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

Katrin Burri¹,², Frank Graf² and Albert Böll¹

¹ WSL Swiss Federal Institute for Forest, Snow and Landscape Research, CH-8903 Birmensdorf, Switzerland. katrin.burri@wsl.ch, albert.boell@wsl.ch
² WSL Institute for Snow and Avalanche Research SLF, CH-7260 Davos Dorf, Switzerland. graf@slf.ch

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

1 Introduction

Soil bioengineering measures combine the use of living plants and inert mechanical constructions to protect slopes against erosion and shallow mass movement. Whereas mechanical constructions are primarily employed to reduce slope angle, the main role of vegetation is to protect and stabilise the wide areas between the technical constructions. In successful soil bioengineering systems, both mechanical and biological elements should work together in an integrated and complementary manner (GRAY and SOTIR 1996). It is thus a major challenge to conduct adequate and comprehensive performance assessments of soil bioengineering measures. Whereas in geotechnical engineering several performance standards and guidelines for structural safety and serviceability of constructions exist, there is a lack of comparable tools in the field of ecological restoration. Numerous authors have noted the need to monitor, assess and quantify the effectiveness of ecological restoration measures in order to facilitate the transfer of technology and knowledge (BERGER 1991; HOBBS and NORTON 1996; PASTOROK et al. 1997; BAER et al. 2002; ANAND and DESROCHERS 2004; GRETA RSDOTTIR et al. 2004).

Recent theoretical models in restoration ecology emphasize the importance of taking an integrated monitoring approach that considers multiple variables. However, limited financial and time resources often prevent such comprehensive assessments (SER 2004;
A solution to this problem may be to use integrated indicators that reflect multiple aspects and, therefore, allow extensive information on ecosystem status to be gathered in a relatively short time. Various indicators have been proposed, including the fractal dimension of soil particle size distribution, microbiological parameters and soil aggregate stability (Arshad and Coen 1992; Alkorta et al. 2003; Tian et al. 2004; Izquierdo et al. 2005; Hernandez-Allica et al. 2006; Wang et al. 2006).

Soil aggregate stability seems the most appropriate indicator with regard to protecting slopes from erosion and shallow mass movements as it is critical to both plant growth and soil erodibility (Barthes and Rose 2002; Canton et al. 2009). Soil aggregate stability refers to a soil’s ability to retain its structure when exposed to different stresses (Angers and Carter 1996; Amezketa 1999; Diaz-Zorita et al. 2002). It is not only an important parameter affecting soil erodibility and soil crusting potential, but it also plays a key role in ecosystem functioning as it affects water, gas and nutrient fluxes and storage and, therefore, influences the activity and growth of living organisms (Angers and Caron 1998; Amezketa 1999; Eldridge and Leys 2003; Wick et al. 2009). Various direct and indirect experimental methods have been used to quantify soil aggregate stability (Lebissonnais 1996; Amezketa 1999; Diaz-Zorita et al. 2002), but the wide variety of approaches and the lack of standardisation complicate the comparison of the results of these studies.

Recently, a new feature of soil aggregate stability has been discovered (Böll and Graf 2001; Frei et al. 2003). Based on triaxial compression tests with planted and unplanted samples, Frei et al. (2003) found that soil aggregate stability correlates with the shear strength of the soil, which is a very critical factor in slope stability. This finding implies that soil aggregate stability may reflect the plants’ contribution to superficial slope stability. Soil aggregate stability tests are much easier to perform than triaxial compression tests and, therefore, may be an easy and appropriate way to obtain crucial information on the effectiveness of revegetation measures in providing protection not only against erosion, but also against shallow landslides. However, only a few studies have collected data on the soil aggregate stability of steep slopes affected by erosion and mass movements (e.g. Barthes and Roos 2002; Gros et al. 2004; Barni et al. 2007; Canton et al. 2009; Pohl et al. 2009), whereas extensive research has been done on agricultural soils (e.g. Degens et al. 1994; Chenou et al. 2000; Idowu 2003; Milne and Haynes 2004).

The objective of this study was to determine whether soil aggregate stability increased along with soil and vegetation development in a landslide area in Central Switzerland. 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). Soil aggregate stability was determined using a wet-sieving procedure (Frei et al. 2003). Immersing soil samples in water is supposed to simulate natural forces occurring in slopes during heavy precipitation, as water saturation is a critical factor in slope failure (Terzaghi and Peck 1967). Various parameters were measured to describe the state of soil and vegetation development at the sites, including the vegetation cover, root length density, ectomycorrhization of roots, grain size distribution of the soil, organic matter content and spore abundance of arbuscular mycorrhizal fungi.
2 Material and methods

2.1 Test sites

The study was conducted in the landslide area “Schwandrübi”, which is situated in the catchment area of the “Flüeligraben” (Community of Dallenwil, Canton Nidwalden, Switzerland, Figs. 1 and 2). The mean yearly precipitation sum and air temperature is estimated to be around 1510 mm and 5.6 °C, respectively. Geologically, the area is part of the “Wildhorn-decke” of the Helveticum, which consists of Mesozoic, Tertiary and Permian sediments (HSÜ and BRIEGEL 1991). According to ASTM standards, the moraine substrate of the study area was classified as a clayey gravel with sand (GC-CL) (FREI et al. 2003).

The area is highly susceptible to soil erosion and landslides. In the past, the downstream villages repeatedly suffered from mass movements and resulting stream flooding. At the beginning of the 1980s, the Canton Nidwalden initiated a project to stabilise the area with soil bioengineering methods.

Sampling was carried out in three 10 × 10 m test sites located in: 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). All three test sites shared the same exposition (north-east), elevation (1120–1165 m a.s.l.) and geology (Table 1).

The control site was located in a bare gully, covering an altitude range of 200 m and an area of approximately 300 ha (Fig. 3c). Work on building retaining walls from the bottom to the top of the gully began in 1983. Since then, no large-scale mass movements have been recorded, but erosion and local sliding processes still occur at this site, and only pioneer vegetation has been able to grow sparsely. The revegetated site was stabilised with gabions and wooden walls in 1981 and 1982 (Figs. 3a and 3b). In 1982, saplings of Alnus incana and cuttings of Salix purpurea were planted. Additionally, a site-adapted seed mixture was applied by hydroseeding. In the following years, the plantation developed into a dense stand of bushes and no mass movements have occurred in the gully since then. The climax forest site was situated between the control and the revegetated site (Fig. 3d). The dominant tree species was Fagus sylvatica.

Table 1. Characteristics of the three test sites.

<table>
<thead>
<tr>
<th></th>
<th>Control site</th>
<th>Revegetated site</th>
<th>Climax forest site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope angle</td>
<td>44°</td>
<td>41°</td>
<td>44°</td>
</tr>
<tr>
<td>Soil bioengineering measures</td>
<td>retaining walls</td>
<td>retaining walls, wire nettings, <em>Alnus incana</em> plantlets <em>Salix purpurea</em>, cuttings, hydroseeding</td>
<td>none</td>
</tr>
<tr>
<td>Vegetation</td>
<td>sparse pioneer vegetation</td>
<td>bush stand dominated by <em>Alnus incana</em></td>
<td>forest stand dominated by <em>Fagus sylvatica</em></td>
</tr>
</tbody>
</table>
Fig. 1. Location of the study area. Swiss National Map (www.swisstop.admin.ch), 1:25 000, no. 1170 “Alpnach”.

Fig. 2. Aerial photo of the study area taken in 1992. A = control site, B = revegetated site, C = climax forest site. Picture: WSL.
2.2 Vegetation

The total vegetation cover of each test site was visually estimated in percentages. Cover-abundance values were determined for all plant species according to BRAUN-BLANQUET (1964).

Roots from the soil core samples (section 2.3) were used to determine the root length density at each test site. The roots were cleaned to remove soil, 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 tips were checked for ectomycorrhizal structures under a stereo microscope and the ectomycorrhization degree was determined with a counting grid (mesh openings 10 mm) according to Equation 1:
2.3 Soil

Soil aggregate stability tests were performed with cylindrical soil core samples. Samples were taken with a steel soil-coring apparatus (Fig. 4a). A sharpened steel cylinder (length = 250 mm, diameter = 50 mm) was driven into the soil with a hammer (5 kg), and the samples were pushed into a plastic tube lining the inside of the steel cylinder. In the laboratory, the soil samples were divided into two sections of about 10 cm length, equivalent to soil depths of 0–10 cm and 10–20 cm. These sub-samples were placed separately onto a sieve and laterally supported by a metal tube with an internal diameter of 80 mm. Sieve mesh openings were 20 mm, according to Frei et al. (2003). The whole set-up was put into a transparent jar (Fig. 4b). The jar was filled with water within 45 sec, and five minutes later, the drain valve at the bottom of the pot was opened to empty the jar within 90 sec. The soil aggregate stability was calculated as the fraction of soil remaining on the sieve relative to the entire soil sample (Equation 2):

\[
agg = \frac{m_{20} - m_{stones}}{m_{tot} - m_{stones}}
\]  

Where:
- \(agg\) = soil aggregate stability [g/g]
- \(m_{20}\) = 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]

Grain size distributions were determined by dry sieving, wet sieving (<10 mm) and sedimentation analysis using the pipette method (<2 mm, Robinson 1922). Organic matter contents were determined by oxidation with \(\text{H}_2\text{O}_2\) (Fal et al. 2000) and the soil pH was measured in 0.01 M \(\text{CaCl}_2\) (soil: solution ratio 2:5). The \(\text{CaCO}_3\) content was determined by volumetric measurement of the \(\text{CO}_2\) released after addition of \(\text{HCl}\) (Fac et al. 1996).

Spores of arbuscular mycorrhizal fungi were isolated from the soil by centrifugation in a 70 % sucrose gradient (Sieverding 1991). Spore abundance was calculated as the number of spores per g dry soil.
2.4 Statistical data analysis

Statistical analysis was performed with the software package R 2.3.1 (2006). For multiple comparisons, the pairwise Wilcoxon rank sum test was used, with correction for multiple testing according to HOLM (1979).

3 Results

3.1 Vegetation

Table 2 lists the plant species occurring on the three test sites. On the control site, only isolated patches of herbaceous pioneer vegetation such as *Saxifraga aizoides* were observed. The revegetated site was characterised by a diverse bush community and a continuous layer of grasses and herbs dominated by *Milium effusum*. The vegetation cover of the revegetated site was estimated to 150 % with a total of 27 species. The climax forest site was dominated by *Fagus sylvatica* and had very little understorey. Vegetation cover was estimated to 110 % with a total of 18 species.

The root length density in the upper soil layer (0–10 cm) was similar on the revegetated site to that in the climax forest (Table 3, p-value = 0.620). At 10–20 cm soil depth, however, the root length density was significantly higher in the climax forest stand (p-value = 0.026). On the control site, the values were about 6 to 10 times lower than on the revegetated site.

The degree of ectomycorrhization was significantly higher in the roots of the climax forest than in those of the revegetated site. On the control site, no ectomycorrhiza-forming plant roots were found.
Table 2. 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 %. 1 (Roem. et Schult) O.Schwarz, 2 (Hedw.) Schimp., 3 (Hedw.) Mitt.

<table>
<thead>
<tr>
<th>Control site</th>
<th>Revegetated site</th>
<th>Climax forest site</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>tree and bush layer</strong></td>
<td><strong>tree and bush layer</strong></td>
<td><strong>tree and bush layer</strong></td>
</tr>
<tr>
<td>+ Salix purpurea L.</td>
<td>3 Alnus incana (L.) Moench</td>
<td>5 Fagus sylvatica L.</td>
</tr>
<tr>
<td>r Salix appendiculata Vill.</td>
<td>2 Acer pseudoplatanus L.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 Rubus idaeus L.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 Salix appendiculata Vill.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 Fraxinus excelsior L.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 Salix purpurea L.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+ Abies alba Miller</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+ Lonicera alpigena L.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+ Lonicera nigra L.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+ Lonicera xylosteum L.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+ Picea abies (L.) Karsten</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+ Sorbus aria (L.) Crantz</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+ Sorbus aucuparia L.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+ Ulmus montana With.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+ Viburnum Lantana L.</td>
<td></td>
</tr>
<tr>
<td><strong>herb layer</strong></td>
<td><strong>herb layer</strong></td>
<td><strong>herb layer</strong></td>
</tr>
<tr>
<td>1 Saxifraga aizoides L.</td>
<td>4 Milium effusum L.</td>
<td>2 Adenostyles alliariae (Gou.) Ke.</td>
</tr>
<tr>
<td>+ Calamagrostis humilis 1</td>
<td>+ Fragaria silvestris (L.) Duch.</td>
<td>1 Mercurialis perennis L.</td>
</tr>
<tr>
<td>+ Campanula rotundifolia L.</td>
<td>+ Geum urbanum L.</td>
<td>1 Milium effusum L.</td>
</tr>
<tr>
<td>+ Tussilago farfara L.</td>
<td>+ Heracleum sphondylium L.</td>
<td>+ Rubus fruticosus L.</td>
</tr>
<tr>
<td>r Carex diversicolor Crantz</td>
<td>+ Phyteuma spicatum L.</td>
<td>+ Carex digitata L.</td>
</tr>
<tr>
<td></td>
<td>+ Polystichum lobatum (Hud.) Che.</td>
<td>+ Carex sylvatica Hudson</td>
</tr>
<tr>
<td></td>
<td>+ Valeriana tripteris L.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+ Knautia sylvatica L. (Duby)</td>
<td>+ Epipactis rubiginosa (Cra.) Gau.</td>
</tr>
<tr>
<td></td>
<td>r Solidago virga-aurea L.</td>
<td>+ Fragaria silvestris L. (Duch.)</td>
</tr>
<tr>
<td></td>
<td>r Stachys sylvatica L.</td>
<td>+ Hordelymus europaeus L. Harz</td>
</tr>
<tr>
<td><strong>moss layer</strong></td>
<td><strong>moss layer</strong></td>
<td><strong>moss layer</strong></td>
</tr>
<tr>
<td>k. Eurhynchium striatum 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>k. Mnium (Hedw.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Table 3. Vegetation properties of the three test sites.</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil depth</th>
<th>Control site 0–10 cm</th>
<th>Revegetated site 0–10 cm</th>
<th>Climax forest site 0–10 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil depth</td>
<td>0–10 cm</td>
<td>10–20 cm</td>
<td>0–10 cm</td>
</tr>
<tr>
<td>Vegetation cover [%]</td>
<td>3</td>
<td>153</td>
<td>112</td>
</tr>
<tr>
<td>Species number</td>
<td>7</td>
<td>27</td>
<td>18</td>
</tr>
<tr>
<td>Root length density [cm/cm³]</td>
<td>0.11 ± 0.21 (n=20)</td>
<td>0.05 ± 0.07 (n=13)</td>
<td>1.51 ± 0.67 (n=20)</td>
</tr>
<tr>
<td>Degree of ectomycorrhization [%]</td>
<td>—</td>
<td>—</td>
<td>64 ± 10 (n=12)</td>
</tr>
</tbody>
</table>
3.2 Soil

Figure 5 shows the grain size distributions of the topsoils sampled on the three test sites. The percentage of clay and silt particles was higher on the revegetated site than on the control site, and still higher on the climax forest site.

Soil aggregate stability was significantly higher on the revegetated site than on the control site (Fig. 6, Table 4). In the upper soil layer (0–10 cm), soil aggregate stability values of the climax forest site were significantly higher than those of the revegetated site. At 10–20 cm soil depth, however, there was no significant difference between the two sites.

The soil dry unit weight and pH decreased between the control site and the revegetated site, and were even less at the climax forest site, whereas the soil porosity and organic matter content increased (Table 5). On the two sampling days, the gravimetric soil-water content was 1.7 to 1.9 times higher on the revegetated site than on the control site (Table 5). On the climax forest site, the water content was 2.3 to 3.4 times higher than on the revegetated site.

The spore abundance of arbuscular mycorrhizal fungi was significantly lower in the soil from the control site than in that from the revegetated site and the climax forest (Table 5).

Fig. 5. Grain size distributions of soil at the three test sites.
Table 4. Aggregate stability [g/g] of soil core samples from the three test sites. N = number of samples, sd = standard deviation.

<table>
<thead>
<tr>
<th>Soil depth</th>
<th>N</th>
<th>mean</th>
<th>median</th>
<th>sd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control site</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–10 cm</td>
<td>20</td>
<td>0.38</td>
<td>0.39</td>
<td>0.17</td>
</tr>
<tr>
<td>10–20 cm</td>
<td>13</td>
<td>0.43</td>
<td>0.39</td>
<td>0.22</td>
</tr>
<tr>
<td>Revegetated site</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–10 cm</td>
<td>20</td>
<td>0.73</td>
<td>0.71</td>
<td>0.19</td>
</tr>
<tr>
<td>10–20 cm</td>
<td>22</td>
<td>0.82</td>
<td>0.86</td>
<td>0.12</td>
</tr>
<tr>
<td>Climax forest site</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–10 cm</td>
<td>21</td>
<td>0.92</td>
<td>0.92</td>
<td>0.06</td>
</tr>
<tr>
<td>10–20 cm</td>
<td>8</td>
<td>0.88</td>
<td>0.90</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Table 5. Soil properties of the three test sites. AMF = arbuscular mycorrhizal fungi.

<table>
<thead>
<tr>
<th>Soil depth</th>
<th>Control site</th>
<th>Revegetated site</th>
<th>Climax forest site</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>0–10 cm</td>
<td>10–20 cm</td>
</tr>
<tr>
<td>Soil dry unit weight [kN/m^3]</td>
<td>6</td>
<td>14.2 ± 0.6</td>
<td>14.3 ± 1.5</td>
</tr>
<tr>
<td>Porosity [cm^3/cm^3]</td>
<td>1</td>
<td>0.469</td>
<td>0.466</td>
</tr>
<tr>
<td>Organic matter [% by weight]</td>
<td>3</td>
<td>0.1 ± 0.2</td>
<td>0.2 ± 0.1</td>
</tr>
<tr>
<td>pH (CaCl2)</td>
<td>3</td>
<td>7.8 ± 0.1</td>
<td>7.9 ± 0.1</td>
</tr>
<tr>
<td>AMF spores [number/g soil]</td>
<td>4</td>
<td>2 ± 2</td>
<td>1 ± 1</td>
</tr>
<tr>
<td>Water content on sampling day 1 [g/g]</td>
<td>(n=2)</td>
<td>0.07 ± 0.00</td>
<td>0.08</td>
</tr>
<tr>
<td>Water content on sampling day 2 [g/g]</td>
<td>(n=18)</td>
<td>0.09 ± 0.02</td>
<td>0.09 ± 0.02</td>
</tr>
</tbody>
</table>

Fig. 6. Soil aggregate stability values at the three test sites at 0–10 cm and 10–20 cm soil depth. Identical subscript letters indicate that the distributions do not differ significantly (p-value > 0.05).
4 Discussion

4.1 Vegetation

Before the implementation of soil bioengineering measures, the study area was subject to
erosion and superficial mass movements for years. Roughly 25 years ago, check dams and
gabions were constructed to stabilise both the revegetated and the control site. However,
their initial conditions for vegetation establishment differed, as the control site was left with
technical stabilisation measures only, whereas the revegetated site was additionally planted
and seeded. On the revegetated site, vegetation development started from artificially intro-
duced seeds and saplings, whereas on the control site, it depended solely upon spontaneous
colonisation. Twenty-five years after implementation, a persistent plant cover has established
on the revegetated site, but only sparse pioneer vegetation has been able to colonise the
control site. These observations support those of REY et al. (2005), who found that plant
abundance and recovery were rather low upstream of soil bioengineering retaining walls in
marly gullies. The spontaneous development and recovery of vegetation depends on the
level of environmental stress and productivity on a site (BURYLO et al. 2007; PRACH and
HOBBS 2008). Data from the control site suggest that soil conditions remained adverse to
plant growth despite slope stabilisation by technical constructions. Several factors, such as
ongoing erosion, coarse-grained soil texture, lack of organic matter and high bulk density,
may have worked in concert and impeded plant establishment on the control site. A short-
age of mycorrhizal propagules may have further delayed vegetation development.
Mycorrhizal fungi improve the water and nutrient supply of their hosts (SMITH and READ
1997), and are one of the driving forces behind plant successional processes (VAN DER
HEIDEN et al. 1998). Furthermore, their vast hyphal networks and glue-like exudates
substantially contribute to a stable soil aggregate structure (MILLER and JASTROW 1990;
GRAF and GERBER 1997; BEARDEN and PETERSEN 2000; JEFFRIES et al. 2003; RILLIG and
MUMMEY 2006). Due to this twofold benefit for both plant nutrition and soil stability, there
has been increasing interest in using mycorrhizal fungi in soil restoration (MILLER and

On the revegetated site, artificial planting and seeding successfully helped to overcome
the adverse soil conditions. The artificially introduced tree species (Alnus incana and Salix
purpurea) survived and developed into a dense stand of bushes. The establishment success
of many tree species is better when they are introduced as saplings or cuttings instead of
seeds (SCHIECHTL 1973). The application of a site-adapted seed mixture increased the seed
availability on the revegetated site, and consequently, the establishment rate of herbaceous
plants and grasses. The relatively high number of plant species that spontaneously grew
suggests that their establishment was facilitated by the artificially introduced species.
Facilitation and nurse plant phenomena play an important role in the colonisation of limiting
habitats and they have been successfully utilized in recent restoration projects (CARRILLO-

4.2 Soil

Prior to the implementation of soil bioengineering measures at the control and revegetated
site, erosion and sliding processes inhibited soil formation, leaving the sites in an initial
successional stage. Before soil formation can start, a certain level of soil stability is required.
In the study area, this was achieved partly by using technical constructions and, on the
revegetated site, by additional revegetation measures. Vegetation is an important factor in
soil formation, and it may thus be argued that the applied revegetation measures, and con-
sequently, the different vegetation developments on the revegetated and control site, are mainly responsible for the differences in soil properties between the two sites. Plants can affect soil formation in several ways. They protect the soil from erosion, constitute the main source of organic matter, influence weathering processes and nutrient cycling, and promote soil organisms (Scheffer and Schachtsschabel 2002).

The plants’ role in reducing erosion processes is probably a main reason for the higher content of fine soil particles on the revegetated site. There, fine weathering products could accumulate over time, whereas on the bare soil of the control site, ongoing erosion and concentrated runoff during heavy rainfall events removed them continuously. Furthermore, the well-developed vegetation on the revegetated site increased physical and chemical weathering. Glos et al. (2004) found a comparable accumulation of fine soil fractions on a chronosequence of restored alpine grasslands. As clays play a key role in the formation of micro-aggregates (Tisdall and Oades 1982; Amezketa 1999), an increase in fine soil particles is expected to improve aggregate stability.

The accumulation of organic matter on the revegetated site can be attributed to an increase in litter supply due to the establishment of vegetation and the development of a functional microbial community. Furthermore, by reducing erosion, vegetation also reduced losses of organic matter. The effect of soil organic matter on aggregate stability has been discussed extensively in the literature (Tisdall and Oades 1982; Amezketa 1999; Milne and Hayes 2004). Depending on the type of ecosystem, the build up of organic matter on disturbed sites is very slow (Arnalds 1987). In this study, the proportion of organic matter on the revegetated site was roughly ten times higher than on the control site, but still approximately ten times lower than in the adjacent climax forest stand. Moreno-de Las Heras (2009) found that the accumulation of organic matter from restored vegetation was the triggering factor for the development of soil aggregation and biological functionality on restored mining slopes. Wick et al. (2009) demonstrated that accumulation of carbon in reclaimed clay loam soil is closely tied to soil aggregation, as well as to the compositions of plant and microbial communities.

The spore abundance of arbuscular mycorrhizal fungi was higher in the soil from the revegetated site than in that of the control site. This can be probably attributed to the reduction of erosion processes as well. Previous studies have shown that sliding and erosion processes drastically reduce mycorrhizal propagules (Parke et al. 1984; Biondini et al. 1985; Amaranthus and Trappe 1993). Depending on the distance from possible inoculant sources, they accumulate only very slowly after disturbance (Greipsson and El-Mayas 2000).

In addition to the above-mentioned indirect effects of vegetation on soil aggregate stability, the dense root network of the revegetated site also contributed directly to the development of a stable soil aggregate structure by enmeshing soil particles and by releasing glue-like root exudates (Tisdall and Oades 1982; Degens et al. 1994). In these ways, plants can improve the soil aggregate stability of undeveloped soils within a very short time, involving only a few months (Gros et al. 2004; Frei et al. 2003).

Data from this study support the theory that soil aggregation and the incorporation of organic matter decrease the bulk density of the soil, increase its porosity, improve its water retention capacity and promote soil organisms. These changes in soil properties are favourable for plant growth. It seems that revegetation is able to promote a positive feedback between biotic and abiotic factors that, in this case, substantially accelerated the vegetation and soil development on the revegetated site compared to the control site. This is in accordance with observations from other restoration projects, where revegetation was found to facilitate spontaneous plant colonisation and the recovery of key soil physico-chemical properties (Gretarsdottir et al. 2004; Gros et al. 2004; Moreno-de Las Heras 2009).
To evaluate the effectiveness of the revegetation measures in the study area, it is important to know whether the increased soil aggregate stability corresponds to a higher resistance of the soil to erosion and superficial slides. As neither the soil erodibility nor the shear strength of the soil was measured during this study, this question cannot be answered definitely. However, numerous studies on a variety of soils have found positive correlations between soil aggregate stability and erodibility. Several authors have suggested that aggregate stability may be a valuable indicator of soil susceptibility to water erosion (Barthes and Roose 2002; Canton et al. 2009), which implies that the high soil aggregate stability on the revegetated site may well correspond to a lower susceptibility to erosion. Frei et al. (2003) found that soil aggregate stability was positively correlated with the shear strength of the substrate. The soil samples used in their laboratory experiments were prepared with substrate from the control site of this study and planted with Alnus incana, the most abundant plant species of the revegetated site. Thus, these laboratory findings may at least qualitatively be related to the field situation in the study area.

Several observations from the study area provide further evidence that soil aggregate stability may be a good indicator of the mechanical stability of the surface soil on the three test sites: On the control site, which had low soil aggregate stability values, erosion rills and isolated traces of small landslides indicated that the superficial slope stability is rather low. In contrast, on the revegetated site, which had significantly higher soil aggregate stability values than the control site, there were no visible traces of erosion. Furthermore, the hill slope was not affected by landslides even after extreme precipitation events, although the slope angle is higher than the critical angle of internal friction of the moraine substrate $\phi^* = 33 \pm 3^\circ$ (Boll et al. this issue). The climax forest, which had the highest soil aggregate stability, has been stable for many decades. Thus, based on these observations and previous studies, it can be argued that the higher soil aggregate stability of the revegetated site corresponds to a lower susceptibility to erosion and shallow mass movements. Hence, it seems that the revegetation measures in the study area successfully perform their function within the soil bioengineering system.

To assess revegetation measures on the basis of soil aggregate stability in other regions, it would be necessary to determine new reference values on an undisturbed site within this specific region. As soil aggregation depends on many site-specific factors such as geology and climate, the values gained in this case study cannot be used as a reference for other areas. Soil aggregate stability tests involve some effort, but they are nevertheless still much easier and faster to perform than assessing soil erodibility with rainfall simulators or estimating the shear strength of the substrate with triaxial compression tests. Thus, soil aggregate stability tests may be a useful tool for assessing the effectiveness of revegetation measures in providing protection against erosion and shallow landslides.

6 References


BARTHELS, B.; ROOSE, E., 2002: Aggregate stability as an indicator of soil susceptibility to runoff and erosion; validation at several levels. Catena 47: 133–149.


FAC; FAP; FAW; RAC, 1996: Bestimmung des Gesamtkalkgehaltes CaCO₃. Referenzmethoden der Eidg. landwirtschaftlichen Forschungsanstalten.


WinRhizo, 2000: In. Régent Instruments Inc, Quebec Canada.

Revised version accepted June 2, 2009