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Soil evolution analysis on a geomorphically active glacial forefield using a high resolution DEM

MASTER THESIS

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DATE
February 5, 2015

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Assessing the influence of micro-relief and erosion processes on soil evolution in a glacial forefield, a case study on the Gepatsch Glacier, Kaunertal, Central Alps Austria.

MSc Thesis

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Master's thesis submitted as partial fulfilment of the Master of Science: Earth and Environment, specialisation Soil Geography and Landscape

Wageningen, February 2015

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Abstract

Climate change has caused the geomorphology of high mountain landscapes to change rapidly over the last 150 years. The evolving high mountain landscapes create great opportunities to increase our understanding of geomorphological processes. Additionally, research in these areas will help to gain insight in the development of these dynamic environments under future climate change. Glacier forefields are one of the most interesting areas in these environments due to the rapid recession of glaciers. The relation between time and soil development has been studied on these forefields before, and the possible influence of other soil forming factors as topography and erosion processes was suggested. This research aims at quantifying the effects of micro-topography and geomorphological disturbances on soil evolution besides time. In total 97 soils were sampled in the forefield of the Gepatsch glacier in the Central European Alps. In the field pH of the soil was measured as well as significant rooting depth. Total soil organic matter contents were measured in the lab using LOI and silt and clay fractions were obtained by dry sieving. These were used as dependent variables for soil evolution. Explanatory variables for micro topography; slope, profile curvature, and aspect, were obtained through DEM analysis. Explanatory variables for geomorphological disturbance were obtained partially from DEM analysis; LS Factor and Stream Power Index, and partially obtained from a DEM of Difference for the period 1953-2012. Relations were found for micro-relief and geomorphic disturbance with organic matter content, pH and silt and clay fraction. Micro-relief variables were found to be important for silt and clay fractions [besides time] and geomorphic disturbance was found to be important for the organic matter content and the pH of the soils. Total explained variation percentages for all dependent variables were low, around 20%, and thought to be caused by the complexity of the Gepatsch glacial forefield. This research can serve as a basis to further investigate the influence of different erosion processes as well as micro-topography on different scales.

1 Introduction

The dynamic and complex high mountain landscapes are areas most sensitive to climate change (Theurillat et al., 1998). Moreover, the warming due to climate change is of greater amplitude in the Alps than the general trend (Jenny, 1980). Glacial and proglacial environments in high mountain landscapes respond strongly to these climate changes as glaciers and permafrost rapidly recede, especially in the European Alps (Preusser et al., 2007).
Recent glacier retreat in the Alps started at the end of the Little Ice Age (LIA), around 1850. Since then Alpine glaciers have steadily receded in general, as response to climate warming (Kääb et al., 2007). Some glaciers have experienced short periods of re-advancement though, for example the Tschierva-glacier (SGMN, 2014). Chiarle and Mortara (2008) present a review of changing geomorphological processes in these areas since the beginning of the 21th century as a result of climate warming. The rapidly evolving high mountain landscapes provide great opportunities to improve our understanding of these geomorphological processes.
Additionally, research in these areas will help to gain insight in the development of these dynamic environments under future climate change. This way potential risks as described by Keiler et al. (2010) and possible future land use opportunities can be recognized.

Some of the most interesting areas for research are areas of land that previously have been covered by glaciers, but where soils now start to develop. These are called the glacier forefields or proglacial areas and are located between the LIA end moraines and the glacier snout. In this research these areas are referred to as glacier forefields.

1.1 Background

The receding glaciers left glacial till and moraines on their forefields. Over time, a soil profile develops from the glacial till and moraine. When glacier retreat rates are known a soil chronosequence can be established. A soil chronosequence is a sequence of soils of different age that have evolved under equal conditions of parent material, organisms, topography and climate; they can be extremely valuable to investigate rates and directions of soil development (Huggett, 1998).
In such approaches the assumption is made that time is the sole varying factor for soil development from the five soil forming factors described by Jenny (1980).

Soil chronosequences on glaciers forefields have been studied for various glaciers. Important work in this field has been done on the Morteratsch and Damma glacier forefields. Correlations for pH, soil depth and organic matter content with time since glacier retreat have been found for the Morteratsch glacier (Egli et al., 2006b; Mavris et al., 2010; Temme and Lange, 2014) and the Damma glacier (Dümig et al., 2011). Additionally Mavris et al. (2010) found higher smectite content on older soils for the Morteratsch glacier. These researches all selected more or less stable sample locations in the glacier forefield in order to limit the influence of soil forming factors other than time. Although clear general trends were found a highly patterned character of soil distribution (Egli et al., 2011; Egli et al., 2006b; Haugland, 2004) or high variability of soil development on small scales (Dümig et al., 2011) was reported.

Multiple soil development states on moraines of equal age were found before. Variation for soils of the same age and changes in variability over time were investigated by Sondheim and Standish (1983). More recent research on the variation between soils of the same age in comparison to the variation of soils of different ages has been carried out by Temme et al. (2014). Variation within soils of the same age is sometimes substantial enough to make the variation due to soil age indistinguishable from the within-age-group variation according to their research – even where the chronosequence assumption was deemed to be valid. It is stated that for stable locations there is divergence in soil characteristics over time, opposed to locations where soil formation is disturbed by external influences where there is convergence in soil characteristics. This suggests that on "stable" locations of the same age there are still subtle differences in the other soil forming factors that influence soil development. Vegetation differences and small scale transport of water and soil material are suggested as causes. Small scale transport of water and soil material differences points towards the possible importance of small scale topographic differences (Phillips, 2014).

At the same time, the idea that some of the other soil forming factors might still play a role in chronosequences at small scales is widely held. Egli et al. (2006b) suggest the influence of differences in micro-topography, micro-climate and inhomogeneous deposition of parent material on soil development as well. Moreover the effect of microclimate on soil is also illustrated by them for a research area in the Altai mountains (Egli et al., 2014) The influence of glacio-fluvial erosion processes and soil moisture is suggested by Dümig et al. (2011); soils formed under wet conditions show a thicker organic surface layer and Ah horizon compared to soil of the same age under drier conditions. The research of Haugland (2004) shows that periglacial processes can result in spatially patterned structures as well.
Geomorphological disturbance is another possible cause for variability between soils of equal age that is often stated (Egli et al., 2006a). Geomorphological processes can cause removal (erosion) and deposition of soil material. The importance of erosion for soil evolution was suggested before for the Colorado Front Range (Dethier et al., 2012). Some of the geomorphological processes that can influence soil development in glacier forefields are: landslides (Korup et al., 2010), debris flows (Chiarle et al., 2007; Curry et al., 2006) and snow avalanches (Ceaglio et al., 2012; Freppaz et al., 2010).

Another field of research closely related to soil chronosequences on glacial forefields is vegetation succession research. Similar factors are found to influence vegetation succession as well as soil development on glacial forefields.
D'Amico et al. (2014) suggest an influence of specific plant community succession on pedogenetic processes. Vegetation, however, cannot be regarded as an independent variable to soil formation according to Egli et al. (2006b) as grain size of the parent material, soil moisture content, and organic matter content are all important factors for vegetation establishment (Burga, 1999). Factors influencing soil development are therefore likely to have an indirect influence on vegetation succession as well.
These interactions between vegetation and soil development can be regarded as a complex system with multiple feedbacks (Murray et al., 2014). Recent research on the complexity of soil chronosequences has looked into the robustness of chronosequences; the degree to which the path of soil development is sensitive to disturbance or change (Phillips, 2014). For vegetation succession research topography on the small scale is also regarded as an influence on plant colonization (Burga et al., 2010; Jumpponen et al., 1999; Nilsen et al., 1999). The research of Moreau et al. (2008) shows that historic runoff patterns are of major influence to plant colonization and possibly to soil development as well.

In soil chronosequence research on three different glacier forefields, Temme and Lange (2014) included the topographic variables: landform, slope, curvature and aspect besides time as factors that might influence soil characteristics. Time since glacial retreat alone explained rarely more than 50% of variation in soil characteristics. Time and topographic variables combined on the other hand explained slightly more but still the overall explained variability remains quite low. Topographic variables seem to be important for soil development besides time, but still only 50% of variability in soil characteristics remains unexplained. A possible explanation for this rather low percentage could be the relatively large resolution ASCII grid that was used to calculate the topographic variables Temme and Lange (2014). Differences in depositional history and the influence of fluvial processes as well as hill slope processes were argued to be of influence.

1.2 Problem description

Time since glacier retreat is generally regarded as the main factor controlling soil development in glacier forefields, yet even so high variability on small scales remains (Temme et al., 2014).
The influence of topographic variables on soil characteristics has been demonstrated (Temme and Lange, 2014) and the influence of vegetation, historic runoff patterns, geomorphic disturbance and soil moisture has been suggested (D'Amico et al., 2014; Dümig et al., 2011; Egli et al., 2006b). Nonetheless, research

rarely goes beyond the suggestion of these influencing factors. Temme and Lange (2014) have made a start in mapping the influence of topographic variables, but found that their DEM resolution was probably too coarse to incorporate the small scale water and particle flows originating from topographic differences. The high spatial variability of proglacial areas has been mentioned before (Darmody et al., 2005), hence the ASTER DEM of 30x30m used by Temme and Lange Temme and Lange (2014) is probably just too coarse to capture the processes in proglacial areas. Therefore the question remains to what extent micro-relief and geomorphological disturbance play a role in soil development in glacier forefields. This research tries to quantify the role of these factors on soil evolution in glacier forefields.

1.3 Objectives

Main objectives
The main objective of this research is to quantify the role of micro-relief and geomorphological disturbance on soil evolution on glacier forefields. This will be done for the glacier forefield of the Gepatsch glacier. The Gepatsch glacier is located in the Central Alps, Kaunertal, Austria.

In order to reach this objective the following questions are addressed:

1. What is the variability in soil characteristics within the Gepatschferner glacier forefield; for soils of different age as well as for soils of the same age?
2. What is the influence of micro-relief on soil evolution within a chronosequence on the glacier forefield of the Gepatschferner?
3. What is the influence of geomorphological disturbance on soil evolution within a chronosequence on the glacier forefield of the Gepatschferner?
4. To what extent are Micro-relief and geomorphological disturbance in combination with time capable of explaining the variation in soil evolution parameters?

1.4 Hypotheses

The following hypotheses for the research questions can be drawn from previous research.

1. The same general trend in soil properties is expected for the Gepatsch glacier forefield as was found for the Morteratsch and Damma glacier (Dümig et al., 2011; Egli et al., 2006b). A general declining trend in pH, and increasing trends for: soil depth, organic matter content and silt & clay fraction are expected. This trend is thought to be related to the time since retreat of the glacier, as is the case in the previous researches. Additionally high variability in soil properties on small scales is expected.
2. In this research, recently acquired airborne LiDAR point clouds with a high point density (>= 10pt/m^2) allow for the construction of DEMs of much higher resolution (1m). Therefore the hypothesis is that the use of a DEM with higher resolution will provide the opportunity to find the best possible resolution to include topographic variables. This ultimately will increase the percentage of explained variance as compared previous research, something which was already suggested by Temme and Lange (2014).
3. Geomorphological processes influence the forefield soils by deposition or erosion of material. Some soils are rejuvenated, whereas other areas will stay uninfluenced. For areas that have experienced geomorphological disturbance it is expected that general soil development is slower. The expected differences between erosion and deposition disturbances are not defined further here as: the type of geomorphological disturbance, the origin of deposited material and the size of the disturbance make them very complex processes. The hypothesis is that areas that are influenced by either deposition or erosion will appear like soils with a younger age than soils with maximum development for that time-interval. Divergence in values is expected as the soils grow older.
4. We expect that Micro-relief and geomorphological disturbance will both increase the explained variation in soil evolution parameters, but it is unclear yet to what extent for this area.

2 Material & Methods

This chapter starts with a description of the study area and continues with a description of the methodology. This includes materials and methods used in the field as well as methods concerning GIS DEM derivations and statistical analysis of the data.

2.1 Study area

The study area is located in the Kaunertal valley in the Austrian Central Alps and is part of the Ötztaler Alps. The main stream in the Kaunertal valley is the Fagge, which is a tributary of the Upper Inn river system. The Fagge is responsible for drainage of melt water from the two glaciers that are present in the valley: the Gepatschferner and the Weisseeferner. Both of those glaciers are rapidly receding (Abermann et al., 2009); The Gepatschferner has receded for about 2 km since the end of the LIA in 1850.
In 1961 a dam was built in the valley about 7km downstream of the LIA end moraines creating the Gepatsch Reservoir. Melt water as well as sediment originating from the Gepatschferner is collected in the Gepatsch Reservoir (Heckmann et al., 2012). The Upper Kaunertal is characterised by relatively low annual precipitation of 800mm $year^{-1}$, which is measured at the Gepatsch Reservoir dam for the period 1988-2011. (Heckmann et al., 2012) The soils in the Ötztal area consist mostly of: Dystric Leptosols, Spodo-Dystric Cambisols, Leptic Podzols, including Ranker (immature silicate soils) soils (soil map Austria).

The parent material in the Kaunertal consists of crystalline rocks (siliceous para- and orthogneiss) from the Ötztal Complex (Hammer, 1924; Thöny et al., 2008). The paragneiss in the Kaunertal holds enrichments of mainly pyrite, pyrrhotite and chalcopyrite. Minor constituents are arsenopyrite, cobaltite, sphalerite, mackinawite, ilmenite and rutile (Vavtar, 1981).

The Upper Kaunertal, or more precisely the part of the Fagge catchment upstream from the dam is the study area for the PROSA-project. The PROSA–project is a cooperation of several Germans universities to investigate the influence of climate change on the proglacial geomorphic activity and its influence in turn on the sediment budget (Heckmann et al., 2012). The project uses high resolution terrestrial LiDAR as well as high resolution Aerial Laser Scanning. The scanning resulted in DEM’s for this area with a very high resolution of 1m. Besides the high resolution laser scanning data there is a lot of knowledge about the geology, geomorphology and morphodynamics of the area as well as old aerial photography.
These high resolution DEM’s in combination with the other data give us the opportunity to investigate the relation of micro-relief and erosion with soil evolution for this area.

Through the PROSA-project the following data is available for this area:

- High resolution DEM (10pt./m^2) (2006 & 2012)
- Geomorphological units map
- Aerial photos for roughly every 10 years from 1953 onwards
- A DEM created from 1953 aerial photography
- Collated shape files of glacier extent from ~1880 till present

Figure 1: Study area, Gepatschferner, Kaunertal, Austria

The study area for this research consists of the glacial forefield of one of the two glaciers in the upper part of the Kaunertal Valley, the Gepatschferner. The glacial forefield of the Gepatschferner is about 2 kilometres long and 400 metres broad. Over these 2 kilometres there is an altitude increase from about 1900m to about 2300m.

In the Southernmost part of the area there is a small side glacier with its own glacial forefield. Due to the strong average altitude difference of this area with the rest of the glacial forefield and the fact that it can be seen as an independent glacier forefield this area was omitted in this research. To reduce errors because of high uncertainty in age of the material at the sides of the glacier (age lines were very close together), as well as the fact that these areas were generally very dangerous those were omitted as well. In the Northern and oldest part of the forefield a road was built. A small area is used for sediment collection and there is a small maintenance shed of the "Kaunertaler Gletscher & Fendels" company. These areas were omitted as well due to anthropologic influence. In the geomorphological map for the area all areas with bare rock were depicted. These areas were clipped from the study area as they have no soil. The research area without bare rock areas can be seen in Figure 2. An image of the detailed geomorphological map can be found in Appendix A.

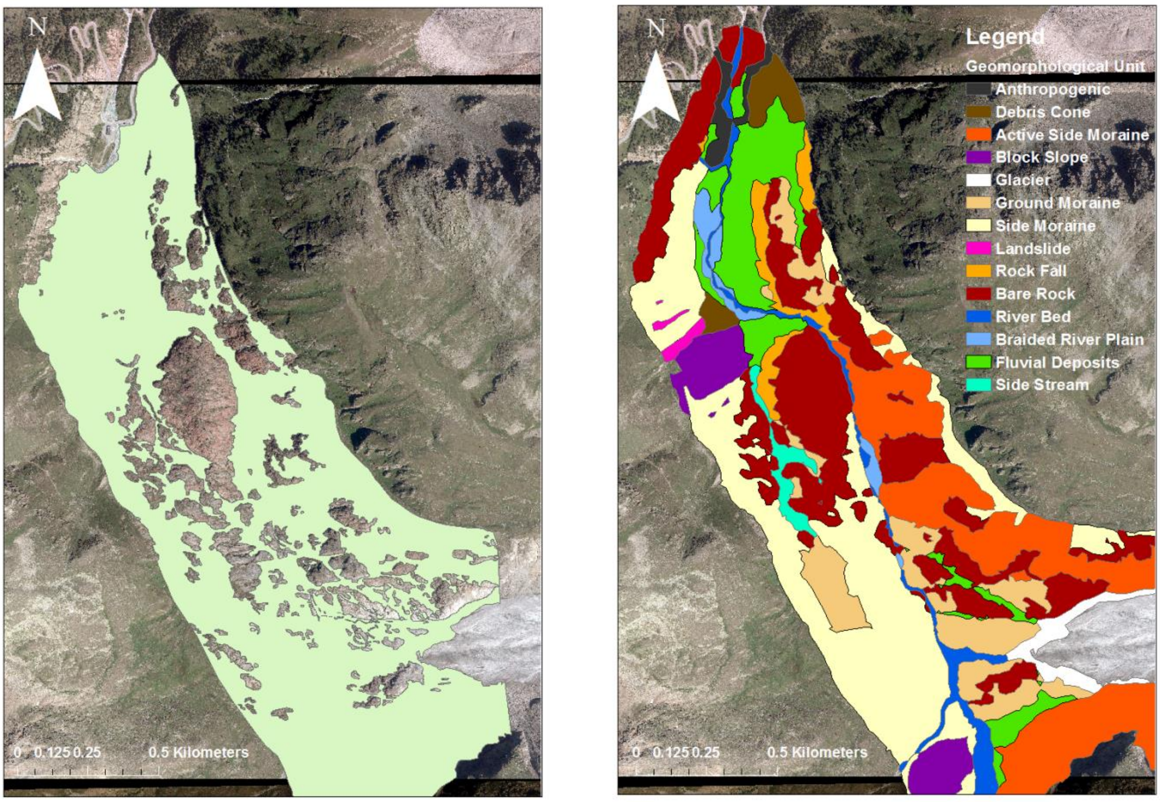


Figure 2: Study area without bare rock areas (Left), and study area divided in large geomorphological units (Right)

The Gepatsch glacier has steadily retreated for the past 150 years with a total length of approximately 2.5km. During the eighties there was a colder period with more precipitation were there have regionally been re-advances of some glaciers, for instance the Tschierva glacier (Temme and Lange, 2014). The Gepatsch glacier has experienced a small re-advance in this period and has stayed at a stable location from about 1970 to 1997 (Figure 3).

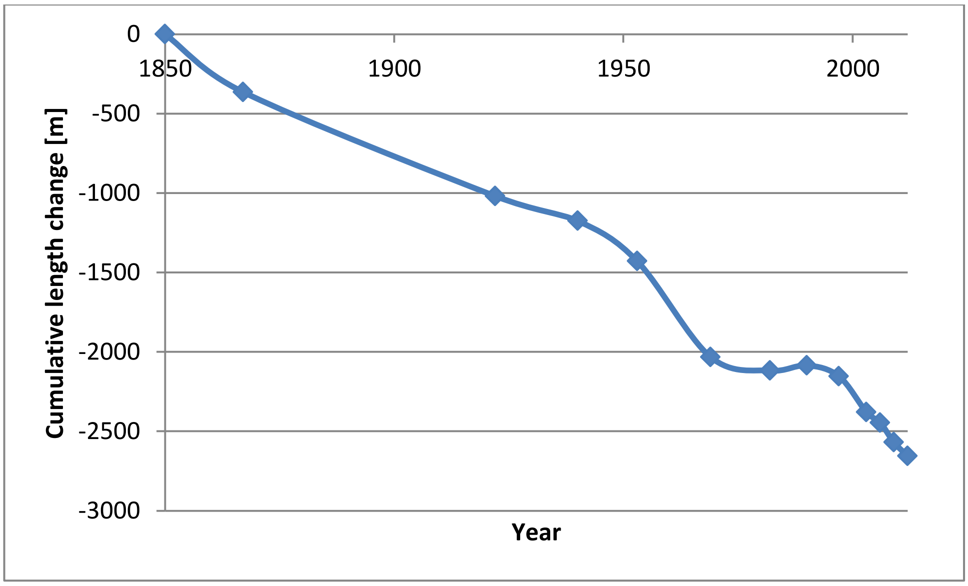


Figure 3: Length variation measurements of the Gepatsch glacier between 1850 and 2012. The glacial extent is considered constant from 1970 to 1997.

In comparison with study areas that were used in previous research, such as glacial forefields of the Morteratsch, Tschierva, Forno and Damma glaciers, the glacial forefield of the Gepatschferner is geomorphologically more dynamic.
The total high difference and general geometry of the glacial forefield of the Gepatschferner is largely similar to that of the previous named glaciers. The glacier forefield of the Gepatschferner is much more diverse, with more relief within the forefield itself. There are large humpback rocks present within the forefield, causing strong elevation differences locally. In some parts the river is very confined, whereas in other areas it forms braided systems. The overall result is a very diverse and dynamic area. Erosion and deposition regimes are therefore different for different areas within the forefield. This is emphasized by a large variety of erosion processes that is observable in the area: landslides, rock fall, debris cones, active side moraines, block slopes and multiple fluvial processes (Figure 2). Different processes seem to be prevailing for different parts of Gepatsch forefield.

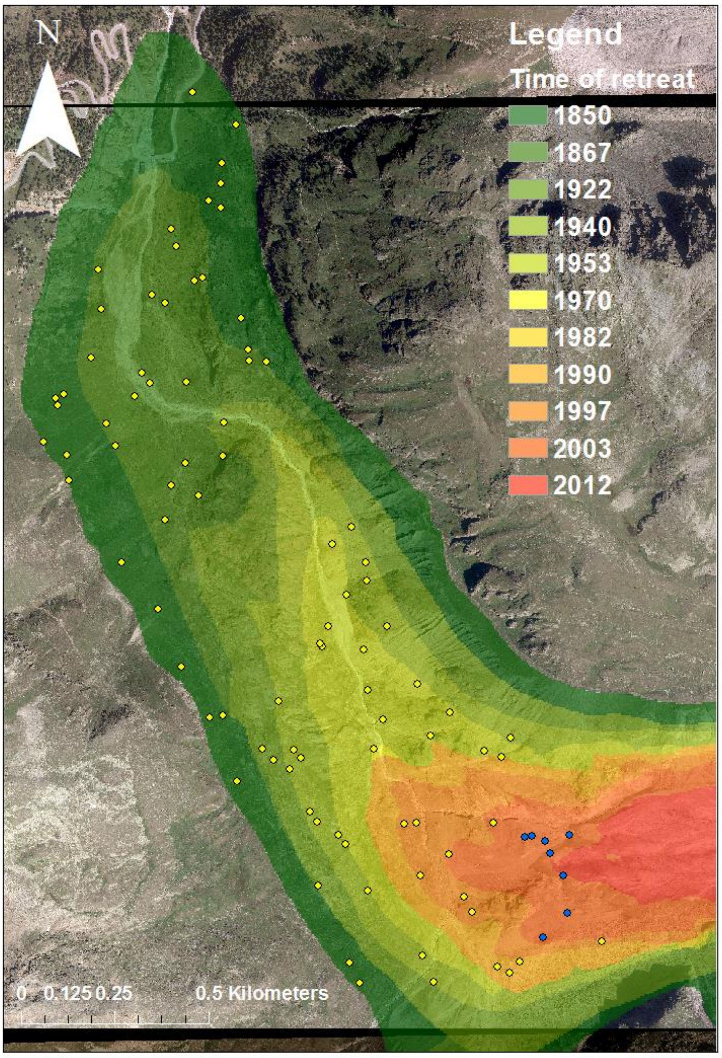
2.2 Sampling design

In previous research sampling was mostly performed on the stable areas within the forefield in order to investigate the relation with age. Areas that were prone to fluvial processes or erosion from side moraines were omitted. In this research we especially want to know the influence of these processes, therefore the entire study area was used for sampling. In previous research often some form of convenience sampling was used, due to lack of accessibility of the area or time restraints. In order to get an unbiased idea of the overall variability in the area in this research it was decided to use a random sampling strategy instead.
To make sure that the sampling points were evenly spread across the range of potentially explanatory variables conditioned Latin Hypercube Sampling (cLHS) was used. In this case the age since glacial retreat and the Topographic Position Index were used as explanatory variables. The cLHS method places a predetermined number of points over the entire range of several explanatory parameters. It incorporates the relative area for the values of the explanatory parameters as well (Minasny and McBratney, 2006). The result of this method is a sampling design where the points are placed in such a way that the give the optimal presentation of the explanatory variables. Data on actual erosion was not used as it was not yet available at the time. The entire study area was assumed to be accessible as it was not possible to determine beforehand which areas were too dangerous and which were not.

In total 140 sampling locations were selected over the area, of which in the end 97 locations were actually sampled. During sampling it became clear that some locations were too dangerous to access, or locations were located either on a small patch of bedrock or inside the river. If possible a nearby spot with more or less the same characteristics was sampled instead. When the entire area was too dangerous to access the points were omitted. It is assumed that this is no problem, as these were almost all locations with a very steep slope. Therefore all TPI locations with a very steep slope were not incorporated, but it was assumed that for those very steep slopes no particular TPI range was overrepresented.

Additionally to the points selected with cLHS, another 16 points were sampled as part of a catena. These catenas were sampled in order to help understand and explain certain processes that were going on in the area. One reference point just outside the LIA end moraine was sampled as well to get an idea of the soil development in these areas over larger timescales.

The actual sampled positions in combination with the different age intervals can be seen in Figure 4.



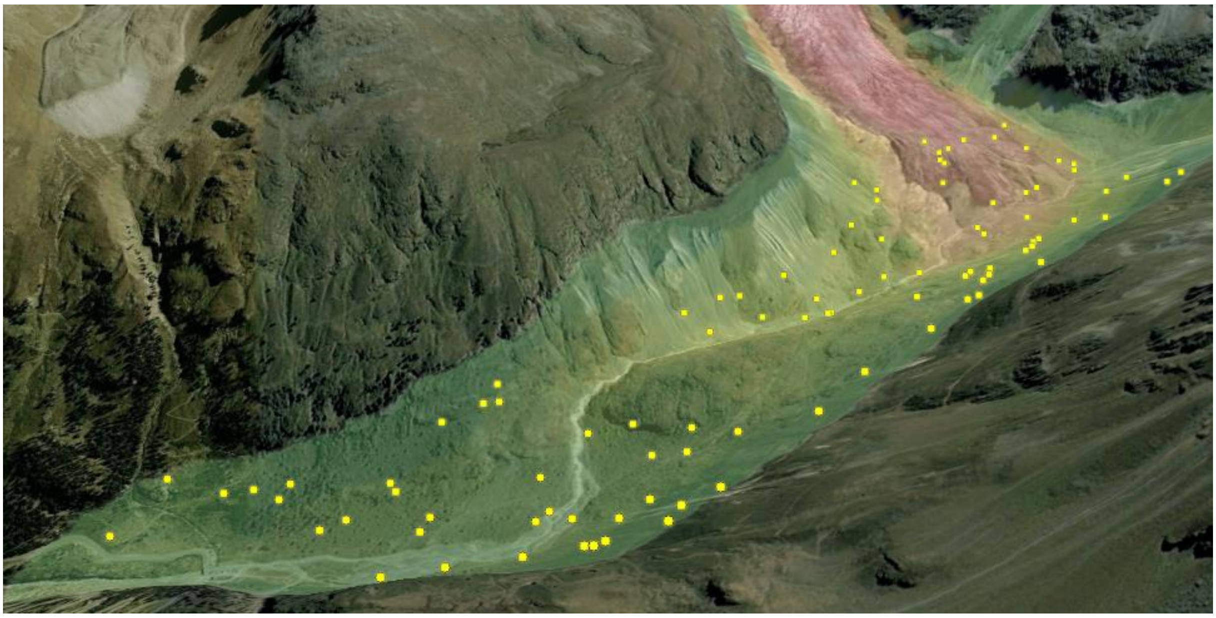


Figure 4: Sampling positions in combination with the different known glacier extents. The eight sampling locations represented with a blue dot were used to calculate the background soil carbon values.

2.3 Sampling method

In previous research organic matter, pH and soil depth have consistently shown a strong correlation with soil evolution (Dümig et al., 2011; Egli et al., 2006b; Mavris et al., 2010; Temme and Lange, 2014). Therefore these parameters were selected as dependant variable for this research. In addition we especially wanted to investigate the influence of micro-relief and erosion processes on those dependent variables. A relation between micro-relief and soil evolution was previously found for slope gradient and curvature with soil texture (Iwashita et al., 2012). Convergent hydrological fluxes frequently occur at concave areas; these areas therefore have higher average soil moisture than convex areas. Convex areas are more prone to erosion processes and mass removal, whereas concave areas have a more depositional environment. Especially silt and clay particles are subjected to transport from convex areas to concave areas. (Heimsath et al., 1997)
In another research for a Semi-Arid area however hillslope erosion rates were not found to be influenced by slope and curvature, but by surface stoniness and vegetation (Nearing et al., 2005). Their findings are however mainly based on overland flow as they are dealing with a Semi-Arid area. The Gepatsch Forefield is more humid and therefore we assume the divergent and convergent hydrological fluxes to be of greater influence. We expect that slope gradient and curvature can be correlated to soil texture in this area. Soil texture was therefore also included as a dependent variable.

The sampling consisted of two parts. For every sampling location the soil profile was described using the standard guidelines (WRB, 2007). A short description of the position in the landscape was recorded for every location as well. Additionally a soil sample was taken for every horizon except the parent material. When there was no visible soil development, one sample was taken in order to determine the pH.

The pH(H_2O) was measured in the field by taking a small composite soil sample from the target layer. The sample was mixed with demineralised water to create a slurry. The pH of this slurry was measured using a pen type field pH measurer with an accuracy of 0.1 pH unit.

The Soil Organic Matter (SOM) was determined in the lab with the Loss On Ignition (LOI) method (Dean, 1974). Eight of the points located closest to the glacier snout and without any signs of erosion influence of side moraines were used to calculate a background value for soil carbon (Figure 4). The LOI results for these eight spots were averaged in order to obtain the background value. This was 0.04 mass percent. This value was subtracted from all other mass percentages before calculation of the total organic matter content of each soil profile. When this resulted in negative values those were put to zero.

Soil texture is part of the standard soil description, but grain size distribution was additionally quantified in the lab with dry sieving. The samples were sieved in the grain sizes shown in Table 1.

Table 1: Texture classes determined through dry sieving

Soil particle size (µm)	Grain size
<63	Silt & clay
63 < … < 2000	Sand
>2000	Gravel

To explain the variation in dependent variables available data from the PROSA project was used as well as a series of DEM-derivatives. Table 2 shows the dependent and explanatory variables.

Table 2: Dependent and explanatory variables

Dependent variables	Unit	Explanatory variables	Unit
Total soil organic matter	[kg m^{-2}] ratio	Time since retreat	[years] ratio
Topsoil pH	[-] ratio	Slope	[-] ratio
Silt fraction	[-] ratio	Profile curvature	[-] ratio
Root depth	[cm] ratio	Aspect	[°] interval
		DOD 1953-2012	[m] ratio
		DOD 2006-2012	[m] ratio
		LS-factor	[-]
		Stream Power Index (SPI)	[-]

2.4 Explanatory variables

2.4.1 Time since retreat

The time since glacial retreat (TSR) was determined from the collated shape files of glacier extent. Data about the extent of the glacier was retrieved from aerial photography for the period from 1953 till present. Older information about the glacier extent came from old maps drawn by the Alpenverein.
For the recent years a lot of aerial photography was available, resulting in a high density of isochrones. Not all of those were used; the isochrones were chosen in a way that there were clear differences between the glacier extents. In total eleven different glacier extents were used to determine the time since glacial retreat. The years for which the glacier extent is used are: 1850, 1867, 1922, 1940, 1953, 1970, 1982, 1990, 1997, 2003 and 2012. During the period from 1970 till 1990 the glacier extent didn't change much. The Gepatschferner, just like a lot of glaciers in the area, experienced a small re-advance during this period. The exact extent and timespan of the re-advance is not known unfortunately.

At the sides of the glacier there is a high uncertainty in TSR due to a high density of glacial isochrones. As the areas at the sides of the glacier were poorly accessible in general as well it was decided to omit them from sampling. For the rest of the area the constraint was used that for locations where two isochrones were less than five meters apart the lines would merge and the area would receive the youngest age.

2.4.2 Micro-relief

Several relief parameters were investigated to get an idea of the influence of micro-relief on soil evolution. All parameters were calculated with a 1m resolution DEM from 2012. The different parameters that were investigated are: Slope, Aspect and Profile curvature.
Before the parameters were calculated the DEM was smoothed using a Gaussian smoothing method with a factor of one and a half (1.5 times the resolution). This was used as a rule of thumb to remove the pixel like behaviour of the detailed DEM.

Slope, profile curvature and aspect were used as explanatory variables for micro-relief. Aspect was transformed from degrees to a value for Easting and a value for Northing. Easting indicates whether a slope face East or not, and Northing subsequently indicates whether a slope faces North or not. The following equations yield a value between -1 for West or South facing slopes and 1 for East or North facing slopes.

$$E = \sin A \tag{1}$$

$$N = \cos A \tag{2}$$

Profile curvatures were calculated for different support scales. This was done by smoothing the original DEM with different factors before calculating the profile curvature. Smoothing factors of: 1, 3, 5, 10, 20 and 30 were tried and correlations with the dependent variables were analysed.

2.4.3 Erosion

To get an idea of the erosion in the area the DEMs of different dates were analysed. DEMs retrieved from ALS were available for 2006 and 2012. Another DEM was created from aerial photography using Agisoft for 1953. Two DEM's of Difference (DOD) were created to analyse the decadal-scale difference between 1953-2012 and the annual-scale difference between 2006-2012.

Additionally there are DEM-derivatives that are a measure of possible erosion. The DEM-derivatives that were analysed in this case are the Stream Power Index (SPI) and the LS-factor.

The SPI (Moore and Wilson, 1992) takes into account the local slope geometry as well as the location in the landscape. It is calculated with the following formula using the slope gradient (G, [-]) and the catchment area (CA, [m^2]).

$$SPI = \ln(CA. \tan G) \qquad 3$$

The LS-factor (Moore and Wilson, 1992) is a relative measure of how erosive a position is. The L is the slope length factor and represents the effect of slope length on erosion. The S stands for slope steepness factor and represents the effect of slope steepness on erosion.

$$LS = \left(\frac{\lambda}{22.13}\right)^{0.3} (65.41 \sin^2\theta + 4.56 sin\theta + 0.065) \qquad 4$$

2.5 Statistical analysis

The overall variability of the dependent variables in the area was calculated using summary statistics for the total data set as well as for the data of individual time intervals. This way the data could be compared to values found in previous research.

The Pearson correlation coefficients were calculated using R to investigate the relation between the dependent and explanatory. The values of DEM-derivatives for the sampling locations were determined by exporting the data in combination with the coordinates using SAGA GIS (export with xyz). The data file obtained from field sampling was then merged by coordinates with the files exported from SAGA.

Not in all cases could relations between variables be explained using correlations, in those cases the relation between variables was explained by the images itself.

A stepwise linear regression analysis was performed to investigate the total percentage of variation within the dependent variables that can be explained with the explanatory variables. This analysis was performed with all the data points. The DOD 1953 values were not used as an explanatory variable here because they are only available for the part of the research are from which the glacier had already retreated before 1953.

To investigate the importance of the actual erosion data from the DOD 1953 for the different dependent variables in relation to the other explanatory variables a tree regression was performed. Here only the values for sample locations from which the glacier had retreated before 1953 were used. The DOD 1953 values were used for this analysis, and therefore the variables that only represent the probability of erosion like LS Factor and Stream Power Index were omitted.

2.6 Materials

The materials that were used for collection of soil samples and description of the profiles can be found in Table 3. Table 4 depicts the different available data files that were used.

Table 3: Materials and Data-files that were used

Materials Field	Materials Lab
GPS	sieve 2 mm
Soil knife	sieve 0.63 mm
Compass	Porcelain crucibles
Tape measurer	Scale (2 digits)
Geological hammer	Oven (550 °C and 150 °C)
FAO soil description guidelines (FAO, 2006)	
Munsell colour charts	
Sand ruler	
Field pH measurement device	

Table 4: Data files used during the research

Data-files	Description	Year	Source
LiDAR Digital Elevation Model (DEM)	Obtained by aerial scanning for the PROSA-project. (Resolution of 1m)	2006	PROSA-project
LiDAR Digital Elevation Model (DEM)	Obtained by aerial scanning for the PROSA-project. (Resolution of 1m)	2012	PROSA-project
Digital Elevation Model (DEM)	DEM created from aerial photos taken in 1953 using the software Argisoft (Resolution of 1m)	1953	PROSA-project
Digital Aerial pictures			PROSA-project
Old glacier extent maps	Old maps of the glacier snout outline, as well as elevation lines for the glacier heights.	1850, 1867, 1922, 1940	Diplomarbeit Roland Henninger via Universität Eichstätt
Geomorphological map	Map with large geomorphological zones created within the PROSA-project	2013	PROSA-project

3 Results

3.1 General Statistics and observations

3.1.1 Observations

Pioneer vegetation in the area was already observed on soil of only a few years old. However, the first signs of soil development were observed on soils with an age of about 40 years. First signs of shrub and forest development were observed on the oldest parts of the glacial forefield, so soils with an age of approximately 150 years.

In general soils had a depth of more than 25cm to bedrock, therefore only a small number of Leptosols were found. The soils that were found ranged from (Skeletic) Regosols for the younger soils to a mix of (Skeletic) Regosols and Cambisols for the older areas (Figure 5). The most developed soil that was found was a weakly developed Skeletic Podzol on a soil with an age of about 160 years. Outside the LIA end moraine a reference soil pit yielded a more developed Haplic Podzol.

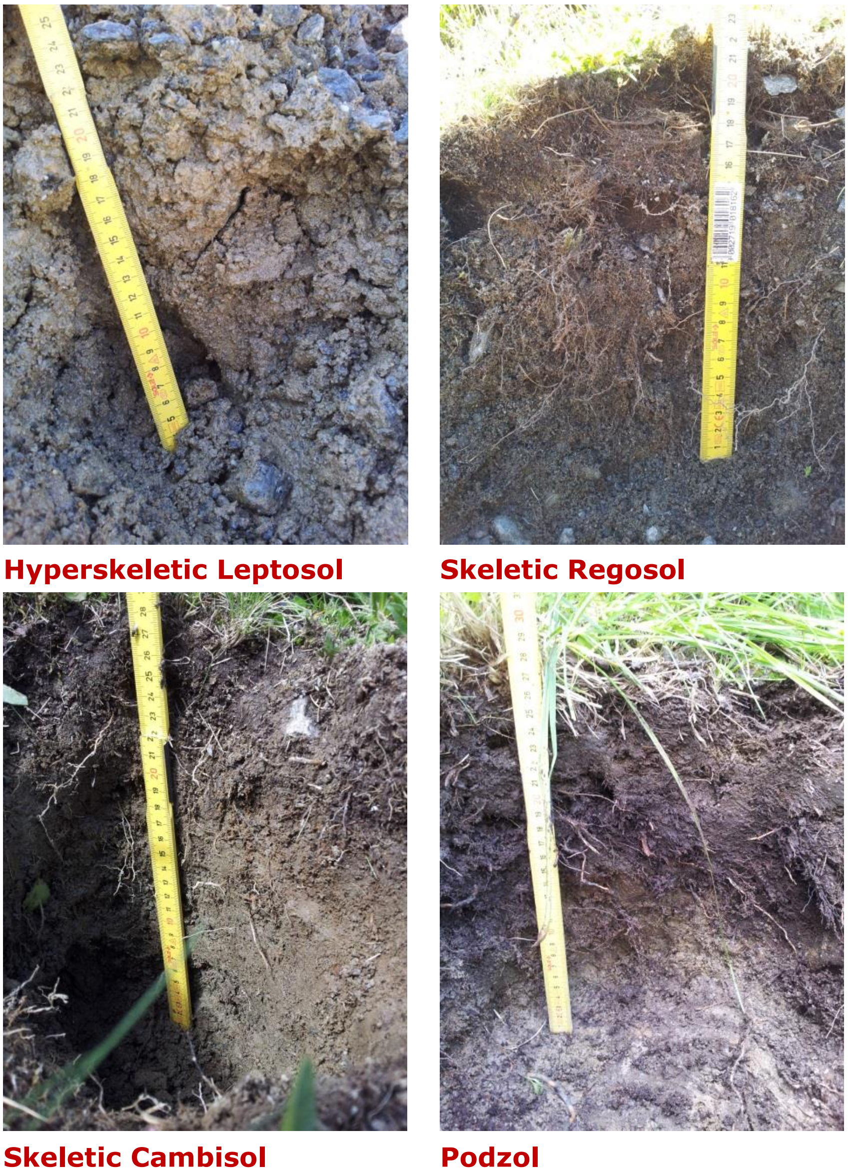


Figure 5: Overview of the different soil profiles found within the Gepatsch forefield

3.1.2 Dependent variables

Total organic matter contents range from 0 kg/m2 in the young soils to 0.131 kg/m2 for one of the oldest soils (Table 5). The highest percentage of organic matter in the topsoil that was found was 88% for almost peaty organic topsoil. The average pH for soils in the study area is 5.71, with a range from 4.4 to 7.4. Quite substantial differences in pH on small scales were observed. Maximum rooting depth in the area was 60cm for the weak Podzol that was found. Root depth was sometimes limited by stoniness, but in general stoniness was low enough for roots to reach down to bedrock. The silt and clay fraction of the soils had a maximum of 0.29. Soils without almost any silt and clay were present as well though. Silt and Clay fractions appeared higher on flat areas near the glacier snout. Maps of the observed values for the dependent variables at the sampling locations can be found in Appendix B.

Table 5: Summary statistics of soil properties

	Total OM [kg m^{-2}]	pH [-]	Root depth [cm]	Silt & Clay fraction [-]
Mean	0.012	5.71	23.49	0.068
Minimum	0	4.40	0	0
Maximum	0.131	7.40	60	0.29
Sd.	0.020	0.63	12.54	0.062

3.1.3 Micro-relief

The maximum slope for the sample locations was around 60 degrees (Table 6). There were steeper slopes present in the area, but those were not sampled because it was deemed too dangerous.
The minimum slope of 0.44 degrees indicates that the entire range of slopes from flat to steep has been sampled. The mean slope of about 25 degrees is quite high, which is a resemblance of the strong relief in the area. The profile curvatures of the sample locations are nicely spread over convex and concave area with a mean value close to zero. The maximum value of 0.107 is slightly larger than the absolute minimum value of 0.077. Apparently slightly stronger convex areas were sampled than concave areas.
The values for the aspect (Table 6) do not tell us much as it is a relative scale. The easting mean of 0.065 shows though that the locations are nicely divided over East and West facing slopes whereas the northing mean of 0.37 indicates that way more North facing slopes have been sampled than South facing slopes. The high percentage of East/West facing slopes (Table 7) is caused by the North-South orientation of the main valley within the forefield (Figure 4). Maps for the GIS output of the explanatory micro-relief variables can be found in Appendix C.

Table 6: Summary statistics of the micro-relief explanatory variables

	Slope [°]	Profile Curvature [3m]	Aspect [Easting]	Aspect [Northing]
Mean	22.40	-0.004	0.065	0.37
Minimum	2.47	-0.077	-1	-1
Maximum	50.79	0.107	1	1
Sd.	10.17	0.023	0.77	0.53

Table 7: Aspect distribution of the soil pits

	N	E	S	W
Percentage	16.50%	50.50%	5.15%	27.84%

3.1.4 Erosion

During fieldwork a range of erosion processes was observed in the area. Those processes ranged from large processes like debris flows and landslides to small scale erosion caused by rain and erosion of thin layers of earth from base rock (Figure 6).

Figure 6: *Upper left:* Large scale erosion in the form of an active land slide. *Upper right:* Large scale erosion on an instable moraine slope with ice core. *Lower left:* Small scale erosion caused by rain. *Lower right:* Small scale erosion from Roche Moutonnées.

The strong negative value for the mean of the DOD for 1953 (Table 8) indicates that in general there has been erosion in the research area since 1953. The stronger minimum value than the maximum value also indicates that erosion processes are apparently more dominant than deposition processes in this area. The mean of the LS factor lies much closer to the minimum than to the maximum, which indicates that for a few of the sampling locations the LS factor is very high in comparison to the rest of the points.
For the Stream Power Index the summary statistics give the same view although here the standard deviation is much higher compared to the mean. Therefore the values for the SPI are more uncertain than those of the LS Factor.

Table 8: Summary statistics of the erosion explanatory variables

	DOD 1953 [cm]	LS Factor [-]	SPI [-]
Mean	-1.33	6.32	563.30
Minimum	-5.64	0.028	0.10
Maximum	2.37	35.35	27820
Sd.	1.77	5.68	3120.22

3.2 Time since glacier retreat

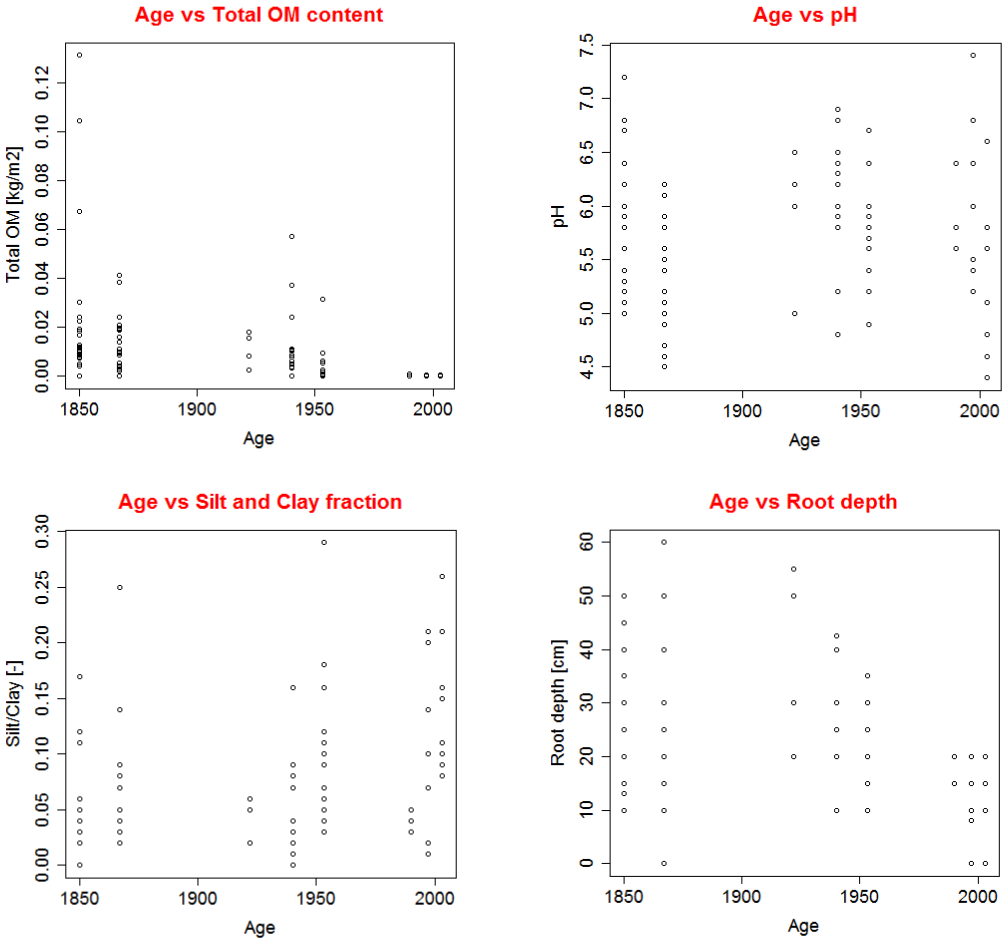


Figure 7: Time of glacial retreat for the soils vs the dependent variables (OM, pH , Silt & Clay fraction and Root depth)

3.2.1 Total OM content

The relation of total organic matter content with TSR is shown in Figure 7. There seems to be an upper boundary more than a clear correlation. The values found for the total organic matter contents seem to diverge with increasing age of the soils. In the younger soils only very low organic matter contents are found whereas for the oldest soils low organic matter contents as well as high organic matter contents are found. This suggests the influence of other processes that play a role over time.

The increase of standard deviation with time for the organic matter content can be seen in Table 9. The coefficients of variance do not seem to follow this trend exactly.

Table 9: Coefficients of variation for the OM content per group of soils with approx. the same age

Age	**2003**	**1997**	**1990**	**1953**	**1940**	**1922**	**1867**	**1850**
n	9	7	3	14	16	4	21	23
Mean	$7.48\ 10^{-5}$	$7.07\ 10^{-5}$	0.00028	0.0043	0.012	0.0062	0.011	0.019
St.dev	0.00020	0.00013	0.00049	0.0083	0.015	0.0077	0.011	0.031
CoV	261.58	178.96	173.21	192.06	125.74	122.98	105.59	161.03

3.2.2 pH

No significant correlation was found between age and pH (Figure 7). Although no correlation was found for pH with age a very slight Podzol was found for one soil pit located in the oldest part of the glacial forefield. The reference soil pit just outside the LIA moraines yielded another young Podzol was found. This Podzol was clearly more developed than the one inside the LIA moraine. The soil is slowly acidified and ultimately forms into a Podzol, which is the climax state of plutonic- or metamorphic parent material soils for this climate. The middle part of the pH-graph (Figure 5) seems to follow this pattern. Low pH values for very young soils as well as high pH values for the oldest soils seem to eliminate this relation for this area. The relation between pH and age appears to be a complex one for this area.

The possibility of other processes that causes acidification in the youngest soils has to be considered. One of these processes is acidification by pyrite oxidation.

Pyrite in parent material is known to be able to temporarily or permanently acidify soils.
Acidification of the soil by pyrite happens through the following equations (Bolan et al., 2003):

	Pyrite oxidation	
Pyrite oxidation by oxygen	$2FeS_2 + 7O_2 + 2H_2O \rightarrow 2Fe^{2+} + 4SO_4^{2+} + 4H^+$	+2
Ferrous iron oxidation	$4Fe^{2+} + O_2 + 4H^+ \rightarrow 4Fe^{3+} + 2H_2O$	−1
Ferric iron precipitation	$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3 + 3H^+$	+3
Pyrite oxidation by ferric iron	$FeS_2 + 14Fe^{3+} + H_2O \rightarrow 15Fe^{2+} + 2SO_4^{2+} + 16H^+$	

Figure 8: Reaction equations of pyrite oxidation in soil, the + and – indicate the number of H^+ molecules that are set free or bound.

The reaction equations for pyrite oxidation (Figure 8) show that the presence of iron can speed up the acidification process initiated by the pyrite. In the study area there were clear signs of the presence of iron in the parent material. The bedrock was coloured red in time by weathering through the oxidation of the iron.

If we consider the possible effect of pyrite acidification a correlation can be found for pH and age (Figure 8). The right part of the figure shows the rise of pH and may resemble the time span that is needed to let all pyrite react. The left part of the figure shows the known relation for pH values to decline with age in areas like this. The p-value is significant for the part from 1850-1990 ($p = 0.0157$) and almost significant for the 1990-2012 part ($p=0.0868$) on the ($p<0.05$) significance level. The R-value for the part from 1850-1990 is 0.27 and for the 1990-2012 part it is -0.40. The high pH values for some very old soils are still striking but are thought to be caused by erosion, which will be discussed in section 4.5.

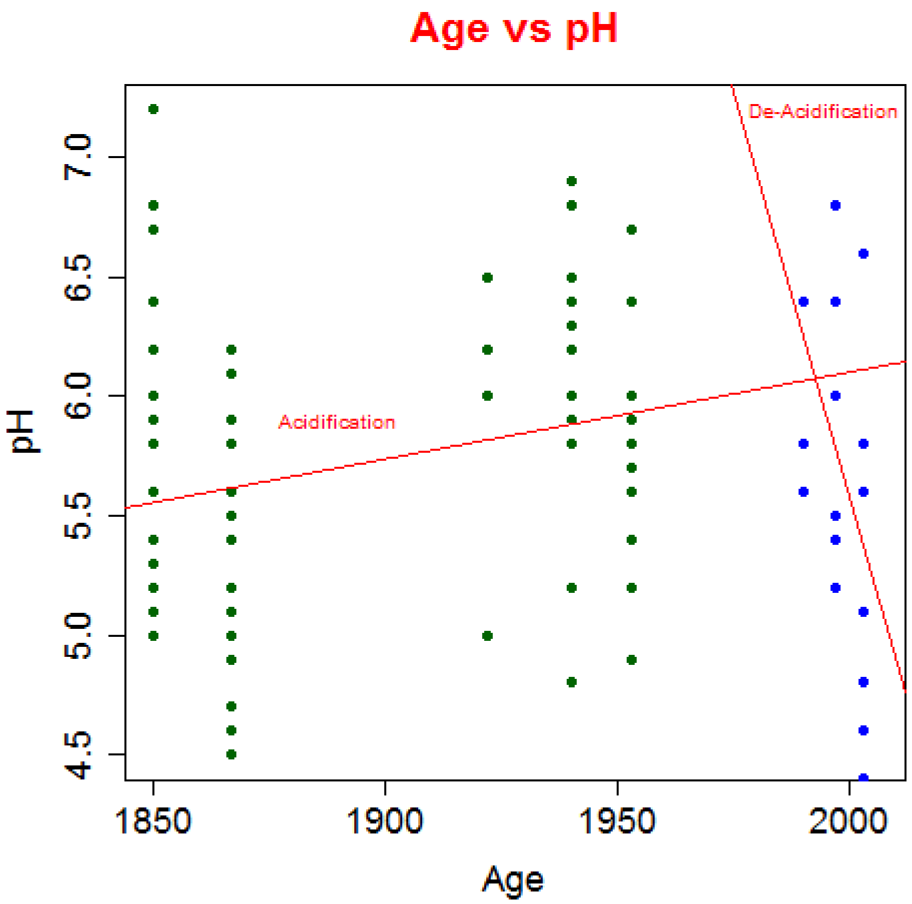


Figure 9: Relations for age and pH when the effect of pyrite acidification is considered

Due to this effect, in further analysis concerning the pH of the soils only the pH of soils older than 1990 will be analysed. This way the pyrite acidification doesn't play a role in these analyses.

3.2.3 Silt and clay fraction

There seems to be no obvious relation between the silt and clay fraction and the age of the soil (Figure 7). There might be a very slight trend in increasing silt and clay fraction with younger soils, but the range of possible silt and clay fraction is very large over the entire age-range.

3.2.4 Root depth

The relation of total root depth with age (Figure 7) seems to follow the same general trend as for the total organic matter content. There again seems to be an upper boundary for which root depth increases with age of the soil. The total root depth diverges with increasing age as well. There is a small difference though, which is the fact that somewhat higher values are found for very young soils besides very low values.

3.3 Micro-relief

A very detailed DEM was available in this research; therefore the influence of micro-relief on different scales could be investigated. This was thought to be particularly important for the correlations of the dependent variables with profile curvature and slope. Therefore the correlations of the dependent variables with the profile curvature and slope calculated from different support sizes were calculated (Figure 10 & Figure 11). The DEM was first smoothed to a: 1.5, 3, 5, 10, 20 and 30m DEM, then the slope and profile curvature was calculated. A maximum size of 30m was chosen as this was earlier deemed too coarse (Temme and Lange, 2014).

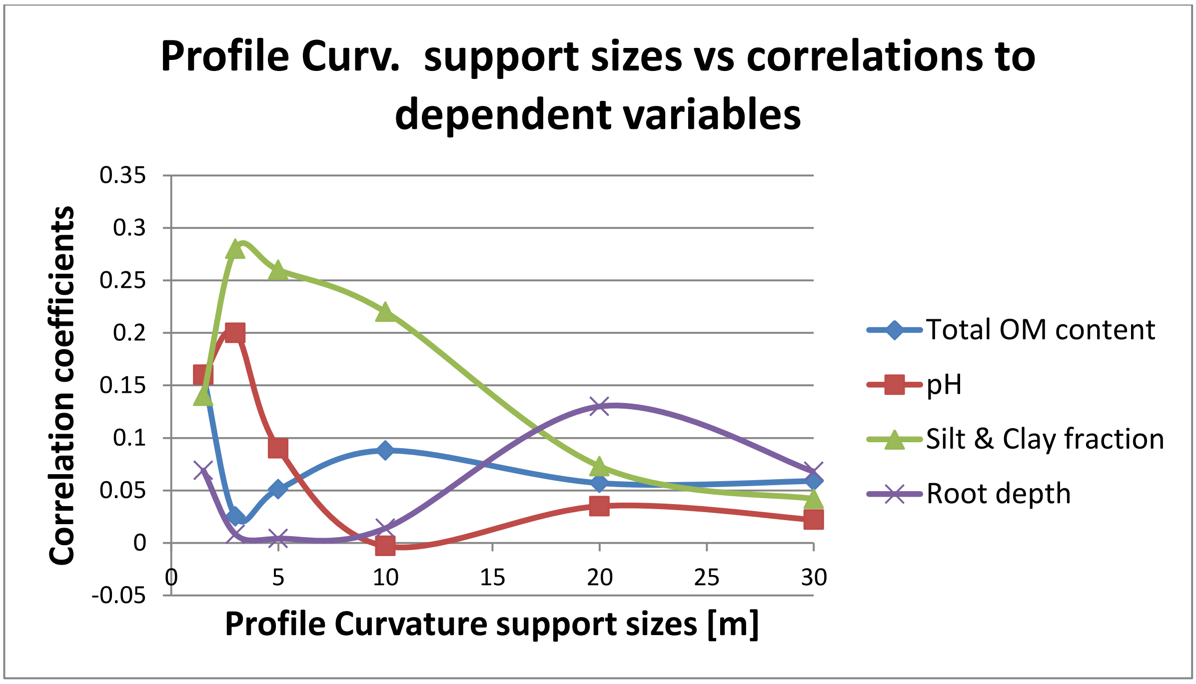


Figure 10: Correlations of the dependent variables with profile curvature calculated from different support sizes

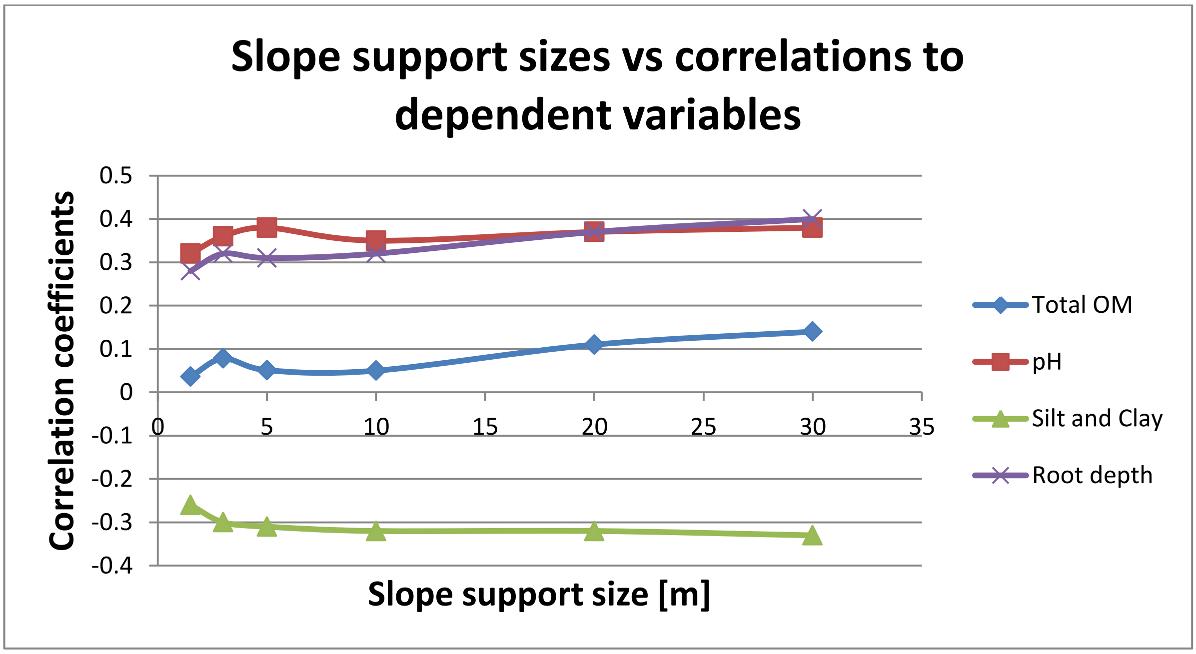


Figure 11: Correlations of the dependent variables with slope calculated from different support sizes

In general the correlations for rooting depth with the profile curvature are small with a slight peak at 20m (Figure 10). The correlation coefficients for the total organic matter content have a strong peak at 1.5m and are for larger support sizes very low. Both pH and silt & clay fractions have a very distinct peak at the 3m support size. The peak for silt and clay fraction is a bit broader around the 3m and 5m support sizes and gradually lowers with larger support sizes. The peak for pH is more distinct and goes quite rapidly to lower correlations for larger support sizes. Particularly for the silt & clay fraction the profile curvature is thought to be one of the main drivers. The pH might be linked to erosion, so it can be driven by profile curvature in a lesser manner as well. Organic matter could be driven by profile curvature as well, but in a more indirect manner and it is probably influenced by a lot more factors as well. Therefore it is deemed less important here. Root depth is deemed less important here as well.
As a result the 3m support size is chosen to be the support size for which profile curvatures influence the dependent variables best in this area.

The correlations for slope with the dependent variables (Figure 11) all seem to slowly increase to larger support sizes. Apparently the average slope of a larger area plays a role here, probably via large scale slope processes. Besides those processes there is however also a tiny peak at the 3-5m point, similar to the peaks found for the profile curvature. The small scale slope is important for processes as well. There seems to be a large scale slope effect, but small scale redistribution as well. We will use the 3m support size for slope as well as we are particularly interested in the influence of micro-relief and to be consistent. The exact correlation coefficients can be found in Table 10 & Table 11. Maps of the profile curvature and slope calculated from different support sizes can be found in Appendices D & E.

Table 10: Correlations for the dependent variables with the different profile curvature sizes

	1.5m	3m	5m	10m	20m	30m
Total OM	0.16	0.025	0.051	0.088	0.057	0.059
pH	0.16	0.20	0.09	-0.003	0.035	0.022
Silt and Clay	0.14	0.28	0.26	0.22	0.073	0.042
Root depth	0.069	0.0082	0.0041	0.014	0.13	0.068

Table 11: Correlations for the dependent variables with the different slope sizes

	1.5m	3m	5m	10m	20m	30m
Total OM	0.036	0.078	0.051	0.050	0.11	0.14
pH	0.32	0.36	0.38	0.35	0.37	0.38
Silt and Clay	-0.26	-0.30	-0.31	-0.32	-0.32	-0.33
Root depth	0.28	0.32	0.31	0.32	0.37	0.40

3.3.1 Total OM content

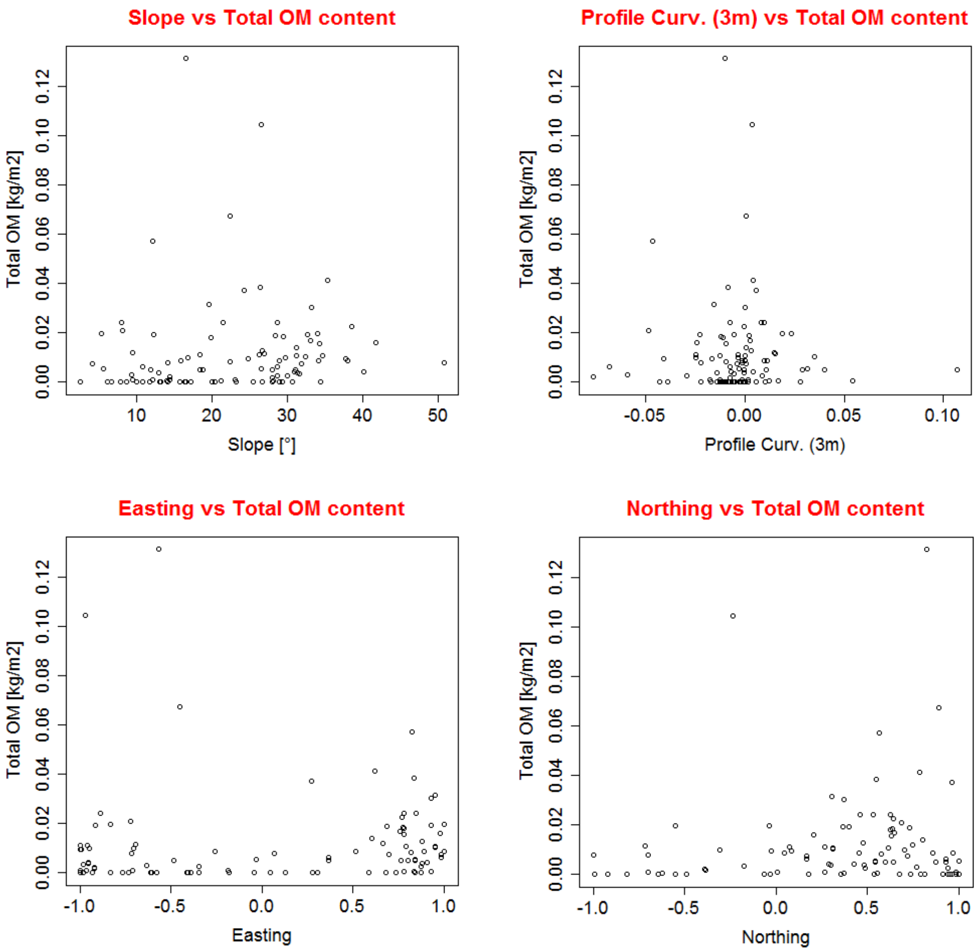


Figure 12: Total OM content vs the explanatory variables (Slope, Profile curvature & Aspect)

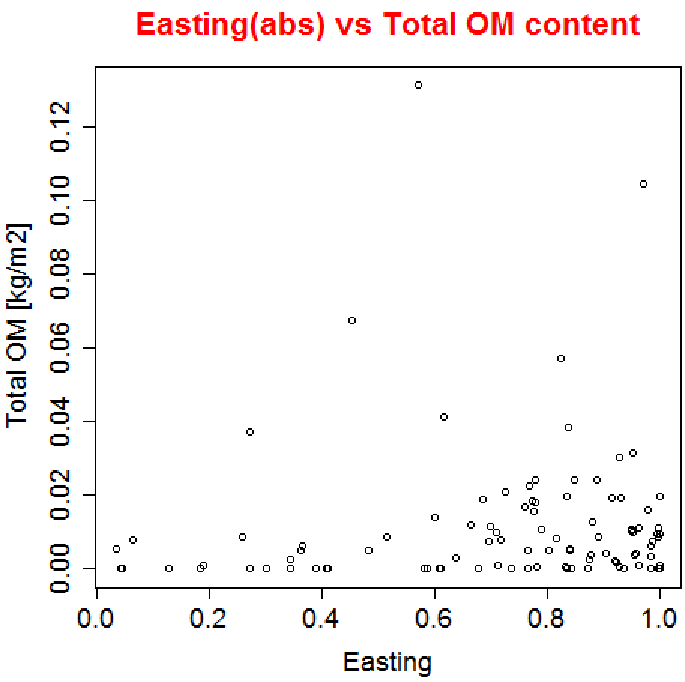


Figure 13: Absolute easting of location in relation to the total OM content of the soil

A clear pattern for slope in relation with the total OM content can be observed (Figure 12). The correlation between the two parameters is significant on the 0.05 significance level; the correlation coefficient is 0.033. There seems to be an upper limit which runs from low OM levels for steep slopes to high OM levels for less steep slopes. Values of OM content seem to diverge toward less steep slope values. On flat areas high and low levels of OM content are found whereas for steep slopes only low levels of OM are found. This would be consistent with erosion on steep slopes reducing organic matter levels.

Profile curvature shows highest OM contents for locations with only slight curvatures. These locations could be seen as the most stable locations, and consequently have undisturbed soil development. The suggestions could be made that higher OM contents are more likely to appear on concave spots than on convex spots which would be consistent with erosion processes. There are however too few measurements in these curvature areas to really say something about this.

High organic matter values seem to occur mainly at values for easting that are close to 1, so either completely west or east facing (Figure 13). In the small figure regarding the Northing (Figure 11) there seems to be a divergent pattern again of the organic matter content increasing in range towards the value of plus one.

3.3.2 pH

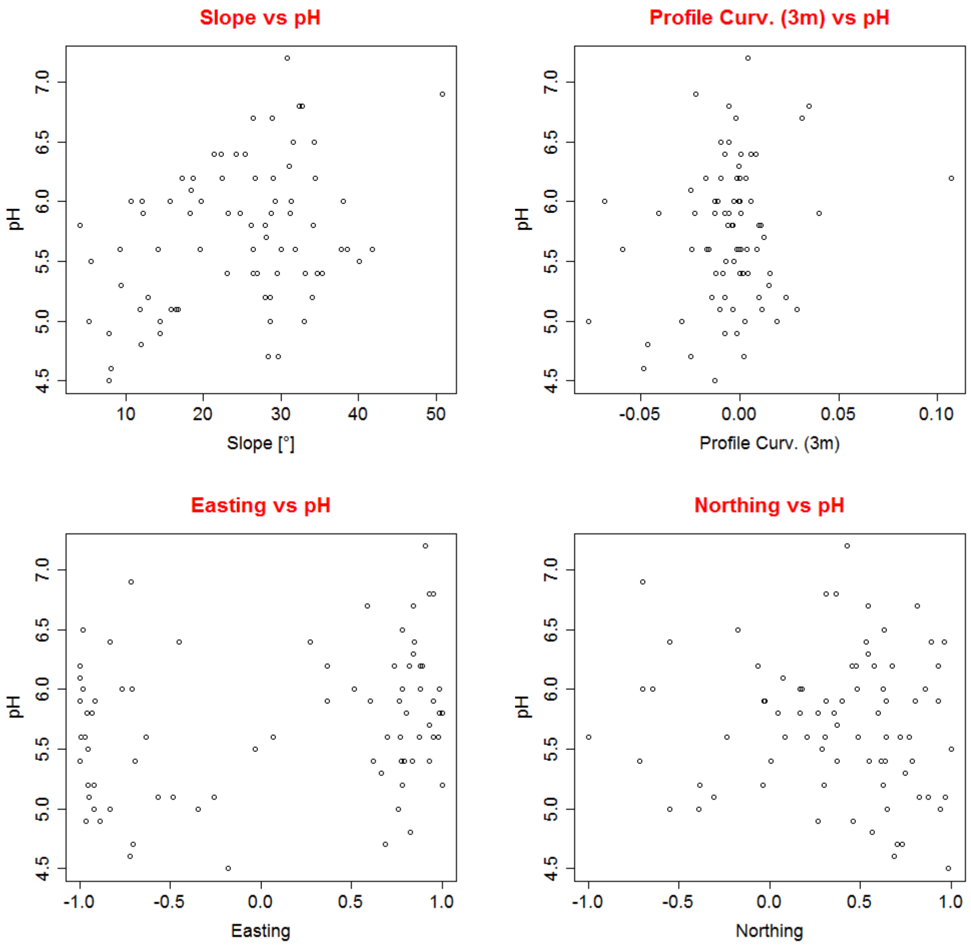


Figure 14: pH of the topsoil vs the explanatory variables (Slope, Profile curvature & Aspect)

The graph for the relation of slope to the pH (Figure 14) shows not much correlation, but a slight trend from low pH on gradual slopes to higher pH on steeper slopes might be observed. The spread of possible pH values on a certain slope is quite big for all slopes. Nonetheless there are no pH values below 5.5 for slopes above 40 degrees and none with pH values above 6 for slopes below 20 degrees.

Although there are almost no values for very convex areas there seems to be a slight trend from low pH values for concave areas and higher pH values towards more convex areas. No pH values below pH 6 have been observed on convex areas whereas clearly the lowest pH values were found on concave areas.

There seems to be no apparent relations between pH and Northing for this area. The figure for the relation between easting and pH does not show a strong relation either. There might be very slight relation between them though. There are two peaks of observations in the graph, in general east and west facing slopes. The second peak seems to have slightly higher pH values than the left peak, although the difference is very small.

3.3.3 Silt & clay fraction

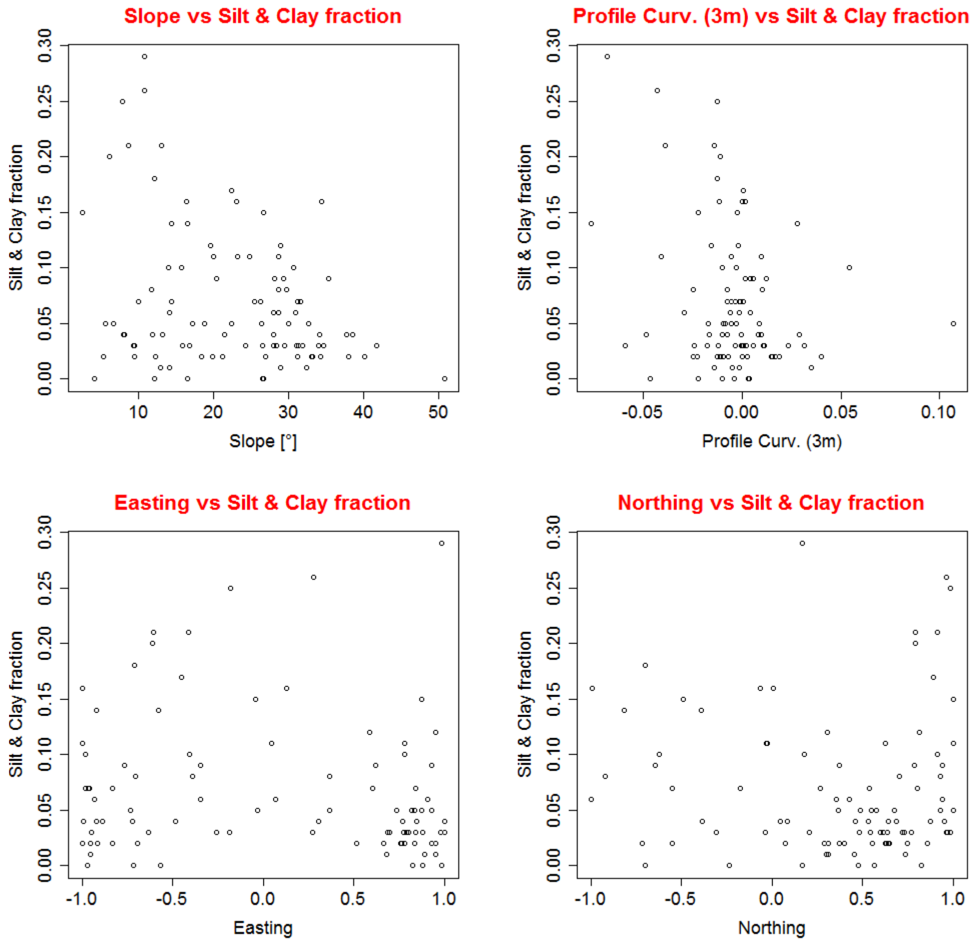


Figure 15: Silt and clay fraction of the topsoil vs the explanatory variables (Slope, Profile curvature & Aspect)

The values for the silt fraction in relations to slope (Figure 15) do not get above a line more or less along the diagonal. Lowest values for the silt fraction occur on the steepest slopes and highest values on the less steep slopes. The spread increases toward the less steep slopes however. On almost flat areas the values for the silt fraction range from 0 to 0.30 more or less.

The picture for the profile curvature vs the silt and clay fraction seems to follow the same pattern. There is a dense group of points around the 0 value, which means that there is only slight concavity or convexity. Locations with high convexity only give low values for silt and clay fraction, whereas locations with high concavity give high and low values for the silt and clay fraction.

Neither the graph for Easting vs silt fraction nor the graph for Northing vs silt and clay fraction gives any indication of trends for aspect with the silt and clay fraction. The correlation is insignificant on the (p <0.05) level for both cases.

3.3.4 Root depth

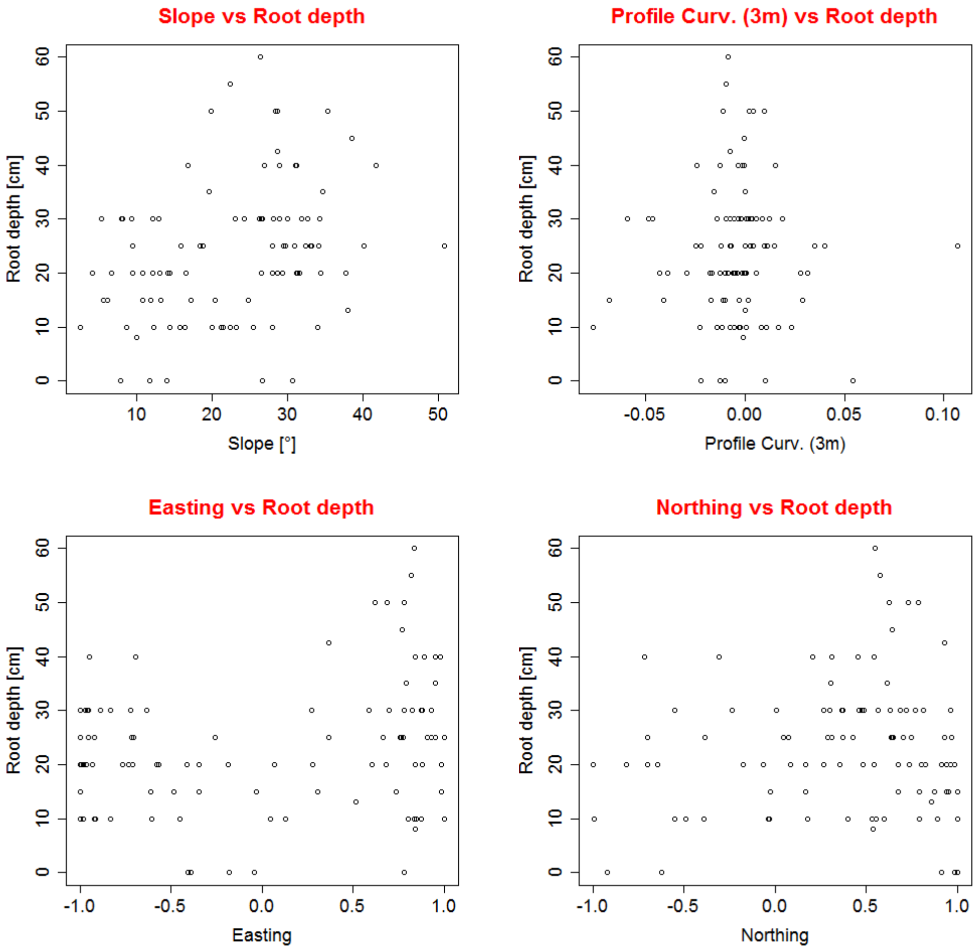


Figure 16: Root depth vs the explanatory variables (Slope, Profile curvature & Aspect)

None of the graphs for root depth versus micro-relief (Figure 16) show any signs of trend between the rooting depth and the micro-relief parameter.

The graphs for aspect seem to be very well spread, and give therefore no sign to any trend.
The first figure, the relation between slope and root depth doesn't show a clear trend, but it is can be seen that some medium values are found for root depth even on steep slopes.

3.4 Erosion

3.4.1 DOD 1953 & 2006

In order to analyse the effect of erosion in the area two DEM's of difference were created, one for the period 1953-2012 and one for the period 2006-2012.

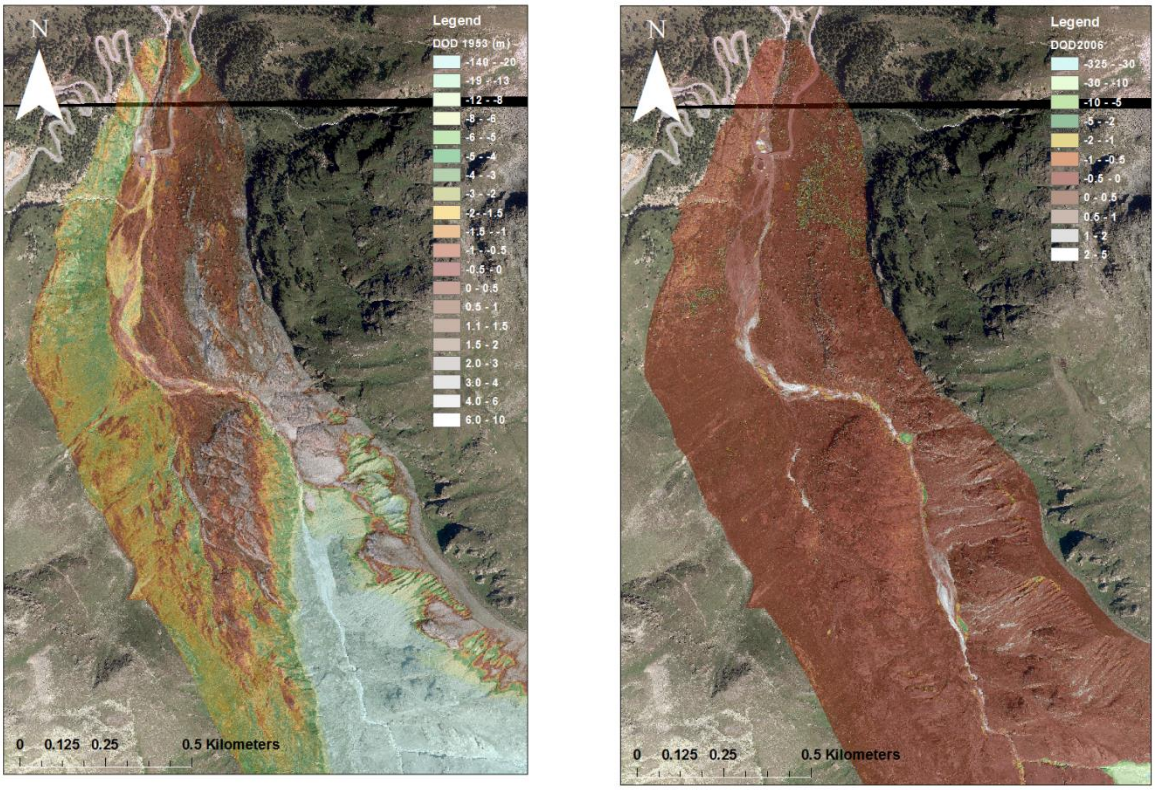


Figure 17: DEM of difference images for 1953-2012 (left) and 2006-2012 (right). The 1953 image still shows part of the glacier snout in the lower right corner. Values are given in cm.

Values for the DOD of 1953-2012 range from about -10 to 4, whereas value for the DOD of 2006-2012 range from about -2 to 1 (Figure 17). The range is much smaller for the smaller time interval.

Clear patterns can be observed for the DOD 1953; the fluvial pattern is clearly visible as well as the large moraine gullies. Moreover even the erosion processes on the long 1850 side moraines at the left part of the image are clearly visible. Several landslides, debris flows and gullies can be seen; which correspond well with aerial photography and field observations (Figure 18).

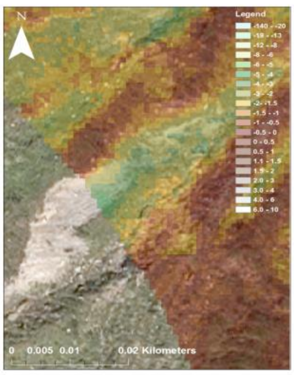


Figure 18: Landslide area with erosion values from DOD 1953

The DOD of 2006 only clearly shows the fluvial pattern and some of the very steep side moraines, that are still active. The rest of the area seems a bit spotted, and is hard to distinguish between significant differences originating from erosion processes and random noise created in processing.

To investigate the influence of erosion for the period 1953-2012 the DOD values for that period were correlated with the dependent variables (Figure 19).

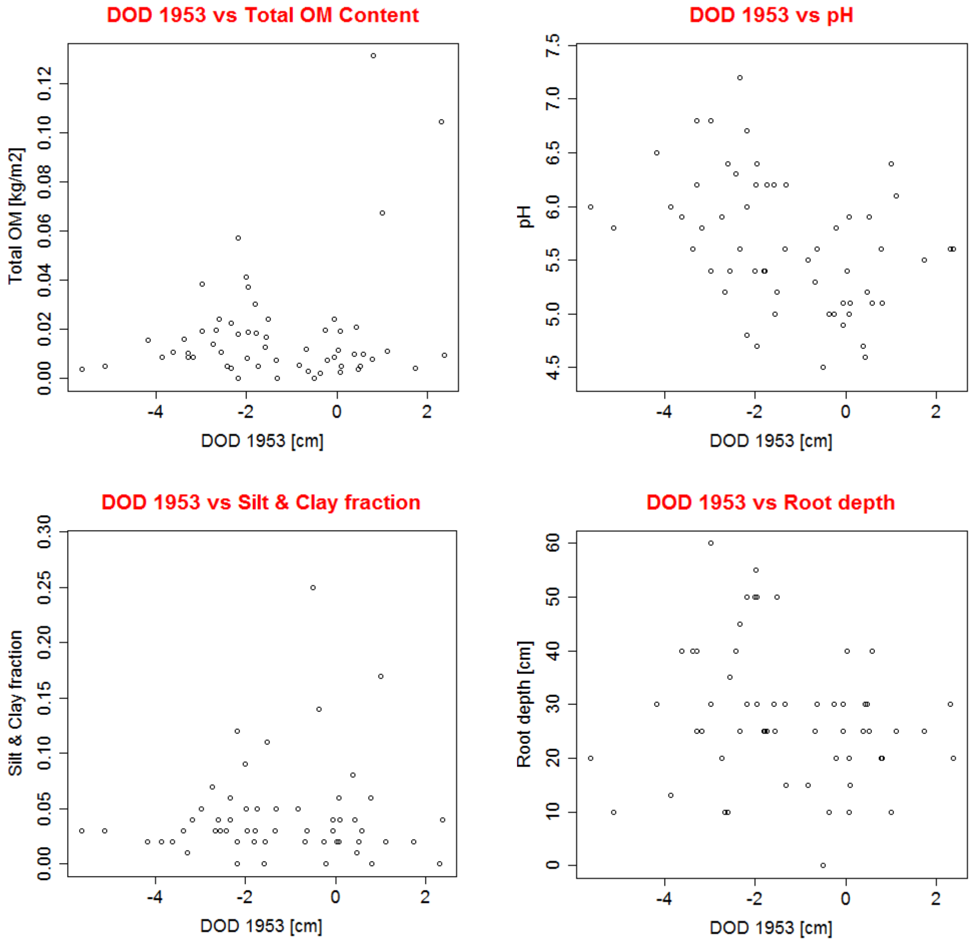


Figure 19: DOD 1953-2012 relations with the dependent variables (Total OM, pH, Silt & Clay and Root depth)

The DOD actual erosion values plotted versus the total OM content give a general trend with low values of OM for areas where erosion has taken place and high values only occurring on locations where depositions has taken place (Figure 19). There is however divergence of values visible towards locations with deposition of material.

The relation of pH versus the DOD values shows a general broad range of measured pH values. There seems to be a small trend of lower pH values towards stable positions and higher pH values towards positions with stronger erosion. The lowest pH values are found on positions with no or only small erosion or deposition. No pH values below 5.7 are found for strongly eroded positions.

The silt fraction appears to be low for positions with strong erosion and increases for locations with less erosion or deposition. The divergence in measured silt fraction also increases with less erosion or deposition. The highest silt fractions are found on the mostly stable positions with few erosion or deposition.

There seems to be no clear relation for root depth versus the DOD values. On positions with very strong erosion there seems to be a smaller rooting depth however.

3.4.2 LS factor

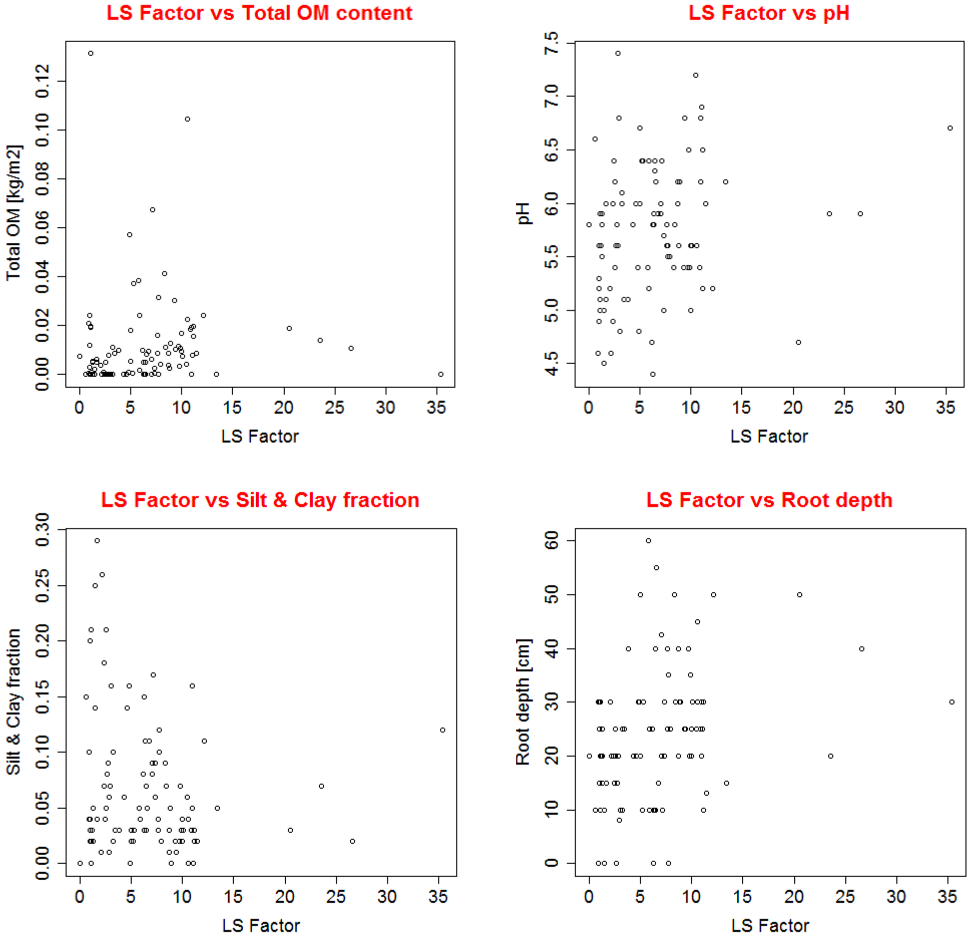


Figure 20: The relations for LS Factor the dependent variables (Total OM, pH, silt & clay fraction and root depth)

The total organic matter content gives a general trend with the LS factor of high organic matter contents for positions with a low LS factor and lower organic matter contents for positions with a higher LS factor (Figure 20). In general the spread in organic matter values increases with lower LS factor. Very high values for OM content are only present on positions with low LS factor, whereas very low values for OM content can exist on positions with all LS factor values.

The graph for pH versus LS factor gives no clear trend, but there seems to be a slight positive relation. No low (<5.5) pH values occur on positions with a very high (> 15) LS factor. On very stable positions on the other, with a low LS factor less soils with a very high pH seem to occur.

The silt and clay fraction relates very nicely to the LS factor; High silt and clay fractions occur only on position with a low LS Factor and small silt and clay fractions occur on a wide range of LS factor values. On the other hand positions with a high LS factor only have a low silt and clay fractions. There is again divergence occurring. The spread in LS factor increases towards positions where lower silt and clay fractions are found.

There seems to be no relation for root depth and LS factor.

3.4.3 Stream Power Index

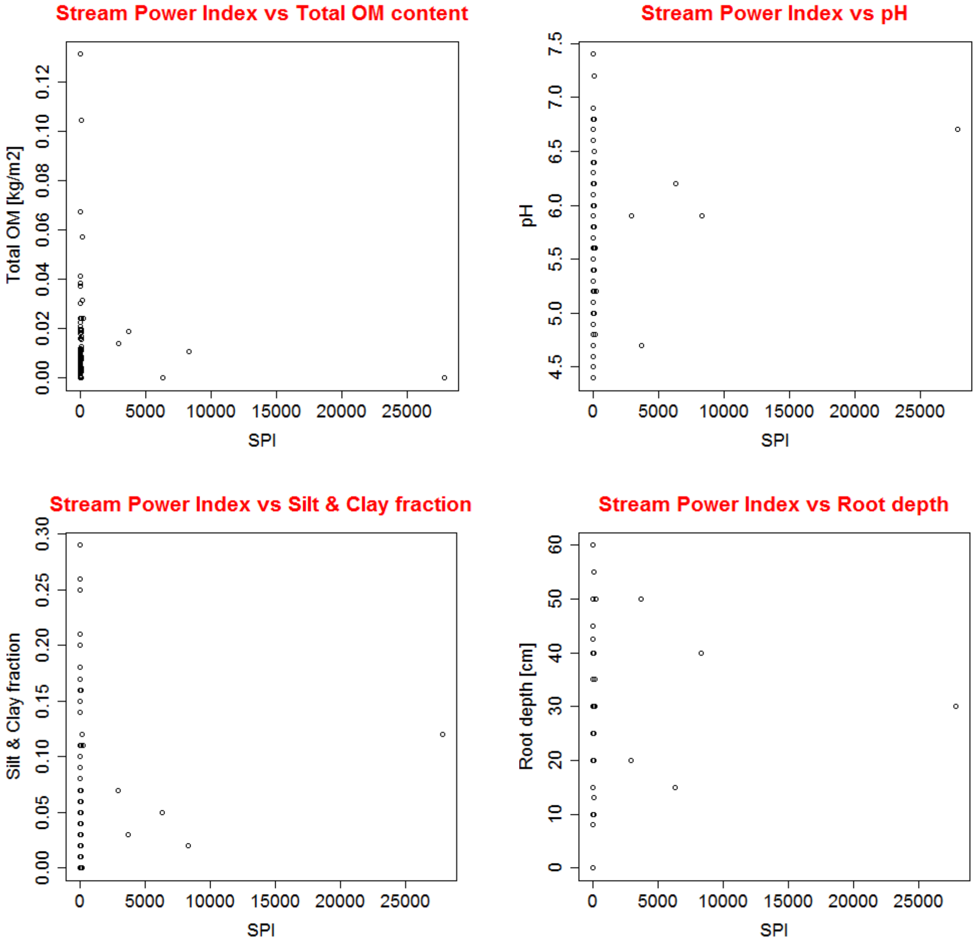


Figure 21: Relations for Stream Power Index with the dependent variables (Total OM, pH, Silt and Root depth)

In general the Stream Power Index relates more or less in the same way to the dependent variables as the LS factor (Figure 21). A clear relation with total organic matter can be observed in the graphs above.

pH and the silt and clay fraction seem to give the same pattern as well although it is difficult to be sure because of the lack of data points with a non-zero SPI value.

No relation of the stream power index with the rooting depth is observed.

3.5 Multiple regression analysis

3.5.1 Stepwise linear regression analysis

Results for the stepwise linear regression models are given in Table 12, 13, 14 and 15. The coefficients for the different explanatory variables are given as well as the significance level. An additional significance code is given as well for clarity.
In case of a skewed distribution a transformation to a normal distribution might result in a higher percentage of explained variation when one uses linear regression. Therefore the skewness (γ) of the distributions for the different explanatory variables was calculated. In case of a skewed distribution of an explanatory variable, a transformation was applied according to Webster (2001). In this case the transformations to a normal distribution did not yield a higher percentage of explained variation, therefore no transformations were used in this analysis.

Table 12: Variables and coefficients to model Organic matter content based on survey points. Significance codes are given as followed: 0 '*', 0.001 '**', 0.01 '*', 0.05 '.', 0.1 '', 1**

Organic Matter Model			
	Coefficients	**Pr (>|t|)**	
(Intercept)	0.279	9.94e-05	***
Age (A)	-1.393e-04	0.000142	***
SPI (SPI)	-1.679e-06	0.149	
LS Factor (LS)	7.521e-04	0.373	
Northing (N)	2.731e-03	0.472	
Slope (S)	-2.315e-04	0.478	
Profile Curv. (C)	-4.387e-02	0.608	
Easting (E)	-7.584e-04	0.789	

For the organic matter model only age was found as a significant explanatory variable on the 0.05 significance level (Table 12). Age has a negative relation to organic matter, so the higher the year of exposure the lower the organic matter content.

Table 13: Variables and coefficients to model pH based on survey points. Significance codes are given as followed: 0 '*', 0.001 '**', 0.01 '*', 0.05 '.', 0.1 '', 1**

pH Model			
	Coefficients	**Pr (>|t|)**	
(Intercept)	-1.996	0.452	
Age	3.906e-03	0.00655	**
Slope	2.118e-02	0.0303	*
Easting	0.169	0.0549	.
SPI	6.101e-05	0.0617	.
Profile Curv.	4.418	0.0879	.
Northing	-0.200	0.161	
LS Factor	-2.300e-02	0.331	

For the pH-Model the young sites with lower pH due to temporary pyrite acidification were omitted. Age and Easting are significant explanatory variables on the 0.05 significance level and profile curvature on the 0.1 significance level (Table 13).

Table 14: Variables and coefficients to model Silt & Clay fractions based on survey points. Significance codes are given as followed: 0 '*', 0.001 '**', 0.01 '*', 0.05 '.', 0.1 '', 1**

Silt & clay fraction Model			
	Coefficients	**Pr (>|t|)**	
(Intercept)	-0.659	0.00163	**
Age	3.914e-04	0.000295	***
Profile Curv.	-0.535	0.0370	*
Slope	-1.313e-03	0.177	
Easting	-6.493e-03	0.440	
SPI	1.719e-06	0.617	
LS Factor	6.457e-04	0.796	
Northing	-1.502e-03	0.894	

Both age and profile curvature are significant explanatory variables for the silt & clay fraction on the 0.05 significance level (Table 14).

Table 15: Variables and coefficients to model Root depth based on survey points. Significance codes are given as followed: 0 '*', 0.001 '**', 0.01 '*', 0.05 '.', 0.1 '', 1**

Root depth Model			
	Coefficients	**Pr (>|t|)**	
(Intercept)	1.547e02	0.000321	***
Age	-7.167e-02	0.00107	***
Easting	2.857	0.0977	.
Profile Curv.	-48.650	0.348	
LS Factor	0.433	0.396	
SPI	-4.732e-04	0.500	
Slope	0.130	0.510	
Northing	0.439	0.848	

Only the explanatory variable age is significant on the 0.05 significance level for the root depth (Table 15).

Table 16: Equations and adjusted R-squared for the final models of the dependent variables

Final Models dependent variables			
	Equation		**Adj. R^2**
OM Content	$OM = -0.000139\ A + 0.279$	5	0.12
pH	$pH = 0.00390\ A + 4.418\ C + 0.0212\ S + 0.169\ E + 0.0000610\ SPI - 0.200\ N - 1.996$	6	0.24
Silt & Clay fraction	$S\&C\ = 0.00039\ A - 0.535\ C - 0.00131\ S - 0.659$	7	0.22
Root depth	$R = \ -0.0718\ A + 2.857\ E + 0.433\ LS - 0.000473\ SPI + 155$	8	0.20

The final models from the stepwise linear regression analysis give rather similar values for the adjusted R-squared, except for the organic matter content model (Table 16). The pH of the soils seems to be most complex to model as most variables are included.

3.5.2 Regression tree analysis

On top of the nodes in the regression trees the criteria are given on which the group division is based. Below the node the average of the remaining group of site is given for the variable of interest. The right branch of every node represents the sites for which the criterion is true, and the left branch represents the sites for which the criterion is false. So for the organic matter content (Figure 21) this means that the average for all sites is 0.018 kg/m^2. The average of the sites for which the first criterion (DOD > 0.790) is true is 0.055 and the average of the sites for which it is false is 0.014. The remaining groups can be subdivided again, until variation in the remaining group cannot be significantly explained by splitting up the group.

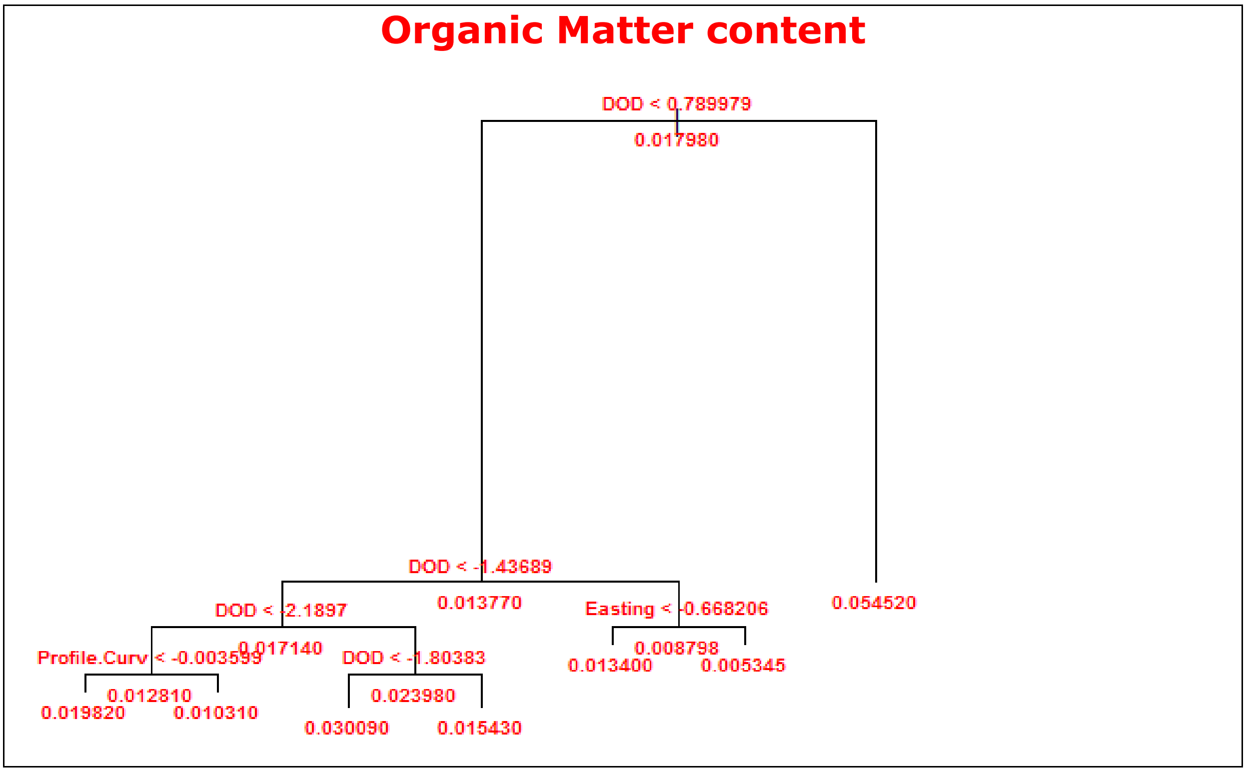


Figure 22: Regression tree for the Organic Matter content [kg/m2]

The first divisions in the regression tree for the organic matter content (Figure 21) divide the sites in five groups based on the DOD 1953. The groups are < -2.190, between -2.190 and -1.804, between -1.804 and -1.437, between -1.437 and 0.790 and > 0.790. The two remaining divisions are based on the micro-relief explanatory variables easting and profile curvature.

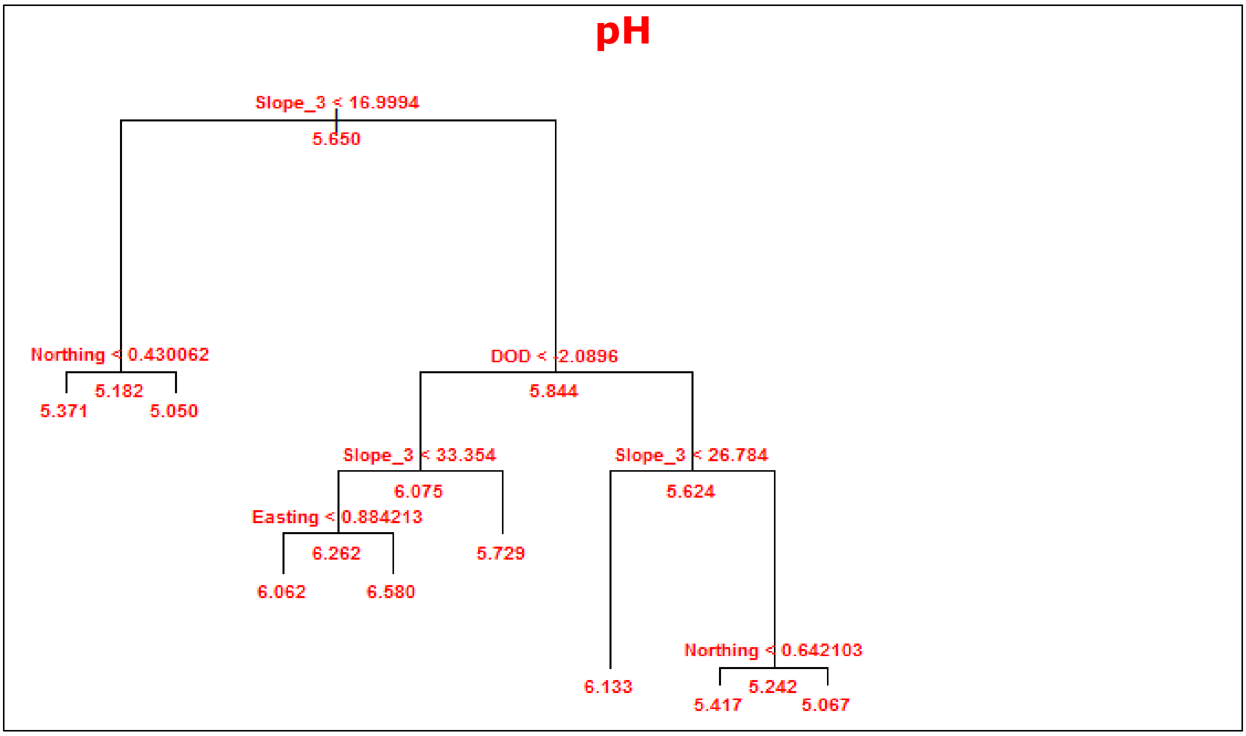


Figure 23: Regression tree for the pH

The main group division for pH is based on the slope (Figure 22). On the steeper slopes the next main division is made base on the DOD 1953 actual erosion data. These two data groups are then again split up according to slope. The last division are made based on aspect.

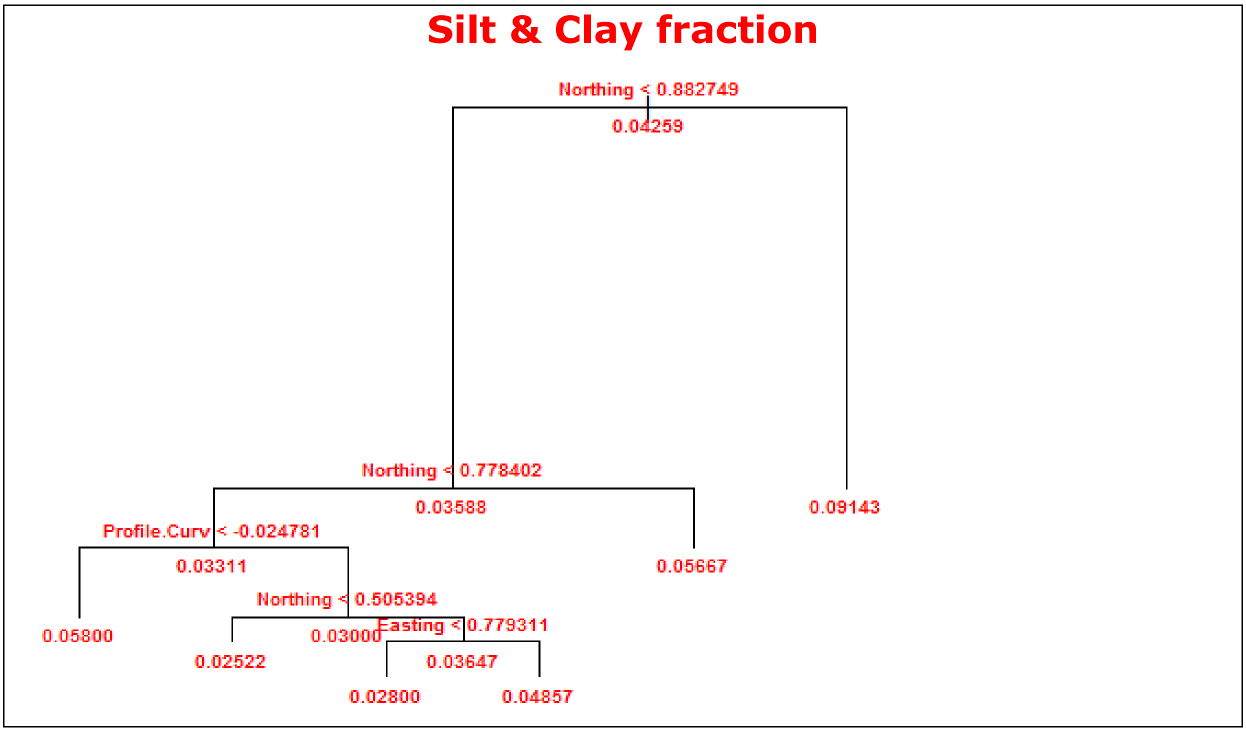


Figure 24: Regression tree for the Silt & Clay fraction

The first two main group divisions for the Silt & Clay fraction are based on Northing (Figure 23). Sites with a strong Northing are extracted from the rest. Next a division is made again based on profile curvature, separating concave and convex sites.

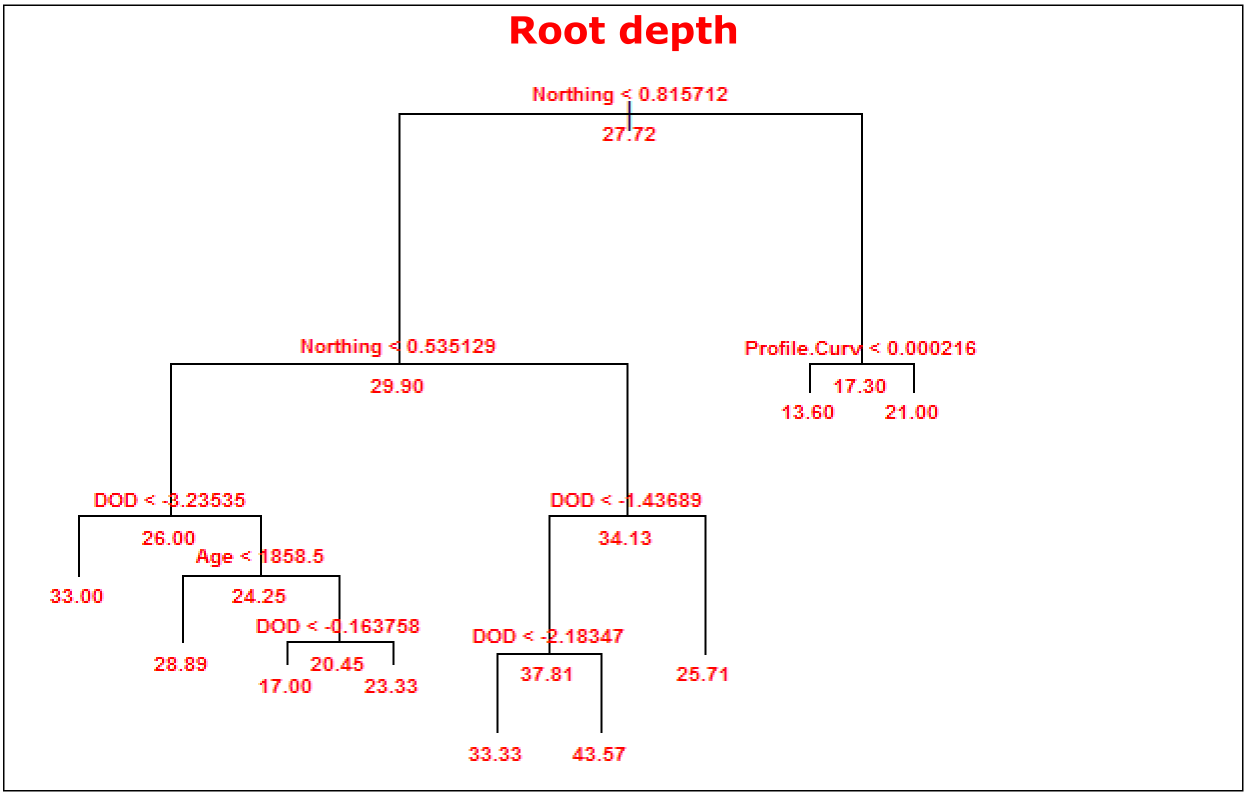


Figure 25: Regression tree for the Root depth [cm]

The main group division for Root depth are made based on Northing (Figure 24). The sites are divided into three groups based on Northing. Further divisions are mainly based on the DOD 1953.

4 Discussion

4.1 Soil formation

Pioneer vegetation in the research area is observed after only a few years. This is similar to previous research (Burga et al., 2010; Conen et al., 2007; D'Amico et al., 2014; Egli et al., 2006b). Egli et al. (2006b) and Burga et al. (2010) both found an age of 7 years for the Morteratsch Glacier.

Soil formation in the Gepatsch glacier forefield starts after approximately 40 years. In previous research this generally is about 30 to 35 years. Egli et al. (2006b) even reports first signs of soil formation after only 20 years, and a 25% coverage of the valley floor by Skeletic/Lithic Leptosols after 30 years. Dümig et al. (2011) found organic surface layers and Ah-horizon after 62 and 70 years, but they did not have any sample points between soil with an age of 15 years and those of 60/70 years. The research of D'Amico et al. (2014) showed strong build-up of organic matter in the first 60/70 years as well, but here as well no soils were sampled between an age of 5 to 10 years and 60 years. In the Gepatsch glacier forefield there are almost no soils present with an age of 30 to 35 years. Soils with that age were covered by the glacier again during the temporary re-advance in the eighties. Most of the area was only uncovered again around 1990 and has therefore an age of less than 20 years. No signs of soil development are found on these soils, which is consistent with previous research. The succession series from skeletic Regosols/Leptosols to skeletic Cambisols to (Skeletic) Podzols is similar to those found by previous research as well (Dümig et al., 2011; Egli et al., 2006b). In the Gepatsch study area however soil formations seems to be a bit faster. Within the 150 year age range quite some (33) Cambisols are found and even one very immature Podzol. None of the previous researches reports a Podzol within 150 years of soil development for glacier forefields.

Total OM contents of the soils in the Gepatsch forefield start to build up after approximately the same as in previous research (Egli et al., 2006b; Temme and Lange, 2014 2014) (Figure 7). Maximum organic matter contents are however much larger, soil evolution seems to go faster here than for previous studied areas. In general the OM contents that were found are similar to what was found by Egli et al. (2006b), between 2 and 10%, but much higher than the 0.3 to 1.8% found by Vilmundardóttir et al. (2014). Their research focused on the proglacial area of the Skaftafell glacier in Iceland, which could explain the lower values due to a shorter growing season and colder climate. In the Gepatsch study area also soils were found with much larger OM percentages. Quite some soils were present with up to 30% of organic matter and the highest was 88%. A probable explanation for this could be that the relief of this area is much stronger than that of the Morteratsch area, where mostly rather flat areas were selected. The higher OM contents that were found could therefore partly be explained by a larger deposition influence.
One of the main differences for the trend of Organic Matter with age in comparison with previous research is the fact that the values diverge towards older ages. This effect is shown by a larger standard deviation for older soils (Table 9). The divergence can be related to the fact that the overall relief of this area is much stronger than those of previous research. Temme et al. (2014) state that a strong influence of relief in the form erosion processes will lead to convergence in soil properties. They state that homogenous erosion processes from the side moraines wipe out any divergence in soil properties that might have previously existed. All soils are rejuvenated by the homogenous erosion influence and therefore equal again. For flat and stable areas the occurrence of divergence in soil properties can be explained by the time-split approach (Sommer et al., 2008). This approach states that some of the soils do not reach maximum state but develop in other directions due to either external influence or self-organization. Previous research usually wanted to eliminate the influence of erosion and deposition processes (Temme and Lange, 2014), and found therefore mostly divergence. However in this research we were actually interested in the influence of those processes on soil formation. It seems that for this area although there is a lot of relief and there is a high erosion influence there still are more or less stable areas to be found were soil develops in a divergent way. This fact in combination with constant influence of erosion and convergence on smaller scales leads to strong divergence of soil properties on

the large spatial scale. In addition the use of a high resolution DEM in this research shows divergence in processes on scales for which previously no information was available.

Vilmundardóttir et al. (2014) also reports acidification of soils along the chronosequence, which is similar in the Gepatsch area. They report highest values of pH 8 close to the glacier snout though and lowest values of pH 5.4 on the oldest moraines. An average decrease of 0.015 pH unit per year is reported for the Skaftafell forefield. A range in pH from about pH 5 to about pH 7 is reported for the Tschierva, Forno & Morteratsch glaciers (Temme and Lange, 2014), which is consistent with a decrease of about 0.012 pH unit per year. Lowest pH values in this research are slightly lower than 5.4, but this can be caused by the warmer climate for our research area. The highest pH value found was 7.4. The average rate of pH decrease is was about 0.012 pH unit per year. This value is consistent with the values found in previous research. The highest pH values in the Gepatsch forefield were not found in front of the glacier snout. In front of the Gepatsch glacier snout very low pH values were observed. In comparison with previous research the fact that very low pH values were found for soils of only a few years old seemed very strange. Whereas normally the highest pH values are found in front of the glacier, in this case some of the lowest pH values for the area were found just in front of the glacier. Apart from the area just in front of the glacier the pH values in this more or less seemed to follow the general pattern of lowering pH with age. Some exceptions were a few high pH values on old soils, which are thought to be caused by erosion of low-pH subsoil. These erosion processes are very clearly visible in this area. The long moraine slopes in the area with soils from 1850 have large areas clearly influenced by landslides and debris flows. Some unexpected high pH values for old soils were also reported by Temme and Lange (2014). They reported no clear sign of erosion processes. The points were located close to the fluvial system however, so erosion seems a likely cause. When the effect of pyrite acidification is taken into account the relations shown in Figure 9 can be obtained. The relation for de-acidification is significant and the relation of the normal acidification trend is almost significant on the 0.05 significance level.

It is likely that something is causing a temporary decline in pH just in front of the glacier after which the pH values rise fast again, only to slowly decline again with age according to the known pattern. A mineral that is known to cause acidification in soils is pyrite. The importance of pyrite oxidation as an early weathering and acidification process and the fact that it largely goes unrecognized due to its relatively rapid occurrence in geological terms was also stressed before for research in Sweden (Darmody et al.). The mineral structure of the rock in this area was not sampled in this research, but pyrite is previously stated as one of the key minerals in the rocks of the area (Vavtar, 1981). Therefore it seems that the low pH values on the young soils just in front of the glacier are a temporary effect caused by acidification through the weathering of pyrite.

No silt and clay fractions were reported by Egli et al. (2006b) for the Morteratsch glacier as they are minimal. It is stated that silt and clay fractions are only partially present and are thought to be caused by Aeolian attribution or fluvial abrasion. Dümig et al. (2011) report combined Silt & Clay fractions up to 0.45 for the Damma-glacier though, which is even more than was found during this research. The combined Silt & clay fractions that were found in the Gepatsch area seem to fit nicely into this range. The large variety in fractions that was found is probably also a result of the strong relief in the area. Silt & clay fractions are strongly correlated to the slope and appear mainly driven by erosion (Figure 13). Silt & clay fractions also seem to have a negative relation with age (Figure 7), where younger soils have slightly higher silt & clay fractions. A possible explanation for this effect could be the existence of katabatic winds coming down from the glacier (Wolfe, 2013). These winds can take up fine material from the debris positioned on top of the glacier and deposit this material on the plain in front of the glacier snout. For the Gepatsch forefield this area is disconnected from the rest of the area by a 90 degree bend of the forefield. The katabatic winds coming from the glacier in combination with the Föhn effect can also transport fine material from the surrounding area or even Saharan dust to this area as was described for the Zugspitze (Küfmann, 2003).

Rooting depths in the Gepatsch forefield give a general trend from shallow to deeper with increasing age, but are in general very divergent. Only for very young soil there seems to be a limit (about 20cm) to the depth that can be reached by the roots, as can be seen in Figure 7. The pioneer vegetation is a precursor for soil development, and as such also rooting depths are found faster than soil development. Vegetation can establish itself already on soils of only a few years old and roots of this vegetation seem to grow in general to a depth of 20cm. It might be that this is the characteristic depth of the species that represent the pioneer vegetation in this area. When other types of vegetation start to appear and the maximum rooting depth increases, but the lower values stay present as well. This gives an indication that not at all locations pioneer vegetation is yet succeeded by other vegetation. Soils at these locations apparently either develop less fast or have been rejuvenated by erosion. There are clear indicators for erosion on all different scales in this area (Figure 6), so this could be a likely cause.

In general soil evolution seems to be faster in the Gepatsch forefield than was found for other glacier forefields. The cause for this is not completely clear and probably just as complex as the area itself, but some suggestions can be made. The Gepatsch forefield is located just North of the main Alpine ridge and hence is influenced by the Föhn effect, which causes slightly higher temperatures than for similar areas without Föhn winds. However this effect would normally cause the area to be a bit drier as well. The Kaunertal valley is however mostly oriented to the North and therefore receives quite some rain as well. The influence of increased soil moisture on North facing slopes for weathering rates has already been suggested (Egli et al., 2006b). This effect in combination with a slightly warmer environment could cause the faster soil evolution that was found for this area. Besides those climatological factors the parent material might influence the soil evolution rates here as well. The parent material is very rich in all sorts of minerals (Vavtar, 1981) and is therefore a very nutritious basis for plant growth.
It seems that the idea that time is the most influencing soil forming factor in glacier forefields still holds for this area, but the assumption of it being the only important factor is out-dated. For the Gepatsch forefield Climate (Föhn winds), Topography (strong relief) and Parent Material (pyrite) seem to have a strong influence as well, and soil fauna was not investigated. The influence of the soil forming factors besides time (Topography, Climate, Biology and Parent Material) apparently cannot just be assumed equal for different forefields. The Gepatsch forefield shows that no clear expectation of soil evolution behaviour (divergence vs convergence, process rates) can be given without investigating the possible influence of all soil forming factors. The same is true for modelling of soil parameters in glacier forefields.

4.2 Micro-relief

In addition to the large scale relief in the area there is a large variety in small scale relief as well with roches moutonnées and a strong fluvial system. It is thought that geomorphic processes at these small scales play a role in this area. In previous research mainly 30m resolution ASTER DEM's were used (Temme and Lange, 2014) as they are available for the entire world. The suggestion was made that this was too coarse too include all relief influences on soil development (Darmody et al., 2005). The smaller scale processes could not be incorporated although it is suggested that they are probably be playing quite a big role. This research used a very small scale DEM, where the question remained what the important scale was for this area on which the micro-relief processes are working. Figure 10 showed that correlations between profile curvature and the dependent variables were highest at a support scale of 3m for silt and clay fraction and pH. silt and clay fraction are mainly influenced by small scale water erosion, where rain and moisture erode fine material from more convex positions and positions without vegetation after which it is transported to more concave areas where it is deposited. The pH of soils is raised again when the soil is rejuvenated, which is the case of course when material is deposited. Therefore silt and clay fraction and in a lesser way pH are thought to be most important indicators to investigate at which scale these erosion processes work. Those both peak at 3m/5m, and therefore I propose this scale as the driving scale for erosion processes on the small scale in this area. As discussed previously the root depth adjust quickly to changes, besides that small amounts of deposition do not necessarily bury vegetation and therefore roots and vegetation might keep on growing; it is not reset like the pH is.

There seems to be a slight relation between the total organic matter content and the slope (Figure 11) where steeper slopes have less organic matter content and more gradual slopes have a higher content, but it is far from sure. The only thing that is is the fact that there are no high organic matter contents for very steep slopes. This is most likely the case because at those locations there is a more or less constant erosion of fine material from the top layer. The soil profile does not get the time to gather organic matter. The same process should be working on strongly convex areas. The second graph shows that this is the case. Locations with an almost neutral convexity are most stable and are therefore able to gather highest organic matter contents. Areas with slight concavity can still collect some organic matter content, but are probably influenced by deposition of small scale erosion. Therefore organic matter contents are lower there, but still higher than at slightly convex areas. Aspect does not really seem to play a role in determining the organic matter content, which is surprising because the difference in wetness and sunshine for north and south facing slopes might play a role in the extent to which small scale water erosion takes place. In this area however there were very little south facing slopes, and therefore almost none were sampled. A slight correlation between the absolute easting values and the organic matter content seems to be present (Figure 12), where more east or west facing slopes have higher organic matter contents. This was not expected and no clear explanation has been found.

As mentioned before, fresh material in this area after a year or 10 has a high pH value and with weathering this value slowly decreases. Therefore rejuvenation of the soil by erosion or deposition results in a higher pH. The effect of these erosion processes on the pH distribution of the soils in this area can be seen in Figure 14. Gradual slopes have the lowest pH values whereas steep slopes have the highest. This can be explained by the fact that steep slopes continuously lose material from their topsoil by erosion processes, revealing new fresh material with a high pH. In some cases no erosion is present on the gradual slopes, only some deposition depending on the source and path of the material. The deposited material will rejuvenate the soil as well to some extent, related to the amount of deposition. The deposited material has already weathered somewhat however and has therefore a lower pH than fresh material. This results in low pH on gradual slopes and high pH on steep slopes, but with a broad range (Figure 14). A similar trend is visible with the profile curvature where concave areas have the lowest pH and more convex areas have higher pH values. Striking is that areas with a curvature of 0 seem to have the highest pH values. This is unexpected, but could be caused by the low number of observations on strongly convex areas. There is no clear relation between aspect and the pH which wasn't expected either. The Easting shows more or less two clusters for pH values, east facing slopes and west facing slopes. The group of points for west facing slopes seems to be slightly higher on average in pH than for east facing slopes. There is no clear explanation for this effect, but it might due to the difference of the slopes in the area. The east facing slopes were located on a vegetated long side moraine whereas the west facing slopes were mostly located on very steep moraine slopes which are still active. Therefore west facing slopes might on average be rejuvenated more often than east facing slopes, hence the higher pH values.

The silt and clay fraction is strongly correlated to the slope (Figure 13), which is caused by small and large scale erosion processes. Water erosion picks up fine material from steep slopes during surface runoff and deposits it at more gradual slopes were the water infiltrates again. This results in higher silt and clay fractions on gradual slopes and lower fractions on steep slopes. There is however a strong diversity in fractions found on the more gradual slopes. This can be explained by the fact that probably all steep slopes are influenced by erosion due to their steepness. Therefore only low silt and clay fractions are found there. Not all gradual slopes are influenced by deposition of this fine material though. The fine material is picked up by surface runoff and to a large extent follow the runoff patters; the fluvial system. Therefore it will probably end up to a larger extent in the areas through which these small streams flow. Not all gradual slopes will receive material this way and the broad range in silt and clay fractions is explained. A trend with profile curvature is similarly explainable. All convex areas are influenced by erosion, whereas not all concave areas receive material through deposition. This results in low values for convex areas and a broad range of possible values for the concave areas. For the aspect there seems to be no relation with the silt and clay fraction. The erosion processes driving the differences might be working stronger on north facing slopes, but this cannot be found in these graphs.

The relation for root depth with slope (Figure 15) shows no clear trend, but there seems to be a peak in root depth at slopes of about 30% which is striking. Maximum root depth would be expected at most stable locations or at locations with slight deposition, but not at slopes of 30%. What is even more striking is that Temme and Lange (2014) found something similar for the effective soil depth. The effective soil depth peaked at low slope percentages, but there seemed to be a second peak around 22-35 degrees in several glacier forefields. They suggested a bimodal distribution. Although they found the relation with effective soil depth and not root depth it is safe to assume a relation between the effective soil depth and the root depth. In comparison with the results of Temme and Lange (2014) here the peak at low slope percentages seems to be missing though. There is no real explanation for this, expect perhaps for the fact that flat areas lower in the valley very often were old fluvial beddings with a large amount of large rocks limiting soil development and root growth. The figure for the profile curvature relation to root depth seems no clear difference between convex and concave areas. The probable cause is that in most of the cases we are talking about small scale erosion processes, which might not necessarily effect the vegetation immediately. Besides that the vegetation is very fast in re-establishing itself after larger scale erosion processes. Largest rooting depths are however found for areas without a neutral curvature. Assuming that rooting depth increases with vegetation succession we can assume that stable areas are most beneficial for fast vegetation succession. Aspect does not have any correlation with the rooting depth. Probably there are differences for vegetation statistics to be found for the different aspects. However on all different aspect plants have no trouble to grow and are very fast to adapt or re-establish after erosion. Therefore probably similar rooting depths are found for all aspects.

4.3 Erosion

The 1953 DOD shows much more erosion and deposition differences than the 2006 DOD (Figure 16). In the 1953 DOD the fluvial systems is visible as well as erosion processes on the moraine slopes, whereas in the 2006 DOD only the fluvial system is slightly visible. Overall for both of the DOD's it is clear that the area is in general eroding. The fluvial erosion system in this area is apparently working on timescales of about 5 years already. The other large scale erosion processes are apparently in general working on larger timescales as well as the small scale erosion processes. Only on the very active moraine gulley's some slight erosion is visible in the 2006 DOD. In the 1953 DOD all erosion gulley's on the active moraines are visible as well as a large number of landslides and debris flows on the other moraine slopes. The DOD data is quite detailed and matches with aerial photography of the area (Figure 16). Field observed landslide and debris flow areas can also be observed in the DOD. There is however some noise in the DOD's caused by vegetation. The DEM's were not filtered for vegetation, but this should not influence the large patterns. Moreover sample plots were never located that close to a tree that erosion values should be influenced by this noise. On average within 60 years 1.5cm of material has been eroded from the area, which corresponds with an average erosion of 4 t ha^{-1} yr^{-1}. This value is similar to values found for hillslope erosion in a semi-arid area (Nearing et al., 2005).

The DOD of 1953 clearly relates with the total organic matter content of the soil. The more material has eroded from a location the lower the organic matter content. Highest levels of organic matter are found on stable locations or locations with deposition. There is added complexity by the fact that no altitude change does not necessarily mean that the position has been stable for all those years. For the locations where deposition of material has taken place there is a large spread in organic matter contents. This might be caused by the different nature of deposition. Some of the observations may be explained by deposition of material by the river in an overall active area. Time after time quite large amounts of material are deposited and limit plants growth and the build-up of organic matter. Whereas on other locations the deposition might have occurred in a single event, perhaps a landslide that happened a long time ago, or by the continuous deposition of small amounts of fine material by small scale erosion processes. In the first case vegetation might have started growing again a long time ago already, in the latter case the deposition might not have been enough to really affect vegetation growth or might even have enhanced it. Those locations can now have rather high organic matter content as compared to the river deposition locations. This variation in possibilities may cause the spread in values. The pH also behaves differently for deposition and erosion areas (Figure 18). Locations were material is eroded and the soil therefore rejuvenated have the highest pH values. On the other hand the locations with deposition have slightly lower pH values as the deposited material has been weathered a little already. Lowest pH values are found on the more stable locations. In general this is the same pattern as was observed previously for pH and slope/profile curvature. Locations with strong erosion have low silt and clay fractions, because those are the particles most vulnerable to erosion. Highest silt and clay fractions are found on stable areas or areas with slight deposition. Highest values are however not found for strongest deposition sites, which could be due to the fact that there so much material is deposited that even larger particles are deposited there and the silt and clay fraction is therefore not raised. There is no apparent relation between the DOD 1953 erosion and root depth, because plant growth restarts very quickly almost immediately reaching to a reasonable root depth. There only seems to be a bit less root depth on very active locations with strong erosion. This could be caused by two things. Either so much material is eroded that the soil depth is becoming the limiting factor, or the location is so active with erosion that plants do not get time to establish.

The LS Factor is a measure for slope length and is an indicator for possible erosion. Therefore similar patterns as for slope and erosion are found (Figure 19). Low organic matter contents are found on locations with a high LS Factor, and hence probably strong erosion. Values diverge towards lower LS Factors, meaning that in general higher organic matter contents are possible on with lower LS Factor, but a large spread of values is possible. This is due to the fact that the organic matter content is influenced by a other parameters as well. The pH of the soils does not give a clear relation with the LS Factor. The only thing that is observed is that there are no extremely low pH values for locations with a high LS

Factor, which is normal for locations with probably strong erosion. The silt and clay fraction relates very strongly to LS Factor. The same pattern is found as for the other erosion indicators, low values with strong erosion diverging towards higher values for locations where there is less erosion. The rooting depth again has the weakest relation to this erosion indicator. What is a little weird is the fact that there are no small rooting depths for the high LS Factors. This might be explained by the fact that when plants grow at those locations they have to have a certain strength and hence a certain rooting depth to secure themselves there.

The relations for the Stream Power Index follow the exact same pattern as for the LS Factor and can be explained via the same concepts. The problem with Stream Power Index in this area is that there are very few sample locations for which the SPI is above 0. Therefore not much can be determined from it.

4.4 Scale problem

In general the redistribution patterns in the area seem to be very complex. It seems that there are different processes working at different spatial scales. On some of the oldest moraine slopes the prevailing redistribution process is that of small scale transport of fine material by water, because the area has in general been stabilized by vegetation. However at the same time at some parts of the slope there are large scale erosion processes happening as well like landslides and block slopes. The influence of those processes at different spatial scales on soil evolution parameters are almost impossible to distinguish from one another and usually strongly interact with each other. It might even be the case that different scales of erosion are working on different timescales as well, which makes it even more complex. One area can for instance be characterised mainly by small scale local runoff erosion processes. In this case the small scale relief is the driving factor. Another area on the other hand could be mainly influenced by large scale erosion processes. It might even be probable for areas to switch in spatial scale over time. A larger scale erosion event can be triggered for instance by an extreme precipitation event and cause the entire system to change to erosion on a larger scale. In the Gepatsch area with its strong large and small scale relief a lot of these systems seem to be active or temporarily dormant at the same time which makes this area very complex.

These processes on different scales seem to be coupled to the general erosion processes that are observable in the area as well. Those are; Debris flows, landslides, rock fall, gulley erosion, block slump, creep and several small scale runoff processes. It is likely that the scale that is active is also partly determined by the state of the area. Areas from which the glacier only just retrieved are more unstable than the vegetated area of 150 years old. It is highly probable that different scales are dominant for different parts of the forefield. This makes it extremely difficult to explain variation in soil properties for the entire area in the same manner. This could also explain the low percentages of explained variation (Table 16).

4.5 Multiple regression analysis

4.5.1 Stepwise linear regression analysis

For the organic matter model only age gave a significant relation (Table 12). The coefficient is negative which means that younger soils have a lower organic matter content. This is the basis of soil chronosequences and is consistent with previous research (Dümig et al., 2011; Egli et al., 2006b; Temme and Lange, 2014).

The explanatory variable age has a positive relation to pH (Table 13), so higher pH levels for younger soils, which is consistent with previous research (Egli et al., 2006b). Easting has a positive relation with the pH as well, so more East facing slopes have a higher pH. This effect could be explained by differences in insolation (Isard, 1989). Lastly the profile curvature has a positive relation with pH as well, indicating that more convex locations lead to higher pH. This can be related to more erosion from convex positions.

The coefficient for age is positive indicating higher silt & clay fractions on younger soils (Table 14), which could be caused by the effect of katabatic winds as explained before. The coefficient for profile curvature is negative which indicates lower Silt & Clay fractions for convex positions with more erosion and is consistent with literature (Iwashita et al., 2012).

The explanatory variable age has a negative coefficient for the root depth model (Table 15), which indicates lower root depths with a lower age. This is the effect of vegetation succession, where coloniser vegetation with a low rooting depth is succeeded by vegetation that is rooting more deeply (Eichel et al., 2013).

The adjusted R-squared values (Table 16) show similar values for pH, silt & clay fractions and root depth around 0.20. The adjusted R-squared is lower. Apparently the organic matter content in this area is more complex and less easy to model with the explanatory variables that we used. The model for pH explains 24% of the variation in the area. In previous research values ranging from 36% to 75% have been found (Temme and Lange, 2014). Coefficients that were found to be significant in their research include easting and curvature as well in combination with some landforms. In general the same coefficient are found as in this research, but still we get much lower explained variation percentages. It is suggested that this previous research might have overestimated the explained variance by using multiple variables that more or less have a similar meaning. The curvature is for instance also determining landform classes. Another explanation could be the fact that this research area is much more complex than theirs; here the entire area was used and not only stable areas were selected for sampling.

4.5.2 Tree regression analysis

The main group divisions for the organic matter content are made based on the DOD 1953 actual erosion data (Figure 21). The first main division extracts all locations with very strong deposition of material. These soils have a significantly higher average organic matter content (0.055 kg/m^2) than the other soils (0.014 kg/m^2). This can be explained by the fact that these locations receive material from elsewhere. This is probably humus rich material that has eroded from topsoil up slope. There might also be transport of humus to these locations by means of small scale water transport. This effect can be confirmed by checking for humus coatings on the grains, but this was not done for this research. In the left branch of the tree all locations are split up in 3 more groups based on the DOD 1953. These values are not directly easy to interpret as we would expect less organic matter for locations where there has been more erosion, but this is not the case. Overall the variation of average values in this branch is much lower (0.088 to 0.024) than the variation between the left and right branch (0.014 to 0.055). We have to keep in mind that the erosion data of the DOD 1953 has a timespan of about 60 years. The temporal resolution of the dataset is therefore very low, and there is no information on when this erosion has taken place during those 60 years. Erosions could have taken place for instance completely at the beginning of this period, which might even be likely due to the very instable environment upon glacier retreat (Curry et al., 2006). If this is the case organic matter production could have been going on for more than 50 years again already leading to higher organic matter contents than expected for a location with such strong erosion. The division based profile curvature are is to interpret again where convex areas lead to higher erosion and hence lower organic matter contents.

For the regression tree of pH (Figure 22) in the first main division soils with steep slopes are separated from the less steep slopes. The soils with a steeper slope have a higher average pH (5.8) than soils with a less steep slope (5.2). This can be explained by the fact that soils with a steep slope will probably experience more erosion over time. The soils are constantly rejuvenated, and the exposed new un-weathered material has a high pH. The division in the left is based on Northing. A strong Northing seems to lead to lower pH values; this can be related to the suggestion in previous literature that weathering is faster on North facing slopes (Egli et al., 2011). The main sub-division in the right branch is made based on the DOD actual erosion data, dividing the sites into sites with extreme erosion and sites with less or no erosion. Sites with strong erosion have a higher pH (6.1) than soil with less erosion (5.6) due to the same effect as discussed for slope, that of rejuvenation of the soil. The next division is again made based on slope, where less steep slopes seem to lead to a higher pH. This is strange and not directly explainable. It might be that the effect we see here has to do with the bi-modal distribution of soil depth with a peak at slopes of 20-30 degrees that was observed here as well in previous research (Temme and Lange, 2014). Slopes with a steepness of 20 to 30 degrees might be the place were some deposition of material occurs from more large scale erosion processes. If this is the case this could explain the higher pH values for slopes less steep than 33 and 27 degrees as the deposited material might be originating from a deeper layer and therefore have a higher pH. The last division based on Northing gives a similar result as for the other division based on Northing.

Divisions for Silt & Clay fractions seem to be mainly based on Northing, where fractions are higher (0.091 vs 0.033) for locations that are more strongly North facing (Figure 23). This effect can once again be explained by lower solar radiation and therefore wetter conditions on North facing slopes (Egli et al., 2011). These wetter conditions lead to higher weathering rates and more small scale water erosion. This small scale water erosion is thought to be especially important for the transport of fine material like silt and clay. In the left branch of the regression tree a second division is made based on profile curvature, once again dividing sites in concave and convex sites. Concave sites have higher silts & clay fractions (0.058) than convex sites (0.030), probably due to small scale water erosion that transports fine material from convex sites to concave sites.

The regression tree for root depth (Figure 24) first divides the sites into three groups based on Northing, but give a contradictory result. In general there is not much to derive from the regression tree for root depth. Some of the divisions are contradicting each other or just not interpretable. Root depth is apparently difficult to relate to the explanatory variables we used or just not influenced by them. This is something that was observed in the regression graphs already as well.

In general the stepwise linear regression shows us that age is still the most important explanatory factor for all our dependent variables. The silt & clay fraction seems to be influenced mostly by micro-relief explanatory variables besides age (profile curvature, aspect). When only half of the area is investigated and the DOD 1953 is used we begin to see the influence of erosion on certain dependent variables. Erosion seems to be mainly influencing the organic matter content and the pH of the soils. The most important factors for the silt & clay fraction are still the micro-relief variables.

5 Conclusions

This chapter concludes this research by addressing the objectives that were listed in the introduction. To what extent have they been accomplished and what knowledge gaps still remain and what are new questions and knowledge gaps that arose while answering the research questions? At the end of this chapter some of those new questions and remaining knowledge gaps will be addressed and some recommendations for further research will be summarized.

5.1 Objectives

The main objective of this research was to quantify the role of micro-relief and geomorphological disturbance on soil evolution on glacier forefield. The results to this main research objective will be given by addressing the results of the three sub-questions that were stated in the introduction.

- **What is the variability in soil characteristics within the Gepatschferner glacier forefield; for soils of different age as well as for soils of the same age?**

The total Organic Matter content and soil depth observed in the Gepatsch Glacier increase strongly with age and behave similarly to other glacier forefields. First signs of pioneer vegetation are found after a few (2-3) years and first signs of soil formation are found after approximately 40 years. The relation for pH and the age of the soils is different to other forefields due to the assumed influence of Pyrite weathering and hence acidification of the soil in front of the glacier snout. The pH relation to age of the soils for the rest of the area is similar to that of other forefields. In general the variability of soil characteristics seemed to increase with age of the soil. This divergence is thought to be caused by the strong spatial variability of the area and the small scale DEM that was used so that this spatial variability could actually be captured. More variation within soil characteristics with the same age was therefore found compared to previous research.

- **What is the influence of micro-relief on soil evolution within a chronosequence on the glacier forefield of the Gepatschferner?**

Some clear relations were found for micro-relief parameters and soil evolution which stress the importance the incorporate these parameters into soil chronosequence as well. Apparently the assumption that the time was the only significant soil forming factor in these areas is not complete true. Topography seems to have a strong relation to soil evolution as well in this area. The support size that captures the driving micro-relief on soil evolution in this area best was found to be three to five meter.
Organic matter content in the soil seemed to be primarily driven by age, but also influenced by slope and profile curvature. Silt and clay fractions of the soils are even primarily driven by slope and profile curvature and not so much by age. The pH of the soils is slightly related to slope and profile curvature as well as age of the soil. The rooting depth of the soils is least driven by micro relief as vegetation seems to be very adaptive and re-establishes itself fast.

- **What is the influence of geomorphological disturbance on soil evolution within a chronosequence on the glacier forefield of the Gepatschferner?**

Two DOD's were used to investigate the influence of erosion and deposition on soil evolution. A time period for 2006-2012 was found to be too short to yield significant differences for the entire area, only the fluvial system and vary active moraine gulley's showed up on the map. A DOD for the period 1953-2012 gave a nice view of all different erosion and deposition processes for the entire area. Average erosion over the sample locations was 1.33m. Relations were found for the DOD 1953 with organic matter and the silt and clay fraction. Erosion led to lower values and deposition to higher values. The pH gave a slight relation where high pH was found for erosive locations and lower pHs for stable and deposition areas. Total OM content and silt and clay fraction are found to have relations with the LS factor as well. Low values are found for large LS Factors, where erosion is probable and higher values

although with a large spread are found for locations with a lower LS Factor and hence lower probability of erosion. There are no low pH values found in the area for locations with a high LS Factor.
Similar trends as with the LS Factor are found for the Stream Power Index.

- **To what extent are Micro-relief and geomorphological disturbance in combination with age capable of explaining the variation in soil evolution parameters?**

Stepwise linear regression showed time as the main explaining variable for all dependent variables. For pH and the silt & clay fraction the profile curvature was an important explanatory variable as well. Easting was a significant explanatory variable for the pH. Besides time mostly the micro-relief seemed to be important for pH and silt & clay fraction. The tree regression analysis showed the importance of the actual erosion data for the dependent variables. Important group divisions based on actual erosion were made for the organic matter content and the pH. The silt & clay fraction division were again mainly based on micro-relief variables. It seems that different variables are important to explain the different dependent variables. Micro-relief seems to be most important in explaining variation in the silt & clay fraction besides time. Whereas the erosion processes seems to be of higher importance in explaining the variation in organic matter content and pH besides time. The root depth seems not to be strongly influenced by anything else than time.

We can conclude that the suggestion that was done by previous research that micro relief and geomorphological disturbance might play a role in soil development in addition to time is indeed true.
Moreover the parent material and climate have proven to be important for soil evolution in the Gepatsch forefield as well. The possible influence of ALL soil forming factors should be investigated before soil evolution behaviour can be determined or a soil properties predicting model can be made.

5.2 Recommendations

Relations are not found for all parameters and tend to be very complex, hence more detailed research will be needed to investigate the role of the different processes and parameters.
The relations that were found for the dependent parameters with the micro relief parameters that play a role in erosion in addition to relations that were found with erosion itself indicate the importance of erosion on soil development. There has however no difference been made between the erosion processes that influence the soil development on different scales. This was discussed in the discussion as well. As several scales of erosion in addition to a large series of erosion processes seem to play a role it is recommended to differentiate between the different erosion processes and the scales on which they act in future research. In this research only a geomorphological map with a quite high resolution was available on which only large units like moraine slopes and ground moraines were distinguished. It is recommended that in future research individual erosion processes like landslides and debris flows are mapped and taken into account.

The support scale that seemed to drive the erosion processes via micro relief in this area was 3 to 5 meters, but seemed to vary slightly per parameter. It is thought that this support size might vary per glacier forefield due to the unique nature of each glacier forefield. The support scale that actually drives processes might even change per location within the forefield as well as with time. Therefore additional research to the scales on which the erosion processes act spatially as well as temporally is recommended.

For this research usable actual erosion data was only obtained from one DOD due to lack of other data. The timespan of this DOD was 60 years, which appeared too large for this research. Erosion in the first few years of this 60 year could already be masked by 50 years of soil development again. It is thought that observed relations between erosion data and the dependent variables are therefore less strong than they are actually. It is recommended for future research to use erosion data with a higher temporal resolution. Differences were hardly visible over a time span of 6 years, therefore a time span of 10 to 15 years is recommended.

Acknowledgements

Over the course of this last half year I have received help of several people without which I would not have been able to complete this thesis. Therefore I would like to thanks the following people:

Arnaud Temme for supplying this interesting topic, for being my supervisor while being very busy, for the help with the fieldwork, for the discussion and positive feedback, for his enthusiasm and keeping me motivated.

Tobias Heckmann for being my second supervisor, for inviting me to Eichstätt, for the warm welcome in Eichstätt, for helping me with his expertise in GIS, statistics and morphodynamics.

Ludwig Hilger & Jana Dusik for showing me around Eichstätt, for sharing and helping me with the data from the PROSA-project, for sharing their office with me, for the great time in Eichstätt and the Kaunertal.

The master students in Eichstätt for showing me around Eichstätt, for the great time, for the party

David Morche for the help with the fieldwork, for his knowledge on the study area, for the discussion about the study area, for the great time I had in the Kaunertal for which I would also like to thank all of the interns from Halle.

Lukas Vehling for his knowledge on the geology of the study area, for the great time in the Kaunertal.

Jetse Stoorvogel for borrowing his field pH-measurer

Alice and Erna for showing me around the lab and sharing it with me.

My girlfriend Nicole for her positive support and for being more stressed about finishing this thesis than I was which gave me the urge to keep on going, for picking me up in Austria.

My mom for picking me up in Austria with all my samples and being interested in the subject.

My housemates for listening to my stories and frustrations during this thesis, for always being positive and interested about the topic.

My fellow thesis-students for drinking coffee, for exchanging experiences and tips during the thesis

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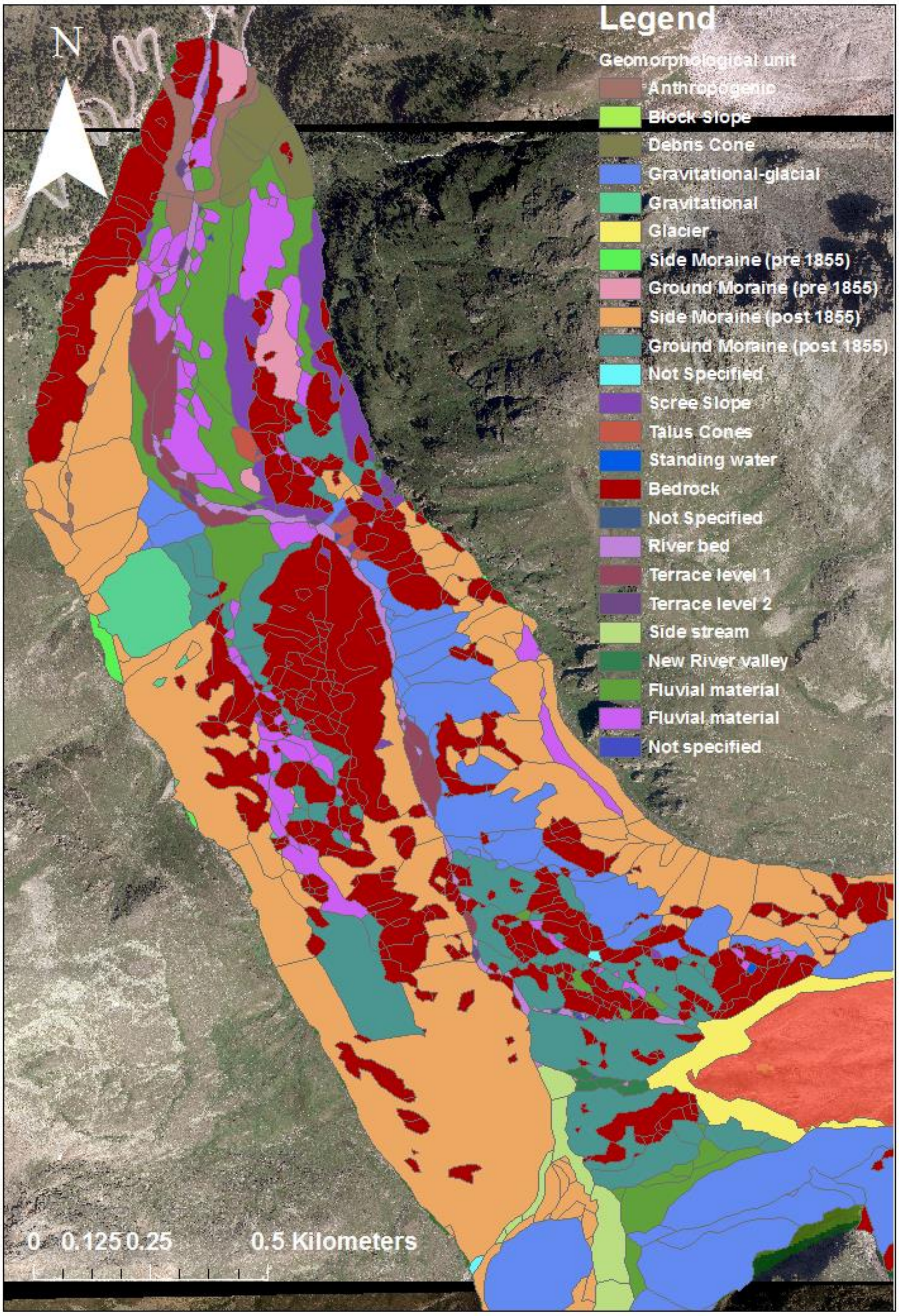
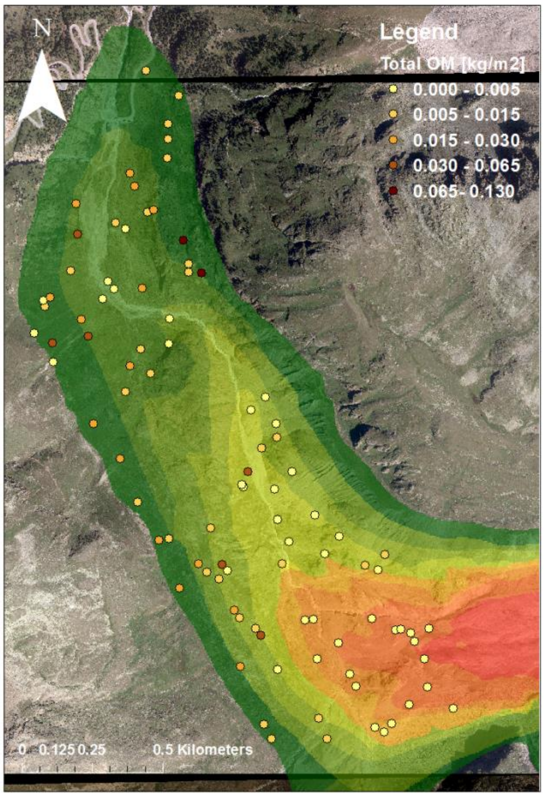
Appendices

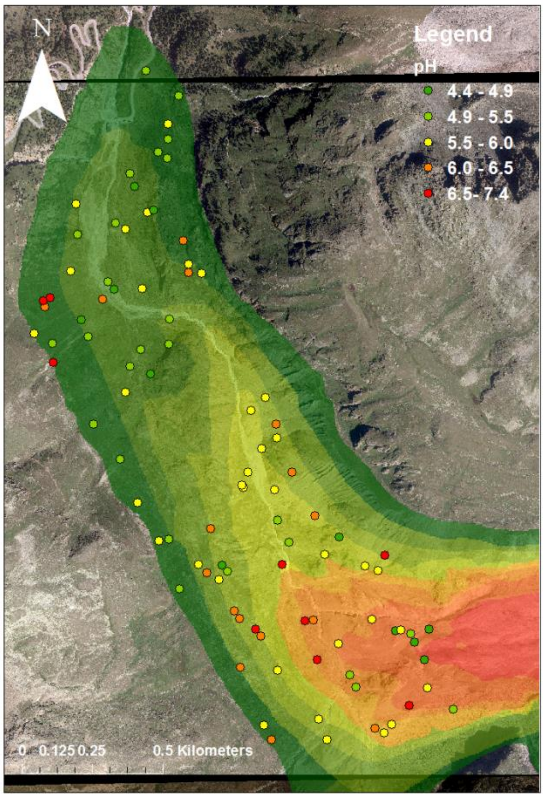
A. **Detailed geomorphological map**
B. **Maps of the distribution of the dependent variables**
C. **Maps of the distribution of the different explanatory variables**
D. **Maps of the profile curvature for different support sizes**
E. **Maps of the slope for different support sizes**

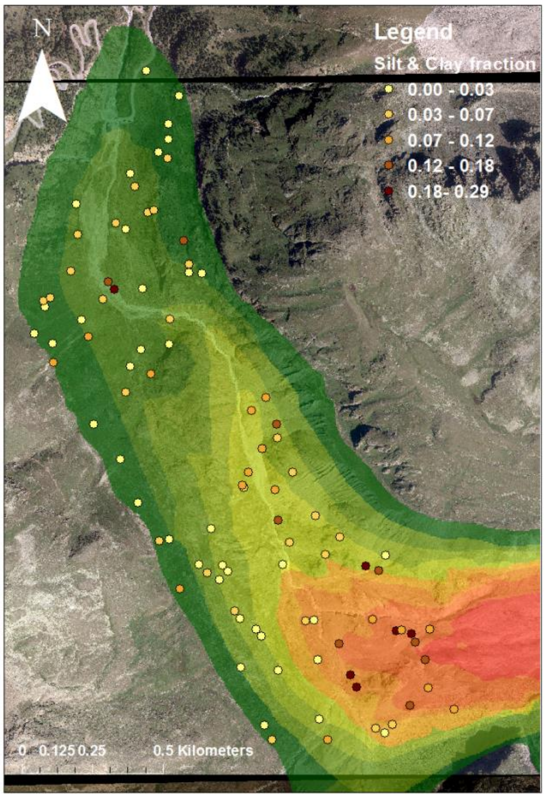
Appendix A: Detailed geomorphological map

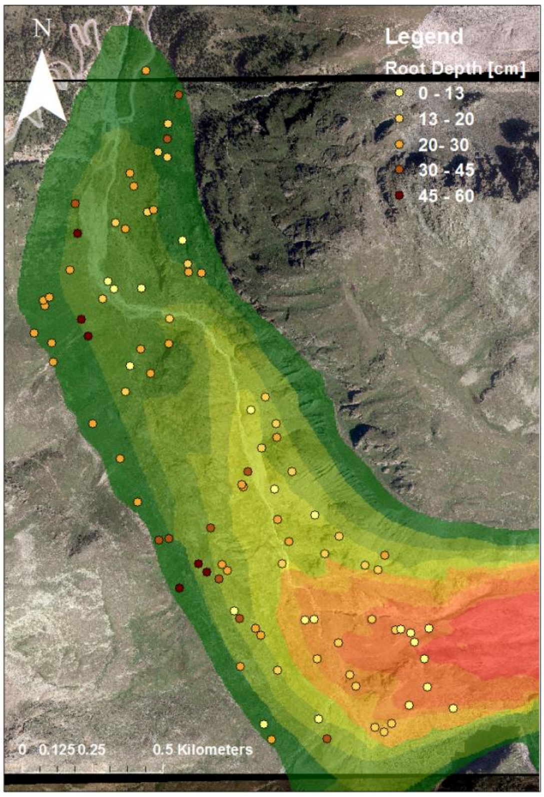


Appendix B: Maps of the distribution of the dependent variables

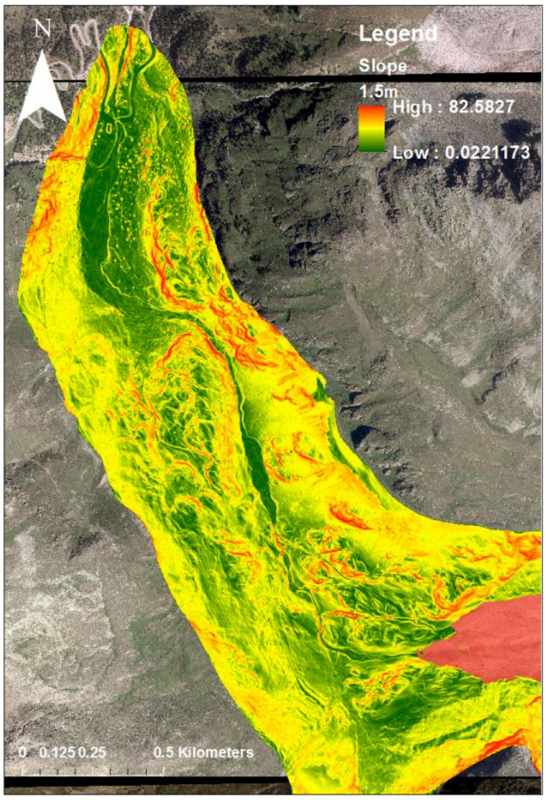


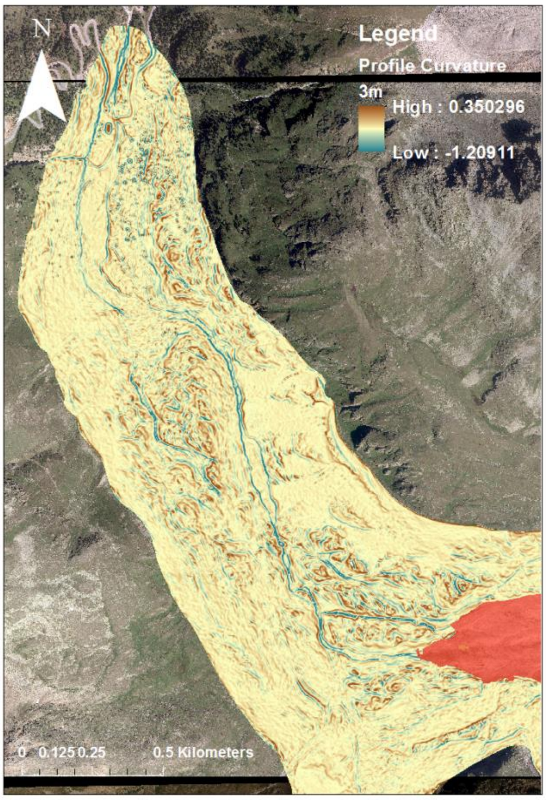


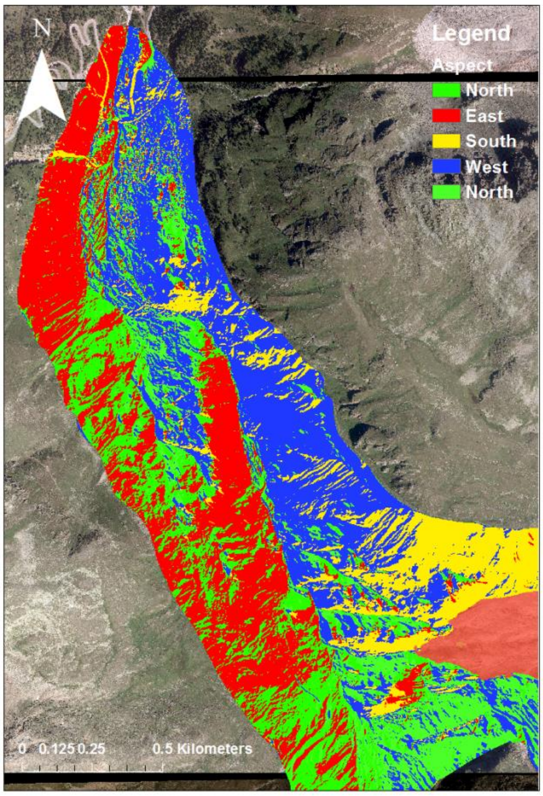




Appendix C: Maps of the distribution of the different explanatory variables

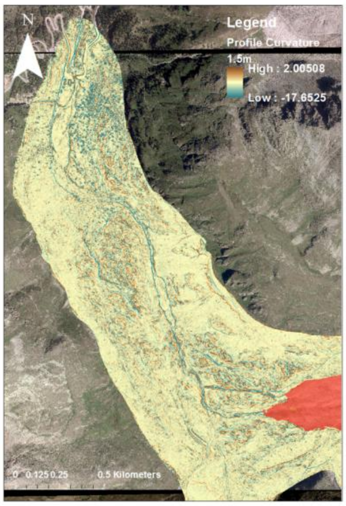


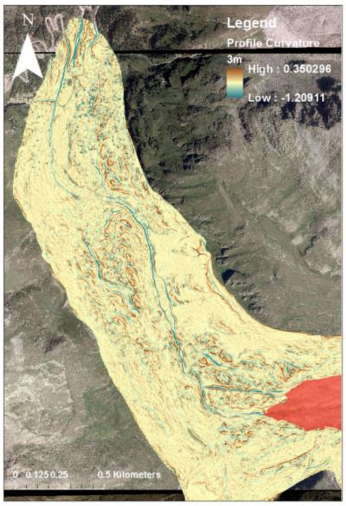


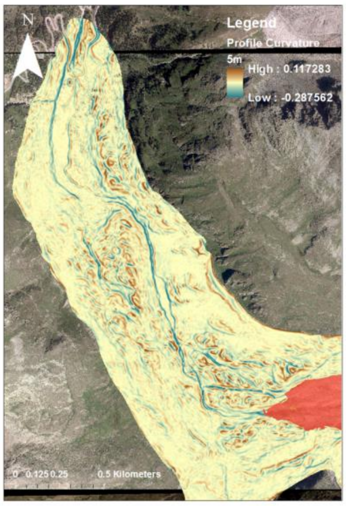


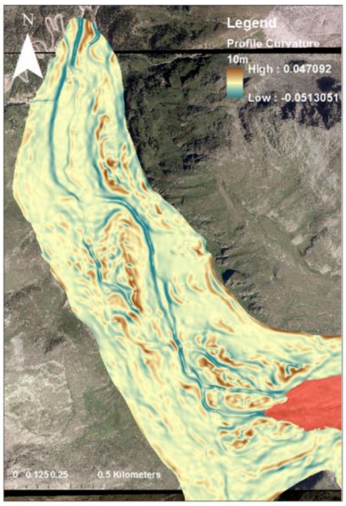
North: 315° to 45°
East: 45° to 135°
South: 135° to 225°
West: 225° to 315°

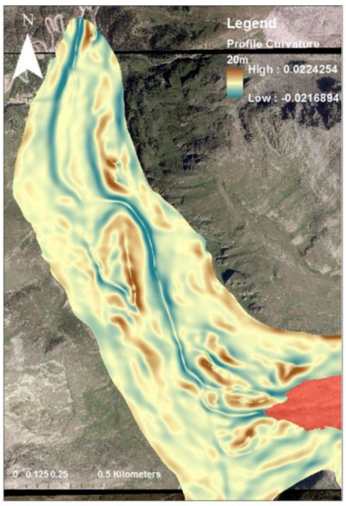
Appendix D: Maps of the profile curvature for different support sizes

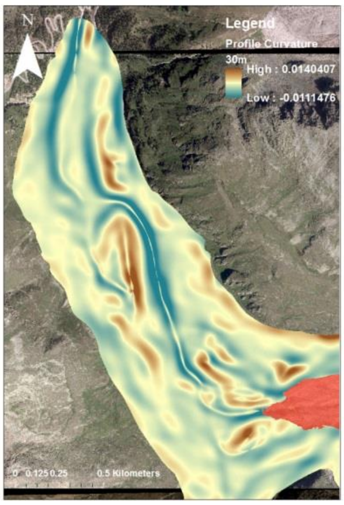












Appendix E: Maps of the slope for different support sizes