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Snowbeds on Silicate Rocks in the Upper Engadine (Central Alps, Switzerland)—Pedogenesis and Interactions among Soil, Vegetation, and Snow Cover

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Abstract

The pedogenesis and interactions among soil, vegetation, and snow cover of four alpine snowbeds on silicate rocks in the Upper Engadine (Central Alps, Switzerland) were investigated. The long-lasting snow cover of snowbeds causes differences in pedogenesis and soil properties compared to adjacent alpine sward. Because of the drainage characteristics of the silicate parent material, pedogenesis of snowbeds varies. On well-drained parent material, percolating meltwater favors podzolization during snowmelt. On less permeable parent material, meltwater causes temporarily water-logged conditions. Thus, the snowbed soils show redoximorphic features such as iron concretions. Snowbed soils are classified as Inceptisols or Entisols. A more detailed differentiation is only possible at the soil family level. Outside the snowbeds, moder humus forms (Rhizic Leptomoder, Rhizic Mullmoder) are common, whereas inside the snowbeds, mull humus forms (Rhizomull) as well as moder humus forms (Leptomoder) occur.

Introduction

Alpine tundra ecosystems show an extreme patchiness of site conditions, depending primarily on microtopography and slope exposure. Microtopography and the prevailing wind direction control the distribution of snow during the winter (Holtmeier and Broll, 1992). The depth and duration of the snowpack and the onset of snowmelt influence plant communities and ecosystem processes in several ways. Alpine snowbeds are characterized by an extremely long-lasting snowpack and a short snow-free growing season of only 2–3 months. Although snowbed vegetation has been described by many authors (among others, Braun-Blanquet and Jenny, 1926; Braun-Blanquet, 1975; Graf, 1994), soil properties beneath snowbeds rarely have been considered (e.g., Posch, 1977, 1980; Mueller, 1983; Tomaselli, 1991). The poor state of knowledge about soils and soil formation beneath snowbeds makes it difficult to understand ecological processes and plant development of snowbeds in detail. More differentiated descriptions of pedogenesis and the interactions among snow cover, soil properties, and vegetation of snowbeds are needed for a better description and understanding of snowbeds. Soils are influenced by many factors: parent material (bedrock, till, block, debris, etc.), vegetation, and climatic conditions. Precipitation and soil-water movement during the growing season are the most important climatic factors. Snowbeds on limestone, for example, become dry during summer because they usually are well drained. We expect the permeability of the parent material to be the key factor for pedogenesis of snowbed soils. As evidenced by some studies (Bednorz et al., 2000; Hiller et al., 2002), humus forms—the group of organic and organic-enriched mineral horizons at the soil surface (definition following Green et al., 1993)—are appropriate indicators of site conditions and thus should be considered when describing snowbeds. As shown by several discussions about topsoil characterization and classification including humus forms, detailed descriptions of humus forms in the Alpine tundra are still rare (Babel, 1996; Broll, 1998; Hiller, 2001).

Objectives

There are four aims of the present study on pedogenesis and soil properties of four snowbeds on silicate rocks located in the Upper Engadine (Central Alps, Switzerland):

1. Examination of the influence of a late-lying snowpack on pedogenesis and soil properties of snowbeds compared with adjacent alpine meadow communities.
2. Analysis of the influence of parent-material permeability on the pedogenesis of snowbeds.
3. Classification of the investigated soils according to the U.S. Soil Taxonomy (Soil Survey Staff, 1998), the World Reference Base (FAO, 1998), the Swiss Soil Classification System (FAP, 1992), and the German Soil Classification System (AG Boden, 1994) and comparison of the results of applying these classification systems to find out which system is the most suitable one for classifying snowbed soils.
4. Description and classification of the humus forms inside and outside the snowbeds according to Green et al. (1993).

Study Area

The study area is located in the Upper Engadine (Central Alps, Switzerland) (Fig. 1). The climate of the study area is continental, characterized by relatively large daily and annual amplitude of temperature and comparatively little annual precipitation, low cloudiness, and intense solar radiation. The mean annual air temperature in Samedan (1706 m) is 1.3°C; the total annual precipitation amounts to 657 mm. Precipitation is much higher above the timberline than on the valley bottom. Also, snow fall increases and the growing season becomes shorter with increasing elevation. Above timberline, the microclimatic conditions are reflected in the vegetation mosaic of *Carex curvula* sward alternating with other alpine plant communities. The structure of the *Carex curvula* sward depends on the site conditions.

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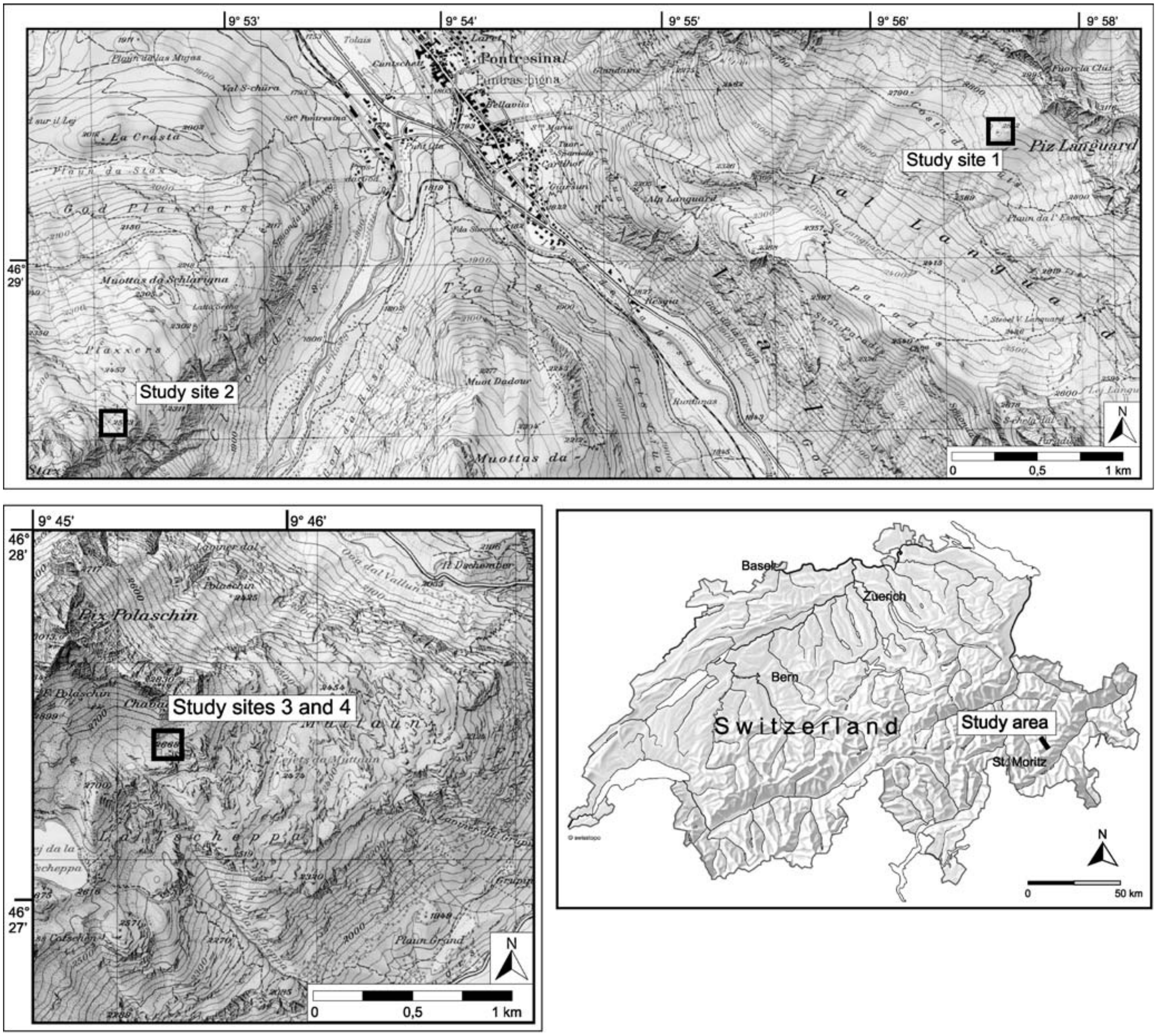

FIGURE 1. Study area (modified after http://www.swisstopo.ch/de/digital/over.htm) and location of the study sites (Upper Engadine, Central Alps, Switzerland). Reproduced with permission of swisstopo (BA056881).

Wind-swept locations are dominated by the lichen-rich *Caricetum curvulae* subass. *cetrarietosum*, whereas the *Caricetum curvulae* subass. *typicum* covers most of the area. Species such as *Carex curvula*, *Leontodon helveticus*, *Avena versicolor*, *Chrysanthemum alpinum*, and *Veronica bellioides* are common at these sites. At wind-protected, snow-accumulating sites outside the snowbeds the *Caricetum curvulae* subass. *hygrocurvuletosum* is common. Also, several snow-tolerating species are typical of this community. Very snow rich sites are dominated by typical snowbed plant communities: the *Salicetum herbaceae* and the *Polytrichetum sexangularis* (Braun-Blanquet and Jenny, 1926; Grabherr, 1993; Ellenberg, 1996). Species of the *Caricetum curvulae* are less frequent. Moreover, the diversity of the snow-rich communities is lower than that of sites outside the snowbeds. The snowbed vegetation tolerates late-lying snowpack and short growing seasons.

Methods

The vegetation of the snowbeds and adjacent *Carex curvula* sward was studied through the use of the Braun-Blanquet method (Dierschke, 1994). The data presented in this paper were collected from four representative snowbeds in the Alpine tundra. The investigated snowbeds meet all typical characteristics of snowbeds on silicate rocks described by several authors (cf. Braun-Blanquet, 1975; Posch, 1977, 1980; Tomaselli, 1991; Graf, 1994). Microtopography, duration and depth of snow cover, and vegetation of the snowbeds were mapped. Four soil profiles inside the snowbeds and four soil profiles in the adjacent alpine meadows were described and sampled according to AG Boden (1994). Soil samples were taken from each mineral horizon and from the organic layer. The air-dried soil samples were sieved (<2 mm). Particle-size distribution was determined by the pipette method and sieving (Schlichting et al., 1995). The pH value was measured in 0.01 M $CaCl_2$ dilution, and organic carbon and total nitrogen were analyzed with an Elemental Analyzer (CARLO ERBA 1500). Iron was determined by using the dithionite-citrate and the oxalate methods (Carter, 1993). The soil horizons designation and soil classification follows to the U.S. Soil Taxonomy (Soil Survey Staff, 1998) and the World Reference Base (FAO, 1998). The Swiss (FAP, 1992) as well as the German Soil Taxonomy (AG Boden, 1994) are also given. The humus forms inside and outside the snowbeds were described and classified according to Green et al. (1993).

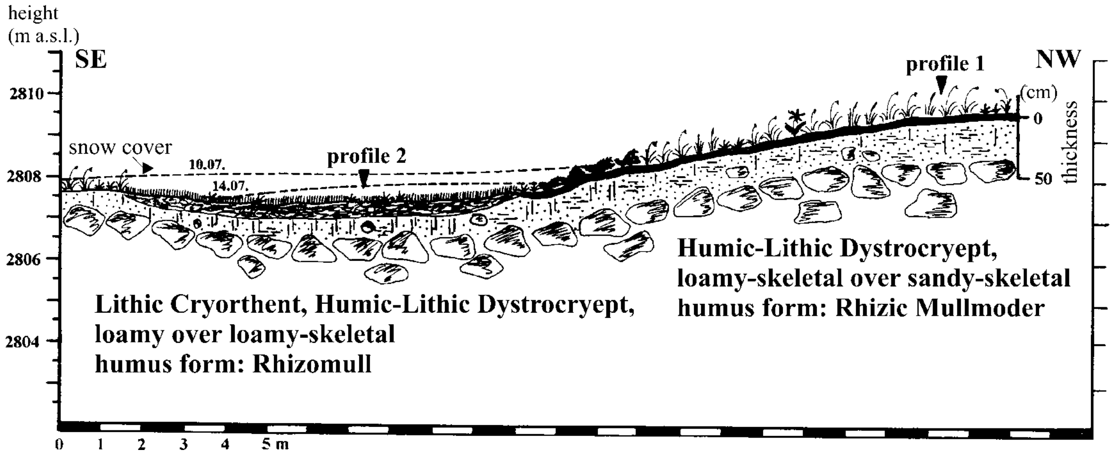

FIGURE 2. Study site 1.

Results

MICROTOPOGRAPHY AND VEGETATION

Snowbeds were studied above the timberline west of Piz Languard (3262 m) at 2810 m a.s.l. (study site 1), north of Piz da Staz (2847 m) at 2560 m a.s.l. (study site 2), and southeast of Piz Polaschin (3013 m) at 2670 m a.s.l. (study sites 3 and 4) (Fig. 1). The investigated snowbeds are located in wind-protected and snow-rich depressions. Study site 1 is located at 2810 m a.s.l. in a shallow depression on a south-facing slope. Solifluction is widespread in the surrounding of the depression. Study site 2, located on a north-facing slope at 2560 m a.s.l., comprises three small and shallow depressions within a gully. Study sites 3 and 4 are located at 2670 m a.s.l. in small depressions on almost-level topography. The area around the snowbeds of study sites 3 and 4 is characterized by solifluction and cryoturbation. All snowbeds are located on silicate parent material. The parent material of study site 1 is till of weathered orthogneiss and paraschist, whereas the soils of study side 2 have developed on talus accumulation of gabbrodiorite, diorite, and essexite (Staub, 1946). The parent material of study sites 3 and 4 is till of weathered granite, diorite, and gneiss (Cornelius, 1912, 1935). In general, the investigated snowbeds become snow free by the middle or end of July. The total snow-free period covers two to three month. Outside the snowbeds, the sedge *Carex curvula* is very common, and the vegetation belongs to the *Caricetum curvulae* subass. *typicum*. Depending on microtopography, the subassociations *Caricetum curvulae* subass. *cetrarietosum* or *Caricetum curvulae* subass. *hygrocurvuletosum* could be found. The vegetation inside the snowbeds is typical of snowbeds on silicate substrate and corresponds to the *Salicetum herbaceae* and also the *Polytrichetum sexangularis* described by several authors (Dierssen, 1984; Tomaselli, 1991; Graf, 1994; Ellenberg, 1996). Plants such as *Salix herbacea*, *Gnaphalium supinum*, and the moss *Polytrichum sexangulare* are very common at the study sites.

SOIL CHARACTERISTICS

The soils inside and outside the snowbeds of study sites 1 and 2 are classified as Entisols and Inceptisols (Soil Survey Staff, 1998) (Figs. 2 and 3). The soil classification of profiles 1–8 according to the World Reference Base (FAO, 1998) and the Swiss (FAP, 1992) and the German Soil Taxonomy (AG Boden, 1994) is given in Table 1. Outside the snowbeds, Humic-Lithic Dystrocryepts, loamy-skeletal over sandy-skeletal (Soil Survey Staff, 1998), are common. They show initial podzolization processes such as a slight iron accumulation in the subsoil. The soil depths vary between 35 and 40 cm (Tables 2 and 3). Inside the snowbeds of study sites 1 and 2, Humic-Lithic Dystrocryepts, loamy over loamy-skeletal (Soil Survey Staff, 1998), with depths of ~25–30 cm occur. They show an accumulation of iron

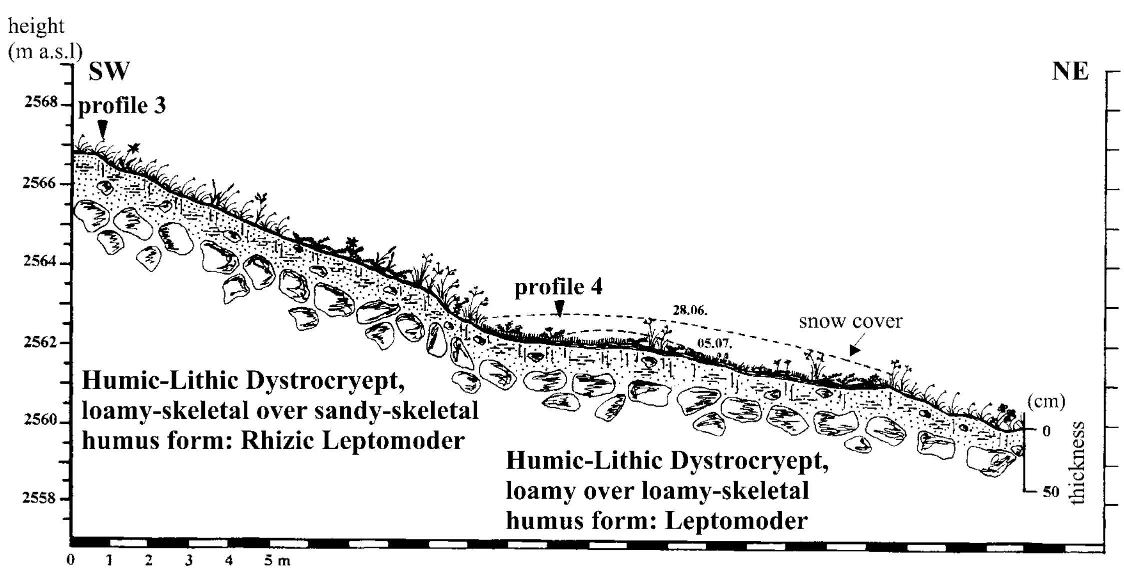

FIGURE 3. Study site 2.

TABLE 1

Classification of the soil profiles 1 to 8.

Study site	Profile	U.S. Soil Taxonomy (Soil Survey Staff, 1998)	World Reference Base (FAO, 1998)	Swiss Soil Taxonomy (FAP, 1992)	German Soil Taxonomy (AG Boden, 1994)
1	*profile 1* outside	Humic-Lithic Dystrocryept, loamy-skeletal over sandy-skeletal*	Lepti-skeletic Cambisol	Podzolige Saure Braunerde	Schwach podsolige Braunerde
	profile 2 inside	Lithic Cryorthent over Humic-Lithic Dystrocryept, loamy over loamy-skeletal	Lepti-skeletic Cambisol	Podzol	Flacher Kolluvisol über Podsol
2	*profile 3* outside	Humic-Lithic Dystrocryept, loamy-skeletal over sandy-skeletal	Lepti-skeletic Cambisol	Podzolige Saure Braunerde	Schwach podsolige Braunerde
	profile 4 inside	Humic-Lithic Dystrocryept, loamy over loamy-skeletal	Lepti-skeletic Cambisol	Modrighumoser Braunpodzol	Braunerde-Podsol
3	*profile 5* outside	Lithic Cryorthent, loamy	Leptosol	Modrighumoser, verbraunter Ranker	Ranker-Braunerde
	profile 6 inside	Humic-Lithic Dystrocryept, loamy over loamy-skeletal	Lepti-skeletic Cambisol (stagnic)	Schwach pseudogleyige Saure Braunerde	Schwach pseudovergleyter Braunerde-Ranker
4	*profile 7* outside	Lithic Cryorthent, clayey-skeletal over loamy-skeletal	Leptosol	Modrighumoser, verbraunter Silikatboden	Braunerde
	profile 8 inside	Lithic Cryorthent, clayey-skeletal	Stagnic Regosol	Schwach pseudogleyiger mullhumoser Silikatboden	Schwach pseudovergleyter Ranker

* On slopes, sometimes influenced by solifluction.

with or without accumulation of organic matter in the B horizons. In these soils, hydromorphic features, such as iron concretions, occasionally occur that indicate temporary wet conditions (Tables 2 and 3).

The soils inside and outside the snowbeds of study sites 3 and 4 also are classified as Entisols and Inceptisols (Soil Survey Staff, 1998). Outside the snowbeds, shallow Lithic Cryorthents, loamy or clayey-skeletal (Soil Survey Staff, 1998), with depths of ~13–16 cm are to be found (Table 4 and 5). In such places, very shallow cambic horizons may develop. Inside the snowbeds, soil depth varies between 40 and 50 cm and exceeds markedly the depth of the soils outside the snowbeds. Humic-Lithic Dystrocryepts, loamy or loamy-skeletal, and Lithic Cryorthents, clayey-skeletal (Soil Survey Staff, 1998), are common inside the snowbeds of study site 3 and 4 (Tables 4 and 5). The soils show hydromorphic features, which are more conspicuous than at study sites 1 and 2. The soil genesis inside the investigated snowbeds of all study sites is influenced by accumulation of organic and mineral fine material from adjacent slopes, which is also evident from the soil texture.

The soils outside the snowbeds are characterized by moder humus forms. The moder humus form order encompasses humus forms in which organic matter accumulates on the soil surface. The humus form is characterized by L horizons (horizon consisting of plant residues), F horizons (horizon composed of partly decomposed plant residues), and H horizons (horizon composed of well-decomposed plant residues) (Green et al., 1993). The humus form of profile 3 is classified as Rhizic Leptomoder, and the humus form of profiles 1, 5, and 7 can be described as a Rhizic Mullmoder with thin Lv and Fz horizons. The L and F horizons are built up mainly by litter and plant residues of *Carex curvula*. The H horizons of profiles 1 and 3 are 2–3 cm thick and show high contents of finely dispersed organic matter. Only a few macroscopic organic residues are recognizable. Fine roots are very abundant. Profiles 5 and 7 lack H horizons.

The humus forms of profiles 2 and 6 inside the snowbeds are classified as Rhizomulls. The mull humus form order encompasses humus forms in which organic matter is incorporated into the upper mineral soil (Green et al., 1993). The humus form inside the snowbeds of study sites 2 and 4 is a Leptomoder exhibiting an H horizon up to 8–10 cm thick. This H horizon is characterized by a high content of finely dispersed organic matter. In the upper part of the soils inside the snowbeds, rhizoids of mosses are common. At a depth of 4 cm, only a few fine roots are recognizable.

SOIL ANALYSIS

All soil profiles have a high percentage of cobbles and gravel that increases with soil depth. In the subsurface horizons, especially near the parent material, the abundance of rock fragments is ~70–80 vol%. The soil texture outside the snowbeds of study sites 1 and 2 is sandy loam or loamy sand; the sand contents increase with depth. The soils inside the snowbeds of these study sites are characterized by higher percentages of silt and clay, resulting in soil textures such as loam and sandy loam. In the subsurface horizons, the sand content also increases. Soil texture is sandy loam. The soils of study sites 3 and 4 are characterized by higher silt and clay contents compared to the soils of study sites 1 and 2. Outside the snowbeds, the soil texture is loam or sandy loam with occasionally higher percentages of clay in the topsoil. Inside the snowbeds the clay content of the soils is higher. Clay loam is the common soil texture (Figs. 4–11).

All soils show a high soil acidity with pH values ($CaCl_2$) ranging from 3.6 to 4.8. The soil acidity decreases by soil depth. Additionally, all soils inside and outside the snowbeds show high organic matter content. The organic layers have an organic matter content of ~32–34%. Inside the snowbeds of study sites 1 and 2, a further accumulation of organic carbon in the Bs horizons is recognizable. The C/N ratio of the organic layer and the mineral topsoil is up to 12–15 without great differences outside and inside the snowbeds (Figs. 4–11).

The soils of study sites 1 and 2 are influenced by podzolization. Outside the snowbeds, only a slight leaching of iron oxides is evidenced. Compared with the slight leaching of iron outside the snowbeds, the leaching is more intense inside. The higher podzolization is reflected in iron oxides accumulated in the subsoil illuvial horizons and in lower contents of iron in the eluvial horizons. The soils of study sites 3 and 4 are not characterized by podzolization processes (Figs. 4–11).

TABLE 2

Site and profile description of study site 1.

PROFILE 1 (OUTSIDE SNOWBED)

Location:	Switzerland (46°29′23″N; 9°56′35″E)	Parent material:	colluvium over moraine material (mainly paraschists)
Elevation:	2809 m	Soil classification:	Humic-Lithic Dystrocryept, loamy-skeletal over sandy-skeletal
Microfeature:	solifluction terrace at the upper slope	Humus form (Green et al., 1993):	Rhizic Mullmoder
Slope:	3°		
Drainage:	rapid drained		
Vegetation:	*Caricetum curvulae* subass. *hygrocurvu-letosum*		

Horizon	Depth (cm)	Description
Oi Lv*	+3–2.5	Discontinuously covered by leaves and stems from *Carex curvula*, mixed with living lichens and mosses; gradual, wavy horizon boundary
Oe Fz*	+2.5–2	Moderately decomposed plant material of *Carex curvula*, lichens, and mosses; loose, gradual, wavy horizon boundary
Oa Hh*	+2–0	Very dark brown-gray (10YR 2/2); finely dispersed and highly decomposed organic matter; abundant very fine and fine roots; clear horizon boundary
A	0–4	Dark gray-brown (10YR 3/3); sandy loam, 10% subangular gravel and cobbles; single-grain structure; abundant, fine and medium roots; gradual, wavy horizon boundary; few bleached mineral grains
AB	4–14	Very dark gray-brown (10YR 2/3); sandy loam, 25% subangular gravel and cobbles; single-grain structure; common fine and medium roots; gradual, wavy horizon boundary
2Bw	14–39	Dark yellowish brown (10YR 4/6); loamy sand, 70–80% subangular cobbles and stones; single-grain structure; few fine roots; gradual wavy horizon boundary
C	39+	Weathered moraine material

PROFILE 2 (INSIDE SNOWBED)

Location:	Switzerland (46°29′23″N; 9°56′35″E)	Parent material:	colluvium over moraine material (mainly paraschists)
Elevation:	2807 m	Soil classification:	Lithic Cryorthent over Humic-Lithic Dystrocryept, loamy over loamy-skeletal
Microfeature:	trough	Humus form (Green et al. 1993):	Rhizomull
Slope:	—		
Drainage:	well drained		
Vegetation:	*Polytrichetum sexangularis*		

Horizon	Depth (cm)	Description
A1 Ah*	0–2	Very dark gray-brown (10YR 2/3); loam, 5% subangular gravel and cobbles; subangular blocky structure; abundant, very fine and fine roots; abrupt, smooth horizon boundary
A2	2–12	Dark gray (10YR 3/1); loam, 10% subangular gravel and cobbles; subangular blocky structure; few, fine roots; abrupt, smooth horizon boundary; common iron concretions
2AE	12–15	Dark gray (2.5Y 4/1); loam, 25% subangular gravel and cobbles; subangular blocky structure; no roots; abrupt, smooth horizon boundary
2E	15–19	Greenish gray (5Y 5/1); loam, 35% subangular gravel and cobbles; subangular blocky structure; no roots; abrupt, smooth horizon boundary
2Bs	19–25	Dark yellowish brown (10YR 4/6); sandy loam, 50% subangular cobbles and stones; single-grain structure; no roots; gradual, smooth horizon boundary
2BC	25–31	Gray-brown (10YR 5/3); sandy loam, 65% subangular cobbles and stones; single-grain structure; no roots; abrupt, wavy horizon boundary
C	31+	Weathered moraine material

* Horizon designation according to Green et al. (1993).

Discussion

PEDOGENESIS AND SOIL CLASSIFICATION

Because of the long-lasting snow cover in snowbeds at the investigated study sites, the composition of plant communities, pedogenesis, and soil properties are different from those of adjacent alpine sward. Further, the pedogenesis beneath snowbeds depends on the drainage conditions of the silicate parent material. At the investigated study sites, two types of snowbeds are common: study sites 1 and 2 are characterized by well-drained conditions, whereas study sites 3 and 4 are only moderately drained because they are on a less permeable parent material.

The pedogenesis of study sites 1 and 2 is characterized by the weathering of silicates and by podzolization that is more intense inside than outside the snowbeds. The sandy soils of these study sites are characterized by good permeability and percolation. The snowbed soils of study sites 3 and 4 exhibit hydromorphic features. Less permeable parent material with higher clay contents compared to study sites 1 and 2 causes temporary wet conditions that result in reduction and translocation of iron and manganese. The investigated snowbed soils of

TABLE 3

Site and profile description of study site 2.

PROFILE 3 (OUTSIDE SNOWBED)

Location:	Switzerland (46°28′55″N; 9°52′34″E)	Vegetation:	*Caricetum curvulae* subass. *typicum*
Elevation:	2566 m	Parent material:	slope deposits (mainly diorite)
Microfeature:	mound	Soil classification:	Humic-Lithic Dystrocryept, loamy-skeletal over sandy-skeletal
Drainage:	rapid drained	Humus form (Green et al., 1993):	Rhizic Leptomoder
Slope:	3°		

Horizon	Depth (cm)	Description
Oi Lv*	+6–5	Discontinuously covered by leaves and stems from *Carex curvula*, mixed with living lichens and mosses; gradual, wavy horizon boundary
Oe Fz*	+5–3	Moderately decomposed plant material of *Carex curvula*, lichens, and mosses; non-compact-matted; abundant fine roots; abrupt, smooth horizon boundary
Oa Hh*	+3–0	Very dark gray-brown (10YR 2/3); finely dispersed and highly decomposed organic matter; abundant very fine and fine roots; clear, wavy horizon boundary
A	0–5	Dark gray-brown (10YR 3/3); loam, 10% subangular gravel and cobbles; single-grain structure; abundant, fine and medium roots; abrupt, wavy horizon boundary; common bleached mineral grains
AB	5–11	Very dark gray-brown (10YR 2/3); sandy loam, 25% subangular gravel and cobbles; single-grain structure; plentiful fine and medium roots; gradual, wavy horizon boundary
Bw	11–17	Very dark gray-brown (10YR 2/3); loamy sand, 25% subangular gravel and cobbles; single-grain structure; plentiful fine and medium roots; gradual, wavy horizon boundary
Bw/C	17–38	Dark yellowish brown (10YR 4/6); loamy sand, 60–75% subangular cobbles and stones; single-grain structure; common fine and medium roots; gradual, wavy horizon boundary
C	38+	Weathered slope deposits

PROFILE 4 (INSIDE SNOWBED)

Location:	Switzerland (46°28′55″N; 9°52′34″E)	Vegetation:	*Polytrichetum sexangularis*
Elevation:	2562 m	Parent material:	slope deposits (mainly diorite)
Landform:	trough	Soil classification:	Humic-Lithic Dystrocryept, loamy over loamy-skeletal
Slope:	1–2°	Humus form (Green et al., 1993):	Leptomoder
Drainage:	well drained		

Horizon	Depth (cm)	Description
Oi/Oe Lv/Fz*	+8.5–8	Discontinuously covered by leaves from *Soldanella pusilla*, lichens, and mosses; loose; gradual, wavy horizon boundary
Oa Hh*	+8–0	Very dark brown-gray (10YR 2/3); finely dispersed and highly decomposed organic matter; common fungal hyphae; plentiful very fine and fine roots; clear, wavy horizon boundary; few iron concretions
A/E	0–4	Gray-brown (10YR 5/3); loam, 25% subangular gravel and cobbles; subangular blocky structure; few fine roots; abrupt, wavy horizon boundary; few iron concretions
Bs	4–12	Brown (7.5YR 5/6); sandy loam, 50% subangular cobbles and stones; subangular blocky structure; few fine roots; gradual, wavy horizon boundary
Bw/C	12–25	Gray-brown (10YR 5/3); sandy loam, 75–80% subangular cobbles and stones; single-grain structure; very few fine roots; gradual, wavy horizon boundary
C	25+	Weathered slope deposits

* Horizon designation according to Green et al. (1993).

study sites 1 and 2 are lacking such intense redoximorphic features. Temporary wet conditions, however, also influence soil development. Inside the snowbeds of all study sites, the topsoils show slightly higher contents of silt and clay caused by the accumulation of allochthonous fine material, probably originating from adjacent slopes. Furthermore, clay and silt particles (alpine loess) accumulate on and in the winter snowpack. After snowmelt, the fine particles remain on the soil surface (Kubiëna, 1953; Retzer, 1965; Bouma and van der Plas, 1971; Walker et al., 1999). Additionally, accumulation of clay and silt may be enhanced by the snowbed vegetation itself (Braun-Blanquet and Jenny, 1926; Fluetsch et al., 1930; Braun-Blanquet, 1975). However, the deposition of alpine loess not only influences soils of snowbeds but high mountains soils in general (Burger and Franz, 1969; Gruber, 1980; Holtmeier and Broll, 1992).

Inside snowbeds on a highly permeable parent material, podzolization is more intense than in the adjacent alpine sward. As to the site conditions and pedogenesis in particular, the onset of snowmelt and the amount of meltwater are of great importance. Also, depth and duration of the winter snow pack influence pedogenesis and soil properties, such as soil temperature and soil moisture, for example. Soil-moisture conditions in snowbed soils differ from soil-moisture conditions in soils of adjacent alpine sward. Meltwater keeps snowbed soils wet through the growing season. In contrast, soils of alpine sward may be affected by summer drought, especially on the well-drained sites. The comparatively high soil moisture in the snowbed soils is additionally increased by interflow from the surrounding convex topography. High soil moisture and highly permeable substrate enhance leaching of iron, aluminum, and organic matter (Mueller, 1987; Angelone et al., 1990), thus resulting in more intense podzolization in the snowbeds.

Outside of the investigated snowbeds of study sites 1 and 2, Humic-Lithic Dystrocryepts, loamy-skeletal over sandy-skeletal (Soil Survey Staff, 1998), are common (Mueller, 1983; Neuwinger, 1978, 1987; Burns, 1990). These soils might show initial podzolization, such

TABLE 4

Site and profile description of study site 3.

PROFILE 5 (OUTSIDE SNOWBED)

Location:	Switzerland (46°27′23″N; 9°45′36″E)	Vegetation:	*Caricetum curvulae*
Elevation:	2650 m	Parent material:	moraine material (mainly granite, diorite)
Microfeature:	mound	Soil classification:	Lithic Cryorthent, loamy
Slope:	9°	Humus form (Green et al., 1993):	Rhizic Mullmoder
Drainage:	moderately well drained		

Horizon	Depth (cm)	Description
Oi, Lv*	+2.3–2	Discontinuously covered by leaves and stems from *Carex curvula*, mixed with living lichens and mosses; gradual, wavy horizon boundary
Oe Fz*	+2–0	Gray-brown (10YR 5/4); finely dispersed and highly decomposed organic matter mixed with moderately decomposed plant material of *Carex curvula*, non-compact-matted; abundant very fine and fine roots; clear horizon boundary
A	0–10	Dark brown-gray (10YR 3/2); loam, 10% subangular gravel; subangular blocky structure; abundant fine and medium roots; gradual, wavy horizon boundary
AB	10–16	Dark brown-gray (10YR 3/2); sandy loam, 25% subangular gravel, cobbles, and stones; subangular blocky structure; plentiful fine and medium roots; clear, wavy horizon boundary
C	16+	Weathered moraine material (granite, diorite)

PROFILE 6 (INSIDE SNOWBED)

Location:	Switzerland (46°27′23″N; 9°45′36″E)	Vegetation:	*Polytrichetum sexangularis*
Elevation:	2650 m	Parent material:	moraine material (mainly granite, diorite)
Microfeature:	trough	Soil classification:	Humic-Lithic Dystrocryept, loamy over loamy-skeletal
Slope:	—		
Drainage:	moderately well drained	Humus form (Green et al., 1993):	Rhizomull

Horizon	Depth (cm)	Description
A Ah*	0–7	Dark gray (10YR 3/1); clay loam, 10% subangular gravel; subangular blocky structure; plentiful very fine and fine roots; clear, wavy horizon boundary; common iron concretions
A/C	7–41	Dark gray (10YR 3/1); clay loam, 50–75% gravel, cobbles, and stones; subangular blocky structure; no roots; abrupt, wavy horizon boundary
BC	41–47	Gray-brown (10YR 5/4); clay loam, 75–80% subangular cobbles and stones; subangular blocky structure; no roots; clear, wavy horizon boundary
C	47+	Weathered moraine material (granite, diorite)

* Horizon designation according to Green et al. (1993).

TABLE 5

Site and profile description of study site 4.

PROFILE 7 (OUTSIDE SNOWBED)

Location:	Switzerland (46°27′23″N; 9°45′36″E)	Vegetation:	*Caricetum curvulae*
Elevation:	2655 m	Parent material:	moraine material (mainly granite, diorite)
Microfeature:	mound	Soil classification:	Lithic Cryorthent, clayey-skeletal over loamy-skeletal
Slope:	9°	Humus form (Green et al., 1993):	Rhizic Mullmoder
Drainage:	moderately well drained		

Horizon	Depth (cm)	Description
Oi, Lv*	+2.7–2.5	Discontinuously covered by leaves and stems from *Carex curvula*, mixed with living lichens and mosses; gradual, wavy horizon boundary
Oe Fz*	+2.5–0	Dark gray-brown (10YR 4/4); finely dispersed and highly decomposed organic matter mixed with moderately decomposed plant material of *Carex curvula*, non-compact-matted; abundant very fine and fine roots; clear horizon boundary
A	0–3	Dark gray (10YR 3/1); clay loam, 10% subangular gravel; subangular blocky structure; abundant fine and medium roots; clear, wavy horizon boundary
AB	3–6.5	Dark brown-gray (10YR 3/2); clay loam, 10% subangular gravel; subangular blocky structure; plentiful fine and medium roots; gradual, wavy horizon boundary
Bw	6.5–13.5	Dark yellowish brown (10YR 4/6); sandy loam, 30–50% subangular gravel, cobbles and stones; subangular blocky structure; plentiful fine and medium roots; gradual, wavy horizon boundary
C	13.5+	Weathered moraine material (granite, diorite)

PROFILE 8 (INSIDE SNOWBED)

Location:	Switzerland (46°27′23″N; 9°45′36″E)	Vegetation:	*Polytrichetum sexangularis*
Elevation:	2655 m	Parent material:	moraine material (mainly granite, diorite)
Landform:	gully	Soil classification:	Lithic Cryorthent, clayey-skeletal
Slope:	4°	Humus form (Green et al., 1993):	Leptomoder
Drainage:	moderately well drained		

Horizon	Depth (cm)	Description
Oa Hh*	+10	Very dark gray (10YR 2/1); finely dispersed and highly decomposed organic matter; plentiful very fine and fine roots; gradual, wavy horizon boundary; few iron concretions
A/C	0–15	Very dark gray (10YR 2/1); clay loam, 50–75% subangular gravel, cobbles, and stones; subangular blocky structure; plentiful fine roots; clear, wavy horizon boundary; few iron concretions
A/C	15–29	Very dark gray (10YR 2/1); clay loam, 50–75% subangular gravel, cobbles, and stones; subangular blocky structure; no roots; clear, wavy horizon boundary
C	29+	Weathered moraine material (granite, diorite)

* Horizon designation according to Green et al. (1993).

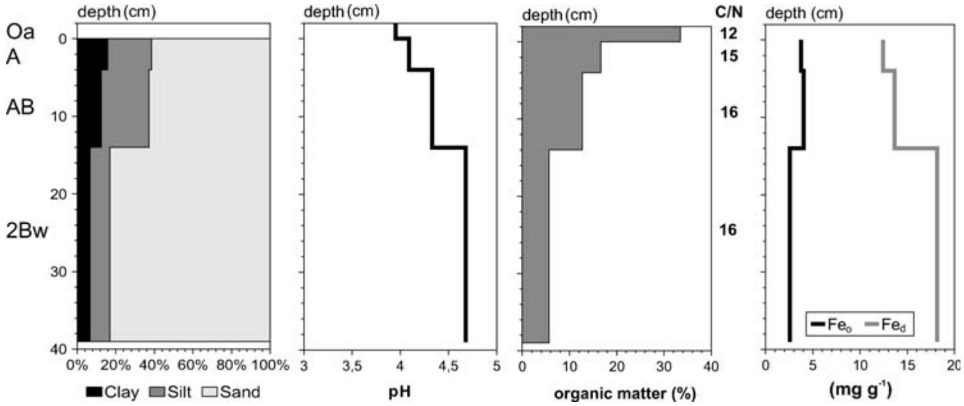

FIGURE 4. Soil texture, pH value (measured in 0.01 *M* $CaCl_2$ dilution), organic matter content, and Fe_d and Fe_o content of profile 1.

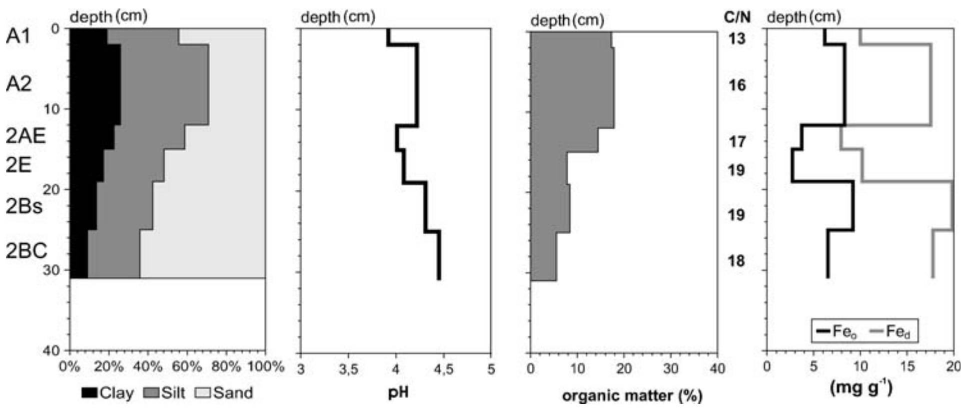

FIGURE 5. Soil texture, pH value (measured in 0.01 *M* $CaCl_2$ dilution), organic matter content, and Fe_d and Fe_o content of profile 2.

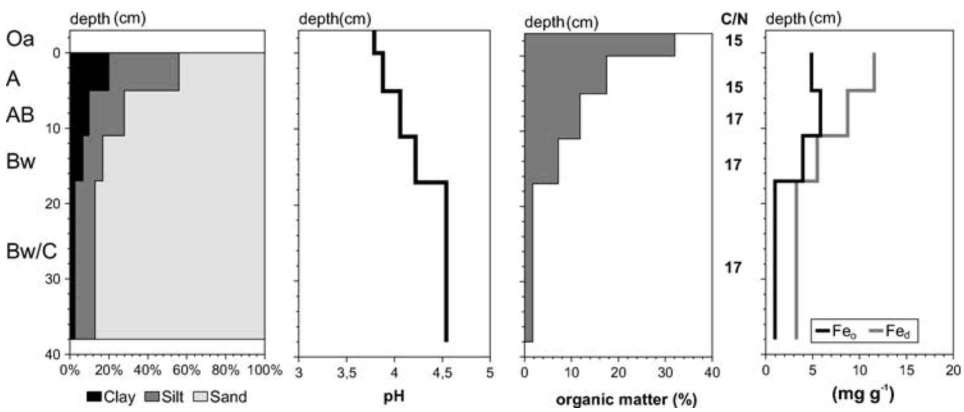

FIGURE 6. Soil texture, pH value (measured in 0.01 *M* $CaCl_2$ dilution), organic matter content, and Fe_d and Fe_o content of profile 3.

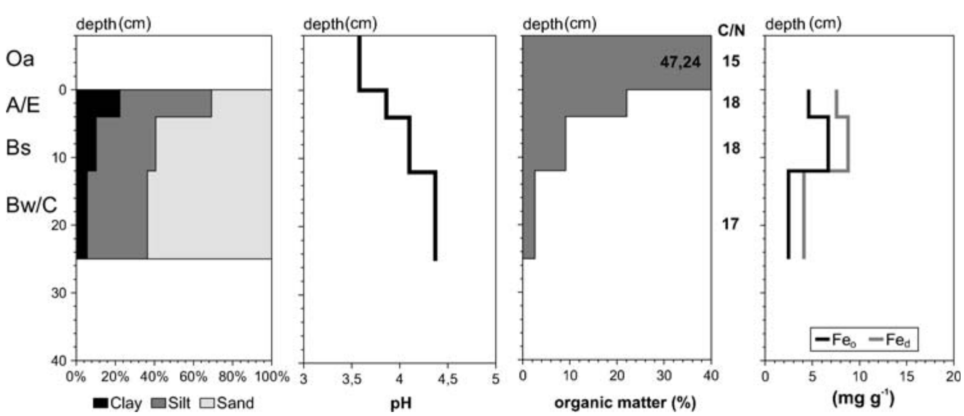

FIGURE 7. Soil texture, pH value (measured in 0.01 *M* $CaCl_2$ dilution), organic matter content, and Fe_d and Fe_o content of profile 4.

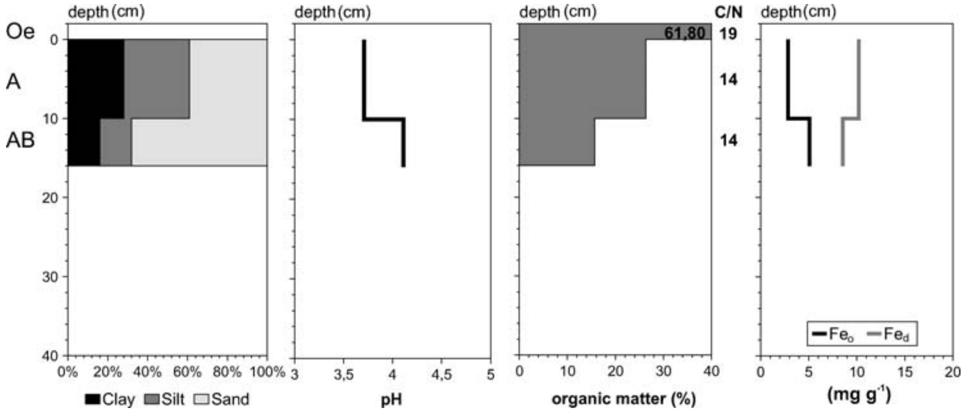

FIGURE 8. Soil texture, pH value (measured in 0.01 *M* $CaCl_2$ dilution), organic matter content, and Fe_d and Fe_o content of profile 5.

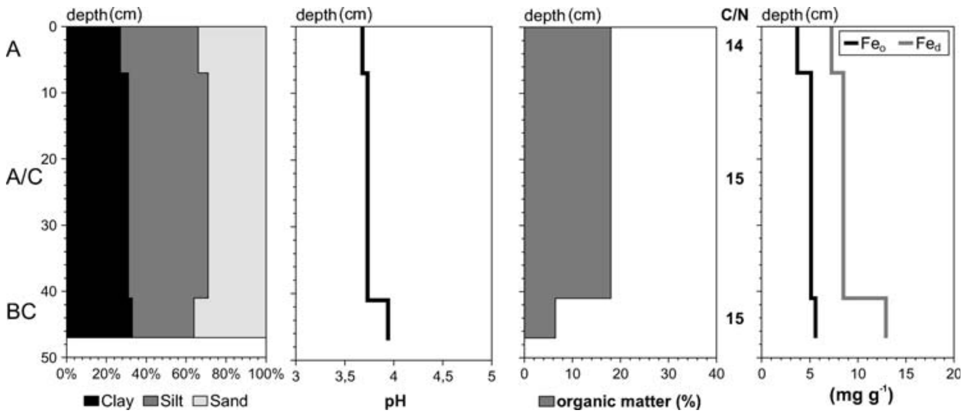

FIGURE 9. Soil texture, pH value (measured in 0.01 *M* $CaCl_2$ dilution), organic matter content, and Fe_d and Fe_o content of profile 6.

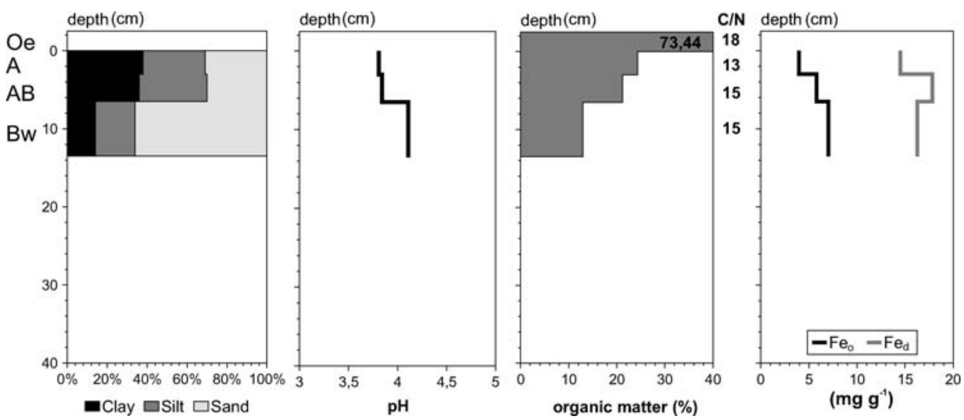

FIGURE 10. Soil texture, pH value (measured in 0.01 *M* $CaCl_2$ dilution), organic matter content, and Fe_d and Fe_o content of profile 7.

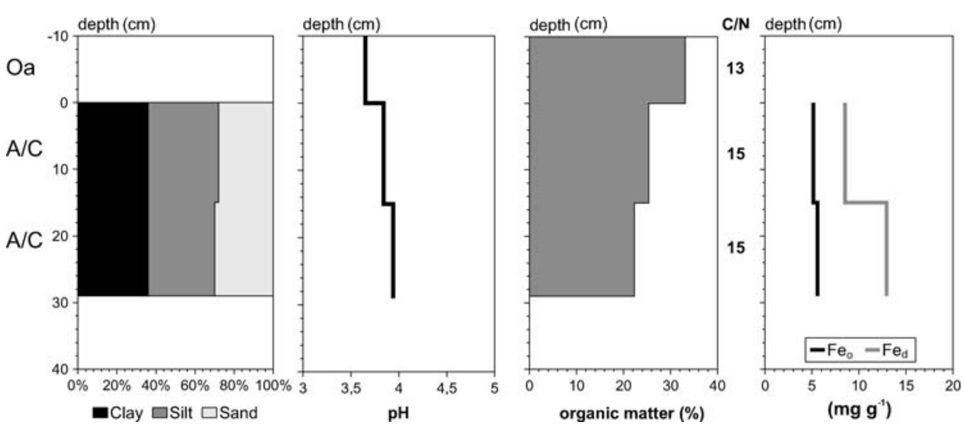

FIGURE 11. Soil texture, pH value (measured in 0.01 *M* $CaCl_2$ dilution), organic matter content, and Fe_d and Fe_o content of profile 8.

as leaching of iron, aluminum, and organic matter, which can be proved only by chemical soil analyses. Inside of the snowbeds, podzolization is more intense (cf. Mueller, 1983). In both investigated snowbeds, an albic horizon is developed. However, the illuvial subsurface horizons do not meet the properties of diagnostic spodic horizons. The soils also belong to the Inceptisols and are classified as Humic-Lithic Dystrocryepts, loamy over loamy-skeletal (Soil Survey Staff, 1998). A further differentiation is only possible at the soil family level by the particle-size class. If the soils of the snowbeds are classified according to the Swiss Soil Taxonomy (FAP, 1992) or German Soil Taxonomy (AG Boden, 1994), a more detailed differentiation of this initial and slight podzolization is possible, which otherwise could be proved only by chemical soil analysis. In the U.S. Soil Taxonomy (Soil Survey Staff, 1998) as well as in the World Reference Base (FAO, 1998), soil color is used to characterize a spodic horizon. However, in the soils of the snowbeds, the soil color differs from the colors that are diagnostic for spodic horizons. Consequently, the illuvial subsurface horizons do not correspond to the properties of spodic horizons. Thus, soil color turns out to be less suitable for spodic horizon differentiation in high mountains, where erosion or solifluction occasionally cause atypical colors.

The soils outside the snowbeds of study sites 3 and 4 are very shallow and are classified as Entisols (Soil Survey Staff, 1998). Inside the snowbeds, Humic-Lithic Dystrocryepts, loamy-skeletal, and Lithic Cryorthents, clayey-skeletal (Soil Survey Staff, 1998), without any albic or spodic horizon are common. The soils inside the snowbeds show hydromorphic features indicating temporary wet conditions. In particular, the snowbed soils of study sites 3 and 4 exhibit distinct hydromorphic features such as iron concretions. From other regions of the Alps, so-called Alpine Pseudogley profiles were described (Posch, 1977, 1980; Neuwinger, 1978; Mueller, 1980; Peer, 1993; Graf, 1994). The development of these Alpine Pseudogley soils is influenced by frozen ground during snowmelt. This frozen ground combined with a less permeable parent material hampers the percolation of meltwater. Under these conditions, reduction and translocation of iron and manganese are possible. Nevertheless, these soils are also influenced by podzolization during the growing season (Bouma and van der Plas, 1971; Franz, 1975, 1980; Posch, 1977, 1980).

HUMUS FORMS

The humus forms of the study sites are specifically influenced by the vegetation and microclimatic conditions. In the Alpine tundra, low temperatures, water-saturated soils during snowmelt, and, occasionally, drought during the growing season may hamper the biological activity. The soils inside and outside the snowbeds are characterized by high contents of organic matter. Litter production exceeds decomposition. Thus, the topsoil in particular is enriched in organic matter. The decomposition is slow and often incomplete. Furthermore, the upper soil is characterized by a dense net of fine roots. They provide additional decomposable organic matter, which remains in the soil (Retzer, 1974; Dannenberg et al., 1980). However, in spite of the short growing season and the unfavorable climatic and edaphic conditions above the timberline, no mor humus forms with a thick organic layer on the soil surface develop. The litter produced by the snowbed vegetation and the adjacent alpine sward is highly decomposable. Although biological activity is high during the snow-free period because of the climatic conditions and litter quality, summer is too short for complete decomposition. Thus, moder humus forms are typical of the study sites. At all study sites, the organic horizons show a remarkably high mineral content. Probably, the high percentage of fine mineral material can be explained by the accumulation of alpine loess and fine material on and in the winter snowpack. Bioturbation is less important to mix mineral and organic material at the study sites than elsewhere.

Outside the snowbeds, moder humus forms can be found. Shallow L and F horizons develop under the *Carex curvula* sward. The low litter accumulation is caused partly by little litter production of *Carex curvula*. Dead leaves of *Carex curvula* remain attached to the living plants. The leaves start withering at the tips during the growing season while the other parts of the leaves continue assimilation. Moreover, wind and runoff remove litter. The higher thickness of the Fz horizon of profile 3 is probably caused by a slower decomposition at dry conditions during summer. From other parts of the European Alps, moder humus forms under *Carex curvula* sward have also been described (Neuwinger and Czell, 1959; Kubiëna, 1953; Posch, 1977, 1980; Bochter et al., 1983; Mueller, 1983; Hiller, 2001).

Inside the snowbeds, wet conditions after snowmelt influence the humus forms, especially in the beginning of the growing season. The humus form classification of Green et al. (1993) only allows us to distinguish well to imperfectly drained sites and poorly to very poorly drained sites. However, the humus forms inside the snowbeds are neither well drained nor saturated for long. Consequently, a more detailed description for only temporarily wet soil conditions is needed.

At profiles 2, 6, and 8, the humus forms are Rhizomulls whereas at profile 4 the humus form is described as a Leptomoder. The humus forms are characterized by shallow L and F horizons caused by low litter production under the moss-rich snowbed vegetation (Mueller, 1983). The litter of *Salix herbacea* and other typical snowbed species easily decomposes (Rehder and Schaefer, 1978). After snowmelt, temporary wet conditions might hamper biological activity. During the growing season, soil-water contents and even soil temperatures favor biological activity and decomposition (Rehder and Schäfer, 1978; Bowman, 1992). At profile 4, fine dispersed organic matter has accumulated in thick H horizons. Probably, fine organic material accumulated where there were temporary wet conditions during the growing season. Generally, the decomposition in the snowbeds depends on soil moisture during the growing season. Translocation of organic material from adjacent slopes can increase organic matter in the snowbeds (Braun-Blanquet and Jenny, 1926). Under snowbed vegetation, both an intense decomposition with low accumulation of organic matter and a high accumulation of finely dispersed organic material in the topsoil occurs. Other investigations in the European Alps described similar humus forms under snowbed vegetation (Posch, 1977, 1980; Mueller, 1983; Neuwinger, 1989).

Conclusions

The pedogenesis of snowbeds differs from soil development on the adjacent alpine sward. However, pedogenesis in snowbeds is very heterogeneous depending on several factors such as parent material, meltwater, slope exposure, and annual precipitation. Drainage of the silicate parent material is an important factor. On well-drained parent material, pedogenesis inside the snowbeds is characterized by podzolization enhanced by high amounts of percolating water during snowmelt. On a less permeable parent material, high meltwater supply causes temporarily water-logged conditions. Thus, the soils inside the snowbeds show redoximorphic features such as iron concretions. Further investigations are necessary to get more detailed information about pedogenesis in snowbeds and the specific influence of soil-forming factors.

The late-lying snowpack of snowbeds causes differences in pedogenesis and soil properties compared to adjacent alpine sward. Textures of the soils inside the snowbeds show higher clay and silt contents compared to the soils outside. Soils belong to the Inceptisols or Entisols. A more detailed differentiation can only be achieved at the soil family level. On study sites 1 and 2, outside the snowbeds, Humic-Lithic Dystrocryepts, loamy-skeletal over sandy-skeletal, are common, whereas Humic-Lithic Dystrocryepts, loamy over loamy-skeletal, are found inside the snowbeds. Inside the snowbeds of study sites 3 and 4, Humic-Lithic Dystrocryepts and Lithic Cryorthents prevail, whereas outside the snowbeds, shallow Lithic Cryorthents are most common. When classifying the snowbed soils, it turns out to be impossible to describe the differences in podzolization according to the U.S. Soil Taxonomy (Soil Survey Staff, 1998) or the World Reference Base (FAO, 1998) guidelines. Consequently, the soils outside and inside the snowbeds have to be classified as Inceptisols. The German Soil Classification System (AG Boden, 1994) and the Swiss Classification System (FAP, 1992) allow a more detailed differentiation of the degree of podzolization. The same holds true for the description of redoximorphic features.

Outside the snowbeds, moder humus forms (Rhizic Leptomoder, Rhizic Mullmoder) are common, whereas inside the snowbeds, mull humus forms (Rhizomull) as well as moder humus forms (Leptomoder) occur. Humus forms can be classified according to Green et al. (1993); however, the soil-water conditions cannot be sufficiently differentiated.

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