

Effects of Mycorrhizal Fungi on Slope Stabilisation Functions of Plants



Frank Graf, Alexander Bast, Holger Gärtner and Anil Yildiz

Abstract Plants essentially contribute to the strength of soil and, in particular, steep slopes susceptible to erosion and shallow landslides. The corresponding functions of vegetation significantly control processes above and below ground such as interception, evapo-transpiration, soil aggregation and root reinforcement. Either way, they are all correlated with plant growth. Consequently, in order to unfold their soil stabilising potential, the plants must grow and sustainably survive. However, what sounds so obvious is anything but given under the often hostile conditions dominating on bare and steep slopes. This is exactly the point where mycorrhizal fungi come into play, known to improve the plants' ability to overcome periods governed by strongly (growth) limiting factors. Within this scope, numerous investigations have been conducted in order to understand and quantify mycorrhizal effects on different plant and soil functions related to eco-engineering and, particularly, to soil and slope stability. Results on plant growth and survival as well as on soil aggregation and slope stabilisation are presented and discussed from a mycorrhizal perspective.

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1 Introduction

Shallow landslides have been a constant threat in mountainous regions, predominantly on steep slopes, and the probability of occurrence of this natural hazard will increase in future, driven by the predicted intensification of heavy rainstorm events [1]. In Switzerland, substantial damage on infrastructure of up to more than 100 million Swiss Francs related to one heavy rainstorm period and sporadically loss of lives have been caused by erosion and landslides in recent years [2]. The protection against as well as prevention and prediction of superficial soil failure are, however, still difficult.

The importance of healthy and intact vegetation in general and forests in particular with regard to slope stability has long been accepted. Even as far back as in ancient Greek it was taught that one has to be concerned about trees and forests in order to ensure the well-being of the Nymphs, the guardians of the woods. Without having access to databases of meteorology and natural hazards, the important regulatory functions of forests related to hydrological processes were well known [3]. Accordingly, the gods punished sinners causing harm as for example Erisichthon who felled a banned tree but rewarded benefactors as in the case of Arkan having protected the tree of a Nymph who gave him her love [4, 5].

Today, these wisdoms are common knowledge and it is well accepted that vegetation considerably contributes not only in respect of regulating water balance but generally in view of protection against natural hazards, such as avalanches, rock-fall or debris flows and, predominantly, shallow landslides and erosion. Consequently, vegetation and the application measures of eco-engineering are widely recognised. In Switzerland incentive and support for biological stabilisation is given by article 19 of the forest law [6]. With regard to superficial soil failure, the protective functions include hydrological regulation through interception and evapo-transpiration as well as soil mechanical and, to a certain extent, chemical stabilisation through root reinforcement (Fig. 1).

Interception by forest canopies accounts for 10–40% of precipitation [7]. However, values vary spatially and depend on rainfall rate as well as on type and structure of forest. Additionally, a more or less distinct seasonal dependency exists. Generally, interception tends to be higher for conifer dominated than for pure broad-leaved forests [8–12]. Yet, regardless of tree species, the interception potential is positively correlated with leaf area [13] and, therefore, strongly related to plant growth performance.

Evapo-transpiration is tightly coupled to interception and describes the process where water within a plant coming from the roots is subsequently lost as vapour through stomata in its leaves. Factors affecting evapo-transpiration include solar radiation, humidity, temperature and wind, as well as the percentage of vegetation cover, species composition and their growth stage. As far as the plant specific parameters are concerned, again, a positive correlation exists between the amount of water transport and biomass, reflected by both roots and shoots whereby leaf area is the dominating driver.



Fig. 1 Soil stabilising functions of plants, e.g. interception, evapo-transpiration, and root reinforcement

Another biomass and, in particular, root length dependent process contributing to the upward water movement is hydraulic lift, a passive dislocation of water from parts of the root system in moister soil layers into soil layers with lower water potential. Usually, considerable amounts of water are transferred from wetter (deeper) layers to the often drier near surface zone of the soil during the night. This partial rehydration of the upper soil layers provides an additional source for transpiration the following day. Lifted water may also contribute to the availability of water soluble nutrients located most plentiful in the upper soil layers and, therefore, indirectly influences survival and growth performance of the plants and associated organisms. Hydraulic lift may prolong or enhance fine-roots activity in the subsurface layers by keeping them hydrated and thus, buffer the rhizosphere organisms from effects of soil drying during persistent periods of lacking precipitation [14, 15].

Root length density does not only strongly influence hydrology, but considerably contributes to reinforcement and aggregation of soil and, consequently, to slope stability. The significant positive correlation between rooting intensity and slope stability has been frequently proven using different methods to test for soil strength, e.g. direct shear tests [16], triaxial compression tests [17], and soil aggregate stability analysis [18–21] considering different approaches and models [22–25].

All the aforementioned plant specific functions related to slope stability require plant growth and development. However, what sounds so obvious is anything but given, particularly under the often hostile conditions dominating on bare and steep slopes. At exactly this point mycorrhizal fungi, the symbiotic partners of almost all

plants used in eco-engineering, come into play. Within this mutualistic partnership the fungus profits from the photosynthetic products, synthesised by the plant and, for its part, supplies the hosts with water and nutrients improving the plants' ability to overcome periods governed by strongly (growth) limiting factors [26]. Numerous studies have shown that mycorrhizal fungi improve plant growth and their survival [21, 26, 27].

Within a functional mycorrhizal symbiosis, the above ground biomass as well as the root network of the fungi's host plants increase considerably compared to non-mycorrhized plants (Fig. 2), due to a much better and more efficient nutrient supply. Read and Boyd [28] measured between 10 and 80 m of ectomycorrhizal hyphae per 1 cm of fine roots of Scots pine seedlings. These immense hyphal networks explore the soil more intensely than roots. Compared to root hairs, fungal hyphae are three to five times smaller in diameter (2–5 μm) and, consequently, have partially access to meso-pores (0.2–10 μm) that root-hairs don't. Thus, the mycelia of the host plants' mycorrhizae increase the absorption surface for water and nutrients up to 50 times [29].

Furthermore, mycorrhizal fungi affect soil aggregate stability indirectly through their host plants, particularly by accelerating the development of their root network and by serving as a distribution vector for associated micro-organisms, themselves soil stabilising alike [30–34].

In addition, the fungi directly contribute with their filamentous growth-form and the vast mycelial networks, growing far beyond the rhizosphere, to aggregate stabilisation by enmeshing loose soil particles and cement them through the production of “sticky” metabolites such as polysaccharides and hydrophobins [35–38].

Subsequently, we present and discuss results of our investigations in order to quantify mycorrhizal effects on plant growth and survival along with soil functions related to eco-engineering in general and to soil and slope stabilisation in particular.

2 Materials and Methods

2.1 Plant Survival

In six research plots, established in the subalpine forest belt in Grisons (Switzerland), the survival rates of mycorrhizal inoculated and non-inoculated plants were determined at the end of the first three growing seasons after their planting in May 2010 [20, 21]. Survival was determined for alder (*Alnus viridis* (Chaix) DC., *Alnus incana* (L.) Moench.) and willow species (*Salix purpurea* L., *Salix sp.*) as the ratio between the originally planted individuals and the still living plants after the corresponding vegetation period. The commercial inoculum “Forest”, hereinafter the “commercial inoculum”, includes 8 ecto- and 3 arbuscular mycorrhizal fungi [39].

In addition, the difference of survival between inoculated and non-treated dwarf willows (*Salix herbacea* L.) planted as cuttings on a graded alpine ski slope (2535 m

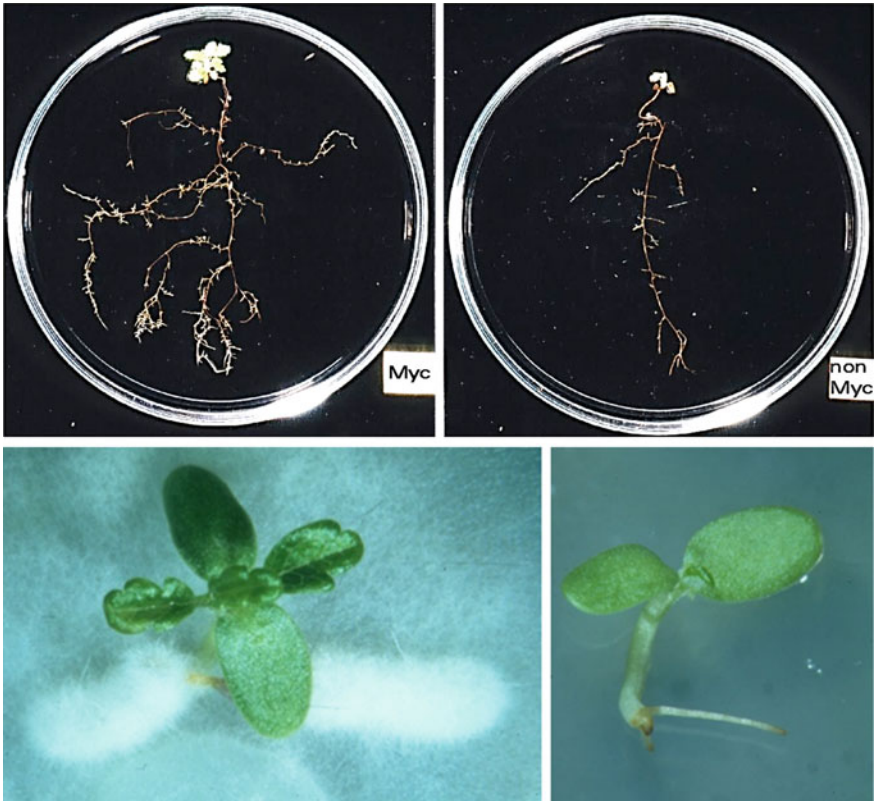


Fig. 2 Roots of a 20 weeks old *Dryas octopetala* plantlet and a 2 weeks old seedling inoculated with *Laccaria bicolor* showing a highly branched root network and the fluffy white mantle and mycelium of the fungus (left) and corresponding non-inoculated controls (right)

asl) in Grisons, Switzerland was investigated [40]. Three representatives of the genus *Laccaria* (two strains of *L. bicolor* (Maire) P.D. Orton, and *L. montana* Singer) were used as inoculi, previously isolated and cultivated from fruit-bodies of naturally grown symbiotic partners of *S. herbacea* plants in an alpine environment [41].

2.2 Plant Growth

Plant growth performance was determined from 5 months old birch seedlings (*Betula pendula* Roth) used for aggregate stability tests (cf. below). Three different treatment series with 12 individuals each were analysed, including one series of non-treated and two series of inoculated specimens. The two inoculi applied were the commercial and a single species, *Hebeloma crustuliniforme* (Bulliard) QuéL., from the mycorrhiza culture collection of WSL, subsequently referred to as “specific inoculum”.

For the above ground biomass, the dry weight was measured. In respect of the belowground part, root length density was determined with the software WinRhizo® [42] following a standardised protocol [43].

2.3 Soil Aggregate Stability

Samples were prepared with the fractions ≤ 10 mm of a soil type “ML” [44] from a recent landslide area in St. Antönien (GR, Switzerland). The material was tamped into PVC plastic tubes (diameter: 70 mm; height: 140 mm) aiming at a specific dry unit weight of ≈ 15 kN m⁻³. Treatments included untreated control, soil planted with *Betula pendula* as well as planted and additionally inoculated with either the commercial or specific inoculum ($n = 12$ per treatment). Samples were maintained in a greenhouse for 20 weeks according to a standardised procedure [43].

Soil aggregate stability was determined with a wet-sieving procedure (mesh opening 20 mm) and defined as ratio between the dry weight of the components above the sieve (aggregates > 20 mm) and the sum of all components [25, 43].

2.4 Direct Shear Tests

Planted and unplanted large-scale specimens (50 cm \times 50 cm \times 30 cm) were sheared to failure in an Inclined Large-scale Direct Shear Apparatus [16]. The specimens were subjected to an artificial rainfall event prior to shearing in order to ensure saturation [45]. The plant assortment included *Alnus incana* (L.) Moench, *Poa pratensis* L., and *Trifolium pratense* L. The growth period in a light, temperature, and humidity controlled climatic chamber was 6 months [16].

2.5 Statistical Analysis

Statistical inference was performed with the software R 3.3.1 [46]. Based on the Kaplan-Meier estimate [47, 48], the difference between the survival curves of the two treated sites was tested by using the Mantel-Haenszel test [49] of the R-package “survival”.

Differences in soil aggregate stability and root length density were calculated using robust Kruskal-Wallis and pair-wise Wilcoxon rank sum tests. In order to test the effect of root length density on soil aggregate stability, robust simple linear regression models were fitted using “lmrob” from the R-package “robustbase”. The response variable was transformed ($\sin^{-1}\sqrt{y}$) following the approach of “first aid transformations” [50].

Residual analysis was conducted in order to check the compliance of the assumptions required and the fit of the linear regression model (Appendix). The corresponding tests included: sample against theoretical quantiles (normal quantil-quantil plot), residuals against fitted values (Tukey-Anscombe plot), residuals against leverages (hat matrix, Cook's distance), and the distribution of the residuals (histogram).

3 Results

3.1 Plant Survival

Within the large-scale investigation on the influence of mycorrhizal inoculation on the performance of eco-engineering measures in a very steep catchment of a subalpine forest belt, it became obvious that survival of plants inoculated with a commercial product [39] was considerably higher compared to the non-treated control plants as shown in Fig. 3 [20, 21, 51].

The survival rates of the two alder species (*Alnus incana*, *A. viridis*) as well as of the two willows (*Salix purpurea*, *Salix sp.*) treated with the commercial inoculum performed significantly better than the corresponding controls right from the outset. Independent of treatment, the willows survived far better and obviously outperformed the alders (Fig. 3). After 3 years, more than 50 and 80%, respectively, of the mycorrhized alder and willow saplings were still alive compared to barely 20 and 50% of the corresponding controls [51].

Similar results were found for dwarf willow cuttings of *Salix herbacea* on a graded alpine ski slope. A significant increase in survival of the mycorrhized plantlets was recognised compared to non-inoculated controls.

However, the time span until the positive effect on survival of the mycorrhized plantlets was established, depended significantly on the mycorrhizal fungal species, although they all belonged to the genus *Laccaria* and two of them even to the same species (different strains). Whereas the cuttings inoculated with strain 2 of *Laccaria bicolor* yielded significant higher survival rates already after the first vegetation period this was the case only after the second year for strain 1 of *L. bicolor* and not until the end of the third year for the species *L. montana* (Fig. 4).

3.2 Plant Growth

Growth performance with regard to the above ground biomass of *Betula pendula* was significantly different for the two treatments with mycorrhizal fungi as well as compared to the non-inoculated control plants (Figs. 5 and 6).

Whereas the specific inoculum yielded no effect, the plants mycorrhized with the commercial one produced significantly higher shoot dry weights compared to both the controls and the treatment with the specific inoculum.

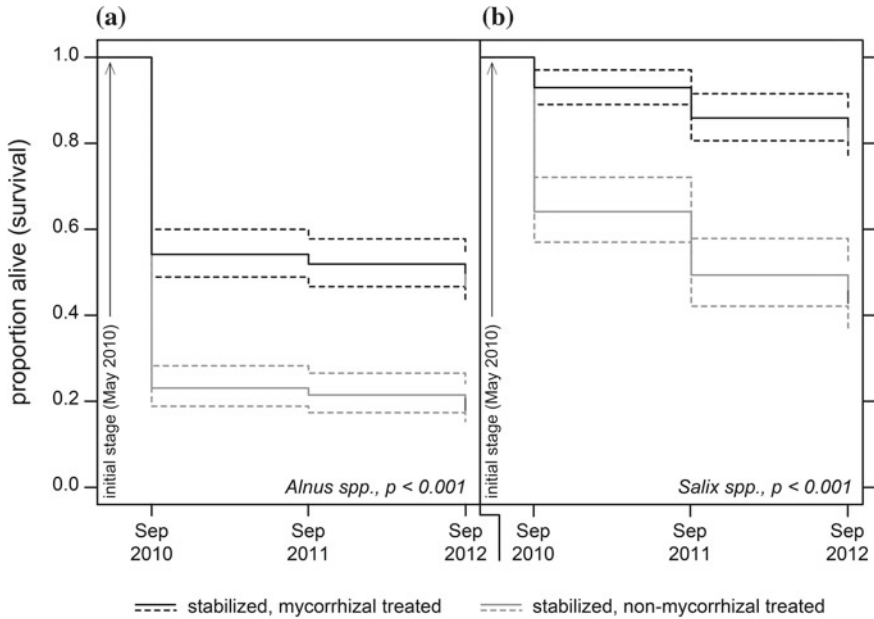
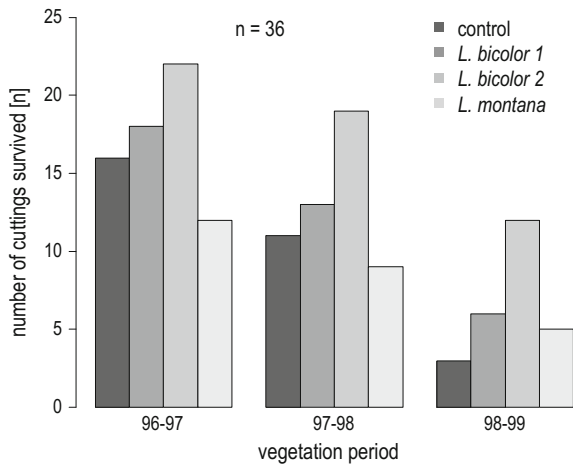


Fig. 3 The black (mycorrhized) and grey (control) solid lines show significant differences ($p < 0.001$) for alder (a, $n = 312$ per site) and willow (b, $n = 156$ per site). Black and grey dashed lines illustrate the 95% confidence interval [51]

Fig. 4 Survival rates of *Salix herbacea* cuttings ($n = 36$ for each treatment) on a graded alpine ski slope (2535 m asl) depending on mycorrhizal inoculum type and the number of vegetation periods [40]

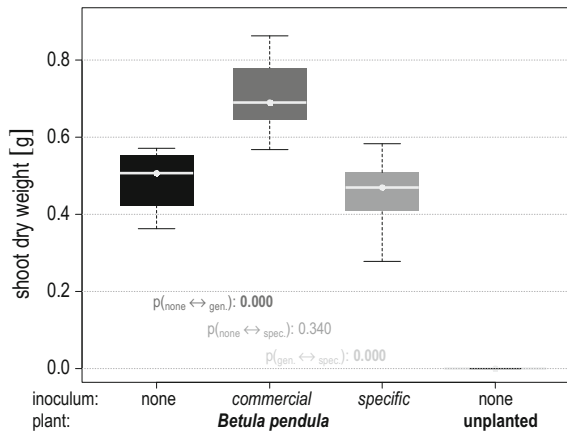


Differences between mean value and corresponding standard deviation (sd) and the robust median and mad (median absolute value) of shoot dry weight per sample, respectively, are negligible in all treatments. This suggests a lack of severe outliers



Fig. 5 Above ground biomass of *Betula pendula* with the commercial inoculum (left) and of a non-treated control (right) after 20 weeks of growing in the greenhouse

Fig. 6 Above ground biomass (dry weight) of *Betula pendula* plantlets (n = 12, per treatment) after the 20 weeks' growth period in the greenhouse measured as the root length per soil volume [cm cm⁻³] for non-inoculated control (black), inoculated with the commercial (dark grey) and specific inoculum (grey) and the untreated soil (light grey)



and a good match to normal distribution assumptions as far as mean and sd are concerned. The corresponding values are given in Table 1.

Similar to the results of the above ground biomass, roots of the plants with the commercial inoculum grew significantly better and produced a much stronger branched root network compared to the control plants and those treated with the specific inoculum (Fig. 7).

Location and dispersion parameters for root length per soil volume per sample of the normal distribution (mean, sd) and their robust equivalents (median, mad) do not obviously differ for the control and specific inoculum. However, a considerable difference results for the treatment with the commercial inoculum, particularly, as

Table 1 Mean, standard deviation (sd), median, and median absolute value (mad) of shoot dry weight [g] per sample (cf. Fig. 6) in terms of soil planted with untreated as well as differently inoculated *Betula pendula* plantlets (n = 12, per treatment)

Shoot dry weight (g)	Mean	sd	Median	Mad
<i>Betula</i> untreated	0.489	0.077	0.507	0.089
<i>Betula</i> with commercial inoculum	0.703	0.095	0.689	0.107
<i>Betula</i> with specific inoculum	0.455	0.088	0.469	0.058

Fig. 7 The rooting performance of *Betula pendula* plantlets (n = 12, per treatment) after the 20 weeks' growth period in the greenhouse measured as the root length per soil volume [cm cm⁻³] for non-inoculated control (black), inoculated with the commercial (dark grey) and specific inoculum (grey) and the untreated soil (light grey)

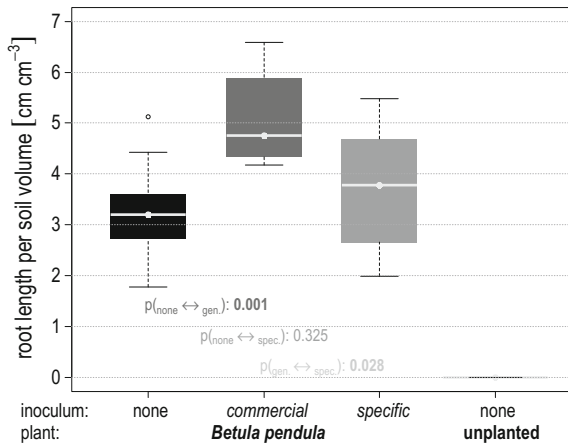


Table 2 Mean, standard deviation (sd), median, and median absolute value (mad) of root length density [cm cm⁻³] per sample (cf. Fig. 7) in terms of soil planted with untreated as well as differently inoculated *Betula pendula* plantlets (n = 12, per treatment)

Root length density (cm cm ⁻³)	Mean	sd	Median	Mad
<i>Betula</i> untreated	3.205	1.005	3.200	0.890
<i>Betula</i> with commercial inoculum	5.375	1.506	4.750	0.815
<i>Betula</i> with specific inoculum	3.691	1.195	3.785	1.342

far as dispersion is concerned, with the standard deviation nearly double that of the robust mad (Table 2).

3.3 Soil Aggregate Stability

The soil aggregation potential of *Betula pendula* was significantly higher for both treatments with mycorrhiza compared to the control plants. Furthermore, the commercial inoculum performed again significantly better than the specific one. All planted treatments performed significantly better than bare soil (Fig. 8).

The comparison of mean and sd on the one hand with median and mad on the other hand of the soil aggregate stability revealed no noticeable differences within the different treatments, except for the dispersion parameters of the treatment commercial with the standard deviation nearly double that of the robust mad (Table 3).

Robust simple linear regression analysis for soil aggregate stability in dependence of root length per soil volume yielded significant positive correlation for the treatment with the specific inoculum (p -value: 0.025) but not for the non-inoculated plants (p -value: 0.191) and the treatment with the commercial inoculum (p -value: 0.836). Taking all treatments into account the model, again, demonstrates the significant

Fig. 8 Soil aggregation potential of *Betula pendula* plantlets ($n = 12$, per treatment) after the 20 weeks' growth period in the greenhouse measured as the root length per soil volume [cm cm^{-3}] for non-inoculated control (black), inoculated with the commercial (dark grey) and specific inoculum (grey) and the untreated soil (light grey)

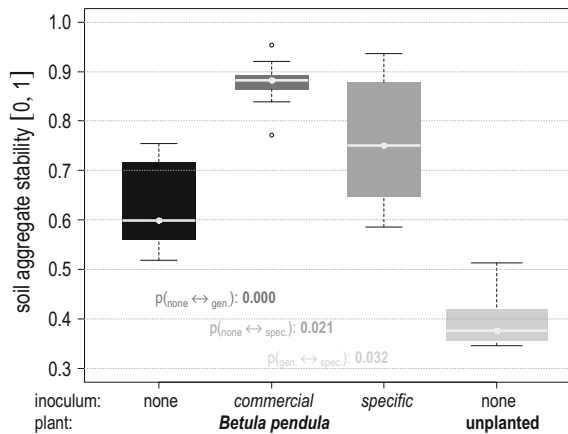


Table 3 Mean, standard deviation (sd), median, and median absolute value (mad) of soil aggregate stability [0, 1] per sample (cf. Fig. 8) in terms of bare soil and soil planted with untreated as well as differently inoculated *Betula pendula* plantlets ($n = 12$, per treatment)

Soil aggregate stability [0, 1]	Mean	sd	Median	Mad
Control	0.369	0.055	0.376	0.042
<i>Betula</i> untreated	0.630	0.091	0.599	0.107
<i>Betula</i> with commercial inoculum	0.877	0.046	0.882	0.025
<i>Betula</i> with specific inoculum	0.761	0.124	0.751	0.174

Fig. 9 Robust simple linear regression models $\sin^{-1}(\text{aggregate stability})^{1/2} \sim \text{root length}$ for non-inoculated (dark grey, dashed), commercial (orange, dashed) and specific inoculum (green, dashed) as well as for the combination of all treatments of *Betula pendula* (blue, solid) including unplanted control (light grey points)

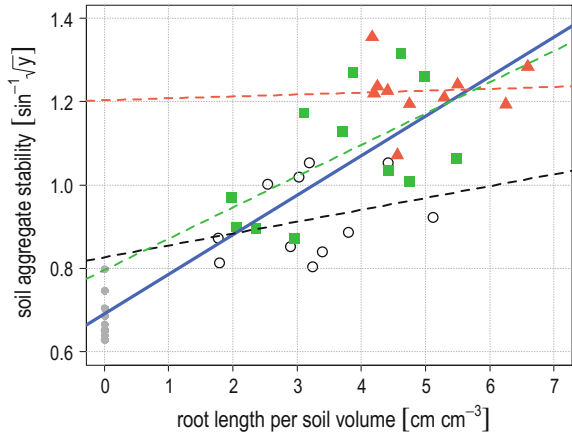


Table 4 Summary of the linear regression model $\sin^{-1}(\text{aggregate stability})^{1/2} \sim \text{root length}$ including all treatments and control, showing significant difference in intercepts and slope

Coefficients	Estimate	Std. error	t value	Pr(> t)	
Intercept	0.6902	0.0172	40.13	$<2.0 \times 10^{-16}$	***
Root length	0.0950	0.0070	13.60	$<2.0 \times 10^{-16}$	***

Robust residual standard error: 0.1196

Multiple R-squared: 0.7324 Adjusted R-squared: 0.7259

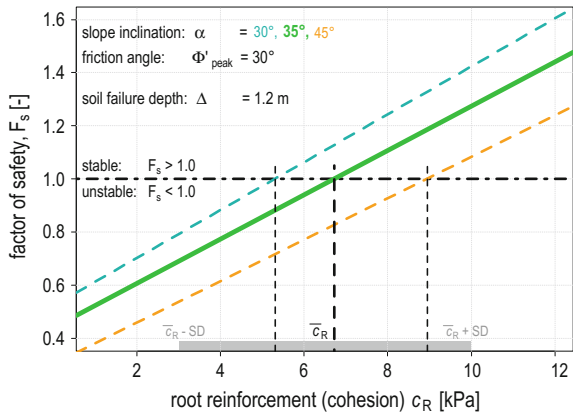
Significance codes: *** <0.001 ; $0.001 \leq ** < 0.01$; $0.01 \leq * < 0.05$

positive influence of roots of *Betula pendula* on soil aggregate stability (Fig. 9; Table 4).

3.4 Direct Shear Tests

Based on limit equilibrium analysis, the direct shear tests with planted (*Alnus incana*, *Poa pratensis*, *Trifolium pratense*) and unplanted large-scale specimens (50 cm × 50 cm × 30 cm) supported clearly the positive stabilisation effect of vegetation (Fig. 10). An average rooting (\bar{c}_R), yielding a reinforcement effect (cohesion) of about 6.5 kPa, enables slope stability up to 5° steeper (35°) than can be expected from the angle of internal friction Φ' of the bare soil material (30°), with the failure plane at a soil depth of 1.2 m [16]. A root reinforcement of ≈ 9 kPa, could theoretically increase slope stability up to 15°. These calculations are conducted for an infinite slope with seepage (parallel to the slope), based on limit equilibrium (Fig. 10).

Fig. 10 Factor of safety calculation for slopes with an angle equal to (blue, dashed), 5° (green, solid), and 15° (gold, dashed) steeper than the friction angle Φ' (30°) for a soil failure depth of 1.2 m with range ($\bar{c}_R \pm SD$) of root reinforcement (cohesion). Calculations for an infinite slope with seepage (parallel to slope), based on limit equilibrium



4 Discussion

Depending on the magnitude of the soil degradation processes, mycorrhizal fungi are severely affected, yielding a lack of the mycorrhizal infection potential [52]. On harshly degraded soil, the natural recovery potential of the symbiotic fungi is considerably obstructed and, particularly, depends on the adjacent regions that are still intact. However, in this neighbourhood the species composition does not necessarily fit the requirements of the site to be re-colonised. In most cases the incompatibility is due to the difference in plant species found in the intact proximity and those applied for re-colonisation. As not every mycorrhizal fungus forms mycorrhiza with every plant, such discrepancy entails serious consequences in view of mycorrhization. A further impediment are successional processes in mycorrhizal communities in the way that perennial plants do have other fungal partners in their juvenile, prime, and senescent living phase [41, 53].

Recent research and experience suggest that the introduction of indigenous plant species together with a managed community of mycorrhizal fungi is an excellent approach in order to overcome the initial deficiencies in respect of a functional seedbed, stimulating and promoting autogenic recovery of degraded ecosystems [54–57]. This concept substantially increases sustainable revegetation success by creating synergies between abiotic and biotic processes and is advantageous not merely under extreme and limiting environmental conditions [58, 59].

The beneficial effect of applying mycorrhizal fungi on plant survival within the scope of the eco-engineering measures in the steep landslide area of the subalpine forest belt [20, 21] as well as on the alpine ski slope in Grisons [40] is in line with results of numerous other studies. Investigations conducted in different fields of applied mycorrhiza, e.g. plant nurseries, weaning of micropropagated plants, agriculture as well as re-colonisation of bare ground, consistently showed the positive effect of mycorrhizal fungi on survival of the corresponding host plants, too [58, 60–64].

The better survival of mycorrhized host plants is closely coupled to their better growth performance both above and below ground. The main reason for this growth stimulating function is the much higher efficiency of water and nutrient supply provided by the mycorrhizal network compared to root-hairs as exemplarily shown in Fig. 2 [28, 29].

However, it has to be kept in mind that different mycorrhizal fungi provide different functions for different host plants in different environments at different time steps [65] explaining the varying results on survival as well as root and shoot growth in dependence of the different inoculi applied. Inoculation with only *Hebeloma crustuliniforme*, although a known mycorrhizal fungus of birch, resulted in significantly lower biomass production both above and below ground as compared to the inoculation with the commercial inoculum. This product consists of 8 ecto- and 3 arbuscular mycorrhizal species and, apart from *H. crustuliniforme*, contains four other species, i.e. *Amanita muscaria* (L.) Lam., *Laccaria laccata* (Scop.) Cook., *Paxillus involutus* (Batsch) Fr., and *Thelephora terrestris*, Ehrh., known to naturally form mycorrhiza with birch [27, 66, 67]. The four additional fungal partners of birch most likely claimed responsibility for the significantly better growth performance and, consequently, the resulting increase in soil aggregate stability (Figs. 6, 7 and 8). It may, therefore, be speculated that *H. crustuliniforme* provides other beneficial functions for birch than particularly better and faster growth—e.g. protection against pathogens or toxic substances [26, 27]. The three arbuscular species of *Glomus* Tul. & C. Tul. included in the commercial inoculum are not of relevance—birch is exclusively colonised by ectomycorrhizal fungi [68].

Nevertheless, most mycorrhizal fungi known to naturally establish partnerships with plants used for stabilisation measures often yield an increase in survival as well as root growth and above ground biomass. However, now and then a more or less distinct time lag is observed until positive effects of mycorrhiza become obvious and significant as compared to untreated control plants. Furthermore, during the initial phase of mycorrhiza formation even a transient worse performance is possible [26].

Plant growth performance and, thus, mycorrhiza has further essential implications in respect of soil and slope stability as a key driver of both interception and evapo-transpiration. It has been scientifically proved under various conditions that above ground biomass in terms of leaf area index is positively correlated with interception of rainfall in forests as well as grassland [10, 13, 69, 70]. With regard to evapo-transpiration the vapour pressure deficit is a most influencing factor and it was demonstrated that it is reflected by aerodynamic resistance, representing surface roughness, the most influential feature of forest canopies [71]. According to the Penman-Montheith equation [72] it follows that evaporation decreases with increasing aerodynamic resistance which, on its part, decreases with increasing leaf area index [12, 73].

Consequently, an increase in above and below ground biomass increases both interception and evapo-transpiration and implies lower soil saturation levels. Thus, with regard to a heavy rainfall event, the soil has a higher water storage capacity and the time span until complete saturation is considerably extended.

In addition to the biomass depending effects of interception and evapo-transpiration, the resistance against pore water pressure is another decisive process

in respect of soil and slope stability. It has been nicely shown that vegetation can reduce pore water pressure in soil by root water uptake resulting in higher shear strength but lower soil water permeability [74]. This soil stabilising effect is, again and obvious, positively correlated to plant growth in general and to root morphology and architecture in particular.

In a study on pore water pressure development during soil aggregate stability tests [75] it was found that the resistance against disintegration of soil aggregates by increasing pore water pressure—measured as the delay until passing from negative to positive pore water pressure—holds longer in samples with higher root length density and finer root networks. Consequently, soil aggregate stability was significantly higher after a plant growth period of about 20 weeks in the samples of the grass *Poa pratensis* in contrast to those of the tree *Alnus incana* for which considerably lower root length density and a much higher portion of middle to coarse roots was observed. Thus, it can be speculated that particularly the portion of fine roots contributes to the retarded increase in pore water pressure at least in a very early phase of plant and soil development. Ng et al. [74] found that exponential root architecture induces the highest negative pore water pressure in the soil followed by triangular, uniform, and parabolic architecture. Roots of *P. pratensis* follow more the exponential architecture whereas those of *A. incana* are more uniform like. This is further evidence for a stronger reducing effect of pore water pressure and an increase in soil aggregate stability by the grass species. Additionally, at equal treatment, *P. pratensis* had higher evapo-transpiration efficiency, indicated by a lower pore water pressure level at the start of the experiments. Therefore, it is conceivable that pore water pressure is associated to soil aggregate stability the same way as root length density, since the latter two are positively correlated as seen in Fig. 9 and demonstrated in numerous other studies, e.g. [20, 25, 38, 43, 76]. The close interrelationship between soil aggregate stability and pore water pressure is anything else than surprising as an increase in the latter provokes disruption and slaking of the former [77].

The direct and indirect effects of roots as well as their associated mycorrhizal fungi contribute to the stability of soil aggregates and, therefore, to the strength of the soil matrix and resistance against breaking [20, 25, 38, 43]. Apart from increasing root length density and chemical cementation by polysaccharides, the mycorrhizal fungi further contribute to soil and slope stability inducing morphogenetic changes in root architecture and increasing their 3D complexity (Fig. 2). It is assumed that a positive correlation exists between root length density and ramification with lateral roots [78]. Therefore, with the mycorrhization of plants, a pronounced increase in the complexity of the roots' 3D-structure is expected. Up to a certain degree, the higher soil aggregate stability provided by birch mycorrhized with the commercial inoculum is most likely due to a gain in 3D complexity, too. A corresponding increase in shear strength can be assumed as certain and was confirmed with triaxial compression tests. Investigations on sand reinforced with artificial 3D inclusions revealed a positive correlation between shear strength and the complexity of the 3D structures added [79]. This is similar to the results of triaxial compression tests of planted moraine, where those specimens with the highest root length density and, correspondingly, most-branched root systems mobilised the maximum peak shear force mirrored by the angle of internal friction Φ' [19].

A resilient soil matrix consisting of stable micro- and macro-aggregates assembled by fungal mycelia and roots is not only a prerequisite for slope stability but provides a significantly higher retention capacity for water and nutrients. In turn, mycorrhized compared to non-mycorrhized plants have much greater access to this enriched nutrient pool yielding better growth performance and survival rates resulting in the development and establishment of a protective vegetation cover. This positive feedback-loop is the central key and essential requirement in respect of successful eco-engineering measures aimed at sustainable slope stabilisation and protection against shallow landslides.

From the soil mechanical perspective, calculations for an infinite slope with seepage (parallel to the slope), based on limit equilibrium applying the data of direct shear tests with large-scale specimens (50 cm × 50 cm × 30 cm) generally support the aforementioned findings. In respect of plant functions on slope stability, particularly the positive correlation between roots and additional strength of soil was demonstrated as shown in Fig. 10 [16]. A difference of 5° between the slope angle α and the angle of internal friction Φ' , reflected by an increase in peak shear force, results from a mean root reinforcement (cohesion) of about 6.5 kPa achieved by planting the moraine with the tree species *Alnus incana*, the grass *Poa pratensis* and the legume *Trifolium pratense*. On slopes covered with well-maintained protection forests such values can be assumed [80] at a depth of 1.2 m for the potential failure plane, representing the mean of more than 200 shallow landslides triggered in forests [81]. The 5° increase in the angle of internal friction Φ' is further confirmed by triaxial compression tests of the same soil material, planted with *A. incana*, and in line with the soil aggregate stability approach [19, 43].

It can be speculated that protection forests meeting the optimal requirements of NaiS, the guidelines for “Sustainability in Protection Forests” [82], keep slopes stable at even greater differences between the angle of internal friction Φ' of bare soil and the effective slope inclination α (Fig. 10). This assumption is based on the soil mechanical experiments with root-permeated soil [16] and investigations on how forest structure affects root reinforcement and susceptibility to shallow landslides [80].

5 Conclusions

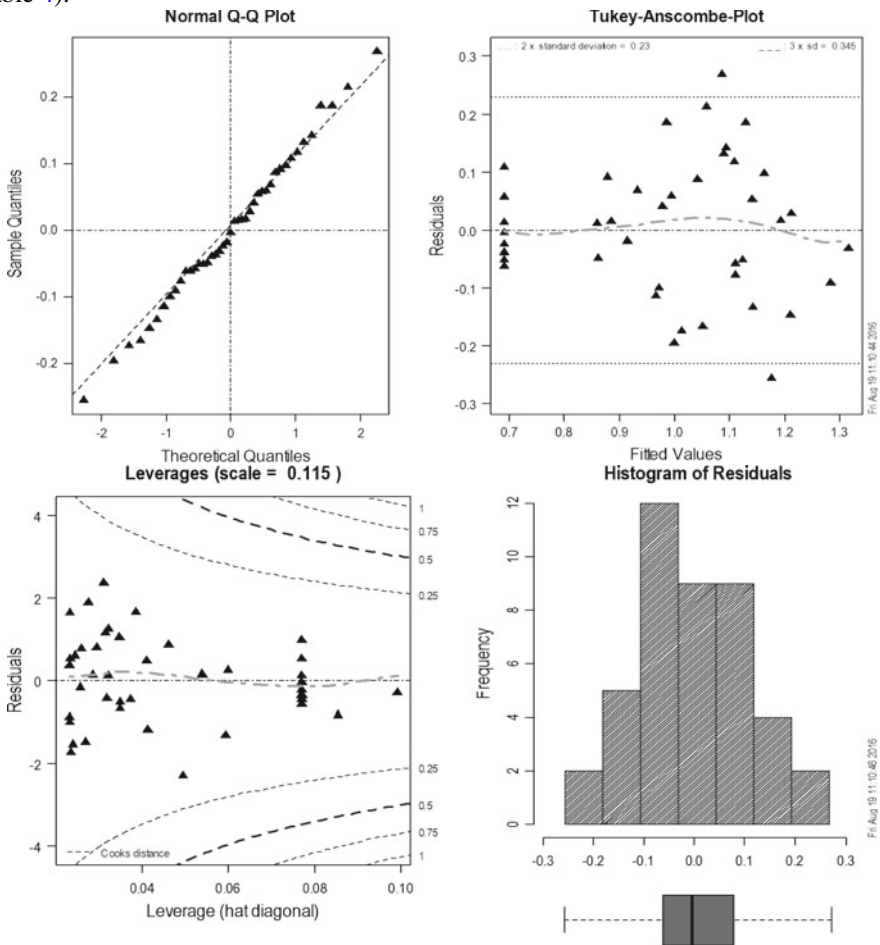
The hostile conditions for vegetation development on severely degraded slopes and the beneficial effects of mycorrhizal fungi elucidate that the application of plants together with their relevant fungal partners is highly recommendable. Mycorrhizal fungi considerably and positively contribute to plant growth, survival, soil stability and corresponding slope stability functions of plants, e.g. interception and evapotranspiration. However, the selection of the fungal species needs to experience careful examination. Sound information on their ecology and sociology as well as on the potential for aggregate formation is required depending on the plant species used as initial step in the re-colonisation process as well as in view of the climax association in mind.

Considering all these aspects, the application of mycorrhizal inoculi in eco-engineering will be undoubtedly an important step towards more sustainability and absolutely merits to be integrated into engineering concepts and risk management.

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Appendix

Residual analysis of the model: $\sin^{-1}(\text{aggregate stability})^{1/2} \sim \text{root length}$ (Fig. 9; Table 4).



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