# EROSION AND RESTORATION IN GUNNARSHOLT, ICELAND

*by Romy Stijsiger*

**MASTER THESIS**

**SLM 80336**

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## I. ABSTRACT

In Iceland due to the combination of climate, natural phenomena, anthropogenic pressures and soil characteristics, almost a quarter of the land is affected by severe to extremely severe erosion. To combat land degradation, restoration efforts have been organized and a total of 571.000 ha has been restored. This research focuses on what the effect of revegetation is on water and wind erosion by studying the revegetation of ryegrass on Andosols in Iceland. Water erosion consisting of both runoff and erosion (transported sediment) resulted in 17 and 16 years of time needed to reduce the runoff and erosion rates from the degraded state of the ecosystem to the natural state of the ecosystem. The wind erosion experiments also resulted in a descending trend over time however the recovery time was substantially larger with 187 years. Only the runoff resulted in a significant change between revegetated sites, identifying a decrease in runoff rates over time and therefore a direct effect of revegetation. PCAs showed that the runoff and erosion, as measured in the water erosion experiments, did not relate to the vegetation cover. Vegetation cover does correlate with the wind erosion at the 10 cm height which consists mainly of the larger particles deposited by saltation. Subsequently, this would mean that the vegetation cover as established in these experiments influences the erosion of larger particles. This theory of particle size was also supported by the bulk density which was closer related to the runoff, erosion in the degraded area than in the natural area.

## II. AKNOWLEDGEMENTS

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# 1. INTRODUCTION

Throughout the world natural resources like soil, water, wildlife, cultivation and natural vegetation are affected by both natural and anthropogenic pressures. These pressures can affect the balance of a landscape in such a way that it destabilizes and new severely degraded land is created. Restoration projects focus on preventing and reducing this land degradation through soil and water conservation. Soil and water conservation are important regarding issues on food security, water conflicts, poverty alleviation, livelihoods improvements and ecosystem services (WOCAT, 2016). One of the places where restoration efforts are initiated to halt thorough and extensive land degradation processes is Iceland. Iceland is one of the few places in the world where tectonic plates diverge and new land is created. The immense forces push materials up creating mountains, volcanoes, earthquakes, eruptions, floods and lava flows. These natural phenomena create a harsh environment for vegetation to grow, however since the settlement of the first Norse men in the 9$^{th}$ century anthropogenic factors have increased pressures. Since then, about 96% of the tree cover has been lost and 60% of the total vegetation has disappeared due to burning, logging and grazing, exposing the soil to erosive processes and the country to severe dust storms (Figure 1a, 1b) (SCSI, 2016). In addition, the specific soil characteristics of Icelandic soils also play a role. The dominant soils in Iceland are andosols which are susceptible to especially wind and water erosion due to their low-density aggregates, lack of particle cohesion and low water holding capacity (Arnalds & Kimble, 2001; Orradottir et al., 2008).

Due to the combination of climate, natural phenomena, anthropogenic pressures and soil characteristics, almost a quarter of the land is affected by severe to extremely severe erosion (Figure 1c) (Arnalds et al., 2001). The loss of vegetation throughout the centuries increased the frequency and severity of dust storms which resulted into loss of livestock, famines, abandonment of farms and wide spread emigration (Crofts, 2011). To combat degradation in Iceland, restoration efforts have been organized following the establishment of the Soil Conservation Service of Iceland (SCSI) in 1907. Since then, the different projects combined have

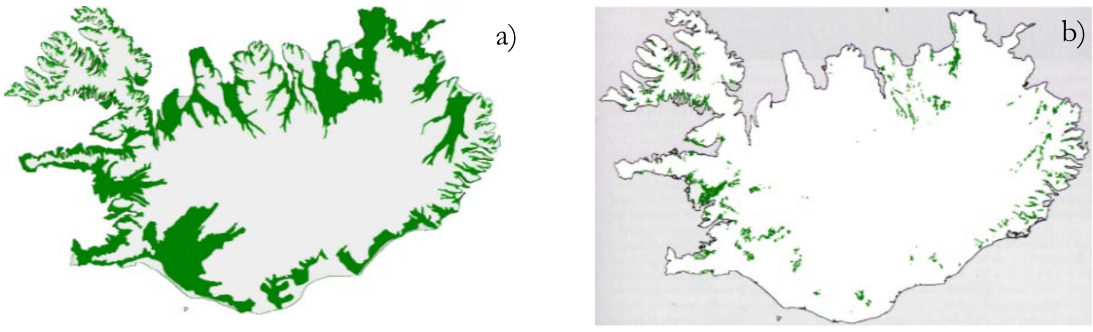


*Figure 1 Iceland's boreal forest cover before human settlement (a), the current boreal forest cover (b,* (A. Arnalds, 2005)

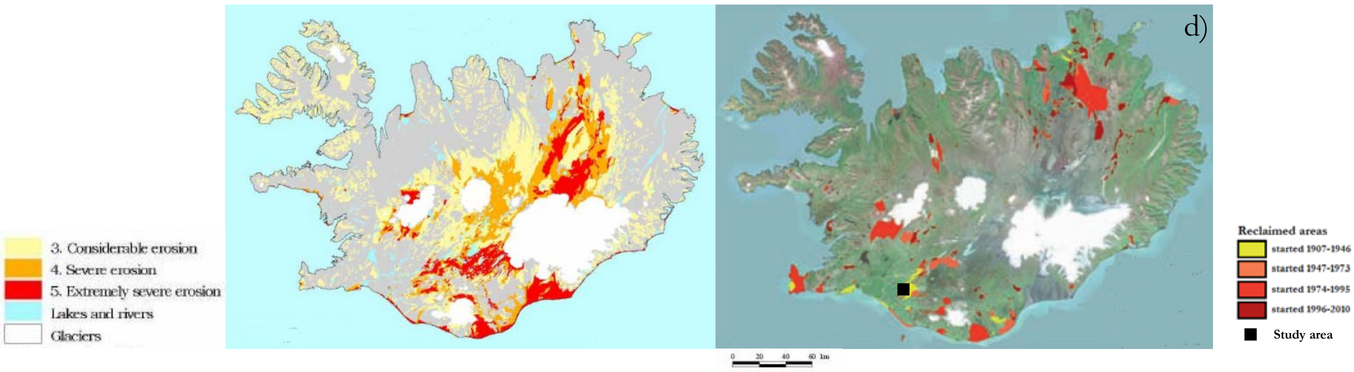


*Figure 2 (continued) Iceland's vulnerability to erosion(c) and Restoration efforts (d)* ( Crofts, 2011)

reclaimed an area of 571.000 ha throughout Iceland (Figure 1d) (Crofts, 2011). The restoration projects introduce primarily different vegetative species to retain sediment on exposed soil species such as Lyme grass (*Elymus arenarius L.*), Nootka lupine (*Lupinus nootkatensis*), native birch trees (*Betula pubescens*), native willow trees (*Salix sp.*) and other grass and legume species(eg. *Lolium sp., Leymus mollis, Poa macrantha, Lathyrus japonicas*). Vegetation cover plays an important role in soil restoration as it increases infiltration, soil porosity and organic matter content which develops a more favorable environment for soil biota (Orradottir et al., 2008). Other methods used in restoring degraded lands in Iceland are the construction of barriers for diminishing sand drifts, irrigation and water level manipulation for wetting the soil surface and increasing cohesiveness, fencing and livestock exclusion to restrain livestock for entering restoration areas and the controlling of rivers to decrease river bank erosion (Crofts, 2011).

Previous research in Iceland included research on the establishment of different vegetation types for restoration (Aradottir, 2004; Aradóttir, Robertson, & Moore, 1997; Aradóttir et al., 2000; Benediktsson, 2015; Einarssoner al., 1993; Greipsson & Davy, 1994, 1995; Gretarsdottir et al., 2004; Gunnarsson & Indridadottir, 2009; Hiltbrunner et al., 2014; Ritter, 2007; Tanner et al., 2015), erosion by wind on volcanic soils (Arnalds, 2010; Arnalds, Gisladottir, & Orradottir, 2012; Arnalds et al., 2013; Gisladottir, Arnalds, & Gisladottir, 2005; Thorarinsdottir & Arnalds, 2012), water erosion through modelling (de Woul et al., 2006; Jónsdóttir, 2010; Smith et al., 2000) and the effect of vegetation type on infiltration, frost formation and snow distribution (Orradottir et al., 2008). However an evaluation of the exact effects of restoration efforts on erosion processes in Iceland had never been done. This study focuses on the main restoration technique used in Iceland and its effect on wind and water erosion in Iceland. Therefore, the aim of the research was to see to which extend water (I) and wind (II) erosion are reduced by the revegetation of ryegrass on Andosols over different timeframes. In addition, the soil characteristics (III) were studied to give a better understanding of the underlying processes determining the water and wind erosion rates.

## 2. MATERIALS & METHODS

### 2.1 STUDY AREA

The SCSI established the Kot research area (63°92'N, 20°03'W) 10 km southwest of mount Hekla in South Iceland. Average temperature is 4 °C with an average wind speed of 4 m/s and annual precipitation of 1218 mm (Iceland Meteorological Office, 2016). The Kot research area is a total of 203 hectares with a distinction made between a natural and a degraded area. The Kot area consists of Andosols layered with ash from eruptions mainly of Hekla. Hekla has produced more tephra than any other volcano measured and this has created large pumice and sand fields with tephra ranging from acid and intermediate tephra to black basaltic tephra (Thorarinsdottir & Arnalds, 2012). The natural site is considered to be the original state of the ecosystem which is a densely vegetated hilly area including mosses (75-100%) and grasses and shrubs (10-15%). The natural site is part of a chain of green areas that have survived under livestock grazing pressures and severe storms. These severe storms blew a total of 4 meters of soil away creating a large eroded area north of the natural site as can be seen in figure 3. This degraded area is the severely degraded state of the same ecosystem. In this degraded area a control site was established representing the unrestored degraded site and, besides this, three sites were revegetated with ryegrass (Figure 2).

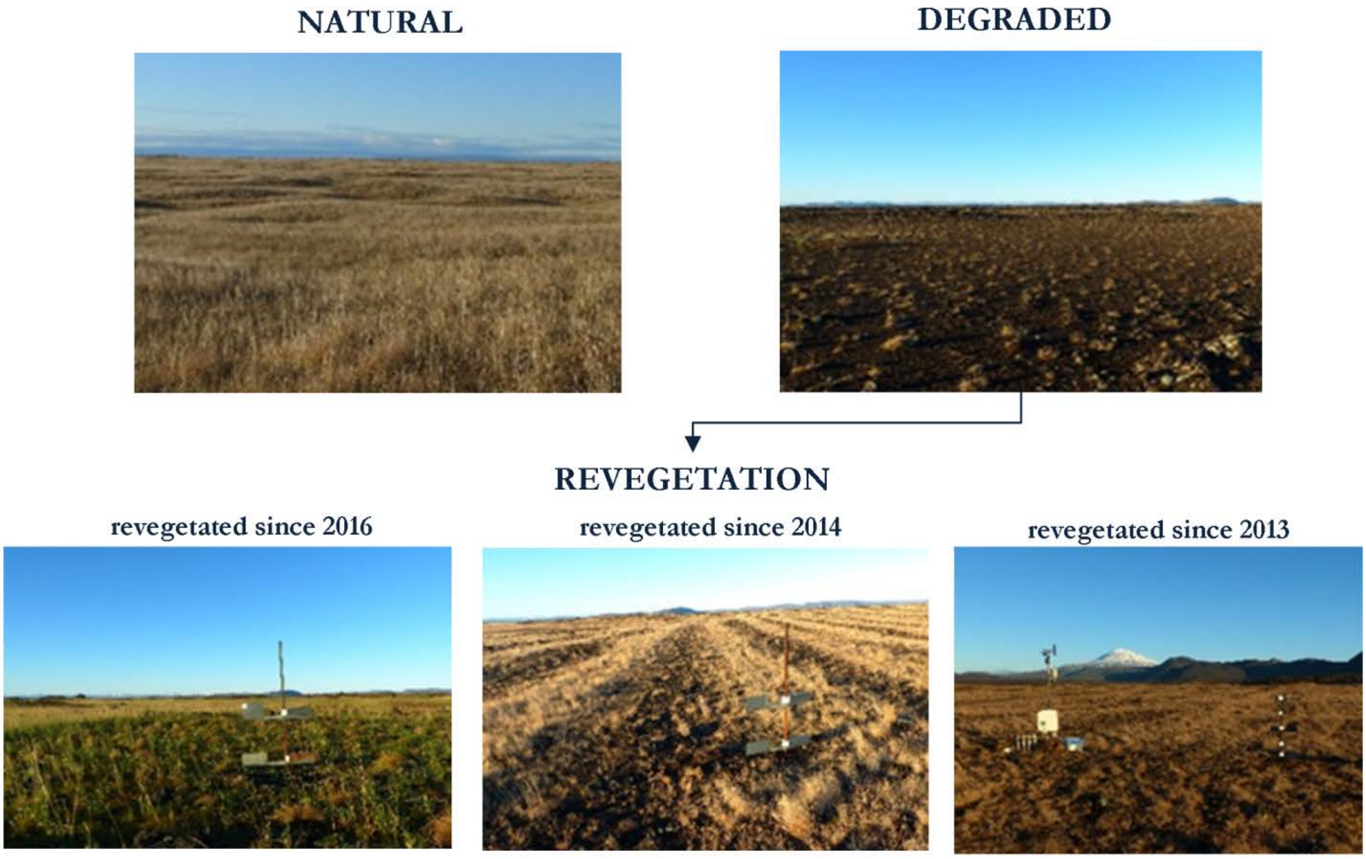


*Figure 2 The Kot research area consisting of a natural site, a unrestored degraded site and three revegetated sites on the degraded area restored since 2016 (age 3 months), restored since 2014 (age 2 years and 3 months), and a site restored since 2013 (age 3 years and 4 months).*

The control site is a sparsely vegetated, slightly hilly, area with grasses and herbs (1-5%), lichens (<<1%) and the occasional dwarf shrub (<1%). The three revegetated sites were restored by the planting of rye grass seeds (*Lolium sp.*) in combination with a onetime application of fertilizers. The sites were restored since May 2013 (RS13), June 2014 (RS14) and June 2016 (RS16), creating a timeframe for change. All the different areas are depicted in Figure 3 and Table 1.

*Table 1 Site specifications*

| | Natural | Degraded | | | |
|---|---|---|---|---|---|
| | | (unrestored) Control | RS13 | RS14 | RS16 |
| Established (year) | ± 920 A.D. | ± 1882 A.D. | May 2013 | June 2014 | June 2016 |
| Age (year, months) | ≥ 1096 y | ≥ 134 y | 3 y, 4 m | 2 y, 3 m | 3 m |
| Area size (ha) | >100 ha | 178.3 ha | 5.6 ha | 9.7 ha | 9.4 ha |
| Vegetation | 75-100% mosses<br>10-15 % shrubs | 1-5% grasses<br><1% dwarf shrubs | 10-15% grasses<br>1-5% mosses<br>1-5% lichens | 15-25% grasses<br>1-5% mosses<br><1% lichens | 1-5% grasses<br><1% lichens |
| Elevation (m.a.s) | 126 | 120 | 130 | 125 | 122 |
| Treatment | Natural state | Degraded state | *Lolium sp.* seeds combined with fertilizers | | |

## 2.2 WATER EROSION MEASUREMENTS

Water and wind erosion were measured from September-October 2016. Water erosion was measured using a rainfall simulator and was setup threefold within each site with a three time repetition around a perimeter of 10m. Water droplets were created at an height of 2 m which were evenly spread over an area of 0.17 $m^2$, simulating the rainfall. This area was enclosed with a steal frame leading the runoff and sediment towards a funnel within the steel frame, from where the runoff and erosion were collected with a bucket (Figure 4). The rainfall simulator was set up a total of 42 times with each marking in figure 3 representing a three time repetition. Due to the weather circumstances, a total of 6 runoff measurements were completed in the RS16 site in comparison to a total of 9 times in the sites of control, RS13, RS14 and natural with each locations in Figure 3 representing a three time repetition.

The rainfall simulator used is a nozzle type simulator designed according to Iserloh et al. (2012). The nozzle is a Lechler 490.604 and is hold by a steal frame 2 m above the plot which has a circular area of 0.16 $m^2$. A 12 V High Pressure pump (Reich Power Jet Plus, KTW C DVGW W270) is powered by a Exide battery (Exide Marine & Multifit Dual, ER550) and pumps water from a 60 L storage container to a flow control unit. The flow control unit reduces variations in pressure and is assembled with a valve and a manometer (Fimet, EN 837-1) leading the water through pipes to the nozzle. The conditions were set for an intensity of 38 mm/hr with a time span of 10 min creating runoff on the plot which is gathered by a metal ring and lead through a funnel where the runoff is collected. A total of 6.3 liters of rain is dropped on the area of 0.17 $m^2$. which has an intensity of 6.3 mm/$m^2$. All in all, the rainfall simulator is enclosed by a plastic cover designed to withhold wind and equalize the conditions between measurements. In the field the ring was placed on a gently to moderately sloping area (3-15%) for which the frame of the rainfall simulator was properly levelled. The soil had to be moderately dry for measurements so a drying time of 12 hours was preferred however conditions were variable so soil moisture content measurements were required. The runoff collected was transferred to the laboratory where sediment and water were separated by filtering paper with 25µm pores. The residue was then dried for 24 hr at 105 °C and weighted. The rainfall simulations were replicated 9 times in the sites of control, RS16, RS14, RS13 and the natural site.

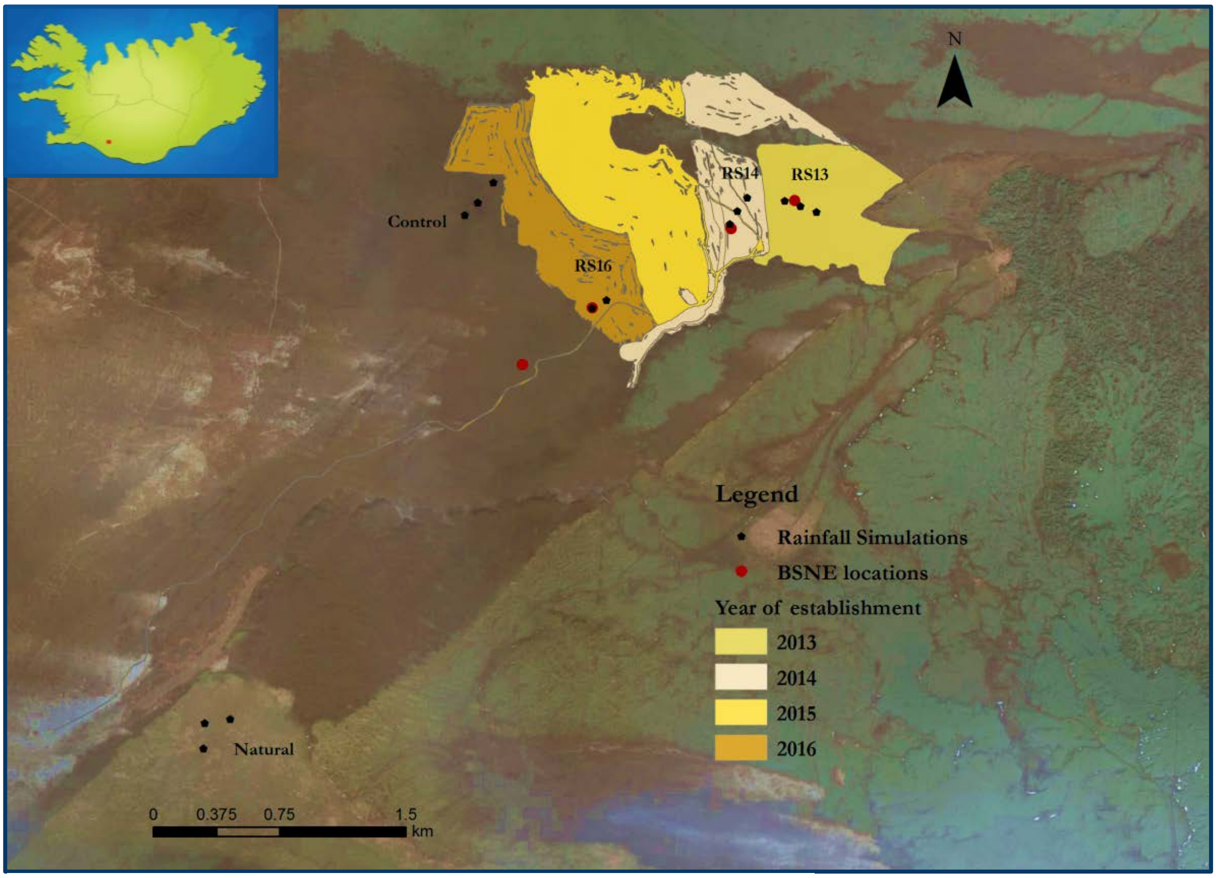

*Figure 3 Kot research area*

## 2.3 WIND EROSION MEASUREMENTS

The wind erosion was examined by measuring Aeolian transport using BSNE samplers (Figure 4). One sampler measured the total sediment transport for a specific storm at a specific site at a specific height. A research unit was set up in the area of RS13 measuring sediment transport at heights of 10, 30, 60 90 and 120 cm with BSNE samplers. In the research sites of RS14, RS16 and control, BSNE samplers were set up at heights of 10 and 60 cm according. According to the 'single dust trap method' as described by Thorarinsdottir & Arnalds (2012), fewer samplers could be used for creating height distribution models. This method is based upon research by Arnalds, Gisladottir, & Orradottir (2012) showing that the height distribution of Aeolian transport is similar at the same location in Iceland for all storms. The total sediment transport is then derived from the curve produced in the main research unit with all the heights and adjusted to the values of the particular plot. After a storm, the dust traps were emptied and the samples were dried for 24 hr at 105 °C weighted and sieved. The grainsize distribution was determined by sieving the collection of the five storms for each area and height through a sieving tower using Udden-Wentworth grain size classification scheme. This grain size classification scheme consist of the grain size classes : <40 µm, >40 µm, >63 µm, >125 µm, >250 µm, >250 µm, >500 µm, > 1mm and >2 mm. The Aeolian transport measurements were replicated a total of five times (five storms) in the sites of control, RS16, RS14 and RS13. The total soil loss was calculated by summating the average of the different heights together.

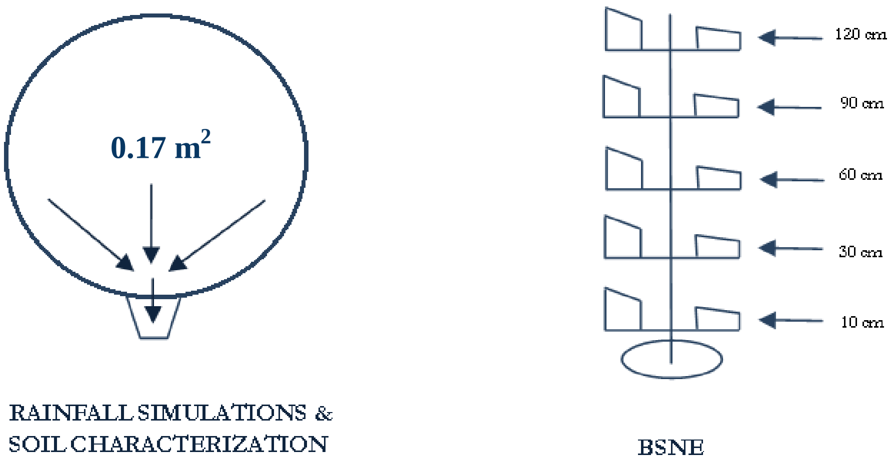


*Figure 4 Experimental set-up*

## 2.4 SOIL CHARACTERIZATION AND VEGETATION COVER

Before the each rainfall simulation, soil was sampled outside the steel frame and vegetation cover was determined for the area within the ring. The soil sampled was used for measurements of soil moisture, bulk density, organic matter, soil depth, soil stability, slope, texture and vegetation cover. Due to the weather circumstances, in the RS16 site a total of 6 times soil were sampled in comparison to a total of 9 times in the sites of control, RS13, RS14 and natural.

Samples were collected at each rainfall simulation using a metal frame (5:10:10 cm) retrieving 500 $cm^2$ of soil from 0-5 cm depth and 5-10 cm depth. For determining the **soil moisture** content three samples of 10g were analyzed for each plot using the oven drying method (105 °C for 24 hr). Using the soil moisture content, the **bulk density** was measured weighting the samples and extracting the residue after sieving the samples with a 2 mm mesh. **Soil organic matter** content was determined using the loss on ignition method (550 °C). **Soil depth**, **slope** and **texture** were analyzed on site. Soil depth was determined by using a steel pin drawn into the soil, slope was determined with a leveler and a ruler, and texture was determined by the 'Texture by feel analysis'. **Vegetation cover** was appointed according to scaling classes: <1%, 1-5%, 5-10% 10-15%, 15-25%, 25-50%, 50-75% and 75-100%. This was done for total vegetation, grasses/herbs, mosses, lichens, trees and dwarf shrubs**. Soil stability** was measured using the Soil Stability Test Kit (Synergy Resource Solutions).

The classification of soil stability determined with five classes: Class 1: 50 % of the structural integrity lost within 5 seconds of immersion in water, or soil too unstable to sample, Class 2: 50 % of the structural integrity lost within 5-30 seconds of immersion in water, Class 3: 50 % of the structural integrity lost within 30-300 seconds of immersion in water, or <10% remains on the sieve after five dipping cycles, Class 4: 10-25% of soil remains on the sieve after five dipping cycles, Class 5: 25-75% of soil remains on the sieve after five dipping cycles, and Class 6: 75-100% of soil remains on the sieve after five dipping cycles.

## 2.5 STATISTICAL ANALYSES

All the statistical analyses were carried out using SPSS Statistics 23. Normality was tested with Kolmogorov-Smirnov's test and homogeneity of variances with the test of Levene. Furthermore, linear regression was used for detecting trends in the runoff data and a principal component analysis (PCA) was used for analyzing the link between soil variables and their predicting abilities. The Mann-Whitney test was used for testing the null hypothesis between samples with a non-normal distribution, the t-test was used for testing this for samples with a normal distribution and homogeneity of variances. The Mann-Whitney test and the t-test were used for testing differences between sites in runoff, erosion, concentration and soil characteristics. The $chi^2$ test was used for testing the null hypothesis for categories (vegetation cover and soil stability). Furthermore curve estimation by SPSS was used for defining the trend within the runoff and erosion measurements, in which the $R^2$ was used as confirmation for the best fit.

## 3. RESULTS

### 3.1 SOIL CHARACTERISTICS

The soil characteristics determined in the field have been summarized in table 2. Differences found in these characteristics are primarily between the natural site and other sites. For instance in the organic matter 0-5 cm both the natural site and the RS14 site are significantly higher than the other site. For organic matter 5-10 cm and soil moisture 0-5 cm the natural site is significantly higher and for the bulk density 0-5 cm the natural site is significantly lower than the other sites.

*Table 2 Soil characteristics for n=9 rainfall simulations: if the data showed a normal distribution the mean ± standard deviation are shown, if the data didn't show a normal distribution the median is shown (with '(lower bound - upper bound)' of the confidence interval). Significance: a<b<c<d .*

| NAME | Control (n=9) | RS13 (n=9) | RS14 (n=9) | RS16 (n=6) | Natural (n=9) |
|---|---|---|---|---|---|
| Slope (°) | 0.08±0.33$^{bc}$ | 0.05±0.01$^{a}$ | 0.12±0.02$^{c}$ | 0.06±0.01$^{ab}$ | 0.09±0.04$^{bc}$ |
| Soil depth (cm) | 63.33±7.39$^{b}$ | 27.65±9.45$^{a}$ | 34.70±12.88$^{a}$ | >70$^{bc}$ | >70$^{c}$ |
| Soil moisture 0-5 cm | 6.86±1.16$^{a}$ | 13.65±1.71$^{b}$ | 7.3 (6.48-12.99)$^{ab}$ | 7.64±1.79$^{a}$ | 20.09±0.97$^{c}$ |
| Soil moisture 5-10 cm | 9.32±1.59$^{a}$ | 18.23±4.96$^{b}$ | 12.04±4.75$^{a}$ | 9.26±1.38$^{a}$ | 16.34±1.84$^{ab}$ |
| Organic matter 0-5 cm | 0.87±0.24$^{a}$ | 0.97±0.27$^{a}$ | 1.49 (0.83-1.18)$^{b}$ | 1.00±0.16$^{a}$ | 3.95±0.11$^{c}$ |
| Organic matter 5-10 cm | 1.11±0.23$^{a}$ | 1.77±0.95$^{a}$ | 1.72±0.56$^{a}$ | 1.34±0.37$^{a}$ | 2.61±0.38$^{b}$ |
| Bulk density 0-5 cm | 1.09±0.12$^{c}$ | 1.01±0.084$^{b}$ | 1.14 (1.05-1.30)$^{c}$ | 1.24±0.15$^{d}$ | 0.76±0.09$^{a}$ |
| Bulk density 5-10 cm | 0.99±0.09 | 0.95±0.12 | 0.94±0.16 | 0.98 (0.89-1.21) | 0.87±0.14 |
| Soil stability (1-6) | 2 (2-2) | 2 (1.28-2.05) | 2 (2-2) | 1 (1-1) | 3 (3-3) |

### 3.2 VEGETATION

The vegetation measured inside the steel ring during rainfall simulations is illustrated in Table 3. The amount of vegetation of each site is significantly different from each other, only RS13 and RS14 are not significantly different from each other and control and RS16 are also not. In the original specific vegetation families, trees was also included but not found at the sites. In the grasses/herbs and mosses the lower categories are dominated by the control and RS16 site.

*Table 3 Vegetation for n=9 rainfall simulations: if the data showed a normal distribution the mean ± standard deviation are shown, if the data didn't show a normal distribution the median is shown (with (lower bound-upper bound) of the confidence interval)*

| NAME | Control (n=9) | RS13 (n=9) | RS14 (n=9) | RS16 (n=6) | Natural (n=9) |
|---|---|---|---|---|---|
| Vegetated (%) | 5 (1.99-11.79) | 26.11±21.18 | 37.22±28.84 | 22.5±3.53 | 100 (100-100) |
| Grasses/Herbs (1-8) | 2 (1.43-2.35) | 4.5±1.41 | 5.11±1.45 | 4±1.41 | 4 (1.39-3.93) |
| Mosses (1-8) | 0 (0-0) | 1.44±0.88 | 2.44±1.88 | 1.5±0.71 | 8 (8-8) |
| Lichens (1-8) | 0 (0-0) | 1 (0.44-1.11) | 0 (0-0) | 0 (0.41-1.26) | 0 (0-0) |
| Dwarf shrubs (1-8) | 0 (0-0) | 0 (-0.21-0.88) | 1 (0.27-1.29) | 1.33±1.21 | 0 (0-0) |

## 3.3 WATER EROSION

Runoff was measured in liters of water collected running of the plot whereas the erosion was the sediment transported by this runoff. The natural site significantly differentiates from the other sites for runoff and erosion. Within runoff, RS16 also significantly differentiate from RS13 (Sig.=0.050). Soil saturation occurred significantly earlier during the rainfall simulations in control and RS16 than in RS13 and RS14. The soil saturation did not occur in natural because the layers of mosses were too thick to observe this. The concentration of control significantly differentiates form RS14 and natural.

*Table 4 Vegetation for n=9 rainfall simulations: if the data showed a normal distribution the mean ± standard deviation are shown, if the data didn't show a normal distribution the median is shown (with (lower bound-upper bound) of the confidence interval). Significance: a<b<c<d.*

| NAME | Control (n=9) | RS13 (n=9) | RS14 (n=9) | RS16 (n=9) | Natural (n=9) |
|---|---|---|---|---|---|
| Runoff ($L/m^2/hr$) | $16.29 \pm 10.86^{b}$ | $9.88 \pm 9.81^{bc}$ | $7.98\ (1.41\text{-}20.37)^{b}$ | $19.57 \pm 10.99^{bd}$ | $0.18\ (-0.36\text{-}1.76)^{a}$ |
| Average runoff reduction (with control as the starting point) | 0 | -39% | -33% | +20% | -96% |
| Erosion ($g/m^2/hr$) | $24.04\ (-2.9\text{-}191.21)^{b}$ | $9.84(2.93\text{-}35.92)^{ab}$ | $15.15 \pm 11.59^{b}$ | $46.56 \pm 42.78^{b}$ | $0\ (-0.6\text{-}0.15)^{a}$ |
| Average erosion reduction (with control as the starting point) | 0 | -79% | -83% | -50% | -100% |
| Concentration (g/L) | $4.62\ (-0.38\text{-}12.84)^{ab}$ | $3.48 \pm 2.35^{a}$ | $0.96\ (-10.49\text{-}44.44)^{ab}$ | $1.74\ (0.74\text{-}3.13)^{a}$ | $0.18 \pm 0.37^{ab}$ |
| Time until soil saturation (s) | $20\ (15.09\text{-}29.91)^{b}$ | $39.375 \pm 10.84^{c}$ | $30\ (26.68\text{-}39.99)^{c}$ | $10\ (10\text{-}10)^{a}$ | NA |
| Time since last rainfall (hrs) | $9.5 \pm 4.48^{b}$ | $23.61 \pm 13.03^{c}$ | $11.33 \pm 3.91^{bc}$ | $4.5 \pm 1.18^{a}$ | $83.5\ (32.17\text{-}100.60)^{c}$ |

The total runoff data was derived from the rainfall simulations. In order to see whether revegetation affects runoff, the average runoff for every site was plotted in a graph in Figure 5. A downward trend can be seen following the data points of Control, RS16, RS14 and RS13. For these points the timespan over which these changes happened is known and therefore a trend can be set over time. However this is not the case for the natural site. Yet, assuming the threshold theory for degrading ecosystems, both the control site and the natural site can be identified as a different example of a stable state in the same ecosystem (Groffman et al., 2006). Presumably the grazing of sheep caused a disturbance in the stable state and shaped the area to fluctuate from the natural state to the degraded state (runoff, y=16). A second disturbance is the initiation of the reclamation projects in which the main aim was to reduce erosion rates back to its original natural state (runoff, y=0.7). The shift from the control state to the natural state is depicted in Figure 5 as an exponential change over time ($R^2$=0.111). So if these states are introduced to the graph, the date shows the time needed for returning to its original state at the cross section of the trend line and the natural state which is 204 months or 17 years. However due to the fact that this is an exponential trend line, the natural state is approached for quite some time.

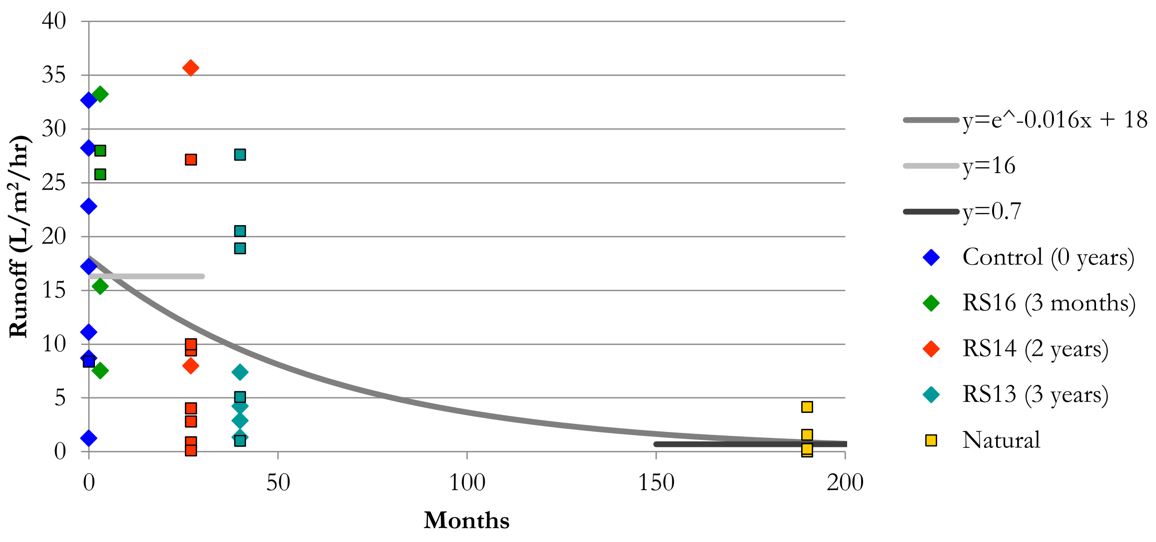


*Figure 5 Runoff of the difference between sites related to time with a trend line included: y = e^-0.016x +186 ($R^2$=0.111). The squares represent the sites with vegetation cover >20%.*

Simultaneous to the runoff, the erosion was measured as total sediment detached during the rainfall simulations. The results shown in figure 6 illustrate a downward trend similar to the runoff. The exponential trend was computed including the data points of Control, RS16, RS14 and RS13 as the timespan between these data points was known ($R^2$=0.097). The same theory on thresholds in degrading ecosystems was used as in the generating the runoff results, although a shift from the degraded state to the natural state seems vastly different as the two states are not connected by the trend. The intersection of the decreasing trend of erosion with the natural state is at 192 months or 16 years. However just as in the previous graph on runoff, the exponential trend approaches the natural state already years prior. Although in both figure 5 and 6 the results from the degraded area significantly differentiates from the natural area, differences within the revegetated sites are still apparent in the runoff results. In the erosion results no significant difference has been found within the degraded sites or within the revegetated sites.

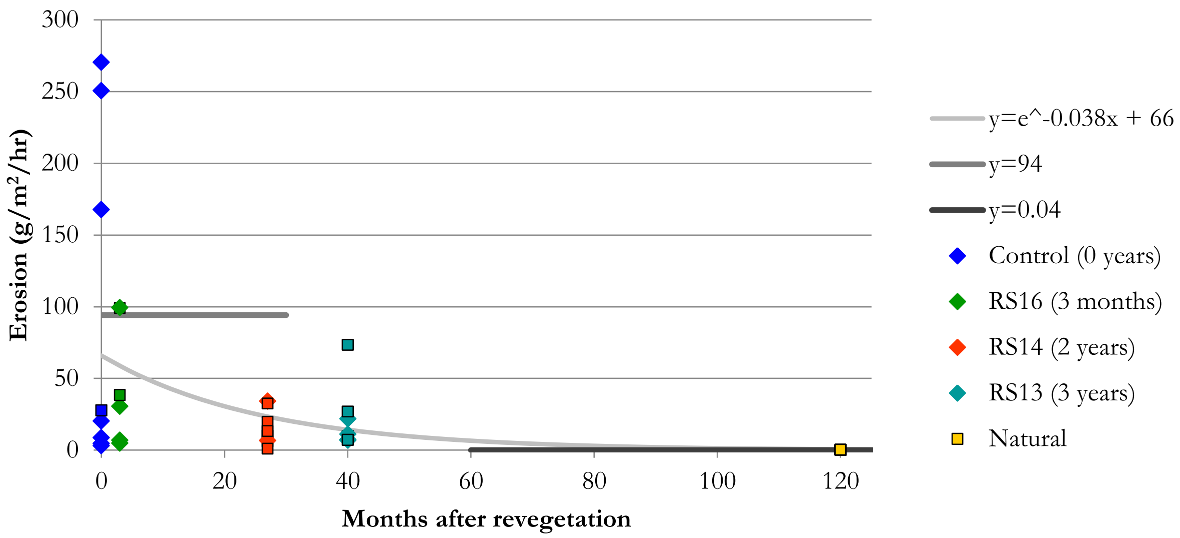


*Figure 6 Erosion of the different sites related to time with a trend line included: y = e^-0.038x + 66 ($R^2$=0.097). The squares represent the sites with vegetation cover >20%.*

## 3.4 WIND EROSION

The results for wind erosion were derived from the Aeolian transport experiments and were averaged for five different storms and computed according to the single dust trap method (Arnalds, Gisladottir & Orradottir., 2012). This theory proclaims that the height distribution of wind erosion is similar at the same location. Therefore the samplers measured erosion at all heights in RS13 and at the heights of 10 and 60 cm at Control, RS16 and RS14. Ideally, if the height distribution is similar, the values of the different sites should be in approximately the same order at both the 10 cm and 60 cm height. However this is not the case, RS13 has the highest value for 10 cm and the lowest value for 60 cm. The computation of the lines of Control, RS16 and RS14 was therefore adapted to have a similar vertical variation and range (Figure 7). The different sites do not differentiate significantly with each other in total soil loss however the different heights do. Both the 10 cm height and the 120 differentiate from the other heights.

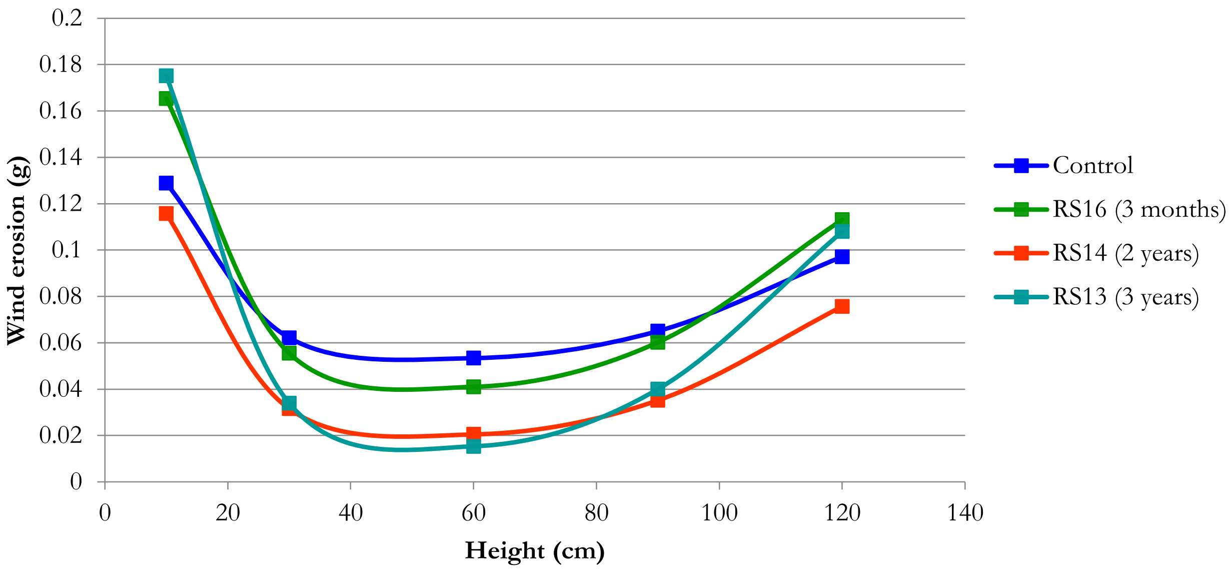


*Figure 7 Wind erosion*

*Table 5 Summation of the erosion found at different height for every sites for the average storm.*

| Site | Total Soil loss per site for the average storm (g) |
|---|---|
| Control | 0.41±0.19 |
| RS16 | 0.44±0.30 |
| RS14 | 0.28±0.19 |
| RS13 | 0.36±0.20 |

All of the collected erosion was afterwards sieved to generate a grainsize distribution of the different sites as illustrated in Figure 8. The particle in suspension are considered to be <63 µm, the particles in saltation are 100-500 µm and the particle of >1 mm are in surface creep. The particles in saltation are significantly higher at 10 cm than at 60 cm. The total erosion measured is significantly higher at the control site at the height of 60 cm.

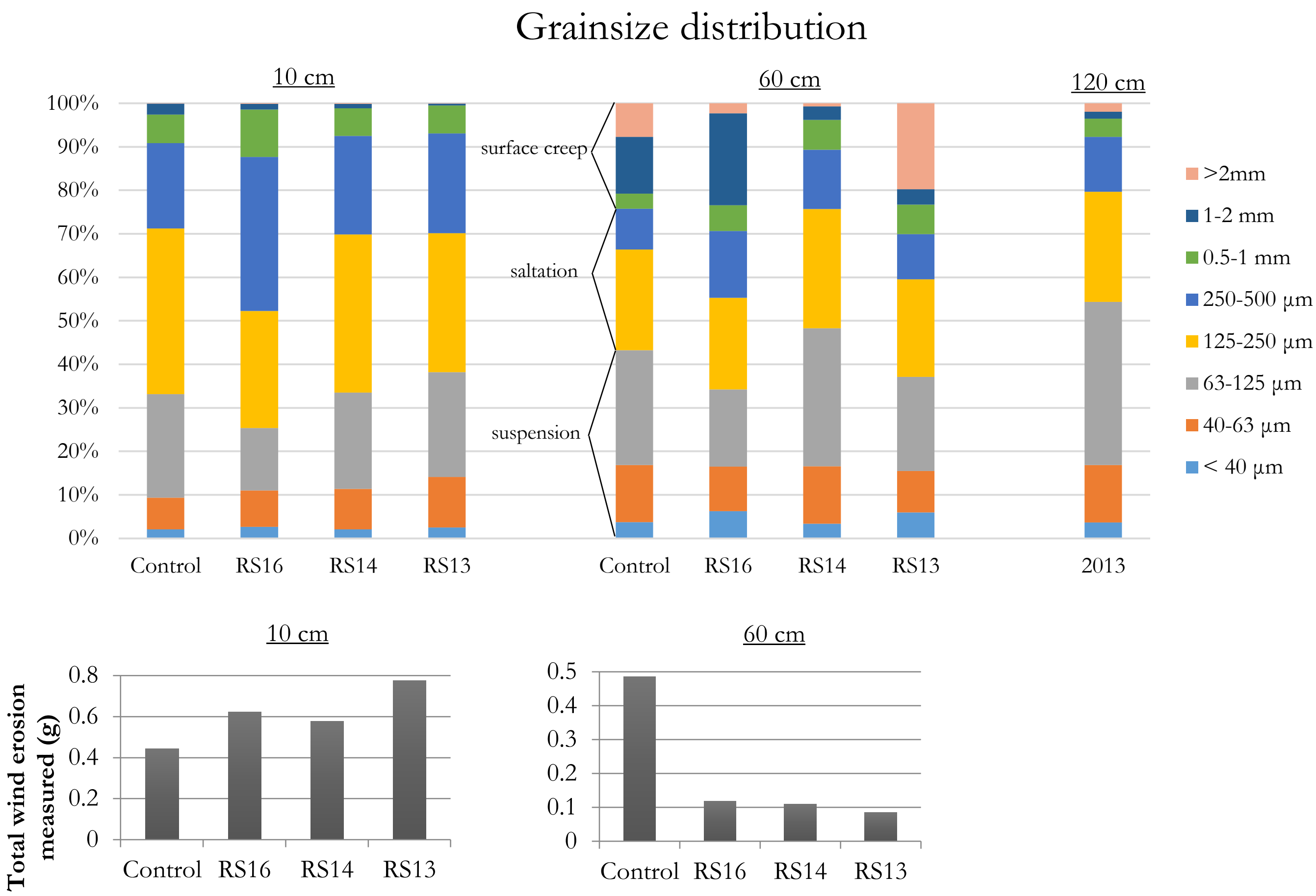


*Figure 8 Grain size distribution and total erosion*

## 3.5 THE INFLUENCE OF SOIL CHARACTERISTICS ON EROSION PROCESSES

In order to see in what way soil characteristics influenced the trends illustrated in the runoff and erosion, a principal component analysis is shown in Figure 5. With this statistical tool, the different soil variables can be related to each other and certain groups are derived from this data. The first group is runoff and erosion. The second group is organic matter soil moisture and vegetation cover.

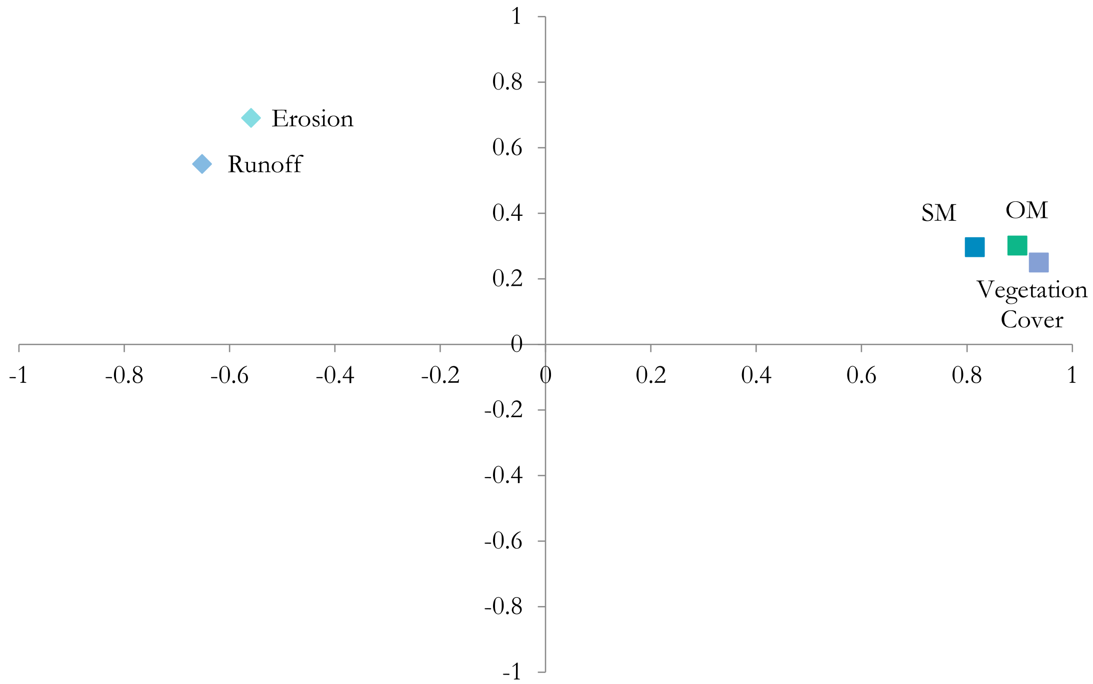


*Figure 9 PCA of the water erosion experiments and soil property collection*

Both the y-axis and x-axis represent a factor that is predicted by the components of the two groups. So this would mean that the soil characteristics do not influence runoff and erosion directly. However this is the case for the results in the water erosion experiments. In figure 10, two PCAs illustrate the predictability of factors including some components derived by the wind erosion experiments, water erosion experiments and the soil characteristics. The wind erosion experiments had a limited amount of measurements, for this reason two different PCAs needed to be computed. The left hand graph illustrates the correlation between the wind erosion measured at 10 and 60 cm height and the runoff and erosion measured (derived from the water erosion experiments). This graph shows the high correlation between the runoff, erosion and wind erosion at 60 cm height. The graph at the right hand side illlustrates the correlation between soil characteristice and wind erosion. Although the soil characteristics do no exactly have the same predictability, they are related. As vegetation cover has the same predictability as the wind erosion at 10 cm height for the factor on the y-axis, the predictabilty of the facotr on the x-axis is the same however the vegetation cover is only negatively correlated with wind at 10 cm height. The is the same case for wind erosion at the 60 cm height and the buldensity measured at the 0-5 cm soil layer, with the factor on the y-axis being negatively corellated.

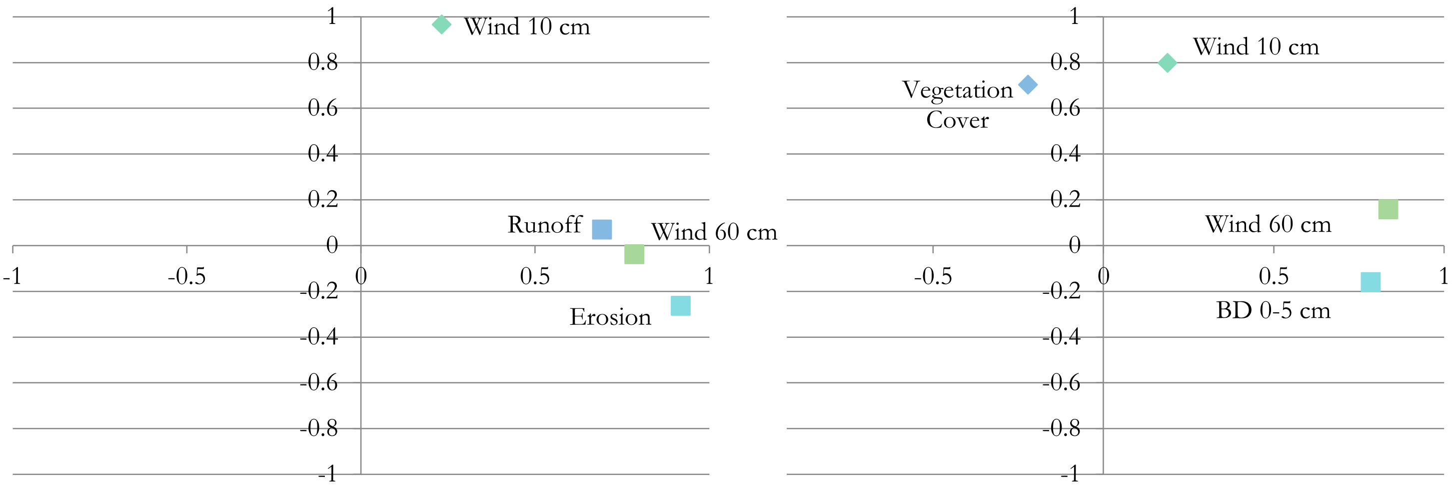


*Figure 10 PCA of wind erosion, these PCAs include 4 different variables as the numbers of measurement is limited.*

PCA also showed the values for the different sites in predictability (Figure 11). This shows that there is a vast difference in predictability between the natural site and the degraded sites. It shows that the values of the different soil characteristics in the natural site have a more distinctive and outspoken predictability than the soil characteristics in the degraded sites and between the degraded sites.

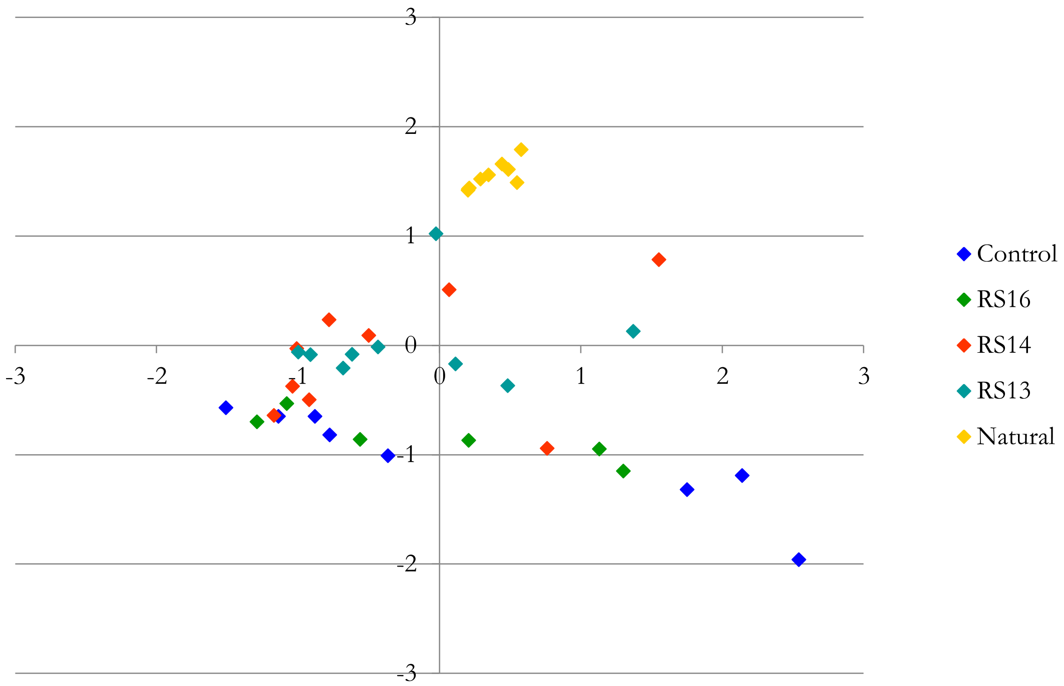


*Figure 11 PCA of the predictability of the variables of organic matter, soil moisture, vegetation cover, runoff and erosion by site*

# 4. DISCUSSION

## 4.1 THE EFFECT OF REVEGETATION ON EROSION

The main aim for this research was to examine what the effect of revegetating degraded land with ryegrass was on erosion by both rainfall and wind. Overall, the results for water erosion show that the revegetation projects have indeed a positive effect on the rates as the amount of runoff and erosion decline over the years. The trend resulted into a output of 17 years needed to reduce the runoff to its the rates of the original natural state and 16 years to reduce the erosion. Moreover, the results for the effect of revegetation on wind erosion as computed according to the dust trap method show that revegetation is decreasing the erosion rates with approximately 0.03 g annually, which would mean that it would take 187 years to reduce the wind erosion to 0. The main theory for this contrast between wind and water erosion could be that wind erosion is less spatially restricted (Ravi et al., 2010). Wind erosion can travel over great distances in suspension which would mean that a distant dust source could limit the rate of decline while the revegetation still has an influence on the decreasing trend. However it must be considered that the wind erosion experiments had a limited amount of measurements. Preferably, more BSNE entrapments were placed in the different sites including the natural site. In addition, the dust trap method was included because of the lack of instruments and this theory encapsulates that the height distribution of Aeolian transport is similar at the same location in Iceland for all storms. However, at the 10 cm height RS13, on which the other distributions were to be based, had the highest value, all the while at the 60 cm height RS13 had the lowest values. The height distribution was therefore adapted to show less variation within the other sites.

Even though the reliability of the results for wind erosion can be questioned, the recovery time of 187 years does correlate better with the natural recovery in dry arctic regions, which is considered to be in the order of 100-1000 years (Forbes & Jefferies, 1999). However this is significantly higher than the projected years for recovery of the water erosion rates. If the process of revegetation is used for establishing plant canopy rather than recreating the natural state, the recovery is a faster process but is still significantly slower than revegetation of disturbed wetlands (10-30 years) (Forbes & Jefferies, 1999). Gretarsdottir et al. (2004) concluded that long-term effects (20-45 years) of revegetation with perennial species (*Fetuca rubra* and *Phleum pretense)* in Iceland resulted in  a persistent plant cover and was promoting plant colonization. In addition, McKendrick (1997) remarked that more than 20 years is needed before the long-term effects may be detectable. Only after 20 years the persistence of the seeded species is become apparent due to the fact that the original fertilizer has dissipated and the litter has decomposed. It therefore seems that the recovery time of the runoff and erosion rates is on the short side compared to other studies that looked into restoring ability by studying the plant cover. This could also imply that the runoff and erosion rates are restored faster than vegetation cover.

Both erosion processes show that the revegetation induces a declining trend but in order to draw solid conclusions on the effect of revegetation on erosion processes, the differences need to be significant between sites. No significant differences were found in the wind erosion experiments regarding the total erosion. Significant differences did occur between the sites in the degraded state and the natural state for both the runoff and the erosion. This indicates that the revegetated sites still significantly differentiate from the natural site and are therefore not approaching the natural environment. So to measure if the revegetation had any effect on water erosion, the different sites in the degraded area should show significant change. This is the case for the runoff where a significant difference was found between the degraded sites in which the rates in RS16 were significantly higher than the RS13 site. Therefore there can be concluded that when the runoff is considered, revegetation indeed has an effect as it reduces the rates significantly. Such is not the case for erosion as no significant differences were found in the degraded sites within a time span of 3 years. Further research could re-examine the erosion processes with an increased the timespan between the revegetated sites and the control site, as the decreasing trend would indicate that the differences between the control site and the revegetated sites would increase significantly.

## 4.2 THE ROLE OF VEGETATION COVER

In order to see in what way the revegetation affected the erosion processes, the soil characteristics were measured. One of the most apparent soil characteristics which is influenced by revegetation is vegetation cover. According to Zuazo & Pleguezuelo (2009), the vegetation cover protects the soil against raindrop impact and by intercepting runoff in the short term. In the long term the vegetation cover increases soil aggregate stability, soil cohesion and water infiltration (Zuazo & Pleguezuelo, 2009). Previous research (Gyssels et al., 2005; Packer, 1951; Zuazo & Pleguezuelo, 2009) has depicted the relation between vegetation cover and runoff as an negative exponential, similar to Figure 5 and 6. The results of figure 5 and 6 are comparable as the vegetation cover does increase from 6% in control to 100% in natural over time (RS16:11%, RS14 37%, RS13: 26%). Zuazo & Pleguezuelo (2009) reviewed data on the relation between vegetation cover and runoff and erosion, and concluded that most data follows for erosion the formula: $E = e^{-bC}$ , and for runoff : $R = e^{-bC}$ in which the range of b in erosion is between 0.0235 and 0.0816 and the range for b in runoff is 0.0103 and 0.0843 (Gyssels et al., 2005). When the runoff and erosion is plotted over the corresponding vegetation cover as derived by the water erosion experiments, the resulting b values are for erosion 0.085 and for runoff 0.036. Both the erosion and runoff measurements relate to the values (0.0816) found by Francis & Thornes (1990) where the measurements were done on a Mediterranean matorral in Murcia, Spain with an intensity of 25.8 mm/hr. This all could be explained by the vegetation that is similar as both the areas dominated by grasses and herbs. However the results of figure 9 show that the vegetation cover and all the other soil characteristics do not relate to the runoff and erosion, suggesting a dissimilarity with previous research on this topic. Although the PCA seems very definitive, the wind erosion results are more explanatory about these results as the PCA on wind erosion show that the wind erosion at the 60 cm height is related to the runoff and erosion measured at the water erosion experiments and the vegetation cover is related to the wind erosion at the 10 cm height.

The wind erosion was measured a total of 20 times incorporating one BSNE structure being placed in the sites of control, RS13, RS14 and RS16 for five different storms. This amounted in the values creating a parabolic shape in the height distribution on every site (Figure 7). The increase from ≥60 cm is unexpected for a sandy soil as the primary wind erosion process on this soil is saltation which occurs in less quantities with an higher elevation (grains size 63-500 µm). The increase would indicate that the process of suspension (grain size <63 µm) becomes more eminent as particles in suspension travel greater distances and substantial heights. An available dust source for suspension in the region is the volcano Hekla which last erupted in 2000 (Crofts, 2011). Thorarinsdottir & Arnalds (2012) studied the wind erosion of volcanic materials in the Hekla area and found that the coarse pumice within 12 km from Hekla is less susceptible to wind than at 12-15 km from Hekla as grain size becomes larger closer to Hekla (averages of >3mm vs. 0.8-1.6 mm). So if Thorarinsdottir & Arnalds (2012) are considered, the increase in wind erosion at ≥60 cm is not likely to be due to suspension of small particles as the study site is at 10 km from Hekla. The measured grain size distribution illustrates the differences as the particles in saltation is significantly higher at 10 cm than at 60 cm (Sig: 0.001) and has a higher mean at 10 cm than at 120 cm. The particles in suspension are higher at 120cm than at both 10 and 60 cm. This indicates that indeed the process of saltation is more dominant in 10 cm height and the process of suspension is more dominant at the 120 cm height. Suspension therefore causes the increase in sediment transport at ≥60cm. This division of the dominant processes of wind erosion at the different height is explanatory for the lack of relation between the runoff and erosion as measured at the water erosion experiments and the vegetation cover.

According to the PCAs in figure 10, the vegetation cover is negatively correlated to the wind erosion at the 10 cm height. As previously concluded, in the wind erosion at this height, the process of saltation is dominant with grain sizes 63-500 µm. On the other hand, the wind erosion at the 60 cm height is related to the runoff and erosion measured at the water erosion experiments. This wind erosion process is less influenced by saltation and more by suspension with grains sizes of <63 µm. All in all, the reason that runoff and erosion as measured in the water erosion experiments are not related to vegetation cover can be because, just like the wind erosion at the 60 cm height, the runoff and erosion are related to the amount of smaller particles deposited by suspension. Vegetation cover does correlate with the wind erosion at the 10 cm height which consists mainly of the larger particles deposited by saltation. This would mean that the vegetation cover as established in these experiments influences the erosion of larger particles. One reason for this can be that the revegetation project at its maximum is three years old. So the short term effects of revegetation like diminishing splash erosion and intercepting runoff are achieved as the larger particles are not eroding. Yet the long term effects are still not achieved, these increase soil aggregate stability, soil cohesion and water infiltration, causing the smaller particles to be eroded more easily.

Overall, the revegetation of rye grasses influenced erosion processes and induced a decline in the erosion rates. However the erosion rates of the revegetated areas are not nearly close enough to be associated with the natural ecosystem. The bulk of the data derived showed a clear significant difference between the natural site and the sites on the degraded land. This difference is also illustrated in Figure 11 where the predictability of the different soil variables of organic matter, soil moisture and vegetation cover illustrate that the natural site has a more outspoken and distinctive predictability than the other sites. One of the major differences between the degraded lands and the natural site is the vegetation cover and specifically, the vegetation types. As ryegrasses were used to revegetate the degraded lands, grasses and herbs were the dominant species in these areas. Whereas the dominant species at the natural site is mosses, and this species covers over 100% of the soil with a thick 30 cm layer. The choice for a grass type species for revegetation in this area can therefore be questioned as mosses dominate the natural ecosystem. The choice for rye grasses can also have influenced the correlation of vegetation cover and erosion rates. The results of water erosion conclude that it will take another 2 decades to diminish the erosion rates entirely however if the mosses are used for revegetation, there is a likelihood that erosion rates will decrease with higher rates. A way to measure this possibility is to measure the pH and HCl levels as mosses tend to grow on more acidic soils.

## 5. CONCLUSION

- Both the water and wind erosion had a descending trend over time. Water erosion consisting of both runoff and erosion (transported sediment) resulted in 17 and 16 years of time needed to reduce the runoff and erosion rates from the degraded state of the ecosystem to the natural state of the ecosystem. The wind erosion experiments also resulted in a descending trend over time however the recovery time was substantially larger with 187 years. Explanations found for these numbers are the involvement of the suspension in wind erosion. No significant differences were found between the sites to conclude a significant change due to revegetation. Only the runoff resulted in a significant change between RS16 and RS13, identifying a decrease in runoff rates and therefore a direct effect of revegetation.

- In order to see in what way the revegetation affected the erosion processes, one of the most apparent soil characteristics namely the vegetation cover was examined. PCAs showed that the runoff and erosion, as measured in the water erosion experiments, did not relate to the vegetation cover but to the wind erosion at the height of 60 cm. The vegetation cover did relate to the wind erosion measured at the 10 cm height. As the wind erosion at the 10 cm height was associated with the wind erosion process of saltation, it was concluded that erosion of larger particles negatively correlated with vegetation cover. As the wind erosion at the 60 cm height was associated with the wind erosion process of suspension and smaller particles, therefore the runoff and (water) erosion were associated with the erosion of smaller particles.

- Revegetation diminishes the erosion rates but the rates are still too high to be associated with the natural ecosystem. It will take another 2 decades to diminish water erosion rates. This means that the water erosion research should be broadened with increasing the timeframe between the control site and the revegetated sites. This could create significant differences between sites and generate more definitive results. However there can also be concluded that the revegetation of ryegrass is not very successful as the dominant species in the natural ecosystem are mosses. In these sites the erosion rates were diminished to approximately 0, therefore revegetation with mosses can be a faster alternative. The sites could be tested for pH and HCl levels as mosses prefer an acidic soil.

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