Biodiversity at high elevation in the Alps: the role of snow in influencing soil formation and nutrient dynamics

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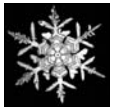

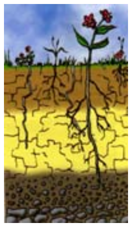

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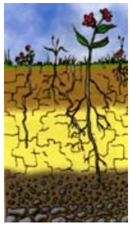
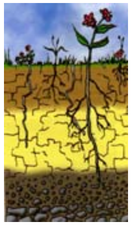
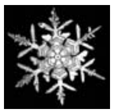
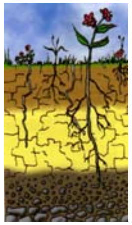


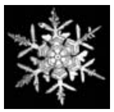
"The two domains, soil and snow, are obviously connected, and perhaps continuous, system. The lack of research directed to snow-soil interaction is not necessarily due to ignorance that such processes occur or to intellectual defects in workers concerned with snow and soil. It is probably related more to the fact that to adequately deal with the problem an ***interdisciplinary approach*** *is required" (Guymon GL, 1978).*





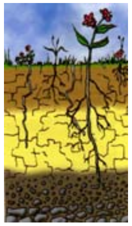
“ It is useful to view the snowcover as a type of sedimentary rock composed of consolidated layers of deposited minerals in their solid state (ice) – thus ***a snowcover is analogous to a sedimentary rock*** *formed of ice, the mineral whose principal property is its temperature. The rock is formed over time through a process of deposition and consolidation, which often involves considerable modification of the original constituents (McKAY GA, Adams WP, 1981).* ***But…..***





“ As the rates of snowcover metamorphism (transformation) are very rapid, the “rock” analogy is not useful for describing the dynamic nature of a snowcover. For this purpose ***snow might be considered as being more like soil****, which is also characterized by layering of particles of different grain size, shapes…but which, contains appreciable quantities of air and water and which is highly dynamic…. !(McKAY GA, Adams WP, 1981).*

1. Soil and snow: an “unique world”



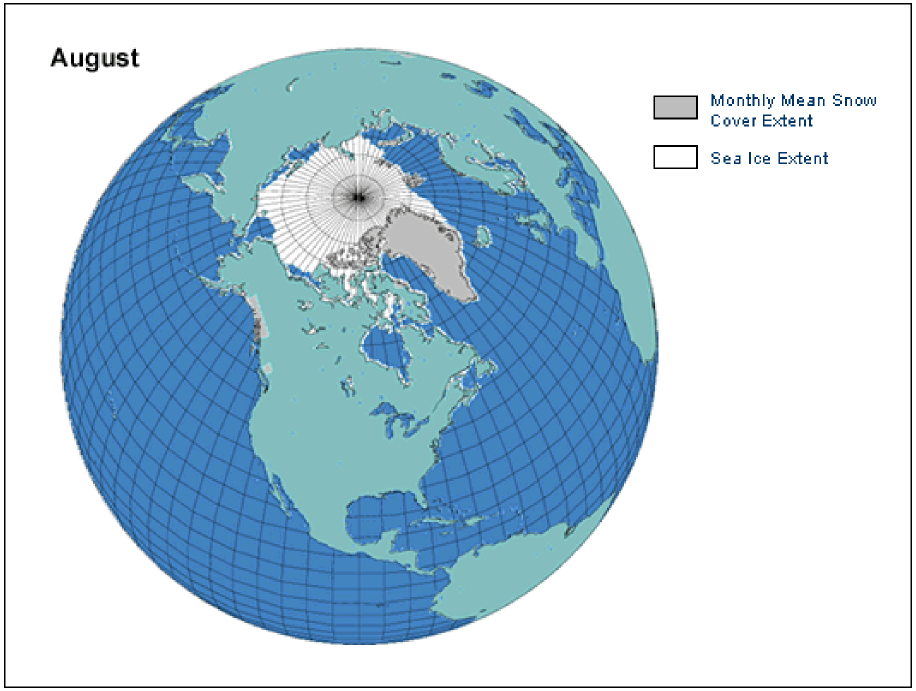
“ Keeping the soil analogy, the snowcover is a network or skeleton of solid particles (ice) enclosing voids or pores of varying size. The horizons which make up a soil profile are in some ways analogous to strata encountered in a snowcover. Snow, like soil, is a medium for life, a sheltered extension of the atmosphere. Also like soil it is a substrate for life” (McKAY GA, Adams WP, 1981).

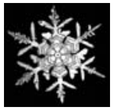
1. Soil and snow: an “unique world”

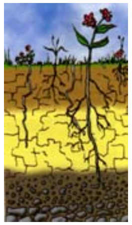
The Soil Profile

The Snow Profile

The length of the snow-cover period varies each year and is dominated by the seasonal cycle. The extent of the snow-covered area in the northern hemisphere ranges each year from an average minimum of 3.6 million square kilometres in August, to an average maximum of 46.8 million square kilometres in late January.

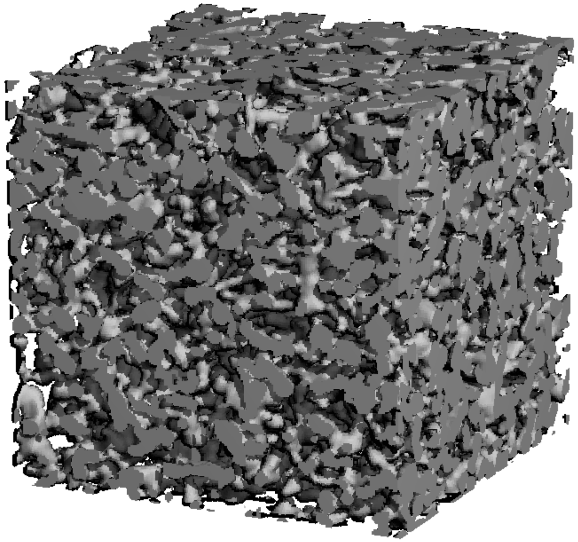






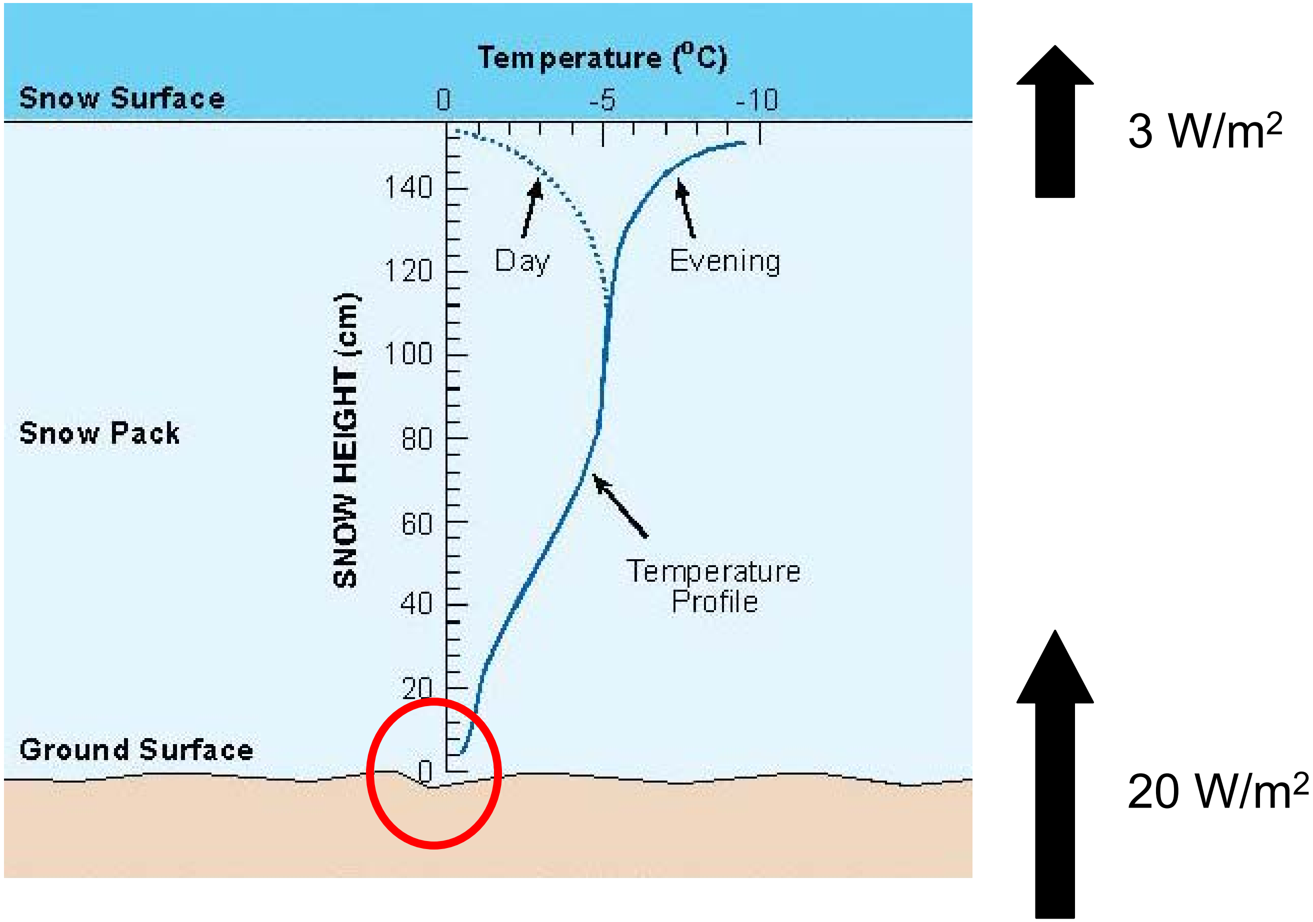
Snow/Soil interactions

- As a porous medium with a large air content, snow has a high insulation capacity and plays an important role protecting soil from severe winter temperatures.

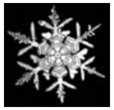


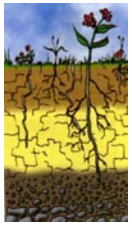
Snow insulation effect

- Low thermal conductivity of snow



1.1. Snow: a great insulator





- The thermal conductivity of a snow cover is low and the insulation effect varies with :

1. **snow depth** and
2. **snow density**.

Table 2.6

TYPICAL THERMAL PROPERTIES OF SOILS AND SNOW (adapted from Van Wijk, 1966).

Soil Type	Volumetric Water Content θ_w[a]	Thermal Conductivity k W/(°C·m)	Volumetric Heat Capacity $C_v = \rho C$ $10^6 J/(m^3 \cdot °C)$	Diffusivity $k/\rho C$ $10^{-6} m^2/sec$	Damping Depth D[b] m
Sand	0.0	0.29	1.3	0.22	1.5
	0.2	1.8	2.1	0.81	2.9
	0.4	2.2	2.9	0.76	2.7
Clay	0.0	0.25	1.3	0.19	1.4
	0.2	1.2	2.1	0.57	2.4
	0.4	1.6	2.9	0.55	2.3
Peat	0.0	0.059	0.50	0.12	1.1
	0.4	0.29	2.2	0.13	1.2
	0.8	0.50	3.9	0.13	1.2
Snow	-	0.063	0.11	0.56	2.5
	-	0.13	0.38	0.34	1.9
	-	0.71	1.1	0.65	2.6

[a] θ_w is the volume of water per unit volume of soil.
[b] D is the damping depth for the annual variation.

Snow depth


Alpine Tundra

Niwot Ridge, Colorado (40°03'N; 105°35'W), 3500-4085 m, LTER site

MAAT: -3.5°C

Annual precipitation: 1050 mm

Cryochrepts

Altered snow regime by snow fences (Walker et al., 1999; Brooks and Williams, 1999)

Alpine Tundra

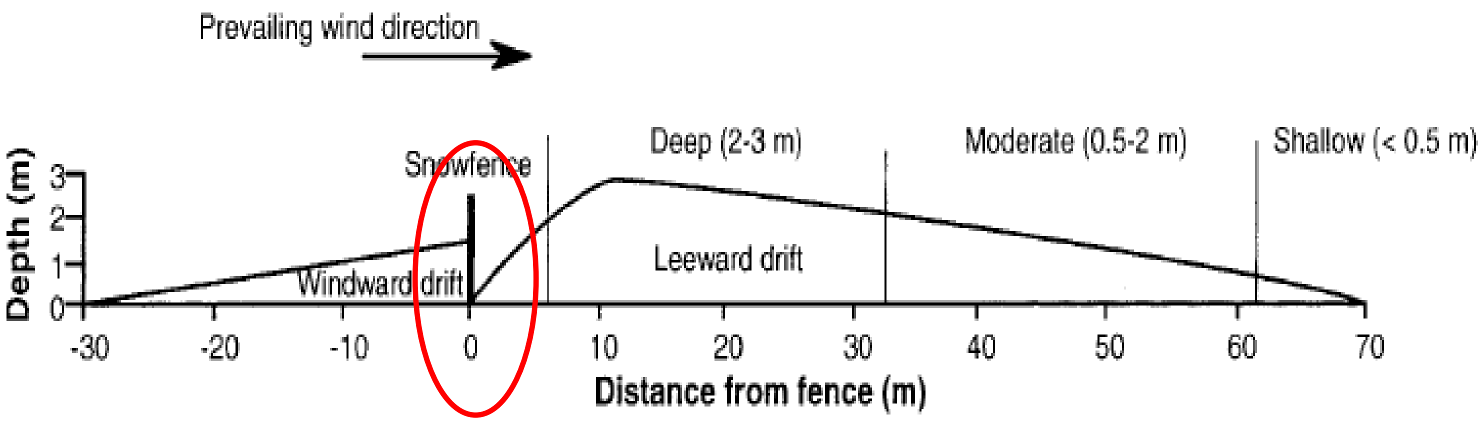
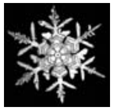
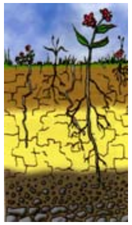
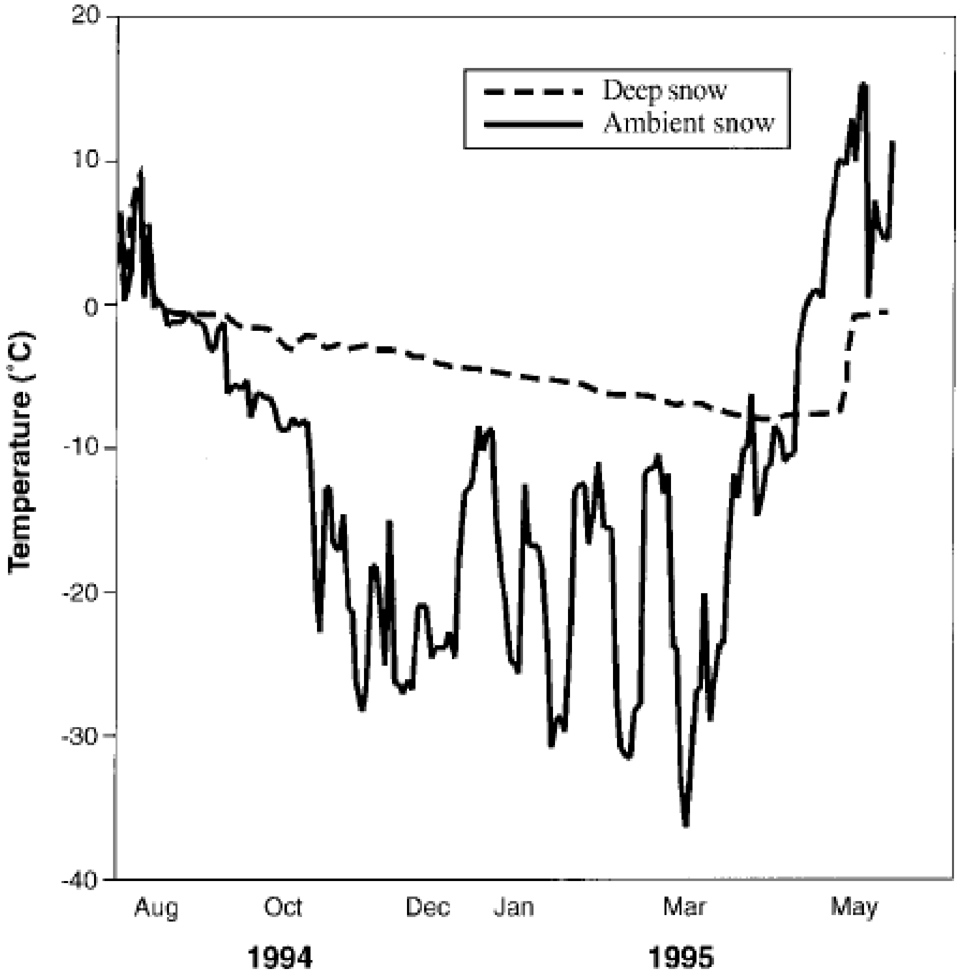


Figure 3. Experimental drift profile. The shape and depth profile of the actual experimental drifts varies somewhat from this theoretical profile, particularly early in the season. Once the drift has filled, however, the shape and depth are quite similar to what is shown here

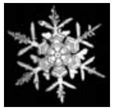


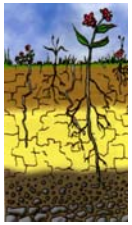


Alpine Tundra

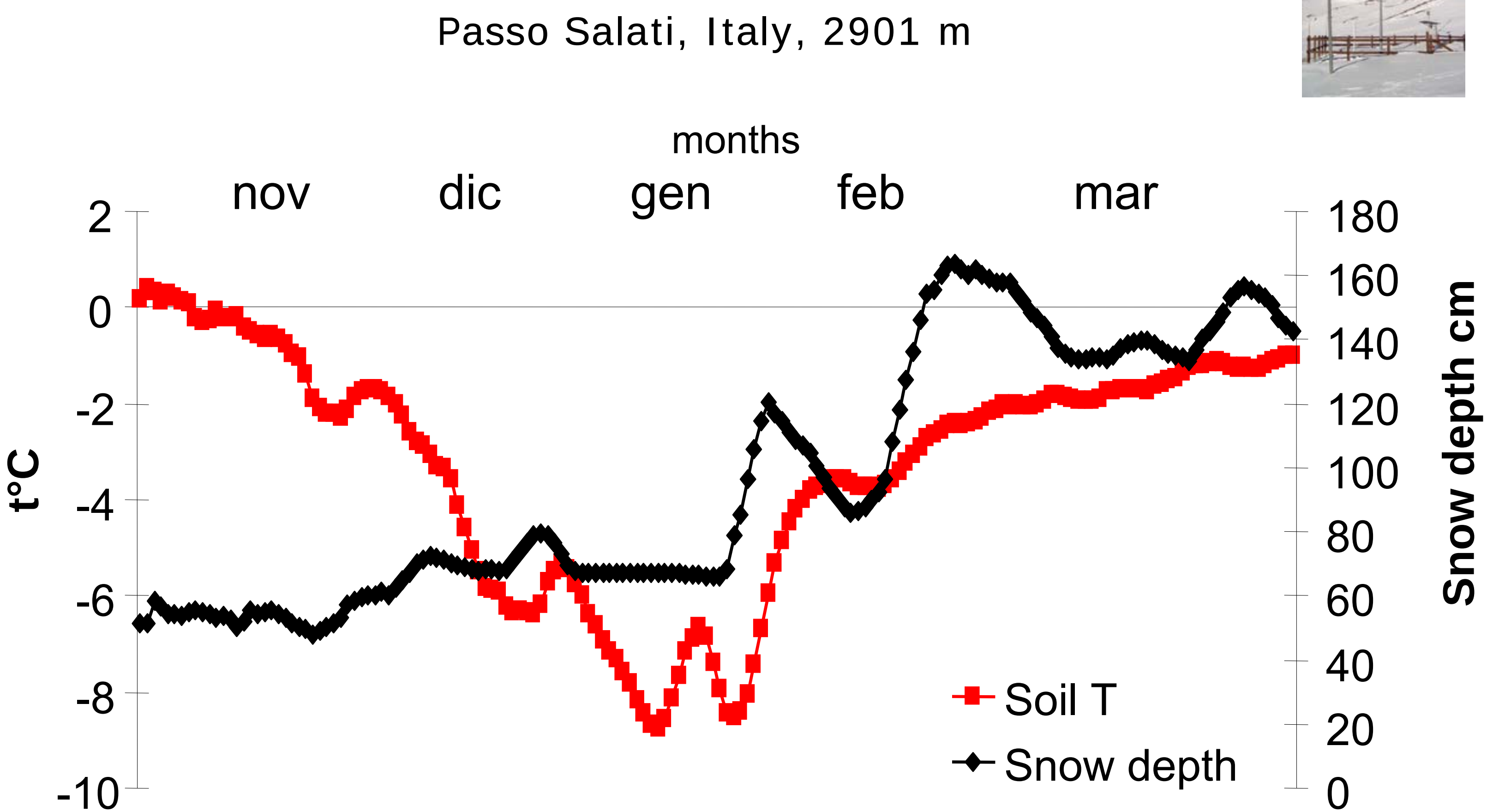


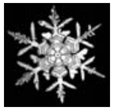
Soil surface temperatures beneath the Toolik Late dry-site fence and control plots, winter 1994-1995. Temperatures were recorded every 48 minutes using Hobo temperature logging devices (Onset Computer Corporation, Pocasset, MA). A very similar pattern was found at Niwot Ridge

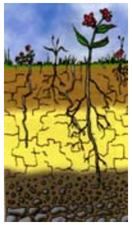


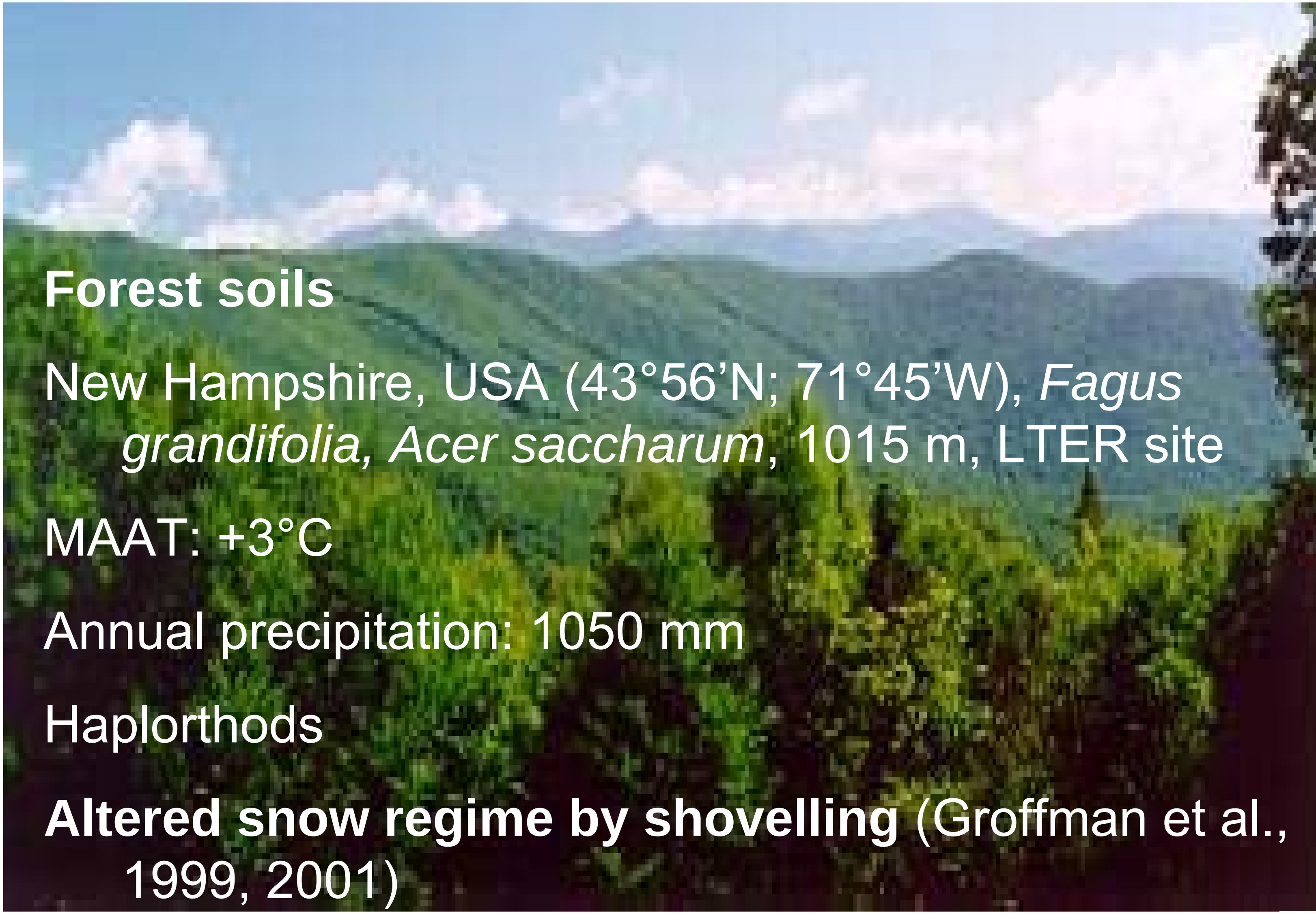


The rate of soil freezing/warming









Forest soils

New Hampshire, USA (43°56’N; 71°45’W), *Fagus grandifolia*, *Acer saccharum*, 1015 m, LTER site

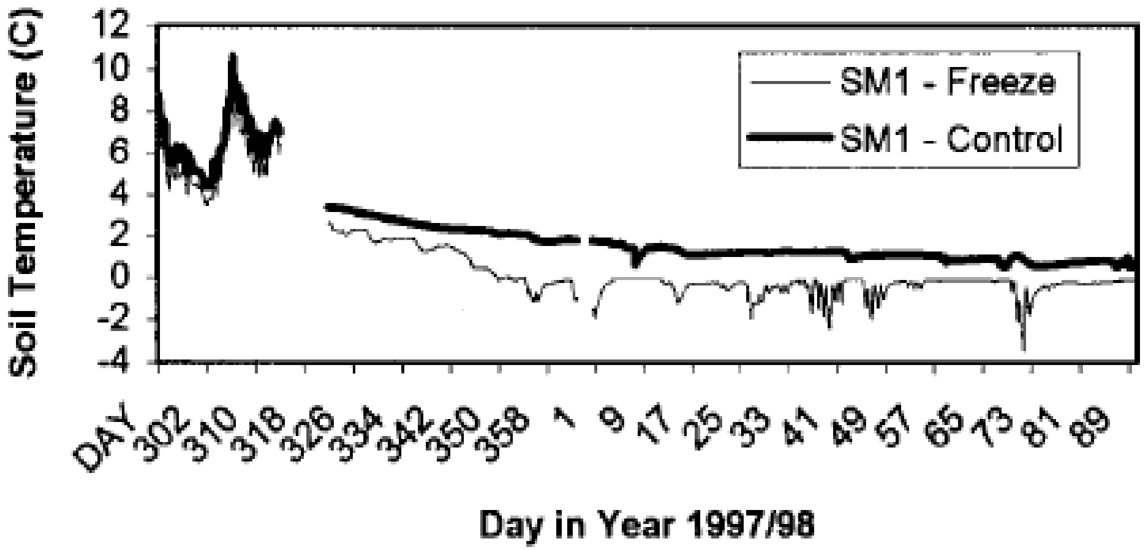
MAAT: +3°C

Annual precipitation: 1050 mm

Haplorthods

Altered snow regime by shovelling (Groffman et al., 1999, 2001)

Montane forest soils

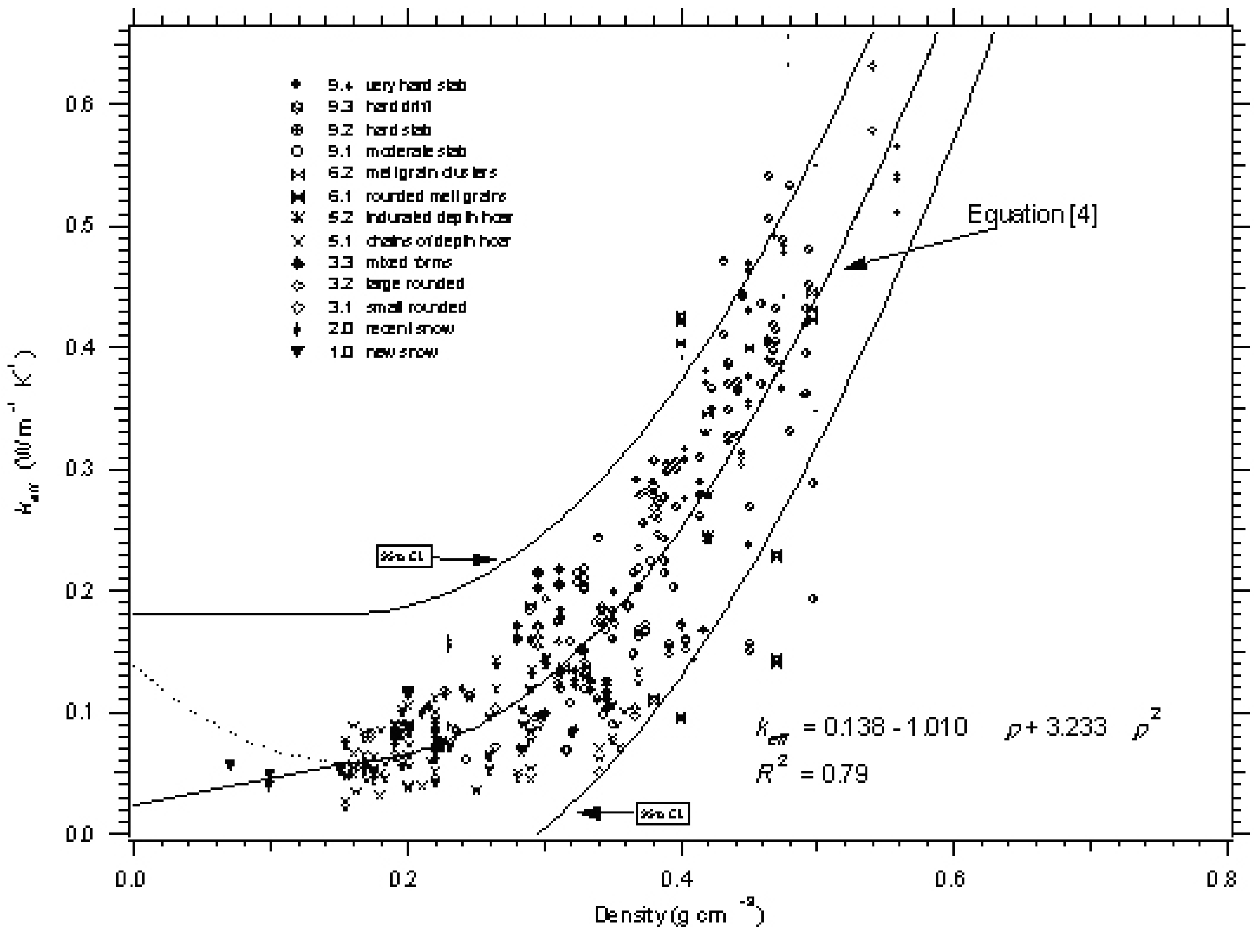


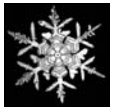
mild freezing events

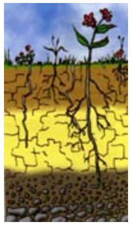
Not only the **depth** but also the quality of the snowcover may affect the soil temperature:

The snow cover density

- A typical thermal conductivity for dry snow with a density of 100 kgm-3 is 0.045 W m^{-1} k^{-1}







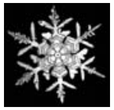
- In temperate mountain regions, the snowpack is often close to its melting point, so that it may respond rapidly to apparently minor changes in temperature. As warming progresses in the future, **regions where snowfall is the current norm will increasingly experience precipitation in the form of rain** with episodes of rain on snow (*Beniston*, 2003).

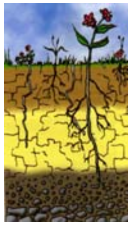
Altered snow properties

Increased snow density by grooming

Swiss Federal Institute for Snow and Avalanche Research (Davos-CH)

Christian Rixen, Michele Freppaz, Veronika Stoeckli, Christine Huovinen, Kai Huovinen & Sonja Wipf (2008) Arctic Antarctic and Alpine Research.

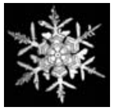


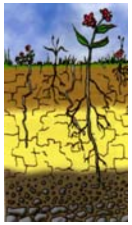


Experimental site

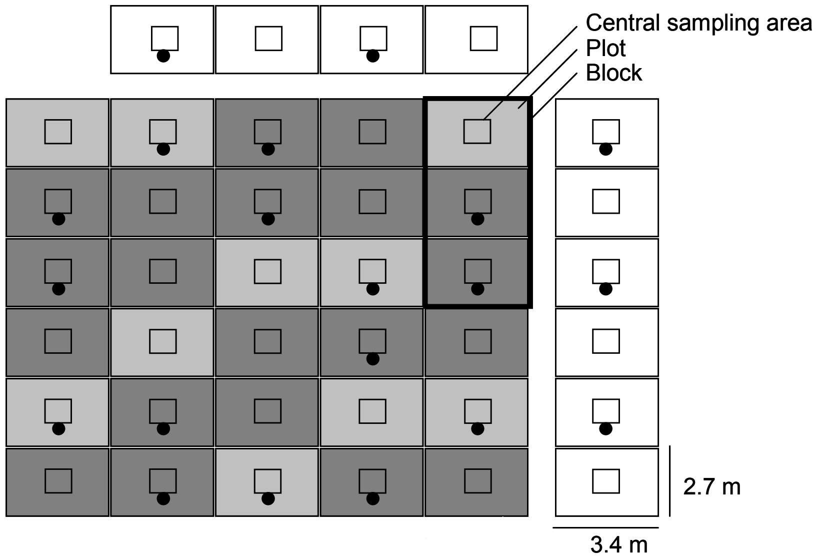
- Davos (CH)
- 1530 m
- MAAT: +2.7 °C

- *Buried bag technique* (Eno, 1960; Adams et al., 1989)
- 5-10 cm depth





Experimental site



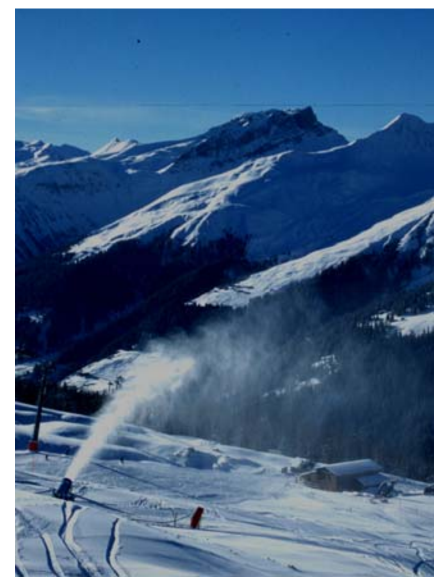
CAS Compacted artificial snow

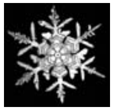
CAA Compacted art. snow with additives

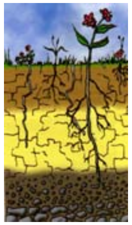
CNS Compacted natural snow

NS Uncompacted natural snow

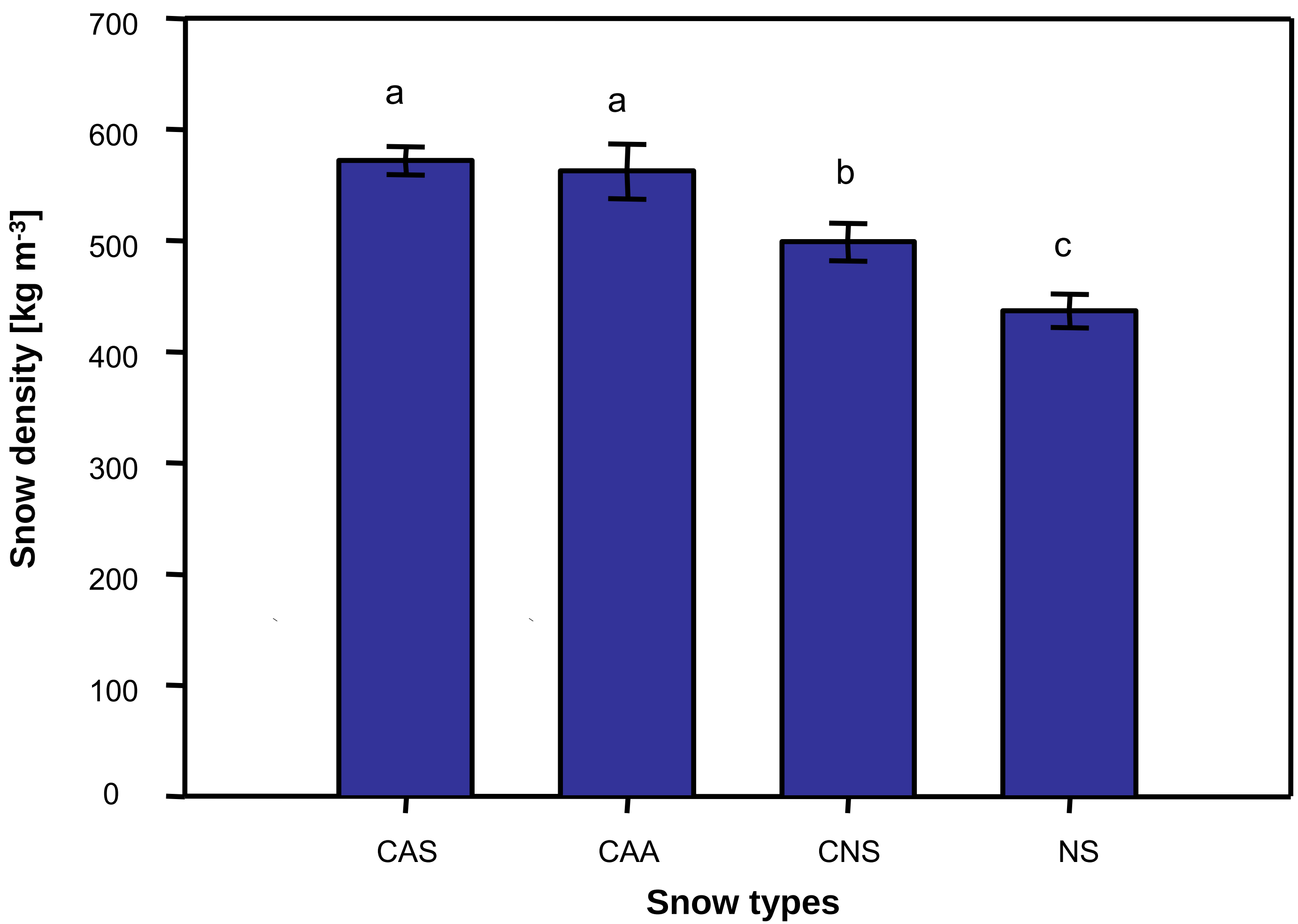
● Temperature sensors, gas collectors and soil bag analysis

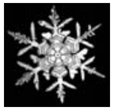


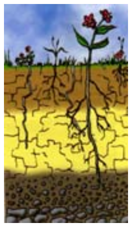




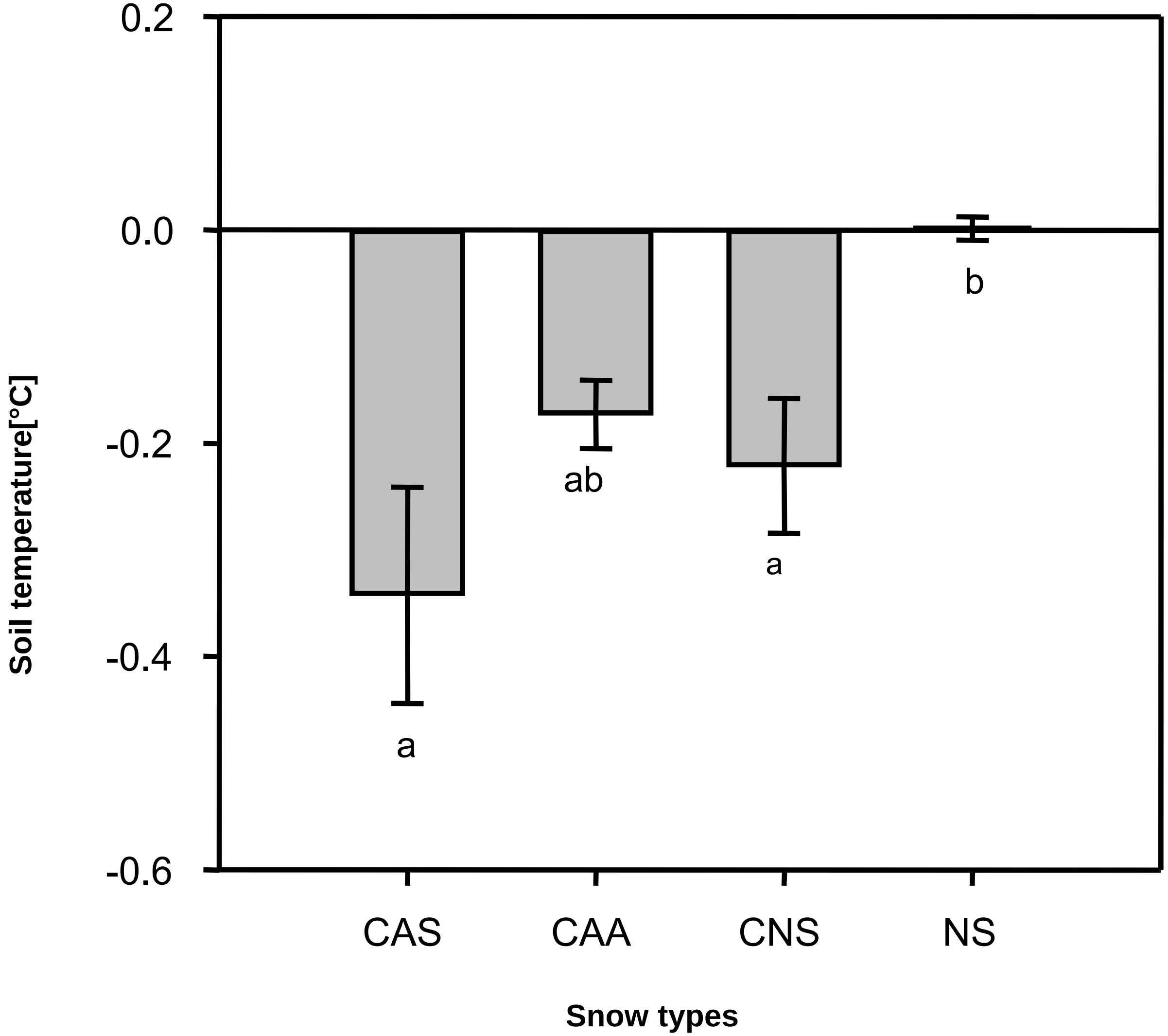
Snow density

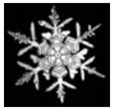


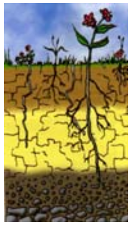




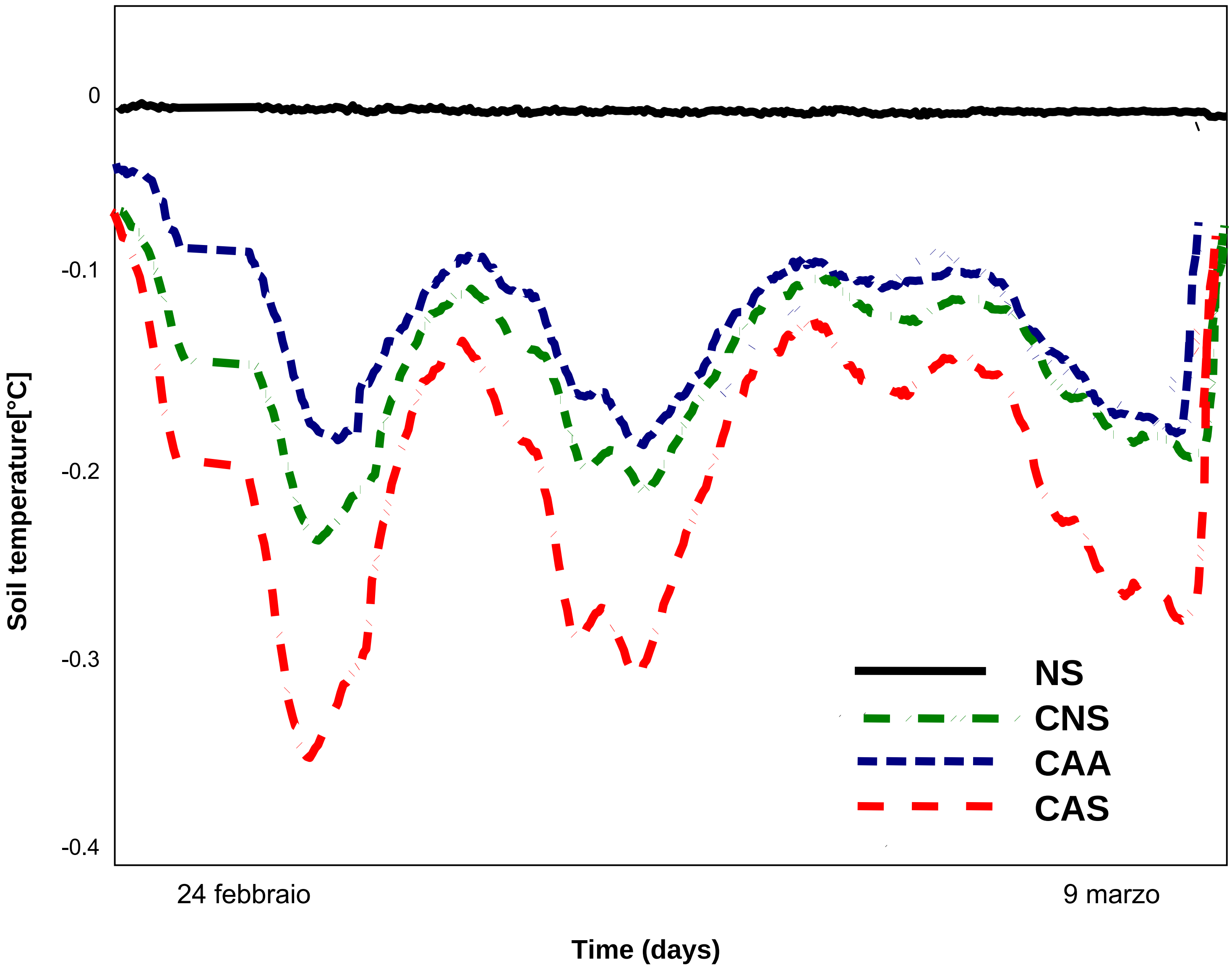
Soil temperature





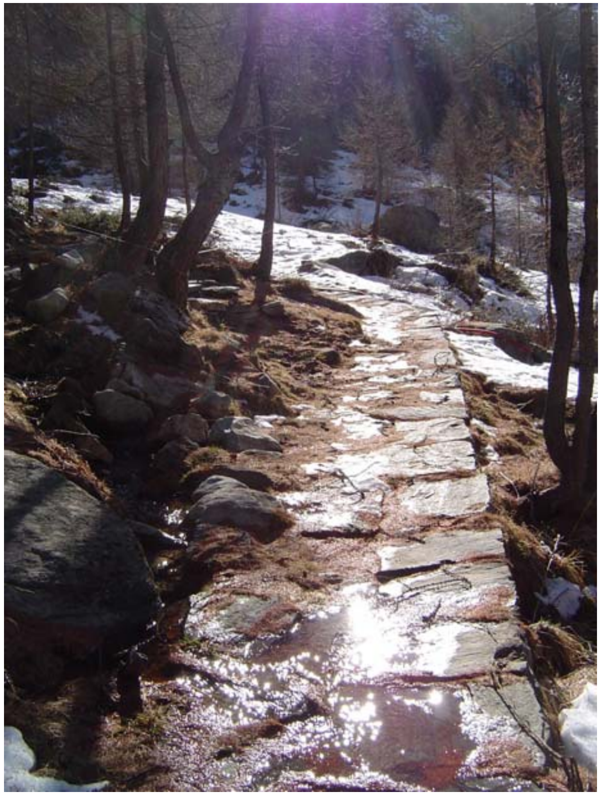


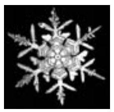
Soil temperature



Snow/Soil interactions

- Snow is a reservoir of water, released into the soil in a short time (Italian Alps, 2000 m, SWE=320 mm).





Snow/Soil interactions

- Snow is a reservoir of nutrients. During the spring melt period, meltwaters deliver nutrients to the soil, up to 2-4 kg ha^{-1} of N within a period of a few weeks.
- 50 to 80 per cent of the solute species are eluted in the first 30 per cent of melt water (**ionic pulse**).
- **Preferential elution** from snow to soil in the sequence SO_4^{2-}>NO_3^->Cl^- was confirmed from field and laboratory measurements.

Profiles of nutrient species

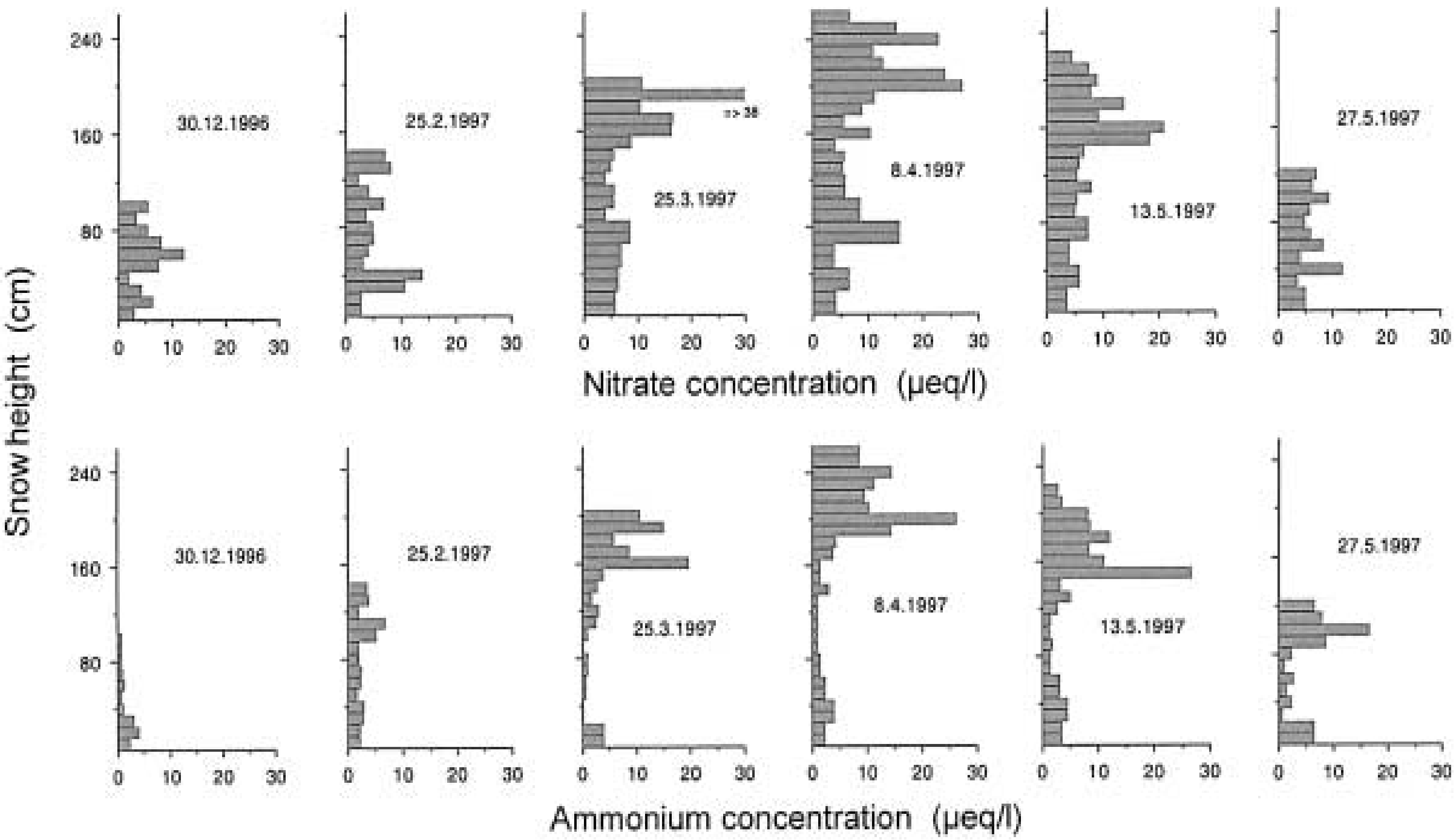


Figure 3. Profiles of two nitrogen species through the winter season. Data from sampling near Lake Gossenkölle at 2400 m elevation in the Tyrolean Alps. Note the strong enrichment in the top layers that were deposited in a well mixed atmosphere in April and May. The simultaneous growth of both snow cover and concentration causes a marked increase of total nutrient load (μeq m^{-2}) in the spring months

Ionic Pulse

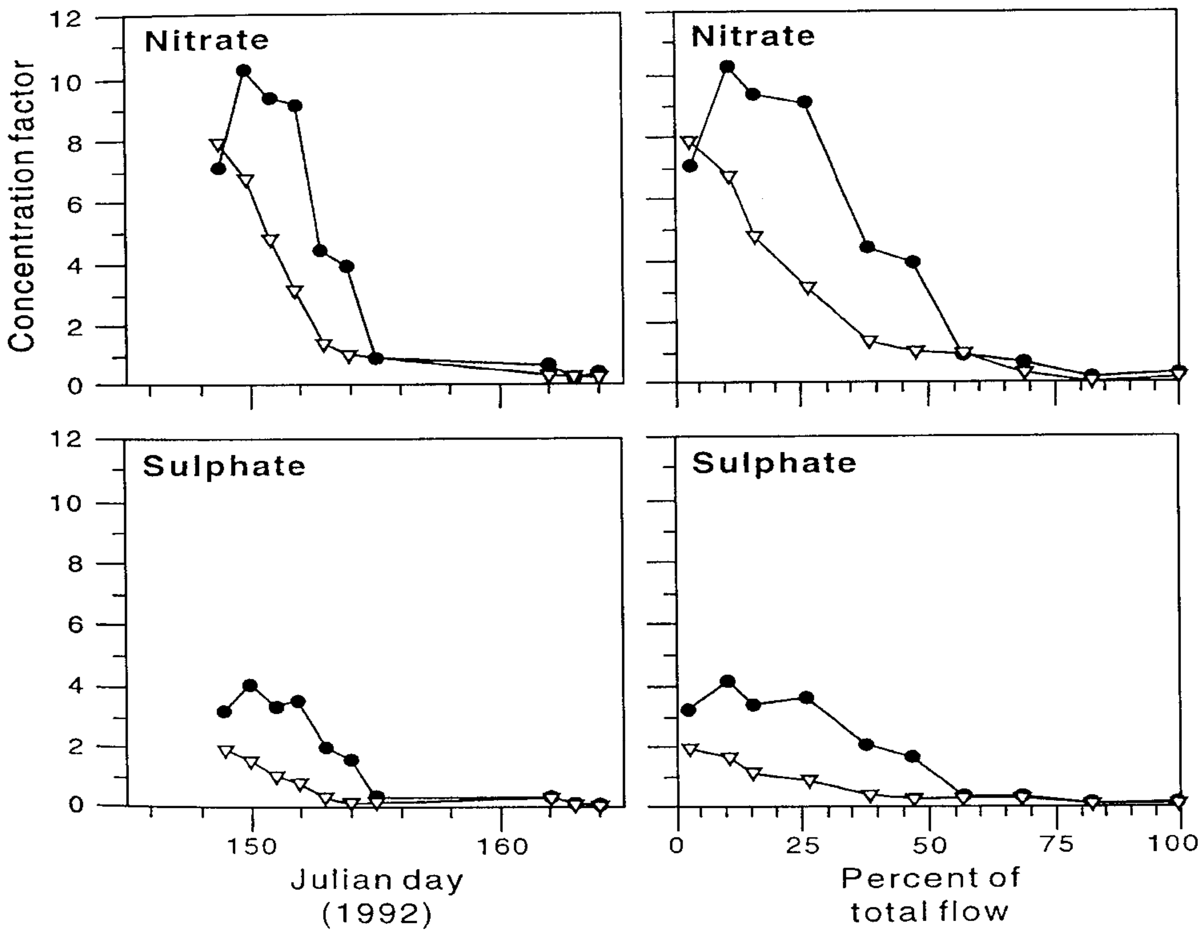


Figure 3.6. The impact of flow rate on the concentration factor of SO_4^{2-}, NO_3^-, and Cl^- in snowmelt. Open symbols denote high rates; closed symbols denote low flow rates (after Marsh and Pomeroy, 1993).

Preferential Elution

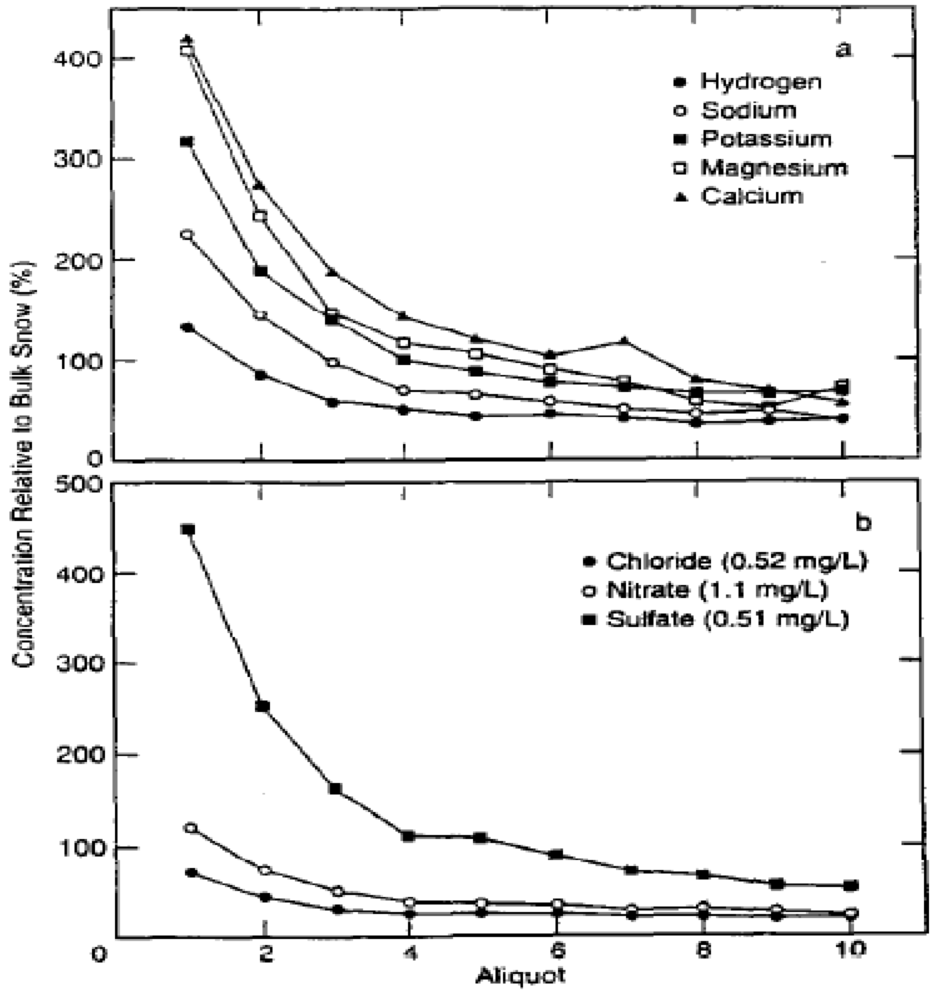
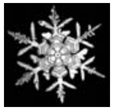
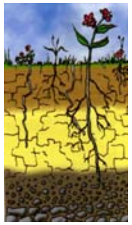
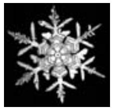


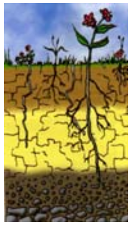
Fig. 3. Concentrations of (a) cations and (b) anions in sequential eluate aliquots for natural snow elution. Values have been normalized to bulk snow concentrations.





- The soil in seasonally snow covered areas is therefore influenced by the snowpack properties (e.g. snow depth).
- All the environmental factors which contribute to a variation in the snow distribution (e.g. wind, morphology), consequently influence also the soil properties.



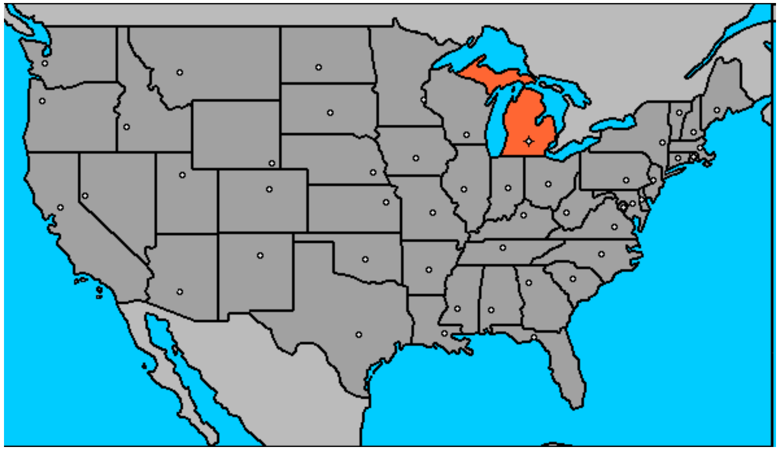


- MIcrotopography influence the soil formation, primarily through the re-distribution of energy and materials, including water, litter and in certain areas the snow cover.

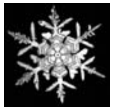
- In forests the morphology of the ground can be strongly influenced by factors such as the tree up-rooting due to the wind.

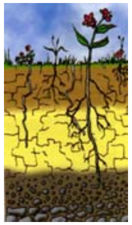
2. Snow and soil formation

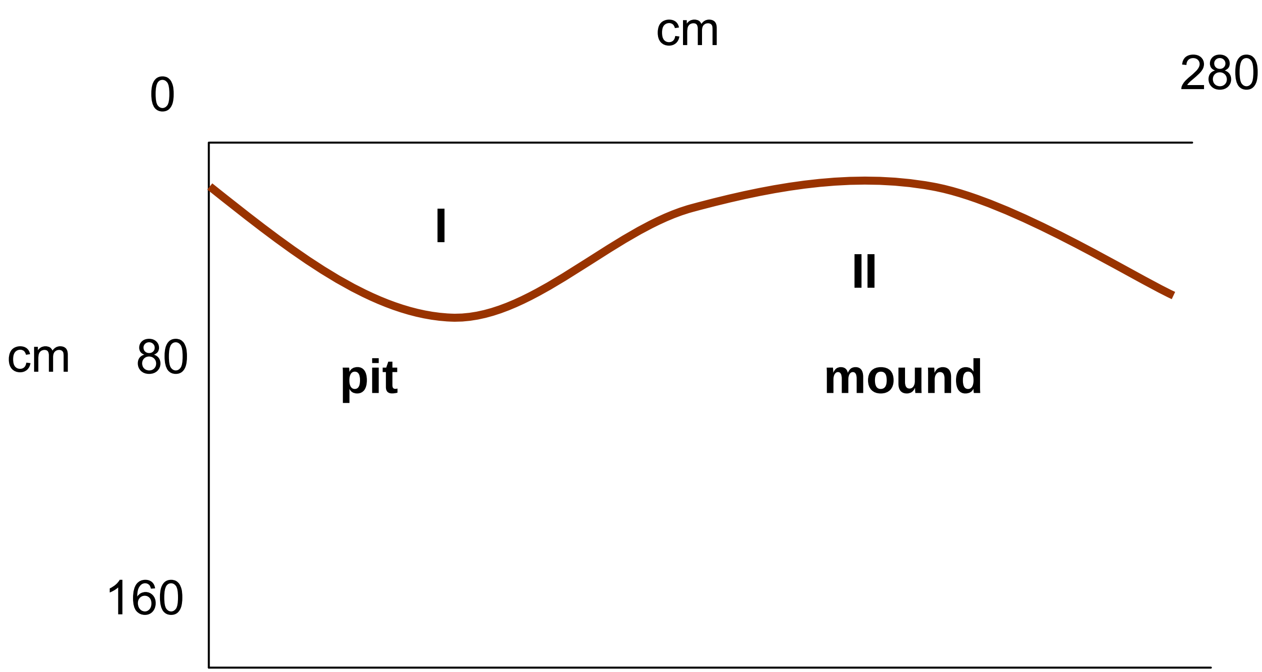
- Michigan, Baraga County (48° 39’N; 88° 28’ W)
- Manto nevoso da fine Novembre a metà Aprile
- *Tsuga canadensis, Acer saccharum, Betula lutea*



Schaetzl and Lansing (1990) Catena

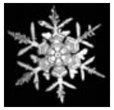


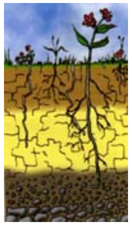




I Pit:

- > snow depth
- > snow duration on the ground





“Mound”

- Upper soil horizons frozen (till 10 cm depth),even one week later the snow melting:

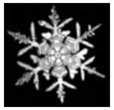
⟹ Little infiltration of the snow melting

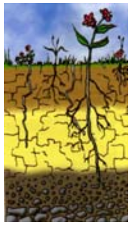
⟹ In early summer reduced soil water content

- Freeze/thaw cycles:

⟹ Influence on soil genetic horizons development

Typic Udipsamments





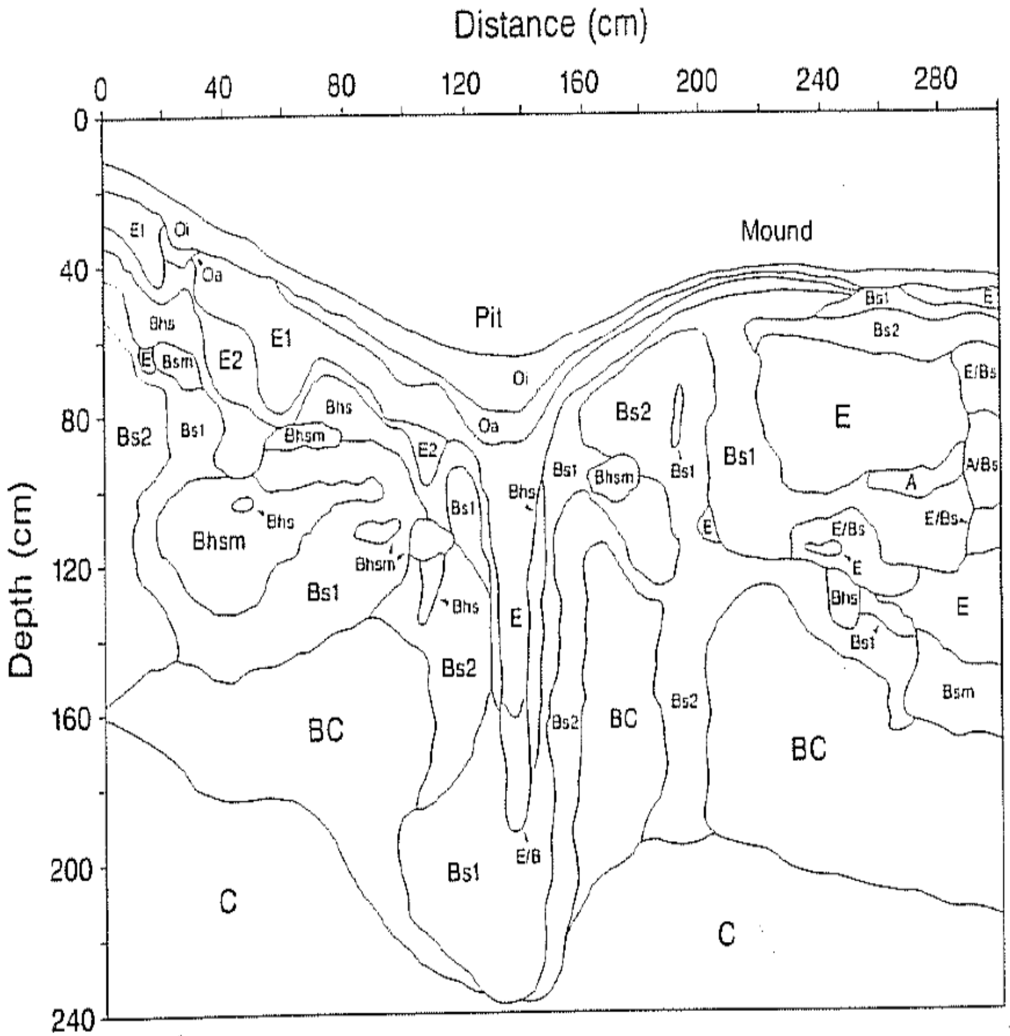
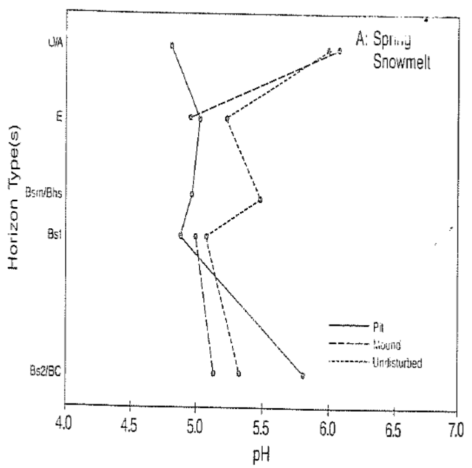
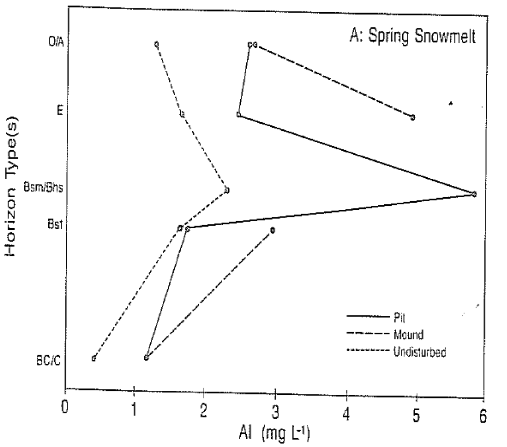


Fig. 1: *Cross section through a pit/mound pair, illustrating deep tongueing of the E horizon in the pit. Soil horizon clasts are mixed in the center of mound, and do not reflect post-uprooting pedogenesis..*

“Pit”

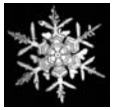
- E horizon well developed
- During spring snow melting great acidification of the upper horizons and traslocations of organo-mineral complexes

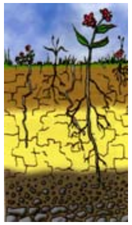




Soluzione del suolo

Entic Haplorthods





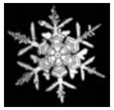
Soil development therefore is greater in pits due to:

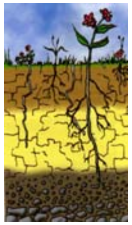
- Reduced freezing, greater water content of the upper horizons:

→ greater alteration processes and leaching

- Greater O horizons:

→ great production of organic acids moved into the deeper soil horizons during the so called “flushing events” (e.g. snpw melting (Ugolini et al., 1982))

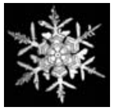


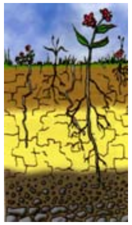


- At higher elevation, close to the tree line, a key factor for snow distribution is constitued by the wind.

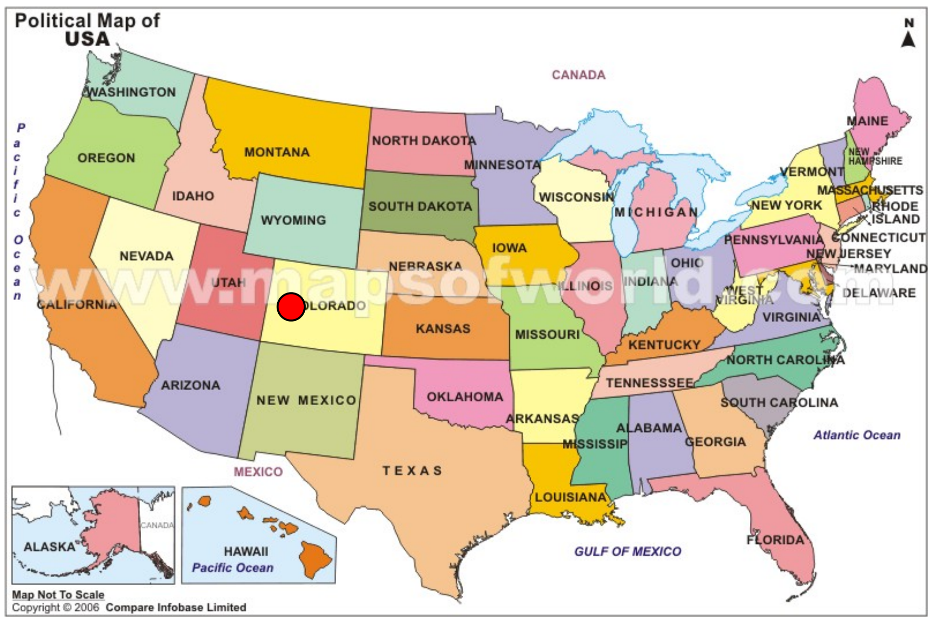
- The presence of “tree islands” can influence the wind action, originating areas with different snow depth.

2. Snow and soil formation



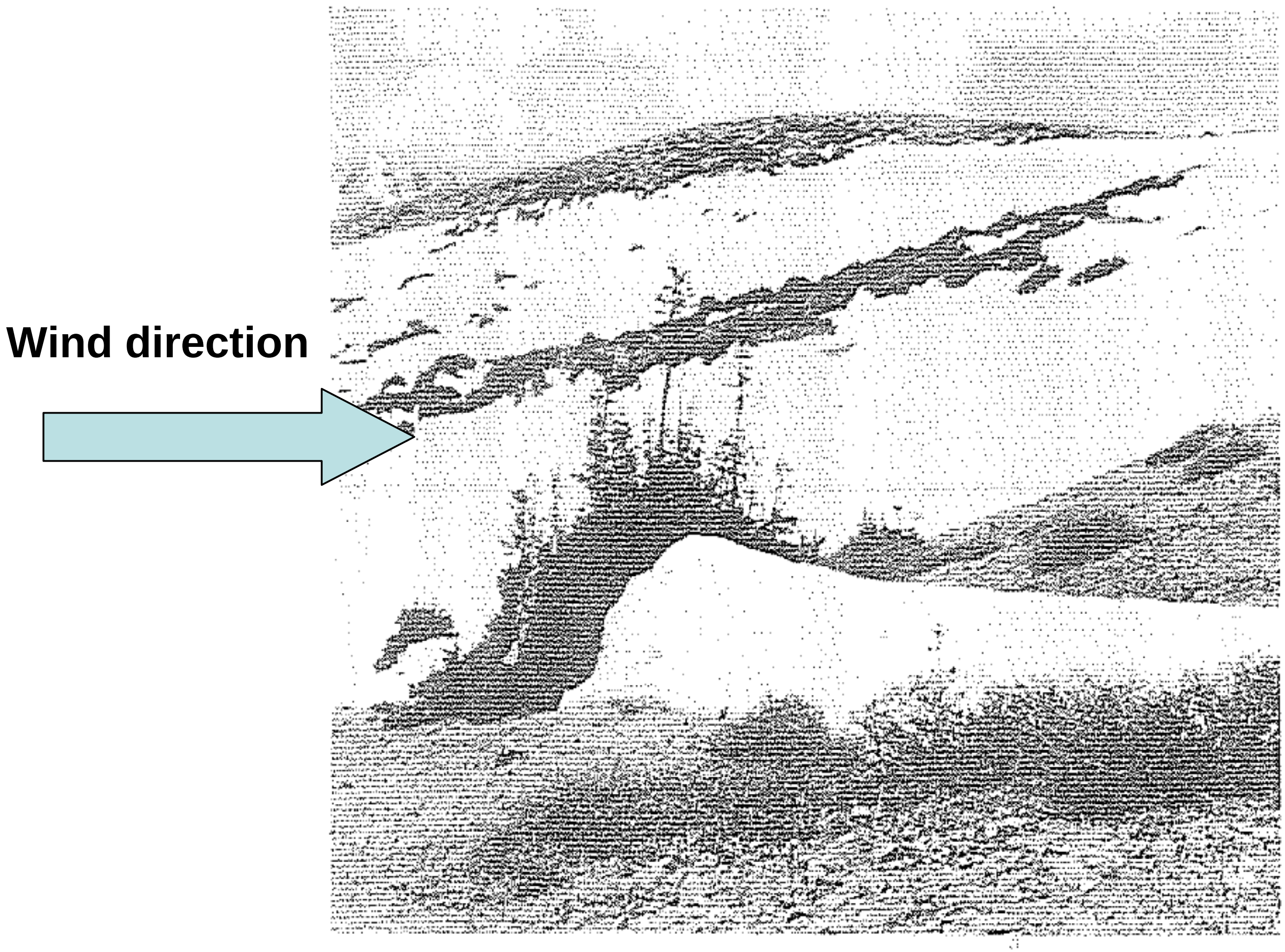


- Colorado, Niwot Ridge (48° 39’N; 88° 28’ W)
- 3400 m asl
- *Abies lasiocarpa, Picea engelmannnii*

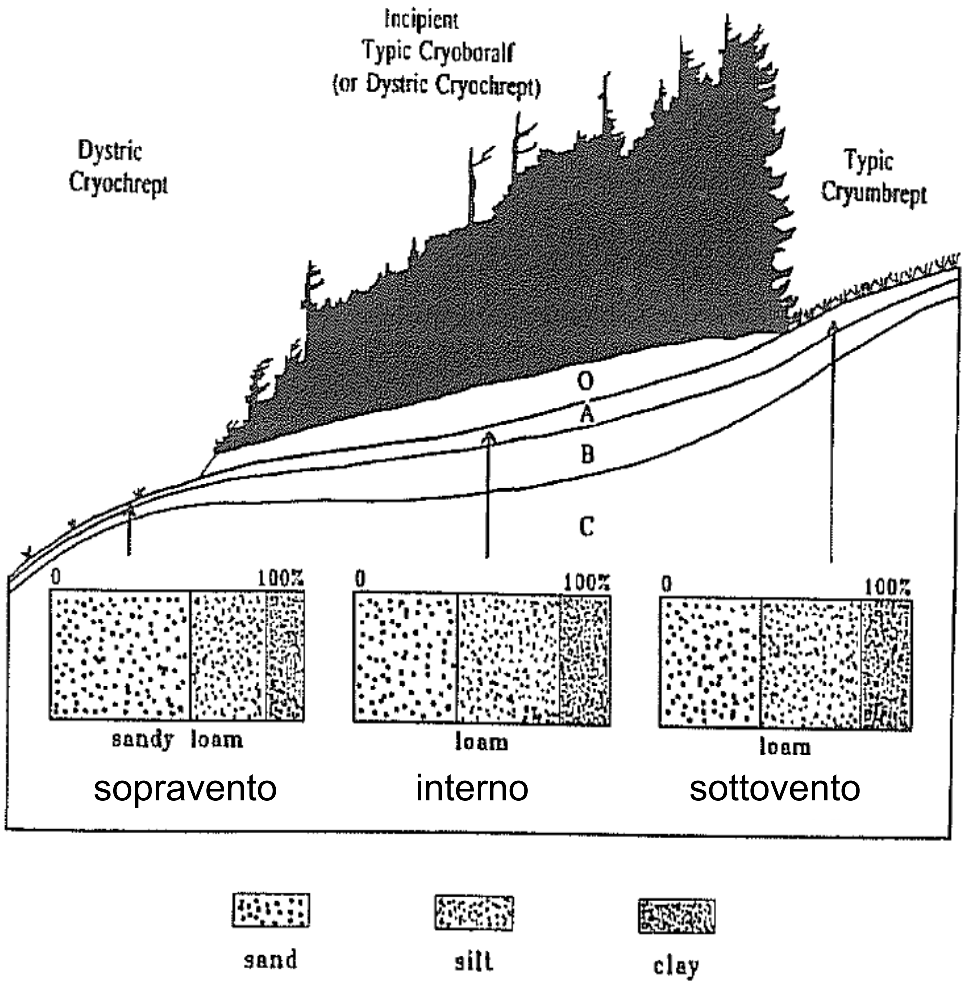


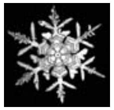
Holtmeier e Broll, 1992 Arctic and Alpine Research

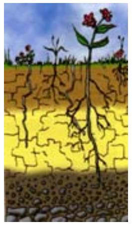
2. Snow and soil formation



- Nel versante sopravento the mineral soil is exposed due to the wind.

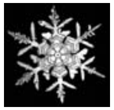


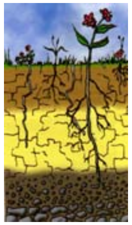




▪Nel versante sottovento the greater snow depth cause also a greater accumulation of fine materials (alpine loess), which contribute to the formation of a deeper B horizon.

▪The depostion of loess cause also an increase of Ca concentration in the A horiozn and an increase of soil pH.



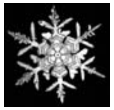


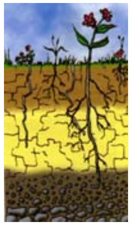
- At higher elevation, above the tree line, the topography and the aspect infuence the environment, determining conditions strongly different even in a small distance.

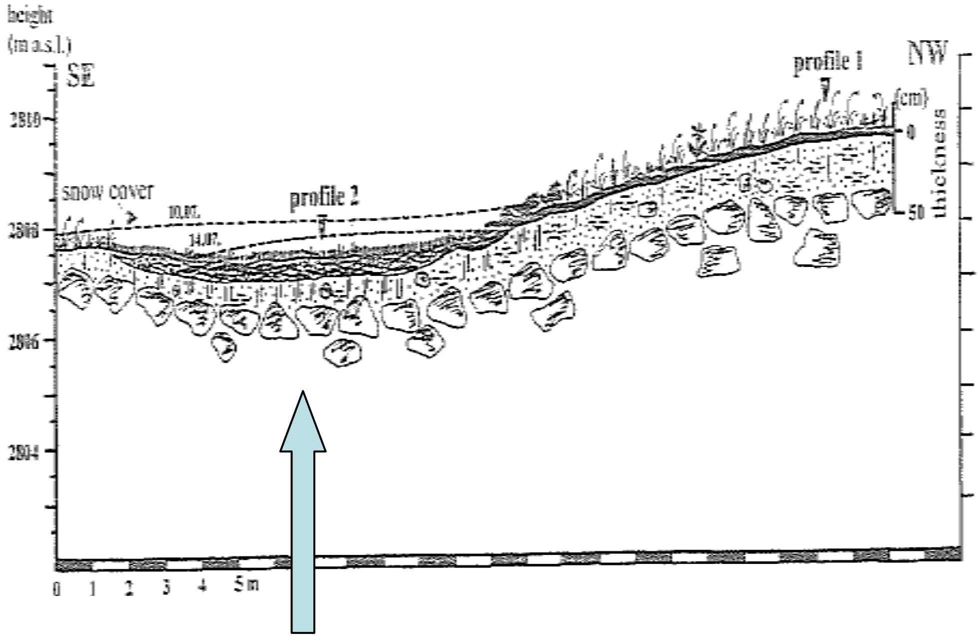
- In particular the snowbeds are characterized by a snow cover which last for 8-10 months, and consequently by a short growing season (2-3 months)

- Engadina, Switzerland 2400 m slm
- MAAT: 1.3 °C

Hiller et al., 2005, 1992 Arctic, Antarctic and Alpine Research

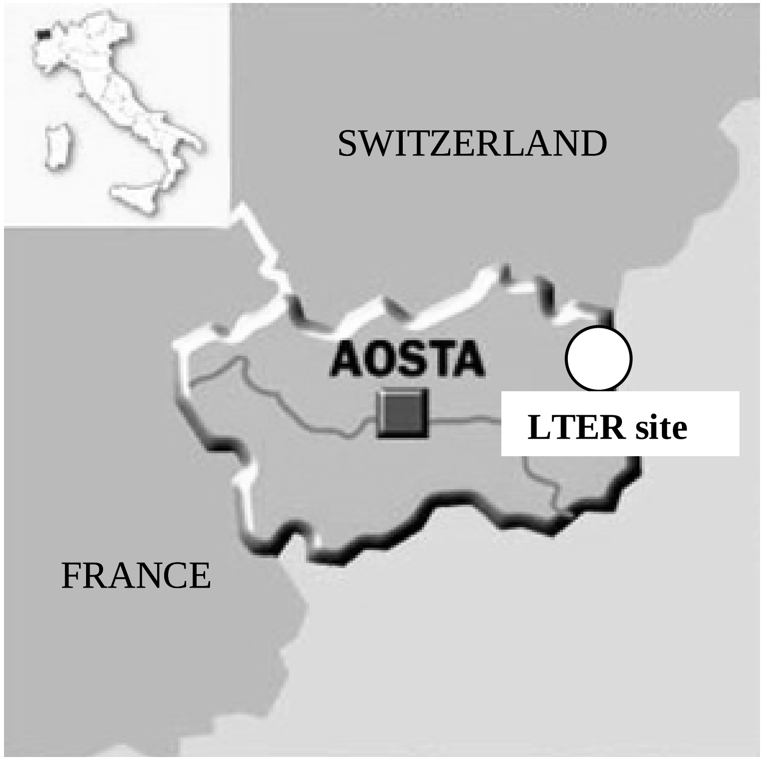


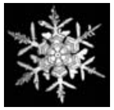


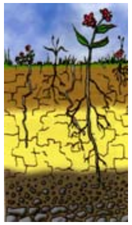


- <u>Drenaggio rapido</u>
- A horizons well developed
- Podzolization: stronger in the snowbed area
- > clay and silt content in the upper horizons (alpine loess)

- Vallone dell'Olen, Valle d'Aosta
- 2800 m slm







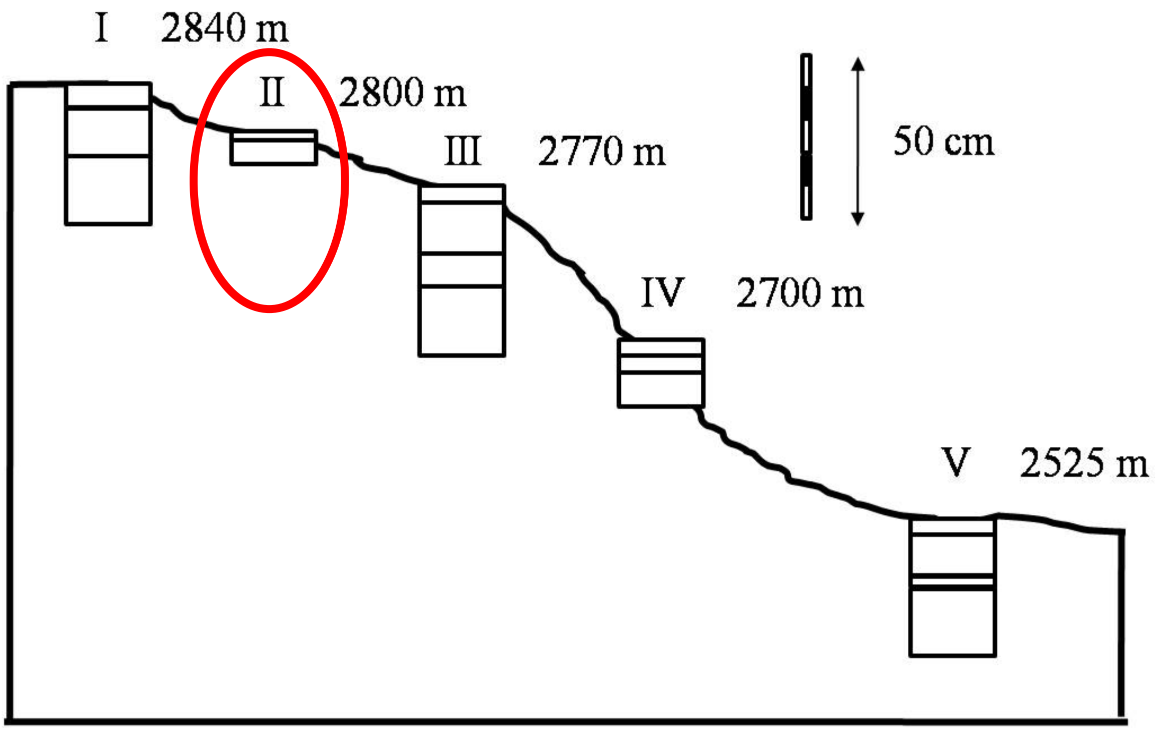
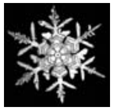
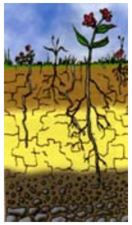


Figure 2. Location of the 5 sampling sites along the elevation gradient. Elevation, horizonation and horizon depths are shown (note that the distance between sites and the elevation gradient are not in scale).

Freppaz et el., 2010





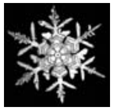
2800 m slm

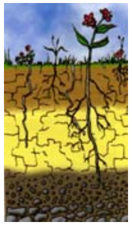
A: 0-5 cm

TOC: 37.9 gkg^{-1}

C/N: 13

Lithic Leptosol Dystric

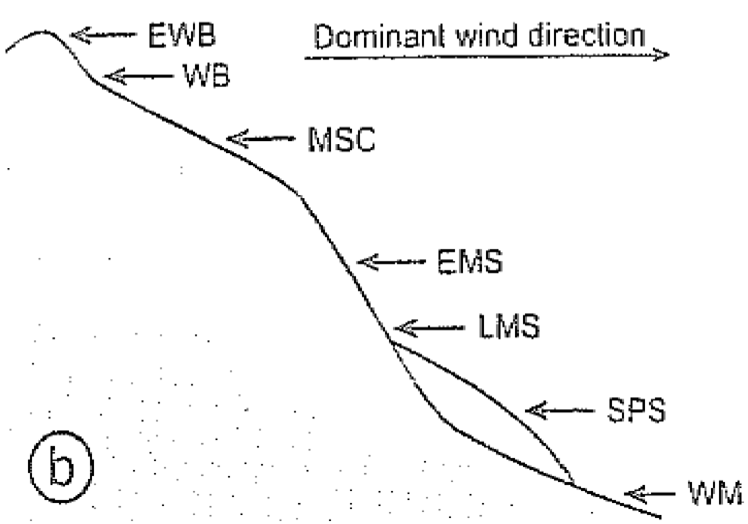




The Synthetic Alpine Slope Model (SAS)

- The SAS model is based on the consideration that spatial variation of alpine soil properties derives from variations of snow distribution.

- Snow distribution is connected to the interaction with the wind and the topography.



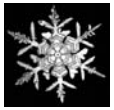
EWB - Extremely wind blown, Dystric Cryochrepts
WB - Windblown, Dystric Cryochrepts (but with thicker A horizons)
MSC - Minimal snow cover, Typic Umbrorthels (coldest soils but with the best-developed sola: most stable sites)
EMS - Early-melting snowbank, Typic and Pachic Cryumbrepts (thickest A horizons; high gopher activity)
LMS - Late-melting snowbank, Dystric Cryochrepts (warmest soils)
SPS - Semi-permanent snowbank, Lithic Cryorthents and Orthels (some buried soils present)
WM - Wet meadow, Aquorthels, Cryaquepts, Historthels, Cryaquolls

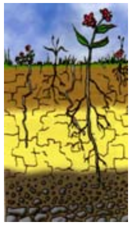
Burns and Tonkin, 1982

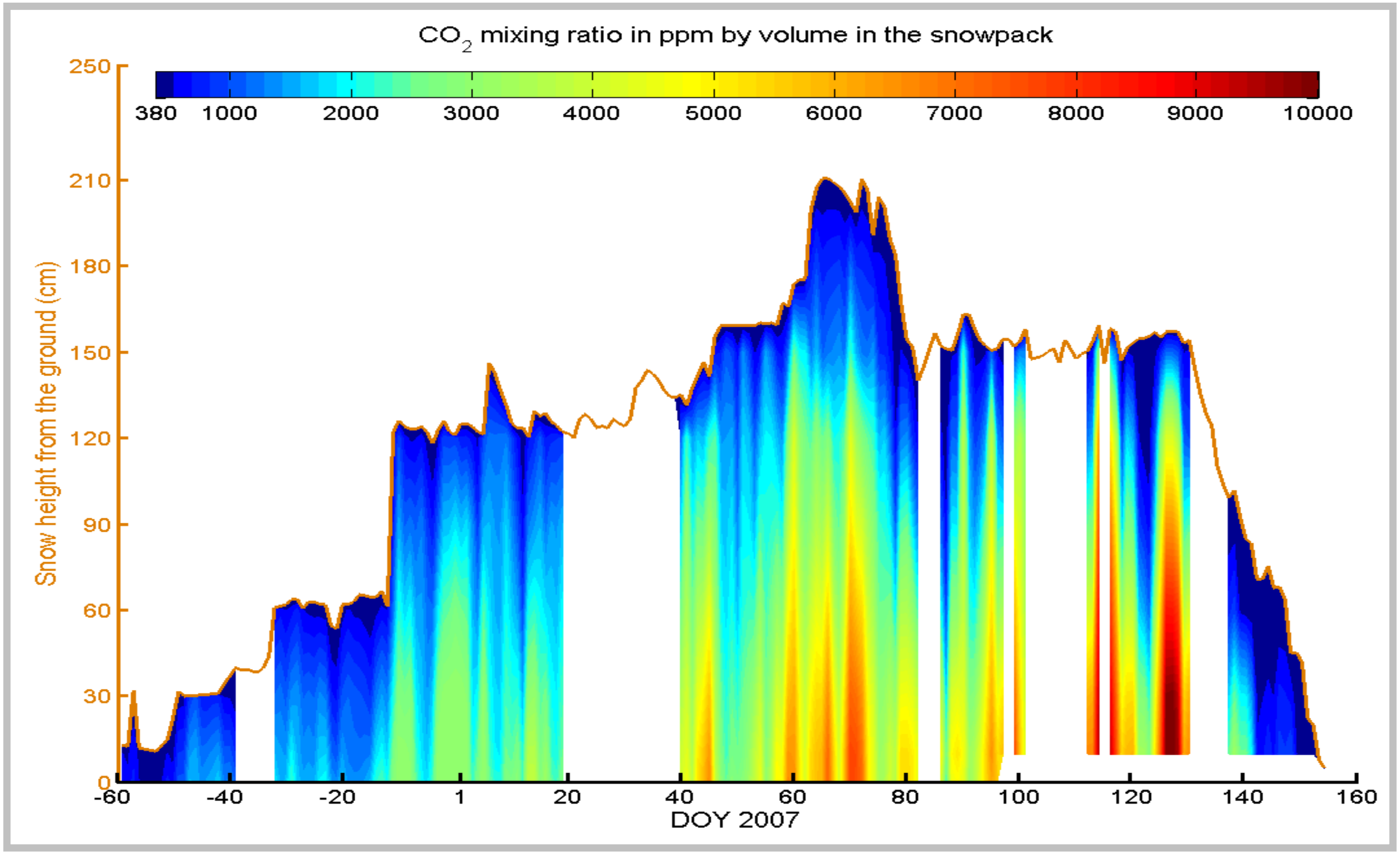
The Synthetic Alpine Slope Model (SAS)

- For example, the areas greatly exposed to winds, with the snow removal, are the driest and the most frost affected.

3. Snow and soil nutrient dynamics







Filippa G., Freppaz M. Liptzin D., Seok B., Chowanski K., Hall B., Helmig D., Williams M.W. (2009) Biogeochemistry

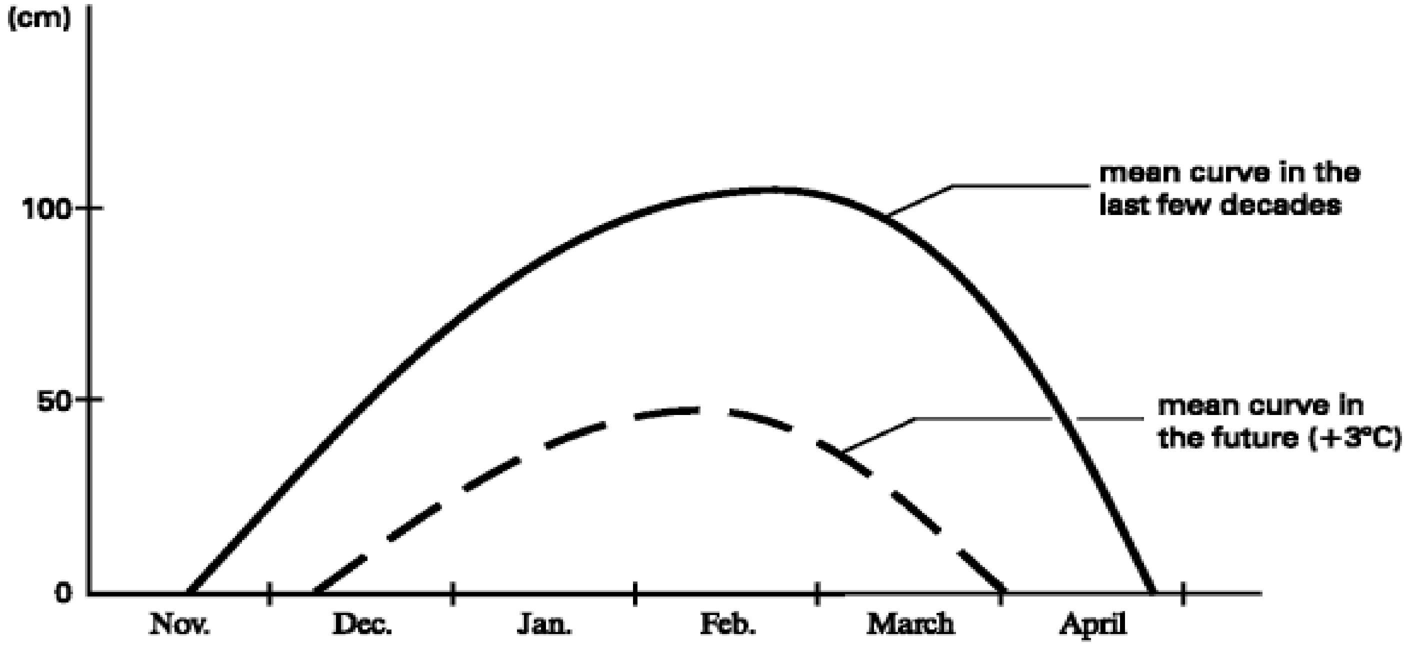


Figure 5 Snow depth and duration of snow cover at an altitude of 1500m in the last decades and in the future (schematic illustration). *Source*: Foehn, 1991

Forest soil

Valle del Lys (AO)

1450 m slm

Larix decidua

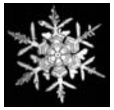
MAAT: +4°C

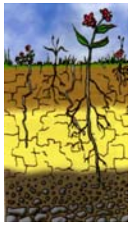
MAP: 1100 mm

Inceptisols

Inverno 2003-2004:Snow manipulaiton by shovelling

Winter 2003-2004: The study site

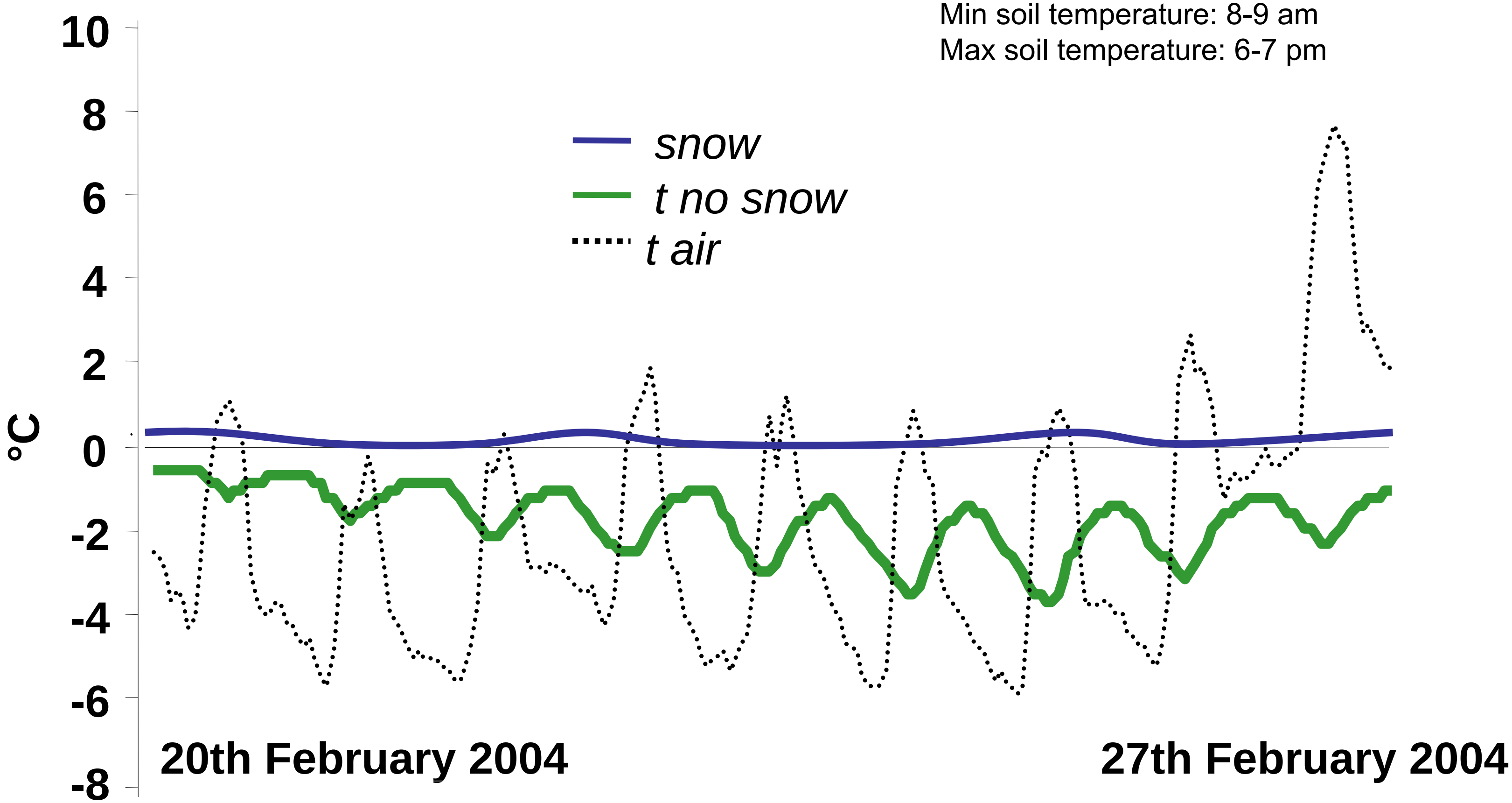




Soil temperature

Min air temperature: 6-7 am
Max air temperature: 3-4 pm

Min soil temperature: 8-9 am
Max soil temperature: 6-7 pm



Freppaz M, Marchelli M, Celi L, Zanini E (2008) Journal of Plant Nutrition and Soil Science

Loss of Biodiversity?

Undisturbed Plot

Shovelled Plot

Colder soils in a warmer world?

michele.freppaz@unito.it