Soil Aggregate Stability in Eco-engineering: Comparison of Field and Laboratory Data with an Outlook on a New Modelling Approach

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Abstract. Stabilisation effects of plants are developing as a function of time. Within this scope, soil aggregation processes play a decisive role in re-establishing a protective vegetation cover. From this perspective we compared bare and vegetated soil, on the one hand artificially prepared and, on the other hand, derived from a recently landslide affected slope and an adjacent gully with 25 year old eco-engineering measures, respectively.

In both cases, the planted specimens had a significantly higher soil aggregate stability compared to their respective control samples, with the relative increase from control to planted equal for both the natural and artificial samples.

Aspects of the development and succession processes of plants are compared as well as rooting and the degree of mycorrhization. Additionally, soil development and the methodical approach are discussed as well as a new approach to modelling soil aggregate stability in respect of eco-engineering measures for slope stabilisation presented.

Keywords: soil aggregate stability, root length, mycorrhiza, field and laboratory samples, modelling, particle flow code (PFC).

1 Introduction

Eco-engineering combines technical and biological measures in order to re-colonise and re-stabilise slopes affected by heavy erosion or landslide processes [1]. For the engineering part several guidelines and standards exist for structural safety as well as maintenance of the technical constructions [2]. However, in respect of the biological part such information is almost completely missing.

In recent years the need to quantify and monitor the effectiveness of the vegetation has been postulated time and again, in particular with regard to the re-stabilisation of

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slopes affected by landslides [3, 4, 5, 6, 7, 8]. Latest concepts in restoration ecology favour an integrated monitoring approach considering different important parameters which is, however, often too time consuming and expensive [9, 10]. Consequently, indicators reflecting multiple aspects are of particular interest in order to overcome the too complex approaches. Besides the fractal dimension of soil particle size distribution and several microbiological parameters, soil aggregate stability has been proposed [11, 12, 13, 14, 15, 16].

The strength of soil aggregates is not only critical to the stability of slopes but plays a key role in ecosystem functioning in general. It mirrors the trait of soil to withstand whatsoever stresses, including superficial soil failure [17, 18] but is additionally a key parameter in ecosystem functioning in general with regard to water, gas, and nutrient fluxes affecting growth and development of all soil organisms [17, 20, 21, 22]. Not by chance, therefore, soil aggregate stability has been suggested as an indicator reflecting multiple aspects allowing extensive information on ecosystem status to be gathered in a relatively short time, in particular in respect of protecting slopes from erosion and shallow mass movements.

With respect to the re-stabilisation of steep slopes affected by superficial soil failure with eco-engineering methods, soil aggregate stability seems preferentially suited. It represents both critical states of plant growth and soil [23, 24]. Furthermore, it seems possible to link this parameter to traditional slope failure models such as the criterion of Mohr-Coulomb [25, 26]. Based on triaxial compression tests with planted and unplanted samples, it was found that soil aggregate stability correlates with the shear strength of the soil, which is a most critical factor of slope stability [27, 28]. This finding implies that soil aggregate stability may reflect the plants' contribution to superficial slope stability and, as a consequence, spurs the development of new approaches for modelling soil stability in general and for slope failure calculations in particular under due consideration of biological effects [29, 30, 31, 32].

Soil aggregate stability is addressed in various ways, differing methodologically and in scale [33, 34, 35, 36]. The variety of approaches, the lack of standardisation, and the application on field as well as laboratory samples complicates the comparison of results from different investigations.

Unlike proposed for other methods assessing soil aggregate stability, we did not focus on small aggregates < 2 mm and, consequently, did not distinguish macro- (> 250 μm) from micro-aggregates (≤ 250 μm) as suggested by [37]. Differently, the starting soil material was composed from a coarse moraine sieved to 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 [32], [38]. This approach is particularly advantageous in order to be compatible with conventional methods addressing soil stability, e.g. triaxial compression test, as well as due to biological reasons. In order to test biological effects on aggregate stability in terms of resistance against slaking [34] 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 [32].

The focus of this article is on the comparison of soil aggregate stability of natural specimens taken from a recent sliding area with samples artificially prepared and maintained in the laboratory using the pure soil material from the same location. A main goal of this analysis was to determine whether soil aggregate stability, naturally increased along with soil and vegetation development over years in a landslide area, is correlated with artificially planted samples developing within months under laboratory conditions. The results are discussed under consideration of methodological aspects, natural soil and plant development including succession processes as well as in view of eco-engineering measures for slope stabilisation. Furthermore, a new approach to modelling superficial soil failure based on a concept of soil aggregate stability and plant development is presented.

2 Material and Methods

2.1 Investigation Area, Soil Material, and Vegetation

The soil material for preparing the laboratory samples was taken from the moraine of the subalpine landslide area "Hexenrübi" (Dallenwil-Wirzweli, Central Switzerland) in 2005. The natural samples, serving as non-planted control, originated from this area, too. In the same year the natural samples representing the planted stage were collected in the adjacent gully "Schwandrübi" which was stabilised with combined technical and biological measures in 1982. The eco-engineering measures particularly consisted of gabions, log cribwalls as well as *Salix purpurea* cuttings and plantlets of *Alnus incana* [38]. At the time of soil sampling the vegetation of the Hexenrübi was represented by a few and sparsely distributed pioneer herb and grass species with a coverage of < 3% whereas in the Schwandrübi a well-developed *Alnetum incanae* (Lüdi) with a considerable number of tree, brush, herb and grass species covered 153% [39].

The moraine was analysed physically and chemically as well as geotechnically classified including particle size distribution, liquid limit, and plasticity index [40, 41, 42]. Furthermore, proctor standard compaction tests were conducted [43]. From oven dried material (24 h at 105°C) the fractions ≤ 10 mm were used to prepare the laboratory samples.

2.2 Laboratory Sample Preparation

All samples were prepared with a water content of 6 % in PVC- plastic tubes (diam.: 70 mm; height: 140 mm) aiming for an average dry unit weight of ~15 kN m^{-3}. The planted samples were planted with *Alnus incana* (L.) Moench (White Alder) and inoculated with the mycorrhizal fungus *Melanogaster variegatus s.l.* (Vittad.) Tul. & Tul. Fifteen alder seeds were applied to each sample and reduced to three seedlings after four weeks of growing. Inoculation was performed according to [32]. The samples were maintained in a greenhouse for 20 weeks with 16 h of daylight and a temperature of 17°C (day) and 10°C (night), respectively. Finally, 20 samples each of the control and planted treatment were used for the soil aggregate stability test.

2.3 Field Sample Preparation

According to [38] a steel soil-coring apparatus was used to collect the field samples. Twenty samples of non- planted moraine from "Hexenrübi" (control) and planted soil from the same moraine in "Schwandrübi" (planted) were taken. Following this procedure, each sample was pushed into a plastic tube (diameter: 50 mm; height: 200 mm) placed inside the steel corer. Subsequently, the samples were maintained for 3 to 5 days in a refrigerator at 4°C until further processing continued. Prior to the soil aggregate stability test, the samples were divided into two parts of about 100 mm of which only the parts corresponding to the soil depth 0-10 cm were considered.

2.4 Soil Aggregate Stability Analysis

The determination of the water stability of soil aggregates followed the protocol described in [38] for the field samples and [32] for those artificially produced. This wet-sieving method using a sieve with mesh openings of 20 mm was applied 3-5 days after sampling in the field and after the greenhouse period of 20 weeks with regard to the laboratory samples. Each sample was tested individually and the aggregated portion remaining on the sieve (aggregates > 20 mm) and the passing part (components ≤ 20 mm) were separately oven dried for 24 h at 105 °C. Soil aggregate stability for the laboratory samples was defined as the dry weight ratio between the components above the sieve (aggregates > 20 mm) and the sum of all components.

With respect to the field samples a correction for non-aggregated particles > 20 mm was applied (Equation 1).

$$agg = \frac{m_{20} - m_{stones}}{m_{tot} - m_{stones}} \quad \left[\frac{g}{g}\right] \tag{1}$$

agg = soil aggregate stability [g g^{-1}]
m_{20} = dry weight of the soil material remaining on the sieve [g]
m_{stones} = dry weight of stones with a diameter > 20 mm [g]
m_{tot} = dry weight of the entire soil sample [g]

2.5 Root Length and Mycorrhization Degree

Immediately after the soil aggregate stability test the roots of the samples were carefully cleaned from soil, spread in a water-filled transparent plastic container, and analysed with a flat-bed scanner using the software WinRhizo® [44]. Total root length was addressed and the root length per sample volume [cm cm^{-3}] calculated. The degree of colonisation by ecto-mycorrhizal fungi (alder roots) was determined under a stereo microscope (Wild M8) applying the gridline intersection method after [45].

With regard to the field samples only alder roots were considered for ecto-mycorrhizal quantification and, therefore, all other roots, particularly those of grasses and herbs (arbuscular mycorrhiza) were not included in the evaluation. A rough estimation of arbuscular mycorrhiza is given by their spore abundance (Equation 2).

Spores were isolated from four samples per plot (control, planted) each of 30 g by centrifugation using a 70%-sucrose gradient [39], [46].

$$abundance = \frac{n_{spores}}{m_{dw\ soil}} \left[\frac{n}{1\,g}\right] \quad (2)$$

with n_{spores} as the number of spores of arbuscular fungi and m_{dwsoil} the dry weight of the soil sample.

2.6 Statistical Analysis

All statistical calculations were performed with the software R 3.0.2 [47]. Differences in soil aggregate stability, rooting, and mycorrhization degree were analysed with robust statistics applying Kruskal-Wallis and pair-wise Wilcoxon rank sum tests considering p-value adjustment for multiple testing in the latter case [48]. In respect of soil aggregate stability additional analysis was conducted with scaled data [49]. Furthermore, mean values and standard deviation, median and median absolute deviation (mad) as well as the Spearman correlation between aggregate stability, rooting, and mycorrhization degree were calculated [50]. In respect of the mycorrhization degree, field samples were not taken into account as only roots of alder were considered but not those of arbuscular mycorrhized grasses and herbs.

3 Results

3.1 Soil Material

The moraine was geotechnically classified as a glayey gravel with sand (GC-CL). The liquid limit was 21.5%, the plasticity index 8.6%, the maximum dry unit weight 21.9 kN m^{-3} at an optimum water content of 7.9%, and the porosity 0.467 m^3 m^{-3}.

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 were: 132.7 mval kg^{-1} (93.97%) for Ca^{2+}, 6.97 mval kg^{-1} (4.94%) for Mg^{2+}, 1.04 mval kg^{-1} (0.74%) for K^+, and 0.50 mval kg^{-1} (0.35%) for Na^+.

3.2 Location and Dispersion Parameters

With regard to the soil aggregate stability, there was no obvious difference between mean value and median and standard deviation (sd) and median absolute deviation (mad), respectively, except for the control samples of the laboratory where mean and sd were an order of magnitude higher than the corresponding median and mad (Tab. 1).

Table 1. Mean, standard deviation (sd), median, and median absolute value (mad) of soil aggregate stability [0,1] in terms of the four different treatments (field control, field planted, laboratory control, laboratory planted)

Soil aggregate stability	mean	sd	median	mad
field samples control	0.378	0.171	0.385	0.104
field samples planted	0.729	0.192	0.710	0.208
laboratory samples control	0.028	0.039	0.005	0.007
laboratory samples planted	0.374	0.208	0.350	0.245

Mean and sd and median and mad of root length per soil volume from the field control samples, respectively, differed again an order of magnitude. No obvious deviation was observed for the other treatments as far as root length is concerned. The same holds true for the corresponding values of the ecto-mycorrhization degree of *Alnus incana* (Tab. 2)

Table 2. Mean, standard deviation (sd), median, and median absolute value (mad) of root length [cm cm^{-3}] and mycorrhization degree [0,1] in terms of the four different treatments (field control, field planted, laboratory control, laboratory planted). *: in the planted field samples only the roots of *Alnus incana* were considered for determining the ecto-mycorrhization degree.

Root length, mycorrhization	mean	sd	median	mad
root: field samples control	0.105	0.214	0.010	0.015
root: field samples planted	1.506	0.666	1.535	0.445
root: lab samples planted	1.482	0.740	1.375	0.927
mycorrhiza: field samples planted *	0.643	0.097	0.605	0.096
mycorrhiza: lab samples planted	0.454	0.224	0.415	0.282

3.3 Correlations and Tests

Correlation between soil aggregate stability and root length per soil volume was generally high but considerably higher in the planted laboratory samples. If control and planted samples of the field are considered together, due to the reason that in the control samples a few roots were observed too, the correlation increases substantially, however, still stays below the coefficient of planted laboratory samples (Tab. 3).

In respect of mycorrhization in the planted laboratory samples, the comparison with soil aggregate stability and root length per soil volume resulted in correlations of 0.88 and 0.89, respectively (Tab. 3). Planted field samples were not considered for this comparison, as the quantification of mycorrhization was restricted to alder roots, which only constituted a certain part of the whole root system in each sample.

Root length per soil volume significantly differed between planted samples of both laboratory and field samples and the control samples of the field (p-values = $3.6\ 10^{-07}$) – no roots were present in the laboratory control samples. However, no such significance was observed between planted samples of the laboratory and the field (Fig. 1).

Table 3. Spearman correlation between soil aggregate stability and root length / mycorrhization as well as between root length and mycorrhization for different sets of samples (all = planted + control)

variables	samples	correlation
aggregate stability x root length	lab samples (planted)	0.87
	field samples (planted)	0.51
	field samples (all)	0.68
aggregate stability x mycorrhization	lab samples (planted)	0.88
root length x mycorrhization	lab samples (planted)	0.89

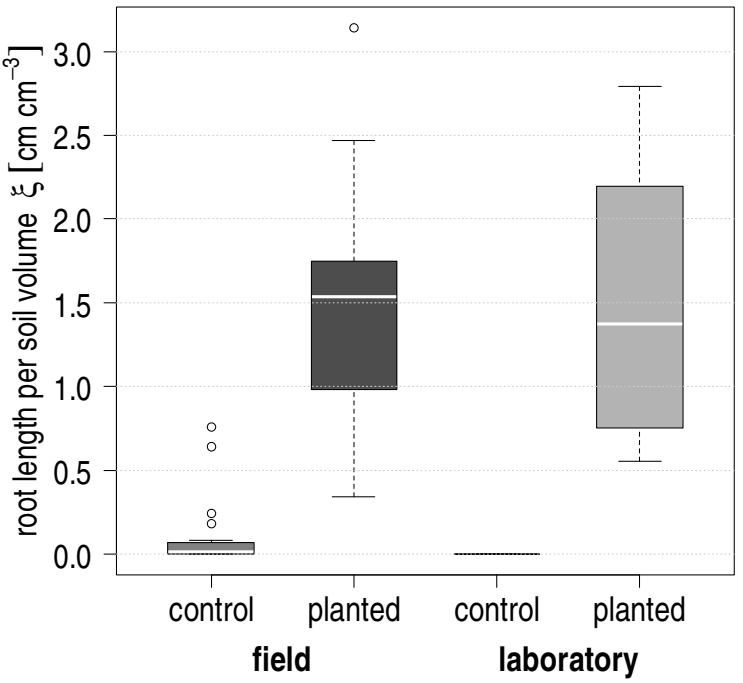

Fig. 1. Boxplots showing the data distribution of root length per soil volume of all samples

The mycorrhization degree of the planted laboratory samples, which consisted exclusively of ecto-mycorrhizal alder roots, was significantly lower (p-value = 0.015) compared to the ecto-mycorrhization degree of alder roots in the planted samples of the field (Fig. 2). In the latter samples arbuscular mycorrhizal roots were present too, however not considered for evaluation of the mycorrhization degree.

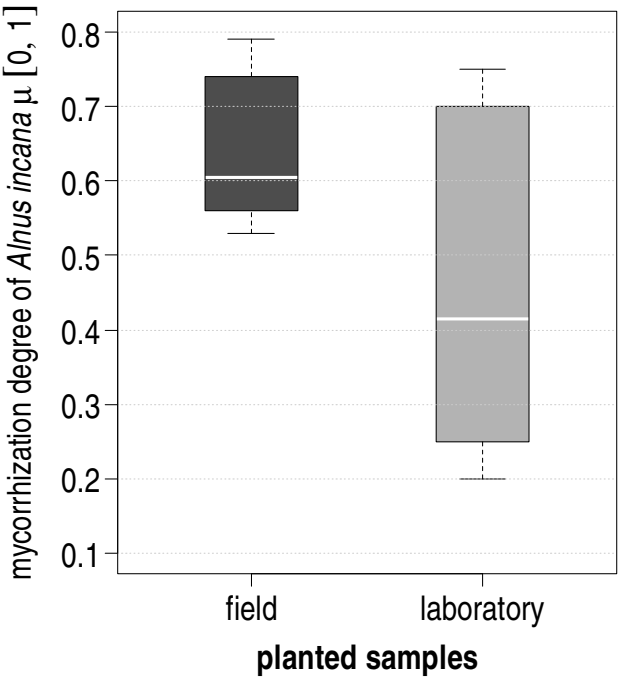

Fig. 2. Boxplots showing the distribution of the mycorrhization degree of *Alnus incana* of the planted samples (field and laboratory)

A significant increase (p-value = 0.013) in spores of arbuscular mycorrhizal fungi was found between the control and the planted field samples. Whereas in the former only 2 (±2) spores per Gramm dry weight of the soil material were found, 30 (±6) spores were counted in the latter. A comparison with regard to the ecto-mycorrhiza in these samples was not meaningful as no ecto-mycorrhizal roots were found in the control samples and, therefore, the degree of ecto-mycorrhization was zero for all specimens (Fig. 3). The mean of the ecto-mycorrhization degree of alder roots in the planted field samples was 0.63 (±0.14).

Asymptotic Kruskal-Wallis tests applied to the soil aggregate stability data of both original and scaled data sets indicate significant differences with p-values of $1.15\ 10^{-12}$ ($\chi^2 = 58.63$) and $6.3\ 10^{-11}$ ($\chi^2 = 50.48$), respectively. The significances of the pairwise Wilcoxon comparisons are shown in Table 4.

In respect of the original data, all sample categories differ significantly from each other except the control samples of the field and the planted samples of the laboratory (p-value = 1.0). Differently, the scaled data show significant differences between planted and control samples but not among themselves ($p\text{-value}_{control} = 0.64$, $p\text{-value}_{planted} = 0.95$). In Figure 4 the distribution of original and scaled data is illustrated.

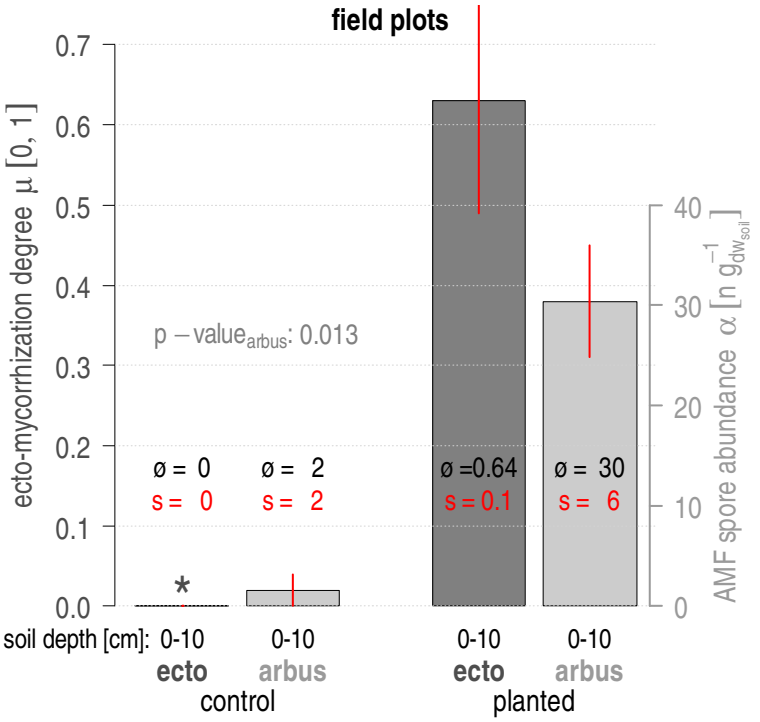

Fig. 3. Barplots with information on distribution, mean (ø), and standard deviation (s) of the degree of ecto-mycorrhization (ecto, left y-axis, dark grey bars) and the abundance of spores (arbus, right y-axis, light grey bars) of arbuscular mycorrhizal fungi (AMF) in the control and planted samples of the field. The p-value indicates significant difference of abundance of AMF spores between control and planted samples. *: no ectomycorrhizal plants found.

Table 4. Comparison of soil aggregate stability of the field and laboratory samples (control and planted) applying pairwise Wilcoxon rank sum test with the p-adjustment method of [48] once for original and once for scaled data. Bold numbers indicate non-significant results.

Original data	field (control)	field (planted)	lab (control)
field (planted)	$2.4\ 10^{-05}$		
laboratory (control)	$3.3\ 10^{-07}$	$3.2\ 10^{-07}$	
laboratory (planted)	**1.0**	$4.9\ 10^{-05}$	$3.2\ 10^{-07}$

Scaled data	field (control)	field (planted)	lab (control)
field (planted)	$2.4\ 10^{-05}$		
laboratory (control)	**0.64**	$1.2\ 10^{-06}$	
laboratory (planted)	$7.2\ 10^{-06}$	**0.95**	$3.2\ 10^{-07}$

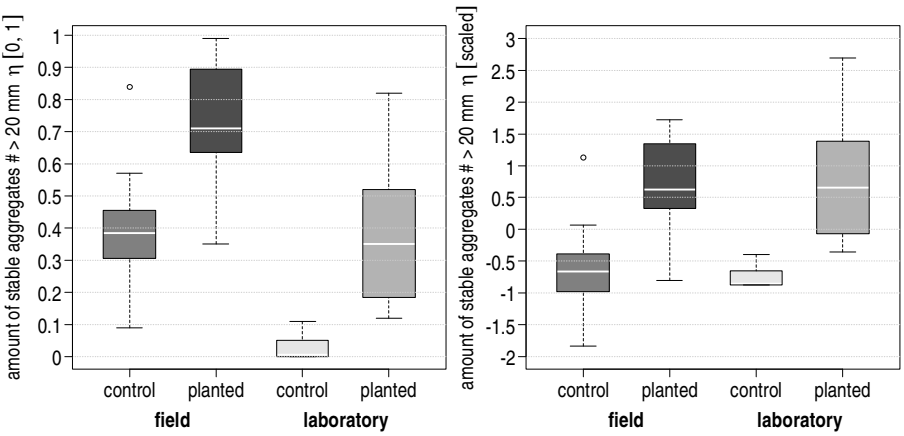

Fig. 4. Boxplots of original (left) and scaled (right) data of soil aggregate stability

4 Discussion

In recent years, the increasing demand for a sound evaluation of the effectiveness of vegetation in respect of their application in eco-engineering in general and slope stabilisation in particular produced different more or less specific approaches and methods [11, 12, 13, 14, 15, 16]. From this development and finding process soil aggregate stability has been emerging as an indicator addressing various aspects in order to quantify biological effects related to restoration and, in particular, in respect of protecting slopes from superficial soil failure [17, 18], [20].

In contrast to other, commonly applied methods addressing soil aggregate stability [23], [33], [36], we did not distinguish macro- (> 250 µm) and micro-aggregates (≤ 250 µm) of aggregates < 2 mm as proposed by [37] but focused on larger scale aggregation processes with components dimensioned > 20 mm [32]. The threshold of 20 mm originates from the fact that the grain size of the soil material used for the laboratory samples was limited to ≤ 10 mm and the next higher fraction in the particle size distribution analysis is > 20 mm [41]. In respect of the field samples, the maximum grain size was not known in advance and, therefore, single grains > 20 mm (non-aggregated particles) were excluded from the analysis. Consequently, from a geotechnical perspective, all components from laboratory as well as field samples considered as aggregated correspond to the particle size class > 20 mm.

Compared to other methods, this "large-scale" approach combines several advantages with regard to biological and hydrological processes. Root growth is one of the most important processes in order to increase soil aggregate stability. A positive correlation between the two has been demonstrated for numerous soil types time and again [32], [51, 52] as well as in this study for both laboratory and field derived samples. In order to soundly investigate the effects of roots on soil aggregate stability and, concomitant, on the pore matrix, an adequate size of the specimen allowing for sufficient root amount and development, respectively, is indispensable.

Furthermore, a representative vadose zone is required to reasonably mirror the distribution of the different pore classes. This is not least because the pore water regime, which is directly linked to the pore structure and its stability, plays a key role in triggering superficial landslides. Correspondingly, a certain minimum volume of the samples and maximum size of grains are necessary. Within the presented investigations the concept of triaxial compression tests was followed allowing maximum grain sizes < $^1/_5$ of the specimen diameter yielding the maximum particle size of 10 mm for both the laboratory and field samples with a diameter of 70 mm and 50 mm, respectively [53, 54]. Due to the correction applied for field samples which omits single grains > 20 mm the requirements were met satisfactorily. In addition, the presented approach for soil aggregate stability analysis allows for comparing results with conventional soil mechanical methods addressing slope stability, e.g. triaxial compression tests [28]. Conclusively, from a methodological point of view, deficiencies due to the different sampling procedure and size of the field and laboratory specimens are hardly distinguishable.

Interestingly, there was no significant difference in root length per soil volume between the planted field and laboratory samples, despite the fact that growth time for alder was up to about 20 years in the former and 20 weeks in the latter (Tab. 2, Fig. 1). Within the 25 year developing period, plant succession processes led the few pioneer plant species of the control plot (*Saxifraga aizoides* L., *Calamagrostis humilis* (Roem. et Schult) O. Schwarz, *Campanula rotundifolia* L., *Tussilago farfara* L.) onto an *Alnetum incanae* (Lüdi) represented by 25 species [39]. Concurrently, soil horizons developed, in particular a humus layer and the soil organic matter content increased tenfold (0.1% vs 1%). None of these developments took place during or was quantifiable after the 20 weeks of growing in the laboratory samples. It may be, therefore, speculated that artificially inoculated alder roots if grown unrivalled and under laboratory conditions develop an equal amount of roots per soil volume in one growth period as is produced by a naturally developed *Alnetum incanae* on a landslide affected slope in its initial phase.

Whereas in the laboratory samples only roots of alder plants were present, the 25 species to be possible for contributing to rooting in the field samples [39] were not distinguished, except for alder. Consequently, there is an uncertainty on the composition of annual and perennial roots within the field samples and, likewise, on the particular contribution of grass, herb, brush, and tree species.

Growth and development of roots are closely related to their associated symbiotic organisms, particularly mycorrhizal fungi, known as essential partners for almost all plants applied in eco-engineering. In general, naturally established partnerships between plant and mycorrhizal fungal species yield an increase in root growth as well as in above ground biomass [55]. This is confirmed in the present study with regard to the mycorrhization degree and the length of alder roots in the laboratory samples resulting in a Spearman correlation of 0.9 (Tab. 3). In this respect no data is available of the field samples as the different roots were not assigned to corresponding plant species, except for White Alder of which, however, the total root length was not addressed separately. Nevertheless, the alder roots of the field samples were significantly stronger mycorrhized than their counterparts of the laboratory samples (Tab. 2,

Fig. 2). This may mainly be attributed to the fact that the alder plants in the field were much older – up to about 20 years – compared to the 20 weeks old laboratory plantlets. Furthermore, the considerably longer development time in the field results in higher production and diversity both of plant and mycorrhizal fungal species. Concurrently, the mycorrhization infection potential (MIP) increases and, additionally, contributes to a higher mycorrhization degree [56]. Further evidence for higher MIP is given by the significant increase in spores of arbuscular mycorrhizal fungi (AMF) within the 25 years of soil and vegetation development (Fig. 3).

The direct and indirect effects of roots as well as their associated mycorrhizal fungi contribute to the stability of aggregates and, therefore, to the strength of the pore matrix [32], [57]. This biological influence on soil aggregate stability is nicely demonstrated in Figure 4 for both the field and laboratory samples, confirmed by the same relative and significant increase from the corresponding control to the planted specimens. The fact that the soil aggregate stability of the field samples is generally higher with their control samples mobilising equal strength as the planted laboratory samples (Tab. 1, 4, Fig. 4) may have different reasons. On the one hand, there was a small amount of roots and, correspondingly, organic matter in the control samples of the field (Fig. 1). On the other hand, the presence of soil micro-organisms, such as bacteria and fungi is beyond debate. For both the contribution to soil aggregation is well known with bacteria particularly contributing to the chemical stabilisation of micro- and fungi to the chemical and mechanical stability of macro-aggregates. Roots stabilise the latter chemically by producing sticky metabolites (polysaccharides) and further reinforce larger scaled soil structures mechanically. Last but not least, soil organic matter contributes by its cementing effects [57]. In respect of the laboratory samples it has to be kept in mind that the soil material was autoclaved, artificially filled into the sample holders and compacted. The material was, therefore, a sterile, single grained mixture and, furthermore, lacking any organic matter. Nevertheless, the scaling of the data clearly demonstrates the equal relative increase in soil aggregate stability from moraine of a recent superficial landslide to a 25 year old *Alnetum incanae*, developed from eco-engineering measures almost exclusively planting alder, and from artificially prepared laboratory samples using the same untreated moraine to identically prepared samples applying alder seeds and the mycorrhizal fungus *Melanogaster variegatus s.l.* after a growth period of 20 weeks (Tab. 1, Fig. 4). This coincidence based on the scaled data set is statistically supported by significant differences between planted and control samples but not among themselves (Tab. 4).

An analysis of covariance (ANCOVA) was applied to compare the effect of the sample location (treatment effect, i.e. field vs laboratory samples) on the response soil aggregate stability (y-variable) while controlling the effect of root length (co-variable, i.e. x-variable). The non-significant interaction of sample location with root length indicates that there is no obvious effect on soil aggregate stability in dependence of sample location, meaning that the slopes of the regression lines are not significantly different. However, the significant intercepts point to substantially different starting levels of aggregate stability depending on the sample location (Tab. 5), strongly supporting the additional stabilisation effects of bacteria, non-mycorrhizal fungi, soil organic matter, and, highly likely, organisms' diversity, too [57, 58].

Table 5. Summary of the linear regression model $\sin^{-1}(\text{aggregate stability})^{½} \sim \text{sample}_{loc} * \log_{10}(\text{root-length})$ showing significant difference in intercepts but not in slopes of field and laboratory samples. Significance codes: *** <0.001; 0.001 ≤ ** < 0.01; 0.01≤ * < 0.05.

Coefficients	Estimate	Std. Error	t value	Pr(>|t|)	
Intercept (samples_{field})	0.97363	0.04267	22.818	$<2.0\ 10^{-16}$	***
Intercept (difference field:lab)	-0.42412	0.05945	-7.135	$2.2\ 10^{-08}$	***
$\log_{10}(\text{root-length}_{field})$	0.64300	0.16662	3.859	0.000454	***
samples_{lab}:$\log_{10}(\text{root-length}_{lab})$	0.21036	0.23386	0.900	0.374362	

Residual standard error: 0.1647 on 36 DF
Multiple R-squared: 0.7421 Adjusted R-squared: 0.7206
F-statistic: 34.53 on 3 and 36 DF p-value: $1.081\ 10^{-10}$

The undisputed higher diversity in the planted field samples compared to their laboratory counterparts may additionally explain the lower correlation (squared Pearson correlation apparent from the individual linear regression models) between root length and soil aggregate stability as well as the higher variance in the former (Fig. 5).

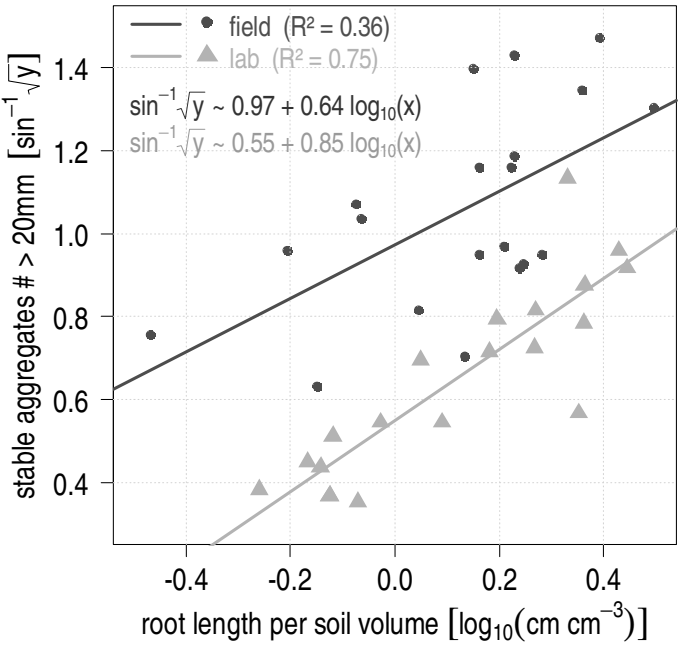

Fig. 5. Linear regression model ($\sin^{-1}(\text{aggregate stability})^{½} \sim \text{sample}_{loc} * \log_{10}(\text{root-length})$) for field (dark grey) and laboratory data (light grey) illustrating almost parallel lines (non-significant slopes), significant difference in intercept as well as the squared Pearson correlation (R^2) and formulas of the individual linear regression models

Nevertheless, root length is a key factor with regard to the strength of soil aggregates in particular and, consequently, in slope stabilisation in general, mirroring the integral effect of the soil rhizosphere including associated mycorrhizal fungi as well as the corresponding community of bacteria and non-mycorrhizal fungi. Associated, soil aggregate stability as addressed in the present article and, for the time being restricted to the corresponding moraine, reflects slope stability reasonably well as it turned out by the comparative study of [32] with shear parameters of triaxial compression tests (angle of internal friction Φ' and cohesion c').

The present comparison of field and laboratory data further suggests the assumption that the underlain "space-for-time-substitution" used for addressing the 25 year succession process in the field is well reflected by the 20 week growth period of the laboratory as related to the relative increase in soil aggregate stability from control to planted samples. Although this is not yet generally applicable on a large scale – local restrictions need to be accepted with reference to soil type, plant associations and eco-engineering measures – it opens an interesting possibility to approach biologically affected slope stability calculation and modelling with relatively short-timed and straightforward laboratory based experiments linked to corresponding field observations. Following this strategy, it will be necessary to develop a new concept integrating in a first minimalistic version the dynamic parameters root growth and soil aggregate stability. Such practice seems adequate as almost all conventional slope stability models finally assign the biological stabilisation part to an additional cohesion coefficient c_r' in the Mohr-Coulomb failure equation as already proposed by [59] in 1984 (Mohr-Coulomb: $\tau_f = c' + \sigma' tan\Phi'$; Wu: $s_r = c' + \sigma' tan\Phi' + c_r'$; with s_r as the shear strength τ_f and r for root) regardless of whether root area ratio (RAR), root tensile strength, or root pull-out resistance are considered [29], [31], [60, 61].

5 Outlook

The particle flow code (PFC) of ITASCA [62] is a distinct element code holding the potential to reproduce and model processes of root and soil development considering their manifold interactions in respect of assembling a structured entity starting from loose particles, increasing in stability, yet resilient with regard to biological succession mechanisms. The fact that dynamic motion is supported and interaction of conglomerates differing in size and associated properties as well as allowing for their continuous gradation, makes this software ideally suited to appropriately integrate biological effects into conventional applied slope failure calculations and models. Conclusively, roots can be addressed by their different diameters and tensile strength properties and, therefore, dependent on their spatial-temporal development. The same holds true for soil aggregates in terms of their specific composition of organic and

inorganic components and corresponding binding agents and stabilisation mechanisms, e.g. polysaccharides, glomalin, mechanical reinforcement, and bio-chemical bonds [57].

PFC^{3D}, therefore, looks ready to accept the challenge of modelling soil aggregate stability in dependence of biological (roots, micro-organisms, soil organic matter, …) and soil mechanical parameters (grain size, pore water pressure, …) in respect of slope stability. PFC^{3D} allows the creation of groups of particles with individual bonds between and among single parts of all interacting categories (grains, aggregates, root-segments, fungal hyphae, …) and, therefore, to interlink these ingredients in the course of the simulation as a function of arbitrary conditions. In addition, the possibility to represent such groups as general grain shapes opens the door to soil mechanical methods and concepts, i.e. particle size distribution, direct shear and triaxial compression tests, embankment stability, fracture mechanics. The link to soil mechanics is further supported by the principles of the default contact physics that include among others linear springs and Coulomb sliding as well as a visco-elastic model.

With this given prerequisites, a first simple 2D model of soil reinforcement has been developed, linking biological parameters and processes with the geotechnical contributions to soil and slope stability (Fig. 6). This new approach based on PFC^{3D} will be followed aiming at coupling the joint development of roots and soil aggregation with existing slope failure models.

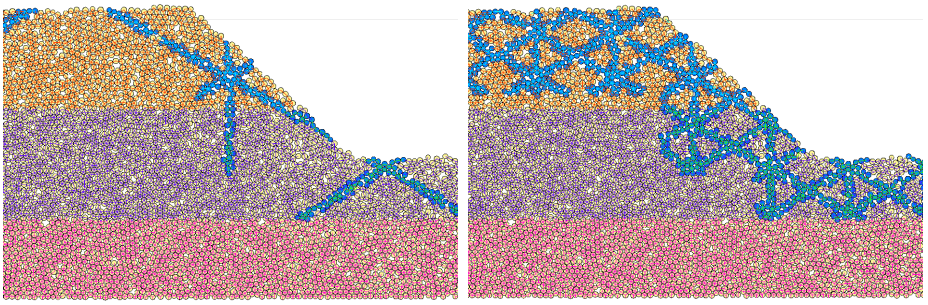

Fig. 6. Simple 2D-PFC models of soil reinforcement with different root densities. Roots are implemented as a group with different strength properties. Blue: roots; orange, purple, red: layers of soil.

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