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Research paper

Soil aggregate stability related to soil density, root length, and mycorrhiza using site-specific *Alnus incana* and *Melanogaster variegatus s.l.*

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ABSTRACT

Eco-engineering aims at stabilising soil and slopes by applying technical and biological measures. Engineering structures are commonly well defined, immediately usable and operative, and their stability effects quantifiable. Differently, the use of plants requires more restrictive boundary conditions and the protection potential is rarely easily calculable and is developing as a function of growth time. Soil aggregation processes play a crucial role in re-establishing soil structure and function and, conclusively, for successful and sustainable re-colonisation. Mycorrhizal fungi are key-players that foster the development of a protective vegetation cover. They accelerate and increase plant growth and, additionally, contribute to soil aggregate stability which, on its part, was recently proposed as an appropriate indicator with regard to the quantification of biological effects on soil and slope stability.

The objective of this study was to determine the effects of mycorrhizal fungi on the host's root system as well as on soil aggregate stability. Furthermore, the biological contribution to soil aggregate stability was compared to mechanical stabilisation effects due to soil compaction. The site-specific plant-fungus symbiosis *Alnus incana* and *Melanogaster variegatus s.l.* of a recently stabilised steep catchment on moraine was used for laboratory experiments.

Aggregate stability tests were performed with samples of differently treated moraine, including soil at low (~15.5 kN m^{-3}) and high (~19.0 kN m^{-3}) dry unit weight, soil planted with *A. incana* (White Alder) as well as the combination of planting with alder and inoculating with the mycorrhizal fungus *M. variegatus s.l.* After a 20 week growth period in a greenhouse, a total of 100 samples was tested and evaluated. Positive correlations were found between the soil aggregate stability and the three variables dry unit weight, root length per soil volume, and degree of mycorrhization. Based on robust statistics it turned out that over all samples dry unit weight and degree of mycorrhization were strongest correlated with soil aggregate stability. Simple linear regression models revealed a significant positive effect of root length per soil volume on soil aggregate stability. Compared to the non-inoculated control plants, mycorrhized White Alder produced significantly more roots and, consequently, higher soil aggregate stability. Furthermore, the combined biological effect of plant roots and mycorrhizal mycelia on aggregate stability in soil with low density (~15.5 kN m^{-3}) was comparable to the compaction effect of the pure soil from 15.5 to ~19.0 kN m^{-3}.

Literature data on the effect of vegetation on the angle of internal friction Φ' of the same moraine showed similar correlations, i.e. that Φ' of low density soil material (~15.5 kN m^{-3}) increased by the same amount whether by planting with White Alder or by compaction to ~19.0 kN m^{-3}. Based on this coincidence and from a soil mechanical perspective, soil aggregate stability is suitable to estimate the joint effect of plants and mycorrhizal fungi with respect to their contribution to soil and slope stability in the near-surface layer.

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1. Introduction

A major goal of eco-engineering measures is their contribution to slope stability. For that purpose, plant growth and the development of a functional vegetation cover are essential. However, on soil affected by erosion and sliding processes, even pioneer plants reach their limits (Coppin and Richards, 1990; Morgan and Rickson, 1995; Gray and Sotir, 1996).

Depending on the degree of degradation of a soil, the pore structure is strongly destabilised due to the almost complete breakup of the soil aggregates. Hence, as water and nutrients are stored in the interstitial of stable soil aggregates, the build-up of a water and nutrient reserve is strongly hampered as the main part is immediately leached out. Under such extreme conditions a gap results between the basic demands of the plants and the effective supply at the time eco-engineering is applied. Consequently, the main requirement of eco-engineering and, actually, any soil restoration practice should be to establish conditions that favour formation of stable soil aggregates, thereby facilitating an important step in the creation of nutrient and water reserves as the basis of plant growth and vegetation establishment (Tisdall and Oades, 1982; Sollins et al., 1996).

Conventional solutions to provide this basis are manifold. Among the most common are the use of synthetic soil conditioners to stabilise the soil surface (Scheffer and Schachtschabel, 1992) and the application of fertiliser to overcome nutrient deficiency. However, these "first aid" measures entail secondary effects, notably fertilising (Cernusca, 1986; Arnolds, 1989, 1992a,b). The pronounced growth stimulation of the above ground biomass compared to roots and the preference of plants that are nutrient indigent in place of autochthonous species are disadvantageous in the long-term. Furthermore, fertilisers hamper the development of important micro-organisms, particularly mycorrhizal fungi (Wallenda and Kottke, 1998). These essential plant partners are already drastically decreased, in dependence of the magnitude of the erosive and sliding incidents (Biondini et al., 1985; Biondini and Redente, 1986; Amaranthus and Trappe, 1993) as well as in relation to the time the corresponding plant partners are missing (Parke et al., 1984).

Recent research and experience suggest that the introduction of indigenous plant species together with a managed community of mycorrhizal fungi is an excellent approach to initiate and promote autogenic recovery of degraded ecosystems (Requena et al., 2001; Caravaca et al., 2003; King and Hobbs, 2006; Chaudhary et al., 2009). Particularly in harsh, limiting environments, this procedural method bears the potential for a substantial increase in long-term revegetation success, by creating synergies between abiotic and biotic processes (Jeffries et al., 2003; Byers et al., 2006).

It is well known that most plants and nearly all species used for eco-engineering measures live in a symbiotic relationship with mycorrhizal fungi. Previous studies have shown that mycorrhizal fungi improve plant growth by increasing the above ground biomass as well as the root network (Cairnay and Chambers, 1999; Smith and Read, 2008). Furthermore, these fungal partners protect their host plants against soil borne pathogens and toxic elements and compounds potentially present in the soil solution (Kottke et al., 1998; Brunner, 2001). In view of plant communities, it was found, that mycorrhizal fungi influence plant diversity, ecosystem productivity and, hence, regulate or accelerate succession processes (van der Heijden et al., 1998).

Another important issue is their contribution to the formation of the soil structure and its strength at different spatial scales directly by charge, adhesive, and enmeshment mechanisms. These interrelationships have been demonstrated time and again for arbuscular mycorrhizal fungi (Tisdall and Oades, 1982; Miller and Jastrow, 2000; Rillig et al., 2002; Ritz and Young, 2004; Bedini et al., 2009; Martin et al., 2012). However, the contribution of ectomycorrhizal fungi to the formation and stabilisation of soil aggregation has not been elaborated that comprehensively, yet. In spite of that, it has been hypothesised (Tisdall, 1991; Rillig and Mummey, 2006) and, up to a certain extent, demonstrated that these fungi may play an important role in soil aggregation too (Thornton et al., 1956; Graf and Gerber, 1997; Tisdall et al., 1997; Tagu et al., 2001; Graf et al., 2006; Ambriz et al., 2010).

As a matter of fact, the filamentous growth-form and the vast mycelial networks far beyond the rhizosphere make them perfectly adapted in view of soil aggregation and stabilisation. Furthermore, the production of "sticky" metabolites (polysaccharides, hydrophobines) strongly supports a functional role in soil aggregate formation (Caesar-Ton That et al., 2001; Tagu et al., 2001; Mankel et al., 2002).

Evidence on the soil aggregation potential of ectomycorrhizal fungi was already given by Thornton et al. (1956) with their investigation on mycelial aggregation of sandy soil under *Pinus radiata*. Tisdall et al. (1997) recorded significant higher aggregation (>50 μm) of a soil clay slurry (<2 μm) prepared from a Vertisol inoculated with an ectomycorrhizal *Hebeloma* species compared to the non-inoculated control. Similar findings are reported from Graf and Gerber (1997). They analysed the aggregate stability of an artificial mixture composed of quartz sand, glass balls and peat of inoculated (*Laccaria bicolor*, *L. montana*) and non-inoculated samples, maintained under sterile conditions. The two inoculated treatments significantly increased the aggregate stability compared to the control and there was a considerable but non-significant difference between the two *Laccaria* species.

The species specificity of ectomycorrhizal fungi in their potential of soil aggregate formation and stabilisation was shown by Graf et al. (2006). In their study, the fine fraction (<2 mm) of moraine was inoculated with different ectomycorrhizal species (*Hebeloma alpinum*, *Hebeloma repandum*, *Inocybe lacera*, *L. bicolor* (2 stems), *L. montana*) and tested against the non-inoculated control. Except for *I. lacera* and stem 1 of *L. bicolor*, all other ectomycorrhizal fungi significantly increased soil aggregate stability. *Laccaria bicolor* (stem 2) and *H. alpinum* were the most effective soil aggregate stabilisers, followed by *L. montana* and *H. repandum*.

Similar findings for arbuscular mycorrhizal fungi were reported from Schreiner et al. (1997) who found that *Glomus mosseae* improved the stabilisation of the aggregate class 2–4 mm significantly more than *Glomus etunicatum* and *Glomus rosea*. Moreover, it was demonstrated that different isolates of the same fungal species (*Glomus intraradices*) may differ in their efficiency of soil aggregate formation and stabilisation (Bedini et al., 2009).

Indirectly, the mycorrhizal fungi affect the soil aggregate stability through their host plants, particularly by accelerating the development of their root network and by serving as a distribution vector for associated micro-organisms, mainly bacteria and archaea themselves soil stabilising alike (Budi et al., 1999; Filion et al., 1999; Bezzate et al., 2000; Hildebrandt et al., 2002; Mansfeld-Giese et al., 2002). Unlike mycorrhizal fungi that strongly influence at the scale of macro-aggregates, bacteria and archaea more directly participate in the formation and stabilisation of micro-aggregates (Chenu, 1989; Oades, 1993).

With all due respect to these important fungal traits, it should not be forgotten that the selection of appropriate species needs to experience careful examination. Sound information on their ecology and sociology 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. Commercially available inoculum does not always fit the site-specific requirements and long-term perspectives. It is well known that not every mycorrhizal fungus

forms mycorrhiza with every plant. Additionally, there 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, respectively (Last et al., 1983; Graf, 1994). Consequently, prospects of success and efficiency are greatest if site-specific and compatible plants and mycorrhizal fungi are selected.

In order to consider these framework conditions we used the soil material (moraine) of a recent landslide area, autochthonous White Alder (*A. incana*) and isolated one of the mycorrhizal partners (*Melanogaster variegatus s.l.*) forming symbiosis during the juvenile phase of its host plant. With these ingredients, differently treated soil samples were prepared. Besides the untreated soil at low ($\sim$15.5 kN m^{-3}) and high dry unit weight ($\sim$19.0 kN m^{-3}), soil planted with *A. incana* as well as soil planted with *A. incana* and inoculated with the mycorrhizal fungus *M. variegatus s.l.* were analysed; the latter two treatments at low dry unit weight ($\sim$15.5 kN m^{-3}). The soil aggregate stability was analysed and calculated according to Frei et al. (2003) and Burri et al. (2009). Additionally, the root length per soil volume was measured to compare between inoculated and non-inoculated alder roots.

The main hypotheses were that the inoculation with a naturally occurring mycorrhizal fungus of *A. incana* (i) increases the root growth of the host plant and (ii) increases the soil aggregate stability and (iii) that the increase in soil aggregate stability due to mycorrhized plants is comparable to the stability of untreated moraine with increased dry unit weight. Furthermore, the results are compared to effects of roots on the angle of internal friction Φ' addressed in a preceding investigation using site-specific White Alder and moraine of the same investigation area (Graf et al., 2009).

2. Material and methods

2.1. Investigation area and soil material

The soil investigated is a moraine of the subalpine landslide area "Schwandrübi" at Dallenwil-Wirzweli in the Canton of Nidwalden in Central Switzerland. The "Schwandrübi" is a steep amphitheatre-like gully on moraine and a part of a larger catchment (Burri et al., 2009). Until 1980 it was a steady source of bed load of the outlet channel and, therefore, a potential danger of the ski resort Wirzweli above as well as the subjacent village Dallenwil. During 1981 and 1982 joint technical and biological measures, in particular gabions, log cribwalls, the application of *Salix purpurea* cuttings and planting of *Alnus incana* had been taken on a large scale.

The subsequently described experiments were performed with untreated soil, i.e. bare moraine without vegetation cover, representing the situation at the time of the stabilisation and restoration measures in 1981. The corresponding soil material was analysed physically and chemically. For a proper soil classification from a geotechnical point of view (ASTM D 2487, 2002) the grain size distribution was performed according to ASTM D 422 (2000), including the liquid limit and the plasticity index (ASTM D 4318, 2000). Furthermore, proctor standard compaction tests were conducted to get the maximum dry unit weight at optimum water content (ASTM D 698, 2000). From oven dried material (24 h at 105 °C) the fractions $\leq$10 mm were used to prepare the samples for conducting all aggregate stability tests.

Chemical analysis included the quantification of exchangeable cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}), determination of organic matter by oxidation with H_2O_2, and soil pH measurement in 0.01 M $CaCl_2$ (Schlichting et al., 1995; Brunner et al., 2002).

2.2. Sample preparation

With regard to the performance of the aggregate stability tests the soil material was moistened to a water content of 6% and tamped into PVC-plastic tubes (diameter: 70 mm; height: 140 mm) aiming for an average dry unit weight of $\sim$19 kN m^{-3} for the compacted soil samples (= compacted) and of $\sim$15 kN m^{-3} for the loose soil samples (= soil), respectively. Four different treatments were applied including untreated soil samples at the two different dry unit weights as well as loose soil samples ($\sim$15 kN m^{-3}) planted with *Alnus incana* (L.) Moench only (=planted), as well as additionally inoculated with the mycorrhizal fungus *Melanogaster variegatus s.l.* (=mycorrhized).

The inoculation was performed with mycelium – derived from naturally mycorrhized root tips of *A. incana* – of cultures on modified Melin Norkrans (MMN) agar (Marx and Bryan, 1975). The amount of one fourth of a Petri dish was applied to each sample, previously cut into small cubes of about 4 mm^3 under sterile conditions. For the planted and mycorrhized treatments 15 alder seeds were applied to each sample and reduced to three seedlings after four weeks of growing. The samples were arranged completely randomly and maintained in a greenhouse for 20 weeks with 16 h of daylight and a temperature of 17 °C (day) and 10 °C (night), respectively. Totally, 100 samples were subject of aggregate stability tests consisting of 18 compacted, 34 soil, 29 planted and 19 mycorrhized specimens.

2.3. Fungal inoculum

The inoculum applied was originally isolated from mycorrhized roots of *A. incana* plantlets used in trap cultures with the soil material under investigation. The identification of the fungus was performed with a molecular-genetic analysis according to Peter (2000). ITS1 and ITS4 sequences were analysed at the laboratories of the Mycosynth AG (Balgach, Switzerland). A nucleotide query was conducted with the database BLAST (2012, www.ncbi.nlm.nih.gov/blast/Blast.cgi) to find similarities between sequences and to check for the most probable species.

2.4. Aggregate stability experiments and root processing

The determination of the water stability of aggregates was carried out according to a slightly modified protocol of Burri et al. (2009) and Frei (2009). A sieve with mesh openings of 20 mm was placed in a Plexiglas pot. After the greenhouse period, each sample was put singly on the sieve. Subsequently, the pot was filled with water entirely covering the sample. After 5 min, the water was drained. In a next step, the roots of planted as well as of planted and inoculated samples were carefully removed. Then, independent of treatment, the soil portion remaining on the sieve and the one passing (components $\leq$20 mm) were separately oven dried for 24 h at 105 °C. The soil aggregate stability was defined as the dry weight ratio between the components above the sieve (aggregates > 20 mm) and the sum of all components, above and below the sieve. The soil portion remaining on the sieve consisted exclusively of aggregates, as the maximum grain size of the soil samples was 10 mm. The portion passing the sieve was a mixture of single grains and aggregates equal to or smaller than 20 mm.

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 the software WinRhizo ® (2000). The root length per sample volume (cm cm^{-3}) was used as an indicator for plant growth. The degree of mycorrhization

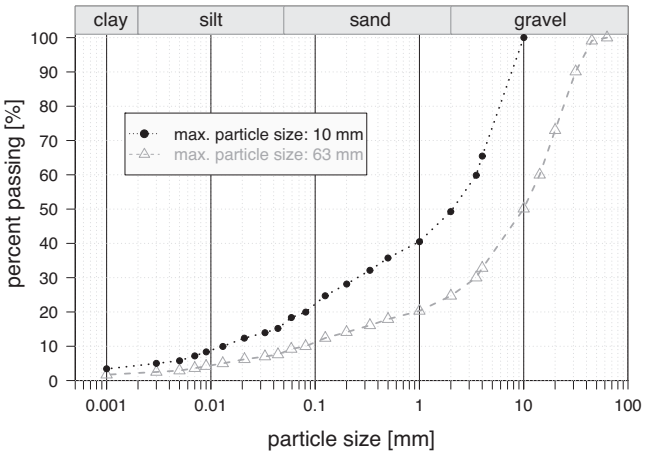

Fig. 1. Grain size distribution curves of the soil material. Δ: distribution curve of the moraine including the coarse grains up to 63 mm, •: distribution curve of the soil material including grain sizes smaller than 10 mm used for all aggregate stability tests in this study as well as for the triaxial compression tests in the study of Graf et al. (2009).

was determined under a stereo microscope (Wild M8) applying the gridline intersection method after Brundrett et al. (1996).

2.5. Statistical analysis

All statistical calculations were performed with the software R 2.15.1 (R Development Core Team, 2012). Differences in aggregate stability, dry unit weight, rooting, and among the four treatments of the 100 successfully maintained samples were calculated with robust statistics. Kruskal–Wallis and pair-wise Wilcoxon rank sum tests were applied considering p-value adjustment for multiple testing (Abdi, 2007). Furthermore, the Pearson and Spearman correlation between aggregate stability, dry unit weight, rooting, and mycorrhization degree were calculated under consideration of all samples (Stahel, 2000).

Due to unbalanced design, a weighting factor (ω) was applied following the formula:

$\omega_i = (N/n_i t)$ with the total number of specimens ($N = \sum_i^t n_i$) divided by the total number of specimens per treatment (n_i, $i = 1, 2, .., t$) and the number of treatments (t).

In order to test the effect of root length on soil aggregate stability, robust simple linear regression models were fitted using an MM estimator (Koller and Stahel, 2011). First aid transformations after Tukey (1957) were applied to the response ($a\sin\sqrt{y}$) and the explanatory variable ($\log_{10}$).

Residual analysis was conducted to check the compliance of the assumptions required and the fit of the models. For that purpose residuals against fitted values (Tukey-Anscombe plot) and against leverages (hat matrix) were analysed as well as the residual distribution and the quantil–quantil plot.

3. Results

3.1. Soil analysis

The grain size distribution including the coarse parts up to 63 mm is divided into: 75.3% gravel, 15.5% sand, 7.1% silt and 2.1% clay (Fig. 1). With a liquid limit of 21.5% and a plasticity index of 8.6% it was classified as clayey gravel with sand (GC-CL). At an optimum water content of 7.9% the maximum dry unit weight was 21.9 kN m^{-3}. The porosity constituted 0.467 m^3 m^{-3}.

Table 1
Cation exchange capacity of the moraine (GC-CL) from the investigation area "Schwandrübi" in Dallenwil-Wirzweli (Switzerland).

	mval kg^{-1}	%
Ca^{2+}	132.70	93.97
Mg^{2+}	6.97	4.94
K^+	1.04	0.74
Na^+	0.50	0.35
Total	141.17	100.00

The $pH_{[CaCl]}$ of the soil material was 7.7 and the organic matter content 0.2 ± 0.1% by weight. The total cation exchange capacity amounted to 141.17 mval kg^{-1}. The corresponding contributions of the individual ions (Ca^{2+}, Mg^{2+}, K^+, Na^+) are listed in Table 1.

3.2. Fungal inoculum

The comparison of the DNA (ITS2, ITS4) with a reference data base of BLAST (www.ncbi.nlm.nih.gov/blast/Blast.cgi) assigned the species under investigation to the genera *Melanogaster* (*Melanogastraceae*). With the molecular data, no further differentiation was possible on species level between *Melanogaster broomeanus* Berk. *apud* Tul. & C. Tul, *M. variegatus* (Vittad.) Tul. & C. Tul., and *M. vittadinii* Soehner *et* Knapp. The latter achieved a slightly higher score in the ITS2 but a somewhat lower one in the ITS4 sequence compared to the former two.

Considering data on ecology, geography, and host species as well as recent taxonomic discussions (Montecchi and Sarasini, 2000), *M. broomeanus* and *M. variegatus* are the ones to be considered. Until further taxonomic clarification we follow a wider species concept and, based on the genus revision of Tulasne and Tulasne (1851), refer to our species as *M. variegatus s.l.* for the time being.

3.3. Correlations and sample characteristics

The 100 samples tested and evaluated were composed of 34 untreated soil samples (= soil), 29 samples planted with *A. incana* (= planted), 19 samples planted with *A. incana* and inoculated with *M. variegatus s.l.* (= mycorrhized), and 18 samples of untreated compacted soil (= compacted). The highest correlation among the considered variables was found between root length per soil volume and mycorrhization degree (0.86). The soil aggregate stability was noticeably correlated with the dry unit weight (0.63) as well as with the mycorrhization degree (0.51). A complete survey on Spearman and Pearson correlation is given in Table 2.

After the 20 week growth period in the greenhouse the dry unit weight was about 19 kN m^{-3} for the compacted samples and around 15.5 kN m^{-3} for the other three treatments (Tabs. 3, 4). The Kruskal–Wallis rank sum test confirmed a significant treatment effect on the dry unit weight ($X^2 = 1248.7$, df = 3, p-value = 2.2×10^{-16}). According to the pairwise Wilcoxon rank sum test the dry unit weight of the compacted samples was significantly higher compared to the other three treatments with

Table 2
Pearson (upper half of the matrix) and Spearman correlation (lower half of the matrix) of soil aggregate stability [0,1], dry unit weight γ [kN m^{-3}], root length per soil volume [cm cm^{-3}], and mycorrhization degree [0,1].

	Aggregation	Dry unit weight	Root length	Mycorrhization
Aggregation	1.00	0.63	0.38	0.51
Dry unit weight	0.57	1.00	0.28	0.16
Root length	0.31	0.09	1.00	0.86
Mycorrhization	0.48	0.02	0.68	1.00

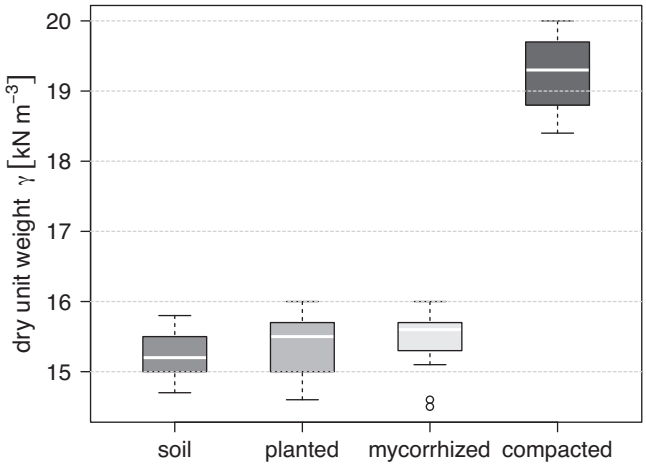

Fig. 2. The dry unit weight γ [kN m^{-3}] of the samples after the 20 week growth period in the greenhouse in dependence of the four different treatments applied (soil, planted, mycorrhized, compacted).

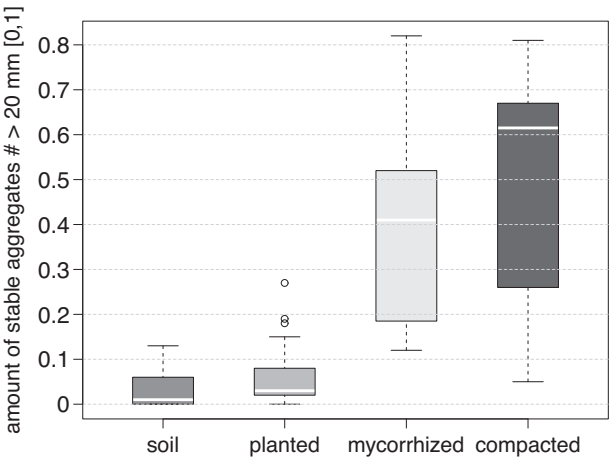

Fig. 3. The aggregate stability in dependence of the four different treatments applied (soil, planted, mycorrhized, compacted), measured as ratio between the dry weight of the stable fraction of particles bigger than 20 mm and the dry weight of the whole sample.

p-values < 0.001. Among these latter three treatments (soil, planted, mycorrhized) no significant differences were noticed (Table 5; Fig. 2).

3.4. Soil aggregate stability and root development

Whereas the mean aggregate stability values of the treatments soil (0.03) and planted (0.06) were higher than the corresponding medians (0.01, 0.03) it was the other way round for the treatments mycorrhized (mean: 0.38, median: 0.41) and compacted (mean: 0.48, median: 0.62). A complete survey on the mean values and corresponding standard deviations as well as medians and median absolute deviations is given in Tables 3 and 4, respectively. The treatment effect on the soil aggregate stability was significant (Kruskal–Wallis: $X^2 = 1538.7$, df = 3, p-value = 2.2×10^{-16}). The pairwise Wilcoxon rank sum test revealed, on the one hand, no significant difference between the treatments mycorrhized and compacted (p-value = 0.176). On the other hand, it turned out that the latter two significantly differed from both soil and planted in all possible combinations with p-values <0.001 (Table 5; Fig. 3).

After the 20 week growth period a significant difference in root length per soil volume [cm cm^{-3}] was found between the inoculated (=mycorrhized) and non-inoculated (=planted)

Table 3
Mean and standard deviation (sd) of soil aggregate stability [0,1] and dry unit weight γ [kN m^{-3}] in terms of the four different treatments (A = soil, B = planted, C = mycorrhized, D = compacted), and of root length per soil volume [cm cm^{-3}] in terms of the treatments B and C.

	Aggregate stability		Dry unit weight		Root length	
	Mean	sd	Mean	sd	Mean	sd
Soil	0.032	0.041	15.2	0.309	0	0
Planted	0.059	0.065	15.3	0.436	0.62	0.196
Mycorrhized	0.380	0.212	15.5	0.415	1.50	0.758
Compacted	0.476	0.263	19.2	0.489	0	0

Table 4
Median and median absolute deviation (mad) of soil aggregate stability [0,1] and dry unit weight γ [kN m^{-3}] in terms of the four different treatments (A = soil, B = planted, C = mycorrhized, D = compacted), and of root length per soil volume [cm cm^{-3}] in terms of the treatments B and C.

	Aggregate stability		Dry unit weight		Root length	
	Median	Mad	Median	Mad	Median	Mad
Soil	0.010	0.015	15.2	0.297	0	0
Planted	0.030	0.030	15.5	0.445	0.59	0.104
Mycorrhized	0.410	0.267	15.6	0.297	1.52	1.127
Compacted	0.615	0.163	19.3	0.667	0	0

Table 5
Kruskal–Wallis and pairwise Wilcox tests of (i) dry unit weight γ [kN m^{-3}] and (ii) soil aggregate stability [0,1] of the four different treatments (A = soil, B = planted, C = mycorrhized, D = compacted), as well as Wilcox test of (iii) root length per soil volume [cm cm^{-3}] of the treatments B and C (bold numbers: significant p-values).

(i)
Dry unit weight ~ treatment (A, B, C, D): $X^2 = 1248.7$, p-value < $\mathbf{2.2 \times 10^{-16}}$

	Soil	Planted	Mycorrhized
Planted	1.00		
Mycorrhized	0.052	1.00	
Compacted	$\mathbf{2.3 \times 10^{-8}}$	$\mathbf{6.7 \times 10^{-8}}$	$\mathbf{1.2\ 10^{-6}}$

(ii)
Aggregate stability ~ treatment (A, B, C, D): $X^2 = 1538.7$, p-value < $\mathbf{2.2 \times 10^{-16}}$

	Soil	Planted	Mycorrhized
Planted	0.025		
Mycorrhized	1.2×10^{-8}	1.7×10^{-7}	
Compacted	1.1×10^{-7}	6.5×10^{-7}	0.176

(iii)
Root length per soil volume ~ treatment (B,C): $W = 57.5$, p-value < $\mathbf{4.5 \times 10^{-6}}$.

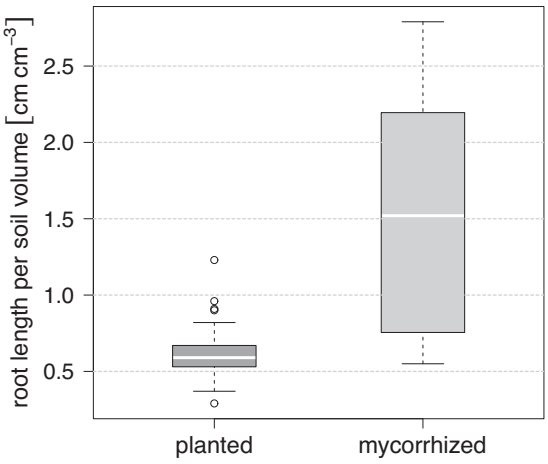

Fig. 4. The rooting performance of *Alnus incana* plantlets after the 20 week growth period in the greenhouse measured as the root length per soil volume [cm cm^{-3}]: 29 non-inoculated individuals (planted, dark grey) and 19 inoculated with *Melanogaster variegatus s.l.* (mycorrhized, light grey).

samples (Fig. 4). The average value of mycorrhized roots was 1.5 (±0.76) cm cm^{-3} compared to 0.62 (±0.20) cm cm^{-3} for non-mycorrhized roots (Tables 3 and 4). According to the Wilcox rank sum test this difference was significant ($W = 57.5$, p-value = 4.5×10^{-6}). The mean value of the mycorrhization degree and the corresponding standard deviation were 46.1% ± 24.0.

The simple linear regression models for soil aggregate stability as a function of root length per soil volume of the treatments planted, mycorrhized, and the combination of them revealed significant positive root effects with p-values <0.001 (Fig. 5). The respective Spearman correlation was 0.57 (planted), 0.86 (mycorrhized), and 0.83 (combination).

4. Discussion

Eco-engineering methods generally aim at contributing to slope stability. The successful application of biological measures

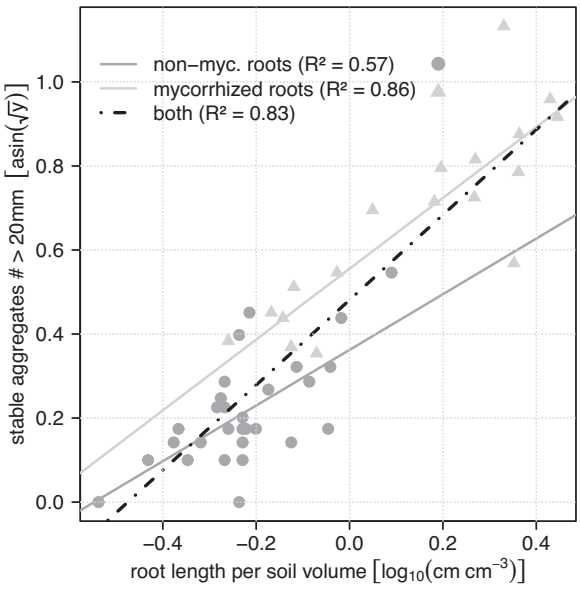

Fig. 5. Simple linear regression models of soil aggregate stability [asin($\sqrt{y}$)] as a function of root length per soil volume [log$_{10}$(cm cm^{-3})] of non-mycorrhized (dark grey), mycorrhized roots (light grey) and the combination of them (black dash-dot line).

demands, however, certain restrictive requirements in respect of soil structural stability and, concomitant, water and nutrient supply (Graf, 1997; Graf et al., 2006). The formation of soil aggregates is a key process with regard to these essential requirements and it is widely accepted that stable micro- and macro-aggregates are interactively assembled by micro-organisms (bacteria, fungi) and plant roots (Rillig and Mummey, 2006).

The results of the present investigation dovetail with this concept showing significant increases in soil aggregate stability from pure soil samples without roots to the planted samples with a root length of 0.6 cm cm^{-3} to the samples with mycorrhized roots (1.5 cm cm^{-3}). Furthermore, a high positive linear correlation is obvious between soil aggregate stability and root length per soil volume for non-mycorrihzed and, even more pronounced, for mycorrihzed roots (Fig. 5). The difference in aggregate stability between pure and planted soil can be attributed to stabilising effects of the roots, particularly mechanical armouring. It is, however, more difficult to untangle the considerable increase in stable aggregates from the planted to the mycorrhized samples. It seems obvious that the mycorrhizal fungus, on the one hand, stimulated root growth (Figs. 4 and 5). Such phenomenon has been recorded for many host plants of both arbuscular and ectomycorrhiza (Smith and Read, 2008). Within this study this is supported by a correlation coefficient of 0.86 between root length and mycorrhization degree and the fact that alder plantlets inoculated with *Melanogaster variegatus s.l.* produced more than twice the root length per soil volume compared to the non-inoculated specimen. On the other hand it is quite likely that the fungus directly increased soil aggregate stability.

According to Rillig and Mummey (2006) the direct effects of fungal mycelia on soil aggregate stability can be loosely categorised into biochemical, biophysical, and biological processes. Biochemically and with respect to the ectomycorrhizal species used in this study, mucilages, polysaccharides, and other extracellular compounds may have contributed to soil aggregate stability (Chenu, 1989; Caesar-Ton That et al., 2001; Bogeat-Triboulot et al., 2004; Ambriz et al., 2010) as well as hydrophobins and related proteins which are supposed having a functional role in soil aggregation (Tagu et al., 2001; Mankel et al., 2002; Linder et al., 2005).

Another stabilising process is the alignment of primary particles, such as clay. Growing hyphae are able to exert pressure on particles of their nearest neighbourhood forcing clay and organic matter together (Tisdall, 1991; Chenu and Stotzky, 2002). Under physiological (or neutral) pH values, micro-organisms have a net negative charge and mostly amino- and carboxyl groups on their surface (Marshall, 1988). In a study on fungal bioweathering (Burford et al., 2003) it was found that soil aggregates stabilised by extracellular polysaccharides persisted for longer when polyvalent cations, e.g. Al^{3+} or Ca^{2+} were present, suggesting that negatively charged polysaccharides were bound to negatively charged clay particles by bridges of polyvalent cations (Martin, 1971). Likewise, such bridges are formed between fungal hyphae and particles of clay having proven to be stronger than some direct bonds between clay and organic matter (Tisdall, 1991).

About 99% of the total cation exchange capacity of the moraine used in this study was made up by the polyvalent cations Ca^{2+} and Mg^{2+}. Therefore, as all negative charges on clay minerals are neutralised, only a thin layer of positive charge surrounds the clay particles. Irrespective of equal charges, this thin layer may have enabled particles to come close together for attractive Van der Waals' forces to take hold and for the clay to flocculate which further supported the soil aggregation process. Although this process proceeds independently of micro-organisms, the fungal mycelial network multiplies the effect, forms stronger bonds, and overcomes spatial limitations (Tisdall, 1991; Rillig and Mummey, 2006).

Table 6
Comparison of aggregate stability (A: this study) and angle of internal friction Φ' (B: Graf et al., 2009) as well as dry unit weight γ and root length per soil volume from both studies (A, B). All experiments were performed with the same soil (moraine) and plant material (*Alnus incana*); n.a.: not available.

	Soil		Planted		Mycorrhized	Compacted	
	A	*B*	*A*	*B*	*A*	*A*	*B*
Dry unit weight [kN m^{-3}]	15.2	15.7	15.3	15.3	15.5	19.2	18.9
Root length [cm cm^{-3}]	0	0	0.6	1.3	1.5	0	0
Aggregate stability [0,1]	0.03	n.a.	0.06	n.a.	0.38	0.48	n.a.
Angle of internal friction [°]	n.a.	34.3	n.a.	39.4	n.a.	n.a.	40.1

The important role of fungal and clay interactions in the processes of soil evolution has been shown amongst others by the investigation of Tisdall et al. (1997) on soil clay aggregation by saprophytic (*Rhizoctonia solani* and *Hyalodendron* sp.) and mycorrhizal fungi (*Hymenoscyphus ericae* and *Hebeloma* sp.).

From a biophysical point of view, hyphae enmesh and entangle small inorganic and organic soil particles in the manner of roots but on a smaller scale (Tisdall and Oades, 1982; Miller and Jastrow, 2000). Interdependently, roots and mycorrhizal hyphae contribute to the stability of micro- and macro-aggregates at different scales and, consequently, to the stability of the soil structure, i.e. the soil matrix and its corresponding void space. Ambriz et al. (2010) reported positive and significant correlation between root volume of *Fraxinus uhdei* and water stable aggregates for plants inoculated with the arbuscular fungus *Glomus intraradices* for aggregates of 0.25 mm and inoculated with the ectomycorrhizal species *Pisolithus tinctorius* for aggregates of 1.0 and 0.5 mm. Bedini et al. (2009) found significantly higher amounts of stable aggregates of 1–2 mm in mycorrhizal compared to non-mycorrhizal soil which was further positively correlated with mycorrhizal root volume as well as with the total hyphal length and hyphal density of arbuscular mycorrhizal fungi. According to Bearden and Petersen (2000) and Bearden (2001) the formation of aggregates in the class 1–2 mm is associated with hyphal length of the mycorrhizal fungi and not with root growth. However, both parameters are involved in the formation of aggregates >2 mm. It is not possible to fractionate the contribution of roots and fungal hyphae for the present study, due to the fact that hyphal length was not addressed. However, the considerable correlation (0.51) between soil aggregate stability and mycorrhization degree seems to support the direct effect of the fungus.

Different to other methods used to assessing soil aggregate stability (Kemper and Rosenau, 1986; Le Bissonnais, 1996; Le Bissonnais and Arrouyas, 1997; Le Bissonnais et al., 2007) we did not focus on small aggregates <2 mm and distinguish macro- (>250 μm) from microaggregates (<250 μm) as proposed by Tisdall and Oades (1982). Instead, the starting soil material was composed of a loose mixture of grain sizes ≤10 mm and, in terms of soil aggregate stability, only components >20 mm were considered, representing the next higher class of grain size from a geotechnical point of view (Fig. 1).

This approach was chosen on the basis of soil mechanical considerations, particularly in order to be compatible with conventional methods addressing soil stability, e.g. triaxial compression test, as well as due to biological reasons. Superficial soil failure related to heavy rainstorms is mainly due to water saturation and corresponding excessive pore water pressure (Iversen, 2000; Kuriakose et al., 2008) and, therefore, directly linked to the stability of the pore structure and the relevant soil matrix. In order to test the biological effects on aggregate stability in terms of resistance against slaking (Le Bissonnais, 1996) a certain volume of the specimen is required to fit for appropriate root development and to ensure the vadose zone is representative in view of natural superficial soil conditions, i.e. distribution of macro-, meso-, and micro-pores according to the relevant soil classification (GC-CL in this study). Both aspects are reasonably well accommodated by the specimen size used in this study (height: 140 mm; diameter: 70 mm) which is a standard for triaxial compression tests, allowing a maximum grain size <1/5 of the specimen diameter (DIN18137-2, 2011; Arnold et al., 2005).

Due to these adaptations of sample size and aggregate dimension of peculiar interest, the results may differ from other studies using "small-scaled approaches" (Le Bissonnais et al., 2007). However, with regard to slope stability and, in particular, to the quantification of biological effects on a large scale, the method used in this study is supposed to be more reliable. Additionally, it has the advantage of comparability to standardised soil mechanical test procedures.

Whereas the key role of soil aggregate stability in ecosystem functioning is well known concerning water, gas, and nutrient fluxes (Angers and Caron, 1998; Amezketa, 1999; Eldridge and Leys, 2003; Wick et al., 2009), only limited information is available with regard to soil mechanical and geotechnical aspects. Although, some investigations on the effectiveness of soil aggregate stability in view of protecting against erosion processes have been performed (Barthès and Roose, 2002; Barni et al., 2007; Canton et al., 2009; Graf et al., 2009; Pohl et al., 2009, 2012) almost nothing is known in terms of slope stabilisation to preventing superficial landslides.

In order to confer the effects of plants and mycorrhizal fungi on soil aggregation to parameters relevant to slope stability assessment, it is indispensable to correlate them somehow to conventional soil failure concepts. From a simplified soil mechanical perspective the angle of internal friction (Φ') characterises the stability of a cohesion-less soil as was the moraine used in this investigation (Terzaghi and Peck, 1967).

Recently, a new approach has been proposed assigning biologically induced soil aggregate stability to the angle of internal friction (Φ') in view of quantifying vegetation effects on slope stability (Böll and Graf, 2001; Frei, 2009). Based on triaxial compression tests using the same moraine, plant material, and sample sizes as in the present study (Table 6), it was found that planted specimen (without mycorrhizal treatment) increased the angle of internal friction by ~5° (Graf et al., 2009). This gain in stability was comparable to the increase in Φ' due to the compaction effect of pure soil samples from a dry unit weight γ = 15.7 to γ = 18.9 kN m^{-3} (Table 6). A similar effect was found in the present study for aggregate stability. The increase from 0.03 for pure soil with a dry unit weight γ = 15.2 kN m^{-3} to 0.48 for compacted soil with γ = 19.2 kN m^{-3} is approximately in the same order as the one for soil planted with mycorrhized alder with a dry unit weight γ = 15.5 kN m^{-3} yielding an aggregate stability of 0.38 (Table 6; Figs. 2 and 3). It seems evident from the data and physically plausible that the angle of internal friction (Φ') as well as the aggregate stability of pure moraine are each positively correlated with the dry unit weight and, consequently, are for their part, too. This coherence and the fact that Φ' of compacted moraine and planted moraine of lower dry unit weight correspond quite well, suggest the assumption that the stability effect of roots may be expressed as a virtual increase in γ. The same supposition may be made for soil

aggregate stability of compacted moraine and moraine with mycorrhized plants. No such conclusion can be drawn for the planted moraine without mycorrhiza for which aggregate stability was significantly lower compared to the compacted and mycorrhized treatments (Table 5). Furthermore, a pairwise Wilcox Test of the root data from both investigations (Graf et al., 2009; this study) revealed that root length per soil volume of the planted moraine of Graf et al. (2009) significantly differed from the planted moraine of this study (p-value = 0.02) but not compared to the planted and mycorrhized samples (p-value = 0.62). Based on these relationships it seems, therefore, acceptable to compare the findings on the angle of internal friction of planted moraine (Graf et al., 2009) with those of the aggregate stability of the samples with mycorrhized plants. By doing so, the joint stability effect of mycorrhiza and plants corresponds to a virtual increase in dry unit weight by $\sim 4\,kN\,m^{-3}$ which corresponds to an effective increase in the angle of internal friction by $\sim 5^\circ$ (Table 6).

That it is not only idle speculation is indicated by the technique of estimating the angle of internal friction (Φ') based on the grain size distribution curve with corrections after Brinch Hansen (in Lang and Huder, 1994). Given the distribution of the soil material classified as GC-CL the estimation of Φ' for the loose material is $\sim 34^\circ$. With the proposed surplus of up to 6° for compaction we finally have $\Phi' \approx 40^\circ$ which is in line with the results of both the triaxial compression tests and, linked by the dry unit weight γ, with the soil aggregate stability analysis (Table 6).

It is subject to speculation if the angle of internal friction (Φ') will further increase in samples with mycorrhized plants. There is, however, some evidence to suggest it. Michalowski and Čermák (2002, 2003) found that the reinforcing effect of fibres in sand is positively correlated with the length of the fibres. Furthermore, Zhang et al. (2006) demonstrated a positive correlation between the shear strength of sand and the complexity of 3D structures added. Graf et al. (2009) reported the highest mobilised shear strength $\Phi' = 41.03^\circ$ (1.64° above the mean value, Table 6) of planted moraine from the sample with the highest root length ($2.17\,cm\,cm^{-3}$) which was about twice the mean value (Table 6). They also observed higher ramification degrees of lateral roots in samples with higher root length per soil volume. Therefore, mycorrhiza may impact on Φ' at least indirectly by its effect on root growth, positively impinge on both root length and ramification.

In the course of this argumentation, the poor aggregate stability of the planted samples compared to them with mycorrhiza can be mainly explained by the 2.5 times lower root length. However, under consideration of the method applied for quantifying soil aggregate stability, the direct fungal effect should not be ignored. It is not just that root length was less than half and ramification low without mycorrhiza. It is also the lack of a fine-meshed hyphal network firmly adhering soil among as well as in the space in between roots and, therefore, eliminating spatial constraints with regard to a continuous three-dimensional structure of stable micro- and macro-aggregates (Bogeat-Triboulot et al., 2004). Due to the tensile strength of fungal hyphae (Li et al., 2002), aggregates enmeshed by mycelia may act as "flexible string bags" and mobilise a certain plasticity to withstand pore water pressure and, therefore, prevent brittle fracture.

Consequently, with regard to the quantification of biological effects on soil aggregate stability and the angle of internal friction Φ' as well as in order to reduce uncertainties of their correlation and facilitate practical application, it is indispensable to consider mycorrhizal fungi. In doing so, it seems reasonable to utilise aggregate stability as a measure for biological effects in soil and slope stability calculations in terms of the angle of internal friction Φ' and, probably, as well as for assessing and quantifying the effectiveness of eco-engineering methods.

5. Conclusions

With respect to landscape restoration the positive influence of mycorrhizal fungi in different ecosystems has been found important in order to promote the relevant plant communities. However, on severely degraded soil, the natural recovery potential of the symbiotic fungi is considerably impeded and the species composition of adjacent intact regions may not necessarily fit the requirements of the site to be re-colonised. Therefore, the application of indigenous plant species with carefully selected mycorrhizal fungi is an excellent eco-engineering measure to initiate and accelerate the re-colonisation of slopes affected by superficial soil failure.

Based on such an integral approach it has been demonstrated with the present study that soil aggregate stability considerably increases and, from a soil mechanical perspective, likewise the soil stability expressed by the angle of internal friction Φ'. The resulting higher resistance of the soil with respect to superficial failure is first and foremost due to better plant root performance and the direct fungal impact on micro- and macro-aggregation. The positive correlation between Φ' and soil aggregate stability deduced from their correlations with the dry unit weight γ is suggesting to estimate and calculate biological effects related to slope stability based on soil aggregation in place of the demanding and time-consuming determination of the angle of internal friction Φ'. However, what was demonstrated for one soil type (GC-CL) and the natural "restoration package" *Alnus icana* with *Melanogaster variegatus s.l.* needs to be verified with other soils and plant-fungus combinations.

If appropriate, the application of carefully selected mycorrhizal inoculi in eco-engineering will be doubtlessly an important step towards more sustainability as well as easier integration into engineering concepts and risk management. Moreover, the biological contribution to slope stability will finally get its true worth in slope stabilisation and protection against superficial soil failure.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecoleng.2013.04.037.

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