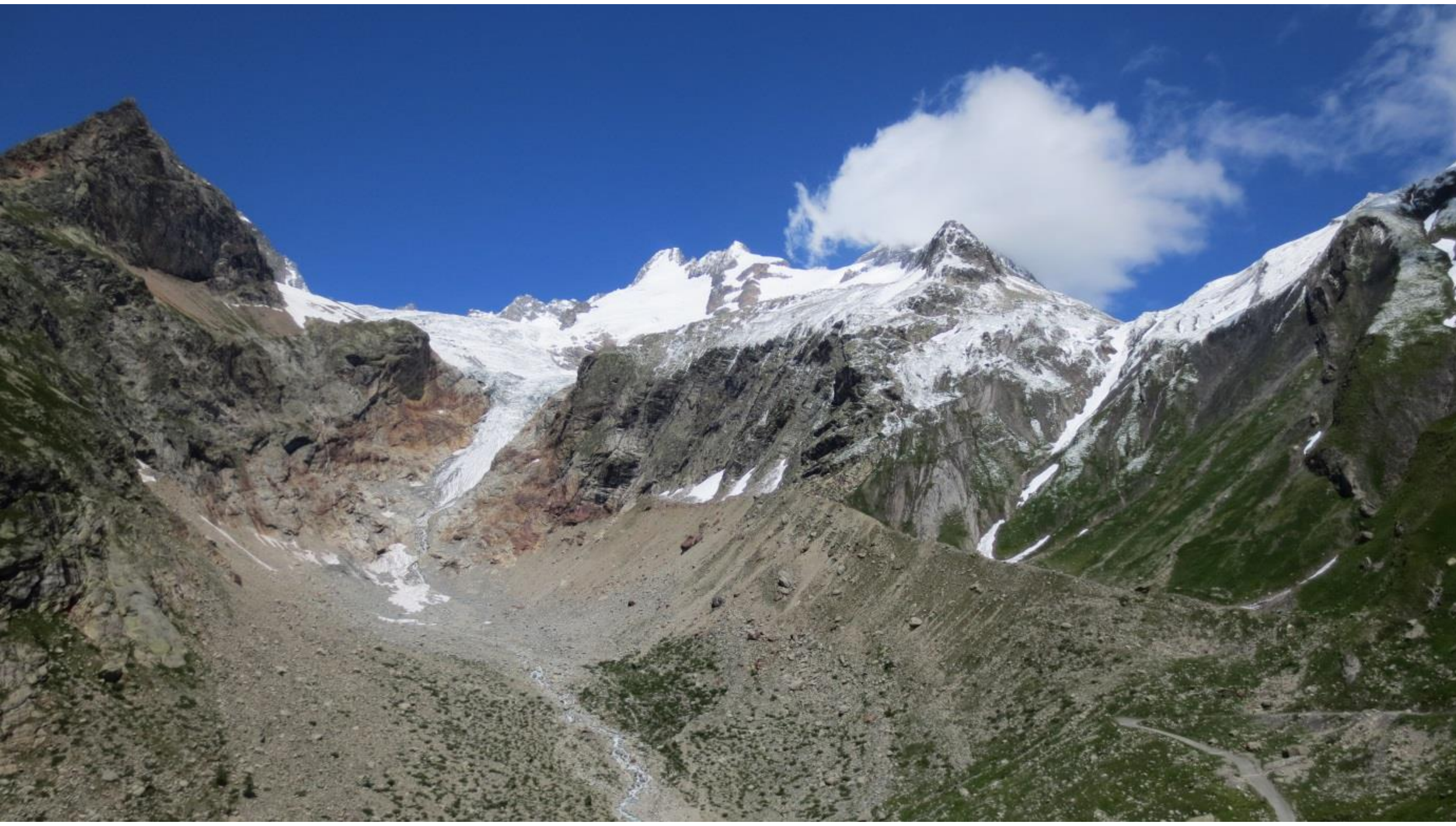
Master Thesis

Climate, A Driving Factor Behind Soil Formation In Proglacial Areas In The European Alps?



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Pictures front page:
Above: Part of the proglacial area of the Pré de Bar glacier and the glacier itself.
Below: Typical surrounding of a soil pit during fieldwork.

Abstract

One of the consequences of the increase of temperature in the world is melting of glaciers. Large areas became and become free of ice so weathering can take place and a soil can start to develop. Several studies have investigated the soil formation in the area between the maximal extent during the Little Ice Age and the nowadays glacier, the proglacial area. However, the effect of climate on this soil formation is still not extensively studied. This paper studied the effect of micro- and macroclimate on soil formation in proglacial areas. In total 103 sample locations were visited in the proglacial area of the Pré de Bar glacier, Valle d'Aosta, Italy. Multiple regression has been conducted to investigate the role of several microclimatic variables on surface stoniness, vegetation cover, root depth, pH, soil organic matter and silt and clay fraction. Next to this, the annual rates of change for vegetation cover, depth of soil formation, soil organic matter and pH have been calculated for several proglacial areas in the European Alps using previous research to these areas and have been related to annual temperature and annual precipitation. It appeared that microclimate, and then especially insolation, had an influence on the soil formation in the proglacial area of the Pré de Bar, but that this influence was very marginal compared to soil age and parent material. Macroclimate on the other hand seemed to have a larger influence on the annual rate of change of the different soil properties. Vegetation cover and depth of soil formation were increasing faster with higher precipitation amounts and soil organic matter seemed to increase slower with higher precipitation amounts. Different suggestions could be made for the reason of these visible trends. Continuation of this comparison can lead to a better understanding of the soil formation in these proglacial areas and can maybe help to predict future conditions.

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1. Introduction

1.1 Background and Problem Description

Climate change is one of the main concerns of people around the globe. A visible consequence of the increase of temperature and the changing climate in general is the melting of ice. One of the most sensitive areas to climate change are the European Alps (Theurillat et al., 1998), because glaciers in this area are retreating fast which has consequences for the environmment as well as for tourism (Beniston, 2003; Singh and Bengtsson, 2005; Zemp et al., 2006). The retreat of glaciers is also called one of the destabilizing processes in glacial areas which has and will have a huge impact on the geomorphology in these areas (Chiarle and Mortara, 2009).

Glaciers in the Alps have been retreating since the end of the Little Ice Age (LIA), so for more or less 160 years now (Orombelli, 2011). The maximal extent of a glacier during the LIA can often be distinguished by the preserved end moraine from this time. The area between the end moraine and the present glacier snout is called the proglacial area or glacier forefield, in this report called proglacial area. These areas became free of ice and so weathering could take place and a soil could start to develop.

The steady retreat of glaciers since the end of the LIA and the development of soils are causing to some extent a soil chronosequence to develop. A chronosequence is a sequence of soils where time is the only soil forming factor which differs (Jenny, 1941). The other four soil forming factors (topography, climate, parent material and biological life) as described by Jenny (1941) are assumed to be constant. Studying soil chronosequences is important to reconstruct soil development in the past and to predict future development of soils and possible land uses.

Chronosequences are widely used to study the development of soil types and soil properties in proglacial areas around the world (Haugland, 2004; Hodkinson et al., 2003; Zhou et al., 2016) and in the European Alps (D'Amico et al., 2014; D'Amico et al., 2015; Dümig et al., 2011; Egli et al., 2006b; Harlaar, 2015; Temme et al., 2016; Temme and Lange, 2014).

One of the earliest studied chronosequences in a proglacial area in the Alps is the proglacial area of the Morteratch glacier. Egli et al. (2006b) confirmed that the differentation between soil types in a proglacial area depends on time. The soil type shifted from Skeletic/Lithic Leptosol, formed after 20 years, to a Humi-Skeletic Leptosol after 100 years. Dystric Cambisols start to develop after 250 years. Another important conclusion made by Egli et al. (2006b) was that slope, exposure and landform also play a role in the soil development in proglacial areas, so time is after all not the only important soil forming factor.

Temme and Lange (2014) also studied the Morteratsch proglacial area in order to quantify the effect of soil age and topography on more detailed properties of the soils in that proglacial area. In addition to the Morteratsch proglacial area they studied the nearby Forno and Tschierva valleys as well. This study confirmed the earlier findings by Egli et al. (2006b) that, besides time, topographical variables also play a significant role in the variation of soil types and soil properties. The study of the three valleys combined indicated that flat and wide proglacial areas protected by moraines with a regular glacier retreat history and with a fast incision of the melt water river are the best areas for time-dependent soil development. In these areas geomorphic acitivities will have a low or neglectable influence on soil development. However, these conditions are rarely met and most proglacial valleys in the Alps are quite different. This makes studies comparing the differences between proglacial areas valuable.

Following the study of Temme and Lange, Temme et al. (2016) used the available information for the proglacial area of the Gepatsch in Austria to quantify the influence of micro-relief and geomorphic disturbances. The proglacial area of the Gepatschferner has undergone severe geomorphic activity and is far from the ideal proglacial area described by Temme et al. (2014). Nevertheless, soil age was still important in describing the soil development. It was also shown that the most commonly used 30 meter resolution DEM is too coarse to take into account all the geomorphic processes that play a role.

Next to topography, also vegetation in a proglacial area has been studied in relation to soil development over time. D'Amico et al. (2014) studied the proglacial area of the Lys glacier in order to look for the effect of alpine and subalpine vegetation on soil development in such a chronosequence. Vegetation appeared to increase the rate of soil development. An E horizon could be found already after sixty years under a subalpine larch-*Rhododendron* forest, although the diagnostic spodic requirements were not yet met.

D'Amico et al. (2015) studied also different lithologies in proglacial areas. The Verra Grande valley consists of serpentinite rock, while the Lys valley consists of gneissic material. The serpentinite valley appeared to have a much slower soil development rate compared to other lithologies. On patches with vegetation or with small quantities of other parent material the soil development rate seemed to be higher in the serpentinite valley.

The last extensively studied proglacial area in the Alps is the area of the Damma glacier in Switzerland. One study showed that soil organic carbon accumulates fast and that the amount of poorly cristalline Fe and Al increased over the years (Dümig et al., 2011). A comparison with older soils just outside the proglacial area showed that soil forming processes slow down after a few hundred years. Next to this study numerous research was out carried at this proglacial area about the development of the soil microbial community (Noll and Wellinger, 2008; Schurig et al., 2013; Welc et al., 2012).

Summarizing these studies, the assumption that chronosequences in proglacial areas are only dependent on time since glacier retreat is not valid any more. Other soil forming factors such as topography, parent material and biological life that were studied in relation to chronosequences in the European Alps were indeed found influencing the evolution of soils significantly. However, climate is not extensively studied yet. Climate is important for soil formation since many soil forming processes depend on the amount of water and the rate of the processes is mainly determined by the temperature (Matthews, 1992). The effect of climate on soil fomation has been studied in many settings, the so called zonal soils (e.g. Birkeland, 1984; Dahlgren et al., 1997). A zonal soil is a mature soil which reflects the climate of the region (Matthews, 1992). Soils in proglacial areas are no zonal soils. A proglacial soil is not mature yet and therefore it belongs to the azonal soils. Matthews (1992) states that proglacial soils are azonal soils which are developing to zonal soils. Also Messer (1988) studied the influence of climate on proglacial areas. Her study on 18 proglacial areas in southern Norway showed that precipitation and temperature affect the evolution of the cation exchange capacity and soil depth. Some suggestions were made regarding microclimate during the studies in the European Alps, especially the effect of slope orientation on weathering (Egli et al., 2006a). However, most soils studied in this perspective are of much higher age than the soils in proglacial areas which started to develop after the Little Ice Age. Another suggestion made by Dümig et al. (2011) was that soil moisture is of influence, because thicker humus layers where found on soils with wetter conditions. The fact that soil moisture plays an important role is also seen in the Russian Altai region (Egli et al., 2015). The evolution on north-facing slopes seems to be enhanced at this location probably due to higher soil moisture content on these slopes. Low temperatures seems not to be the limiting factor regarding weathering in cold alpine regions.

Until now, the influence of climate on proglacial areas in the Alps is not extensively studied while recent literature is indicating the need of research of this aspect (Heckmann et al., 2016; Temme et al., 2016). Particularly, there has not yet been a comparison between different proglacial areas from different locations and thus different climates in the Alps. The relation between microclimate and soils in proglacial areas is also unstudied till so far.

1.2 Objectives

The objective of this study is to investigate the effect of climate on soil development rates within and between proglacial areas. The proglacial area which is used for this study is the Pré de Bar glacier in the Valle d'Aosta region, northwest Italy.

In order to reach the objective the following questions were formulated:

1. What is the variability in soil development and soil properties within the proglacial area of the Pré de Bar?
2. What is the effect of microclimate on the evolution of soil formation and soil properties within the Pré de Bar proglacial area, compared to the effects of other soil forming factors?
3. What is the effect of large-scale climate differences on rates of soil development and soil properties between the Pré de Bar and previously studied proglacial areas?

1.3 Hypotheses

The following hypotheses are made for the research questions:

1. The same trends are expected as seen in previous research on proglacial areas. Vegetation cover, root depth, soil organic matter and silt and clay fraction increase with time and pH and surface stoniness will decrease with time.
2. Based on the different suggestions made after other studies on proglacial areas, especially by Egli et al. (2015), it is expected that soils developed with wetter conditions will be more developed than soils developed under drier conditions. Therefore, places with for instance higher solar insolation, leading to higher temperatures and evaporation, will have slower soil development. It is hypothesized that on these places the pH will be higher, the soil will be less deep and less soil organic matter will be found compared to soils with the same age but with lower solar insolation.
3. Messer (1988) showed that mean annual precipitation and mean annual temperature has a positive effect on soil depth in Norway. It is hypothesized that this will be the same for the proglacial areas in the Alps.

2. Methods

2.1 Study area

The study area of this project is the proglacial area of the Pré de Bar glacier. The area is situated in the Val Ferret in the province Valle d'Aosta, northwest Italy (Figure 1). The glacier descends from the Mont Dolent and the Aigulle de Triolet which are both part of the Mont Blanc Massif. In this area of the Alps no soil chronosequence study in a proglacial area has been published yet. However, Letey et al. (2010) did already some research on the Pré de Bar proglacial area, although results are not published.

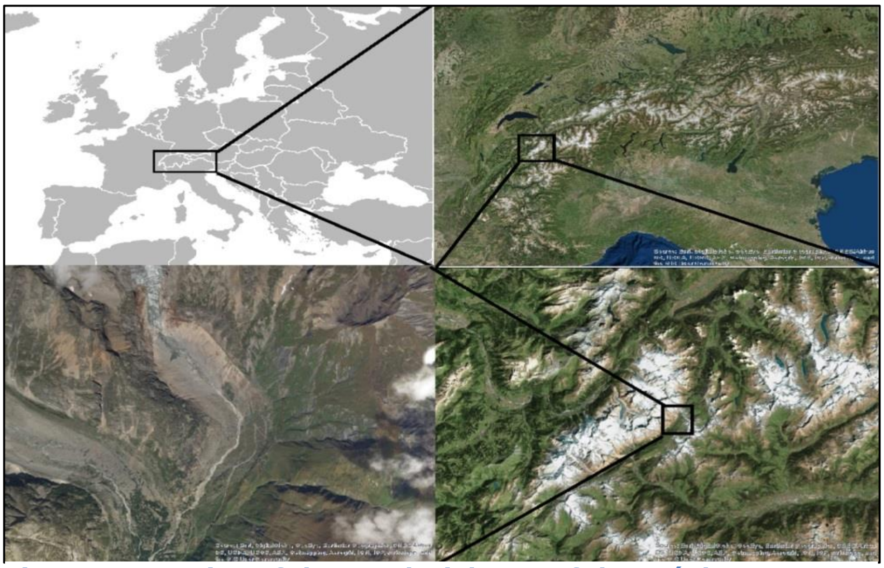

Figure 1: Location of the proglacial area of the Pré de Bar.

The proglacial area is not running straight, but has a bend (Figure 1). The lithology of the Mont Blanc massif consists mainly of granite. However, the valley floor of the Val Ferret, over which the glacier flows after the bend, is part of Mesozoic sediments which contain quite variable metamorphosed sedimentary rocks. Calc-schist is the most abundant rock type (Deline and Kirkbride, 2009; Leloup et al., 2005). Conclusively the lithology of the proglacial area of the Pré the Bar consists partly of granite and partly of calc-schist. Further complicating the chronosequence, unpublished data of researchers of the Université Savoie Mont Blanc shows that calc-schist was also deposited on top of granitic proglacial soils by colluvial processes. These deposits were found between the river and the outer bend of the proglacial area.

The proglacial area is 1600 meters along the valley axis and descends from 2250 meters to 1850 meters. Directly next to the proglacial area a climate station is located. A mean annual temperature of 3 ^{o}C is measured (RAVA, 2016). No annual precipitation amount could be obtained since large gaps are present in the data. The next closest meteorological station is the station on the Grand St. Bernhard pass, situated 8 kilometres southeast from the Pré de Bar glacier but at higher elevation (2472 m.a.s.l.). The annual precipitation at this station is 2368 mm and the average temperature is -0.6 ^{o}C (Meteoswiss, 2016).

Imhof (2010) has done valuable work to construct the retreat history of the Pré de Bar glacier. The Pré de Bar glacier reached its maximum during the LIA at around 1818. The glacier did not retreat very regularly and had multiple phases of re-advancing (Figure 2). These periods of re-advance caused several terminal moraines which are still visible in the field.

2.2 Fieldwork

A sampling scheme was made using the conditioned Latin hypercube method (Minasny and McBratney, 2006). Three variables were used as input for the conditioned Latin hypercube: age, slope and insolation. The age of the soil was defined via interpolation between the known extents of the glacier (Figure 2). Inverse distance weighing in ArcGIS was used to interpolate between the last maximum till the glacier re-advanced again. It is assumed that the glacier retreated with a constant speed in this period. To explain how the interpolation was carried out, an example will be given with the help of Figure 3 doing the interpolation between the maximum glacier extent in 1818 and the

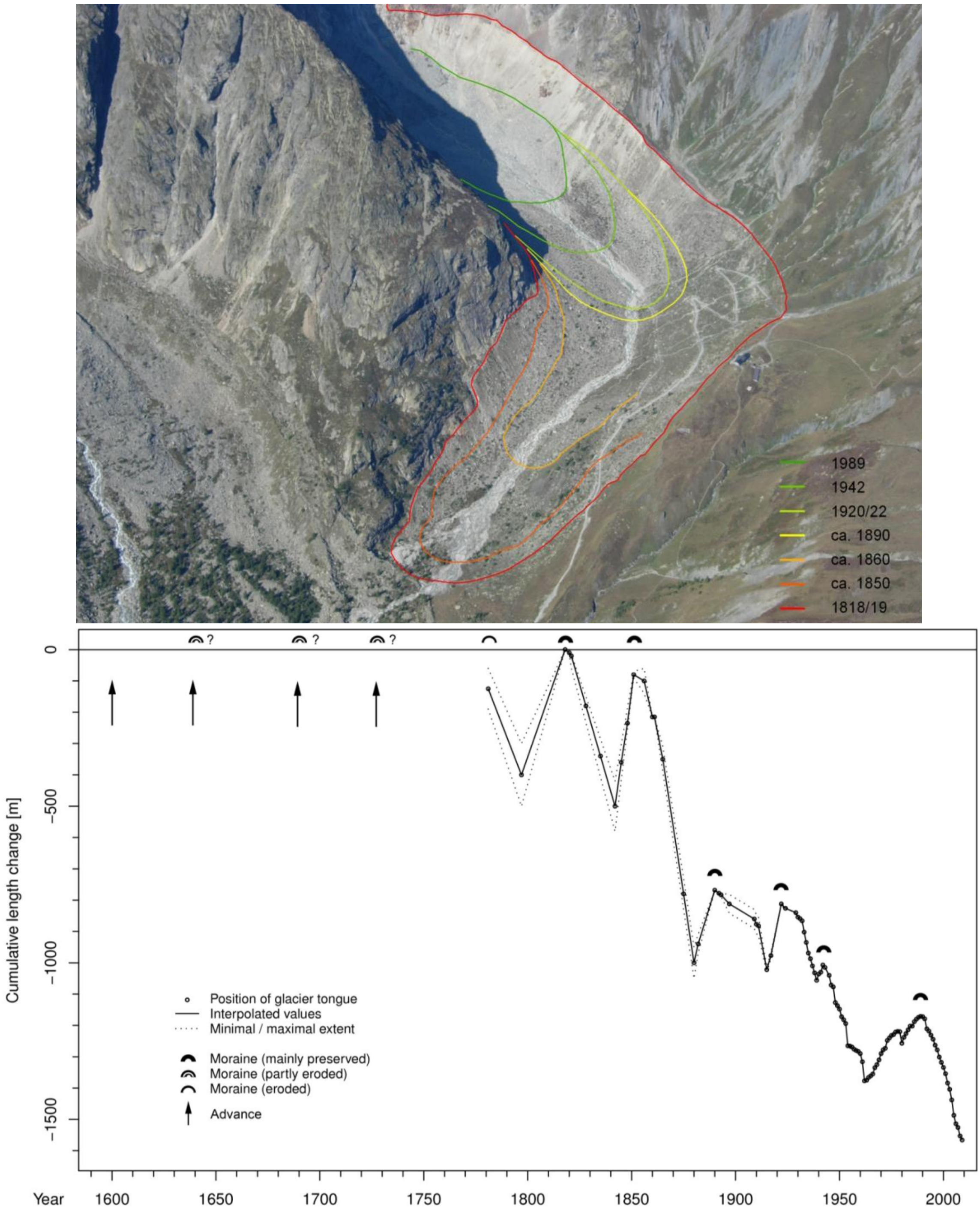

Figure 2: Glacier retreat history of the Pré de Bar glacier. The aerial view shows the location of the glacier during several moments in the retreat history since the LIA. The graph shows the cumulative length fluctuations of the glacier since the LIA. Figures adapted from Imhof (2010).

local minimum glacier extent in 1842. First the extent of the glacier in 1818 was drawn in (Figure 3A) based on the aerial view in Figure 2. Next the location of the glacier in 1842 was determined based on the graph in Figure 2 and drawn in the map (Figure 3B). On the half of the red (1818) and blue (1842) lines another line was drawn in (Figure 3C). This line was the extent of the glacier in 1830 since it was assumed that the glacier was retreating steadily. Next the two green lines were drawn in (Figure 3D) between the red and the yellow lines (glacier extent at 1824) and between the yellow and blue lines (glacier extent at 1836). Based on these lines the interpolation was done. The yellow and green lines were drawn in to help the inverse distance weighing process. Interpolations were done for all the retreat periods and later the age map was created with overlaying the different interpolation maps.

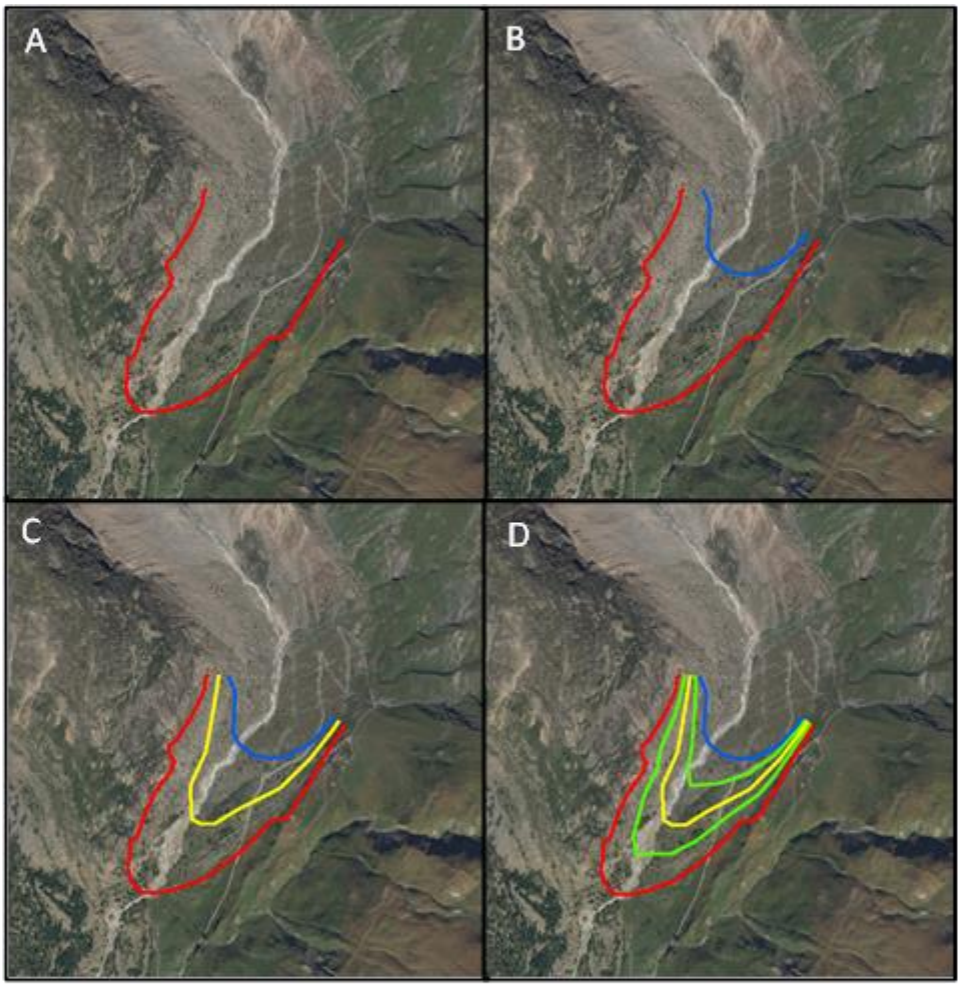

Figure 3: Drawing in the former extents of the glacier for interpolation. Red line: 1818; blue line: 1842; yellow line: 1830; green lines: 1824 and 1836.

Other studies have shown that, besides age, also erosion and stability of a slope play an important role (Temme et al., 2016; Temme and Lange, 2014). The slope angle is used as proxy for these processes. The annual solar insolation was used as a measure of microclimate. Other studies used aspect as variable to express microclimatic differences (Egli et al., 2015; Egli et al., 2006a), but the proglacial area of the Pré de Bar has almost no north-facing slopes, so no big differences in aspect are present. North-facing slopes are important in this perspective since they receive less solar insolation and thus have wetter conditions and more snow cover days which can enhance the rate of soil evolution (Egli et al., 2015). Instead, the solar insolation map is used which is arguably more closely related to microclimate. This map shows quite distinctive patterns and can therefore be used to make a sampling scheme. All the maps were made with ArcGIS. For the slope and insolation map a 2 meter Digital Elevation Model (DEM) was used. This DEM was smoothed to 5 meter to minimize the effect of possible mistakes and artefacts. The steepest areas and the very near river areas were excluded from the maps since these are not reachable. The three maps were used as input in the cLHS function in the program R to create 150 sample points. These sample points were evenly spread over the three input variables (Minasny and McBratney, 2006).

When in the field, 47 of the 150 points were too dangerous to reach, were still located in the river or located directly on a road. These points were omitted, so a total of 103 points were visited. The sample points were located in the field using an accurate aerial photograph (Esri, 2016). The location could be found within the resolution of the used DEM preserving the designed values for slope angle and annual solar insolation. At each location a soil pit was dug and the soils were described using the standard FAO guidelines (IUSS Working Group, 2006). Next to these guidelines the vegetation cover and surface stoniness were roughly estimated on a square of 1 m^2 around the soil pit. Since a part of the proglacial area was covered by calc-schist, also the percentage of calc-schist present in the soil was estimated. The soil stoniness was estimated per soil horizon as well. A soil sample between 200 and 300 gram for every soil horizon was taken for analysis in the lab.

2.3 Lab work

In total 256 soil horizons were distinguished and a total of 224 samples were taken to the lab. A sample of the other 32 horizons could not be taken since the horizon was too stony. Five of these horizons were the upper horizon at their location. Three soil properties were measured in the lab: pH, soil organic matter and silt and clay fraction. Because five upper horizons could not be sampled, analysis during this study for these three soil properties was done with 98 sample points.

The pH was measured by taking 10 grams of the soil sample and adding 25 grams of demineralized water. After one minute of shaking the pH was measured with a WTW pH-320 pH measurer with a precision of 0.01.

The rest of the sample was oven dried (105 ^oC) for 24 hours and sieved to obtain the fine earth fraction (grain size < 2 mm). A part was used to determine the soil organic matter content. This was done by using the loss on ignition method (Dean, 1974). A sample size of five grams was used with a temperature of 550 ^oC and a duration of three hours.

The other part of the oven dried soil sample was used to obtain the silt and clay fraction by dry sieving. Aggregates were crushed prior to sieving using a mortar and pestle. Two classes of grain size were separated: bigger than 63 µm was sand and smaller than 63 µm was silt and clay. Sieving was done by hand with a duration of two minutes per sample.

2.4 Variables

The variables used for statistical analysis can be separated in two components: dependent variables (soil properties) and explanatory variables (soil forming factors) (Table 1).

Table 1: Variables used for statistical analysis and their source.

Dependent variables (soil properties)		**Explanatory variables (soil forming factors)**	
Variable	Source	Variable	Source
Surface Stoniness	Field	Age	ArcGIS and Imhof (2010)
Vegetation Cover	Field	Insolation	ArcGIS
Root Depth	Field	Slope	ArcGIS
pH	Lab	Calc-schist	Field
Soil Organic Matter	Lab	Convergence Index	SagaGIS
Silt and Clay Fraction	Lab	Flow Accumulation	SagaGIS
		Vertical Distance of a Channel Network	SagaGIS
		LS-factor	SagaGIS
		Integrated Moisture Index	ArcGIS
		Heat Load Index	ArcGIS

The dependent variables and the age, insolation, slope and calc-schist were discussed earlier in this chapter. The other variables will be discussed now.

The convergence index is a measure of curvature. The range of values can be between -100 (divergent, convex convex) and 100 (convergent, concave concave). A location with a high convergence index is likely to experience deposition of soil and water. A location with a strong negative convergence index is more prone to erosion. Both (erosion and deposition) can influence the soil evolution.

Flow accumulation was chosen as explanatory variable because a substantial amount of sample locations were noted which could be of influence of a water stream. A high flow accumulation can cause erosion of soil and will have its impact on soil evolution. The flow accumulation is calculated in SagaGIS using a multiple flow direction approach. This means water is routed down towards all lower neighbours of a certain cell using a convergence factor of 1.1. Multiple flow accounts better for diverging and converging properties of a DEM landscape.

Vertical distance of a channel network was also chosen in the perspective of water influence on soil evolution by a river. If a sample point is located near a river, it can be occasionally flooded which would influence the soil formation.

The LS-factor was chosen as a factor of erosion. L is the slope length and S is the slope steepness. This value was chosen as explanatory factor since other studies showed that erosion and geomorphological processes play a role in soil evolution in proglacial areas.

The integrated moisture index (Iverson et al., 1997) was calculated using the Geomorphometric and Gradient Metrics Toolbox in ArcGIS (Evans et al., 2016). Three components are used to calculate the integrated moisture index: hillshade, flow accumulation and curvature. Hillshade captures the effect of other DEM derivatives, such as aspect, slope, position and shading from nearby hills. For the calculation of hillshade a default solar altitude of 45 degrees and solar azimuth of 22 degrees are used. A higher value for hillshade leads to less solar radiation and so higher soil moisture. Flow accumulation is discussed earlier. Next to a higher erosion, flow accumulation leads also to a soil with a higher moisture content. Small depressions will have a higher soil moisture since water streams generally to these positions. This process is taken into account by the curvature. This all is integrated in one formula (Iverson et al., 1997).

The heat load index (McCune and Keon, 2002) is constructed due to the main process of having a colder southeast facing slope and a warmer southwest facing slope. Regions with an evening sun will have higher temperatures than regions with the same insolation, but with a morning sun. Also the steepness of the slope is taken into account in this variable. The value of the index is ranging from 0 to 1 with 0 being the coolest slopes (generally northeast) and 1 the warmest (generally southwest).

Insolation, integrated moisture index and heat load index were chosen as a measure of microclimate. Erosion and deposition are represented by slope, convergence index and LS-factor. Flow accumulation and vertical distance of a channel network were chosen since a substantial amount of water was streaming through the area which could be of influence on the soil evolution.

2.5 Analysis

Summary statistics were done for the dependent variables to express the variability in the proglacial area. The relation between dependent variables and time since glacier retreat was analysed to compare the Pré de Bar area with other proglacial areas in the Alps. Since it was expected that calc-schist plays a role in the evolution of the dependent variables, this analysis was repeated using only the sample points without calc-schist. Then, backward stepwise multiple regression was conducted in R for all the dependent variables with the explanatory variables (soil properties). Since it was not possible to take soil samples at all the sample locations (section 2.3), the analysis for pH, soil organic matter and silt and clay fraction was done with 98 points instead 103 points. Analysis was done only with the samples of the upper soil horizon.

2.6 Macroclimate

In addition to the Pré de Bar studied here, seven other proglacial areas which were developed since the Little Ice Age have been studied in a chronosequence perspective in the Alps (Figure 4). All of these areas used at least time as explanatory variable and soil properties which were studied most often in these areas are vegetation cover, depth of soil formation, topsoil organic matter and pH. All the data present in the different papers of the studied proglacial areas were collected and the annual rate of change was determined per study area and soil property. If the soil organic carbon values were presented in the papers, they were converted into soil organic matter using the van Bemmelen factor (Van Bemmelen, 1890). For the sake of simplicity in this first order exploration, it was assumed that no vegetation, soil depth or soil organic matter was present at a soil age of 0 years and that all relations were linear. The annual rates of change of the soil properties were related to temperature and precipitation. A very high resolution climate map was used (Hijmans et al., 2005) to obtain the temperature and precipitation since the climate in mountain areas like the Alps is very spatially variable. Using one climate map allows to obtain the temperature and precipitation of all eight proglacial areas in a comparable way. The mean annual temperature (MAT) and mean annual precipitation (MAP) were used. Since only eight areas have been studied no statistics was conducted but the outcomes were analysed in a more qualitative way.

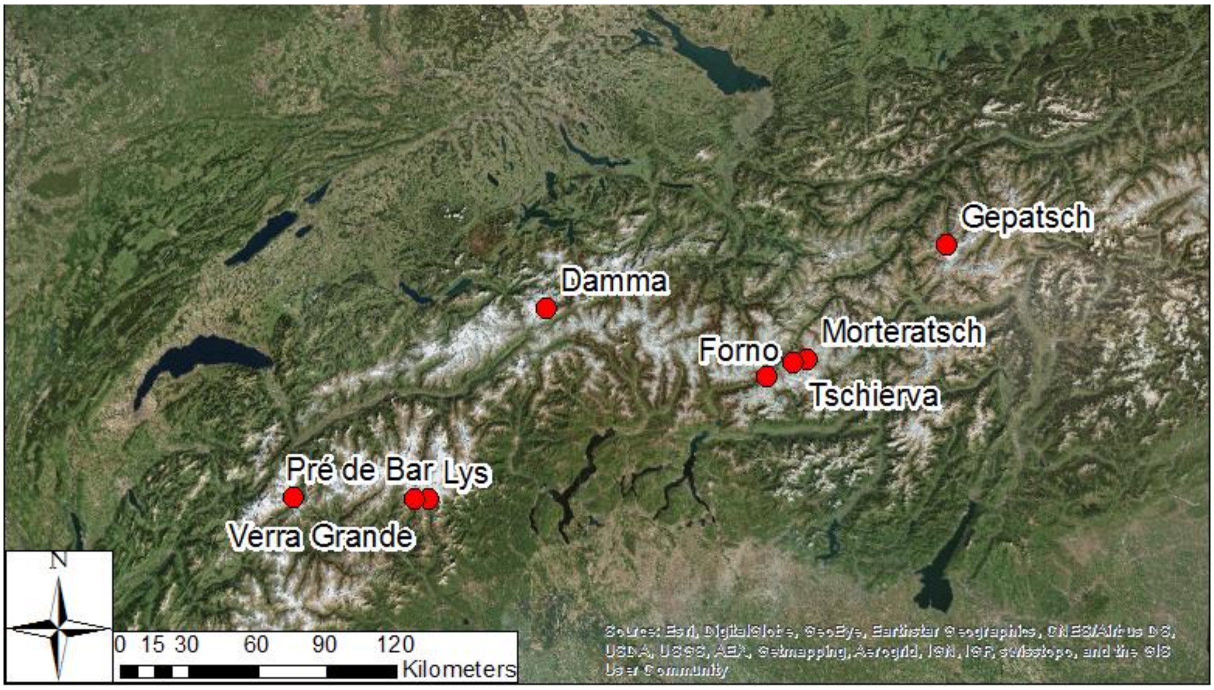

Figure 4: Locations of the eight proglacial areas studied in a chronosequence perspective in the Alps.

3. Results

3.1 Description proglacial area

The soil types in the proglacial area of the Pré de Bar, ranges from Leptosols to Regosols. No Cambisols are found yet in the area. Vegetation is quite abundant with shrubs found on soils with an age of 70 years in very wet parts and full grown trees after 150 years. Calc-schist is found at 52 of 103 sample locations. Almost all of the locations with calc-schist are at least 100 years old (Figure 5). Eight soils are found with a layer containing calc-schist above a granite layer. This indicates that the calc-schist was deposited by colluvial processes acting after glacier retreat. All of these soils are found between the river and the outer bend of the proglacial area.

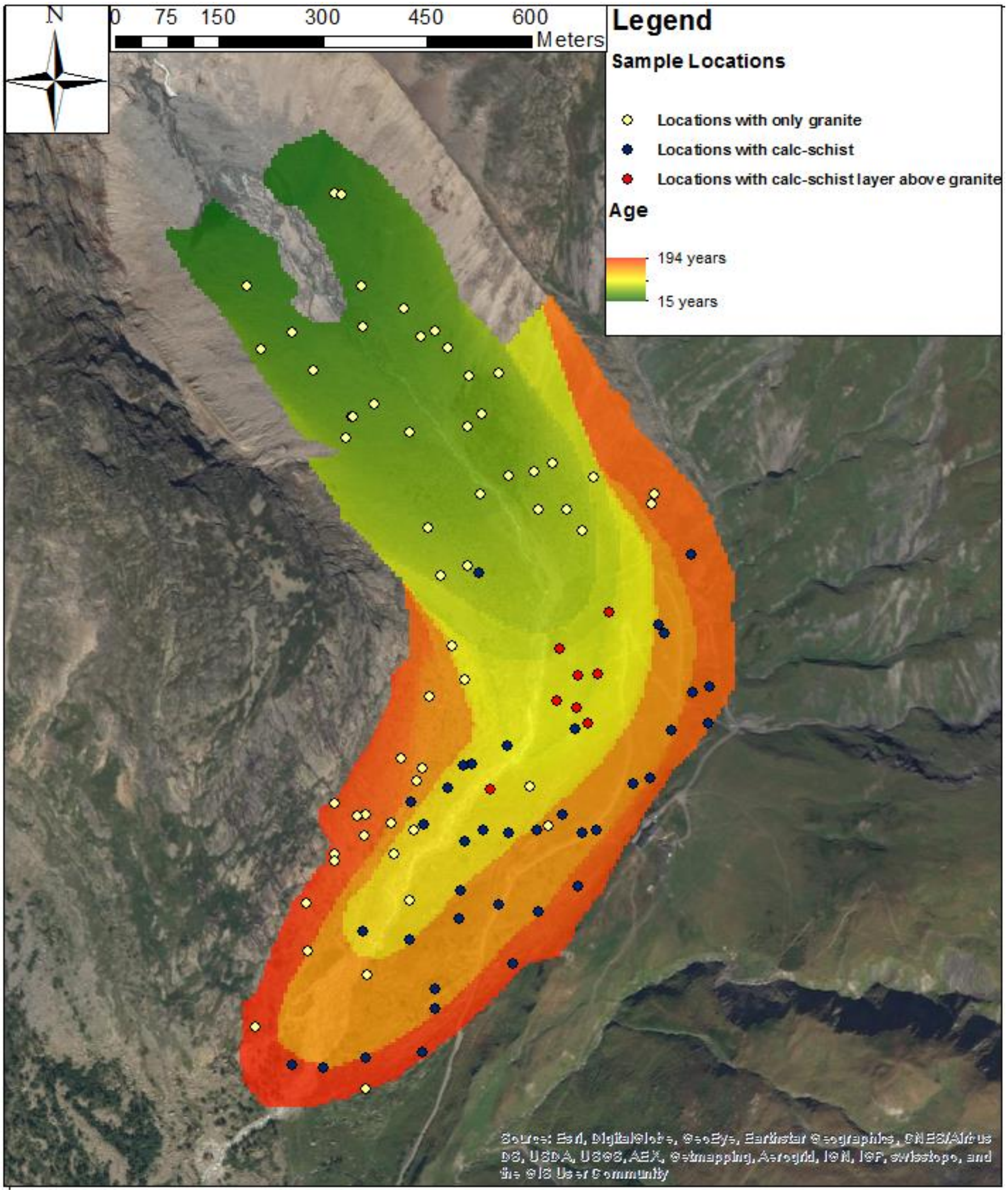

Figure 5: Locations of sample points divided in locations with only granite, locations with calc-schist and locations containing a calc-schist layer above a granite layer. The interpolated soil ages are also indicated.

3.2 General statistics

3.2.1 Dependent variables

In most cases stones and vegetation completely cover the soil. This means that surface stoniness and vegetation cover are almost completely inversely proportional (Table 2). Highest values of surface stoniness are located in the youngest soils near the glacier snout and lowest values are found at the oldest soils as well as soils with lots of calc-schist. On the other hand, the highest values of vegetation cover can be found in the oldest soils and soils with calc-schist. Almost no vegetation can be found near the glacier snout. The average root depth in the proglacial area is almost 20 centimetres. Obviously the lowest values are near the glacier snout where also no vegetation could be found. The higher values are at older soils and soils with shrubs or trees.

An average pH of 5.70 is measured in the topsoil of the sample points. The pH values range from 4.30 till 7.52. The topsoil organic matter values range from 0.59% to 56.12% and have an average of 9.35%. The lowest values are found closest to the glacier snout. Similar to the pH values, the highest values of silt and clay fraction are also found in the area of more calc-schist. The very high amounts of silt and clay in the area of calc-schist cause also a relatively high average of silt and clay fraction (0.12) over the whole proglacial area.

Table 2: Summary statistics of the dependent variables (soil properties).

	Surface Stoniness (%)	Vegetation Cover (%)	Root Depth (cm)	pH (-)	SOM (M %)	Silt and Clay Fraction (-)
n	103	103	102	98	98	98
Average	49.03	48.54	19.36	5.70	9.35	0.12
Stand. Dev.	27.33	26.66	10.90	0.74	9.55	0.08
Minimum	5	1	0	4.30	0.59	0.02
Maximum	99	95	45	7.52	56.12	0.50

3.2.2 Relation with age

Figure 6 shows the relation between the dependent variables and the time since glacier retreat.

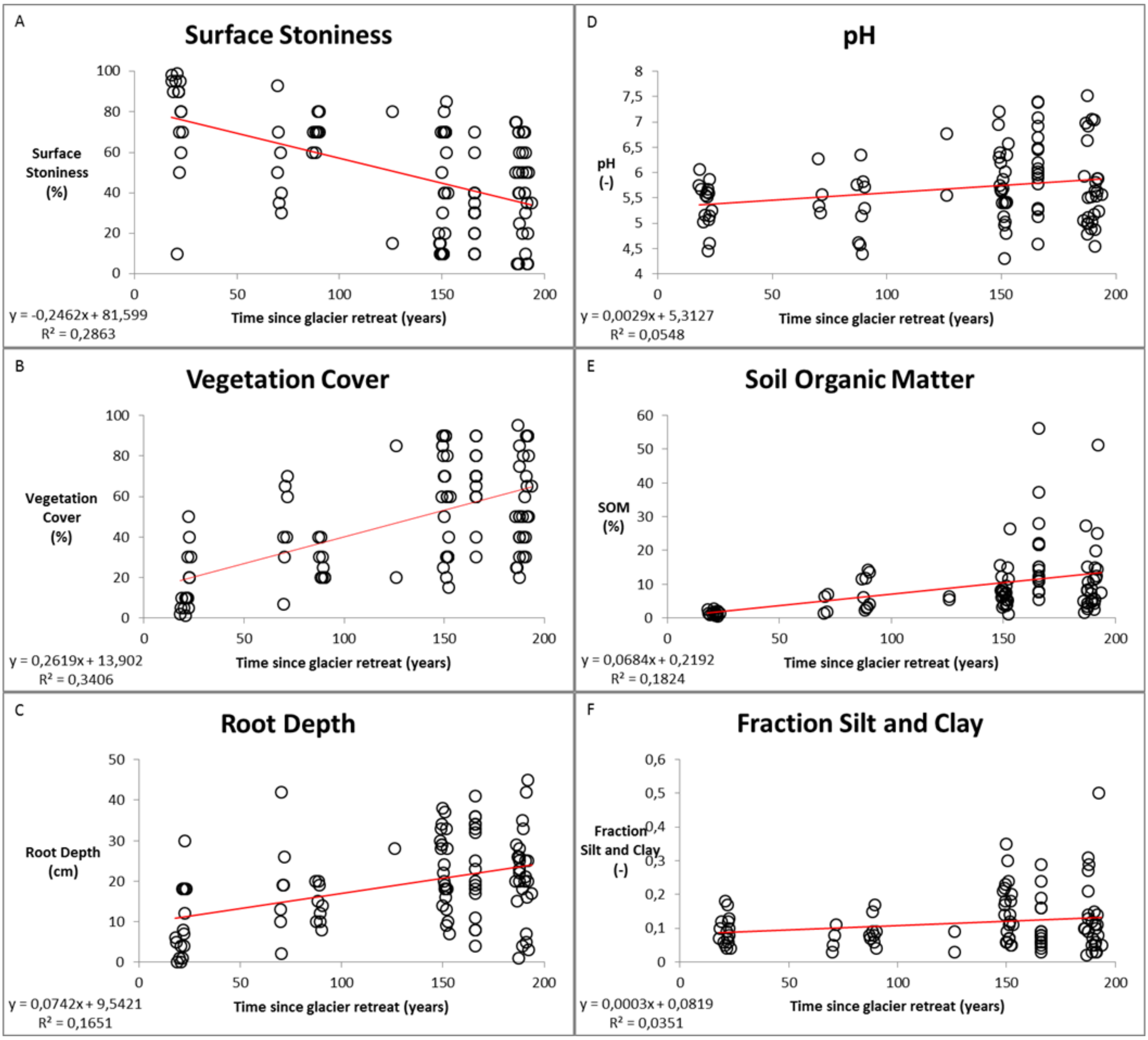

Figure 6: Relation between the dependent variables and time since glacier retreat of all the sample locations. Red line is the trend line with the equation and R^2 in the lower left corner.

Surface stoniness decreases with soil age and vegetation cover increases with soil age. The variation within sample locations of more or less the same age, is however high. Surface stoniness ranges between 0% and 80% for the oldest soils. Vegetation cover ranges between 20% and 100% for the oldest soils. Figure 6 shows an increase of root depth with age. Low root depths are not only found at young soils but also at older soils.

Surprisingly the upper limit of pH values seems to increase with soil age. Low pH values can be found over the whole range of soil ages. There is no statistical relation between pH and time since glacier retreat. Soil organic matter increases with time too. Younger soils contain almost no organic matter. After about 70 years the topsoil organic matter starts to increase in a seemingly exponential way. Silt and clay fraction shows a slight different pattern with an increase in silt and clay fraction with soil age, but with slight higher fractions at younger soils since they are located near the glacier snout, a source of silt and clay particles (Thayyen et al., 1999). No statistical relation is found between silt and clay fraction and time since glacier retreat.

3.2.3 Relation with age without calc-schist

The R^2 of vegetation cover and root depth increase substantially when sample locations containing calc-schist are not taken into account in the analysis (Figure 7). Surface stoniness, vegetation cover and soil organic matter does not change considerably in R^2.

The relation of pH and silt and clay fraction with time since glacier retreat changes. Both variables do still not have any statistical relation with time since glacier retreat. However, also the high values for pH as well as for silt and clay fraction at older soil ages are gone. This removes the apparent increase of pH and silt and clay fraction over time.

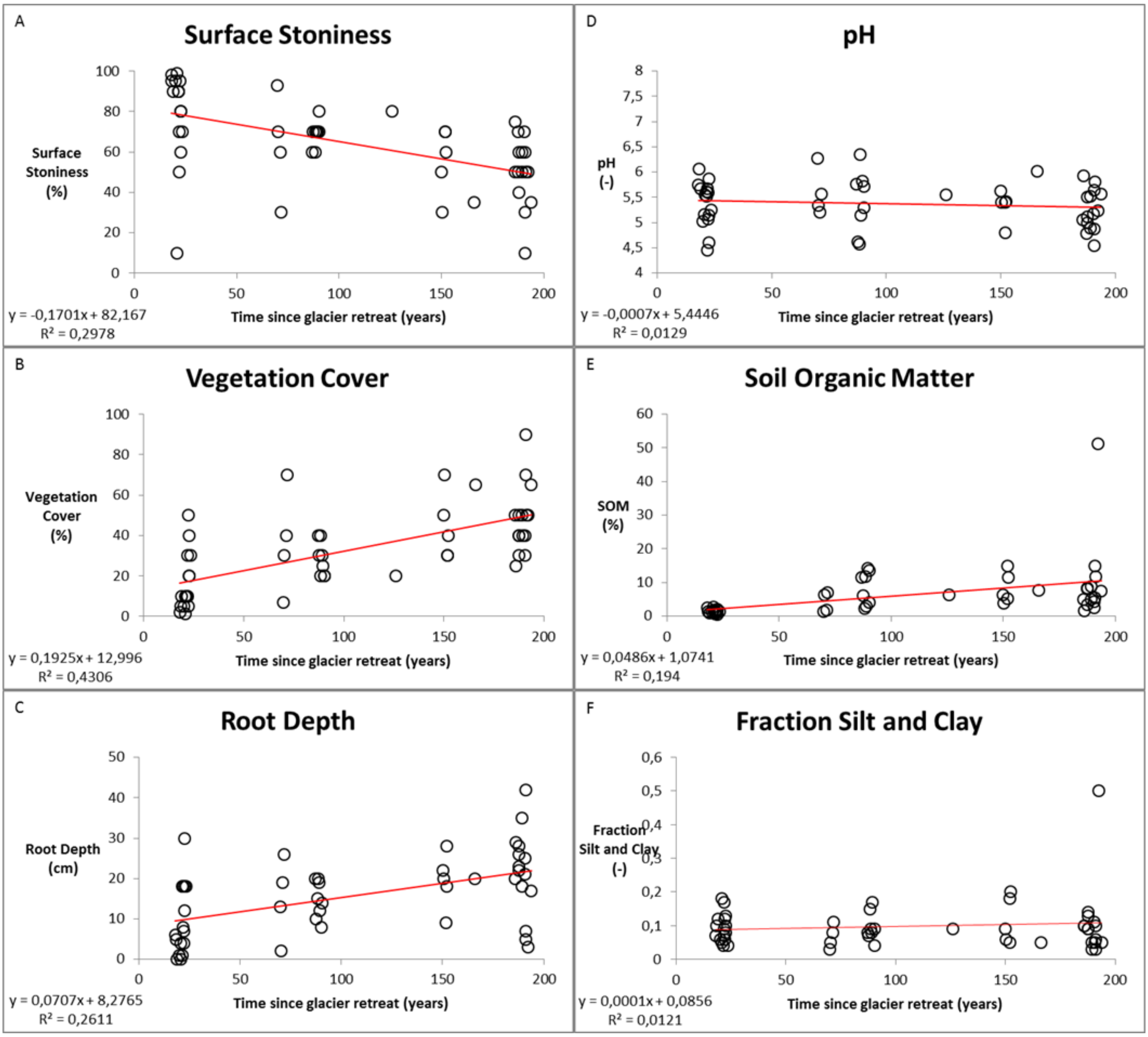

Figure 7: Relation between the dependent variables and time since glacier retreat of the sample locations without calc-schist. Red line is the trend line with the equation and R^2 in the lower left corner.

3.3 Multiple Regression

The best models to predict the soil properties with the explanatory variables are shown in Table 3.

Surface stoniness and vegetation cover can be explained for 56% and 58%. Age plays a role, but for both soil properties in a not surprisingly opposite way. Older soils have a lower surface stoniness and a higher vegetation cover. The variation in root depth can be explained for only 20%.

Surprisingly age participates not in predicting the pH using the best model. Calc-schist is the most important and almost only variable which predicts the pH. However, still an R^2 of 0.45 is found. The variation in soil organic matter can be explained for 30%. Age and insolation plays the most important role in this perspective. A higher age results in more soil organic matter. The silt and clay fraction can be declared for only 16%. Slope and calc-schist are the most important factors. Age plays only a marginal role here.

Table 3: Best models and adjusted R^2 for predicting the soil properties. Also the standard errors (S.E.) for the coefficients are given. Variables in decreasing order of significance. VDC=vertical distance of channel network; HLI=heat load index; FlowAcc=flow accumulation; IMI=integrated moisture index; ConvIndex=convergence index.

Surface Stoniness			Vegetation Cover			Root Depth		
	Coefficient	S.E.		Coefficient	S.E.		Coefficient	S.E.
Intercept	69.57	± 38.62	Intercept	66.50	± 25.12	Intercept	9.03	± 2.69
Age	-0.19	± 0.04	Age	0.23	± 0.04	Age	0.04	± 0.02
Calc-schist	-0.28	± 0.06	Calc-schist	0.28	± 0.06	IMI	-4.55e-3	± 2.25e-3
Slope	1.32	± 0.35	Slope	-0.74	± 0.25	Calc-schist	0.05	± 0.03
Insolation	3.54e-5	± 1.62e-5	FlowAcc	-4.54e-5	± 2.00e-5	LS	0.51	± 0.32
VDC	-0.98	± 0.55	Insolation	-2.53e-5	± 1.44e-5			
HLI	-91.39	± 56.78						
FlowAcc	2.91e-5	± 2.11e-5						
Adj. R^2	**0.56**		**Adj. R^2**	**0.58**		**Adj. R^2**	**0.20**	

pH			Soil Organic Matter			Silt and Clay Fraction		
	Coefficient	S.E.		Coefficient	S.E.		Coefficient	S.E.
Intercept	6.84	± 0.58	Intercept	13.18	± 16.32	Intercept	0.11	± 0.02
Calc-schist	0.011	± 0.002	Age	0.077	± 0.018	Calc-schist	6.50e-4	± 2.15e-4
Insolation	-9.47e-7	± 3.60e-7	Insolation	-3.00e-5	± 7.05e-6	Slope	-2.31e-3	± 8.69e-4
FlowAcc	9.60e-7	± 6.32e-7	Slope	-0.37	± 0.13	Age	2.53e-4	± 1.51e-4
			HLI	56.24	± 22.01	ConvIndex	-4.97e-3	± 3.39e-3
			Calc-schist	-0.046	± 0.028			
Adj. R^2	**0.45**		**Adj. R^2**	**0.30**		**Adj. R^2**	**0.16**	

3.4 Macroclimate

Five of the researched proglacial areas in the Alps have granite bedrock (Table 4). The other proglacial areas consist of gneiss and serpentinite. The mean annual temperatures range from -0.8 °C to 2.1 °C with the Damma proglacial area having the lowest and the Forno proglacial area having the highest temperature. The Damma proglacial area has, next to the lowest temperature, also the highest annual precipitation: 1929 millimetres per year. The Gepatsch proglacial area has with 1008 millimetres the lowest precipitation amount per year.

The annual rates of change for the Morteratsch glacier are all based on Temme and Lange (2014) except for soil organic matter since they did not measure this soil property. The annual rate of change for soil organic matter in this area is therefore based on Egli et al. (2010). The annual rates of change for the proglacial area of the Pré the Bar are based on the sample locations without calc-schist.

There was no relation between vegetation cover and time in the proglacial area of the Tschierva. Vegetation cover increases the fastest in the Lys proglacial area and the slowest in the Pré de Bar proglacial area. The Pré de Bar (0.093 cm yr^{-1}) has the highest annual rate of change and Tschierva the lowest (0.014 cm yr^{-1}) for depth of soil formation. The change of soil organic matter could be determined for six proglacial areas. The increase of soil organic matter is the slowest for the Verra Grande and the fastest in the Gepatsch proglacial area. The annual rate of change for pH is negative for all the proglacial areas except for the Pré de Bar where no relation could be found. The Morteratsch has the highest annual rate of change and the Damma glacier has the lowest annual rate of change.

Table 4: Parent material, mean annual temperature (MAT), mean annual precipitation (MAP) and the annual rates of change of four soil properties for the eight studied proglacial areas in the Alps. n.r.=no relation; n.d.=not determined; *=based on Egli et al. (2010).

Glacier	Parent Material	MAT (°C)	MAP (mm yr^{-1})	Vegetation Cover (% point yr^{-1})	Depth of Soil Formation (cm yr^{-1})	Soil Organic Matter (% point yr^{-1})	pH (unit yr^{-1})
Pré de Bar (This study)	Granite	1.8	1630	0.28	0.097	0.056	n.r.
Damma (Dümig et al., 2011)	Granite	-0.8	1929	n.d.	0.027	0.034	-0.0074
Morteratsch (Temme and Lange, 2014)	Granite	2	1046	0.53	0.021	0.061*	-0.017
Tschierva (Temme and Lange, 2014)	Granite	1.7	1107	n.r.	0.014	n.d.	-0.014
Forno (Temme and Lange, 2014)	Granite	2.1	1150	0.50	0.061	n.d.	-0.008
Gepatsch (Temme et al., 2016)	Gneiss	1.2	1008	n.d.	n.d.	0.105	-0.0035
Lys (D'Amico et al., 2014)	Gneiss	-0.6	1788	0.59	0.07	0.025	-0.0078
Verra Grande (D'Amico et al., 2015)	Serpentinite	0.7	1673	0.52	0.03	0.015	-0.0075

The annual rate of change of vegetation cover seems to be lower with higher temperatures and slightly higher with more precipitation (Figure 8). Also the depth of soil formation increases faster when precipitation values are higher. Soil organic matter shows the opposite trend. Soil organic matter increases with slower rates in areas with more precipitation. Precipitation and temperature does not have a relation with the annual rate of change of pH.

Figure 8: Relation between annual rate of change for the difference soil properties and the MAT and MAP. Different colours indicate different parent material.

4. Discussion

4.1 Relation with age

Most of the dependent variables show similar trends with time since glacier retreat in the dataset with sample locations with only granite as well as in the dataset with all the sample locations. Surface stoniness decreases with time since glacier retreat and vegetation cover, root depth and soil organic matter increase with time since glacier retreat. This was also hypothesized for these soil properties and is in line with earlier findings in several other proglacial areas in the European Alps (D'Amico et al., 2014; D'Amico et al., 2015; Dümig et al., 2011; Temme et al., 2016; Temme and Lange, 2014).

However, pH does surprisingly not have a relation with time since glacier retreat looking at the analysis with sample locations with only granite which means that the hypothesis has to be rejected. Other proglacial areas in the Alps have a decreasing pH trend with time (D'Amico et al., 2014; D'Amico et al., 2015; Dümig et al., 2011; Temme et al., 2016; Temme and Lange, 2014). Most likely calc-schist plays an important role in this case. All high values of pH are found in areas where calc-schist is present. Mass movements of calc-schist and even siliceous limestone occurs in the area of the Val Ferret (Deline and Kirkbride, 2009). That these mass movements also happen in the proglacial area of the Pré de Bar is confirmed by the findings of researchers of the Université Savoie Mont Blanc who did also a soil survey in the proglacial area of the Pré de Bar (unpublished data). They also found higher pH values in the area where colluvial calc-schist is present. The sample points which contain calc-schist are, next to having higher pH values, all older than 100 years. The high pH in calc-schist areas in combination with the high soil age for calc-schist areas, lead to the increase of pH with time since glacier retreat when taking all the sample locations into account. The relation only removes and not reverts when sample locations with calc-schist are discarded. This may be explained by an influence of calc-schist on pH in areas where calc-schist was locally not observed, for instance through groundwater, or when amounts of calc-schist are so small that they were not observed. Next to this also fewer older soil samples are left in the analysis leading to a higher uncertainty indicated in a standard error of 0.0008 which is higher than the coefficient (-0.0007).

Calc-schist also influences the relation of the silt and clay fraction with time since glacier retreat. Silt and clay fractions are obviously higher in soils where calc-schist is present. This is on the one hand because calc-schist produces clay particles as weathering product. This was concluded after research on the proglacial area of the Werenskiold glacier on Svalbard (Kabala and Zapart, 2012). On the other hand the colluvial calc-schist consists of smaller stones and pebbles than the big granite blocks leading to a larger physical and chemical weathering surface so a faster increase of the silt and clay fraction. Furthermore, these soils with calc-schist are again at least older than 100 years leading to an increase in silt and clay fraction with time since glacier retreat. However, excluding the sample points with calc-schist lead to a less convincing relationship with time since glacier retreat. Also Temme et al. (2016) found no relation between silt and clay fraction with time since glacier retreat in the proglacial area of the Gepatsch, while Dümig et al. (2011) found only a slight increase in silt and clay fraction in the proglacial area of the Damma glacier. Because of the influence of calc-schist, results obtained here for the proglacial area of the Pré de Bar cannot reliably contribute to the discussion whether silt and clay fraction increase with time since glacier retreat.

Soil organic matter increases with time since glacier retreat. Additionally one can ask if this relation should be considered linear or rather exponential. The exponential relationship shows a much higher R^2 (0.47) than the linear relationship (R^2=0.18). Also when sample points with calc-schist are deleted from the analysis, the exponential relationship has a higher R^2 (0.47) than the linear relationship (R^2=0.17). This means that the relation of soil organic matter with time in the Pré the Bar area is rather exponential than linear. An exponential relationship of soil organic matter with time has been suggested earlier in proglacial areas (Conen et al., 2007; Egli et al., 2012; Zhou et al., 2016).

The fact that calc-schist has such an influence on the soil evolution (in this case pH and silt and clay fraction) makes the proglacial area of the Pré de Bar not the most ideal area to study chronosequences. However, finding disturbances in these areas can help further proglacial studies to take these disturbances in consideration (in this case colluvial calc-schist as additional soil forming material). The influence of calc-schist confirms the findings of D'Amico et al. (2015) that parent material plays next to time a role in the soil evolution in proglacial areas. Also the role of colluvial processes in soil evolution is again approved after already earlier concluded during research in other proglacial areas (Egli et al., 2006b; Temme et al., 2016; Temme and Lange, 2014). Next to this a new, unexplored proglacial area in the Alps is investigated with the help of the chronosequence concept in a part of the European Alps where this kind of study was not abundant yet.

4.2 Multiple regression

The largest part of the variation of the dependent variables can be explained by age and calc-schist. Table 5 shows the adjusted R^2 of the best model and the adjusted R^2 when only calc-schist and age are used as explanatory variables. Only for soil organic matter variables other than calc-schist and age play a substantial role. Calc-schist and age are for almost all models the most significant parameters and have the lowest standard error.

Table 5: Adjusted R^2 for the best model and for the model when only calc-schist and age are taken into account for the different soil properties.

	Adj. R^2 Best model	Adj. R^2 Only calc-schist and age
Surface Stoniness	0.56	0.51
Vegetation Cover	0.58	0.54
Root Depth	0.20	0.18
pH	0.45	0.41
Soil Organic Matter	0.30	0.17
Silt and Clay	0.16	0.11

Next to calc-schist and age other soil forming factors play still a role in the explanation of the variation within the soil properties. Also the microclimatic soil forming factors play in some cases a role.

A higher surface stoniness can be found with a higher insolation and a lower heat load index. This is contradictory to studies which show that the influence of insolation on weathering indicates that higher insolation leads to higher temperatures and larger temperature differences which will enhance the physical and chemical weathering (Rech et al., 2001). However, since the Pré de Bar region and proglacial areas in general are covered by snow a large part of the year, another process earlier described by Egli et al. (2006a), takes over. Higher temperatures increase the evaporation leading to a thinner snow pack and a shorter snow cover. These two elements cause reduced water fluxes and so reduced weathering and mineral dissolution. The findings in the Pré de Bar proglacial area, higher surface stoniness with higher insolation, confirm this process. As discussed above the vegetation cover is highly related to surface stoniness so it is reasonable that a negative relation between insolation with vegetation cover is found. However, the standard error of the coefficient of the insolation is relatively high for vegetation cover indicating that the uncertainty in the influence of insolation is relative high.

Root depth does not have any direct relation with insolation and heat load index. The integrated moisture index plays here a significant role. Locations with higher values for the integrated moisture index have higher root depths. This can be explained by the fact that roots which suffer drought stress, grow deeper in the soil to find water (Mahmood and Hubbard, 2007). When the values of the integrated moisture index are higher, there is enough water for the roots and they do not need to grow deep in the soil.

A higher insolation leads to a lower pH. This is in line with the hypothesis and what Egli et al. (2015) found in the Russian Altai region. Again this can be explained by a lower chemical weathering rate due to higher temperatures, higher evaporation, thinner snow pack and less snow cover and reduced water fluxes.

The variation in soil organic matter can be explained by a substantial amount of variables other than soil age and calc-schist. Microclimatic variables which play significantly a role in the best model are insolation and heat load index. The multiple regression of soil organic matter with only these microclimatic variables leads still to an adjusted R^2 of 0.17. Insolation is the second variable in terms of significance in the best model for soil organic matter and has a relatively low standard error. Locations with less insolation have more soil organic matter. This is also in line with the hypothesis and what Egli et al. (2015) found in the Altai region. They found an accumulation of organic matter on the colder and wetter north-facing slope. They suggested that the reason for this can be a reduced microbial activity due to a cold and wetter environment which decreases the rate of organic matter decomposition. This Pré de Bar study confirms the theory.

Studies searching for the effect of microclimatic aspects on soil formation all performed this sampling on the most extreme positions, such as clear north-south slopes. Secondly, they were all searching for locations where other soil forming factors were equal between the sample locations. All the studies concluded that an influence of microclimate on soil formation is present. This study sampled in a random geographical way through the whole chronosequence. Next to this, the studied chronosequence is far from ideal, experiencing colluvial processes. Also here it is found that microclimate has an influence on the soil evolution and so the hypothesis made earlier is confirmed. However, its role is very marginal compared to other soil forming factors, particularly age and parent material. Only the variation in soil organic matter is for a large part determined by microclimate.

Next to the microclimatic variables also erosion and deposition variables and runoff variables are taken into account since it was expected that they would also have an influence on the soil evolution of the Pré de Bar. Also these variables are not contributing for a large part to the variation in the soil properties.

4.3 Macroclimate

Eight proglacial areas are studied in the Alps till so far. This is not enough to conduct statistical analysis but based on these eight points already some trends are visible regarding the influence of large-scale differences in temperature and precipitation on soil evolution in these areas.

A slight increase in annual rate of change for vegetation cover with precipitation can be seen in Figure 8 (Section 3.4). Lower precipitation amounts leading to less plant growth is suggested before in studies about proglacial areas in drier areas than the European Alps, such as Svalbard and Canada (Jacobson and Birks, 1980; Kabala and Zapart, 2012). The increase in rate of vegetation growth is most likely explainable by the weathering process. Weathering rates are highly related to precipitation and moisture amounts. Precipitation and soil moisture are for example often used in models for soil formation (Norton et al., 2014). In these models precipitation leads to higher weathering rates. This will lead to less stones, boulders and rocks and more soil where vegetation can grow. This relation is also found in the proglacial area of the Pré de Bar (Section 4.2). Vegetation itself can subsequently increase the weathering rates and soil formation as well (Egli et al., 2011).

The possible slight decrease of the annual rate of change for vegetation cover with temperature may itself also reflect the effect of precipitation. Higher altitudes have lower temperatures but also higher precipitation rates. A R^2 of 0.62 is found for the inverse relation of temperature with precipitation. Next to this the earlier described theory of the relation between higher temperatures and lower weathering rates of Egli et al. (2006a) can also play a role here.

The annual rate of change of the vegetation cover for the proglacial area of the Pré de Bar is most likely underestimated. The sample locations are determined in a geographical random way. The other proglacial area studies sampled fewer locations and determined the locations by selecting soils that were considered the most representative for their age. It is imaginable that with this sampling strategy soils with vegetation are chosen in older areas and in the oldest areas the vegetation cover appeared to be almost always 100% in these studies. When sampling much more soils and in a random way, it is much more likely that sample locations in older areas are prescribed on places where still lots of big rocks and stones can be found leading to lower vegetation covers on older soils and so an underestimation of the annual rate of change for vegetation cover compared to the other areas. On the other hand it is also likely that the random sampling scheme prescribes sample locations with more vegetation than representative soils would have in younger areas. In this way the uncertainty in the annual rate of change will be higher using a random sampling scheme compared to searching for the most representative locations.

The annual rate of change for depth of soil formation seems to increase with precipitation in the Alps. This would confirm the hypothesis. Vegetation increases soil formation (D'Amico et al., 2014) so a relation between the annual rate of change for vegetation cover and annual rate of change for depth of soil formation would not be unexpected. Also the precipitation itself is more often found to be a factor influencing the soil formation. The effect of precipitation on weathering is discussed above. Furthermore, Messer (1985) found that soil depth increases statistically faster with higher precipitation amounts comparing eighteen proglacial areas with each other in southern Norway. This means that the soil formation rate increases with higher precipitation amounts.

With an increasing rate of soil formation with higher precipitation amounts and several papers indicating an increase of soil organic matter with vegetation cover (e.g. Burga et al., 2010; Mavris et al., 2010), one would expect that the increase of soil organic matter would be faster for proglacial areas with more precipitation as well. However, surprisingly, the opposite seems to be true. The amount of soil organic matter accumulated in the soil depends on the integration over time of two processes: (i) the formation rate of soil organic matter and (ii) the decomposition rate of soil organic matter. When vegetation cover and depth of soil formation increase faster with higher precipitation amounts, soil organic matter would also increase faster with higher precipitation amounts based on a higher rate of soil organic matter formation. However, decomposition also plays a role and its rate depends among others on the amount of available water and temperature. It can be suggested that decomposition is limited by water availability and a higher amount of precipitation may increase the water availability, leading to higher decomposition rates which lower the rate of soil organic matter accumulation. Based on this it is expected that the proglacial areas of the Damma and Lys glaciers, having the highest precipitation amounts, would have the lowest rates of change for soil organic matter. However, they have higher annual rates of change for soil organic matter than the proglacial area of the Verra Grande. A possible explanation for this could be that these proglacial areas also have the lowest mean annual temperatures. These low temperatures could limit the decomposition of soil organic matter again which results in a higher annual rate of change for soil organic matter. However, the proglacial area of the Verra Grande is also the only area which has serpentinite as bedrock. D'Amico et al. (2015) concluded earlier that soil formation is slower on serpentinite compared to gneiss and this will also be of influence. A conclusive decision cannot be drawn yet.

The annual rates of change for soil organic matter in the proglacial areas of the Pré de Bar and the Gepatsch glaciers can be a bit overestimated since another sampling method was used here. In these areas a geographic random approach was chosen which means that not only the most representative soils were sampled, but also soils with extreme values in some soil properties. In this case the topsoil organic matter values measured in the Gepatsch and Pré de Bar proglacial area regularly exceed 10% while the soil organic matter values in the other proglacial areas are rarely above 5%. This can be the reason that the annual rates of change of soil organic matter are slightly overestimated for the Gepatsch and Pré de Bar.

No relation is found between the climatic variables and the annual rate of change of pH. Also Messer (1988) did not find a relation in the proglacial areas of southern Norway. She suggested that the evolution of pH is more related to the initial state of the system. Based on Figure 8 (Section 3.4) it could be that parent material plays a role. The highest annual rates of change for pH are all found in proglacial areas with granite as bedrock. Maybe the evolution of pH over time depends more on parent material then on climate factors. Another sign that the initial state of a proglacial area influences the pH evolution is shown in the proglacial area of the Gepatsch (Temme et al., 2016). The presence of pyrite in this area has a large influence on the pH evolution. However, no hard conclusions can be made in this perspective.

The processes discussed above can only be seen as first suggestions in unravelling the influence of climatic differences on soil evolution. The lack of data points on soil chronosequences in the proglacial areas in the Alps give serious constraints in the analysis of the effect of climatic variables on soil evolution in this area. Next to the different kind of sampling strategies, also different lithologies lead to different rates of soil formation (D'Amico et al., 2015). Three different lithologies where till so far analysed in the proglacial areas. All these different aspects of studies on proglacial areas lead to disturbances in comparing the areas with each other and so the analysis of the role of macroclimate on soil evolution in proglacial areas. Before the suggestions made here can be confirmed, more proglacial areas in the Alps need to be investigated.

The climate map used for the analysis was chosen because of its high resolution. A high resolution map is needed since the studied proglacial areas are rarely larger than 3 km^2. Climate in mountainous regions is very spatial variable because of high elevation differences (Hijmans et al., 2005). Meteorological stations are scarce in the Alps (Chiarle et al., 2007) and meteorological data mentioned in the papers of the different studies on the proglacial areas are often under- or overestimating temperature and precipitation since the meteorological stations are located on different altitudes (D'Amico et al., 2015). This is illustrated by the differences between the temperature and precipitation in the papers and in the high resolution climate map (Table 6).

Table 6: Comparison between the MAT and MAP values from the climate map and from the papers for the different proglacial areas. MAT papers and MAP papers of the Morteratsch are from Egli et al. (2006b).

Proglacial Area	MAT climate map (°C)	MAT papers (°C)	MAP climate map (mm)	MAP papers (mm)
Pré de Bar	1.8	3	1630	n.d.
Damma	-0.8	0 till 5	1929	2400
Morteratsch	2	0.5	1046	1200
Tschierva	1.7	n.d.	1107	n.d.
Forno	2.1	n.d.	1150	n.d.
Gepatsch	1.2	-0.3	1008	800
Lys	-0.6	-1 till 2	1788	1200
Verra Grande	0.7	0 till 2	1673	730

During research to soil formation in proglacial areas in the Alps, several papers were discussing their rates of soil formation with others found in other proglacial areas (e.g. Smittenberg et al., 2012). But no one did this comparison collecting all the rates of all the proglacial areas and compared them with each other like it was done here. The quality of this work can still be improved by for example more studied proglacial areas, by taking seasonality into account for the climatic factors and by determining the uncertainty in the annual rates of change for the soil properties. However, some trends are already visible between the soil properties and temperature and precipitation which make this work valuable for continuation. Further analysis and improvements can lead to the understanding of the processes going on in soil formation and can predict what will happen with all the areas which became free of ice and will become free of ice in the coming decades.

5. Conclusion

5.1 Objectives

The conclusion will be based on the answers of the earlier addressed research questions.

1. **What is the variability in soil development and soil properties within the proglacial area of the Pré de Bar?**

Surface stoniness decreases with time since glacier retreat and vegetation cover, root depth and soil organic matter increases with time since glacier retreat. This is as expected since this is found in most proglacial areas in the Alps. However, no relation is found between pH and time since glacier retreat due to the presense of colluvial calc-schist. Again this shows that erosion and deposition, and differences in parent material strongly influence the soil evolution in proglacial areas. No relation between silt and clay and time since glacier retreat is found leaving the question open if there is a clear relation between these factors in proglacial areas. Soil organic matter increases in an exponential way, also in other young soils in proglacial areas.

2. **What is the effect of microclimate on the evolution of soil formation and soil properties within the Pré de Bar proglacial area, compared to the effects of other soil forming factors?**

Microclimate does have an influence on the soil evolution in the proglacial of the Pré de Bar. Nonetheless, the influence is very marginal compared to time since glacier retreat and the impact of the (colluvial) calc-schist. Only the variation in soil organic matter can be explained for a substantial part by climate variables and then espescially by insolation.

3. **What is the effect of large-scale climate differences on rates of soil development and soil properties between the Pré de Bar and previously studied proglacial areas?**

Suggestions can be made regarding the influence of macroclimatic differences on soil formation in the Alps. The rate of soil formation in the Alps seems to be positively related with precipitation. A faster increase of vegetation and a faster development of soils with higher precipitation amounts could be suggested based on the results. However, soil organic matter seems to increase slower with higher precipitation rates. It is proposed that the decomposition of soil organic matter is limited by water availability in these proglacial areas leading to more decomposition with more precipitation and so lower annual rates of change. No relation between the annual rate of change for pH and the climatic variables is being found. It is suggested that the initial state of a proglacial area is more important in the evolution of pH.

5.2 Recommendations

After this research still some knowledge gaps are existing and some recommendations for further research can be given.

During this research it is shown that microclimatic variables do have a certain influence on the soil evolution in the proglacial area of the Pré de Bar. This influence is however very marginal since colluvial processes in the form of calc-schist play an essential role in this proglacial area. It would be interesting to conduct this same research in a geomorphological more quite area with more obvious differences in insolation values. It could be well possible that microclimatic variables play a larger role in soil formation in these areas.

Since this study is the first study comparing different proglacial areas with each other in the Alps in the way it was done here, numerous recommendations for further research can be given. The most important element which can lead to confirmations of the suggestions made in this study is the enlargement of the amount of researched proglacial areas in the Alps so more data points can be added. This can lead to a more sophisticated analysis and maybe even a statistical analysis. It could also be interesting to add proglacial areas from other locations in the world. A higher diversity and more extreme values of temperature and precipitation can help to clarify the effect of macroclimate on soil evolution.

Next to more data points it would also be valuable to assess the uncertainty in the calculations of the annual rates of change for the different soil properties. Only one study is known which compares different parent materials with each other in chronosequences in the Alps. Especially proglacial areas with parent materials other than granite are still insufficient. It is also still questionable if all the relations between time since glacier retreat and soil properties are strictly linear. Probably this is not the case, so a study to this component is certainly needed for improving the analysis between macroclimate and soil evolution. Taking seasonality into account for the climate variables is an improvement which could certainly enhance the chance of resolving the processes present in the formation of the proglacial soils.

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