Documentation of technical and biological slope stabilisation

Dallenwil-Wirzweli (Schwandrübi and Hexenrübi)

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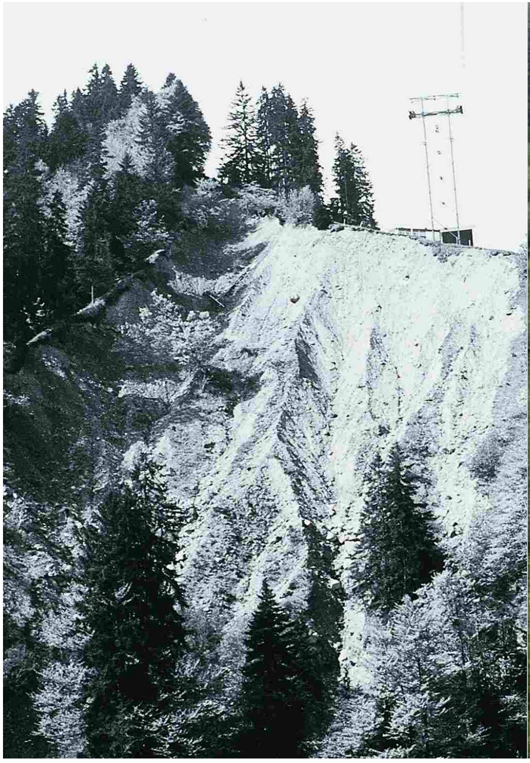


Schwandrübi 1981

Schwandrübi 2012

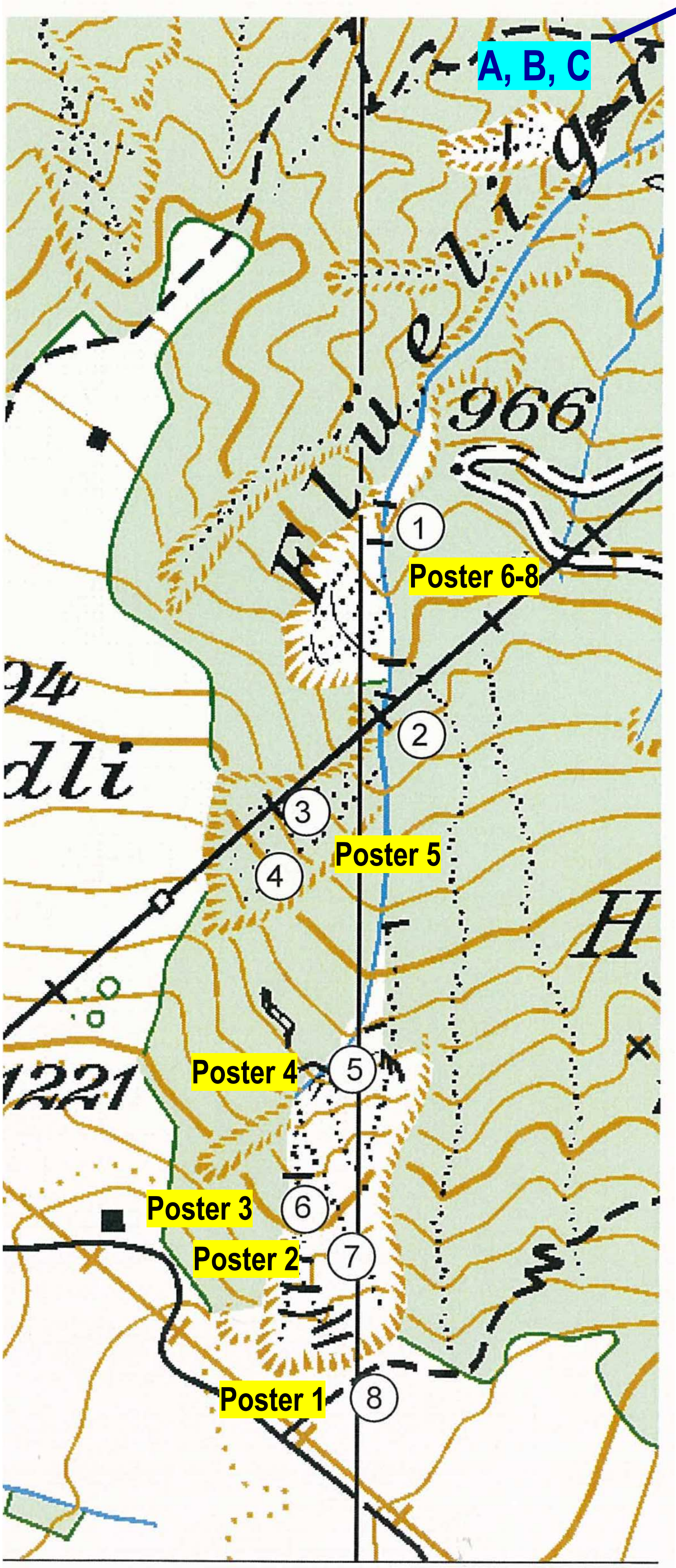
Hexenrübi 1982

Hexenrübi 2012

Excursion guide

Werner Gerber, FAN 2009

start 8 → 1, C → A end



End of excursion in Dallenwil

A. Sediment retention and timber grill constructions; problems of timber debris

B. Drainage channels

C. Wooden crib wall for slope stabilisation and road support

1. Flüeligraben

- Torrent processes
- Channel deposition
- Check dams made of concrete
- Rockfall
- Problems of re-colonisation by plants

2. Overview Schwandrübi

- Toe protection
- Overview on technical measures
- Overview on biological measures

3. Technical measures

4. Biological measures

5. Technical measures

6. Biological measures

7. WSL investigation plots

8. Overview Hexenrübi

- Erosion processes in the gullies
- Situation of inclination in 1985
- Supporting structures
- Biological measures

Start of excursion at top of Hexenrübi

Upper and lower Hexenrübi
Situation in 1982 and rehabilitation concept

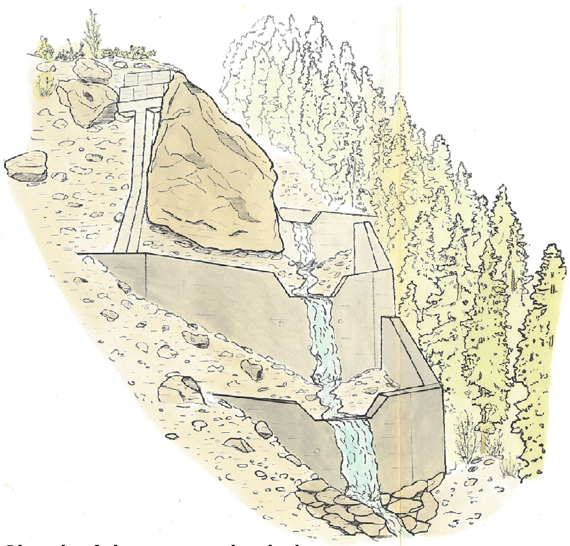
A huge natural ridge which, at its bottom, is underpinned by big boulders divides the Hexenrübi into two parts. These boulders were prone to undermining and endangered to crash entailing the destabilisation of the ridge behind.

Top of the upper Hexenrübi in 1982

The upper Hexenrübi is characterised by deep erosion gullies. Due to weathering processes they are heavily fed by soil material and blocks of the steep side flanks. During heavy rainstorms considerable bed-load discharge is triggered, permanently threatening the village Dallenwil.

Excessively steep slope in 1982

Apart from erosion gullies, the lower part of Hexenrübi is characterised by high and excessively steep slopes which are an ever active source of erosion, superficial landslides, and rockfall. As a result of this permanent soil movements, the natural re-establishment of a protecting vegetation cover was continuously doomed to fail.



Sketch of the torrent check-dams

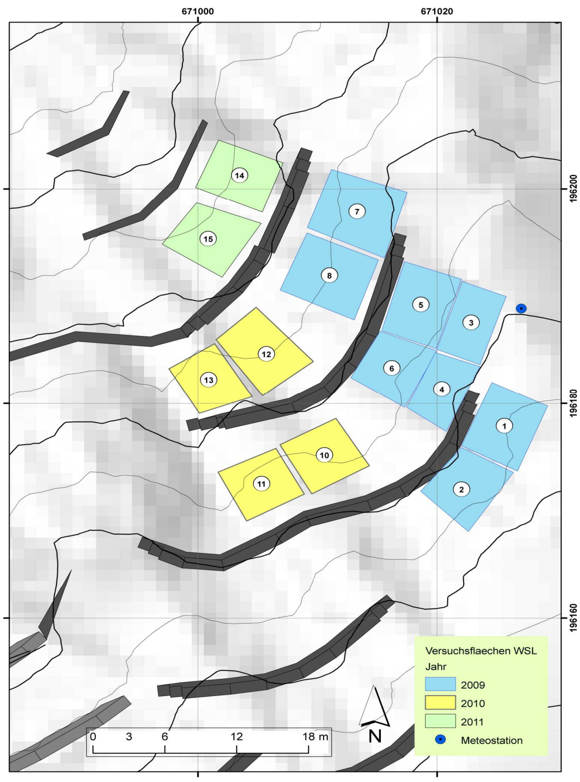
Within the rehabilitation concept first priority was given to the stabilisation of the boulders and blocks between the lower and upper Hexenrübi. In a second step the bottom of the slopes had to be fixed. Only then it was possible and reasonable to start with the proper slope stabilisation work.

Upper Hexenrübi
Planting experiments

The upper Hexenrübi has been exclusively planted with White Alder following the Schwandrübi approach. Within the concept of biological stabilisation WSL was offered 15 plots (~6 x 6 m) in order to test further plant species (*Salix spp.*), different strategies (cuttings, rooted saplings), and the application of mycorrhizal inoculum.

WSL field plots 1-8 soon after after planting in 2009

Planting of rooted saplings and cuttings of *Salix spp.*



Field plot disposal in 2011

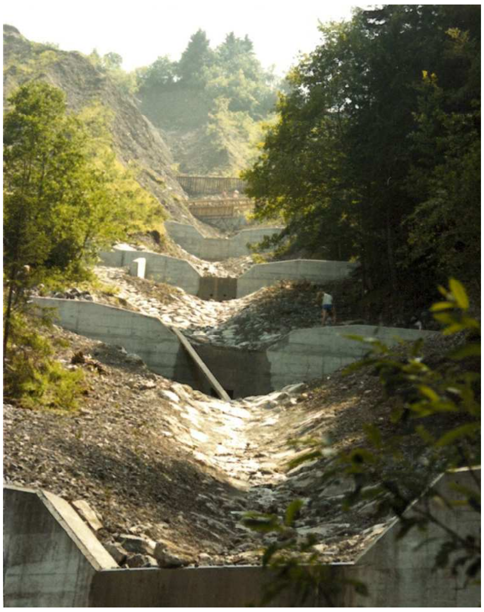
Situation of WSL field plot no. 7 in 2010

no.	plant species	plant type	mycorrhiza	number of plants	year of planting
1	*Salix daphnoides*	cuttings	without	36	2009
2	*Salix purpurea*	cuttings	without	36	2009
3	*Salix purpurea*	rooted saplings	with	36	2009
4	*Salix daphnoides*	rooted saplings	with	36	2009
5	*Salix daphnoides*	cuttings	with	36	2009
6	*Salix purpurea*	cuttings	with	36	2009
7	*Salix purpurea*	rooted saplings	without	36	2009
8	*Salix daphnoides*	rooted saplings	without	36	2009
10	*Salix appendiculata*	cuttings	without	49	2010
11	*Salix appendiculata*	rooted saplings	without	39	2010
12	*Salix appendiculata*	cuttings	with	39	2010
13	*Salix appendiculata*	rooted saplings	with	42	2010
14	*Salix daphnoides*	cuttings	with	36	2011
15	*Salix daphnoides*	cuttings	without	36	2011

Species distribution on the field plots of upper Hexenrübi

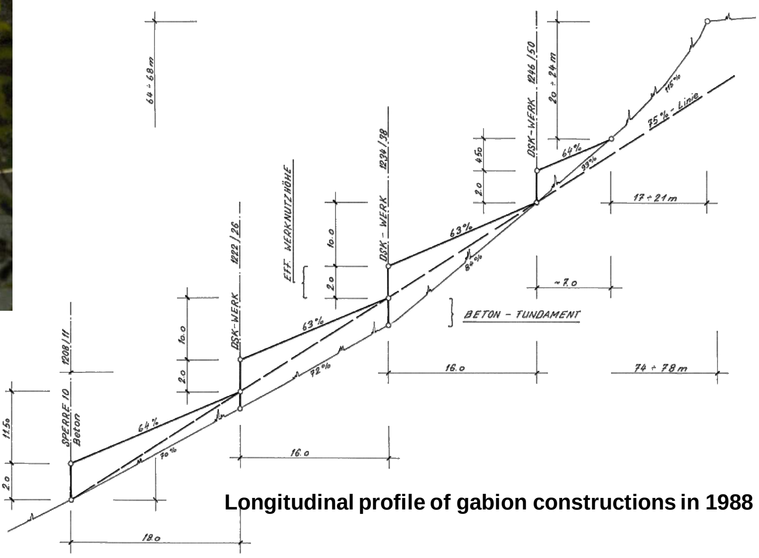
Upper Hexenrübi

Technical measures



Gully gabions and bed fixation in1988

The gully check-dams and the bed fixation were built in 1987 and 1988.
Subsequently, the gabion walls have been built step by step. Due to this walls it was possible to reduce the original slope angle from up to more than 45° to about 33° which corresponds to the limit of the soil material (angle of internal friction).



Longitudinal profile of gabion constructions in 1988

The big ridge in 1988

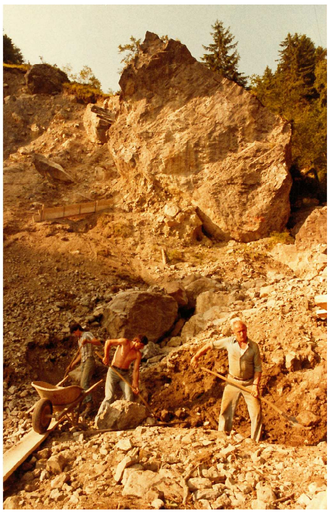
A particular challenge were the huge and excessively steep ridges. In respect of their stabilisation they were "wrapped" with gabion walls.

Ridge stabilised with gabion walls in 2011

Lower Hexenrübi

Technical measures

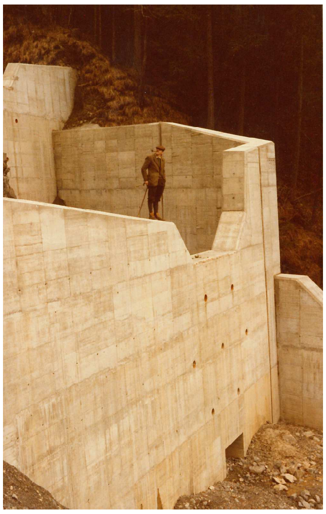
The key element of the rehabilitation concept was and is the series of torrent check-dams underpinning the blocks and boulders. In addition, gully check-dams, bed protection, embankments, gabion walls, and anchored net constructions were applied.



Handwork in 1982

The series of the torrent check-dams was built in 1983. Subsequently, bed protection and gully check-dams were completed in the lower Hexenrübi providing the basis for slope stabilisation with gabion walls.

Bed fixation, gully check-dams, and embankments in 1985



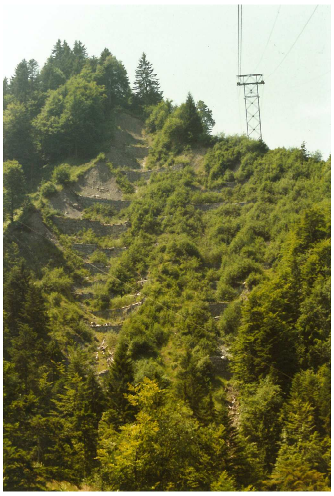
Check-dam no. 4 with designer Albert Böll in 1983

Anchored net constructions in 2005

First working steps in the excessively steep slopes started in 2005. Below a bearing steel net two additional nets were fixed in order to prevent leaching of the fine material.
As this approach was only partly successful further anchored nets had to be installed afterwards.

Schwändlirübi
30 years of vegetation development

In 1981 the technical requirements were established with respect to protect and support the development of the vegetation (White Alder). The alders with their triple symbiosis (*Frankia*, ecto- and endomycorrhiza) were supposed to improving the hostile soil and microclimatic conditions in respect of facilitating natural (re-) colonisation for more demanding species and to spur succession processes.



This concept has been working quite well. However, at certain parts the slope angle was still too steep compared with the limit angle of the soil material (angle of internal friction). Consequently, further technical constructions were installed in 1990 and 1991.

In 2004 first tending measures were applied in order to fasten natural succession processes in direction to the climax association aimed at.

Situation in 1989

After tending measures in 2004

A survey in 2005 showed that the number of tree and brush species increased to 16. Among the 15 "new-comer" were already all species required for the site-adapted climax forest proposed by NaiS (Nachhaltigkeit im Schutzwald), i.e. *Abies alba, Acer pseudoplatanus, Alnus incana, Fraxinus excelsior, Picea abies, Sorbus aria, Sorbus aucuparia*. Noteworthy is *Salix appendiculata* which naturally established, too in considerable abundance.
Above ground diversity is also reflected in the soil by the different types of root systems (shallow, deep, tap, heart, …) important for soil aggregation and slope stabilisation.

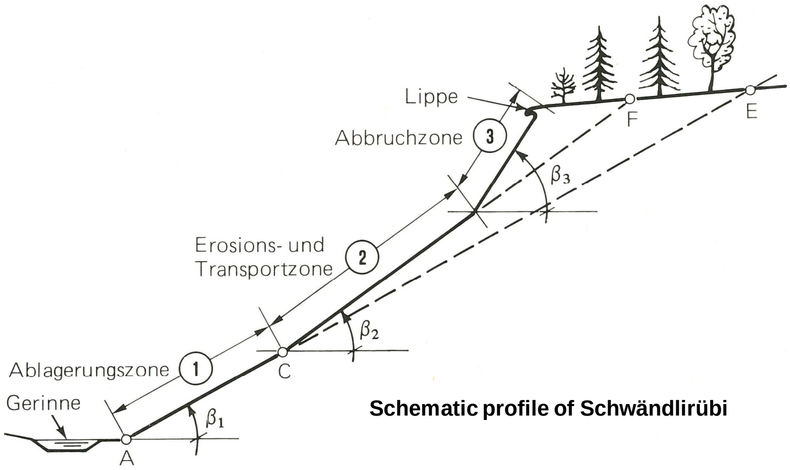
In 2011 a second tending measure was applied particularly aiming at cutting back White Alder and at reducing Norway Spruce.
Another step towards diversity and the climax association.

Situation in May 2011

After tending measures in 2011

Schwändlirübi
Situation in 1975 and first measures

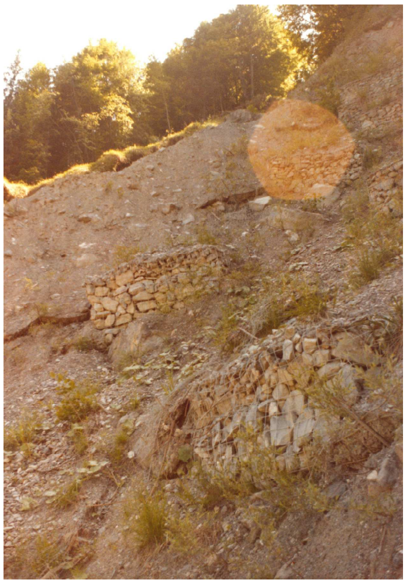
Schwändlirübi in 1975



Schematic profile of Schwändlirübi

The Schwandrübi, a large, amphitheatre like gully and bare of vegetation, was an ever source of danger. During heavy rainstorms considerable amounts of debris were mobilised and flushed down to Flüeligraben and Steinibach. As a consequence, the village Dallenwil was flooded and affected by enormous damages time and again.

In 1975 gabions were installed as first measures against superficial soil failure. However, these constructions of about 1 m height were damaged within short time and, subsequently, useless.



Damaged gabion walls in 1979

East gully in 1979

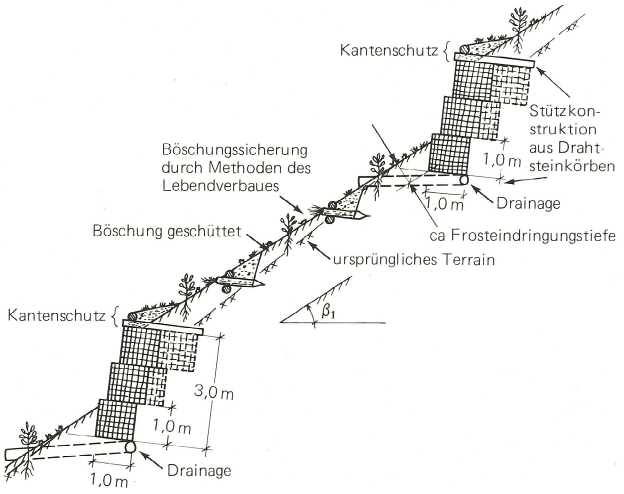
Acer pseudoplatanus

The few naturally upcoming spots of vegetation sooner or later vanished due to erosion, superficial landslides, and rockfall.

Schwändlirübi

Technical and biological measures

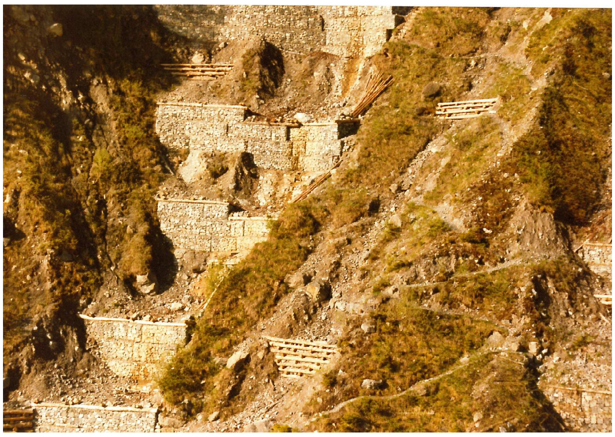
WSL, the former EAFV (Swiss Federal Institute of Forestry Research) was given the mandate to comprehensively investigate the problematic situation and to propose a rehabilitation concept.



Concept of the technical and biological measures

An approach combining technical and biological measures was suggested.
From a geotechnical point of view it was aimed at reducing the established slope angle β_2 in between the technical constructions to the limit angle of the loose soil material β_1 (angle of internal friction) yielding a theoretical factor of safety $F_s = 1$.
Vegetation was applied in respect of an increase in the factor of safety ($F_s>1$) as well as to protect the surface from raindrop impact.

In 1981 and 1982 first walls of gabions were built and the areas in between seeded with a commercial seed mixture.
Furthermore, willows and, particularly, White Alder were planted (10'000 pc.).



Additional log crib-walls in 1985

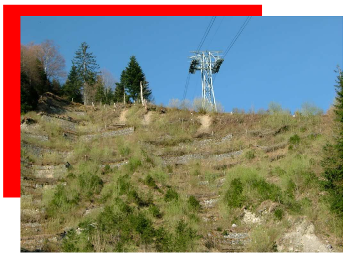
At some problematic spots additional log crib-walls had to be built in 1985.

Stabilised gully in 1983

Biological measures
Research on their stability effects

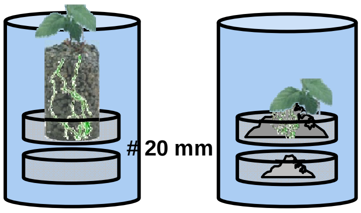
A site-adapted vegetation cover is an efficient protection against superficial soil failure. In order to quantify the biological contribution to soil and slope stabilisation investigations have been conducted at three different places with different vegetation cover: Hexenrübi (bare soil with few spots of pioneer vegetation), Schwandrübi (*Alnetum incanae* in transition to *Aceretum pseudoplatani*), Hornwald (natural climax forest *Abieti-Fagetum*).

Hexenrübi (0-5 years)



Schwandrübi (20-30 years)

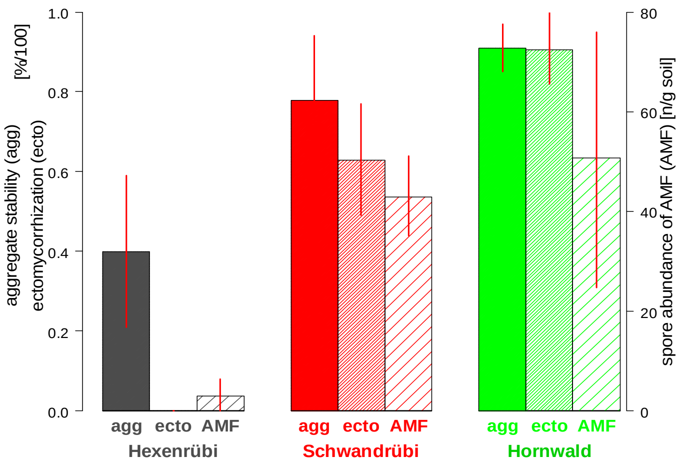
Hornwald (> 100 years)



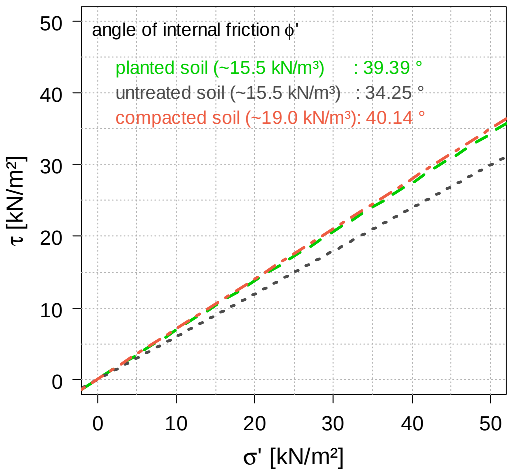
Test for aggregate stability

Research focused on soil aggregate stability, root growth as well as the mycorrhization of White Alder used in the experiments. It was distinguished between arbuscular mycorrhizal fungi (AMF) and ectomycorrhizal fungi (ecto).

It has been found that soil aggregate stability, mycorrhization degree, and root length per soil volume are positively correlated and increase in the course of time from Hexenrübi over Schwandrübi to Hornwald. Furthermore, it has been demonstrated based on triaxial compression tests that the correlation between soil stability and root length holds also true from a soil mechanical point of view.



Soil aggregate stability (agg) **and mycorrhiza** (ecto, AMF)



Angle of internal friction Φ' of soil and planted soil

Tannen-Buchenwälder auf wechselfeuchtem Boden 18w, 18v

Ökologie und Waldbau

Baumarten im Naturwald:	
18w	Buche und Tanne dominieren, dazu Fichte, Bergahorn, Esche, Vogelbeere, Mehlbeere; Pionierbaumarten.
18v	Buche dominiert, dazu Tanne, Fichte, Bergahorn, Esche, Vogelbeere, Mehlbeere, Pionierbaumarten.
Maximale Bestandeshöhe:	
18w	15 - 25 m
18v	10 - 20 m
Bemerkungen:	
18v, 18w	Schlussgrad locker bis aufgelöst, oft stufig.
18w	Oft rutschige Standorte, meistens Steilhänge.
18v	Oft rutschige Standorte, meistens Steilhänge, häufig durch Schneebewegungen beeinflusst. Teilweise niederliegende Baumformen.
Limitierende Faktoren:	
18v, 18w	**Erosion:** Kann an Steilhängen die Verjüngung behindern.
18v	**Kleine Lawinen:** Die Nadelbäume werden dadurch stellenweise ausgekämmt.
18v, 18w	**Schneegleiten:** Besonders an Sonnenhängen häufig.
18v, 18w	**Austrocknung:** Wegen der langen Baumkronen ist die Verjüngung seltener direkt unter Schirm zu finden als auf wüchsigen Standorten.
Waldbau:	
18v, 18w	Die Standorte sind wenig produktiv.
18w	Die Stabilität der Bestände kann durch Eingriffe auf wenig strukturierten Standorten mit homogenen Beständen verbessert werden. Die Verjüngung kann mit Auflichten (Entfernen von 2 - 3 Bäumen) eingeleitet werden.
18v	Die Stabilität der Bestände kann durch Eingriffe kaum positiv beeinflusst werden.
Naturgefahren:	
18v, 18w	**Rutschungen:** Häufig Entstehungsgebiet von flachgründigen Rutschungen, Erosion, Murgängen.
Übergang 18w, 18v zu vernässten Standorten (z. B. 27h)	**Rutschungen:** Häufig Entstehungsgebiet von flach- bis tiefgründigen Rutschungen.
18v, 18w	**Wildbach/Hochwasser:** Klasse 2, waldbaulicher Einfluss mittel

Vergleichstabelle

Standortstypen	AG	BE/ FR	GL	GR	JU/ J-BE	LU	NE	NW	SG	SO	SZ	UR	VD	ZG	ZH
Buntreitgras-Tannen-Buchenwald															
- Typischer 18w	**18w**	**18w**	**17h**	**18w**	**18w**	**18w**	*12el*	**18w**	**18w**	**18w**	**18w**	**18w**	**166m**	**17ho** 18w	**8w**
- mit Rostsegge 18v				**18v**				**17***	**18v**		**18v**				

Anforderungen auf Grund des Standortstyps

18w Typischer Buntreitgras-Tannen-Buchenwald 18v Buntreitgras-Tannen-Buchenwald mit Rostsegge		
Bestandes- und Einzelbaummerkmale	**Anforderungen minimal**	**Anforderungen ideal**
Mischung Art und Grad	Bu 30 - 80 % Ta 20 - 50 % Fi 0 - 40 % BAh, Es, Mb, Vb, WEr Samenbäume - 50 % *Lawinen:* *Immergrüne Ndb 30 - 70 %*	Bu 40 - 60 % Ta 30 - 50 % Fi 0 - 20 % BAh, Es, Mb, Vb, WEr 10 - 30 %
Gefüge BHD-Streuung	Genügend entwicklungsfähige Bäume in mind. 2 verschiedenen Durchmesserklassen pro ha	Genügend entwicklungsfähige Bäume in mind. 3 verschiedenen Durchmesserklassen pro ha
Horizontal	Einzelbäume und Kleinkollektive	Einzelbäume und Kleinkollektive, Schlussgrad locker - räumig
Stabilitätsträger Kronen	Höchstens die Hälfte der Kronen stark einseitig	Wenige Kronen stark einseitig
Stand/Verankerung	Meistens lotrechte Stämme mit guter Verankerung, nur vereinzelt starke Hänger	Lotrechte Stämme mit guter Verankerung, keine starken Hänger
Verjüngung Keimbett	Fläche mit starker Vegetationskonkurrenz < 3/4	Fläche mit starker Vegetationskonkurrenz < 1/2
Anwuchs (10 cm bis 40 cm Höhe)	Auf mind. 1/10 der Fläche vorhanden	Auf mind. 1/5 der Fläche vorhanden
Aufwuchs (bis und mit Dickung, 40 cm Höhe bis 12 cm BHD)	Pro ha mind. 2 Trupps (je 2 - 5 a, durchschnittlich alle 75 m) oder Deckungsgrad mind. 5 % Mischung zielgerecht	Pro ha mind. 3 Trupps (je 2 - 5 a, durchschnittlich alle 60 m) oder Deckungsgrad mind. 9 % Mischung zielgerecht

"Sachseln"

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Semences UFA Samen
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Die Mischung eignet sich für die Einsaat auf die Rüfen (1000 bis 1600 m/ü.M.) Sie ist anspruchslos, wurzelt rasch und tief und bringt sicher während 3 bis 5 Jahren einen guten Erosionsschutz. Dank Einsatz von ca. 500 Pflanzen/m2 von Hybridraigras wird die Mischung wenige Tage nach der Aussaat grün und bringt schon sehr rasch einen **Erosionsschutz**. Das Hybridraigras wird nach einer Ueberwinterung verschwinden

Zusammensetzung

Name deutsch	Name lateinisch	Samen/m2	Anteil Gew.%
Eng. Raigras Arvicola	Lolium perenne Arvicola	665	15
Ausläufertr. Rotschwingel Echo	Festuca rubra r Echo	559	7
Horst-Rotschwingel Lifalla	Festuca rubra commutata Lifalla	588	7
Bastard Raigras Dalita	Lolium hybridum Dalita	485	25
Kammgras	Cynosurus cristatus	1073	10
Wiesenschwingel Preval	Festuca pratensis Preval	570	15
Fioringras Kita	Agrostis alba Kita	2254	3
Rotes Straussg.Highland	Agrostis tenuis Highland	2347	2.5
Weissklee Milkanova	Trifolium r Milkanova	494	5
Gelbklee Virgo	Medicago lupulina Virgo	469	10
Hornschotenklee Odenwälder	Lotus corniculatus Odenwälder	466	7

Impressions of the construction phase in the Hexenrübi





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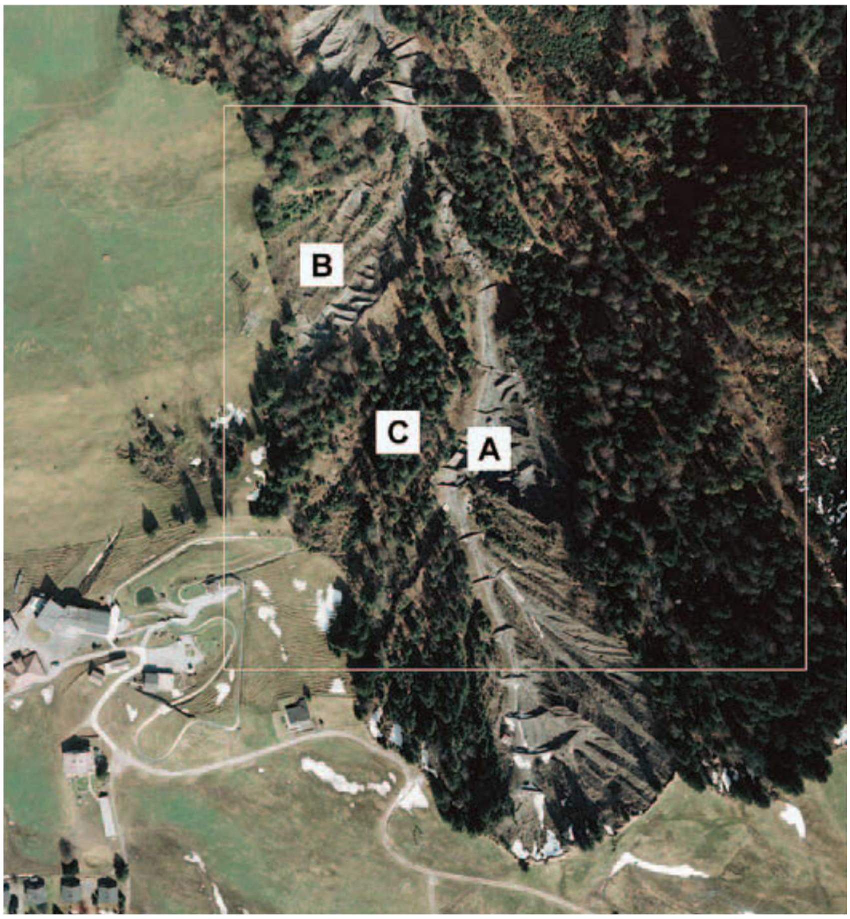
Revegetation measures improve soil aggregate stability: a case study of a landslide area in Central Switzerland

Katrin Burri, Frank Graf and Albert Böll

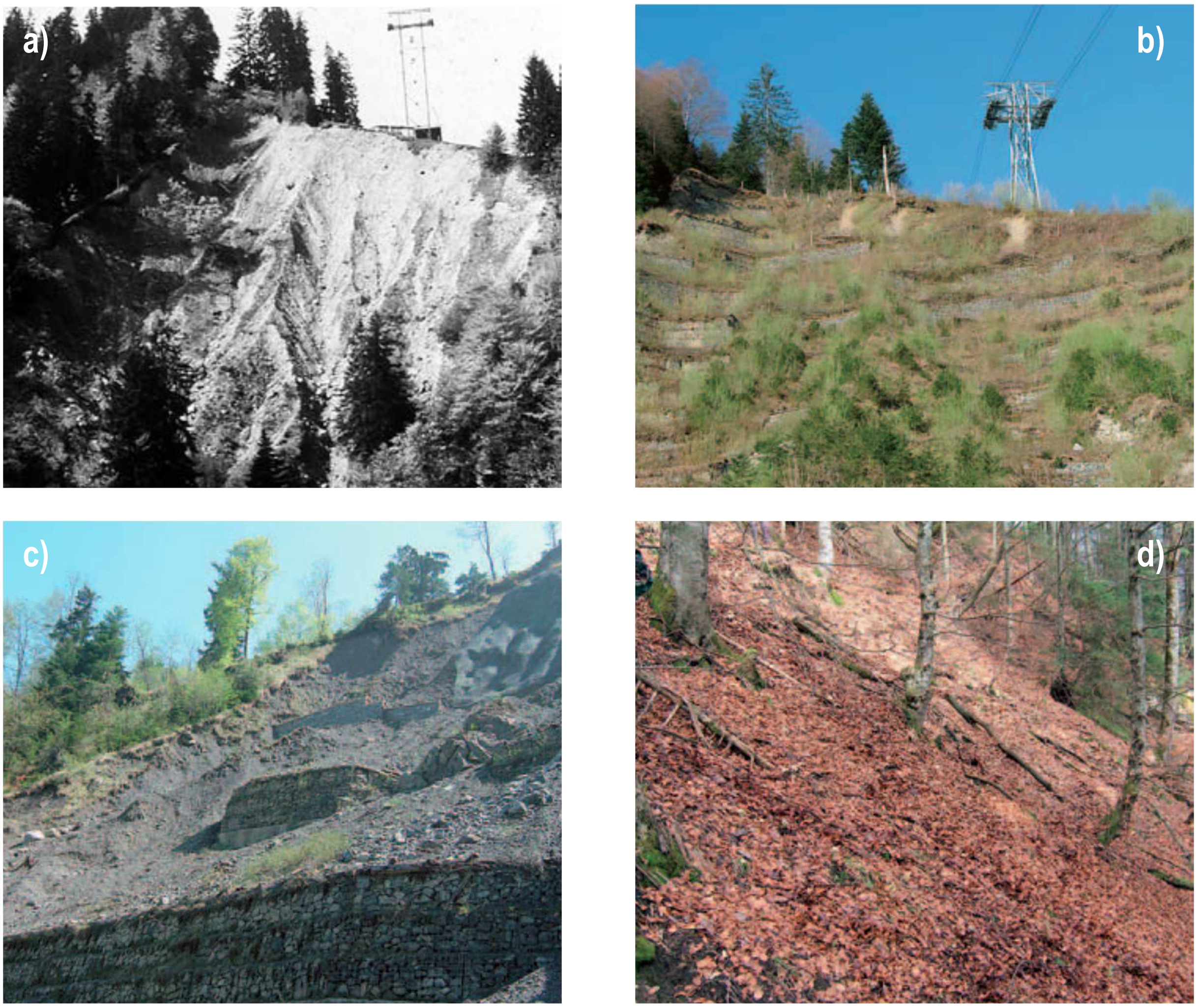
Abstract

In soil bioengineering, revegetation measures are applied to improve soil structure and to protect the soil against erosion and shallow landslides. Soil aggregation processes play a crucial role in re-establishing soil structure and function. The objective of this study was to determine whether soil aggregate stability increased along with soil and vegetation development in a landslide area that was stabilised with soil bioengineering measures. Three adjacent sites were compared with regard to soil aggregate stability: i) a gully with combined technical and biological stabilisation measures dating back 25 years (revegetated site), ii) a gully with only technical stabilisation measures of the same age (control site), and iii) a climax forest stand (climax forest site). On the revegetated site, the soil aggregate stability was significantly higher than on the control site, approaching the values of the climax forest. The revegetated site was characterized by a dense stand of bushes, whereas on the control site, only sparse pioneer vegetation had established spontaneously. Data suggest that revegetation measures increased soil aggregate stability by substantially accelerating vegetation development and by promoting soil formation processes such as accumulation of fine soil particles, organic matter and mycorrhizal propagules.

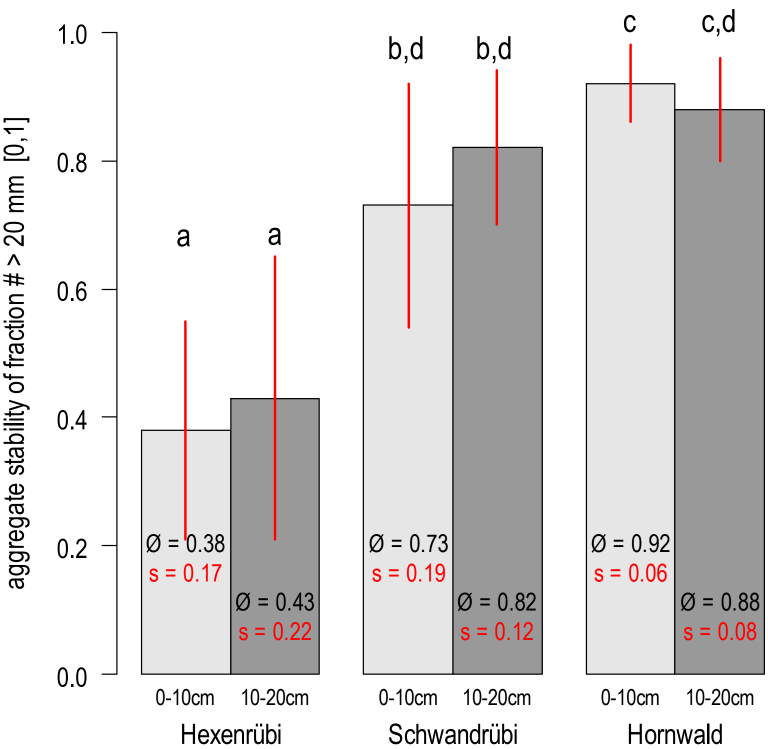
Keywords: soil aggregate stability, soil bioengineering, ecological restoration, mycorrhiza



Aerial photo of the study area "Hexenrübi / Schwandrübi" taken in 1992. A = control site, B = revegetated site, C = climax forest site. Picture: WSL.



The three test sites: a) Schwandrübi: revegetated site in 1974 prior to the application of soil bioengineering measures, b) Schwandrübi: revegetated site in 2006, c) Hexenrübi: control site in 2006, d) Hornwald: climax forest site in 2006. Pictures: Forestry service Nidwalden (a), WSL (b, c, d).



Soil aggregate stability values at the three test sites Hexenrübi (control), Schwandrübi (revegetated), and Hornwald (climax forest) at 0–10 cm and 10–20 cm soil depth with mean (ø), and standard deviation (s). Identical letters indicate non-significant differences (p-value > 0.05).

Cover-abundance values according to BRAUN-BLANQUET (1964) of the plant species in the study area. r = 1 to 2 plant individuals, + = covering < 1 % and only a few plant individuals, 1 = covering 1–5 % or many individuals, 2 = covering 5–25 % or less if very numerous, 3 = covering 25–50 %, 5 = covering > 75 %, na = not available. [1] (Roem. et Schult) O.Schwarz, [2] (Hedw.) Schimp., [3] (Hedw.) Mitt.

Hexenrübi (control site)		**Schwandrübi** (revegetated site)		**Hornwald** (climax forest site)	
tree and bush layer		**tree and bush layer**		**tree and bush layer**	
+	*Salix purpurea* L.	3	*Alnus incána* (L.)Moench	5	*Fagus silvatica* L.
r	*Salix appendiculata* Vill.	2	*Acer pseudoplatanus* L.		
		2	*Rubus idaeus* L.		
		2	*Salix appendiculata* Vill.		
		1	*Fraxinus excelsior* L.		
		1	*Salix purpurea* L.		
		+	*Abies alba* Miller		
		+	*Lonicera alpigena* L.		
		+	*Lonicera nigra* L.		
		+	*Lonicera xylosteum* L.		
		+	*Picea abies* (L.)Karsten		
		+	*Sorbus aria* (L.)Crantz		
		+	*Sorbus aucuparia* L.		
		+	*Ulmus montana* With.		
		+	*Viburnum Lantana* L.		
herb layer		**herb layer**		**herb layer**	
1	*Saxifraga aizoides* L.	4	*Milium effusum* L.	2	*Adenostyles alliariae* (Gou.)Ke.
+	*Calamagrostis humilis* [1]	+	*Fragaria silvestris* (L.)Duch.	1	*Mercurialis perennis* L.
+	*Campanula rotundifolia* L.	+	*Geum urbanum* L.	1	*Milium effusum* L.
+	*Tussilago farfara* L.	+	*Heracleum sphondylium* L.	+	*Rubus fruticosus* L.
r	*Carex diversicolor* Crantz	+	*Phyteuma spicatum* L.	+	*Carex digitata* L.
		+	*Polystichum lobatum* (Hud.)Che.	+	*Carex sylvatica* Hudson
		+	*Valeriana tripteris* L.	+	*Epipactis rubiginosa* (Cra.)Gau.
		r	*Knautia silvatica* L.(Duby)	+	*Fragaria silvestris* L. (Duch.)
		r	*Solidago virga-aurea* L.	+	*Hordelymus europaeus* L. Harz
		r	*Stachys silvatica* L.	+	*Polystichum aculeatum* (L.)Roth
				r	*Dryopteris dilatata* (Hof.)A.Gra.
				r	*Epilobium montanum* L.
				r	*Neottia nidus-avis* (L.)Rich.
				r	*Solidago virga-aurea* L.
moss layer		**moss layer**		**moss layer**	
		na	*Eurhynchium striatum* [2]	+	*Eurhynchium striatum* [2]
		na	*Mnium* (Hedw.)	+	*Mnium* Hedw.
				+	*Ctenidium molluscum* [3]

Vegetation properties of the three test sites Hexenrübi (control), Schwandrübi (revegetated), and Hornwald (climax forest).

	control site		**revegetated site**		**climax forest site**	
soil depth [cm]	0-10	10-20	0-10	10-20	0-10	10-20
vegetation cover [%]	3		153		112	
species number [n]	7		27		18	
root length density [cm cm^{-3}]	0.11±0.21	0.05±0.07	1.51±0.67	0.3±0.20	1.61±0.38	0.50±0.23
number of replicates [n]	20	13	20	22	21	8
degree of ectomycorrhization [%]	—	—	64±10	58±24	90±9	92±9
number of replicates [n]	—	—	12	4	12	4

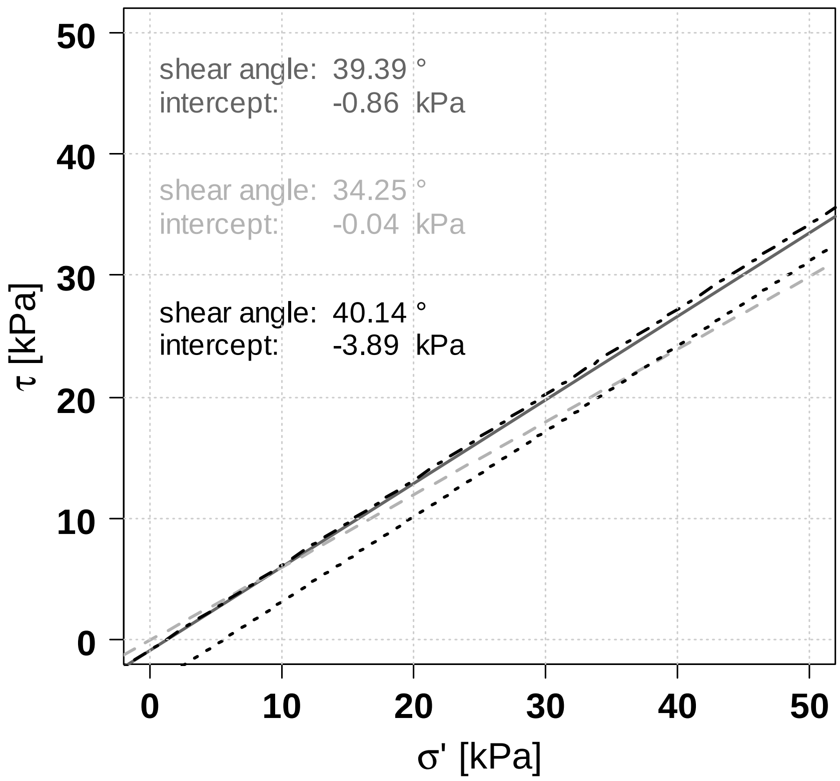
For. Snow Landsc. Res. 82, 1: 61–77 (2009)

Effects of vegetation on the angle of internal friction of a moraine

Frank Graf, Martin Frei and Albert Böll

Abstract
Vegetation clearly affects soil strength, but how to take these effects into account in conventional calculations of slope stability is still an unsolved problem. In order to quantify the important influence of plant roots on shear strength of a moraine, we performed isotropic, consolidated-undrained triaxial compression tests with different confining pressures (σ_3' = 50, 75, 100 kPa). Three different types of samples were tested: A) planted soil and B) pure soil at low dry unit weight ($\gamma \approx$ 15.5 kN m^{-3}) as well as C) pure compacted soil at $\gamma \approx$ 19 kN m^{-3}. The planted samples were prepared with alder seeds *(Alnus incana).* For each sample type, failure lines (kf lines) were calculated using the peak shear strength points of the corresponding p'-q paths. Robust statistics were performed to fit the failure lines and to test for significance.
No differences were found in the cohesion (*c'*) of the different soils. However, there was a significant difference in the angle of internal friction (Φ') of about 5° between the samples of pure soil at low dry unit weight and those of both compacted and planted soil. The vegetation effect is thus apparent as an increase in the angle of internal friction Φ' in planted soil compared to pure soil at the same dry unit weight. This finding can also be considered as a virtual increase in soil density (from $\gamma \approx$ 15.5 to $\gamma \approx$ 19 kN m^{-3}).

Keywords: triaxial compression tests, plants, slope stability, robust statistics



Comparison of cohesion (intercept) *c'* [kPa] and angle of internal friction (slope = shear angle) Φ' [°] of the three different treatments; planted, pure, and compacted soil. Dotted black = compacted soil ($\gamma \approx$ 19 kN m^{-3}); dashed light grey = pure soil ($\gamma \approx$ 15.5 kN m^{-3}); and solid dark grey = planted soil ($\gamma \approx$ 15.5 kN m^{-3}). The dash-dotted black line represents the curve of the compacted soil displaced parallel to the intercept of the curve of the planted soil.

Ecological Engineering 57: 314– 323 (2013)

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

Frank Graf, Martin Frei

Abstract

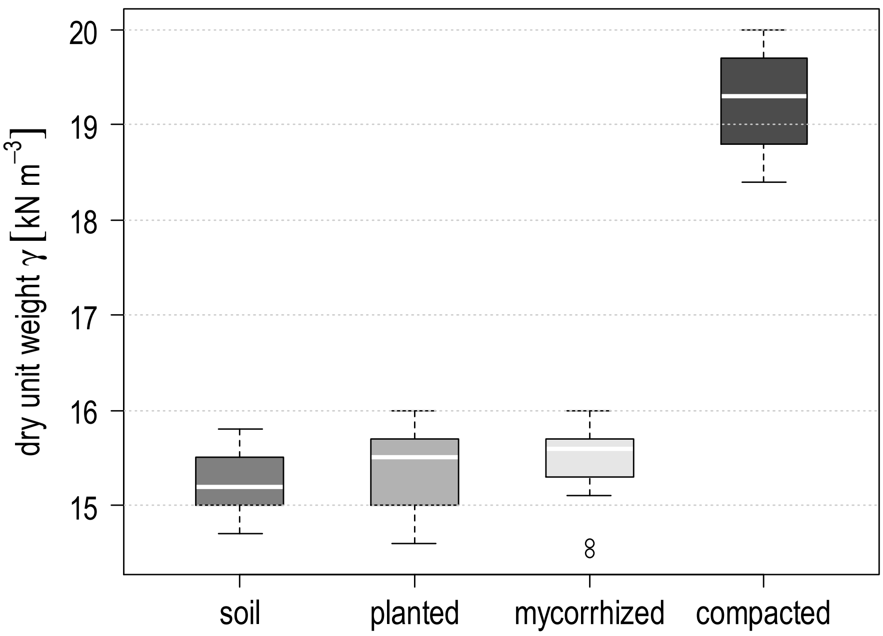
Eco-engineering aims at stabilising soil and slopes by applying technical and biological measures. Engineering structures are commonly well defined, immediately usable and operative, and their stability effects quantifiable. Differently, the use of plants requires more restrictive boundary conditions 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.

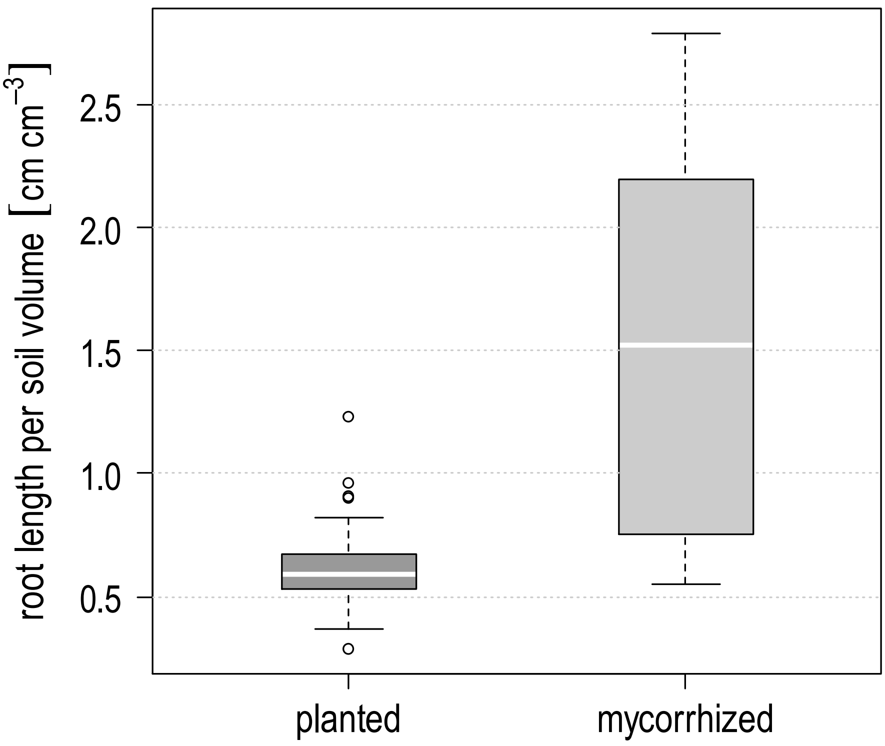
Aggregate stability tests were performed with samples of differently treated moraine, including soil at low ($\sim$15.5 kN m^{-3}) and high ($\sim$19.0 kN m^{-3}) dry unit weight, soil planted with *A. incana* (White Alder) as well as the combination of planting with alder and inoculating with the mycorrhizal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

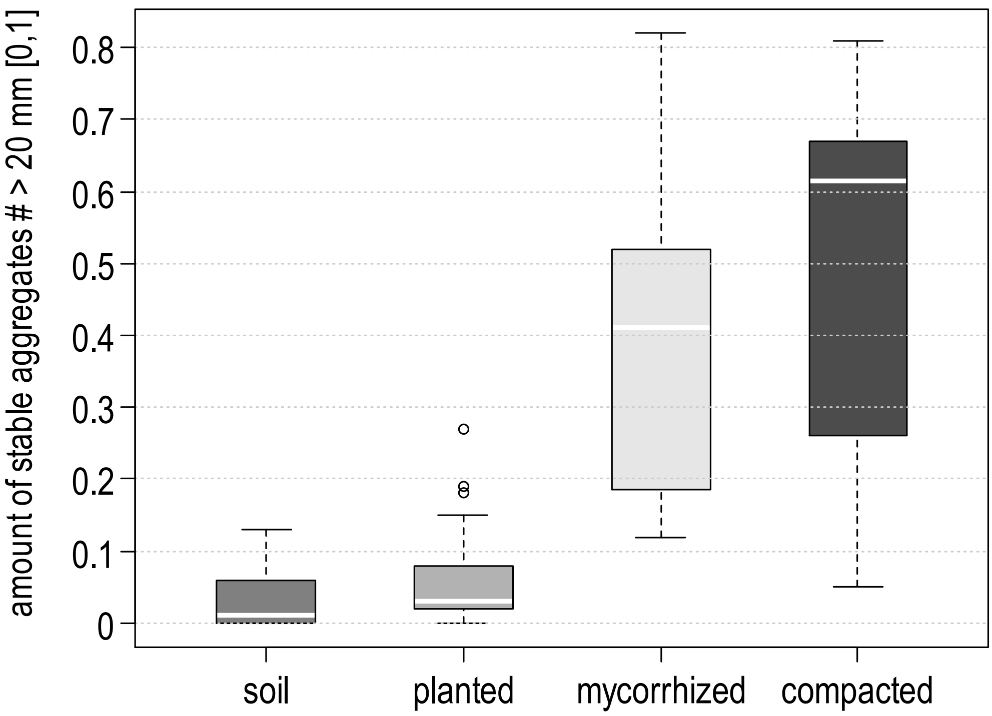
Keywords: Ectomycorrhiza, Alder, Root growth, Soil mechanics



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



The rooting performance of *Alnus incana* plantlets after the 20 weeks 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).



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.

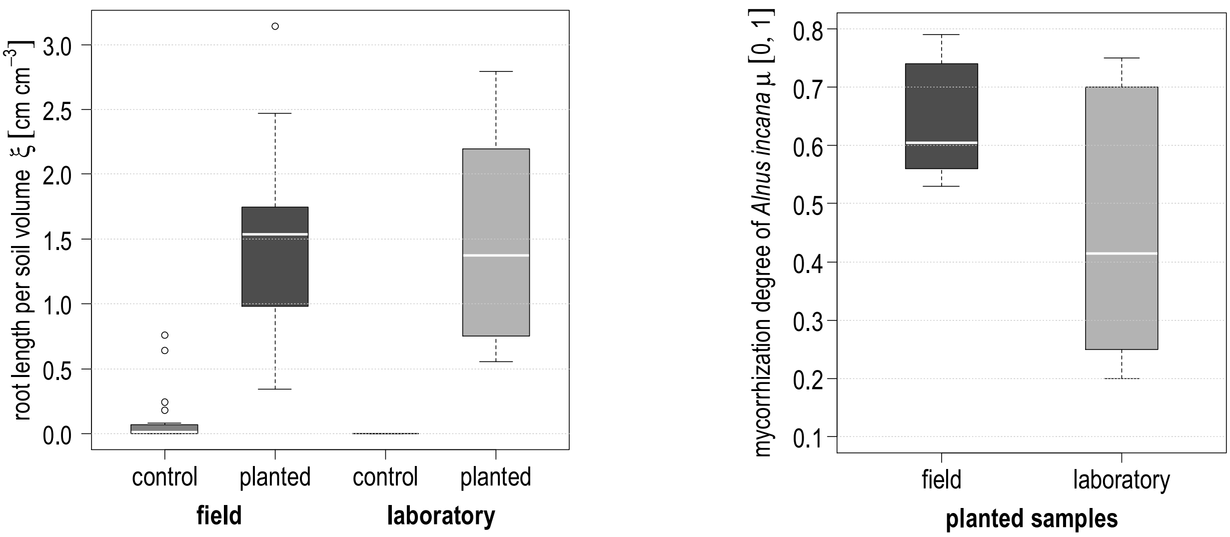
Geomechanics and Geoengineering (Book chapter; in press)

Soil aggregate stability in eco-engineering: comparison of field and laboratory data with an outlook on a new modelling approach

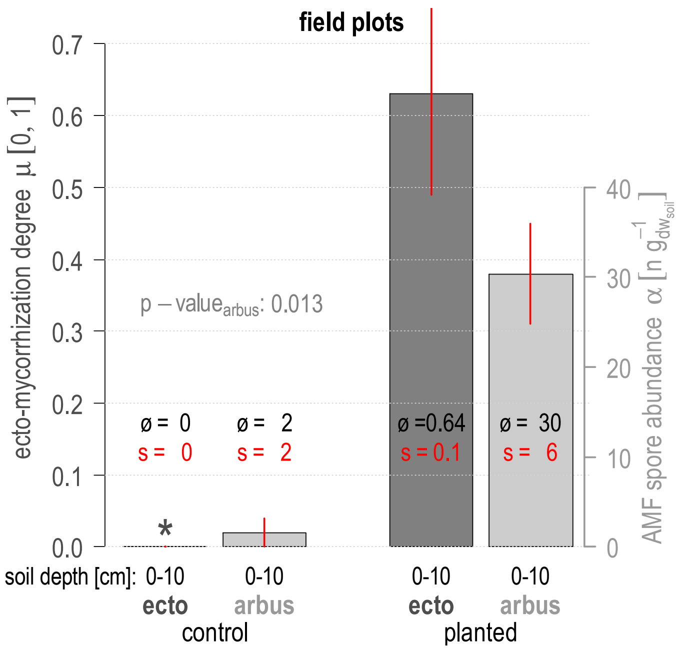
Frank Graf, Lothar te Kamp, Michael Auer, Madhu Sudan Acharya, Wei Wu

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.

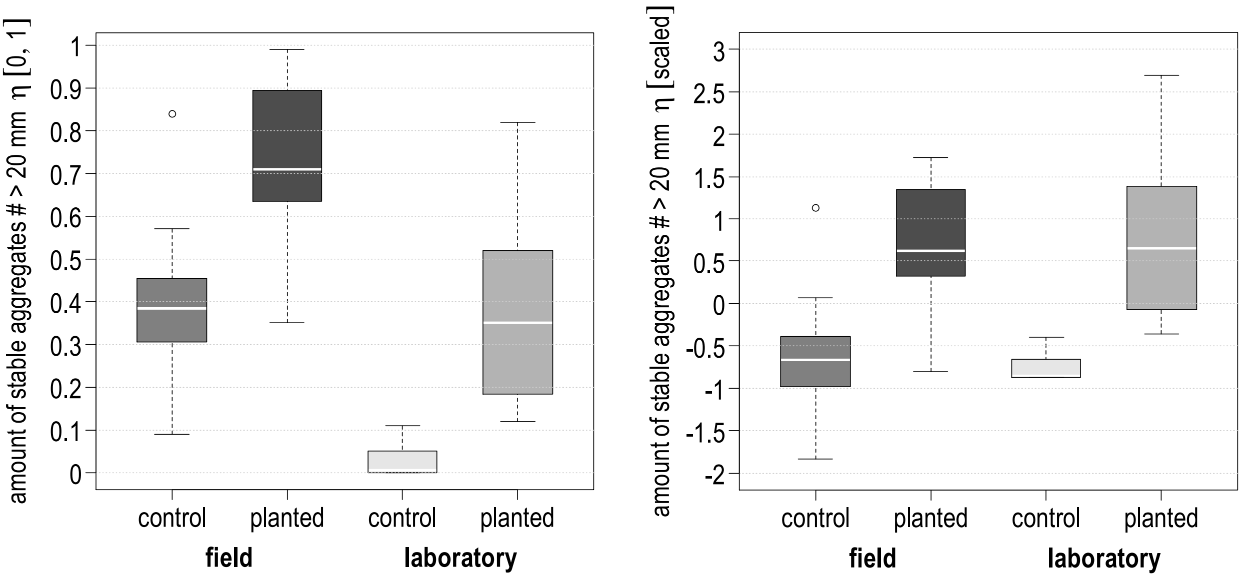
Keywords: soil aggregate stability, root length, mycorrhiza, field and laboratory samples, modelling, particle flow code (PFC)



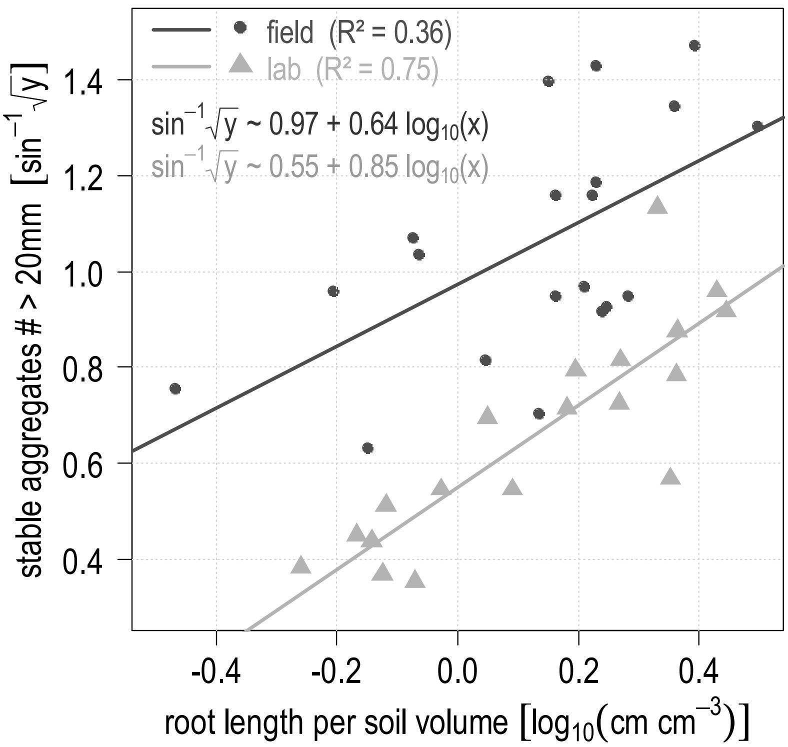
Left: Root length per soil volume of all samples. Right: Mycorrhization degree of *Alnus incana* of the planted samples.



Distribution, mean (ø), and standard deviation (s) of the degree of ectomycorrhization (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.



Original (left) and scaled (right) data of soil aggregate stability of control and planted samples from field and laboratory.



Linear regression model ($\sin^{-1}$(aggregate stability)$^{1/2}$ ~ sample$_{loc}$ * $\log_{10}$(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.

Outlook: *This comparison of field and laboratory data 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 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 concept opens a chance to explore new avenues in order to reliably and relatively easy up-scale laboratory results to catchment level in respect of slope failure prediction.*
In respect of this new approach, the biological stabilisation part will not be assigned as usually to an additional cohesion coefficient c_{root}*' in the Mohr-Coulomb failure equation but addressed with the particle flow code PFC*^{3D} *of ITASCA.*