Alpine Soils

Jérôme Poulenard
Université de Savoie, Le Bourget du Lac, France

Pascal Podwojewski
L'Institut de Recherche pour le Développement (IRD), Hanoi, Vietnam

INTRODUCTION

Alpine soils are found in mountainous regions above the natural subalpine tree line. This high-altitude belt is characterized by a lack of trees and dominance of a continuous grass carpet. The global land area covered by alpine soils is fragmented into many mountain regions (Rocky Mountains, Alps, Himalayas, Atlas, Andes, East Africa Mountains, New Guinea Highlands, New Zealand Alps, etc.) and approaches approximately 4×10^6 km^2 (Table 1). As a function of time, topographic conditions, and parent materials, a large range of soil types exists. However, alpine belt environment specificity leads to common features for all alpine soils. Because of the last glaciation, alpine soils are young (<10,000 years BP) and strongly influenced by a periglacial environment. On steep slopes, soils are often thin, regularly truncated, and in a constant process of rejuvenation. However, deep soils are found in some alpine grasslands on highly weatherable parent materials. Organic matter accumulation, acidification process, and a great role of aeolian dust deposition are other general characteristics of alpine soils genesis. The alpine soils are fragile and currently submitted to severe environmental threats, such as overgrazing, acid deposition, and climate change.

THE ALPINE BELT ENVIRONMENT

The altitude of the tree line (i.e., the zone of transition between the continuous forest and the alpine grassland) varies strongly with latitude. Close to the equator, this tree line is found at approximately 3600 m a.s.l., whereas in the regions above 60°, this limit is virtually at sea level (Table 1). This limit also varies in space with slope exposition and in time according to both climatic changes and human activities. The Alpine ecosystem is often called "alpine grassland," "alpine tundra," or "Alpine meadow." In tropical zones, this belt is often known by local names: "paramos" and "punas" in the Andes, and "afroalpine belt" in east Africa. Other than graminoid tussock, alpine vegetation is composed mainly of dwarf shrubs and herbaceous dicotyledonous species, which typically occur in a complex mosaic of communities as a function of topographic position, soil properties, and distribution of snow.[1]

The Alpine soil temperature regime[2] is generally cryic with an average decrease of 0.6°C for every 100 m of elevation increase. The alpine belt experiences considerable fluctuations in temperature between day and night, with frequent night frost in tropical as well as in temperate zones. In addition to the diurnal cycles, deeper soil freezing and thawing may occur following seasonal cycles in temperate zones.

Rainfall generally increases with altitude. However, in high mountains, condensation occurs well before air masses attain the summit, leading generally to a lower annual rainfall in the Alpine belt than in the subalpine forest. Substantial cloud moisture input is another important characteristic of alpine climate. The snow regime has a great impact on preventing soil and plant exposure to low-temperature extremes. The general pattern of alpine climate may be disrupted by a number of local factors (e.g., the "foehn effect" with opposition between the very wet windward and the very dry leeward).[1,3]

Erosional ("cirques," "U-shaped valley") and depositional ("moraines") glacial landforms are prominent in the alpine belt. Steep upper slopes, usually consisting of rough rock outcrops, and extensive lower slopes of rock debris are commonly observed (Fig. 1).

FACTORS OF ALPINE SOILS FORMATION

Erosion and Rejuvenation

Steep slopes are subject to strong erosion, especially if stabilizing vegetation is absent. In these slopes where soil losses are higher than the rate of soil formation, alpine soils are regularly truncated and in a constant process of rejuvenation with shallow depth, high skeleton soil content, and low fine Earth fraction[3] (Fig. 2).

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Table 1 Latitudinal distribution of the areas of alpine life zone and main mountain ranges with alpine environment

Latitude range (°)	Approximate altitudinal boundaries of alpine life zone (m. a.s.l.)	Area within alpine life zone (km^2)	Main mountain ranges
<60°N	0–500	824,000	Brooks Range, Alaska Range (USA), Kjollen Range (Norway, Sweden), Gory Putorana, Chersky Range, Verkhoyansk Range, Kolyma Mountains (Russia)
60°N–50°N	1000–2500	428,000	Rocky Mountains (Canada), Saigan Mountains, Yablonovy Range (Russia)
50°–40°N	2000–3500	724,000	Cascade Range, Rocky Mountains (USA), Alps (France, Italia, Switzerland, Austria), Apennines (Italia), Pyrenees (Spain, France), Carpathians (Slovakia, Ukraine, Romania), Caucasus (Armenia, Georgia, Azerbaijan, Turkey, etc.), Altaï (China, Mongolia, Russia, Kazakhstan), Tien Shan (China)
40°N–30°N	3000–4500	1,088,000	Sierra Nevada, Rocky Mountains (USA), Atlas Mountains (Morocco, Algeria), Zagros Mountains (Turkey, Iraq, Iran), Hindu Kush, Pamirs, Karakoram, Kunlun Mountains, Plateau of Tibet, Himalayas, Ningling Shan, Dxue Shan, Bayan Schan (Afghanistan India, China, Pakistan, Kyrgyzystan, Uzbekistan)
30°N–20°N	3250–4750	208,000	Sierras Madre Occidental and Oriental (Mexico), Himalayas, Plateau of Tibet (India, Nepal, Bhutan, China)
20°N–0°	3500–5000	18,000	Andes (Colombia, Ecuador), Sierra Madre del Sur (Mexico, Guatemala, Salvador, Honduras) Cordilleras de Talamanca (Costa Rica), Ethiopian Highlands (Ethiopia, Eritrea), East African Highlands (Kenya)
0°–20°S	3250–4500	280,000	Andes (Ecuador, Peru, Bolivia), East African Highlands (Kenya, Tanzania), Pegunungan Maoke (Indonesia, New Guinea)
20°S–30°S	2750–4000	150,000	Andes (Bolivia, Chile, Argentina), Drakensburg (South Africa)
30°S–40°S	2000–3000	60,000	Andes (Chile, Argentina)
>40°S	1000–2000	220,000	Andes (Chile, Argentina), New Zealand Alps (New Zealand)

Periglacial Phenomena

Among the physical effects on alpine soil formation, the processes caused by freezing play a central role. Permafrost and their related cryosols[4] or gelisols[2] are found only in the nival belt above the upper limit of higher plant distribution.[1] In the alpine belt, soils are strongly affected by freeze/thaw cycles with fragmentation of rocks, creeping, solifluction, and cryoturbation phenomena, which disrupt and dislocate horizons, displace and incorporate materials from other horizons, and mechanically sort soil particles[1,3] (Fig. 3). In flat terrain, deep frost tables can induce water logging.

Aeolian Dust Deposition

Aeolian dust is an important soil-forming factor in alpine soil pedogenesis.[3] In acidic materials (quartzitic residuum, granite, and gneiss), the steady supply of eolian carbonates through wind-blown materials greatly contributes to raise the pH of surface horizons close to neutrality.[5,6] The original particle size of the soil may

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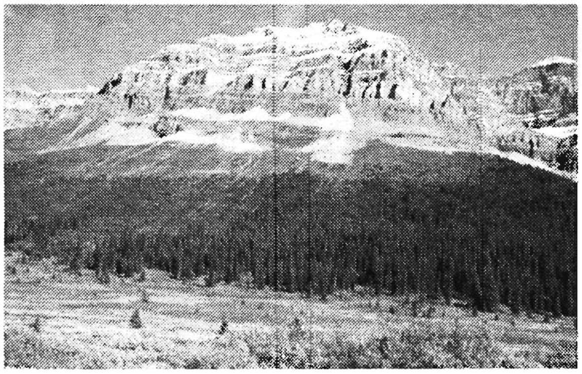

Fig. 1 Narrow alpine belt strongly submitted to the active erosion processes of the rock outcrops (Banff National Park, Canadian Rocky Mountains). (Photo from L. Trosset.) (*View this art in color at www.dekker.com.*)

be changed if the allochtonous particles mix with autochthonous ones.[3] In volcanic regions (Northern Andes, East African Mountains, New Zealand, etc.), alpine soils are developed from volcanic pyroclastic materials, and volcanic ash can strongly influence alpine soil genesis even in the case of nonvolcanic parent materials.[7]

Weathering and Soil Formation Rate

After the glacier retreat, the greatest change in soil chemistry of alpine soils occurred within the first 3000–4000 years of soil development.[3] Despite the cold climate, chemical weathering was intense[3] and soil development proceeded more rapidly in the alpine zone

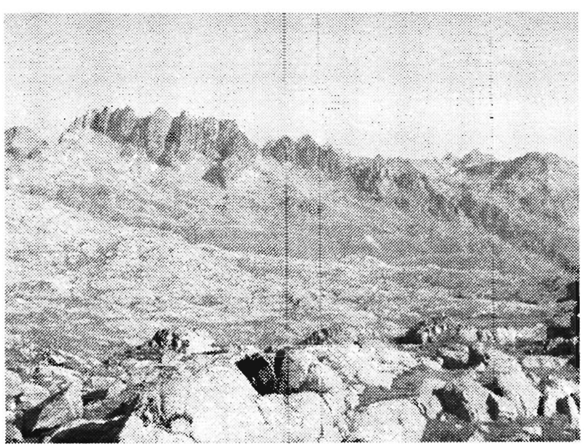

Fig. 2 First development of alpine soil formation on "roches moutonnées" after glacier withdrawal (Rousses, French Alps). (Photo from J. Poulenard.) (*View this art in color at www.dekker.com.*)

Fig. 3 Solifluction and grazing step terrassettes in alpine slope (Vanoise, French Alps). (Photo from J. Poulenard.) (*View this art in color at www.dekker.com.*)

than in the subalpine and mountain forests.[6] However, it is the degree of parent material fragmentation that largely controls the rate of alpine soil formation.[3]

In parent rocks containing carbonates, solubility phenomena are especially important. High precipitation and low temperature of the percolating water increase carbonate solubility. Rapid dissolution of $CaCO_3$ is a common feature of alpine soil weathering.[3,8]

Soil Organic Matter and Biological Activity

Alpine soils are often characterized by relatively high organic matter content (>50 g kg^{-1}) in the surface soil with a good incorporation of organic matter through the profile linked with abundant below-ground production of meadow grasses.[1,9] Both substrate properties with high organic content resistant to mineralization and climate conditions prolong the mean residence time of organic matter.[1] Faunal and microbial activity of carbon mineralization is clearly reduced under alpine field conditions.[1,10] Soil biodiversity and activity have been found to vary strongly with characteristic seasonal microclimatic conditions (snow regime, soil moisture, etc.) and spatial distribution of vegetation.[1]

MAJOR SOILS IN ALPINE BELT AREAS

Using the two current international systems of classification,[2,4] one can find a large variety of alpine soil types over very short distances. However, in the former U.S. soil classification system, the soils of grassy meadows above the timberline were all classified in the "Alpine meadow soils" overgroup of the intrazonal order.[11]

In the steep slopes and in the zone with constant rejuvenation of the profiles, leptosols (Rendzic leptosols over calcareous materials and Umbric leptosols over acid rocks) and regosols[4] are the main soil types found in the alpine belt (Fig. 1). The stability of the slope and the rate of water erosion are the main factors controlling the occurrence of these poorly differentiated soils in the Alpine zone.[3] On stable slopes and over parent materials highly weatherable and providing weathered materials rich in clay (e.g., some micashist), cambisols[4] or inceptisols,[2] frequently deep soils are found.[3,9] On stable slopes and over granular crystalline acid rocks, we can sometimes observe the occurrence of podzols in the Alpine belt.[3] However, the podzolization process is often limited by aeolian dust of calcareous materials.[6,7] Over limestone and parent materials containing both large amounts of phyllosilicates and calcite (calcshale, calcareous micashist, etc.), the rapid and intense decalcification process leads to the formation of a large range of alpine soil from more or less decalcified cambisols[3] to locally true podzols.[8]

The occurrence of poorly drained soils (gleysols) in Alpine environment is common.[5] Their distribution is a function of topography and they show a morphology that is primarily determined by the effect of frost. They may have peat surfaces. Histosols are also frequent in flat topographic situations[1] (Fig. 4).

In wet climate conditions, when the Al availability of the parent rock is high, especially on recent volcanic ash but also in nonvolcanic areas, nonallophanic andisols with high amounts of Al–humus complexes and great accumulation of organic matter have a great extension in the alpine belt.[7,12]

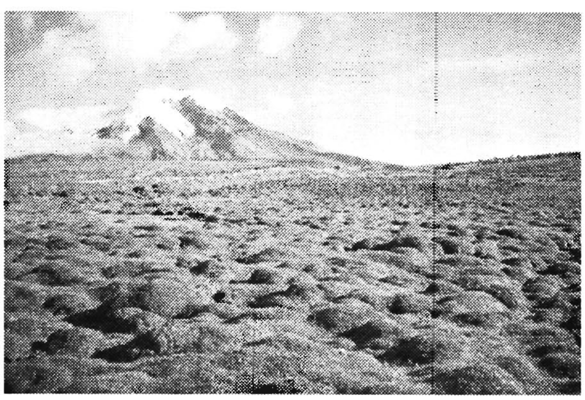

Fig. 4 Cushion plants formation developed over Histosol (see paramo soils entry) (Chimborazo Volcano, Ecuadorian Andes). (Photo from P. Podwojewski.) (*View this art in color at www.dekker.com.*)

ALPINE SOIL LAND USE AND MANAGEMENT

Alpine soils play a major role in the functioning and conservation of the unique alpine ecosystem[1] and in the hydrologic function of mountain belts.[13] Thus change of alpine soil properties linked with land-use change has raised concerns.[1,13] Traditional, man-made alpine pasture near the tree line has been common in all mountainous regions for at least 7000 years.[1,13] In parts of Europe, abandonment of these pastures affects soil dynamics.[1,8] However, in most of the world, Alpine soils are submitted to increasing grazing pressure, leading to rapid degradation and erosion.[13] Other more localized form of alpine land use is the construction of ski runs, which frequently leads to the complete destruction of natural soils. Acid deposition, with the low buffering capacities of thin soil layers in alpine areas, is an other important threat for alpine soils.[1,13]

ALPINE SOIL AND GLOBAL CLIMATE CHANGE

High mountain ecosystems are generally considered to be particularly sensitive to climate warming. Therefore they appear to be useful "ecological indicators" and extensive work has been done to study climate changes in alpine ecosystems.[1,13,14] Overall warming and associated change in precipitation patterns and snow cover will drastically influence alpine vegetation with change in diversity and abundance of certain species. The possible impact of projected climate change on Alpine soils is then firstly linked with the alpine vegetation change.[13,14] As in other regions but possibly with higher intensity, the climate change will influence both carbon balance (C mineralization vs. C sequestration) and mineral balance (weathering vs. erosion) in Alpine soils with apparent contradictory effects. The increase in temperature could substantially increase the depth of soil's active layer, leading to: 1) higher rates of soil organic carbon decomposition but with a longer growth season; and 2) increase of C inflow (increase of the C Pool in Alpine soils). In the same way, the consequences of climate change on the mean soil depth are unclear. With higher temperature, an increase of the weathering rate is anticipated. However, evidences are accumulating that as heavy rainfall events (associated with global warming) become more frequent, erosion of Alpine soils is likely to be enhanced.[1,13,14]

REFERENCES

1. Körner, C. *Alpine Plant Life: Functional Plant Ecology of High Mountain Ecosystems*; Springer-Verlag: Berlin, 1999.

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2. Soil Survey Staff. *Soil Taxonomy. A Basic System of Soil Classification for Making and Interpreting Soil Surveys*; USDA-NRCS: Washington, DC, 1999.
3. Legros, J.P. Soils of Alpine Mountains. In *Weathering, Soils and Paleosols*; Martini, I.P., Chesworth, W., Eds.; Elsevier: Amsterdam, Netherlands, 1992; 155–181.
4. FAO. *World Reference Base for Soil Resources*; 84 World Soil Resources Reports, FAO, ISRIC, ISSS: Rome, 1998.
5. Litaor, M.I. The influence of eaolian dust on the genesis of alpine soils in the front range, Colorado. Soil Sci. Soc. Am. J. **1987**, *51*, 142–147.
6. Bockheim, J.G.; Munroe, J.S.; Douglass, D.; Koerner, D. Soil development along an elevational gradient in the southeastern Uinta Mountains, Utah, USA. Catena **2000**, *39*, 169–185.
7. Allen, C.E.; Burns, S.F. Characterization of Alpine soils, Eagle Cap, Wallowa Mountains, Oregon. Phys. Geogr. **2000**, *20* (3), 212–222.
8. Buurman, P.; Van Der Plas, L.; Slager, S. A toposequence of Alpine soils on Calcareous Micaschists, Northern Adula Region, Switzerland. J. Soil Sci. **1976**, *27*, 395–410.
9. Bartoli, F.; Burtin, G. Etude de quatre séquences sol-végétation à l'étage alpin. Doc. Cartogr. Ecol. **1979**, *XXI*, 79–93.
10. Mancinelli, R.L. Population dynamics of Alpine Tundra soil bacteria, Niwot Ridge, Colorado Front Range, U.S.A. Arct. Alp. Res. **1984**, *16*, 185–192.
11. Thorp, J.; Smith, G.D. Higher categories of soil classification, order, suborder, and great soil groups. Soil Sci. **1949**, *67*, 117–126.
12. Poulenard, J.; Podwojewski, P.; Herbillon, A.J. Characteristics of non-allophanic Andisols with hydric properties from the Ecuadorian Páramos. Geoderma **2003**, *117*, 267–281.
13. Messerli, B.; Ives, J.D. *Mountains of the World—A Global Priority*; The Parthenon Publishing Group: London, 1997.
14. Steininger, K.W.; Weck-Hannemann, H. *Global Environmental Change in Alpine Regions. Recognition, Impact, Adaptation and Mitigation*; Edwar Elgar Publishing: Cheltham, UK, 2002.

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