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Pro-glacial soil variability and geomorphic activity – the case of three Swiss valleys

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ABSTRACT: Soils in pro-glacial areas are often approached from a chronosequence viewpoint. In the chronosequence approach, the objective is to derive rates of soil formation from differences in properties between soils of different age. For this reason, in chronosequence studies, soils are sampled in locations that are assumed geomorphically stable and that have different age. As a result, these studies do not necessarily yield a complete view of soil variability in pro-glacial areas, and may miss important relations between geomorphology and soil development. In this contribution, we present new soil observations from three closely related pro-glacial areas in Switzerland. These observations were intended to get closer to a complete view of soil variability, and to assess impacts from factors other than time on soil development. About 40 soils were visited in each pro-glacial valley in a combined design-convenience sampling scheme and described in the field. Linear modelling was used to assess effects of time and topographic factors on soil properties. The time since glacial retreat turned out to rarely explain more than half of the variation in soil properties, and a linear model combining effects of time and topographic variables explained typically about half of the variation in each pro-glacial valley. Models differed and were not transferable between valleys. Apparently, time and the present-day shape of the landscape combined are insufficient information to accurately predict soil properties. Field evidence points to the importance of the geomorphic history and regime of the valleys as a reason for this. Copyright © 2014 John Wiley & Sons, Ltd.

KEYWORDS: chronosequence; pro-glacial; pedometrics; soil formation; soilscape

Introduction

Soils in pro-glacial valleys have received much attention in recent decades. This is due to the realization that known glacial retreat rates can be used to establish chronosequences – of vegetation (e.g. Burga *et al.*, 2010), of microbial life (Sigler and Zeyer, 2002; Schurig *et al.*, 2013), and of soil formation (Bernasconi *et al.*, 2008; Egli *et al.*, 2010; Mavris *et al.*, 2010; Egli *et al.*, 2011). Process rates can be estimated from such chronosequences, which in the case of soil formation is particularly interesting from a geomorphic viewpoint because it allows soils to be used in dating landforms (Birkeland *et al.*, 2003).

The main assumption behind the soil-chronosequence approach is that the difference in soil age is the determinant of the difference in soil properties (Birkeland, 1990; Sauer *et al.*, 2014). In other words, one of Jenny's (1941) five well-known soil forming factors; time, is the only relevant one. The other four factors – parent material, climate, organisms and topography, are assumed constant or themselves strongly correlated with time. Therefore, pro-glacial soil chronosequences are only valid if climate and parent material are homogenous over the pro-glacial area, if vegetation depends on time since glacial retreat, and if the effect of topographical differences is negligible. In an attempt to ensure the latter condition, soil chronosequence studies typically take samples on locations that are believed to be geomorphically stable (Dethier *et al.*, 2012).

Only few pro-glacial soil studies have taken a more general approach that allows an assessment of the validity of pro-glacial soil chronosequence studies. An important case is the work of Egli and colleagues on the pro-glacial area of the Morteratsch glacier in Switzerland (Egli *et al.*, 2006a). Using a pre-existing map of soil types, they found only a weak correlation between the relative area that soil types covered in sections of the pro-glacial area, and the time since glacial retreat for these sections. However, for individual landforms such as (weakly expressed) ridges, summits, and valleys and for individual slope classes, a strong quadratic relation existed between the relative area that soil types covered and time since glacial retreat. Egli *et al.*'s (2006a) results are interesting from a chronosequence viewpoint, first because they show that within one pro-glacial area, several soil types may be found with the same soil age, all on supposedly stable locations. Apparently, in their case, the soil chronosequence approach does not work very well. Second, results indicated that the relatively subtle topographic differences within a pro-glacial area may play a strong role – which suggests that it is mainly the assumption of uniform topography that is violated.

The more general approach of Egli *et al.* (2006a) is not new in itself. It is widely used in digital soil mapping studies, or pedometrics, where the observed variation in soils is regressed upon a range of possible explanatory factors including climatic, topographic and geological factors (Heuvelink and Webster, 2001). In such studies, the attention is usually on the prediction of individual numerical soil properties (e.g. Follain *et al.*, 2006), rather than on the prediction of classified soil types (e.g. Kempen *et al.*, 2009). Almost without exception, results of these pedometric studies indicate that topography, in the form of variables such as slope steepness, profile curvature and plan curvature, plays an important role in determining soil properties.

Therefore, the relation between soil properties, time since retreat and topographical variables in pro-glacial areas deserves a closer look. First, to attempt to determine to which degree time since glacial retreat remains an important factor in determining different soil properties. It is conceivable that some soil properties are more determined by soil age, and less by topography than others. This may offer valuable suggestions for pro-glacial soil chronosequence studies [such as provided by Sauer (2010) for Mediterranean chronosequence studies]. Second, to find out to which extent the pedometric approach that includes topographic variables is successful in predicting soil properties within and between pro-glacial areas. If this is unsuccessful, factors other than current topography must be considered in understanding pro-glacial soil development. An important candidate factor in geomorphically active regions such as pro-glacial areas could be a different geomorphic history or regime for different parts of the pro-glacial area.

In this pursuit, new observations are necessary. Using a set of such point-based pro-glacial soil observations, our objectives are (1) to test the importance of time since glacial retreat in explaining soil properties in pro-glacial areas, (2) to create and validate linear models explaining soil properties with time since glacial retreat and topographic variables, and (3) to make inferences about the geomorphic history of sites where soil properties cannot be well predicted.

Study Sites

Three de-glaciating valleys in the eastern Swiss Alps were selected as study sites; the Forno, Tschierva and Morteratsch valleys (Figure 1). This choice was informed by the existing research infrastructure in the case of the Morteratsch valley, and proximity in the case of the Forno and Tschierva valleys. All three valleys run generally to the north. The valleys inherit their lithology from the Bernina and Stretta crystallines, which contain granitic and metamorphic rock (Buchi, 1994). Minor lithological differences between the valleys mainly concern the relative abundance of acidic rocks, with the Forno valley having the highest proportion of granites, and the Tschierva valley having the lowest proportion (Swiss Federal Office of Topography, 2010).

Glacial extent in the three valleys reached its most recent maximum during the Little Ice Age, around 1850 (Figure 2). The subsequent glacial retreat, which in the Alps as a whole may have been largely caused by deposition of soot from factories and trains (Painter *et al.*, 2013) and only later by increasing temperatures, has been documented in detail (SGMN, 2010). In all three valleys, retreat since 1850 exceeds 1400 m along the valley axis. Almost uninterrupted retreat was observed for the Morteratsch and Forno glaciers. For the Tschierva glacier, which separated into several tongues after it retreated beyond a confluence, retreat was interrupted between 1959 and 1985. The total glacial re-advance between these years was about 250 m. As a result, no soils started forming in the Tschierva glacier's pro-glacial area between 1959 and 1985.

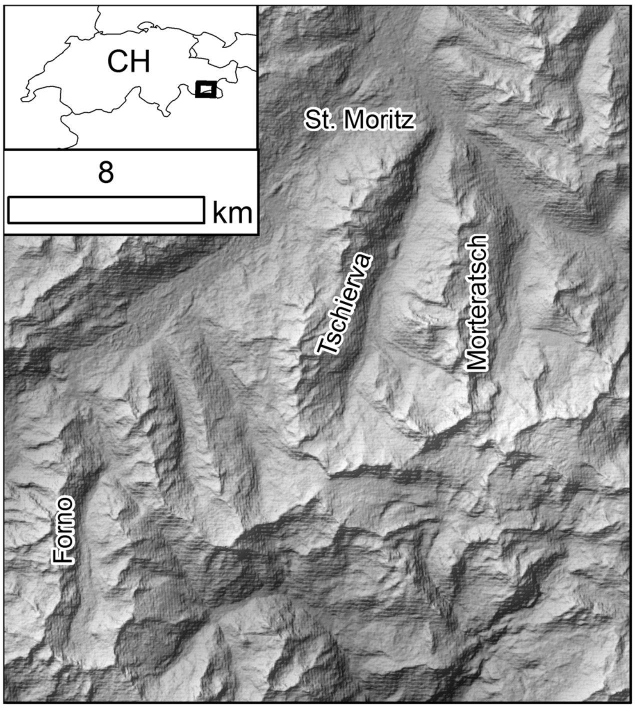

Figure 1. Position and morphology of the three study sites in the east of Switzerland, close to the city of St Moritz. The background is a hillshade image of the ASTER GDEM 30-m resolution digital elevation model. ASTER GDEM is a product of METI and NASA.

In general, soils in the three valleys are rocky, thin and acidic. Soil properties differ between different parts of the valleys, with pro-glacial soils the least developed and millennia-old soils in valley bottoms outside of the 1850 end-moraine the best developed, for instance into Podzols. Pro-glacial soils in the three valleys have been best studied in the pro-glacial area of the Morteratsch valley. They have been reported to vary from Lithic Leptosols, which are most prevalent close to the glacier, to Dystric Cambisols, which are found in some areas close to the 1850 moraine (Egli *et al.*, 2006a). The relative proportion of different soil types in this pro-glacial area was found to be a function of time since glacial retreat and of topography. Using these results and an assumed post-glacial landscape, Egli *et al.* (2006b) were able to predict future prevalence of different soil types after deglaciation. The Tschierva and Forno pro-glacial areas have received no pedological attention beyond the general level.

Morphologically, there are significant differences between the pro-glacial areas of the three valleys. The Morteratsch pro-glacial area is 2500 m long and 700 m wide at its widest point, with an average slope along the valley axis of about 8%, and a slope of the hillslopes to the sides of about 50%. More than half of the valley is protected from activity of these hillslopes by side moraines almost on all sides. The Tschierva pro-glacial area is shared by two glaciers, is 2000 m long and 500 m wide at its widest point, with an average slope along the valley axis of about 14% and of the hillslopes to the sides of about 60%. Only the most recently de-glaciated part of the pro-glacial area is protected by moraines. The Forno pro-glacial area is 2500 m long, 350 m wide at its widest point, has an average slope along the valley axis of about 10%, and of the hillslopes to the side of about 100%. It is not protected by moraines. It follows that the Morteratsch pro-glacial area is potentially least disturbed by geomorphic activity such as hillslope processes or redistribution in the valley itself, and the Forno valley probably most disturbed.

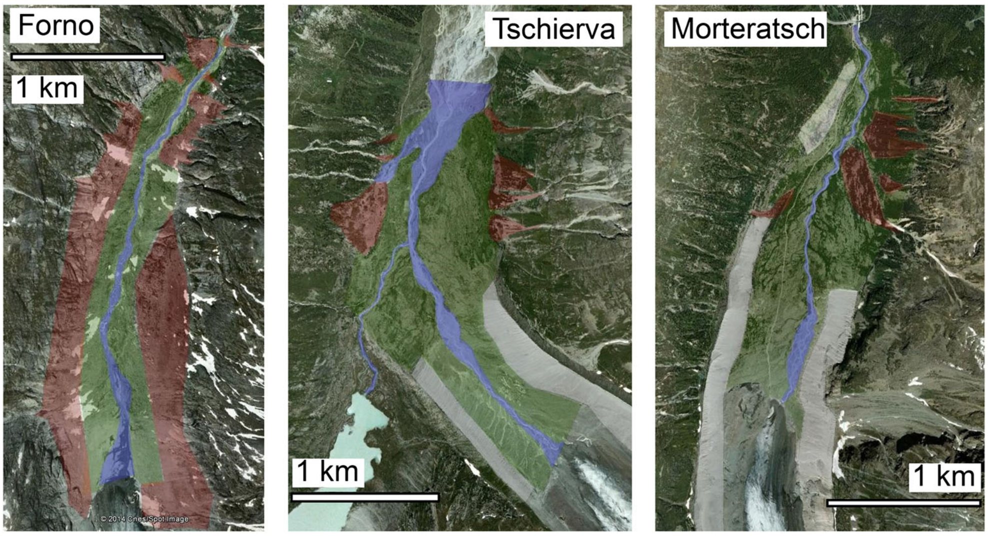

Figure 2. Subdivision of the three studied valleys into the steep slopes of side-moraines (grey), the floodplains of pro-glacial streams (blue), stable pro-glacial area (green) and areas influenced by debris flows (red). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Methods

In each of the three valleys, the pro-glacial areas were divided and mapped into (a) the steep slopes of side-moraines, (b) the floodplains of pro-glacial streams, and (c) presumably stable zones making up the rest of the pro-glacial areas. It was presumed that in both the steep slopes of moraines and fluvial zones, disturbance is intense, soil formation is continuously reset and that consequently soil–age relations are weak. No observations were planned in the steep and dangerous slopes of moraines, and only a few were planned in the floodplains. Conversely, in the third, seemingly undisturbed and stable part of the pro-glacial zone, which is almost flat, soil–age relations were expected to be strong, except in cases where debris flows and other influences from the hillslopes surrounding the pro-glacial area have affected it. Possible debris flow disturbance was recorded, which was difficult for older debris flows, closer to the 1850 end moraine. Almost all observations were in the stable zone, which also occupies the largest surface area (Figure 2). None of these observations had indications of instability and we assert that none of them would have been disqualified from a soil chronosequence study.

In the summer and autumn of 2011, soils were observed in each zone in each of the glacial valleys using a combined design and convenience sampling scheme. Each observation was considered to have a 1 m^2 support, i.e. a 1 m^2 validity. Observations were intended to cover a wide range of age and topographic conditions. If planned locations were dangerous to reach, they were excluded and no replacement location was visited. Especially in the narrow and steep Forno valley, this resulted in the exclusion of a significant number of the initially selected locations. Ultimately, a total of 111 locations were visited; 46 in the Morteratsch valley, 36 in the Tschierva valley and 29 in the Forno valley (Figure 3).

Soils were described using standard guidelines (IUSS Working Group WRB, 2007), with some adaptations that were intended to better describe pro-glacial soils. First, a decision on assignment of the qualifier *skeletic*, indicating stone content of over 40%, formally requires observation of the soil profile to a depth of 1 m. Since often only shallow profiles could be dug in the very rocky parent material in the pro-glacial areas (between 40 and 60 cm), this qualifier was assigned when soils had 40% stoniness over the depth of the profile. Second, a decision on assignment of the qualifier *humic* requires

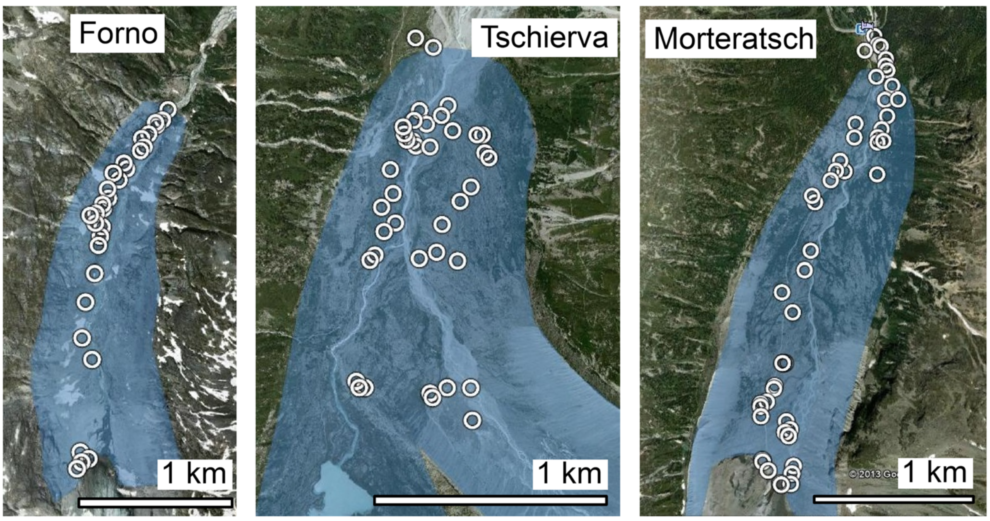

Figure 3. Soil sample locations in the three studied valleys. The 1850 glacial extent is indicated in blue. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

quantification of the organic matter content. Since this was not possible in the field, this qualifier was assigned when soils had a well expressed A horizon. Third, the corrected depth of visible soil formation was defined and recorded as the combined thickness of the A, AB, AC and/or B horizons in each profile multiplied by the fine earth fraction to correct for stoniness. This definition, and particularly multiplication with the fine earth fraction, was intended to correct for the fact that the same volume of soil formed reaches a greater depth in soils that have a lower fine earth fraction. Soil colour was assessed with the Munsell soil colour charts, and pH was measured in the field with a pH indicator of the Hellige type, which has an accuracy of about 0.5 pH units. The *T*-test was used to test for differences in mean soil properties between the different zones in pro-glacial areas.

Slope, aspect and plan and profile curvature were also measured in the field, to allow an ex-post assessment of the role of topography on soil development. Possible geomorphic disturbances to the stable zone, such as indications of debris flows, were noted. In addition, annual insolation (relating to climate) and overall curvature (relating to topography) were calculated for every visited location using an ASTER 30-m resolution global digital elevation model (DEM) and standard ArcGIS functionality.

The time since glacial retreat for every location was derived from the one-dimensional retreat histories for every year since 1850 (SGMN, 2010) and the digital two-dimensional glacial outlines for 1850, 1973, and 1999 from the Digital Atlas of Switzerland 3 (2010). These outlines are based on historical maps, aerial photographs and satellite images (Müller *et al.*, 1976; Maisch, 1992; Maisch *et al.*, 2000; Paul, 2004). The annual glacial retreat lengths (SGMN, 2010, with accuracy significantly better than 5 m) were used to hypothetically place the snout of the glacier further up-valley from the 1850 terminal moraine. In case of a temporary advance, in the case of the Tschierva valley, the snout was hypothetically placed down-valley. No major changes in the shape of the snout were observed between 1850, 1973 and 1999, which validates this essentially one-dimensional approach. Hence the year of glacial retreat was known for each point in the valleys, and hence for each of our soil-observations. Finally, a soil age was calculated from the year of glacial retreat, by subtracting this year from 2011 (the year of observation). Soil ages were thus inferred rather than directly measured from samples, an approach which is widely adopted for recent pro-glacial studies in the well-described European Alps (e.g. Egli *et al.*, 2006a, Bernasconi *et al.*, 2008). Table I summarizes characteristics of the list of variables.

The combined soil and landscape dataset was used in linear regression to assess the role of time since glacial retreat and topography in determining soil properties. Slope measurements, which had a skewed distribution, were normalized using the natural logarithm (cf. Webster, 2001). Linear models were estimated for each of the numerical soil properties for each pro-glacial valley. The models predicted the soil properties with time since retreat, slope, aspect, insolation and the three curvature measures as explanatory variables for the supposedly stable zones in the pro-glacial areas (hence, excluding the slope and fluvial zones and excluding the locations disturbed by debris flows). Regression was performed forward stepwise with significance (*p*-) values for inclusion of a variable in the regression model equal to 0.20 and exclusion equal to 0.25. Multicollinearity was not a problem: all pairs of explanatory variables had a Pearson correlation coefficient smaller than 0.6. Finally, in a cross-validation setup, those linear models that performed satisfactorily for one valley were used to predict soil properties for the other two valleys.

Results

The distribution of the three zones; stable, fluvial and slope-influenced, and of the debris flows over the three valleys reflects their general characteristics. The Morteratsch valley has the widest and least disturbed pro-glacial area, and the Forno valley has a narrow and intensively disturbed pro-glacial area.

Soils in all three zones in all three valleys have high stoniness, both on the surface and in the profile, with the fine earth fraction typically having coarse sand texture – reflecting the ground and side moraine parent material. In some cases, very low stoniness and sandy loam textures are found in small depressions, particularly in the stable zone. Sorting however is generally poor, befitting young glacial till deposits, and soil structure is absent. Soil colours in the topsoil have yellowish or yellow-red hues of 2.5Y or 10YR, reflecting limited weathering, and relatively high values of three and higher, reflecting low organic matter content. For the parent material in the subsoil, hues are almost exclusively yellowish (2.5Y), and values are typically four or higher.

Table II presents summary statistics for some numerical attributes of the soils for every pro-glacial valley for the stable and fluvial zones. The average depth of soil formation over the entire dataset is 2 cm, further indicating the very limited development of the young pro-glacial soils. The average pH is 6.1, with differences between the valleys reflecting the fraction of granite in the parent material: less granite in the Tschierva valley's moraines leads to slightly higher pH values than in the Morteratsch valley and the Forno valley.

Observations in the fluvial zone confirmed the expectation of disturbed, rejuvenated soil formation, in the sense that pH values are higher ($p = 0.001$), the depth of soil formation is smaller ($p = 0.031$), and vegetation cover is lower than in the supposedly stable zone ($p = 0.448$, but with abundant additional field evidence with spatial support larger than points).

Soil profiles are dominantly AC profiles, with a thin organic-rich A horizon overlying the parent material in the C horizon. In a quarter of cases, the A horizon is absent, and only parent material is found. On few occasions, mainly in and near the fluvial zone, weakly developed (palaeo-) soil profiles are buried under newly forming soils.

Table I. Overview of non-soil variables

Variable	Code	Datatype	Unit	Support	Source
Slope	1	Continuous, ratio	[deg]	10 m	Field
Plan curvature	2	Discrete, ordinal	[–]	10 m	Field
Profile curvature	3	Discrete, ordinal	[–]	10 m	Field
Overall curvature	4	Continuous, ratio	[–]	90 m (3 cells)	GIS
Annual insolation	5	Continuous, ratio	[$\mathrm{Wh\,m^{-2}}$]	30 m (1 cell)	GIS
Time since glacial retreat	6	Continuous, ratio	[yr]	Various	SGMN, 2010

Note: Code refers to the codes used in Table IV to identify variables. Support refers to the spatial scale of the observations.

Table II. Summary statistics of soil observations

Pro-glacial area		All	Forno		Tschierva		Morteratsch	
Zone		All	Stable	Fluvial	Stable	Fluvial	Stable	Fluvial
Number of observations		111	25	4	29	7	43	3
pH	Mean	6.1	5.9	6.9	6.3	6.6	5.8	7.0
	Standard deviation	0.9	0.7	0.0	0.8	0.9	0.9	0.0
	p (s = f)	0.001	0.000		0.517		0.000	
Depth of soil formation (cm)	Mean	2.0	2.4	1.8	2.2	0.6	1.3	0.0
	Standard deviation	2.7	2.8	2.5	1.3	0.8	3.1	0.0
	p (s = f)	0.031	0.824		0.002		0.000	
Vegetation cover (%)	Mean	38.0	30.0	33.0	49.0	38.0	38.0	1.0
	Standard deviation	25.5	25.5	23.8	28.8	35.4	33.4	0.9
	p (s = f)	0.448	0.717		0.840		0.000	
Soil stoniness (%)	Mean	30.0	37.0	29.0	24.0	31.0	31.0	17.0
	Standard deviation	16.9	19.1	13.9	14.3	17.8	16.1	11.8
	p (s = f)	0.730	0.266		0.140		0.202	
Surface stoniness (%)	Mean	55.0	66.0	29.0	50.0	52.0	57.0	37.0
	Standard deviation	29.8	27.1	27.5	30.5	34.1	30.6	25.8
	p (s = f)	0.631	0.426		0.491		0.395	

Note: *p* (s = f) gives the probabilities that the fluvial and stable zones have equal means.

Soil classifications mainly reflect the high stoniness of the soil, with humic, humiskeletic and skeletic Leptosols dominating. Some soils in the fluvial zone with finer parent material are classified as humic Fluvisols (Figure 4).

Locations in the stable zone where debris flows were presumed based on surface morphology, often have soil properties that differ from other locations in the stable zone. This is best illustrated in the Forno valley, which is most strongly influenced by debris flows. From Figure 5, it is clear that observations on the recognized debris flows have pH values that are relatively high, like observations on the fluvial locations, and unlike the other observations in the stable zone. This suggests that debris flows, which originate from hillslopes outside the pro-glacial area and that have been de-glaciated for millennia, nevertheless provide relatively fresh and unweathered material to the pro-glacial area.

Relation with time since glacial retreat

Pearson correlation coefficients were calculated to assess the strength of a linear effect of time since glacial retreat on soil properties. Coefficients were only calculated for the supposedly stable zone in each valley (Table III). Locations on recognized debris flows were excluded.

For pH, soil and surface stoniness, correlations are predominantly negative; older soils have lower pH values and less stones, both in the profile and on the surface. Conversely, older soils are typically deeper developed and have higher vegetation cover. Relations with time since retreat are strongest in the Morteratsch valley, where the probability of non-correlation is less than 1% in all but one case (soil stoniness), and weakest in the Tschierva valley, where soil properties and time are typically uncorrelated. In the Forno valley, correlations of time since retreat with soil properties are strong with the exception of pH, where no significant correlation was found (cf. Figure 5).

Linear model

Linear models for the various numerical soil properties were estimated with time and topographical properties as explanatory variables in order to assess the joint effect of time and topography. Table IV summarizes model performance for each of the soil properties in each of the valleys.

Figure 4. Examples of soils found in the three pro-glacial areas. Left, a humic leptosol with a thin topsoil overlying very rocky parent material. Right, a less often observed humic fluvisol with visible layering. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

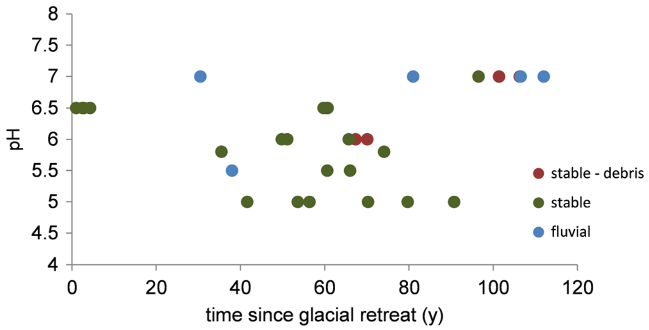

Figure 5. pH Values as a function of time since glacial retreat for observations in the fluvial and stable zones, with potential debris flows in the stable zone separated from the rest of that zone. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Table III. Strength (r) and significance (p ($r = 0$)) of the correlation between the time since glacial retreat and soil properties, for the stable zone of the pro-glacial areas in all three valleys

Pro-glacial area		Forno	Tschierva	Morteratsch
Zone		Stable	Stable	Stable
Number of observations		20	29	31
pH	r	−0.030	−0.437	−0.797
	p ($r = 0$)	0.880	0.020	0.000
Depth of soil formation (cm)	r	0.650	0.400	0.600
	p ($r = 0$)	0.001	0.033	0.000
Vegetation cover (%)	r	0.530	0.000	0.590
	p ($r = 0$)	0.007	0.847	0.000
Soil stoniness (%)	r	−0.577	0.200	−0.381
	p ($r = 0$)	0.003	0.306	0.010
Surface stoniness (%)	r	−0.469	0.000	−0.624
	p ($r = 0$)	0.021	0.875	0.000

Note: Potential debris-flow affected observations were excluded from the stable zone.

Table IV. Multiple linear regression model performance (r^2 value) for soil properties for each valley

	Forno		Tschierva		Morteratsch	
	r^2	Variables	r^2	Variables	r^2	Variables
pH	0.20	−1,5	0.38	4, −6	0.82	1, −3,4, −6
Depth of soil formation (cm)	0.46	1,2,4,6	0.10	6	0.41	3,6
Vegetation cover (%)	0.44	−1,6	0.43	−5	0.64	2,6
Soil stoniness (%)	0.45	−2,−4,−6	0.27	−1,3,6	0.31	−3,−6
Surface stoniness (%)	0.37	1	0.12	5	0.54	−2,−6

Note: Variable codes refer to the variables in Table I: 1 = slope, 2 = plan curvature, 3 = profile curvature, 4 = overall curvature, 5 = annual insolation and 6 = time since glacial retreat. Signs before the codes indicate the sign of the regression coefficient for each variable.

Eight of the 15 models have r^2 values over 0.4. Model performance is generally best in the Morteratsch valley, and worst in the Tschierva valley, mirroring the strength of the correlation with time since glacial retreat (factor 6), which is an important factor in most models. Next to time since retreat, all three curvature factors (factors 2, 3 and 4) often play an important role. Slope (factor 1) is mainly important in the Forno valley. Annual insolation (factor 5) is rarely a relevant factor. Average performance is highest for vegetation cover and pH, although there is large variation between valleys. The depth of soil formation, soil stoniness, and surface stoniness are more difficult to predict. Surface stoniness and vegetation cover have models with almost similar variables with opposite signs, and are negatively correlated to each other in all three valleys. This is related to their competition for surface area, and confirms field observations.

Model validation

Cross-validation was performed with the models that had an r^2 value over 0.5; the pH, vegetation cover and surface stoniness models in the Morteratsch valley. For each property, Morteratsch-based predictions for the Forno and Tschierva valleys consistently have r^2 values of less than 0.25 with the exception of vegetation in the Forno valley, which had an r^2 value of 0.32. Apparently, soil patterns formed under different conditions in the three valleys.

Discussion

We set out to determine the strength of the effect of time since glacial retreat on soil properties in pro-glacial areas. This strength varies between valleys and between soil properties. Based on linear regression, it is generally lower than expected based on the work of Egli *et al.* (2006a), both in the Morteratsch valley where Egli and colleagues worked and especially in our other two case study valleys. Quadratic functions of time hardly explain more variation. We suggest that the difference between Egli and colleagues' and our results in the Morteratsch valley originates in the support and type of the observations.

Whereas Egli and colleagues based their regressions on a map of soil types with polygons (much) larger than 100 m^2, our results are based on point observations of soil properties with spatial support of approximately 1 m^2. Some of the variation observed at the point level may be lumped in soil maps, and some variation in soil properties is lumped in soil types. Indeed, in another study, Egli *et al.* (2011) use point observations in the Morteratsch valley and conclude that the amount of smectite formation is only weakly correlated with time.

This is important information in the context of pro-glacial soil chronosequence studies, which are usually based on point observations. Such studies may run the risk of incorrectly assigning variation in soil properties to time since the start of soil development. Datasets that replicate observations with similar age, such as the one used in this study, may allow an assessment of this risk.

Nevertheless, soil age is an important factor that explains a significant portion of the variation in our observations. In particular, pH seems to respond rapidly and clearly to incipient weathering and soil development in the acidic parent materials in our study area. In this sense, it joins the surprisingly rapid formation of smectitic clay minerals (Egli *et al.*, 2011) as a soil property that changes perceptibly over centennial timescales in alpine climates (cf. Sauer, 2010). The same is true for the soil-related vegetation cover (cf. Burga, 1999; Burga *et al.*, 2010).

The (weak) negative relation of soil and surface stoniness with soil age that was observed in half of the cases is surprising, and shall be discussed later.

The pedometric approach, where soil age and topography together were used to explain variation in soil properties (Table IV), was more successful than the chronosequence approach (Table III). Topographic variables were clearly significant in explaining a portion of the variation for most soil properties. In particular, the subtle differences in curvature were often significant, suggesting that lateral redistribution of water and perhaps of the finer fraction of soil material plays a role in pro-glacial areas over the spatial scales of dozens of metres over which curvatures were observed. This suggestion is strengthened by our field observations of finer textured soils with a larger fine earth fraction in slightly lower lying areas – each of which would nevertheless have been selected for a chronosequence approach. Relatively low lying areas would also be covered with a thicker layer of snow, which would lead to a larger water availability and faster weathering (Benedict, 1993; Egli *et al.*, 2011; Langston *et al.*, 2011). Apparently, even in the parts of the pro-glacial area that are stable in the sense that they are not disturbed by outside geomorphic processes, the assumption underlying the chronosequence approach that topographical differences are negligible, is to some extent invalid.

However, much soil variation is left unexplained. We argue that the geomorphic history of the three case study valleys and the pro-glacial environment can explain a large part of this variation. First, glacial deposits are poorly sorted over spatial scales up to dozens of metres. In some places, there are more relatively fine sub-glacial deposits, and in others, coarser supra-glacial deposits dominate. The process of deposition of supra-glacial deposits in particular has a somewhat pulsating behaviour when summer melt exceeds winter growth of a glacier's snout. At smaller scale, the presence of crevasses near a melting snout can provide hotspots of deposition when supra-glacial debris falls into them. The result of these factors is a variable parent material for soil formation once the glacier has receded – which has indeed been observed during fieldwork.

Second, the role of the glacial stream may have changed over time. Sections of the supposedly stable zone may have been part of the floodplain before incision, and may have experienced a small but significant influx of finer fluvial sediment during floods.

Finally, in case no clearly expressed side moraine is present that shields the pro-glacial area from hillslope influences, the latter must also be taken into account. In our case study areas, side moraine protection is only present to some degree in the Tschierva and Morteratsch valleys, and absent in the Forno valley where we observed most debris flows. Full-depth snow avalanches, which scour the thin soils on the hillslopes, can also deposit sediment and plant material on the pro-glacial area (Ceaglio *et al.*, 2012; Confortola *et al.*, 2012). Although such full-depth avalanches are unobservable in summer, they at least occur in the Morteratsch valley, where anecdotal evidence is available because it is a well-known ski area. Since older soils would have experienced more avalanches, more finer material may have accumulated in them, which could explain the lower stoniness that was observed. In addition, avalanches provide water and thereby increases weathering speeds as discussed earlier.

In all these cases, geomorphically-caused differences in soil stoniness, the fine earth fraction and organic matter, may lead to different rates of soil formation. Although different pathways of development likely exist for different locations and geomorphic regimes (Sommer *et al.*, 2008), soils with a larger fine earth fraction would generally hold more water, experience faster weathering and allow faster plant colonization, all leading to more rapid soil formation (e.g. Burga *et al.*, 2010; Langston *et al.*, 2011).

To the extent that the earlier-mentioned reasons are valid, spatial differences in soil formation do not necessarily relate to the present-day topography, but to the geomorphic and pedomorphic history and conditions in the pro-glacial area. It is clearly not possible to capture such differences with variables derived from a present-day DEM. An alternative would be combined modelling of soil and landscape development (Temme *et al.*, 2013; Vanwalleghem *et al.*, 2013), which has recently been undertaken in a chronosequence context (Sauer *et al.*, 2012). In such 'soilscape' models, non-linear and non-quadratic co-development of soils and landscapes, as observed in our study sites, would be a possible outcome of simulations.

Regarding the possibilities for the extraction of valid soil chronosequences in pro-glacial valleys, the aforementioned reasoning suggests that valleys that are wide, flat, protected by side moraines, and that have experienced regular glacial retreat and rapid post-glacial fluvial incision, offer the best possibilities. Out of our three case study valleys, the Morteratsch valley is closest to this ideal image, despite its limited incision. The Forno valley is narrow, steep and unprotected by moraines, and the Tschierva valley is wide and flat, but as mentioned earlier has experienced an irregular glacial retreat history, which must have caused redistribution of material from previously formed soils over the pro-glacial area. Such redistribution is not visible morphologically in the field, but may nevertheless be present. In addition, a former confluence between two glaciers is present in the current pro-glacial area of the Tschierva valley (as opposed to upstream of it, which is the case in the Morteratsch valley). Seen from this perspective, the pro-glacial area of the Damma glacier in the central Swiss Alps, which is also often used in chronosequence studies (e.g. Bernasconi *et al.*, 2008; Guelland *et al.*, 2013), has the disadvantages that it is steep, narrow and affected by a side-stream which has breached the protective side-moraine. All pro-glacial valleys probably have a large variability in the grain size of the parent material, which will continue to present difficulties for soil chronosequences.

Conclusions

Time since glacial retreat only rarely explains more than half the variation in soil properties in the three studied pro-glacial valleys. The strength of the relation between time since retreat and soil properties varies between valleys and between soil properties. In the Morteratsch valley, and for pH, time seems to have the largest effect. Time and topographical variables combined typically explain about half the variation in soil properties, and always more than time since retreat explains in isolation. Apparently, location is important, even in supposedly stable locations in pro-glacial areas. It is argued that the depositional history, uneven fluvial influence and uneven supply of material from hillslopes surrounding pro-glacial areas can explain the remaining variation. A dynamic soilscape simulation model can potentially incorporate such factors. As it stands, for chronosequence studies, a wide, flat pro-glacial area with protective side moraines, a regular glacial retreat history, and quick subsequent fluvial incision would be the best choice.

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