Morphoseries for soil monitoring in the European Alps - a case study in the Montafon, Austria

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Abstract

The importance of soil protection is internationally recognised as soils are vital non-renewable resources that are increasingly under pressure. This study aims to develop a monitoring system for Alpine soils based on soil-landscape relationships and geomorphological knowledge. Our hypothesis is that landforms derived from topographic features related to soil-forming factors will be correlated with the characteristics of the soils in those areas. Soils in mountainous zones are often strongly influenced by slope processes, resulting in soil losses superior to the rate of soil formation. To investigate the soil-landscape relationship and to be able to monitor soils, geomorphological (expert) knowledge is inextricable and essential. This paper presents a method to capture geomorphological knowledge in a map in order to create a soil map in high Alpine regions by using morphoseries. These are zonations of units with homogeneous morphological properties on mountainous slopes that are placed within a multi-hierarchical landscape system.

Keywords: Alps, Soil Mapping, Geomorphology, Erosion

1. Introduction

Soils are, as water and air, essential for life on earth. They are a vital non-renewable resource increasingly under pressure, which performs a number of key environmental, social and economic functions. Due to its wide range of vital functions, maintaining soil conditions is essential for sustainability.

In this paper we focus on the European Alps. Currently the only available harmonised soil database covering the Alps is created at the European Soil Bureau (ESB) within the framework of the European Soil Information System (EUSIS). Their actions to address soil protection are based on incomplete information, e.g. (i) lack of uniform methodologies for collecting data leading to (ii) a lack of comparability of data and (iii) scale (Montanarella and Nègre, 2001). To encounter these problems a uniform soil monitoring methodology for the Alpine region is proposed in this paper. Emphasis is put on the soil- landscape relationship and based on geomorphological knowledge.

The term soil-landscape refers to the combination of soil and landscape properties within a given geographic location, which is a complex interaction of the two. Many studies have investigated the soil-landscape relationship, e.g. Chaplot et al. (2003), Gobin et al. (2001), Thompson et al. (2001), de Bruin et al. (1999), which all emphasizes the spatial difference and scarcely documented expert knowledge to address this concept. Our hypothesis is that landforms and terrain elements derived from topographic features related to soil-forming factors can be related to soil characteristics in those areas.

Soils in mountainous areas are often strongly influenced by slope processes, resulting in soil losses superior to the rate of soil formation. This process leads to relatively shallow soils in which a surface horizon, frequently rich in organic matter and of varying thickness, covers bedrock or parent material. A detailed geomorphological study enables the reconstruction of the landscape development and gives insight in the dynamics of the soil system.

To investigate soil development and its relation with site topography, soils are approached as an integrated part of the landscape as terrain elements, which are placed within a multi-hierarchical land system. Wielemaker (2001) stated to fully profit from contextual information, soils should not be presented separately but as part of a multi-hierarchical land system. This is a system of terrain units in which smaller units are nested within larger ones at different scale levels. This paper tries to apply this concept by using morphoseries. The objective is to capture the soil-landscape relationship and to characterize soil information by using (geo) morphological information.

2. Background and method

Pedogenesis can be defined as a progressive process that transforms parent material into a soil profile with one or more distinct horizons with increasing thickness (Johnson 1985). The necessity for a quantitative analysis of pedogenesis has become more compelling in the last decades (Hoosbeek and Bryant 1992, Minasny and McBratney, 2001). To investigate pedogenesis and its relation with site topography, soils are approached as an integrated part of the landscape as terrain elements. This is referred to as a multi-hierarchical landsystem. Multi-hierarchical landsystems are discussed by many others, e.g., Wright (1996), Molenaar (1996), de Bruin et al. (1999), Wielemaker et al. (2001). Within a landscape many hierarchical systems at different levels can be defined and are interlinked to different scales, both spatial and temporal. As a concept it includes a multi-level system of terrain units in which smaller units are nested within larger ones. In this study we focused on the level varying from the soil profile up to the morphoseries.

Morphoseries are (slope) units with homogeneous morphological properties in which the main soil forming factors are homogeneous. Figure 1 gives an abstracted, not to scale, slope transect with 7 different morphoseries. The slope transect is representative for slope development in metamorphic bedrock (van Noord 1996) and could, after specific adaptation, be applied to different locations.

Our study area is located in the Rellstal, which is part of the in the Montafon valley in Austria. It is located between 46°50´ and 47°8´latitude and 9°41´and 10°9´ longitude. Landforms, materials and processes in the Montafon valley had experienced profound geomorphological impact during Pleistocene glaciations. This is both in terms of production and distribution of sediments and because of pronounced glacial erosion, which resulted in oversteepened slopes (Dorren and Seijmonsbergen 2003). Cirques of former hanging glaciers, U-shaped valleys, morainic ridges, fossilised rock-glaciers and subglacial till are the direct relicts of these former processes and determine local soil conditions.

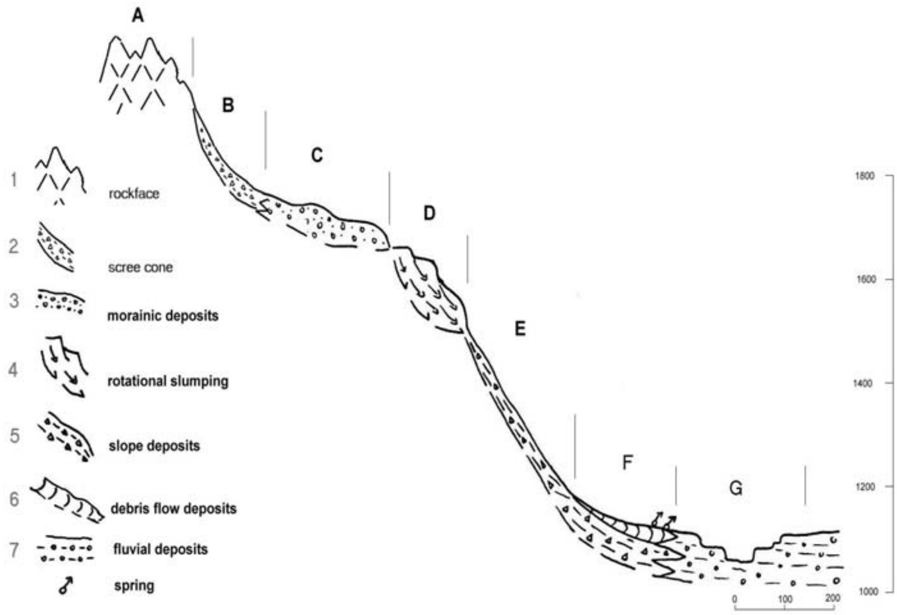

Figure 1: Simplified Alpine slope transect with different morphoseries, representative for slope development (After van Noord, 1996). A: Rockface, bare rock, 45-90°. No soil material and dominated by rockfall; B: Scree cone, 25-35°. Accumulation zone of rockfall. Soil material absent; C: Flat to slightly inclined section, 10-20° often with glacial deposits. Soil processes are determined by vertical water flux; D: Valley shoulder, 20-35°, subject to deep-seated mass movement. Soil processes depends on spatial position determined by vertical and lateral water fluxes. E: Steep transport zone, 20-45°, mosaic of thin slope deposits. Soil formation on stable areas determined by lateral water flux; F: Colluvial foot slope, 5-20°, with debris cones and colluviation, exfiltration. Soil formation by both lateral as vertical water fluxes; G: Fluvial valley floor with alluvial terraces. Soil development by vertical water flux.

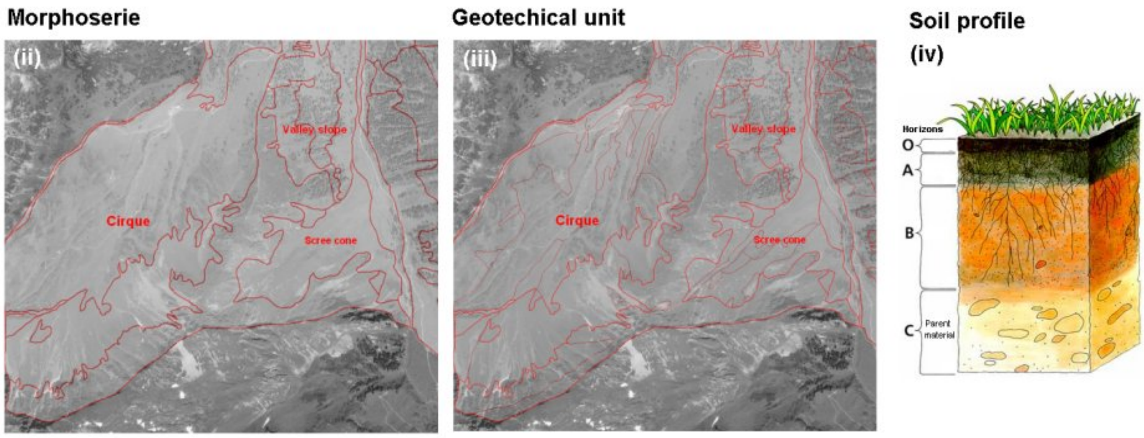

Figure 2: Hierarchical levels as proposed in this paper. This figure shows a geographic representation of the disaggregating and classification procedure, which is illustrated by the step-by-step zooming in principle, from morphoserie to soil profile. The morphoseries could easily recognized in the field and relatively easily derived from a geomorphological line symbol map.

Figure 2 shows the hierarchical levels used in our study, which are derived from the multi-hierarchical landsystem described by Wielemaker (2001): the morphoserie, the geotechnical unit and the soil profile level. Geotechnical units are described as: a spatial unit which is homogeneous concerning soil profile, soil development and main soil forming factors that are relevant for pedogenesis and nested within the morphoserie. During fieldwork we delineated spatial soil units at morphoserie level, we recorded morphometric data for each geotechnical unit and we described the following soil properties for a characteristic soil in each geotechnical unit: soil development, soil stability, soil depth, stoniness, average stone size, drainage and compaction. Soil depth was measured, while stoniness and average stone size were estimated in the field. The classification of soil development and soil stability are based on several criteria expressed in respectively Table 1 and Table 2, on a scale from 1 (poor) to 5 (very good). We chose to investigate this set of soil properties as they are commonly used, they could relatively easy be obtained in the field and they are not very time consuming. We also described the sedimentological characteristics roundness and texture following the method described by Seijmonsbergen (1992) to distinguish between alluvial, colluvial, glacial and peri-glacial environments.

Soil development	*Horizon differentiation*	*Soil profile*	*Colour*	*Soil texture*	*Soil structure*
(1) Very poor	No horizon differentiation	H / (AC) R	No colour diff.	Sandy	Loose
(2) Poor	Some horizon differentiation	AH (AC) / (C) R	Some colour diff.	Loamy sand	Loose/friable
(3) Moderate	Horizon differentiation	AH/AC/R	Colour diff. between horiz.	Loamy silt	Sub rounded
(4) Good	Good horizon differentiation	AH/AE/AC/R	Sharp colour diff.	Silty clay	Sub rounded / angular blocky
(5) Very good	Very good horizon differentiation	AH/AE/B/C/R	Very sharp diff.	Clay	Sub angular blocky

Table 1: Soil criteria, which determined the soil development.

Soil stability	*Slope curvature*	*Slope angle(°)*	*Mass movement activity*			*Morphoserie*
			Flow	Slide	Fall	
1. Very poor	Concave	35-50	5	4/5	3/4/5	A/B/E
2. Poor	Concave/straight	25-35	3/4	3	3/4/5	B/E
3. Moderate	Straight	15-25	3	3	2/3/4/5	D/F
4. Good	Convex/straight	5-10	2	2	2/3/4/5	C/G/F
5. Very good	Convex	0-5	1/2	1/2	1/2/3/4/5	C/G

Table 2: Geomorphological criteria, which determined the soil stability.

In order to underpin the morphoserie concept and to determine a quantitative soil-landscape relationship, field data were analysed and processed in the statistical program S-plus. The used statistical tests are binominal, to (i) determine the range of morphometric characteristics and to (ii) investigate a relationship between soil development and these morphometric properties by using a cross tabulation matrix. The relation between morphoseries and soil development and soil stability and other variables are analysed through cross tabulation matrixes. The result of the cross tabulation and related χ^2-test determines the relation between the field characteristics with consecutively the measure of soil development and soil stability. It shows whether variables of interest are independent (not related) or dependant (related).

3. Results

The slopes in our study area could be characterised by 7 morphoseries: 1) Rock face, 2) debris/scree cones, 3) Glacial deposits, 4) Valley shoulder, 5) Transport zone, 6) Alluvial fan and 7) Valley floor. The characteristics per morphoserie are presented in Table 3. This table shows that soil development was high on the valley shoulders and very low on rock faces and on debris/scree cones. The process of fall occur when slope angle is higher then 30 degrees and below this angle slide and flow dominates. Curvature, slope angle and mass movement processes influence soil stability and is most stable in morphoserie C, D and in morphoserie G. Soil stability is very poor on rock faces and debris/scree cones as result of the high slope angle and high process activity. Table 3 shows, not surprising, decreasing altitude from rock faces to the valley floor. Slope angle decreases when moving down from rock face to the glacial deposits in morphoserie C. Concerning slope angle, the valley shoulder is a transition zone, since a second sequence of decreasing slope angle is found from the transport slope into the valley floor.

Morphoserie	Description	Process	Soil properties (mode)		Morphometric properties (DEM)		
			Soil development	Soil stability	Curvature	Altitude (m)	Slope angle (°)
A	Rock face	Colluvial, Fall	1	1	Concave	1997 (180)	41 (8,4)
B	Debris/scree cone	Colluvial, Fall/slide	1	1	Concave	1956 (143)	30.2 (8.7)
C	Glacial deposits	(Peri) glacial Fluvial	3	4	Straight/ Convex	1863 (110)	19.4 (8.7)
D	Valley shoulder	Colluvial Flow/Slide	5	4	Convex	1773 (104)	29.6 (8.0)
E	Transport slope	Colluvial Slide/fall	2	2	Straight	1677 (134)	34.0 (7.1)
F	Alluvial fan	Colluvial Flow/slide	2	2	Concave	1510 (93)	22.5 (8.8)
G	Valley floor	Fluvial	3	4	Straight	1514 (136)	13.4 (7.6)

Table 3: Characteristics per morphoserie. Soil properties are determined in the field, which were assigned semi-quantitative values. The morphometric properties are derived from the DEM, within brackets the standard deviation is mentioned.

According to the soil properties as mentioned in table 4, soil depth and thickness of loose soil material increases when moving down from rock faces into the valley bottom, which is the result of accumulated slope material. Relationships exist between slope angle and thickness of slope material since slope angle mostly exceeds loose material rest angle. Stoniness and stone size obviously decreases when moving down from the upper rock face to the lower valley floor. Drainage and compaction depends on roundness and texture of the material, drainage is preferentially internal in course, very angular material. Rock roundness increases from very angular on rock faces to (sub) rounded on alluvial fans and valley floor. This is related to transport distance, where rocks are more rounded when transported over a longer distance. Texture depends both on position on slope and by parent material and tends to be finer when moving down into the valley, from cobbles to clayish material.

Morphoserie	n	Soil properties (0-5)						
		Soil depth (cm)	Stoniness (%)	Stone size (cm)	Drainage 1-5	Com-paction	Roundness	Texture
A	4	1.3 (2.5)*	98.8 (2.5)	33.8 (18.8)	2.8 (4)**	1.8 (2)	Very angular to angular	Gen.cobbles and larger
B	25	4.0 (6.0)	74.0 (33.9)	13.0 (11.9)	4.1 (4)	2.3 (2)	Very angular to angular	Gen.granule and larger
C	44	7.3 (5.8)	39.5 (35.4)	8.0 (7.5)	3.4 (4)	2.8 (2)	(very) angular to sub rounded	Sandy/ Clay to cobbles
D	14	9.2 (11.4)	30.4 (34.8)	7.9 (5.2)	3.9 (5)	2.4 (2)	Angular to subrounded	Clay to cobbles
E	47	10.4 (11.1)	29.6 (28.1)	7.6 (8.9)	3.3 (4)	2.3 (2)	Very angular to angular	Gen.granule and larger
F	22	17.9 (15.3)	30.5 (22.4)	6.4 (4.9)	3.1 (4)	2.5 (2)	Very angular to subrounded	Clay to cobbles
G	3	0 (0)	36.7 (25.0)	7.3 (4.6)	4.0 (4)	2.0 (2)	Angular to subrounded	Clay to cobbles

*Table 4: Soil properties as indicated during field observation. Soil depth and stoniness are measured in the field while drainage and compaction are interpreted based on decision rules and scaled from 1 to 5. * In brackets, standard deviation is given. **In brackets, the most frequent values (mode) mentioned.*

The results of the χ2 – test show morphometric properties which are related to soil development, e.g. zone, curvature, altitude and slope. There is no direct relationship between morphoserie and soil development and discussed in the following section. Concerning the relationship with soil stability as classified in this study slope class is directly related.

Soil development	H0	H1	Soil stability	H0	H1
Morphoserie	X		Morphoserie	X	
Zone		X	Zone	X	
Curvature vertical		X	Slope vertical	X	
Altitude classes		X	Altitude classes	X	
Slope class		X	Slope class		X

Table 5: Results of the χ2 – test, which shows if site characteristics are related (H1) or not related (H0) with soil development and soil stability.

4. Discussion

Soil development is absent in morphoserie A and B, due to lack of fine soil material and existing rock faces. Slope material consists predominantly of course to very angular boulders and scree material. Morphoserie C exits of more stable soil conditions. Material has been (re-) distributed since the last glacial phase. Preferential soil forming factors dominate, although, thick well developed soils are lacking due the cold, extreme conditions and limitation of nutrient input. Deep seated mass movement processes (slumping) is characteristic for morphoserie D and does not influence soil development. The valley slopes, Morphoserie E, are dominated by a dense forest cover, mainly coniferous forest. The forest cover increases favourable nutrient input and temperature conditions, which result in good developed soils. However, soil development and soil thickness is limited by the high mass movement activity. The material from the steep valley slopes is deposited in the alluvial fan zone (morphoserie F) and is influenced by the mass movement activities. The valley floor has stable soil conditions, although well developed soils do not prevail since deposition time is relatively short.

The statistical analyses were carried out to give insight in morphoserie properties and to underpin the morphoserie concept. Since the number of observation points is limited (159), the results should be interpreted as first indication of morphoserie characteristics.

The soil-landscape relationship is determined by cross tabulation validation. The results show no linear relationship (H0) of soil development with morphoserie but indeed a relationship (H1) between zone (source, transport or accumulation), curvature, altitude and with slope classes. These characteristics are used to determine morphoserie properties and combined to create automatically classified morphoseries. No significant relation between morphoseries and soil development was determined when using the complete sequence of morphoseries. On slope scale two sequences of source, transport and accumulation zones can be distinguished. The first sequence consists of morphoserie ABCD, the second of DEFG. If these two sequences are treated separately soil development is strongly related with morphoseries, given that the soil sample distribution is equal.

The method to use morphoseries could be a useful basis, but uniformity of the soil properties is not sufficient. Therefore some recommendations are proposed:

1. Due to high soil variability in the Alps, it is not useful to investigate at large scale (> 1: 50,000). Diversity in soil and lithology will be neglected and morphoseries cannot be distinguished.
2. Since soils in mountainous areas do not depend solely on topography and lithology, the aspect of vegetation and vegetation influence on soil stability and soil development should be investigated in order to gain more detailed information on the principle of soil development in mountainous areas.
3. The role of exposition should be involved when monitoring soils in Alpine regions, as it strongly affects soil hydrology.
4. To determine morphoseries, vegetation cover and patterns are helpful as they reflect soil and slope stability. These can be extracted from aerial photographs or high-resolution satellite images.
5. Besides determining different morphoseries, the concept of source, transport and accumulation zone has potential since there is a significant relationship with soil development and these zones show similarities with morphoseries.

5. Conclusions

Morphoseries provide the basis to study soil-landscape relationship, although other data and should be incorporated. When focusing only on geomorphological data, vegetation influence is neglected in the process of soil formation. In summary we conclude that:

1) Soils in mountainous zones are often strongly influenced by the relatively steep slopes on which they occur resulting in soil losses superior to the rate of soil formation.
2) To investigate the soil-landscape relationship in mountainous areas, geomorphological knowledge is essential.
3) A soil-landscape relation is obtained if soils are placed within the framework of a multi-hierarchical land system.
4) The concept of morphoseries is promising when focussing on soil-landscape modelling.
5) A relationship exists between the degree of soil development and morphoseries.
6) DEM derivatives provide the possibility to partially distinguish morphoseries

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