm cm^{-3})
Epilobium fleischeri	3	2.1 ± 1.1	6.7	1.3 ± 0.4	0.002 ± 0.000	0.018 ± 0.004	0.17	0.40 ± 0.13[b]	9.3 ± 9.4[c]
Trisetum distichophyllum	5	6.9 ± 4.1	6.1	4.7 ± 1.9	0.004 ± 0.000	0.053 ± 0.000	0.21	0.83 ± 0.12[a]	85 ± 14[ab]
Trifolium pallescens	6	5.6 ± 2.6	6.4	2.8 ± 0.2	0.009 ± 0.006	0.112 ± 0.106	0.30	0.80 ± 0.14[a]	33 ± 22[abc]
Luzula spicata	5	8.5 ± 3.3	6.1	1.3 ± 0.9	0.004 ± 0.000	0.028 ± 0.004	0.16	0.84 ± 0.06[a]	81 ± 28[a]
Silene exscapa	6	6.5 ± 3.5	6.5	3.0 ± 1.5	0.017 ± 0.001	0.192 ± 0.009	0.24	0.71 ± 0.25[ab]	49 ± 15[abc]
Minuartia recurva	4	4.6 ± 4.8	6.1	4.3 ± 2.1	0.006 ± 0.003	0.085 ± 0.068	0.29	0.68 ± 0.20[ab]	29 ± 14[b]
Festuca halleri	6	4.4 ± 0.0	6.5	2.6 ± 1.1	0.007 ± 0.000	0.072 ± 0.006	0.26	0.88 ± 0.07[a]	59 ± 10[ab]
Poa laxa	2	5.7 ± 4.0	6.4	4.1 ± 2.7	0.007 ± 0.000	0.068 ± 0.002	0.31	0.93 ± 0.04[a]	47 ± 3.5[abc]
Salix helvetica	4	9.2 ± 4.0	6.4	2.1 ± 1.6	0.004 ± 0.000	0.043 ± 0.007	0.28	0.89 ± 0.01[a]	67 ± 21[ab]
Leucanthemopsis alpina	6	6.1 ± 2.9	5.8	2.1 ± 1.0	0.016 ± 0.000	0.217 ± 0.007	0.26	0.68 ± 0.09[ab]	53 ± 34[abc]

n is the number of individuals tested, values are means with s.d.

Table 4
ANOVA table with multiple comparisons of aggregate stability among the different plant species.

Dependent Variable: Soil aggregate stability (g g^{-1})

Tukey HSD

(I) Species	(J) Species	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
E. fleischeri	T. pallescens	−0.3968[*]	0.1018	**0.013**	−0.7393	−0.0542
	L. spicata	−0.4414[*]	0.1052	**0.006**	−0.7952	−0.0875
	T. distichophyllum	−0.4355[*]	0.1052	**0.007**	−0.7893	−0.0816
	L. alpina	−0.2804	0.1018	0.190	−0.6230	0.0621
	S. helvetica	−0.4890[*]	0.1100	**0.003**	−0.8590	−0.1189
	S. exscapa	−0.3109	0.1018	0.102	−0.6535	0.0316
	M. recurva	−0.2828	0.1100	0.267	−0.6529	0.0871
	F. halleri	−0.4850[*]	0.1018	**0.001**	−0.8276	−0.1425
	P. laxa	−0.5281[*]	0.1315	**0.009**	−0.9703	−0.0858

[*] The mean difference is significant at the 0.05 level. Significant differences are also shown in **bold**

3.2. Root analysis

The mean root diameter results showed no significant differences between the species F (9, 22)=1.78, p=0.129 values The results ranged between 0.16 mm and 0.31 mm. The lowest mean root diameter was recorded for *L. spicata* and *E. fleischeri* (0.16 mm and 0.17 mm respectively) and the highest for *P. laxa* and *T. pallescens* (0.31 mm and 0.30 mm respectively).

Root length density showed a great variability among the studied species (9.3–85 cm cm^{-3}) (Fig. 4). The lowest density was recorded for *E. fleisheri*, *M. recurva* and *T. pallescens*, with 9.3, 29 and 33 cm cm^{-3} respectively and the highest was recorded for *T. distichophyllum* and *L. spicata* with 85 and 81 cm cm^{-3} respectively. A one-way ANOVA was conducted to compare root length density among the different plant species. There was a significant difference at the p < 0.05 level in root length density among the species F (9, 22) =4.78, p < 0.001. The actual difference in mean scores between the groups was large. The effect size, calculated using eta squared, was 0.66. Post-hoc comparisons using the Tukey HSD test indicated that root length density differed significantly (Table 5) (p < 0.05) between *E. fleisheri* and *L. spicata*, *T. distichophyllum*, *S. helvetica* and *F. halleri* as well as between *M. recurva* and *L. spicata*. There was no statistically significant difference in root length density between the other species. However, the difference was close to significant between *T. pallescens* and *L. spicata* as well as between *M. recurva* and *T. distichophyllum*. Specifically, the results suggest that out of the ten studied species, only *E. fleisheri's* and *M. recurva's* root system resulted in a significantly lower root length density compared to the majority of the studied plants. It should be noted that in most but not all cases higher root length density was found among graminoid or shrub species.
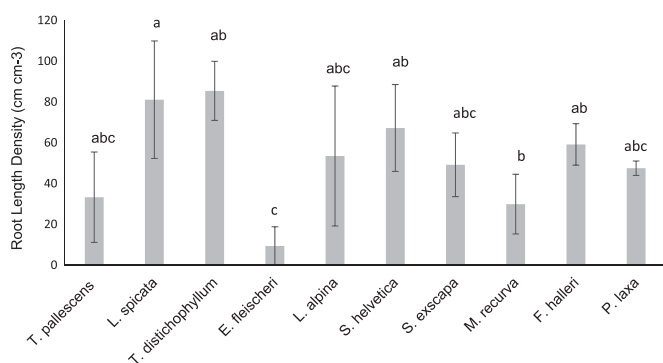
Fig. 4. Mean root length density of the ten pioneer alpine species with error bars indicating the standard error of the mean.

Fig. 5 shows a simple linear regression where aggregate stability shows a positive correlation with root length density (r^2=0.73) suggesting that higher RLD results in a higher aggregate stability.

4. Discussion

4.1. Soil aggregate stability

The measured soil aggregate stability showed significantly higher values for all studied species compared to the soil without roots (i.e. glacial till). These results can be divided into three groups: a) plants providing high (graminoid and shrub species); b) intermediate (forbs) and c) low soil aggregate stability (*E. fleischeri*). The higher aggregate stability results (Fig. 3.) provided by the graminoid and shrub species compared to forbs, is in line with the findings of Pérès et al. (2013). These findings could be related to root morphology, as monocotyledonous species, and in particular graminoids, generally have a dense fibrous root system with greater biomass than forbs (Amezketa, 1999). The lowest aggregate stability were measured for *E. fleischeri* compared to the graminoid and shrub species. These results can also be linked to the difference in root morphology as the RLD results for *E. fleischeri* showed a significantly lower value compared to the other studied species (Table 4). In addition, its lateral roots are positioned in deeper soil horizons (Hudek et al., under revision) providing the plant a greater resistance to uprooting (Stokes, Atger, Bengough, Fourcaud, & Sidle, 2009) in disturbed soils but also leaving the upper soil horizon vulnerable to degradation. The soil chemical analysis showed no significant differences among the studied species, (Table 3) signifying that the difference in soil aggregate stability between the considered species cannot be related to the difference in the amount of available P, TOC or TN in the soil of the study site. Pohl, Alig, Körner, and Rixen (2009) also found no correlation between soil organic matter content and aggregate stability of a soil permeated by the roots of a selection of alpine species on a machine graded ski slope above the timberline. In different plant communities in the Mediterranean ecosystem however, Erktan et al. (2016) found soil organic carbon content to be the main factor in soil aggregate stability differentiation. Pérès et al. (2013) and Stanchi at al. (2015) found soil organic carbon content in grasslands an important explanatory variable in differences in soil aggregate stability measures. These contrasting results can be explained by the fact that both in the present study and on the machine graded ski slope, soils were young and organic matter evolution was generally limited (Pohl et al., 2009) compared to the more developed soils in the study of Erktan et al. (2016), Pérès et al. (2013) and Stanchi at al. (2015).

Table 5

ANOVA table with multiple comparisons of root length density among the different plant species.

Dependent Variable: Root Length Density (cm cm^{-3})

Tukey HSD

(I) Species	(J) Species	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
T. pallescens	L. spicata	−47.7584	14.5190	0.078	−98.6514	3.1344
E. fleischeri	L. spicata	−71.6803[*]	14.5190	**0.002**	−122.5732	−20.7874
	T. distichophyllum	−76.0172[*]	17.3536	**0.007**	−136.8459	−15.1886
	S. helvetica	−58.8807[*]	14.5190	**0.015**	−109.7737	−7.9878
	F. halleri	−49.7578[*]	13.8828	**0.042**	−98.4208	−1.0950
M. recurva	L. spicata	−51.7247[*]	13.4420	**0.024**	−98.8424	−4.6070
	T. distichophyllum	−56.0616	16.4630	0.062	−113.7688	1.6455

[*] The mean difference is significant at the 0.05 level. Significant differences are also shown in **bold.**
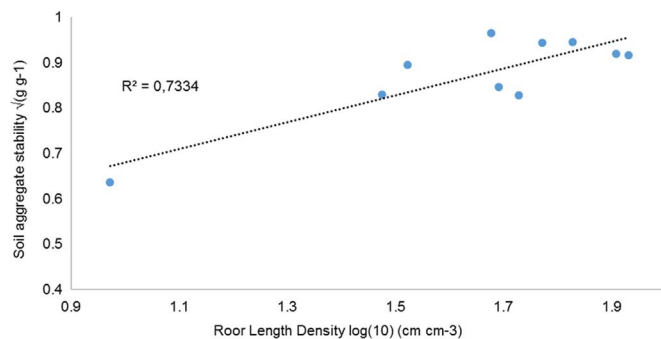
Fig. 5. Relationship between aggregate stability and root length density of the ten pioneer alpine species.

4.2. Root length density

The strong correlation between RLD and aggregate stability (Fig. 5.) was apparent in the present study, which is in line with the findings of Vergani and Graf (2015). As the soil chemical analysis showed no significant differences among the samples, it can also be concluded that it had no effect on the difference in RLD among the studied species. This suggests that the significant differences in RLD (Table 3) can be related to the fact that root morphology is largely controlled by genetic characteristics (Gray & Sotir, 1996). Root systems also alter with age (Stokes et al., 2009) and also alter due to competing roots from neighbouring plants (Tasser & Tappeiner, 2005; Wahid, 2001) which would affect RLD. Although the age of the sampled plants was not identified in the present study, plants at similar stages of growth without neighbouring plants were sampled. The symbiotic effect on plant-fungus systems also has to be taken into consideration as it has already been shown to have a significant altering effect on root system development, as it also has on RLD (Bast et al., 2014; Graf & Frei, 2013; Tisdall, 1991). While the present study did not quantify the effect of mycorrhizal symbiosis on the aggregate stability of the soil, various studies have shown that mycorrhizal fungi promotes root growth (Graf & Frei, 2013; Smith & Read, 2008) and increases the water and nutrient uptake of the plant (Smith & Read, 2008). Therefore, the presence of mycorrhizal symbiosis on pioneer alpine species in soils developed on recently deglaciated moraine sites is crucial even though Bast et al. (2014) pointed out that sparse vegetation indicates a low mycorrhizal diversity.

4.3. Root diameter

Previous studies have highlighted that root diameter can also be a factor in explaining variations in aggregate stability as in general, very fine roots (< 0.5 mm) and fine roots (0,5−1 mm) can significantly contribute to a higher soil aggregate stability (Erktan et al., 2016; Pohl et al., 2009) than thicker roots. Rillig and Mummey (2006) attribute this to a greater presence of mycorrhizal fungi interaction with roots. In the present study, it was not possible to make any correlation between aggregate stability and average root diameter since there was no significant difference among the studied species in their average root diameter. However, it can be said that in the present study the high RLD along with very fine mean root diameters can be an additional factor in explaining the high level of soil aggregate stability among the studied species (Amadine et al., 2016; Pohl et al., 2009).

The results did not reveal any connection between soil aggregate stability and the successional stages of the studied plant species. This also reinforces the theory that any degree of aggregate stability in the soil can be mainly attributed to the presence of roots and their mechanical binding of soil particles. It also has to be recognized that due to the quick turnover of very fine roots that supply organic residue and supporting microbial communities as well as discharging poly-valent cations (Amezketa, 1999), the stability of soil aggregates increases.

5. Conclusions

The present study provided unique quantitative data on the effect of ten pioneer alpine plant species on the stability of a soil, developed on a recently deglaciated moraine site by measuring the aggregate stability of soil in the presence of roots. This was with the view to encourage the use of indigenous species as an effective rehabilitative tool for degraded mountain ecosystems.

On its own, soil on recently deglaciated moraine shows little to no aggregate stability. The protective and recuperative role that indigenous plant root systems play in mountain areas has been shown by the present study to be a vital influencing factor on increasing soil aggregate stability. The study also revealed significant differences in soil aggregate stability as well as RLD among the studied species. Moreover the aggregate stability and root length density was found to be positively correlated.

These results can contribute to identifying the processes of soil stabilization in areas prone to soil erosion processes (e.g. recently deglaciated areas). Due to the effects of climate change, the prevalence of such surfaces is increasing in alpine regions which contributes to greater amounts of potentially unstable soil material.

Larry York for the access to and support with the image analysing software and Michele Lonati for his help on the identification of graminoid species.

References

Amezketa, E. (1999). Soil aggregate stability: a review. *Journal of Sustainable Agriculture*, 14, 83–151.

Bast, A., Wilcke, W., Graf, F., Lüscher, P., & Gärtner, H. (2014). The use of mycorrhiza for eco-engineering measures in steep alpine environments: Effects on soil aggregate formation and fine-root development. *Earth Surface Processes Landforms*, 39, 1753–1763.

Bast, A., Wilcke, W., Graf, F., Lüscher, P., & Gärtner, H. (2015). A simplified and rapid technique to determine an aggregate stability coefficient in coarse grained soils. *Catena*, 127, 170–176.

Brevik, E. C., Cerdà, A., Mataix-Solera, J., Pereg, L., Quinton, J. N., Six, J., & Van Oost, K. (2015). The interdisciplinary nature of SOIL. *SOIL*, 1, 117–129.

Burri, K., Graf, F., & Boll, A. (2009). Revegetation measures improve soil aggregate stability: A case study of a landslide area in Central Switzerland. *Forest, Snow and Landscape Research*, 82, 45–60.

Cerdà, A. (1996). Soil aggregate stability in three mediterranean environments. *Soil Technology*, 9, 133–140.

Cerdà, A. (1998). Soil aggregate stability under different mediterranean vegetation types. *Catena*, 32, 73–86.

Cerdà, A. (1998). The influence of geomorphological position and vegetation cover on the erosional and hydrological processes on a mediterranean hillslope. *Hydrological Processes*, 12, 661–671.

Cerdà, A. (1999). Parent material and vegetation affect soil erosion in Eastern Spain. *Soil Science Society of America Journal*, 63, 362–368.

Cerdà, A. (2000). Aggregate stability against water forces under different climates on agriculture land and scrubland in Southern Bolivia. *Soil and Tillage Research*, 57, 159–166.

Chiaradia, E. A., Vergani, C., & Bischetti, G. B. (2016). Evaluation of the effects of three European forest types on slope stability by field and probabilistic analyses and their implications for forest management. *Forest Ecology and Management*, 370, 114–129.

D'Amico, M. E., Freppaz, M., Filippa, G., & Zanini, E. (2014). Vegetation influence on soil formation rate in a proglacialchronosequence (Lys Glacier, NW Italian Alps). *Catena*, 113, 122–137.

Erktan, A., Cécillon, L., Graf, F., Roumet, C., Legout, C., & Rey, F. (2016). Increase in soil aggregate stability along a Mediterranean successional gradient in severely eroded gully bed ecosystems: Combined effects of soil, root traits and plant community characteristics. *Plant Soil*, 398, 121–137.

Food and Agriculture Organization of the United Nations, (2015a). Understanding Mountain Soils: A Contribution from mountain areas to the International Year of Soils 2015 In R. Romeo, A. Vita, S. Manuelli, E. Zanini, M. Freppaz, & S. Stanchi (Eds.), Rome, Italy.

Food and Agriculture Organization of the United Nations (2015b). World reference base for soil resources 2014: International soil classification system for naming soils and creating legends for soil maps. Rome, Italy.

Frei, M. (2009). *Validation of a new approach to determine vegetation effects on superficial soil movements* Zürich: Swiss Federal Institute of Technology, 203.

Gelaw, A. M., Singh, B. R., & Lal, R. (2015). Organic carbon and nitrogen associated with soil aggregates and particle sizes under different land uses in Tigray, Northern Ethiopia. *Land Degradation and Development*, 26, 690–700.

Gobiet, A., Kotlarski, S., Beniston, M., Heinrich, G., Rajczak, J., & Stoffel, M. (2014). 21st Century climate change in the European Alps — a review. *Science of the Total Environment*, 493, 1138–1151.

Graf, F., & Frei, M. (2013). Soil aggregate stability related to soil density, root length, and mycorrhiza using site-specific Alnus ncana and Melanogaster variegatuss. l. *Ecological Engineering*, 57, 314–323.

Gray, D. H., & Sotir, R. B. (1996). *Biotechnical and soil bioengineering slope stabilization. A practical guide for erosion control* New York: Wiley, John Sons, 1–105.

Keesstra, S. D. (2007). Impact of natural reforestation on floodplain sedimentation in the Dragonja basin, SW Slovenia. *Earth Surface Processes and Landforms*, 32, 49–65.

Keesstra, S. D., Kondrlova, E., Czajka, A., & Seeger, M. (2012). Assessment of the impact of riparian and channel vegetation on water and sediment retardation using a catchment and channel scale model. *Netherland Journal for Geosciences*, 91, 245–256.

Keesstra, S. D., Bouma, J., Wallinga, J., Tittonell, P., Smith, P., Cerdà, A., & Fresco, L. O. (2016). The significance of soils and soil science towards realization of the United Nations Sustainable Development Goals. *SOIL*, 2, 111–128.

Kögel-Knabner, I., & Amelung, W. (2014). Dynamics, chemistry, and preservation of organic matter in soils. In reference module in earth systems and environmental sciences treatise on geochemistry (Second Edition). Organic geochemistry, 12, 157–215.

Liu, Y. J., Wang, T. W., Cai, C. F., Li, Z. X., & Cheng, D. B. (2014). Effects of vegetation on runoff generation, sediment yield and soil shearstrength on road-side slopes under a simulation rainfall test in the Three Gorges Reservoir Area, China. *Science of the Total Environment*, 485, 93–102.

Mamedov, A. I., Huang, C.-H., Aliev, F. A., & Levy, G. J. (2016). Aggregate stability and water retention near saturation characteristics as affected by soil texture, aggregate size and polyacrylamide application. *Land Degradation and Development*. http://dx.doi.org/10.1002/ldr.2509.

Mercalli, L. (2003). *Atlante climatic della Valle d'Aosta* Torino: Societa Meteorologica Italia, 405.

Nagelmuller, S., Hiltbrunner, E., & Korner, C. (2016). Critically low soil temperatures for root growth and root morphology in three alpine plant species. *Alpine Botany*, 126, 11–21.

Pérès, G., Cluzeau, D., Menasseri, S., Soussana, J. F., Bessler, H., Engels, C., & Eisenhauer, N. (2013). Mechanisms linking plant community properties to soil aggregate stability in an experimental grassland plant diversity gradient. *Plant Soil*, 373, 285–299.

Pohl, M., Alig, D., Körner, C., & Rixen, C. (2009). Higher plant diversity enhances soil stability in disturbed alpine ecosystems. *Plant Soil*, 324, 91–102.

Pohl, M., Stroude, R., Buttler, A., & Rixen, C. (2011). Functional traits and root morphology of alpine plants. *Annals of Botany*, 108, 537–545.

Pohl, M., Graf, F., Buttler, A., & Rixen, C. (2012). The relationship between plant species richness and soil aggregate stability can depend on disturbance. *Plant Soil*, 355, 87–102.

Pulido Moncada, M., Gabriels, D., Cornelis, W., & Lobo, D. (2015). Comparing aggregate stability tests for soil physical quality indicators. *Land Degradation and Development*, 26, 843–852. http://dx.doi.org/10.1002/ldr.2225.

Rillig, M. C., Aguilar-Trigueros, C. A., Bergmann, J., Verbruggen, E., Veresoglou, S. D., & Lehmann, A. (2015). Plant root and mycorrhizal fungal traits for understanding soil aggregation. *New Phytologist*, 205, 1385–1388.

Rillig, M. C., & Mummey, D. L. (2006). Mycorrhizas and soil structure. *New Phytologist*, 171, 41–53.

Smith, S. E., & Read, D. J. (2008). *Mycorrhizal symbiosis* Cambridge: Academic Press.

Soil Survey Staff, (2010). Keys to soil Taxonomy. United States Department of Agriculture, Eleventh edition. Natural Resources Conservation Services.

Stanchi, S., Freppaz, M., Godone, D., & Zanini, E. (2013). Assessing the susceptibility of alpine soils to erosion using soil physical and site indicators. *Soil Use and Management*, 29, 586–596.

Stanchi, S., Falsone, G., & Bonifacio, E. (2015). Soil aggregation, erodibility, and erosion rates in mountain soils (NW Alps, Italy). *Solid Earth*, 6, 403–414. http://dx.doi.org/10.5194/se-6-403-2015.

Stokes, A., Atger, C., Bengough, A. G., Fourcaud, T., & Sidle, R. C. (2009). Desirable plant root traits for protecting natural and engineered slopes against landslides. *Plant Soil*, 324, 1–30.

Tasser, E., & Tappeiner, U. (2005). New model to predict rooting in diverse plant community compositions. *Ecological Modelling*, 185, 195–211.

Tisdall, J. M. (1991). Fungal hyphae and structural stability of soil. *Australian Journal of Soil Research*, 29, 729–743.

van Hall, R. L., Cammeraat, L. H., Keesstra, S. D., & Zorn, M. (2017). Impact of secondary vegetation succession on soil quality in a humid Mediterranean landscape. *Catena*, 149, 836–843.

Vargas, R., Castro, A., & Ziadat, F., (2015). Mountain soils and ecosystem services. R. Romeo A. Vita S. Manuelli E. Zanini M. Freppaz & S. Stanchi (Eds.), Understanding Mountain Soils: A Contribution from mountain areas to the International Year of Soils 2015. (pp.8). Rome, Italy.

Vergani, C., & Graf, F. (2015). Soil permeability, aggregate stability and root growth: A pot experiment from a soil bioengineering perspective. *Ecohydrology*, 9, 830–842.

Wahid, P. A. (2001). Radioisotope studies of root activity and root level interactions in tree-based production systems: A review. *Applied Radiation and Isotopes*, 54, 715–736.

Zhao, C., Gao, J., Huang, Y., Wang, G., & Xu, Z. (2016). The contribution of Astragalus adsurgens roots and canopy to water erosion control in the water-wind crisscrossed erosion region of the Loess Plateau, China. *Land Degradation and Development*, 28, 265–273.

Zhao, C., Gao, J., Huang, Y., Wang, G., & Zhang, M. (2016). Effects of vegetation stems on hydraulics of overland flow under varying water discharges. *Land Degradation and Development*, 27, 748–757. http://dx.doi.org/10.1002/ldr.2423.