Vegetation, interrill erosion and aggregate stability on grazed alpine meadows

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Abstract

Alpine meadows are prone to serious soil erosion due to terrain steepness but also due to ongoing climate change. Widespread and intensive grazing activities lead additionally to the reduction of the protective vegetation cover. For a better understanding of the functions of the protective vegetation cover, 111 rainfall simulation experiments were conducted on cattle grazed Suisse alpine meadows differing in the degree of vegetation cover, but not in slope inclination (20°). Micro plots (25 cm * 25 cm) were irrigated for approximately five minutes with a simulated rainfall intensity of 48 to 60 mm h^{-1} which corresponds to a heavy and rare rainfall event in Switzerland. The influence of a decreasing vegetation cover was investigated on interrill erosion but also on various soil parameters.

Results showed that a reduction of vegetation cover led to an exponential increase in soil particle yield. Negligible soil particle yields were measured when micro plots were covered with more than 50% of living or dead plant material. Furthermore, a decrease in vegetation cover led to an increase in runoff but to no significant changes in infiltration. Concerning soil properties, a decrease in vegetation cover was related to a decrease in soil organic matter and root density. It was hypothesized that these changes in soil lead to a lower aggregate stability which in turn is responsible for variations in interrill erosion parameters. Results showed that aggregate stability was significantly influenced by the decrease in root density but had no significant impact on interrill erosion parameters. Variations in soil particle yield could be best predicted with the variables total cover and runoff. It was finally concluded that interception, instead of aggregate stability, was most likely responsible for the increases in soil particle yield and runoff with decreasing vegetation cover. The non-significant changes in infiltration might have been due to aggregate stability which showed high values nearly independent of vegetation cover.

This study indicates that vegetation cover protects soil from interrill erosion by its significant influence on various soil parameters. Therefore the maintenance of an intact vegetation cover with little open ground is essential for the protection of grazed alpine meadows.

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1. Introduction

1.1. Problem definition

Soil erosion is one of the most critical environmental and social problems facing humanity today (Toy et al. 2002, Brady & Weil 2010, Zuazo et al. 2011). The main reason for this is that erosion makes soil less capable of producing the plants on which animals and people depend (Brady & Weil 2010). It can be particularly dangerous because it occurs gradually, leaving little or no signs of soil removal (Osman 2014). However, on- and off-site effects of soil erosion are multiple. The main on–site effect is that the eroded area loses its upper soil layer which consists most often of organic and nutrient rich fine mineral particles (Brady & Weil 2010). This loss influences water- and nutrient supply of the affected soil (Osman 2014). In addition, aesthetics and cultural heritage of the area can be affected (Meusburger & Alewell 2008). The lost soil particles can cause great damages downstream, the so called off-site effects. Water quality is reduced through the process of eutrophication caused by excessive nitrogen and phosphorus (Brady & Weil 2010). Soil particles can also lead to siltation of reservoirs (Osman 2014). Furthermore, the additional sediments make the water more turbid. This influences the fish habitat and the aquatic food chain by decreased photosynthesis due to a reduced amount of incoming sunlight (Brady & Weil 2010).

These days human activities, especially the ones related to agriculture, have a strong impact on soil erosion (Brady & Weil 2010), which leads to accelerated erosion rates. Under the influence of mankind soil is commonly eroded away faster than new soil can form by weathering or deposition. As a result, soil depth is reduced (Boardman & Poesen 2006, Brady & Weil 2010). Although most of soil erosion occurs on cultivated land (Boardman & Poesen 2006), uncultivated can also suffer from significant soil erosion (Evans 2006). Soil erosion on uncultivated land is often driven by grazing animals (Boardman & Poesen 2006).

Especially mountain terrain is affected by soil erosion due to the extreme topography and climate, which make the ecosystem more instable, fragile and sensitive (Weisshaidinger & Leser 2006, Bini & Zilioli 2011, Schindler Wildhaber et al. 2012). Mountain terrain is dominant in Switzerland because the Alps cover 65% of the total country area (Odermatt & Wachter 2004). A considerable part of the Alps is grazed by animals (Odermatt & Wachter 2004). It is common that during summertime herds go to high mountain pastures while spending wintertime at the valley bottom (Odermatt & Wachter 2004). This illustrates that studies about soil erosion on grazed mountain terrain are crucial for Switzerland. However, such studies are rare because most studies facing erosion were done at agricultural sites

(Siegrist et al. 1998, Grande et al. 2005, Rienzi et al. 2013) or in Mediterranean regions (Casermeiro et al. 2004, Zuazo & Pleguezuelo 2008, Zorn 2011).

During the last decades, the understanding about soil erosion got more important because land use management changed substantially (Baur et al. 2007, Meusburger & Alewell 2008). For Switzerland, a decrease in the grazed area is reported (Tappeiner et al. 2006, Baur et al. 2007, Gellrich & Zimmermann 2007, Meusburger & Alewell 2008). The grazed area decreased because

- reforestation was promoted for flood protection and erosion control
- permanent herding was replaced by uncontrolled grazing within fenced pastures
- remote and less productive areas were abandoned
- the number of alpine cattle alps decreased
- shrubs appeared due to the decrease of grazing activities

The BFS (2013) asserted that the alpine pasture area decreased by about 4.4% between 1985 and 2005. Parallel to this development the number of cattle did not decrease considerably (Baur et al. 2007, Meusburger & Alewell 2008). To sum up, it can be said that the remaining alpine pastures had been grazed with higher intensity since the beginning of 1970 (Baur et al. 2007). For example in the Urseren Valley, Switzerland, the area per animal declined from 1.55 ha in 1955 to 0.6 ha in 2006 (Meusburger & Alewell 2008). In the same region soil erosion was investigated: aerial photographs demonstrated that landslides and sheet erosion increased strongly over the last 45 years (Alewell et al. 2008).

In the near future the importance of understanding will even increase because soil erosion might intensify significantly by global climate change (Fuhrer et al. 2006, Zuazo et al. 2011). On one hand scientists predict an increase in temperature and on the other hand an increase in heavy rainfall events for many regions (IPCC 2014, Routschek et al. 2014). Both would have an influence on soil erosion. The increase in temperature might lead to an earlier snow melt in the alpine terrain (CH2011) so that soil is protected by the snow cover for a shorter amount of time, and exposed to rainfall events for longer periods without fully developed vegetation cover. Heavy rainfall events might show a higher rainfall intensity which is known as a key factor controlling soil erosion: the higher the intensity is, the more soil particles detach during a rainfall event (Toy et al. 2002, Yan et al. 2008, Routschek et al. 2014). Asselmann et al. (2003) investigated the impact of climate and land use change on soil erosion. The result of the modelled estimations of sediment delivery to the river Rhine from alpine regions show an increase of 200% by the year 2100 compared to today.

Soils under natural vegetation cover have high infiltration rates and high resistance to erosion. Even under extreme rainfall conditions runoff is unusual and if it occurs, then without soil particles (Boardman & Poesen 2006). The importance of an existing vegetation cover in controlling soil erosion is widely accepted (Morgan 1999, Toy et al. 2002, Zuazo et al. 2011) and it is known that grazing can reduce vegetation enough to increase erosion (Evans 2006, Zuazo et al. 2011, Osman 2014). However, it is not clear, how exactly vegetation cover is controlling soil erosion on grazed meadows because a decreasing vegetation cover is influencing multiple erosion and soil parameters. One parameter influenced by vegetation is aggregate stability which refers to the ability of the soil aggregates to remain intact when exposed to different stresses (Amézketa 1999). The stability of aggregates and the pores between them affect the movement and storage of water, aeration, biological activity and as a consequence also soil erosion (Amézketa 1999, Toy et al. 2002).

With the understanding of the role of aggregate stability in connection with interrill erosion, the importance of vegetation cover in mountain terrain could be better assessed. This information would be helpful for the Suisse federal government, local agricultural policy-makers in the alpine regions and also farmers of mountain terrain. The aim of this study is therefore to examine the influence of vegetation cover on aggregate stability, and consequently the influence of aggregate stability on interrill erosion parameters.

This study is part of the project "Soil stability and natural hazards" (SOSTANAH), a national research project (NRP 68) founded by the Suisse National Fond. The main objective of the SOSTANAH project is to understand the processes which cause landslides but also erosion at regional scale. In addition, the project's main goal is to define critical thresholds and transfer knowledge into action at large scale. This study should contribute to the SOSTANAH project through the identification of the threshold of vegetation cover which is needed to avoid serious interrill erosion. Furthermore, the role of aggregate stability in the context of interrill erosion should be investigated due to its possible link to shallow landslides.

1.2. Theoretical background

1.2.1. Interrill erosion

Soil erosion is defined as the detachment of materials from earth surface from its original assemblage and position, and transport to other places by various agents, including water and wind (Osman 2014). Soil erosion refers to the detachment of soil particles from the surface but also to large mass movements like landslides (Osman 2014). This study focuses on surface erosion and more exactly on interrill erosion which is a kind of sheet erosion. The term interrill erosion is used when sheet erosion takes place primarily between irregularly spaced rills (Brady & Weil 2010).

As shown in Figure 1, soil erosion consists of three processes: detachment, transportation and deposition (Brady & Weil 2010). Detachment of soil particles occurs by the impact of raindrops in two ways

(Le Bissonais 1996). Firstly, moistening provokes a breakdown of the aggregates. Secondly, raindrops can lead to a mechanical breakdown of soil aggregates. Besides that, soil particle detachment can occur by the flow of running water (Duttmann 2001). The detached soil particles, mostly fine particles, can lead to surface sealing and crust formation (Osman 2014). Concerning transportation, the detached soil particles are transported either by the strike of the raindrop or by runoff (Duttmann 2001). The last step of an erosion process is the deposition of the soil particles which occurs at some place lower in elevation (Zuazo et al. 2011). Soil particle yield, runoff and Δ soil moisture play a key role concerning interrill erosion and therefore this study terms them as interrill erosion parameters.

Rainfall erosivity (= eroding capacity of the rain (Boardman & Poesen 2006)) can be described by the variables rainfall intensity, kinetic energy and amount of rainfall (Toy et al. 2002). Rainfall intensity determines the number of drops per unit surface (Angulo-Martinéz et al. 2012). Kinetic energy is related to the size of the raindrops: smaller raindrops strike the soil with a lower velocity and therefore exert a lower force on soil which results in reduced soil particle yields, regardless of rainfall amount and intensity. The kinetic energy of a rainfall event is the sum of the kinetic energies of individual raindrops (Toy et al. 2002). The amount of rainfall is mainly important for the total amount of runoff (Toy et al. 2002).

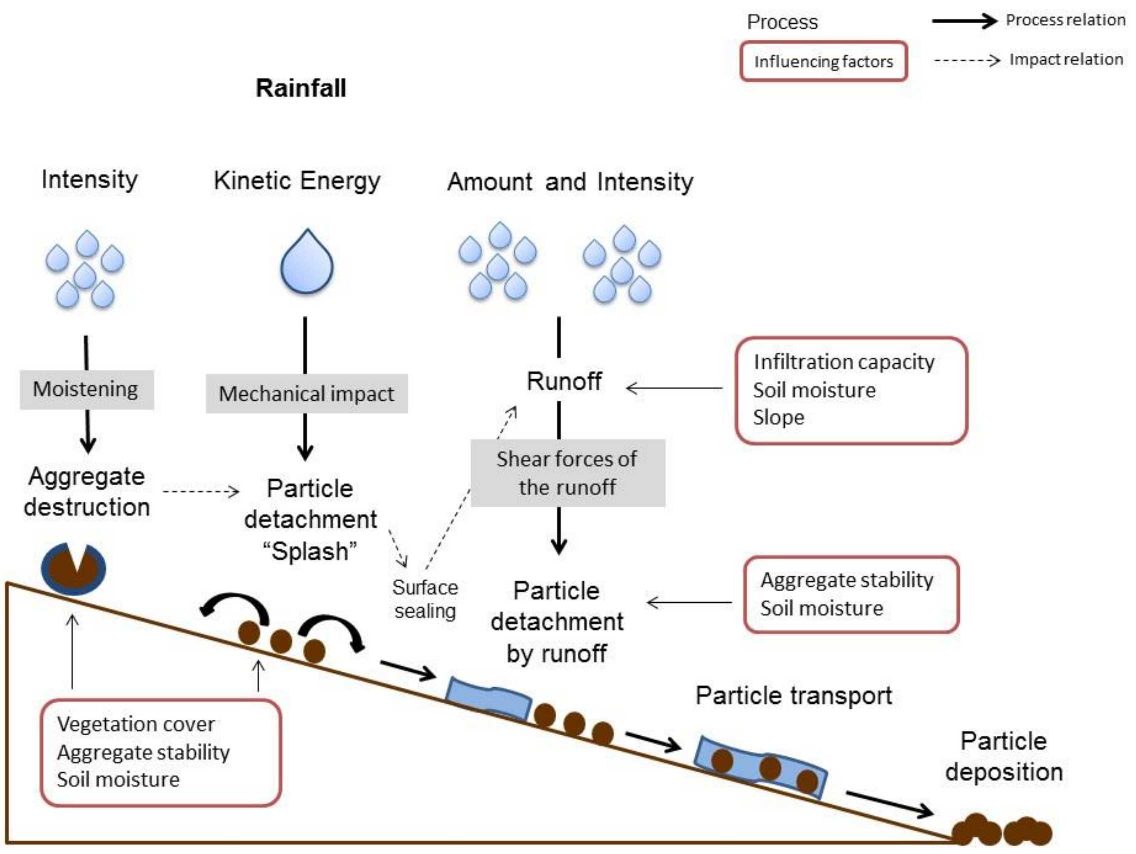

Figure 1: A schematic figure of the process of soil erosion. The figure shows the different processes and their influencing factors. Source: Duttmann 2001, modified by the author.

As shown in Figure 1, the different processes of soil erosion are influenced by many factors. The next chapters should give a deeper insight in these influencing factors controlling interrill erosion in mountain terrain.

1.2.2. Vegetation cover

Vegetation cover can influence soil erosion by interception of rainwater (Zuazo et al. 2011). Interception leads to a lower kinetic energy of the raindrops, so that they are less capable to detach soil particles (Duttmann 2001). Besides that, vegetation can influence soil erosion indirectly by its impact on aggregate stability as shown in Chapter 1.2.3.1.

1.2.3. Aggregate stability

Soil aggregates are secondary particles which are formed through the joining of sand, silt and clay particles and stabilized by inorganic and organic materials (Tisdal & Oades 1982, Bronick & Lal 2005). As a consequence of formation and stabilization, soil consists of aggregates and pores differing in size (Amézketa 1999).

Inorganic stabilizing agents include clay minerals, cations such as Ca^{2+}, Fe^{3+} and AL^{3+}, aluminium and iron oxides, calcium and magnesium carbonates, and gypsum (Amézketa 1999, Abiven et al. 2007). Organic binding agents include microbial- and plant derived polysaccharides (Amézketa 1999). Additionally, roots, hyphae and some fungi can contribute to stabilization (Amézketa 1999). All these binding agents can decrease aggregate breakdown by increasing the inter-particle cohesion (Abiven et al. 2007). Besides that, soil organic matter can increase hydrophobicity of aggregates, leading to reduced wettability and consequently to a decreased breakdown by slaking (Amézketa 1999, Abiven et al. 2007). The influence on cohesion and hydrophobicity depends on the type of soil organic matter, its intrinsic characteristics and its decomposing microflora or exudates (Abiven et al. 2007).

Besides the influence of organic and inorganic stabilizing agents, aggregate stability depends on external factors including climate, age, biological factors and agricultural management (Amézketa 1999). Graf & Frei (2013) for example illustrated that aggregate stability was correlated positively with the dry unit weight of soil: a compacted soil sample showed a significantly higher aggregate stability than the related non-compacted sample. Soil compaction might be of importance on grazed meadows because the weight of the cattle executes a pressure on soil during grazing (Trimble & Mendel 1995).

Aggregate breakdown can result from several physico-chemical and physical mechanisms. Le Bissonais (1996) reviewed four main mechanisms of breakdown: 1) Slaking (breakdown by compression of trapped air). 2) Breakdown by differential swelling. 3) Mechanical breakdown by raindrop impact.

4) Physico-chemical dispersion. Their relative importance depends on the nature of the rain as well as on soil properties (Le Bissonais 1996).

1.2.3.1. The influence of vegetation cover on aggregate stability

As already mentioned, vegetation can influence soil erosion indirectly by its impact on aggregate stability (Zuazo et al. 2011). Aggregate stability can be influenced by vegetation in two ways. Firstly, the resulting dead plant material of vegetation dieback, which covers the soil surface, increases the microbial activity (Scheffer & Schachtschabel 2010, Zuazo et al. 2011). This increase in activity has in turn a positive influence on aggregate stability because the microorganisms produce enzymes, responsible for mineralizing high molecular weight compounds (Amézketa 1999). Furthermore, microorganisms release extracellular polysaccharides which stabilize the soil aggregates (Amézketa 1999). The input of plant residues increases aggregate stability within one and three months (Abiven et al. 2007).

Secondly, vegetation cover is linked with a belowground root network. Roots influence soil aggregation in many ways (Tisdall & Oades 1982): 1) Roots enmesh fine particles into stable macro-aggregates. 2) Roots release decomposable organic residues to soil. 3) Roots support the microbial population in the rhizosphere. 4) Roots supply food for soil animals like earthworms and other larger fauna. They in turn stabilize structure by ingesting soil and mixing it intimately with humified organic materials in their guts, and egesting it as casts or pellets (Amézketa 1999). Graf & Frei (2013) showed a significant positive correlation between the root length of *Alnus incana* and aggregate stability of a moraine soil. The root system can be also associated with fungal hyphae, especially at grass pastures. Mycorrhizal fungi and their hyphae of mycorrhiza can also influence aggregate stability positively in many ways (Tisdall & Oades 1982, Graf & Frei 2013).

1.2.3.2. The influence of aggregate stability on interrill erosion parameters

Aggregate stability can influence soil erosion in three different ways. Firstly, a high aggregate stability prevents aggregates from breakdown which leads to lower soil particle yields (Le Bissonais 1996). Secondly, a high aggregate stability is linked with an increased porosity which leads to increased infiltration and consequently to reduced runoff (Amézketa 1999, Zuazo et al. 2011). Thirdly, a high aggregate stability can protect soil from surface sealing because weak aggregates can collapse by wetting or the impact of a raindrop. Fine particles can enter into the soil macro pores, leading to reduced infiltration and consequently to an increase in runoff (Scheffer & Schachtschabel 2010, Osman 2014). The second and third point leads indirectly to lower soil particle yields by reducing runoff amounts which in turn enhance soil particle detachment by runoff.

Aggregate stability can be associated with the susceptibility of soil to erosion (Amézketa 1999). Most studies showed that a high aggregate stability led to a decrease in interrill erosion (Barthes & Roose 2002, Yan et al. 2008, Schindler Wildhaber et al. 2012, Rienzi et al. 2013), but there were also studies which showed a negative influence of a high aggregate stability on interrill erosion (Bajracharya et al. 1992).

1.2.4. Further factors controlling erosion

1.2.4.1. Slope inclination

Slope inclination influences erosion significantly due to its influence on volume and velocity of surface runoff (Fox & Bryan 1999, Morgan 1999, Zuazo et al. 2011). Interrill erosion can increase linearly with an increase in slope inclination (Fox & Bryan 1999). Balacco (2013) showed that soil particle yields on slopes with a steepness of 8° were up to three times higher than on slopes with a steepness of 2°.

1.2.4.2. Infiltration capacity and soil moisture

Infiltration capacity describes the maximum rate at which water enters the soil. Besides aggregate stability and texture, infiltration depends on soil moisture: an increase in soil moisture leads to less infiltration because the hydraulic gradient is reduced (Duttmann 2001). As soon as the rate of precipitation exceeds the infiltration rate, runoff occurs (Toy et al. 2002). The higher the soil moisture is at the beginning of a rainfall event, the less water can infiltrate into soil during the rainfall event and the higher surface runoff is (Duttmann 2001). So it can be said that runoff is dependent on infiltration capacity of the soil and therefore also indirectly on soil moisture. Furthermore, soil moisture influences soil particle detachment in a negative way. Firstly, an increase of soil moisture leads to a decrease of aggregate breakdown by slaking because the volume of air entrapped during wetting is decreased (Le Bissonais 1996). Secondly, moist aggregates seem to be more stable than dry aggregates concerning aggregate breakdown by raindrop impact (Duttmann 2001). However, aggregate stability decreases rapidly when soil moisture gets close to water saturation (Duttmann 2001). Balacco (2013) showed that there was a strong influence of soil moisture on soil loss and runoff and therefore demanded to consider the initial degree of saturation on the interrill erosion process.

1.3. Aim of the study and hypotheses

The aim of this study is to identify if and how vegetation cover is influencing interrill erosion on grazed alpine meadows. More exactly, it is of interest if vegetation cover is influencing aggregate stability and if aggregate stability is controlling interrill erosion on grazed meadows. The consideration of multiple soil and vegetation factors which are affected and can affect interrill erosion processes made this study outstanding.

These were the research questions and hypotheses of the study:

Does a reduction of vegetation cover influence interrill erosion on grazed meadows?
Hypothesis 1: *A reduction of vegetation cover leads to higher soil particle yields, runoff and lower* Δ *soil moisture on grazed meadows.*

How does a reduction of vegetation cover influence interrill erosion on grazed meadows?
Hypothesis 2a: *A reduction of vegetation cover leads to a lower aggregate stability due to less input of dead plant material and a lower belowground root density.*
Hypothesis 2b: *A reduction of aggregate stability leads to higher soil particle yields, directly by increasing aggregate breakdown but also indirectly by increasing runoff.*

To understand the functions of vegetation and aggregate stability, 111 rainfall simulation experiments were conducted on cattle grazed Suisse alpine meadows, differing in the degree of vegetation cover but not in slope inclination. Micro plots (25 cm * 25 cm) were irrigated for approximately five minutes with a simulated rainfall intensity of 48 to 60 mm h^{-1} which corresponds to a heavy and rare rainfall event in Switzerland. The influence of a decreasing vegetation cover was investigated on interrill erosion but also on various soil parameters.

2. Methods

2.1. Study area

The study took place at the south eastern slopes above the village St. Antönien (1460 m a.s.l.), Canton Graubünden, Switzerland (Figure 2). The study site shows a mean annual precipitation of approximately 1500 mm and a mean annual temperature between 4° and 6° C (Klimabericht Kanton Graubünden 2012). However, for the summer 2014 Switzerland recorded extraordinary many and intensive rainfall events and a below average number of sunshine hours (MeteoSchweiz 2015).

The whole study area measured around 0.66 km^2. At the lower part was the alp called "Alpe Meierhofer" (1800 m a.s.l., 46° 58' 36'' N, 9° 48' 42'' E) and in the upper part the alp called "Alpe Bärgli" (2140 m a.s.l, 46° 59' 3'' N, 9° 49' 10''E). A road up to the Alpe Bärgli simplified access to the study area. Inclination increased with altitude: the lower part had a mean inclination of around 25° and the upper part of around 35°. Figure 3a gives a visual impression of the study area.

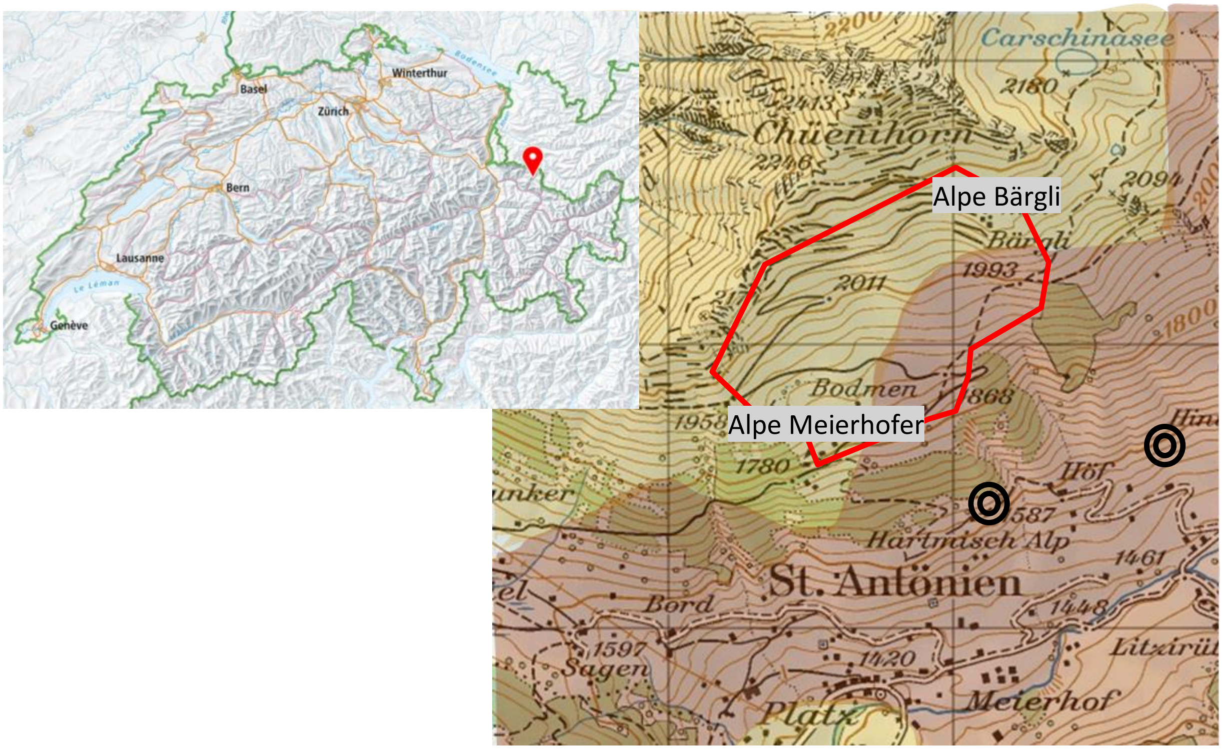

Figure 2: Location and map of the study area. At the left there is a map of Switzerland with a red arrow which indicates the position of St. Antönien. The right picture shows the topographical map (Scale: 1:20`000) of St. Antönien. The area colours indicate the geological unit: The orange colour stands for Tomül and Prättigauer Flysch and the red one for moraine material. The polygon in red shows the extent of the study area. The two black circles indicate the investigated areas of Rickli et al. (2005). Source: map.geo.admin.ch and Geologische Karte der Schweiz (1:500 000), Swisstopo (modified by the author).

The geologic unit of the area under the Chüenihorn is *Tomül- and Praettigauer Flysch*, whereas the geologic unit around the village St. Antönien is moraine material (Geologische Karte der Schweiz 1:500‘000). In the study area both geologic units were represented (Figure 2). Rickli et al. (2008) determined soil close to the investigated area as GC (clayey gravel with sand) according to the USCS standard (Figure 2).

Various studies (Rickli et al. 2005, Mattli 2014, Moos 2014) were already done in the area of St. Antönien, most often at the Rotwald (46° 58’N, 9° 47’E). The main reason for it was that the area was prone to shallow landslides.

Figure 3a, b: Impressions of the study area. At the left picture measurements were done at meadow 8M. At the horizon there is the Alpe Bärgli. The right picture shows a part of the cows grazing at the study area. Photos: Regula Christon.

2.1.1. Grazing at the study area

Except of one flat meadow in the middle of the study area, all meadows in the study area have been grazed for at least the last 20 years. The study area consisted of nine fenced meadows differing in size, steepness and vegetation (2M – 9M, 7R) (Figure 4). During summer 2014 around 80 pieces of cattle (suckler cow husbandry) were grazing at these meadows (Figure 3b). Grazing started at Alpe Meierhofer at the beginning of July and adjacent the whole cattle was moved upwards towards Alpe Bärgli. Grazing was finished by the end of September. The individual meadows were grazed between 1 and 14 days depending on size, amount of cattle and weather conditions.

This study made the assumption that the reduced vegetation cover at the study area is due to related grazing activities in this area. This assumption is based on the observation that the area seemed to be completely covered before grazing activities started. Consequently, it was assumed that a decrease in vegetation cover on the investigated plots went along with an increase in grazing intensity. However, it remained an assumption because the real grazing activity on each micro plot was not known.

2.2. Experimental design

To understand the functions of vegetation and aggregate stability, 22 subareas were identified: 2M1, 2M2, 2M3, 3M1, 4M1, 4M2, 5M1, 5M2, 6M1, 6M2, 7R1, 7R2, 7R3, 8M1, 8M2, 9M1, 9M2, 9M3, 9M4, 10M1, 10M2, 10M3 (Figure 4). The most important criteria for the selection of a subarea was slope inclination and ease of access due to the big amount of experimental material. In general, on each subarea five rainfall experiments were conducted.

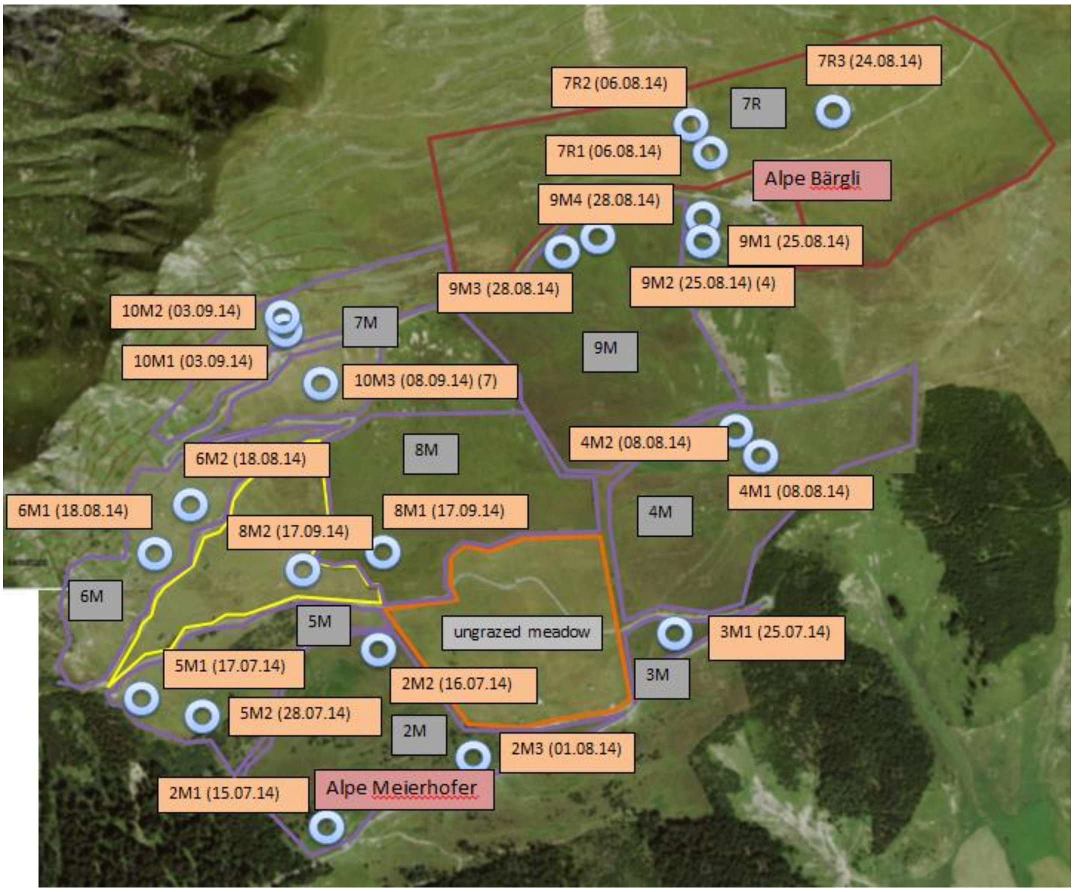

Figure 4: Aerial picture of the study area. The grey squares show the traditional notations of the fenced meadows. For orientation the location of Alpe Meierhofer and Alpe Bärgli is shown. At each subarea, indicated with a blue circle, five measurements were done. Beside the circle, the name of the subarea and date of the rainfall experiments are shown. The last number in brackets shows the number of conducted rainfall experiments if the number differs from five. Scale: 1:25`000. Source: map.geo.admin.ch (modified by the author).

Plot selection was done depending on three criteria. Firstly, slope inclination had to be between 18° and 22°. Secondly, the plot’s relief had to be flat and homogenous enough that the rainfall simulator stood stable and water could not flow away at the sides of the rainfall simulator. Besides that, at each subarea the aim was to investigate plots differing as much as possible in vegetation cover.

In total, 111 rainfall experiments were conducted at dry day conditions between July and September 2014. Per working day, a civil servant and I were able to do between five and ten rainfall experiments. The rainfall experiments were twice done during grazing (subarea 9M1 and 9M2), but mainly after grazing (between 1 and 31 days after the cows left the meadow).

2.3. Rainfall simulator and rain characteristics

To simulate a rainfall event the 09.06 mini rainfall simulator, produced by Eijkelkampf Agrisearch Equipment (www.eijkelkamp.com), was used. The rainfall simulator, shown in Figure 5, consisted of three parts (Eijkelkamp, 2005):

A) A sprinkler with built-in pressure regulator to calibrate the rain intensity. The sprinkler plate included 49 capillaries to generate an artificial rainfall event.

B) An adjustable support for the sprinkler to place the sprinkler stable at any kind of slope inclination. The average fall height of the drops was 40 cm.

C) An aluminium ground frame to prevent lateral movement of water from the test plot to the surrounding soil. On the downstream site of the plot, a gutter with a bordering sample collection bowl was installed to collect runoff and soil particles during the experiment.

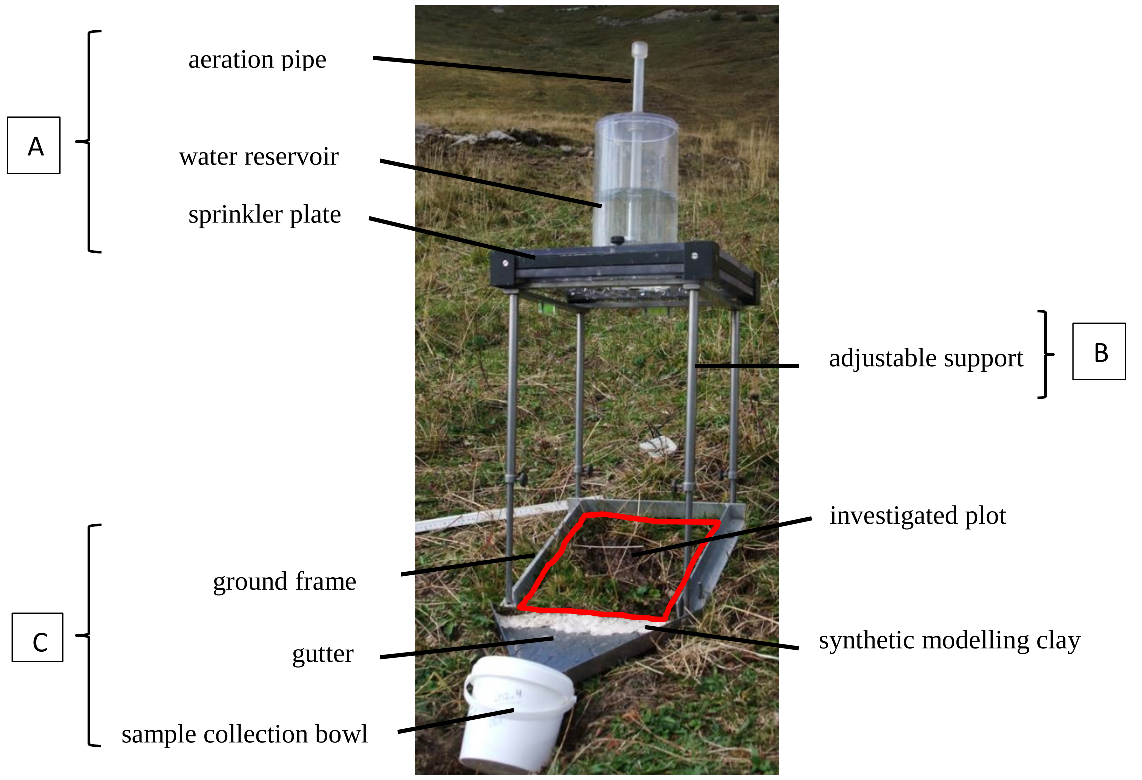

Figure 5: Eijelkamp rainfall simulator with all its components in use. A, B, C refer to the three main components of the rainfall simulator. The investigated plot is marked in red. Photo: Regula Christon.

The investigated plot, which is marked red in Figure 5, measured 25 cm * 25 cm. Thanks to the small size of the plot, the rainfall simulator was portable by one person. Furthermore, required water amounts for ten measurements did not exceed 40 litres. The manageable amount of material (complete list given in Appendix E) and water made it possible to do many rainfall experiments.

All plots were irrigated with a rainfall intensity of 375 ml min^{-1} (360 mm h^{-1}) during approximately 5 minutes. This resulted in a total irrigation amount of 1875 ml water per plot. The discharge rate of 375 ml min^{-1} was recommended by Eijkelkamp (2005). The high rainfall intensity was needed to compensate the short falling distance of the drops. Even though the produced raindrops were bigger and heavier (Diameter: 5.9 mm; Mass: 0.106 g) than natural raindrops, the simulated raindrops had a lower volume specific kinetic energy (KE_{mm}) when hitting the soil. According to the equation $KE_{time}=I * KE_{mm}$, (Salles et al. 2002) it was possible to compensate the volume specific kinetic energy (KE_{mm}) by increasing the rainfall intensity (I). This resulted in an adapted time-specific energy (KE_{time}). Time-specific kinetic energy of the simulated rain shower was KE_{time} = 1440 J m^{-2} h^{-1}. According to Martin (2008) rainfall events with a time-specific kinetic energy of KE_{time} = 1440 J m^{-2} h^{-1} refer to approximate natural rainfall intensities of I = 48-60 mm h^{-1}. A rainfall event with such an intensity over such a short timespan corresponds to a heavy precipitation event (DWD 2015). For Switzerland, it is known that a rainfall event with a rainfall intensity of 80 mm h^{-1} during 10 minutes can occur each 2.33 years (Geiger et al. 1992). Therefore it is assumed that a rainfall event of 60 mm h^{-1} during 5 minutes simulates a rare but possible rainfall event for Switzerland.

The regulation of the rainfall intensity was possible by adapting the distance between the reservoir and the upper side of the aeration pipe. The higher the distance of the aeration pipe was, the higher was the rainfall intensity. Besides the atmospheric pressure, the distance was dependent on water temperature which influenced the viscosity of the water. Cold water had a higher viscosity than warm water and therefore the aeration pipe had to be placed a bit higher (around 14 cm) in the morning. During the day water heated up and the distance between the aeration pipe and the reservoir was reduced down to 12 cm.

2.4. Rainfall simulation procedure

After plot identification, the ground frame was fixed with two nails on each side. Afterwards, a hole for the sample collection bowl was dug around 30 cm in front of the ground frame. At the area between the ground frame and the sample collection bowl, vegetation cover and the upper soil part was removed. For placing the gutter, a groove was made with a sharp knife. Most often a small gap between the gutter and the ground frame was not avoidable. This gap was filled with synthetic modelling clay to minimize losses of runoff and soil particles during the experiment. In a next step, the support was installed and adjusted with the help of the two bubble levels, depending on slope inclination and bumpiness. The water reservoir was filled with water, closed with the aeration pipe and placed on the support. By removing the plug from the aeration pipe, the rainfall simulation started. During the simulation the sprinkler head was moved to ensure that the whole plot was at the mercy of raindrops. The simulation was stopped as soon as 1875 ml water left the reservoir and the experiment duration was noted. The mean duration time was 4 min 50 sec, but duration times between 4 min 30 sec and 5 min 30 sec were accepted. Soil particles and water left behind at the gutter were added to the sample collection box by the use of a rubber wiper.

2.5. Field plot survey

2.5.1. Soil chemical properties

pH and calciumcarbonate ($CaCO_3$) measurements were directly made in the field with soil samples taken in or in front of the investigated plot in a depth of around 5 cm. pH value of the topsoil was determined using a Hellige pH test kit. $CaCO_3$ content was tested with some drops of hydrochlorid acid (HCl). If soil material showed no bubbles, it was assumed that the soil was free of any calcareous material. It has to be added that pH was measured only at 83 plots and $CaCO_3$ only at 45 plots due to missing awareness at the beginning of the study.

2.5.2. Soil moisture

Before each rainfall experiment, soil moisture content was measured with the ThetaProbe type ML2x produced by DELTA-T Devices (see www.delta-t.co.uk). That is a soil moisture sensor which measures the volumetric soil water content of the soil as vol. %. The instrument creates a 100 MHz waveform and applies it to four stainless steels (length 5.5 cm) which are lanced into soil. The steels transmit an electromagnetic field into the soil. Water content of the soil dominates the permittivity of the electromagnetic field which can be detected by the instrument (Delta-T Devices 2013, Miller & Gaskin).

Before the rainfall experiment, the so called “initial soil moisture” was measured outside the plot to prevent damages inside of it. After the rainfall experiment, measurements for the determination of the final soil moisture were done inside the plot. Five measurements before and after each experiment were conducted and the average of them was calculated. To get the information about how much water infiltrated into soil during the rainfall experiment, the parameter Δ soil moisture was calculated. This was done by subtracting the initial soil moisture value from the final soil moisture value. Therefore the term “Δ soil moisture” is a mass for infiltration into soil. It quantifies the parameter infiltration and can replace it.

In addition to soil moisture measurements in the field, soil moisture was determined in the laboratory. The exact proceeding is illustrated in Chapter 2.6.1.

As already mentioned, initial soil moisture was not determined inside the plot to avoid any damages. To prevent the influence of other factors like relief, slope inclination and exposition, the measurement was done as close as possible to the plot. However, the surrounding of the plot often did not show the same vegetation cover than the investigated plot. This could have had an influence on the measured Δ soil moisture values in the field and the laboratory.

2.5.3. Slope inclination

Slope inclination was measured with the help of a clinometer. The clinometer was placed on each side of the ground frame and the mean over both sides was noted. A mean between 18° and 22° was accepted.

2.5.4. Vegetation cover characteristics

Concerning vegetation cover characteristics the following variables were recorded:

- Number of functional groups and their proportion on overall vegetation cover: The presence of shrubs, grasses and forbs was recorded. Mosses and lichens were most often not present but also overlooked due to the coverage by higher-growing species.
- Vegetation coverage: Vegetation cover was estimated visually and rounded to 5%. Vegetation cover estimation did not exceed over 100%, which means that overlapping was not taken into account.
- Total cover: Total cover included besides the vegetation cover, the cover by dead plant material, the so called litter. Total cover was estimated visually and rounded to 5%.
- Average growth height of the plants (in cm)
- Species number and vegetation cover per species: Total species number was counted for each plot. In addition, the proportion of each species on vegetation cover was estimated.
- Species determination: Determination was done only for shrub and forb species due to a gap of knowledge concerning grass species.
- Permanent vegetation cover at the bottom line of the investigated plot: It was noticed if the bottom line of the investigated plot was continuously covered or not (Figure 6).

Figure 6: Vegetation cover arrangement at the border area to the gutter. The left figure shows a continuous vegetation cover and the right figure shows a jaggy vegetation cover at the border area to the gutter. The red rectangle indicates the continuous covered area. Photos: Regula Christon.

Plant diversity measurements

Plant diversity of each plot was calculated with the Shannon Index. The Shannon Index describes the plant diversity of a plot by considering the number of species as well as their individual proportion on the vegetation cover (Dierschke 1994).

Following equation was used to calculate the Shannon index:

$$H's = -\sum_{i=1}^{n} \mathrm{p}_{\mathrm{i,S}} \ln \mathrm{p}_{\mathrm{i,S}}$$

H's = Shannon Index for species diversity

n = total number of species present in the investigated plot

$p_{i,s}$ = proportion of vegetation cover percentage of species i on overall vegetation cover

The higher the Shannon index is, the more and the better balanced the species are in the plot. A Shannon Index H's = 0 means that all individuals belong to the same species (Dierschke 1994).

2.6. Laboratory plot survey

At each plot three soil samples of a length of 30 cm and a diameter of 5 cm were removed right-angled to the slope with a Humax boring rod. One sample was taken outside of the investigated plot (for the determination of the initial soil moisture in the laboratory) and two inside the investigated plot (for the determination of final soil moisture/soil bulk density/soil organic matter and aggregate stability/root density). During the day, samples were stored in cooling bags which were positioned in the shadow. In the laboratory, the samples were stored in the fridge at 4° C. Soil moisture samples were stored horizontally and for maximum 3 days and samples for aggregate stability tests were stored vertically, with the topsoil part up, for maximum 14 days. Except of the soil organic matter content which was tested at the WSL in Birmensdorf, Zurich, laboratory work was done at the SLF in Davos.

2.6.1. Soil moisture

In the laboratory, soil moisture was determined for a depth of 0-10 cm and 10-20 cm. The soil samples were dried for at least 36 hours at a temperature of 80° C. Soil moisture content of each sample was calculated by the difference in weight of the sample after drying (wt. %).

2.6.2. Soil particle yield and runoff

The sample collection bowl with the mixture of runoff and soil particles, was directly weighted after arrival in the laboratory. Afterwards, the bowl was kept in rest so that the soil particles in suspension could deposit to the ground. Adjacent, as much runoff as possible was drained. The remaining runoff with soil particles inside was placed in the oven for at least 24 hours at a temperature of 80° C. Soil particles were weighted after drying. Runoff was calculated by subtracting the dry weight of the soil particles and the empty weight of the sample collection bowl, of the total weight of the bowl. It was assumed that 1 g of water equals a runoff volume of 1 ml.

The term “soil particle yield” is a mass for the sum of small particles which were detached during a rainfall experiment. It quantifies the parameter interrill erosion and can replace it. The term “runoff” is a mass for the amount of water collected in the bucket after a rainfall experiment.

In total, 101 rainfall experiments were used for analysis concerning soil particle yield ($n = 101$). The reason for the reduced data number was that in ten rainfall experiments, the soil particle yield was influenced by other factors like a too high soil edge at the passage to the gutter. This led to artificial high soil particle yields. The runoff value was not usable for the vegetation cover in 25 rainfall experiments due to strong wind, problems during the change of the bowl or lateral runoff. In total, 86 rainfall experiments were used for analysis concerning runoff ($n = 86$). For the remaining parameters, all available data were used in general.

2.6.3. Aggregate stability tests

Aggregate stability tests were done for the upper 0-10 cm of each soil sample with the wet-sieving method according to a slightly modified protocol of Frei (2009) and Burri et al. (2009). Following modifications were done: 1) Instead of using two crosswise fixed flexible wire mesh strips, a metal tube with a height of 13 cm and a diameter of 9.5 cm was utilised (Figure 7a). 2) Filling of the acrylic glass pot took about 3 minutes in average due to a reduced water pressure in the laboratory in Davos. 3) Water lowering to the 20 mm sieve took around 4 minutes.

Soil remaining at the 2 mm sieve was given into a bowl and stones larger than 20 mm were removed. Soil which went through the 20 mm sieve, was given into a bowl. Both bowls were kept in rest so that the soil particles in suspension could deposit on the ground. Depending on the sample, this took several days. Water was drained and the bowls were put into the oven for at least 48 hours at a temperature of 80° C. Soil which remained at the 20 mm sieve, was given to a 2 mm sieve where roots where washed out (Figure 7b). Roots were stored in 15% ethanol in the fridge at a temperature of 4° C.

Figure 7a, b: Aggregate stability test and root cleaning. The soil sample was placed in the metal tube and then flooded. Adjacent, roots were extracted from soil which remained on the 20 mm sieve. Photos: Regula Christon.

The aggregate stability was calculated with the help of the following formula:

$$stab = \frac{DW_{20} - DW_{stones}}{DW_{tot} - DW_{stones}} \frac{(g)}{(g)}$$

stab = aggregate stability (g g^{-1})
DW_{20} = dry weight of the soil remaining in the 20 mm sieve (g)
DW_{tot} = dry weight of the total soil sample (g)
DW_{stones} = dry weight of stones bigger than 20 mm (g)

The explained method focuses on larger scale aggregation processes (Graf et al. 2015) and simulates aggregate breakdown by slaking. Slaking is caused by the compression of air entrapped inside aggregates during wetting (Le Bissonais 1996). The method was used due to three reasons. Firstly, Bast et al. (2015) showed that this method was suitable for alpine slopes where soil texture was dominated by particles > 2 mm and comparable with other frequently used methods. Secondly, the method was a simple, cheap and timesaving way to test the aggregate stability of a large numbers of samples. Thirdly, this study was done in the frame of a project focusing on Eco-Engineering where this method was used frequently in the last years (Burri et al. 2009, Frei & Graf 2013, Graf et al. 2015).

2.6.4. Soil organic matter content

Preparative dried soil samples (0-10 cm) were sieved up to 2 mm to get the fine soil fraction. Soil organic matter content was determined by the use of the method “loss-on-ignition” (LOI) at the WSL in Birmensdorf, Zurich. Two times 5 g of soil was ashed stepwise, up to a temperature of 550° for 15 minutes. It is assumed that decomposition conditions and rates did not differ at the study area and therefore a comparable high soil organic matter content represents a comparable high input of dead plant residues.

2.6.5. Root density

After storing the roots for around 3 months in the fridge, they were removed and ethanol was washed off. Afterwards, they were dried in the oven for at least 12 hours at a temperature of 80° C. Root density was calculated using following formula:

$$RD = \frac{DW_{roots}}{V_t} \frac{(g)}{(cm^3)}$$

RD = root density (g cm^{-3})

DW = dry weight of the roots (g)

Vt = volume of the soil core sample (0-10 cm) (cm^{-3})

2.6.6. Soil bulk density

For the determination of the soil bulk density of 0 – 10 cm and 10 – 20 cm the following equation was used:

$$\rho = \frac{M_s\,(g)}{V_t\,(cm^3)}$$

ρ = soil bulk density (g cm^{-3})

M_s = mass of dry soil (g)

V_t = volume of soil core sample (cm^3)

Whenever possible, the soil sample taken inside the plot was used for the determination of the soil bulk density. However, sometimes the samples were crumbly or included big stones at the separation area so that volume was difficult to determine. In these cases, the corresponding sample which was taken outside the investigated plot was used.

2.7. Statistical analysis

Data from the field and laboratory protocol (see Appendix F) were entered into Excel Sheets and afterwards imported to SPSS 21.0 for Windows for further statistical analysis. Except figures with a logarithmic trend line (created in Microsoft Excel), plots were created in SPSS 21.0. Even though scatter plots in chapter 3 show partly untransformed values, all statistical analyses were done with transformed values. The reason for showing untransformed data is the improved readability.

Dependent variables were soil particle yield, runoff, Δ soil moisture and aggregate stability. Explanatory variables were vegetation cover, total cover, initial soil moisture, root density, soil organic matter, soil bulk density and stone content (> 20 mm). Depending on the scientific question asked, aggregate stability, runoff and Δ soil moisture were used also as an explanatory variable while soil bulk density, root density and soil organic matter were also used as dependent variables.

In SPSS, dependent and explanatory variables were transformed if not normally distributed. The normal distribution was tested with the Kolmogorov-Smirnov Test. The following variables were transformed with following functions:

- Vegetation cover with square root
- Total cover with square root
- Soil particle yield with logarithm naturalis
- Aggregate stability with arc sine

The choice of the transformation was based on visual examination of the histogram. The variables aggregate stability, vegetation cover and total cover did not get normally distributed after transformation.

Boxplots were used to show differences in mean values between two or more observations (ordinal data). To test if the mean value differed significantly, the T-Test for independent samples (for two observations) or analysis of variance (ANOVA) (for more than two observations) in combination with Post-Hoc tests of means (LSD) was used. The prerequisites of these statistical tests are normal distribution of the dependent variable and equality of variance (Methodenberatung UZH 2010). The equality of variance was tested with the Levene's Test of Variance.

To show the relationship between a continuous dependent variable and a continuous explanatory variable, scatter plots with linear or logarithmic trend lines were used. To test if the relationship was significant, simple linear regression was used. The following points had to be fulfilled (Methodenberatung UZH 2010):

- Linearity: Linearity was visually tested by plotting the standardized residuals on the y-axis and the dependent variable on the x-axis.
- Homoscedasticity: A linear regression was done to test if the residuals had not the same variance. The dependent variable was the unstandardized residual (absolute value) and the explanatory variable was the unstandardized predicted value.
- No autocorrelation of the residuals: Autocorrelation was tested with the Durbin-Watson-Test.
- Normal distribution of the residuals: The standardized residuals were tested with the Kolmogorov-Smirnov Test.

In case that linear regression did not fulfil the prerequisites of the tests, visual examination of the figure was done. If the figure looked acceptable, linear regression was accepted nonetheless. If not, robust regression, a method which is less influenced by outliers (Jann 2010), with an MM-Estimator was done. The P-value was calculated based on t-distribution. If it seemed that the residuals were unequal distributed, the histogram is shown in Appendix C. For robust regression, the open-source data analysis environment R (Version 3.1.2) was used.

If any covariates had a significant influence on a dependent variable, a two-step procedure was done. At first, a linear regression was calculated between the dependent variable and the covariate. In a next step, the effect of the explanatory variable of interest was tested on the residuals of the dependent variable after fitting the effect of the covariate.

For an overview over all influencing factors, stepwise multiple linear regression was carried out. Stepwise multiple linear regression selects a set of predictor variables which make an appreciable contribution in explaining variance of the dependent variable (Backhaus et al. 2011).

Path analysis was calculated to get a clearer picture of the main factors influencing soil particle yield. The advantage of path analysis compared to multiple regression is that it provides an instrument of decomposing the correlation between two variables into components representing both causal and noncausal contributions (Schemske and Horvitz 1988). The magnitude of the path coefficient (standardized regression coefficient) indicates the strength of the direct effect of an independent variable on a dependent variable.

During the present master thesis the following levels of significance were used:

Marginally significant	(*)	$0.1 > P \geq 0.05$
Significant	*	$P < 0.05$
Highly significant	**	$P < 0.01$
Very highly significant	***	$P < 0.001$

3. Results

3.1. Soil properties

The mean pH of the study area was 4.5 ± 0.6. Besides that, five plots had an alkaline pH: three plots showed a pH of 7 (9M3_3, 9M3_4, 10M2_3) and two plots a pH of 8 (9M3_2, 9M4_5). Six plots showed indications of containing $CaCO_3$.

3.2. Initial soil moisture

Soil samples measured in the field showed a mean initial soil moisture of 59.2 ± 11.0 vol. %. Initial soil moisture ($P < 0.001$) differed significantly between July and the months August and September (Appendix B, Figure a). The point in time of the measurement during the day ($P = 0.146$) and rain at the day before the measurement ($P = 0.207$) had no significant influence on initial soil moisture (Appendix B, Figure b and c). If not mentioned differently, soil moisture measured in the field was used for further analysis.

Soil samples measured in the laboratory showed a mean initial moisture of 35.5 ± 7.7 wt. % and 26.3 ± 4.8 wt. % for 0-10 cm and 10-20 cm, respectively. 44 soil samples measured in the laboratory showed a lower soil moisture value after compared to the beginning of the rainfall experiment.

3.3. Vegetation characteristics

Mean vegetation cover over all plots was 56%. The distribution of measured vegetation covers was more or less balanced (Figure 8). The most common vegetation covers were between 80% and 85% with 21 measurements in total. Plots with a vegetation cover below 20% were slightly underrepresented because they often did not fulfil experimental prerequisites. Areas with a very low vegetation cover at slopes with a steepness of around 20° often showed too many cow hoof prints so that the installation of the rainfall simulator was not possible. Most of the areas with low cover were found in too flat areas, for example close to standpipes.

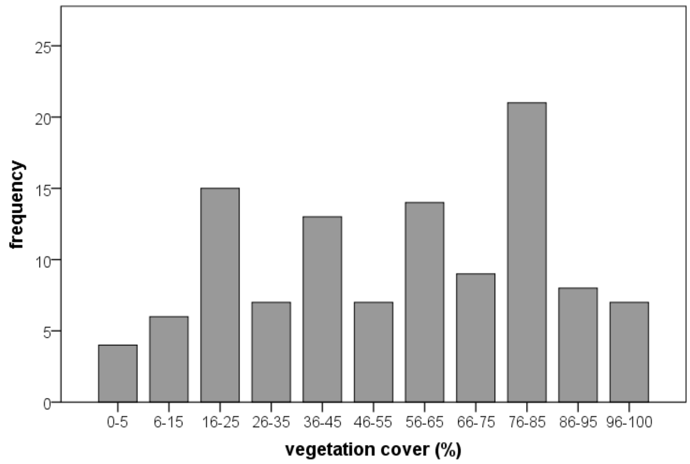

Figure 8: Frequency of measured vegetation covers. In this figure vegetation covers are summarized to vegetation cover classes. It is shown how many measurements were done of the individual vegetation cover classes.

On average, plots were covered 1.8% by shrubs, 30.5% by forbs and 23.8% by grasses. The average growth height of the plants was 5 cm. In the study area 48 forb and six shrub species were found. The most common forbs were *Plantago alpina, Crepis aurea, Plantago atrata, Hieracium pilosella, Trifolium pratense* and *Prunella vulgaris*. The most common shrub was *Calluna vulgaris*. The complete species list can be found in Appendix D. The highest number of plant species found on one plot was 14. The Shannon index varied between 0 and 2.33 with a mean of 1.61 ± 0.44.

3.4. Impact of vegetation cover, experimental and site variables on interrill erosion parameters

3.4.1. Soil particle yield

Mean soil particle yield for the experiments was 9.0 ± 26.9 g m^{-2}. A decrease in vegetation cover led to a significant increase in soil particle yield ($P < 0.001$) (Figure 9a). Plots with high vegetation cover (76-100%) showed in average 94% less soil particle yield than plots with low vegetation cover (0-25%) (see Appendix A, Table i). The visual interpretation of Figure 9b is that interrill erosion got negligible if more than 50% of the ground was covered by vegetation.

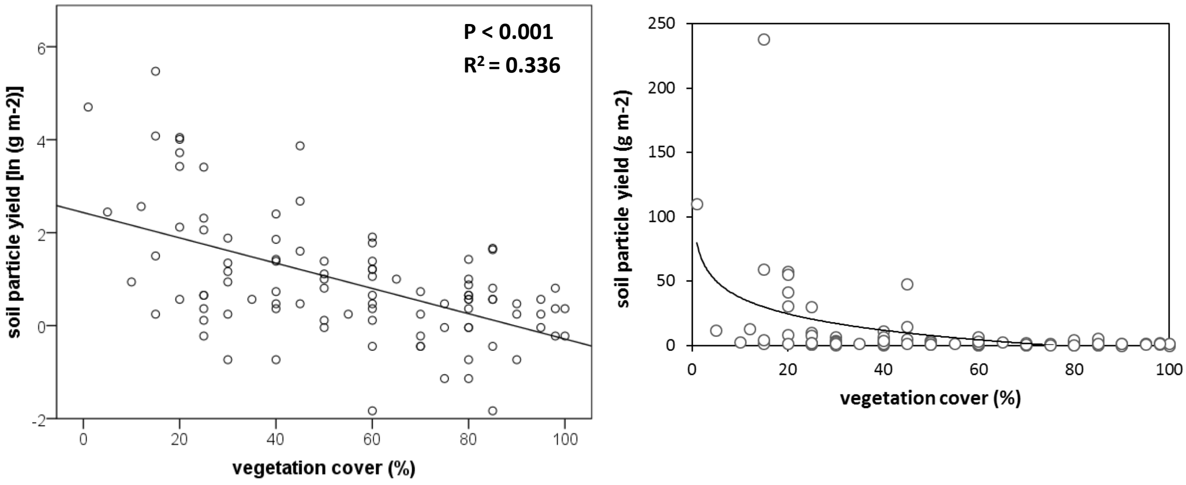

Figure 9a, b: The influence of vegetation cover on soil particle yield. The left figure shows the transformed data of soil particle yield and includes the linear trend line, the level of significance (P-value) and the coefficient of determination. The right figure shows the untransformed data of soil particle yield and includes only the logarithmic trend line.

Soil particle yield was marginally significant influenced by plant diversity, expressed as Shannon index (P = 0.080), but not significantly influenced by the presence of shrubs (P= 0.409) (Appendix B, Figure d).

Furthermore, neither the number of days after cattle grazing (P = 0.618) nor altitude (P = 0.817) did influence soil particle yield significantly (Appendix B, Figures e and f). The month of the measurement (P = 0.887), the point in time of the measurement during the day (P = 0.748) and rain at the day before the measurement (P = 0.333) also had no significant influence on soil particle yield (Appendix B, Figures a, b and c).

Results showed that there was no significant influence of the initial soil moisture on soil particle yield (P = 0.156) (Figure 10) which indicates that moist aggregates were not more susceptible to breakdown than drier aggregates.

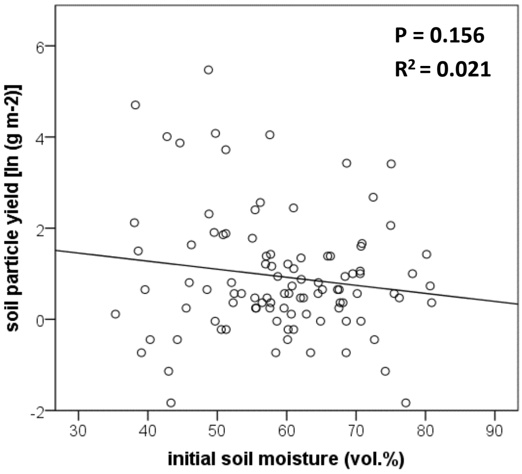

Figure 10: The influence of initial soil moisture on soil particle yield. Shown is the linear trend line, the level of significance (P-value) and the coefficient of determination

An important aspect was whether the border part of the area to the gutter was covered or not. Plots with a continuous vegetation cover showed a significantly lower soil particle yield than plots without or jaggy vegetation cover in this area ($P < 0.001$) (Figure 11). The relationship between soil particle yield and vegetation cover was only significant if the border part of the area to the gutter was not completely covered (Figure 12).

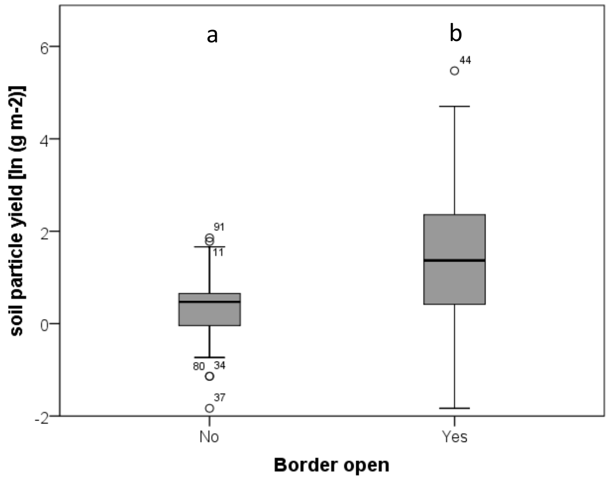

Figure 11: The influence of an open border area at the investigated plot on soil particle yield. Different letters above the boxplot indicate significant differences between mean values of soil particle yield.

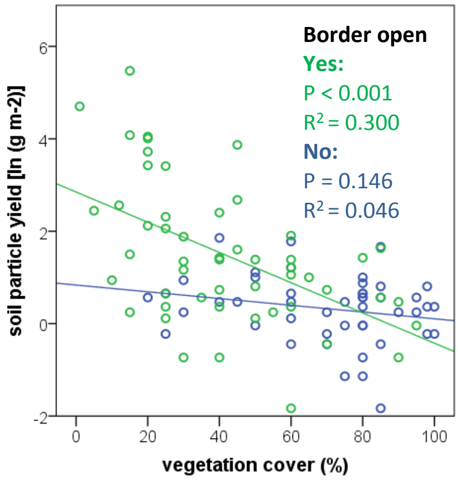

Figure 12: The influence of vegetation cover on soil particle yield when considering the vegetation pattern at the border area. Shown is the linear trend line, the level of significance (P-value) and the coefficient of determination

The investigated plots were covered up to 60% by dead plant material. The relationship between soil particle yield and total cover showed a higher coefficient of determination ($R^2 = 0.381$) (Figure 13a) than the relationship between soil particle yield and vegetation cover ($R^2 = 0.336$) (Figure 9a). The visual interpretation of Figure 13b is that interrill erosion became negligible if more than 55% of the ground was covered by vegetation and litter. This in turn shows that it was not important whether the ground was covered by living plants only or by a combination of them with dead plant material.

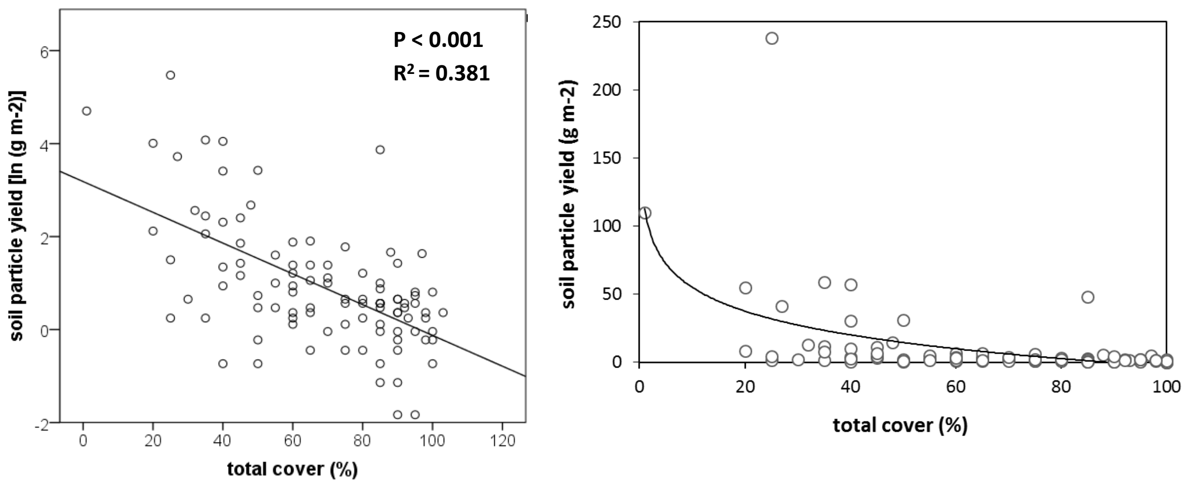

Figure 13a, b: The influence of total cover on soil particle yield. The left figure shows the transformed data of soil particle yield and includes the linear trend line, the level of significance (P-value) and the coefficient of determination. The right figure shows the untransformed data of soil particle yield and includes only the logarithmic trend line.

3.4.2. Runoff

The experiments showed a mean runoff of 16.1 ± 6.5 mm m^{-2}. Runoff increased only marginally significantly with a decrease in vegetation cover ($P = 0.086$) (Figure 14). A reason for this was that runoff was depending significantly on initial soil moisture ($P < 0.001$) (Figure 15).

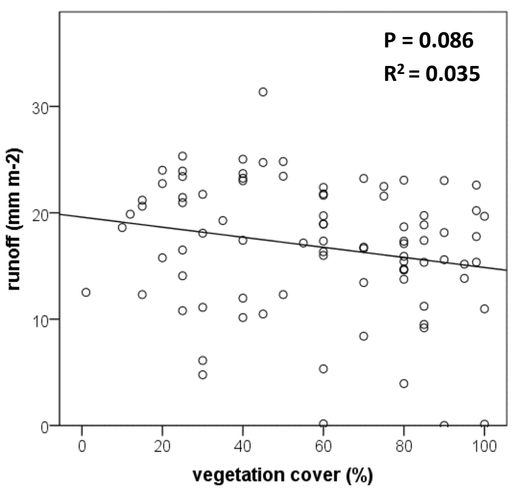

Figure 14: The influence of vegetation cover on runoff. Shown is the linear trend line, the level of significance (P-value) and the coefficient of determination.

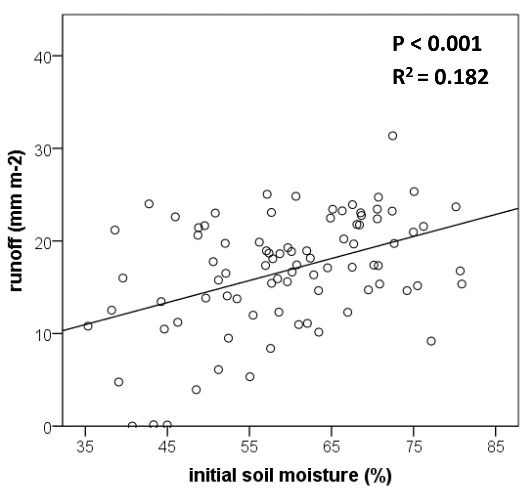

Figure 15: The influence of initial soil moisture on runoff. Shown is the linear trend line, the level of significance (P-value) and the coefficient of determination.

Considering the strong influence of the covariate "initial soil moisture" in the model, a reduction of vegetation cover led to a significant higher runoff (P = 0.004) (Figure 16).

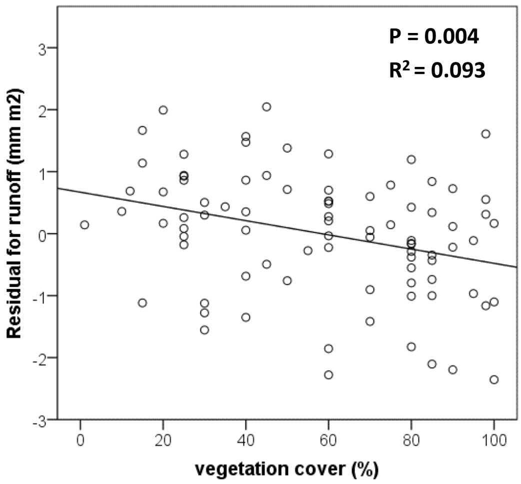

Figure 16: The influence of vegetation cover on the residuals for runoff after fitting the effect of initial soil moisture. Shown is the linear trend line, the level of significance (P-value) and the coefficient of determination.

3.4.3. Δ soil moisture

Field measurements showed a mean Δ soil moisture of 11.4 ± 8.2 vol. %. A reduction of vegetation cover did not lead to significant changes in Δ soil moisture measured in the field (P = 0.112) (Figure 17a). Laboratory measurements showed a mean Δ soil moisture of 1.1 ± 5.8 wt. %. A reduction of vegetation cover led to a marginally significant increase of Δ soil moisture measured in the laboratory (P = 0.087) (Figure 17b). It must be noticed that plots with a low vegetation (0-25%) showed a negative Δ soil moisture value in average (-0. 3 ± 5.6 wt. %).

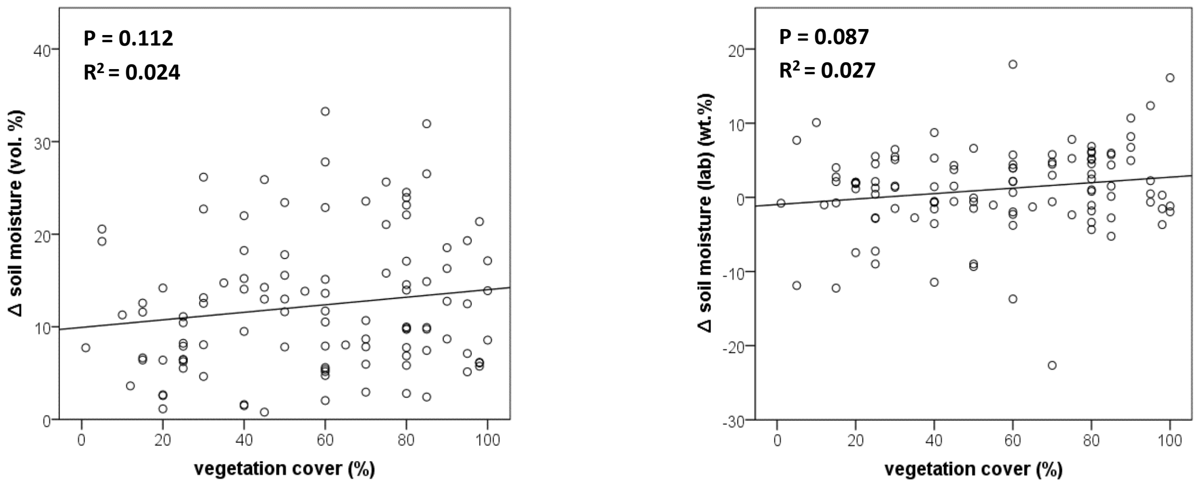

Figure 17a, b: The influence of vegetation cover on Δ soil moisture. The left figure shows the data of the field measurements whereas the right figure shows the data of the laboratory measurements. In both figures, the linear trend line, the level of significance (P-value) and the coefficient of determination is shown.

Further analyses showed that Δ soil moisture was significantly dependent on soil bulk density (P = 0.001) (Figure 18) but not on initial soil moisture (P = 0.449) (Figure 19).

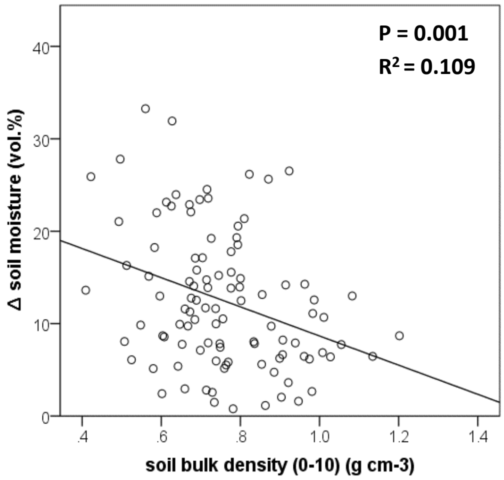

Figure 18: The influence of soil bulk density (0-10 cm) on Δ soil moisture. Shown is the linear trend line, the level of significance (P-value) and the coefficient of determination.

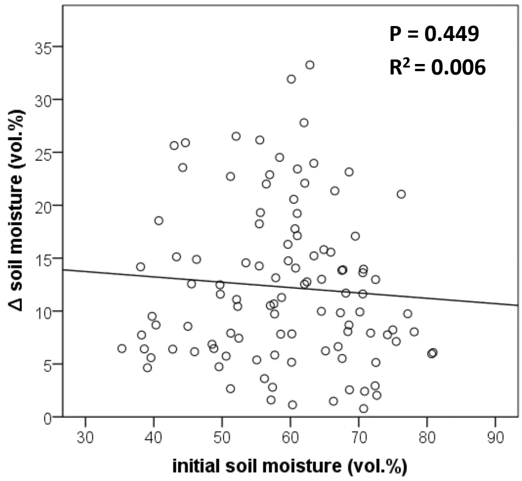

Figure 19: The influence of initial soil moisture on Δ soil moisture. Shown is the linear trend line, the level of significance (P-value) and the coefficient of determination.

Table i (see Appendix A) gives an overview of the influence of vegetation cover on interrill erosion and soil parameters. The table shows mean values of the variables for the vegetation cover classes 0-25%, 26-49%, 50-75%, 76-100% and overall data. The vegetation cover classes were chosen in dependency of a more or less equal number of measurements.

3.5. The relationship between soil particle yield, runoff and Δ soil moisture

Runoff formation was not significantly dependent on Δ soil moisture (P = 0.199) (Figure 20). But soil particle yield was significantly positively correlated with runoff (P = 0.012) (Figure 21).

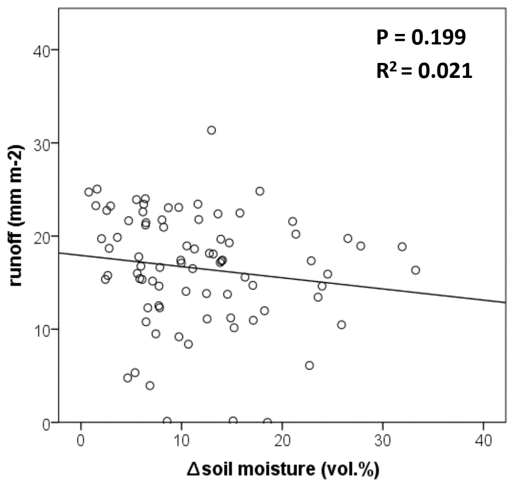

Figure 20: The influence of Δ soil moisture on runoff. Shown is the linear trend line, the level of significance (P-value) and the coefficient of determination.

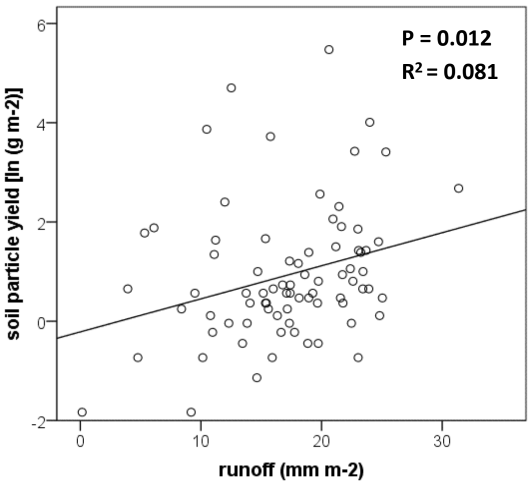

Figure 21: The influence of runoff on soil particle yield. Shown is the linear trend line, the level of significance (P-value) and the coefficient of determination.

3.6. Aggregate stability

3.6.1. Direct relationship between vegetation cover and aggregate stability

Mean measured aggregate stability was 0.97 ± 0.09 g g^{-1}. 82% of the plots showed an aggregate stability between 0.95 and 1.00 g g^{-1}. The lowest measured aggregate stability value was 0.70 g g^{-1}, but only 11 samples showed an aggregate stability value between 0.70 and 0.90 g g^{-1}.

Results showed that vegetation cover did not correlate significantly with aggregate stability (robust regression; t = 0.7196; P = 0.4730 (based on t-distribution)) (Figure 22).

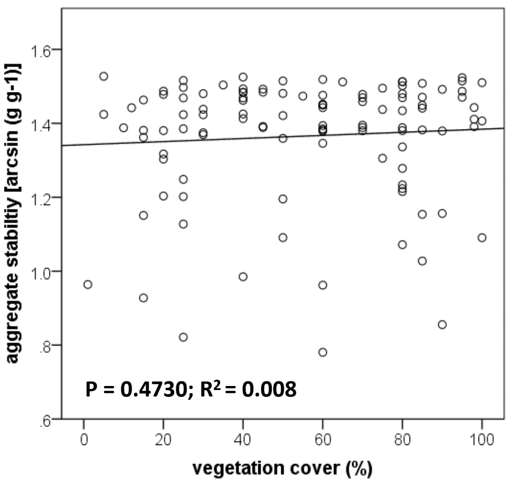

Figure 22: The influence of vegetation cover on aggregate stability. Shown is the linear trend line, the level of significance (robust regression; P-value based on t-distribution) and the coefficient of determination. It must be noted that the residuals of this regression were unequally distributed (see Appendix C, Figure i).

3.6.2. Indirect relationships between vegetation cover and aggregate stability

Vegetation cover can indirectly influence aggregate stability by its influence on soil organic matter and root density. Furthermore, a decrease in vegetation cover, which is assumed to be due to grazing activities, can be related to soil compaction. This chapter on one hand illustrates the influence of vegetation cover on these three variables and on the other hand the influence of these three variables on aggregate stability.

Mean soil organic matter content of the study area was 15.9 ± 5.3 wt. %. Soil organic matter content decreased significantly with a reduction of vegetation cover ($P = 0.006$) (Figure 23) but had no significant influence on aggregate stability (robust regression; $t = 0.5944$; $P = 0.5540$ (based on t-distribution)) (Figure 24).

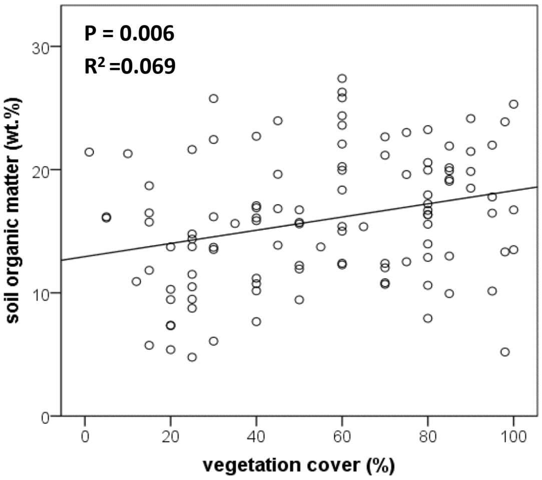

Figure 23: The influence of vegetation cover on soil organic matter. Shown is the linear trend line, the level of significance (P-value) and the coefficient of determination.

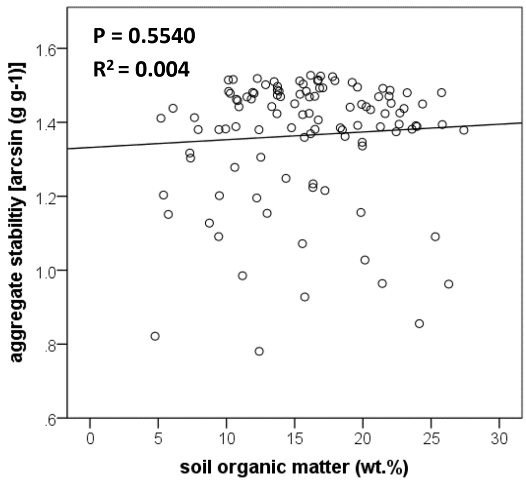

Figure 24: The influence of soil organic matter on aggregate stability. Shown is the linear trend line, the level of significance (robust regression; P-value based on t-distribution) and the coefficient of determination. It must be noted that the residuals of this regression were unequally distributed (see Appendix C, Figure j).

Mean root density was 0.009 ± 0.006 g cm^{-3}. Root density was significantly positively correlated with vegetation cover ($P = 0.002$) (Figure 25) and had a significant positive influence on aggregate stability (robust regression; $t = 2.3677$; $P = 0.0197$ (based on t-distribution)) (Figure 26).

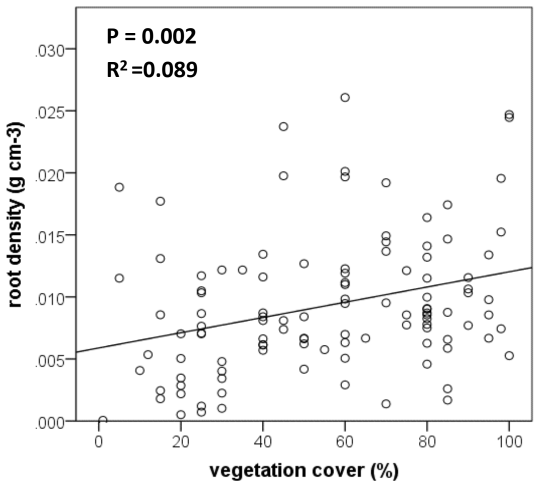

Figure 25: The influence of vegetation cover on root density. Shown is the linear trend line, the level of significance (P-value) and the coefficient of determination.

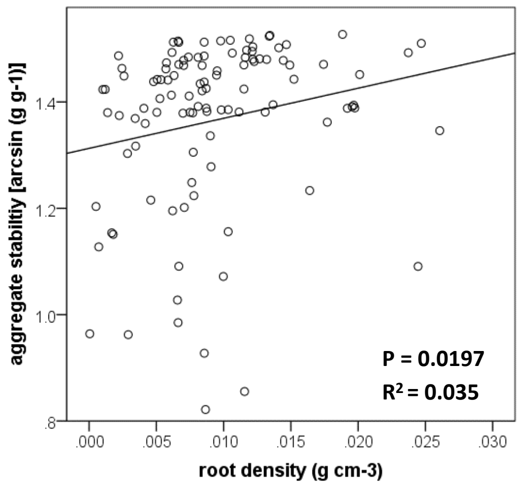

Figure 26: The influence of root density on aggregate stability. Shown is the linear trend line, the level of significance (robust regression; P-value based on t-distribution) and the coefficient of determination. It must be noted that the residuals of this regression were unequally distributed (Appendix C, Figure k).

The mean value for soil bulk density was from 0-10 cm 0.78 ± 0.17 g cm^{-3} and from 10-20 cm 0.98 ± 0.12 g cm^{-3}. Vegetation cover was significantly negatively correlated with soil bulk density of 0-10 cm ($P < 0.001$) (Figure 27) but not with soil bulk density of 10-20 cm ($P < 0.748$) (Appendix B, Figure g). Soil bulk density (0-10 cm) at plots with low vegetation cover (0-25%) was 21% (+0.11 g cm^{-3}) higher than at plots with high vegetation cover (76-100%) (see Appendix A, Table i). Soil bulk density of 0-10 cm had no significant influence on aggregate stability (robust regression; t = -1.2930; P = 0.1990 (based on t-distribution)) (Figure 28).

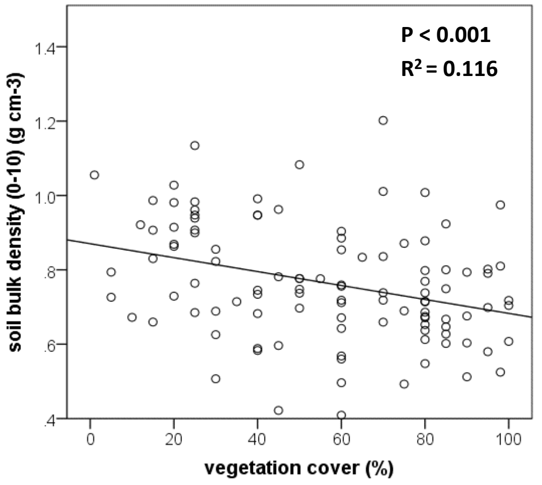

Figure 27: The influence of vegetation cover on soil bulk density (0-10cm). Shown is the linear trend line, the level of significance (P-value) and the coefficient of determination.

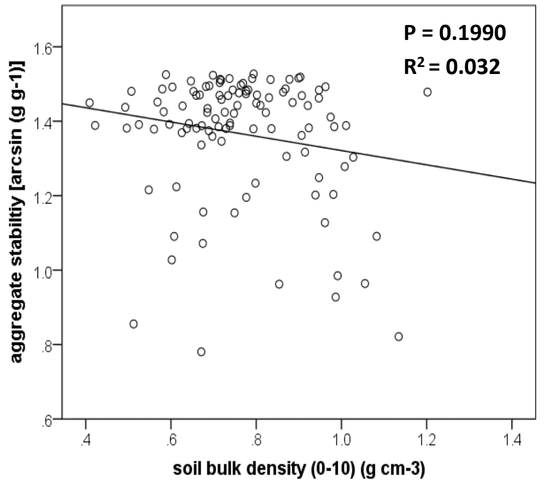

Figure 28: The influence of soil bulk density (0-10cm) on aggregate stability. Shown is the linear trend line, the level of significance (robust regression; P-value based on t-distribution) and the coefficient of determination. It must be noted that the residuals of this regression were unequally distributed (Appendix C, Figure l).

3.6.3. Further influences on aggregate stability

Other possible explanatory variables for aggregate stability were the amount of stones (> 20 mm) and the altitude where the sample originated. The amount of stones (> 20 mm) had a significant influence on aggregate stability (robust regression; t = - 12.3466; P < 0.001 (based on t-distribution)) (Figure 29).

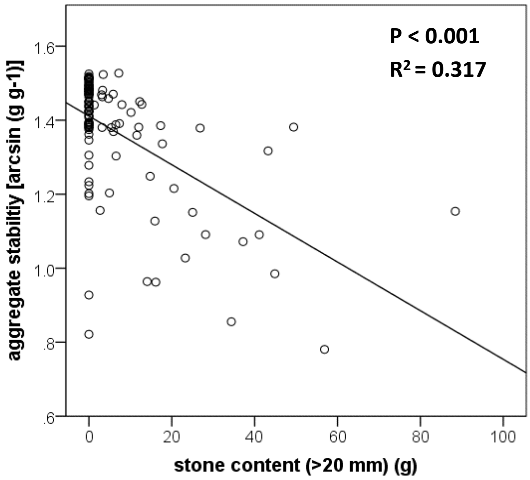

Figure 29: The influence of stone content (>20 mm) on aggregate stability. Shown is the linear trend line, the level of significance (robust regression; P-value based on t-distribution) and the coefficient of determination. It must be noted that the residuals of this regression were unequally distributed (Appendix C, Figure m).

Altitude had no significant influence on aggregate stability (robust regression; t = - 0.1687; P = 0.8660 (based on t-distribution)) (Appendix B, Figure f).

3.6.4. The influence of aggregate stability on interrill erosion parameters

Aggregate stability was not significantly correlated with soil particle yield (P = 0.230) (Figure 30) and Δ soil moisture (P = 0.767) (Figure 32). But a decrease in aggregate stability had a marginally significant influence on runoff (P = 0.081) (Figure 31). However, the trend in runoff was different than expected: runoff increased with an increase in aggregate stability.

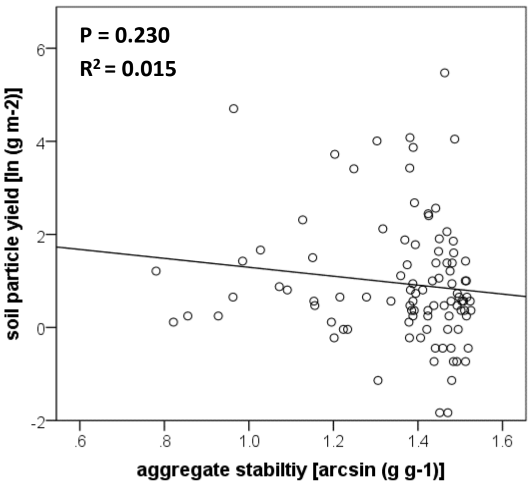

Figure 30: The influence of aggregate stability on soil particle yield. Shown is the linear trend line, the level of significance (P-value) and the coefficient of determination.

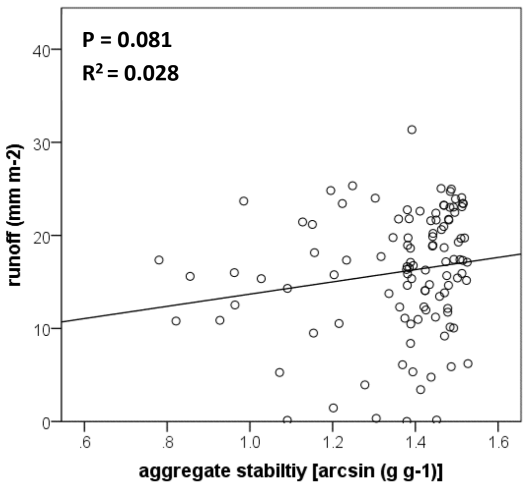

Figure 31: The influence of aggregate stability on runoff. Shown is the linear trend line, the level of significance (P-value) and the coefficient of determination.

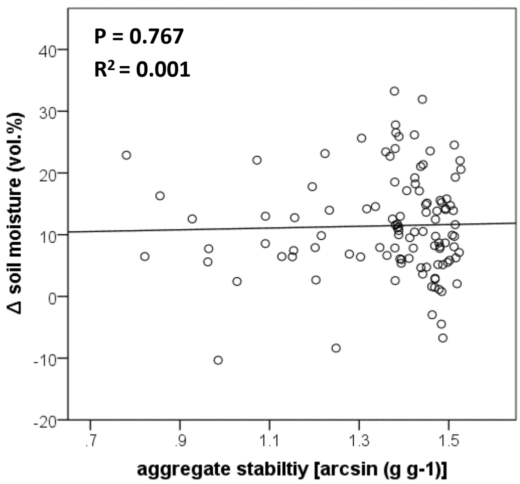

Figure 32: The influence of aggregate stability on Δ soil moisture. Shown is the linear trend line, the level of significance (P-value) and the coefficient of determination.

3.7. Main responsible variables for soil particle yield

Stepwise multiple regression analysis proposed two possible sets of predictor variables for soil particle yield. Model 1 included total cover and explained 37.6% of variance in soil particle yield ($R^2 = 0.376$) with a significance of $P < 0.001$. Model 2 also included runoff besides total cover and explained 42.7% of variance in soil particle yield ($R^2 = 0.427$) with a significance of $P < 0.001$. The variables vegetation cover, initial soil moisture, root density, soil organic matter, soil bulk density, aggregate stability and stone content (> 20 mm) did not lead to improvements of the model.

A path analysis was carried out to get information about the relative importance of total cover and runoff in connection with soil particle yield. Figure 33 shows that total cover influenced soil particle yield much more directly (B = - 0.577) than indirectly by its influence on runoff (B = - 0.219 and B = + 0.228).

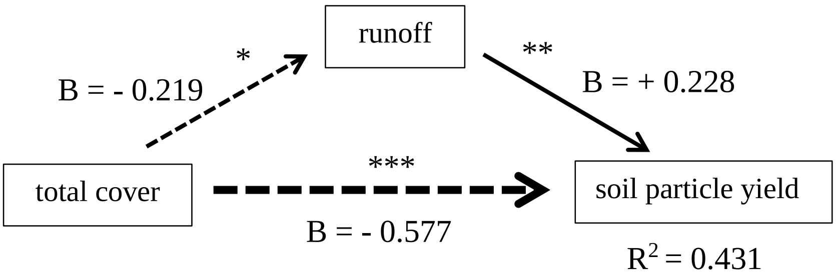

Figure 33: Results of the path analysis for the influencing factors of soil particle yield. Solid lines indicate positive relationships, dashed lines indicate negative relationships. Stars indicate the level of significance P < 0.05 (*), P < 0.01 (**), P < 0.001 (***). The B-values are path coefficients. Furthermore the coefficient of determination is shown (R^2).

4. Discussion

4.1. Impact of vegetation cover on interrill erosion parameters

4.1.1. Soil particle yield

Results showed that a decrease in vegetation cover led to significantly higher soil particle yields on grazed meadows (Figure 9a). This is in line with other studies conducted in mountain terrain (Isselin-Nondedeu & Bédécarrats 2007, Martin et al. 2010). Furthermore, this study confirmed that the reduction in soil particle yield with a decrease in vegetation cover can be described as a negative exponential curve (Figure 9b) (Morgan 1999, Zuazo et al. 2011, Schindler Wildhaber et al. 2012).

Soil particle yield showed quite high standard deviation, especially at plots with a low vegetation cover (27.9 ± 51.3 g m^{-2}) (see Appendix A, Table i). One possible explanation for this is the observation in the field that plots with a low vegetation cover showed cow hoof prints. There, soil particles could have been retained which led to variations in the data. Isselin-Nondedeu & Bédécarrats (2007) observed in their experiment that soil particle accumulation in cow hoof prints represented erosion activities at slope scale. This indicates that considerable amounts of soil particles can accumulate in such prints.

Soil particle yield was only significantly correlated with vegetation cover if the border part of the area to the gutter was jaggy or not covered (Figure 12). A continuous vegetation cover at this area might have retained soil particles and therefore led to significant lower soil particle yields (Figure 11). This shows that the way how vegetation is spatially distributed influences interrill erosion (see also Zuazo et al. 2011). For the restoration of eroded gullies, Erktan et al. (2013) even recommended narrow rows of permanent vegetation to trap soil particles and to slow down runoff. The positive benefit of so called vegetative barriers in connection with interrill erosion was confirmed by this study.

The investigated plots were covered up to 60% by dead plant material. The high amount of dead plant material resulted probably from cattle which damaged vegetation cover not only by feeding but also by trampling. Results showed that the influence of total cover on soil particle yield (Figure 13a) was even more significant than the one of vegetation cover (Figure 9a). This indicates that dead plant material contributed to the protection of soil from interrill erosion. Protection by dead pant material can be provided by interception of raindrops (Toy et al. 2002). It is known that even roots of dead plant material can enmesh fine soil particles into stable macro-aggregates (Amézketa 1999). Shi et al. (2012) investigated the protective influence of straw mulch rates on interrill erosion processes. Plots covered with 70% of mulch showed 90% less soil particle loss than bare soil. It is shown that protection provided by vegetation is underestimated if dead plant material is not considered.

Soil particle yield got negligible at the investigated plots when vegetation or total cover exceeded 50 % (Figure 9b and Figure 13b). Other studies, even when differing in scale and steepness, showed comparable threshold values. Martin et al. (2010) investigated the relationship between vegetation cover and interrill erosion at same steepness and micro plot size: soil particle yield decreased significantly at plots with a vegetation cover of 60%. Schindler Wildhaber et al. (2012) showed that plots of 1 m^2 at steep subalpine grassland (40°) could be protected from interrill erosion with a vegetation cover above 50%. Isselin-Nondedeu & Bédécarrats (2007) investigated soil erosion at 100 m^2 plots with slope steepness between 20° and 40°. Their results showed that at plots with 60% vegetation cover almost no deposition of soil particle occurred.

The present results in combination with literature indicate that micro to macro plots can be protected from serious interrill erosion by a vegetation cover of more than 50%. However, this threshold value might be not applicable directly to slope or even catchment scale. The reason is that with increasing slope length, the volume and velocity of runoff is increasing (Zuazo et al. 2011). Therefore soil particle detachment by runoff, instead of raindrop impact, becomes the dominant mechanism at slope scale (Duttmann 2001). Although upscaling of the measured value is not so easily possible, the understanding of the processes at larger scale firstly requires studying processes at smaller scale (Isselin-Nondedeu & Bédécarrats 2007). Furthermore, it has to be considered that the measurement of large-scale erosion processes in mountain terrain is quite difficult due to low accessibility and steep topography (Alewell et al. 2008). Additionally, available models are most often designed for agricultural environment and are not suitable for mountain regions due to the extreme topography and climate (Alewell et al. 2008).

Besides scale, also time has to be considered. Soil properties can show systematic seasonal variations depending on frost action, soil water conditions and microbial activity (Bryan 2000). A change in soil properties can lead to significantly higher soil particle yields independent of vegetation cover (Bryan 2000).

4.1.2. Runoff

An increase in vegetation cover led to significantly lower runoff (Figure 14). This cannot be ascribable to an increase in infiltration because runoff was independent of Δ soil moisture (Figure 20). Therefore it is concluded that the reduction in runoff with an increase in vegetation cover was the consequence of increased interception. It is known that canopies that cover a high percentage of the soil surface intercept a large proportion of the rainfall (Toy et al. 2002) and consequently reduce runoff (Zuazo et al. 2011). The reason for the reductions in runoff is that a part of the intercepted rainfall is evaporated without ever influencing erosion (Toy et al. 2002).

It has to be considered that the measured runoff values were related to the very high experimental rainfall intensity of 360 mm h^{-1} and not to the simulated rainfall intensity of 60 mm h^{-1}. Consequently, the measured runoff values were excessively too high for the simulated rainfall event of 60 mm h^{-1}. Martin (2008) pointed out that the application of a highly increased rainfall intensity in order to generate a more realistic time-specific kinetic energy of rain is legitimate when studying splash erosion at micro plots where runoff is not an important factor. Although there were restrictions concerning the use of artificial rainfall, the benefit was that same experimental conditions were applicable to each of the investigated plots.

4.1.3. Δ soil moisture

By trend, an increase in vegetation cover led to higher Δ soil moisture values but the relationship was not significant (Figure 17a, b). An explanation for this would be that an increase in infiltration goes in general along with an increase in aggregate stability (Amézketa 1999, Zuazo et al. 2011). The non-significant relationship between Δ soil moisture and vegetation cover might be therefore the consequence of the non-significant relationship between vegetation cover and aggregate stability (Figure 22).

Plots up to 75% vegetation cover showed very low Δ soil moisture values (laboratory dataset; see Appendix A, Table i). The negative mean value (-0.3 ± 5.6 wt. %) of cover class 0-25% might be due to measurement inaccuracy. An explanation for the general low infiltration could be that surface sealing and consequently infiltration prohibition occurred due to the missing vegetation cover. Seal formation during rainfall simulation experiments was observed by many other studies (Assoulin & Ben-Hur 2006, Molina et al. 2007, Yan et al. 2008), even for experiments short in time (Nciizah & Wakindiki 2014). However, surface sealing is the result of aggregate breakdown (Osman 2014) and due to the constant high aggregate stability in the study area a high rate of aggregate breakdown seems unlikely. The only possibility would be that soil in the study area was clay-rich which led to a high aggregate stability but also promoted aggregate breakdown by differential swelling (Le Bissonais 1996). In this study soil type was not assessed due to time restrictions and therefore no statement about the clay content could be done. However, Rickli et al. (2005) investigated soil type close to the study area (between 0.8 and 2 km). Soil samples showed a relatively low clay content (between 10% and 20%). Therefore seal formation as explanation for the very low Δ soil moisture values seems unlikely although it cannot be excluded completely.

A second possible explanation for the very low Δ soil moisture values on plots up to 75% vegetation cover could be compaction. Compaction reduces porosity and consequently water infiltration (Pietola et al. 2005, Hiltbrunner et al. 2010). In the present study grazing could have been responsible for compaction at plots with non-intact vegetation cover. The observation that soil bulk density from

0-10 cm was increased significantly with a decrease in vegetation cover supports this consideration (Figure 27). In addition, Δ soil moisture was significantly dependent on soil bulk density (0-10 cm) (Figure 18). Many other studies reported that grazing activities led to compaction (Hiltbrunner et al. 2010, Leitinger et al. 2012) and that meadows showed consequently a higher soil bulk density and lower infiltration (Pietola et al. 2005, Leitinger et al. 2012). The risk for soil compaction at the study area was accelerated during rainy summer 2014 because wet structural particles disintegrate more easily than drier ones (Trimble & Mendel 1995). It is concluded that compaction due to grazing seems to be the main reason for the measured low Δ soil moisture values.

The study area showed a low soil bulk density (0.78 ± 0.17 g cm^{-3}) compared to other grazed meadows (Pietola et al. 2005, Hiltbrunner et al. 2010). Such a low soil bulk density for grazed meadows was also measured in the study of Leitinger et al. (2012). The mentioned study observed additionally that soil bulk density could recover during winter season, presumably due to freezing-and-thawing cycles and bioturbation. It seems that this occurred also at the present study area so that severe compaction with reductions in plant vitality could have been avoided.

4.1.4. Summary

The decrease in vegetation cover led to a significant increase in soil particle yield and runoff but to no significant decrease in Δ soil moisture. Therefore hypothesis 1 can be only partly accepted. The non-significant relationship between vegetation cover and Δ soil moisture might be due to the non-significant changes in aggregate stability with vegetation cover. For the very low infiltration amounts at plots with a vegetation cover up to 75%, compaction, probably triggered by grazing, seems to be responsible.

4.2. Aggregate stability

4.2.1. The influence of vegetation on aggregate stability

Results showed that a reduction of vegetation cover did not directly lead to lower aggregate stability values (Figure 22) as observed in other studies (Pohl et al. 2012, Schindler Wildhaber et al. 2012). However, a decrease in vegetation cover led indirectly to a decrease in aggregate stability by its influence on root density (Figure 26). This is in line with the study of Pohl et al. (2012). Other studies (Fattet et al. 2011, Graf & Frei 2013) showed that root length per soil volume, a similar parameter, had a significant positive effect on aggregate stability. Although many possible influences of roots on aggregate stability are proposed (Amézketa 1999, see Chapter 1.2.3.1), the enmeshment of aggregates by dense and fine roots was most likely responsible for the positive correlation between root density and aggregate stability. This is concluded because the investigated plots were mainly covered by forbs and grasses. Forbs and grasses possess mats of dense, fine roots (Reubens et al. 2007) which count mainly for holding together macro-aggregates greater than 2 mm (Amézketa 1999). The importance of fine roots in relation with aggregate stability was shown in the studies of Pohl et al. (2009) and Fattet et al. (2011). Given that the used method for aggregate stability focuses on aggregates larger than 20 mm (Graf et al. 2015), this seems to be a probable explanation.

Even plots with low vegetation cover showed a high mean aggregate stability (0.95 ± 0.07 g g^{-1}) although root density was lower (0.007 g cm^{-3}) than at high vegetation plots (0.011 g cm^{-3}) (see Appendix A, Table i). A possible explanation for this is that vegetation cover recovered fast, so that aggregate stability was not influenced. Another explanation is that the contribution of dead roots by enmeshing soil particles was sufficient to retain the high aggregate stability (Amézketa 1999). Both explanations are in line with literature which reports that vegetation cover can be altered rapidly, whereas physical and biological changes within soil affecting erosion, may take longer periods (Zuazo & Pleguezuelo 2008, Zuazo et al. 2011).

An increase in vegetation cover went along with an increase in soil organic matter (Figure 23). Nevertheless the amount of soil organic matter had no significant influence on aggregate stability (Figure 24). The overall high soil organic matter content (15.9% ± 5.3 wt. %) might have been responsible for the non-significant relationship: even plots with low vegetation cover showed a soil organic matter content of 12.7 ± 5.0 wt. % (see Appendix, Table i). A positive relationship between soil organic matter content and aggregate stability was found in various studies (e.g. Auerswald & Hofmann 1994). Especially important is the observation of Le Bissonais et al. (2007) who pointed out that above a threshold of 1.7 to 2.3% organic carbon, aggregate stability became high. It seems that the measured soil organic matter content in the present study was sufficient to retain a high aggregate stability even at plots with low cover.

An increase in soil bulk density did not significantly influence aggregate stability (Figure 28). No significant relationship can be expected if soil bulk density is not related to compaction but rather influenced by other variables. However, further analysis showed that soil bulk density was not significantly influenced by stone content (>20mm) (see Appendix A, Figure h). Therefore, I still suppose that a decrease in soil bulk density was the consequence of compaction triggered by grazing. It could be that the influence of roots and soil organic matter dominated aggregate stability so that compaction got quasi "useless". Li et al. (2007) observed also no difference in water stable aggregates larger than 0.25 mm on conventional and intensive grazed plots with a quite high aggregate stability. Frei & Graf (2013) observed the positive influence of compaction on aggregate stability at soil samples with a very low aggregate stability.

Aggregate stability was significantly related to stone content above 20 mm (Figure 29). This relationship could be in connection with the used method (wet-sieving technique). A part of the soil samples included stones larger than 20 mm (n = 42). So it could have been that stones larger in size were surrounded by loose soil which detached during immersion in water. Consequently, lower aggregate stability values might be ascribable to the random presence of stones and probably not to a lower stability of individual aggregates. Possibly, a method like the one after Le Bissonais (1996) would have been more suitable because the stability of individual aggregates is tested. In addition, the proposed method tests all mechanisms for aggregate breakdown (slaking, differential swelling, raindrop impact, physico-chemical dispersion) and not only aggregate resistance to slaking as the used method does. However, the method after Le Bissonais (1996) would have been too time consuming and therefore not applicable for this study due to the high number of samples. The fact that there is no standardized methodology to determine aggregate stability is a general problem because the different methodologies complicate the comparison amongst data.

As already mentioned in the introduction, this master thesis was done in the frame of the SOSTANAH project. An objective of the SOSTANAH project was to investigate if aggregate stability is a link between shallow landslides and soil erosion. This study can contribute to this objective because the present study area showed strong, previous shallow landslide activities (Rickli et al. 2005). Due to this high shallow landslide activity, it was assumed that the study area possessed quite a low aggregate stability. Results showed the contrary. An important aspect is that shallow landslides can be triggered up to 2 m depth (Lateltin 1997) and consequently aggregate stability up to there is of importance. However, this study investigated only aggregate stability from 0-10 cm which was strongly influenced by vegetation as previously shown. It could be that aggregate stability is decreasing rapidly with depth because the influence of vegetation is decreasing. This would indicate that topsoil aggregate stability measurements might be not representative for soil’s susceptibility to shallow landslides due to the strong influence of vegetation.

The present results showed that topsoil aggregate stability was remarkably influenced by vegetation. Vegetation had a significant positive influence on aggregate stability by its connection to root density. Soil organic matter increased with an increase in vegetation cover but had no significant influence on aggregate stability. Therefore hypothesis 2a can be only partly accepted. Nevertheless, if the overall high aggregate stability in the study area is considered, it is supposed that the high amounts of soil organic matter contributed at least partly to the high aggregate stability. Other studies mentioned that soil type and especially clay content was the main influencing factor for aggregate stability (Yan et al. 2008, Schindler Wildhaber 2012). If this is valid for this study cannot be assessed due to missing analysis. However based on the observations of Rickli et al. (2005) samples may have included between

10% and 20% of clay. Therefore, it could be that this clay content also contributed to the high aggregate stability in the study area.

4.2.2. The influence of aggregate stability on soil particle yield

No significant relationship was found between aggregate stability and soil particle yield (Figure 30), runoff (Figure 31) and Δ soil moisture (Figure 32). These results are in contrary to the ones of Barthès & Roose (2002), Yan et al. (2008) and Schindler Wildhaber (2012). The non-significant relationships could be due to the only small changes in aggregate stability values (0.97 ± 0.09 g g^{-1}). Another consideration is that the measured aggregate stability might not represent the stability of the individual aggregates as illustrated in chapter 1.2.3.1. However, for the influence of aggregate stability on interrill erosion parameters, the stability of the individual aggregates is crucial.

Although not significant, results showed that runoff was increasing with aggregate stability. For this the strong dependency of aggregate stability on stone content (> 20 mm) could be an explanation. The increase in runoff could be the consequence of increased infiltration rates which were facilitated by an increase in belowground cracks connected to the stone content. The increase in Δ soil moisture was not measurable because water was conducted to deeper soil layers by the cracks. This would explain the reduced runoff at low aggregate stability plots without a change in Δ soil moisture.

To sum up, results do not support hypothesis 2b: soil aggregate stability had neither a direct nor an indirect influence on soil particle yield and runoff. Most likely the non-significant relationships were due to the overall constant aggregate stability in the study area and methodical influences.

4.3. Main responsible variables for soil particle yield

The previous chapter showed that aggregate stability was not responsible for changes in soil particle yield. Therefore the question remains how vegetation cover influenced the variable soil particle yield. Multiple regression analysis showed that the variables total cover and runoff were the best predictors for soil particle yield. They could explain 42.7% of the variance. Therefore it could be that interception of the rainfall by the vegetation canopy played a key role. Besides the part of the intercepted water which is directly evaporated, a part of the water reaches the soil as stem flow or water drops that fall from the canopy to the soil surface (Toy et al. 2002). In the case of grasses and forbs, the distance between canopy and surface is close enough so that energy of the raindrops is reduced significantly compared to raindrops that are not intercepted (Toy et al. 2002). Therefore, interception can influence interrill erosion directly by decreasing rainfall erosivity (Zuazo et al. 2011). Secondly, interception can influence interrill erosion indirectly by decreasing runoff as already illustrated in Chapter 4.1.2.

Soil particle yield was significantly correlated with runoff (Figure 21). Due to the strong correlation between soil particle yield and runoff, two questions arise. The first is if runoff only transported or also detached soil particles and the second is if the investigated plots were transport-limited or detachment-limited. Concerning the first question, path analysis showed that total cover had a stronger influence on soil particle yield in a direct way than by runoff (Figure 33). This indicates that a decrease of rainfall erosivity by interception was responsible for lower soil particle yields at plots with high vegetation cover. Literature supports this conclusion: detachment on interrill areas occurs mainly by raindrop impact and not by runoff because amount and velocity is limited (Toy et al. 2002, Brady & Weil 2010). However, the plots in this experiment were irrigated with an extraordinary high rainfall intensity (360 mm h^{-1}) so that extraordinary high runoff amounts were generated. Therefore detachment by runoff cannot be excluded completely at the present plots. Concerning the second question, transport-limitation is unlikely because extraordinary high water amounts were applied. Additionally, the study of Assouline & Ben-Hur (2006) showed that slopes steeper than 14° were in general detachment-limited and therefore no layer of loose soil particles accumulated at the soil surface. All the investigated plots in the study area were steeper than 14°. Both questions cannot be answered finally with the existing dataset. Based on results and literature I suppose that detachment occurred mainly by raindrop impact and plots were not transport-limited.

Although analysis showed that aggregate stability values could not improve the model, the possible role of aggregate stability is discussed in the following part. Martin (2008) conducted a study at machine graded ski slopes with a mean slope steepness of 18° close to Davos, Switzerland. Rainfall experiments were done with the same intensity, duration and instrument (Eijkelkamp Rainfall Simulator) at micro plots differing in vegetation cover. Pohl et al. (2009) investigated aggregate stability in the same study area as Martin (2008) and with the same method as used in the present study. Due to same experimental methods and designs, a comparison of soil particle yield and aggregate stability was done: the soil particle yields determined by Martin (2008) were, depending on vegetation cover, between 40% and 85% higher than the one measured in this study. The aggregate stability determined by Pohl et al. (2009) was around 55% lower than the one determined in the present study. For the present study it is therefore concluded that although there was no direct relationship between aggregate stability and soil particle yield, the high aggregate stability of the study area might have been responsible for the comparable low soil particle yields, especially at plots with low vegetation. The lab experiment of the study of Schindler Wildhaber et al. (2012) supports this conclusion: soil particle yields were around 80% lower on soil with a high aggregate stability (0.99 g g^{-1}) compared to soil with a low aggregate stability (0.21 g g^{-1}). Unfortunately, no further studies which used completely same experimental methods were found for further comparisons. One problem is that many studies irrigated the plot over longer timespans (e.g. Schindler Wildhaber et al. 2012). However, a comparison with interpolation is not possible because soil particle yield is not constant over time: soil particle yield shows a peak at the beginning of the rainfall experiment which is followed by a strong decrease to a final constant rate (Schindler Wildhaber et al. 2012, Balacco 2013).

To sum up, it is concluded that interception might have led to a decrease in soil particle yield with an increase in vegetation cover whereas soil aggregate stability might have been responsible for the overall low particle yields measured at the study area. However, it has to be considered that Martin (2008) investigated plots with another land-use, soil texture and at a higher altitude (2300 m a.s.l.). Therefore it cannot be finally decided if it was really the comparable low aggregate stability which led to the much higher soil particle yields at the study area of Martin (2008).

5. Conclusion

Rainfall experiments on micro plots on cattle grazed alpine meadows showed that a reduction of vegetation cover led to an exponential increase in soil particle yield. The study indicates that micro plots of around 20° steepness and with a cover of more than 50% of living and dead plant material are protected from serious interrill erosion.

A high degree of vegetation cover influenced aggregate stability in a positive way due to its connection to belowground root density and probably due to related elevated input of organic matter. A decrease in aggregate stability had no significant influence on neither soil particle yield nor runoff and infiltration. Instead of aggregate stability, total cover and runoff were the best predictor variables for soil particle yield. A comparable experiment (Martin 2008) at an area with moderate aggregate stability showed that a decrease in vegetation cover can lead to much higher soil particle yields than measured in the present study. Consequently, it is supposed that interception was responsible for variations in soil particle yield with changes in vegetation cover, whereas the high aggregate stability led to the overall low soil particle yields.

It is shown that an intact vegetation cover can protect cattle grazed meadows from serious interrill erosion. The reason for this is that vegetation cover has various positive ecosystem functions: it reduces rainfall erosivity, runoff, soil bulk density and it increases soil organic matter content and root density. Indirectly, it has a positive influence on aggregate stability. All these aspects help to keep the ecosystem in balance, especially if it is challenged with changing environmental conditions like more frequent and more intensive rainfall events. This study underlines the importance to keep vegetation cover as intact as possible when an area is grazed.

Furthermore, this study showed that aggregate stability might have a considerable influence on interrill erosion at meadows with a low vegetation cover. This would indicate that a high aggregate stability is especially important to protect meadows during times when vegetation cover is damaged or not completely developed. In the context of climate change and an earlier snowmelt, this aspect will gain increasing importance. However, it was not possible to answer the question to what extent aggregate stability influences interrill erosion. In order to gain more information about the important relationship, future research is required. Important would be soil erosion experiments on areas with similar land-use and soil texture, but differing in aggregate stability. To get a better comparability between studies, a standardized method to measure aggregate stability is required. Additionally, future research should focus on interrill erosion on slope scale to control if the determined vegetation cover threshold is also applicable on larger scales.

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Front page: Impression of the study area. Photo: Regula Christon.

Appendix A: Data overview

Table i: The influence of vegetation cover on different soil and interrill erosion parameters. Mean values and standard deviations of the parameters are shown for vegetation cover class 0-25%, 26-49%, 50-75% and 76-100%. In addition, mean values and standard deviations over all samples are shown.

	Vegetation cover (0-25%)	**Vegetation cover (26-49%)**	**Vegetation cover (50-75%)**	**Vegetation cover (76-100%)**	**Mean over all samples**
number of measurements (n)	25	20	30	36	111
soil particle yield (g m^{-2})	27.9 ± 51.3	6.0 ± 10.5	4.1 ± 8.9	1.6 ± 1.3	9.0 ± 26.9
initial soil moisture (0-10) (vol. %)	54.6 ± 11.4	58.4 ± 10.5	61.2 ± 11.2	61.2 ± 10.1	59.2 ± 11.0
initial soil moisture (0-10) (wt. %)	31.5 ± 8.0	34.8 ± 7.2	37.6 ± 6.4	37.0 ± 8.0	35.5 ± 7.7
initial soil moisture (10-20) (wt. %)	24.9 ± 5.2	25.8 ± 3.7	26.8 ± 5.2	27.1 ± 4.6	26.3 ± 4.8
Δ soil moisture (0-10) (vol. %)	6.8 ± 6.8	11.2 ± 9.9	13.3 ± 8.0	13.2 ± 7.3	11.4 ± 8.2
Δ soil moisture (0-10) (wt. %)	-0.3 ± 5.6	1.1 ± 4.5	0.3 ± 7.4	2.7 ± 4.9	1.1 ± 5.8
Δ soil moisture (10-20) (wt.%)	-0.6 ± 5.4	0.5 ± 5.2	2.2 ± 5.4	0.6 ± 4.8	0.7 ± 8.2
runoff (mm m^{-2})	17.2 ± 6.1	16.3 ± 7.7	16.9 ± 6.5	14.6 ± 6.0	16.1 ± 6.5
soil bulk density (0-10 cm) (g cm^{-3})	0.89 ± 0.14	0.79 ± 0.24	0.75 ± 0.17	0.71 ± 0.12	0.78 ± 0.17
soil bulk density (10-20 cm) (g cm^{-3})	0.97 ± 0.12	1.03 ± 0.13	0.94 ± 0.10	0.98 ± 0.12	0.98 ± 0.12
soil organic matter (wt. %)	12.7 ± 5.0	15.8 ± 5.3	17.3 ± 5.3	17.1 ± 4.8	15.9 ± 5.3
root density (g cm^{-3})	0.007 ± 0.005	0.009 ± 0.006	0.010 ± 0.006	0.011 ± 0.005	0.009 ± 0.006
aggregate stability (g g^{-1})	0.95 ± 0.07	0.98 ± 0.04	0.97 ± 0.06	0.96 ± 0.05	0.97 ± 0.09

Appendix B: Further results

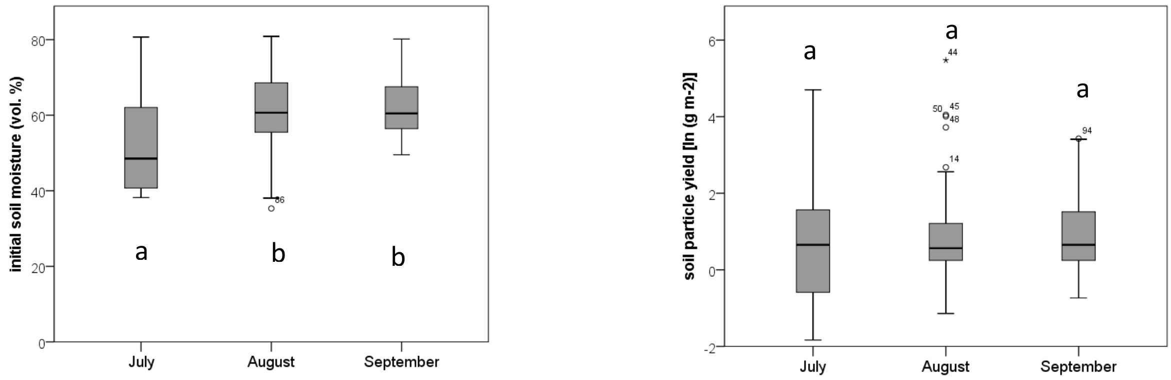


Figure a: The influence of the measurement month on initial soil moisture and soil particle yield. Different letters under or above the boxplots indicate significant differences between the mean values.

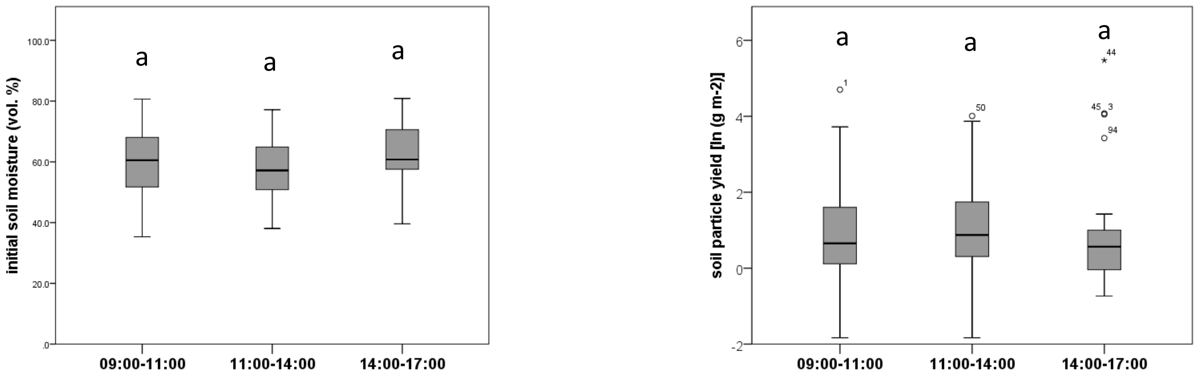


Figure b: The influence of the daytime on initial soil moisture and soil particle yield. Different letters above the boxplots indicate significant differences between the mean values.

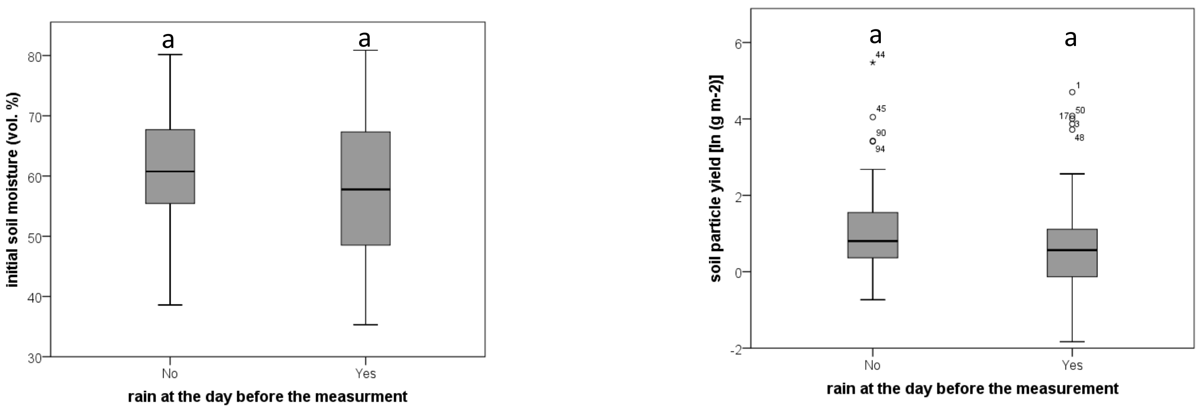
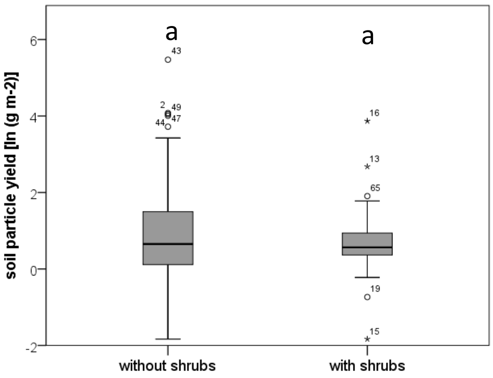


Figure c: The influence of rain at the day before the measurement on initial soil moisture and soil particle yield. Different letters above the boxplots indicate significant differences between the mean values.



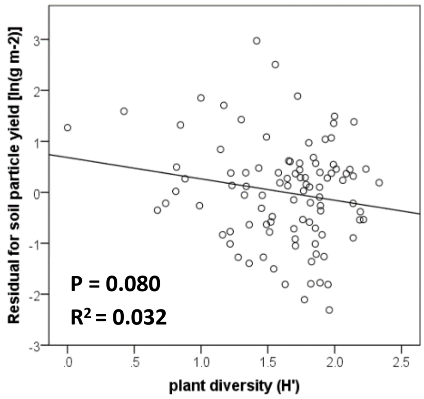


Figure d: The influence of the presence of shrubs and plant diversity on soil particle yield. In the left figure different letters above the boxplots indicate significant differences between the mean values. The right figure includes the linear trend line, the level of significance (P-value) and the coefficient of determination.

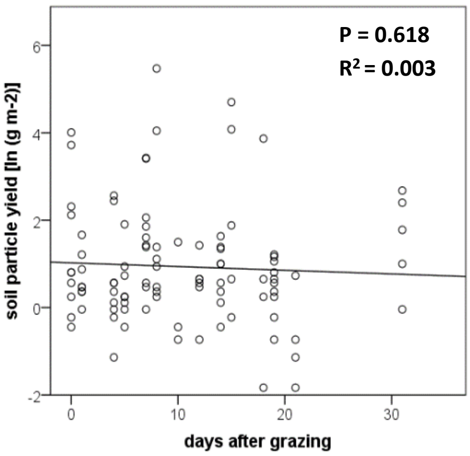
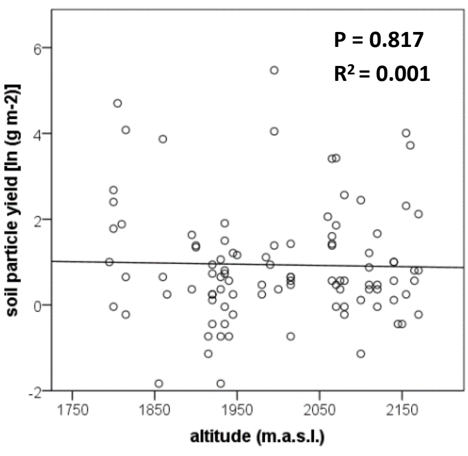


Figure e: The influence of the number of days after grazing and soil particle yield. Shown is the linear trend line, the level of significance (P-value) and the coefficient of determination.



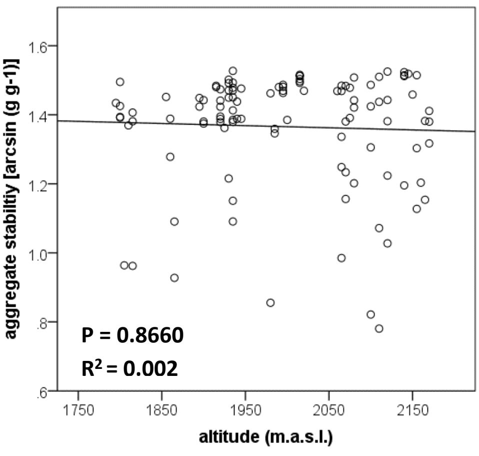


Figure f: The influence of altitude on soil particle yield and aggregate stability. In the left figure the linear trend line, the level of significance (P-value) and the coefficient of determination is shown. In the right figure the linear trend line, the level of significance (robust regression; P-value based on t-distribution) and the coefficient of determination is shown. It must be noted that the residuals of this regression were unequally distributed (Appendix C, Figure n).

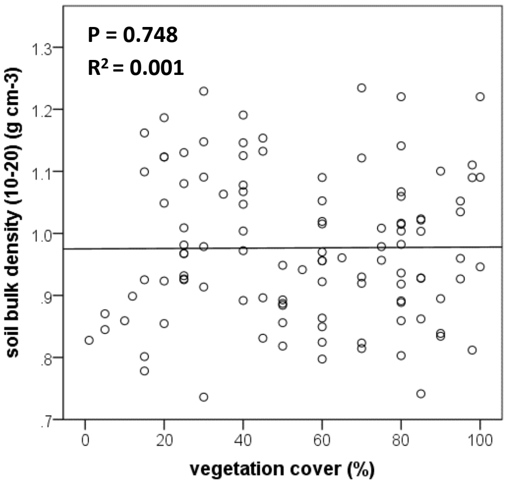


Figure g: The influence of vegetation cover and soil bulk density (10-20 cm). Shown is the linear trend line, the level of significance (P-value) and the coefficient of determination.

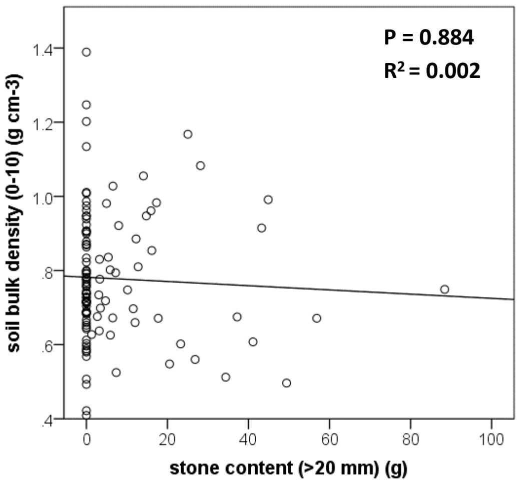


Figure h: The influence of stone content (> 20 mm) on soil bulk density (0-10 cm). Shown is the linear trend line, the level of significance (P-value) and the coefficient of determination.

Appendix C: Residuals of robust regression analysis

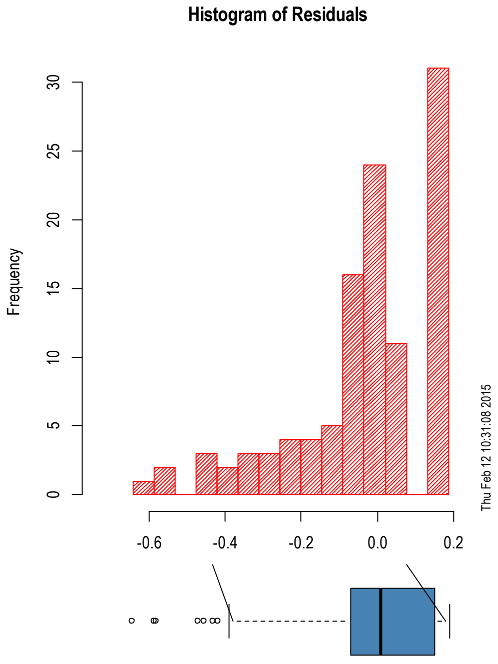


Figure i: Histogram of residuals of robust regression for the relationship aggregate stability – vegetation cover.

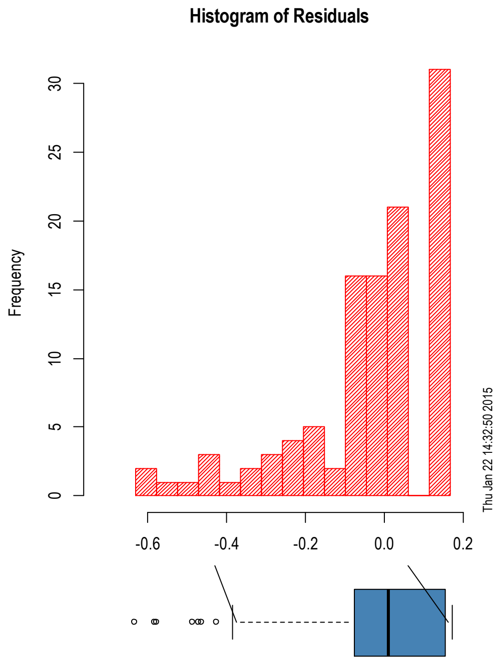


Figure j: Histogram of residuals of robust regression for the relationship aggregate stability – soil organic matter.

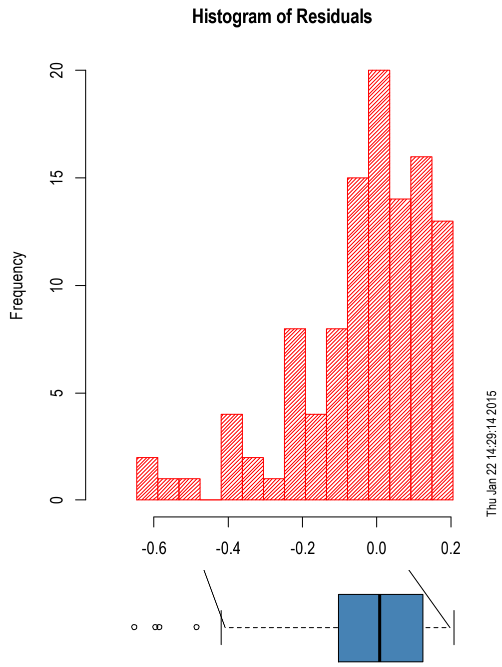


Figure k: Histogram of residuals of robust regression for the relationship aggregate stability-root density.

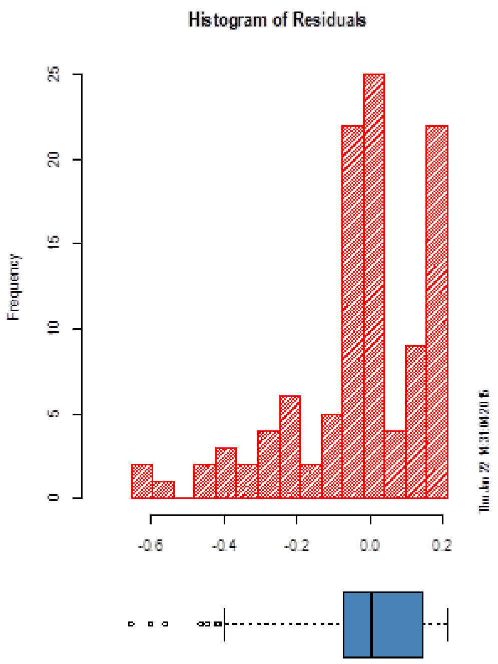


Figure l: Histogram of residuals of robust regression for the relationship aggregate stability – soil bulk density.

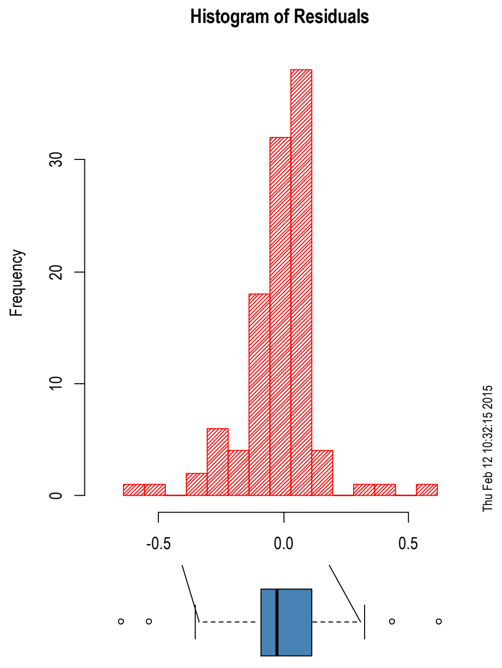


Figure m: Histogram of residuals of robust regression for the relationship aggregate stability – amount of stones (>20 mm).

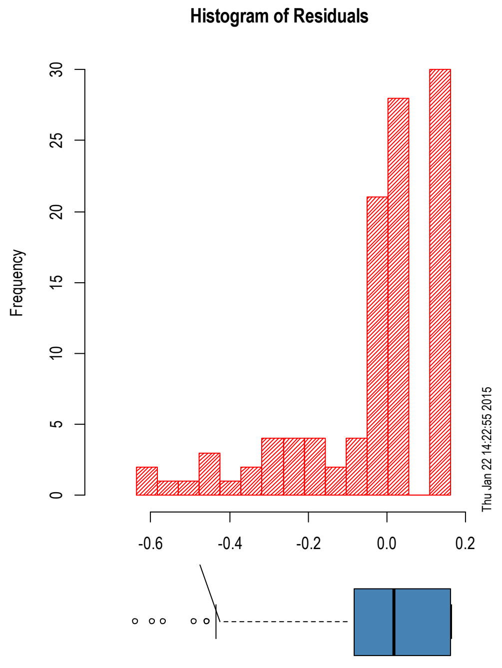


Figure n: Histogram of residuals of robust regression for the relationship aggregate stability – altitude.

Appendix D: Species list

Shrubs

Calluna vulgaris	*Polygala chamaebuxus*	*Helianthemum nummularium*
Vaccinium myrtillus	*Vaccinium uliginosum*	*Vaccinium vitis-idaea*

Grasses

Carex pallescens	*Alopecurus pratensis*	*Festuca rubra*
Carex flacca	*Briza media*	*Danthonia decumbens*
Carex ornithopoda	*Dactylis glomerata*	*Agrostis capillaris*
Luzula sylvatica	*Poa alpina*	*Anthoxanthum odoratum*
Phleum alpinum	*Nardus stricta*	

Forbs

Ligusticum mutellina	*Campanula barbata*	*Soldanella alpina*
Pimpinella major	*Campanula scheuchzeri*	*Ranunculus montanum*
Achillea millefolium	*Silene vulgaris*	*Alchemilla xanthochlora*
Cirsium acaule	*Trifolium pratense*	*Alchemilla conjuncta*
Cirsum spinosissimum	*Lotus corniculatus*	*Alchemilla alpina*
Carlina acaulis	*Anthyllis vulneraria*	*Alchemilla vulgaris*
Arnica montana	*Hippocrepis comosa*	*Potentilla erecta*
Hieracium pilosella	*Thymus serpyllum*	*Fragaria vesca*
Hieracium spec	*Prunella vulgaris*	*Gentiana acaulis*
Crepis aurea	*Plantago lanceolata*	*Geum montanum*
Taraxacum officinalis	*Plantago alpina*	*Linum catharticum*
Leucanthemum vulgare	*Plantago atrata*	*Polygala vulgaris*
Homogyne alpina	*Veronica chamaedrys*	*Euphrasia spec.*
Hypochaeris uniflora	*Veronica officinalis*	*Equisetum telmateia*
Taraxacum officinalis	*Globularia nudicaulis*	
Phyteuma orbiculare	*Rumex arifolius*	

Appendix E: Material list (written in German)

Materialliste

Höhenmesser
GPS
Neigungsmesser
Fotoapparat
20 Aufnahmeprotokolle
Schreibzeug und wasserfeste Stifte
Karte der Region
1 gorsses Messer (für Schlitz)
5 Fahnen zur Markierung
Küchenrolle und Lumpen
Tragerucksack für Wasser

Flora Helvetica
Massstab
Schere
Plastiksäcke (gross und klein)

ThetaProbe, inkl. Ersatzbatterien
1 Bohrstock (Humax)
1 Hammer gross (aus Holz)
30 Humax Zylinder (24 gebraucht, 6 Reserve)
1 Zange
HCl
pH Messmaterial (Hellige pH kit)
1 Hammer klein
2 Schaufeln klein
1 Spaten gross
2 Kühltaschen und 2 Einkaufstaschen

Zwei Wasserkanister (10 Messungen = 20 Liter, 20 Liter Reserve); 40 Liter Wasser
Knetmasse (Plastilin)
Box Regensimulator inkl. 4 Nägel
Joghurtbecher (eingewogen)
Stoppuhr
Trichter
Wasserwaage
Thermometer für Wasser
Teigschaber

Appendix F: Field and lab protocol (written in German)

Feld- und Laborprotokoll

Feld: Datum: _____ ._______ 2014   Start: _____:_______   Protokollführer: _______

1. Makroplot

Durchschnittliche Höhe: __________m ü. M.   Mutterkühe: □   Rinder: □

Grösser Fläche: Länge:_____m * Breite:_____m   Durchschnittliche Neigung der Fläche: _____°

Kühe im Sommer 2014:   □ Ja, das 1te Mal   □ Ja, das 2te Mal

Beweidungszeitraum: ______ ._______ bis _____ ._______ 2014

Offener Boden: _______ %

Vorherrschendes Wetter: □ sonnig   □ bewölkt

Wetter gestern: □ sonnig   □ bewölkt   □ Regen

Oberflächliche Vegetation abgetrocknet: □ Ja   □ Nein

Bodenoberfläche abgetrocknet: □ Ja   □ Nein

Makroplot

Zwergsträucher: ________ %   Gräser: ________%   Kräuter: ________%

Bemerkung Vegetation:

____% ___________________________________   Sack Nr.______   Foto Nr.__________

____% ___________________________________   Sack Nr.______   Foto Nr.__________

____% ___________________________________   Sack Nr.______   Foto Nr.__________

____

____

2. Mikroplot

Datum: _____ ._______ 2014 Start: _____:_______ Protokollführer: _______

Beregnungsnummer: □ 1 □ 2 □ 3 □ 4 □ 5

Höhe: __________m ü. M. Neigung des Plots: _____°

Koordinaten (x/y): _________________/_________________ Genauigkeit: _____m

Bodenfeuchte 1 Boden VOR Beregnung: ________% NACH Beregnung: ____________%

Bodenfeuchte 2 Boden VOR Beregnung: ________% NACH Beregnung: ____________%

Bodenfeuchte 3 Boden VOR Beregnung: ________% NACH Beregnung: ____________%

Bodenfeuchte 4 Boden VOR Beregnung: ________% NACH Beregnung: ____________%

Bodenfeuchte 5 Boden VOR Beregnung: ________% NACH Beregnung: ____________%

Vegetation

Durchschnittliche Vegetationshöhe: _____ cm Vegetationsbedeckung: _______%

Stelle offener Boden: □ rechts □ links □ oben □ unten □ Mitte

Zwergsträucher: ________ % Gräser: ________% Kräuter: ________%

Anzahl Arten: _______Stück Streu (bezogen auf offenen Boden): ________%

Vegetationsaufnahme: (Prozent /Name)

____% _________________________________ Sack Nr.______ Foto Nr._________

____% _________________________________ Sack Nr.______ Foto Nr._________

____% _________________________________ Sack Nr.______ Foto Nr._________

____% _________________________________ Sack Nr.______ Foto Nr._________

____% _________________________________ Sack Nr.______ Foto Nr._________

____% _________________________________ Sack Nr.______ Foto Nr._________

____% _________________________________ Sack Nr.______ Foto Nr._________

____% _________________________________ Sack Nr.______ Foto Nr._________

____% _________________________________ Sack Nr.______ Foto Nr._________

____% _________________________________ Sack Nr.______ Foto Nr._________

____% _________________________________ Sack Nr.______ Foto Nr._________

____% _________________________________ Sack Nr.______ Foto Nr._________

____% _________________________________ Sack Nr.______ Foto Nr._________

Wasserstand VOR Beregnung: _______ ml Dauer der Beregnung (1875 ml): _______ min

Wasserstand NACH Beregnung: _______ ml

Leergewicht Joghurtbecher Nr.____: ________ g Leergewicht Joghurtbecher Nr.____: ________ g

Wind bei Beregnung: □ Ja □ Nein

3. Boden

Tiefgründigkeit: □ Steine in ca. 10 cm □ Steine in ca. 20 cm □ kein Anstoss

Vegetationsbedeckung Bodenprobe Aggregatstabilität:

____% ____________________________________ Sack Nr.______ Foto Nr.__________

____% ____________________________________ Sack Nr.______ Foto Nr.__________

____% ____________________________________ Sack Nr.______ Foto Nr.__________

____% ____________________________________ Sack Nr.______ Foto Nr.__________

Offener Boden: _______ %

pH Wert: ______

HCl: Brausen: □ Nein □ Schwach □ Mittel □ Stark

Bewertung Beregnung:

□ sehr gut □ gut □ ok □ schlecht

Bemerkungen Feld:

____

____

____

____

____

4. Labor

A. Abfluss/Sediment

Leergewicht Joghurtbecher 1: ________ g   Leergewicht Joghurtbecher 2: ________ g

Totalgewicht Joghurtbecher 1: ________ g   Totalgewicht Joghurtbecher 2: ________ g

Leergewicht Schale: ________ g

In den Ofen am: ___.___.2014   ___:___

Totalgewicht Schale trocken: ________ g

B. Bodenprobe BFV

Kürzel: _____

Länge gesamte Bodenprobe: _________ cm

Stabilität: □ zerbröselt □ viel Bruch □ wenig Bruch □ kein Bruch

Steine: □ keine sichtbar/störend □ wenige □ viele

Vollständigkeit: □ vollständig □ unvollständig, Horizont:______

0-10 cm □ ungeeignet für Dichte   Genaue Länge: _________ cm

Leergewicht Schale: ________ g   Totalgewicht Schale nass: ________ g

In den Ofen am: ___.___.2014   ___:___   Aus dem Ofen am: ___.___.2014   ___:___

Totalgewicht Schale trocken: ________ g

10-20 cm □ ungeeignet für Dichte   Genaue Länge: _________ cm

Leergewicht Schale: ________ g   Totalgewicht Schale nass: ________ g

In den Ofen am: ___.___.2014   ___:___   Aus dem Ofen am: ___.___.2014   ___:___

Totalgewicht Schale trocken: ________ g

C. Bodenprobe BFN

Kürzel: _____

Länge gesamte Bodenprobe: _________ cm

Stabilität: □ zerbröselt □ viel Bruch □ wenig Bruch □ kein Bruch

Steine: □ keine sichtbar/störend □ wenige □ konzentriert, Horizont:______ □ viele

Vollständigkeit: □ vollständig □ unvollständig, Horizont:______

Bezeichnung Horizont 1:_______ bis: _________ cm

Bezeichnung Horizont 2: _______ bis: _________ cm

Bezeichnung Horizont 3:_______ bis: _________ cm

Bezeichnung Horizont 4: _______ bis: _________ cm

Bezeichnung Horizont 5: _______ bis: _________ cm

0-10 cm □ ungeeignet für Dichte Genaue Länge: _________ cm

Leergewicht Schale: ________ g Totalgewicht Schale nass: ________ g

In den Ofen am: ___.___.2014 ___:___ Aus dem Ofen am: ___.___.2014 ___:___

Totalgewicht Schale trocken: ________ g

10-20 cm □ ungeeignet für Dichte Genaue Länge: _________ cm

Leergewicht Schale: ________ g Totalgewicht Schale nass: ________ g

In den Ofen am: ___.___.2014 ___:___ Aus dem Ofen am: ___.___.2014 ___:___

Totalgewicht Schale trocken: ________ g

D. Bodenprobe AG

Datum: ___.___.2014 ____:____ Kürzel: _____ Länge gesamte Bodenprobe: _________ cm

Stabilität: □ zerbröselt □ viel Bruch □ wenig Bruch □ kein Bruch

Steine: □ keine □ wenige, Horizont:______ □ viele

Vollständigkeit: □ vollständig □ unvollständig, Horizont:______

Länge der Probe für AG: _________ cm

(Gewicht Probe 10 cm in Humax (ohne Deckel, ohne loses Material): ________ g)

(Leergewicht Humax 10 cm: ________ g) Gewicht Bodenprobe, feucht: ________ g

Zeit für Auffüllen des Wassers: ______ min

Beobachtung Zerfallprozess:

Auffüllen: □ fast nichts □ wenig □ viel

Stehend: □ fast nichts □ wenig □ viel

Ableeren: □ fast nichts □ wenig □ viel

Probe (Start): □ frei stehend □ anlehnend □ grossflächig zerbrochen □ feinkörnig zerbröckelt

Wassertemperatur (nach 2.5 min):______°C Zeit Ableeren des Wassers: ______ min

---

Steine > 20 mm:

Leergewicht Becher: ________ g

Totalgewicht Becher trocken: ______________ g

Material in 20 mm Sieb:

Leergewicht Schale 1: ________ g

In den Ofen am: ___.___.2014 ___:___ Aus dem Ofen am: ___.___.2014 ___:___

Totalgewicht Schale 1 trocken: ______________ g

Leergewicht Schale 2: ________ g

In den Ofen am: ___.___.2014 ___:___ Aus dem Ofen am: ___.___.2014 ___:___

Totalgewicht Schale 2 trocken: ______________ g

Material in 10 und 0.2 mm Sieb:

Leergewicht Schale: ________ g

In den Ofen am: ___.___.2014 ___:___ Aus dem Ofen am: ___.___.2014 ___:___

Totalgewicht Schale trocken: ______________ g

Wurzelanalyse Dauer der Suche: _____ min

Gewicht Wurzelmasse nass: ___________________ g

In den KS am: ___.___.2014 ___:___

In den Ofen am: ___.___.2014 ___:___ Aus dem Ofen am: ___.___.2014 ___:___

Masse Wurzeln trocken: ___________________ g

RD = ___________________ g*cm^{-3}

Personal Declaration

I hereby declare that the submitted thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the thesis.

Zurich, 24.04.2015

Regula Christon